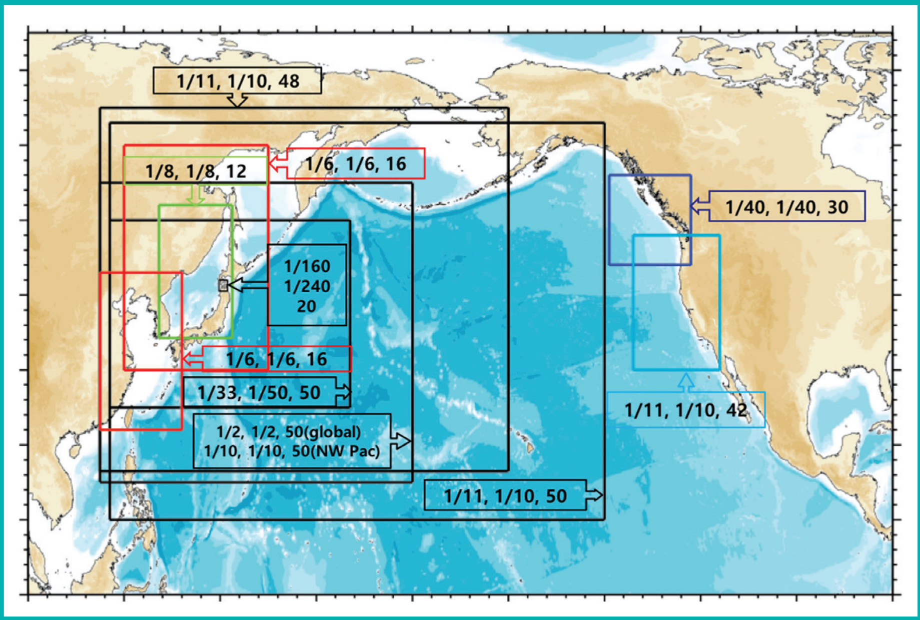
ISBN 978-1-927797-31-0
ISSN 1198-273X

PICES SCIENTIFIC REPORT
No. 54, 2018



Report of Working Group 29 on Regional Climate Modeling

NORTH PACIFIC MARINE SCIENCE ORGANIZATION

PICES

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This report was developed under the guidance of the PICES Science Board and its Biological Oceanography Committee and Physical Oceanography and Climate Committee. The views expressed in this report are those of participating scientists under their responsibilities.

This document should be cited as follows:

Jang, C.J. and Curchitser, E. (Eds.) 2018. Report of Working Group 29 on Regional Climate Modeling. PICES Sci. Rep. No. 54, 177 pp.

PICES Scientific Report No. 54
2018

Report of Working Group 29 on Regional Climate Modeling

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January 2018
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Introduction

In recognition of the important roles of regional climate modeling in providing information on climate variability and change at regional scales and in filling the gap between global climate models (GCMs) and the growing demand for climate predictions and scenarios on highly resolved spatio-temporal scales, PICES Working Group on *Regional Climate Modeling* (WG 29) was established in October 2011 at PICES-2011 in Khabarovsk, Russia. The formation of this Working Group was largely based on recommendations during the International Workshop on "*Development and Application of Regional Climate Models*" held October 2011 in Seoul, Korea on. To accommodate new outputs from CMIP5 models, and to participate in the upcoming 2015 PICES/ICES/IOC Symposium on the "*Effects of climate change on the world's oceans*" in Santos, Brazil, WG 29 was granted an extension of one more year (to 4 years) by Science Board and Governing Council at the PICES-2013 in Nanaimo, Canada. The parent committees of WG 29 were the Physical Oceanography and Climate Committee (POC) and Biological Oceanography Committee (BIO), and the Co-Chairs of the Working Group were Chan Joo Jang and Enrique Curchitser. The Terms of Reference (TORs) and the membership of the Working Group can be found in Appendices 1 and 2.

This report includes:

- An Executive Summary which briefly outlines the achievements of the Working Group as applied to the TORs, and provides recommendations for future follow-up activities within PICES;
- Thirteen sections describing specific activities of the Working Group members (and colleagues) directed at one or more of the TORs; the reports are arranged, starting from a basics for CMIP5 and downscaling, to ocean projection, coupled modeling, atmosphere-focused modeling, and ecosystem modeling;
- The history of WG 29 through its reports from past annual and inter-sessional meetings (Appendix 3), and featured articles in PICES Press issues (Appendix 4).

Executive Summary

Summary of WG 29 activities against each Term of Reference

1. Assemble a comprehensive review of existing regional climate modeling efforts.

   - Before the PICES 2012 Annual Meeting in Hiroshima, Japan, a survey was emailed to WG 29 members to assemble basic information (*e.g.*, model type, domain, and resolution) and future directions of regional climate modeling by each member country. The regional climate models developed by members cover most of the North Pacific Ocean, ranging from local- to basin-scale, and the purposes of these models range from short-term forecasting to future climate projections. Most of the regional climate modeling pursuits by members and other colleagues are summarized in the section on "Activities of Working Group Members".

   - To provide information on data resources of global climate models (CMIP5) that can be used as boundary conditions for regional climate modeling, Christian and Jang (subsection 1) summarized some essential information of CMIP5 outputs including lists of models, surface forcing fields, experiments and ocean biogeochemistry fields.

2. Assess the requirements for regional ecosystem modeling studies (*e.g.*, how to downscale the biogeochemistry).

   - Along lateral boundaries of an RCM (Regional Climate Model), biogeochemical as well as physical variables need to be specified. In particular, the inorganic components (*e.g.*, nutrients, dissolved inorganic carbon, alkalinity) of a biogeochemical model are required whereas the organic components (*e.g.*, plankton and organic particles) reach an internal equilibrium very fast, being insensitive to boundary values.

   - Observed biogeochemistry data are very limited in space and time so that, in many cases, either climatological values or data from basin- or global-scale models are used to set initial and boundary conditions. It is still uncertain how the coarse spatial resolution of initial conditions and lack of interannual and seasonal variability at the boundaries influence model results. In CMIP5, physical variables are available as three-dimensional monthly fields whereas ocean three-dimensional biogeochemical fields (NO_3, Si, DIC, Alk and O_2) are available only as annual means.

3. Continue the development of RCM implementations in the North Pacific and its marginal seas.

   - North Pacific RCMs that have been developed or are under development by WG 29 members and colleagues are covered in the "Activities of Working Group Members" section:

     ✓ The British Columbia shelf (Foreman *et al.*);

     ✓ The Northwest Pacific Ocean (Jang *et al.*, Seo *et al.*, Ito *et al.*, Li *et al.*, Hasumi, and Kuroda *et al.*);

  - ✓ The waters off Primorye (Stephanov *et al*.);
  - ✓ Ocean–atmosphere coupled models (Jang *et al*. and Li *et al*., and Song *et al*.);
  - ✓ Ecosystem modelling (Kang *et al*. and Peña *et al*.).

- Foreman *et al*. (2014) described future climate changes for the British Columbia continental shelf and offshore waters based on an RCM (ROMS Regional Ocean Modeling System) with pseudo-global warming in which the future-minus-contemporary anomalies from the Canadian Regional Climate Model were applied. (See their section for more details.)

- For future climate projection for the Northwest Pacific focusing on Korean waters, Jang *et al*. (this report) developed a regional ocean–atmosphere coupled model based on the COAWST (Coupled Ocean–Atmosphere–Wave–Sediment Transport) modeling system (Warner *et al*., 2010) and have presented preliminary results on the sea surface temperature changes.

- Seo *et al*. (2014) presented future climate changes in the Northwest Pacific marginal seas projected by dynamical downscaling using an RCM constrained by three different global climate model (GCM) projections. (See their section for more details.)

- Ito *et al*. (this report) introduced the current status of RCMs, coupled with lower trophic ecosystem models in many cases, which have been developed by the Japanese community for the Northwest Pacific and its marginal seas.

- Hasumi (this report) introduced a two-way nested-grid modeling system for the Northwest Pacific and Japanese coasts to overcome a limitation of one-way downscaling for future climate change projections.

- Kuroda *et al*. (this report) presented the current status of an RCM forecast system (called FRA-ROMS) for nowcasting and two-month forecasting, which is being coupled to lower trophic ecosystem models.

- Stepanov *et al*. (this report) investigated atmospheric forcing induced climate variability of the circulation in the Primorye and Tsushima Current systems for the years 1948–2009 using the INMOM (Institute of Numerical Mathematics Ocean Model) regional model and suggested that interannual variability of the cyclonic gyre is associated with variability of the positive wind stress curl in the northern basin.

- Li *et al*. (this report) introduced the development of a new atmosphere–wave–ocean RCM for the Asia–Australia monsoon region based on the COAWST (Coupled-Ocean-Atmosphere-Wave-Sediment Transport) model framework and applications to hindcast and forecast experiments.

- Based on a moisture budget analysis, Jung *et al*. (2015) analyzed future changes in the East Asian summer monsoon as projected by dynamical downscaling using a WRF (Weather Research and Forecasting) atmospheric model (Skamarock *et al*., 2008). (See the section by Jang *et al*. for more details.)

- Song *et al*. (2013) analyzed the summer mean water vapor transport (WVT) and cross-equatorial flow over the Asian–Australian monsoon region from 22 CMIP5 models and suggested that WVT is projected to strengthen over the Indian Ocean and northwestern Pacific, and weaken in the low latitudes of the tropical Indian Ocean. (See their section for more details.)

- Kang *et al*. (this report) presented preliminary results on marine ecosystem variability in the East Asian marginal seas simulated from a circulation–ecosystem coupled model (POLCOMS-ERSEM).
- Peña *et al*. (this report) presented ecosystem future changes on the west coast of Canada.

4. Convene special sessions and inter-sessional workshops dedicated to the RCM topic.
   - Three WG 29 members co-convened an international workshop entitled "*Regional climate models-II*" (2013, Busan, Korea);
   - Four WG 29 members co-convened a topic session entitled "*Recent trends and future projections of North Pacific climate and ecosystems*" at PICES-2013 (Nanaimo, Canada);
   - Six WG 29 members co-convened a topic session entitled "*Regional climate modeling in the North Pacific*" at PICES-2014 (Yeosu, Korea);
   - A WG 29 member co-convened a session entitled "*Regional models for predictions of climate change impacts: methods, uncertainties and challenges*" at the 3rd PICES/ICES/IOC International Symposium on "*Effects of climate change on the world's oceans*" (2015, Santos City, Brazil);
   - A WG 29 member co-convened a session entitled "*Recent advances in regional climate modeling: Development challenges and applications*" at AOGS (Asia Oceania Geosciences Society) 12th Annual Meeting (2015, Singapore);
   - Four WG 29 members co-convened a topic session entitled "*Past, present, and future climate in the North Pacific Ocean: Updates of our understanding since IPCC AR5*" at PICES-2015 (2015, Qingdao, China).
5. Publish report and/or review paper on best practices for regional coupled modeling.
   - Three RCM-related PICES Press articles were published in 2012 and 2014 (see Appendix 4).
6. Establish connections between PICES and climate organizations (*e.g*., CLIVAR) and global climate modeling centers (*e.g*., NCAR, JAMSTEC, CCCMA).
   - Two WG 29 members (Qiao and Curchitser) are also members of the CLIVAR Ocean Model Development Panel, and so they have been actively involved in CLIVAR RCM-related activities.
   - Shoshiro Minobe, a member of the CLIVAR Climate Dynamics Panel, presented several RCM-related talks at PICES Annual Meetings.
   - Ito was invited to present regional modeling efforts for climate change impacts on small pelagic fishes in the western North Pacific at an RCM-related session (*Regional models for predictions of climate change impacts: methods, uncertainties and challenges*" at the 3rd International Symposium on "*Effects of climate change on the world's oceans*" (March 23–27 2015, Santos City, Brazil).
   - Experts from different climate organizations or institutes were invited to give presentations at RCM-related sessions at PICES Annual Meetings to foster collaboration for RCM development: for example, Minobe (CLIVAR), Im (SMART, Singapore-MIT Alliance for Research and Technology), Kang (NIMR, National Institute of Meteorological Research, Korea), Sakamoto (MRI, Meteorological Research Institute, Japan) and Seo (WHOI, Woods Hole Oceanographic Institution,

USA), Yu (State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, China)

- Qiao and Jang co-convened a session entitled "*Ocean and climate model development and applications*" at the 10th IOC/WESTPAC International Conference on "*Advancing ocean knowledge, fostering sustainable development: from the Indo-Pacific to the globe*" (2017 Qingdao, China), providing an opportunity to discuss the status of RCM development by PICES and IOC-WESTPAC member countries.

- Ito presented some WG 29 activities at the session on "*Transformative pathways to sustain marine ecosystems and their services under climate change*" at the International Scientific Conference on "*Our common future under climate change*" (2015, Paris, France), contributing to international partnerships, including Future Earth.

7. Collaborate with other PICES expert groups such as WG 27, S-CCME and the FUTURE Advisory Panels possibly by producing "Outlooks".

   - Jang and Ito were invited to present WG 29 activities at a S-CCME workshop entitled "ICES/PICES Workshop on "*Modelling effects of climate change on fish and fisheries*" (2015, Seattle, USA).

   - WG 29 members, including Co-Chairs Jang and Curchitser, were also members of WG 27 which allowed exchange of information between the two groups, including active contributions to WG 27, in particular, to TOR 2 on Pacific climate variability.

8. Publish a final report summarizing results.

This report summarizes the WG 29 activities.

Recommendations

1. The development of Regional Climate Models (RCMs) around the North Pacific should be continued. In particular, PICES should provide a venue for attracting modelers from other disciplines including atmospheric regional modeling, land surface modeling, and sea-ice modeling. These RCMs will be coupled increasingly to more modeling components including sea-ice and atmosphere, resulting in regional Earth system models or integrated regional models that can provide more integrated information on climate variability and change at regional scales.
2. The imperfect knowledge and model description of biogeochemical processes represent a critical source of uncertainty when performing climate projections. Further work should be promoted to compare model configurations and results, carry out sensitivity analysis and identify critical observations needed to run and validate models. This work would characterize uncertainties with more confidence and improve future projections of ecosystems.
3. WG 29 mainly focused on downscaling issues; however, upscaling effects are important regarding future projections. Biastoch *et al*. (2014) demonstrated the importance of regional air–sea coupling for the global climate. In addition, Small *et al*. (2015) demonstrated the importance of proper treatments of air–sea interaction at the coastline. Some recent studies also suggested the importance of high

frequency (hourly) atmospheric forcing to ocean circulation. Other studies suggested the importance of strong oceanic frontal effects on synoptic-scale atmospheric phenomena. Further elucidation of regional climate modeling challenges, including full coupled regional climate modeling, should be continued under PICES activities.

4. A new working group to investigate oceanic mesoscale and submesocale processes and their interactions should be created since mesoscale and submesocale phenomena affect not only their own scales but also regional- and global-scale climate. Although mesoscale processes, including fronts and eddies at 10 to 100 km spatial scales have been actively studied for their dynamics and effects on ecosystem variability, submesocale processes at an order of a 1- to 10-km scale and associated ecosystem processes have been less well known. A draft proposal for this new working group entitled "Mesoscale and Submesoscale Processes" was presented to the Science Board meeting at PICES-2016 in San Diego, USA. The working group should be under the direction of the Physical Oceanography and Climate (POC) (and possibly Biological Oceanography (BIO)) committee(s).[1]

5. Microstructure and mixing turbulence are other issues of ocean phenomena which current regional climate models cannot resolve well enough. For material transport, including nutrients, mixing is one of the most important processes and hence is vital for biological production. Of course, geographical distributions of mixing intensity have an influence on global thermohaline circulation. Therefore, further investigation on mixing processes and their parameterization in regional climate models is recommended.

6. Tidal forces are one of important driving forces in the ocean. However, only a few climate models have incorporated the tidal components. Tides are also important for ocean mixing processes especially when the bottom topography or horizontal coastlines are complex. Interactions between tides and topography sometimes have an influence on water formations and circulations, and hence on the regional and global climate. More regional climate modeling efforts incorporating tidal effects are recommended.

7. As the scale of phenomena become smaller, the time scales become shorter. This fact indicates the difficulties in conducting systematic observations for the phenomena regarding climate issues. To improve regional climate models, of course, validation of observational data is essential. Integrated observations using high resolution satellites (*e.g.*, SWAT), research vessels, Argo floats, underwater gliders, microstructure profilers, *etc*. are recommended.

8. Live-access servers or ftp sites and links to RCM/GCM websites should be created to archive and provide easy access to results from North Pacific RCMs, analogous to the Program for Climate Model Diagnosis and Intercomparison (PCMDI) archive for International Panel on Climate Change GCM results. Related observations and historical re-analyses could also be included on this site. The RCM output would provide fishery scientists with climate change variables on much finer spatial scales than can be resolved with the GCMs.

9. PICES needs to suggest (or, at least contribute to) the initiation of a coordinated regional ocean climate downscaling experiment for improved regional climate change projections for many regions of the global ocean. CLIVAR may be one of the possible organizations to collaborate with to initiate this program. In CMIP6, there are more than 20 CMIP6-endorsed Model Intercomparison Projects (MIPs), most of which deal with global models. One exception is CORDEX (Coordinated Regional Climate

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[1] The new working group was endorsed by Science Board and approved by Governing Council and was established in November 2016. The Terms of Reference for the Working Group on *Mesoscale and Submesoscale Processes* can be found on the PICES website at http://meetings.pices.int/members/working-groups/wg38.

Downscaling Experiment project), but its major concern is terrestrial regional climate, not the ocean. The coordinate regional ocean climate downscaling experiment, if it started, could contribute to reducing uncertainties in future ocean climate change projections by providing many ensemble RCM experiments for the same regions. Through this project, PICES could contribute not only to North Pacific climate study communities, but also to global ocean study communities.

References

Biastoch, A., Curchitser, E., Small, R. and Boning, C. 2014. Nested ocean modelling. CLIVAR Exchanges, No. 65, Vol. 19, No. 2, pp. 52–55.

Foreman, M.G.G., Callendar, W., Masson, D., Morrison, J. and Fine, I. 2014. A model simulation of future oceanic conditions along the British Columbia continental shelf, Part II: Results and analyses. *Atmos.–Ocean* **52**: 20–38, doi:10.1080/07055900.2013.873014.

Jung, C.Y., Shin, H.-J., Jang, C.J. and Kim, H.J. 2015. Projected change in East Asian summer monsoon by dynamic downscaling: Moisture budget analysis. *Asia-Pacific J. Atmos. Sci*. **51**: 77–89.

Seo, G.-H., Cho, Y.-K., Choi, B.-J., Kim, K.-Y., Kim, B. and Tak, Y. 2014. Climate change projection in the Northwest Pacific marginal seas through dynamic downscaling. *J. Geophys. Res*. **119**: 3497–3516, doi:10.1002/2013JC009646.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X-Y., Wang, W. and Powers, J.G. 2008. A description of the Advanced Research WRF Version 3. NCAR Technical Note NCAR/TN–475+STR, National Center for Atmospheric Research, Boulder, Colorado, USA, 123 pp.

Small, R.J., Curchitser, E., Hedstrom, K., Kauffman, B.G. and Large, W.G. 2015. The Benguela upwelling system: Quantifying the sensitivity to resolution and coastal wind representation in a global climate model. *J. Climate* **28**: 9409–9432, doi:10.1175/JCLI-D-15-0192.1

Song, Y., Qiao, F., Song, Z. and Jiang, C. 2013. Water vapor transport and cross-equatorial flow over the Asian-Australia monsoon region simulated by CMIP5 climate models. *Adv. Atmos. Sci*. **30**: 726–738.

Warner, J.C., Armstrong, B., He, R. and Zambon, J.B. 2010. Development of a coupled ocean–atmosphere–wave–sediment transport (COAWST) modeling system. *Ocean Model*. **35**: 230–244.

Activities of Working Group Members

1. CMIP5 data resources for downscaling climate projections

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Introduction

Global climate models (GCMs) provide information about future climates, both seasonal to decadal predictions and longer-term projections using forcing scenarios which are usually based on anthropogenic emissions of greenhouse gases (GHG) and aerosols. These projections can be downscaled using higher resolution regional ocean-only, atmosphere-only, or ocean–atmosphere coupled models. While regional coupled models can also be used for climate prediction (*e.g.*, Chen and Cane, 2008) and can simulate additional feedback processes that may enhance the realism of the downscaling model simulation, most regional models are forced atmosphere-only or ocean-only models. We focus here on regional ocean models which will normally be forced with surface fluxes (heat flux, wind stress) derived from observationally based reconstructions of past and present climate (reanalysis) or from projections made with GCMs, although much of what we discuss will be applicable to regional coupled models as well (*e.g.*, open ocean boundary conditions).

The fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor *et al*., 2012) provides an unprecedented archive of GCM output to the global user community. All of these data are in the public domain and are archived in an accessible standardized netCDF format. An important innovation relative to previous experiments is that ocean biogeochemistry fields (*e.g.*, dissolved inorganic carbon (DIC), dissolved oxygen, inorganic nutrient concentrations) have been included for the first time. Although three-dimensional ocean biogeochemistry fields in CMIP5 models are available only as annual means, these biogeochemistry data provide an unprecedented opportunity to define boundary conditions for regional ecosystem models. Fields are ranked priority 1, 2, or 3, depending on perceived demand: priority 1 fields are those for which demand is expected to be high, and all groups are expected to provide them if at all possible. CMIP5 also employs a new family of emissions scenarios known as Representative Concentration Pathways (RCPs) (Moss *et al*., 2010).

CMIP5 includes a broad range of experiments in addition to the historical and RCP experiments that will be most familiar to most readers. These experiments represent the best available simulation of historical (1850–2005) climate and several plausible scenarios for future (2006–2100) climate, ranging from the "strong mitigation" RCP2.6 (anthropogenic GHG emissions peak early and then decline) to the "no mitigation" RCP8.5 (anthropogenic GHG emissions continue to increase through 2100). Additional experiments include, for example, an abrupt increase in atmospheric CO_2 concentration to four times preindustrial, and a steady increase of 1% per year (a fourfold increase over 140 years). These idealized forcing scenarios are useful for some applications but are of little interest to the downscaling community and are not considered further in this section. Similarly, decadal prediction experiments could conceivably be downscaled, but even the theoretical best achievable forecast skill is quite low, so it is unlikely that downscaling such experiments would have much practical utility.

An important consideration is that GCMs can reproduce climate variability only in a statistical sense: the timing of particular changes or events can never be simulated accurately. In the North Pacific, where natural variability is large, this means that climate projections can only be a meaningful representation of future climate if the anthropogenic forcing is large relative to natural variability. To downscale a projected climate only 10 to 15 years from the present is of questionable value, as errors in the phasing of natural variability are likely to exceed the increase in anthropogenic forcing. It is also important when defining "time slice" experiments to average at least 20 years to minimize the influence of internal variability (the climate model's equivalent of natural climate variability) (Sen Gupta *et al.*, 2009). CMIP5 experiments also include multiple ensemble members (simulations with identical forcing but different initial conditions) and averaging across these to minimize the effects of internal variability may, in some cases, be feasible but whether multiple ensemble members are actually available varies among data fields, models, and experiments.

Improvement in model resolution since CMIP3

For model performance, grid size or resolution is one of the most important factors. Most of the CMIP5 ocean models have an irregular grid (see Table 1.3), so resolution varies in space. One way to estimate the average resolution is to divide 360° (*x* direction) or 180° (*y* direction) by the total number of the grid points. Figure 1.1 shows histograms of horizontal (zonal) and vertical resolution in CMIP3 (Meehl *et al.*, 2007) and CMIP5 models (the *y* direction resolution is assumed to be similar to the *x* direction). In the horizontal direction, most CMIP5 models have 1° to 2° resolution and models with a grid size of 3° to 4° are rare, indicating moderate improvements in CMIP5 compared with CMIP3. For vertical resolution, most CMIP5 models have more than 40 levels, while CMIP3 models have fewer on average, indicating a possibility of better representation of, for example, vertical mixing.

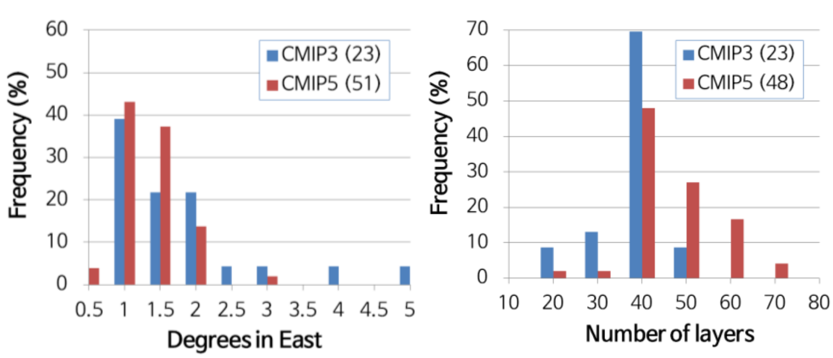

Fig. 1.1 Histograms of the resolution of CMIP5 (red) and CMIP3 (blue) ocean models: (left) approximate horizontal grid size in the east–west direction and (right) number of vertical levels. The numbers shown in parentheses indicate the total number of models used for the evaluation.

A review of available data

Table 1.1 lists all of the models that could be confirmed as having contributed data to CMIP5. It is important to note that the way the Earth System Grid works makes it very difficult to confirm that particular data do not exist. When a search is submitted, datasets are listed only if the node from which they are served is currently available. So it is possible that we missed a few models or listed them as not including biogeochemistry fields simply because those data were not available at the time we conducted our searches. We have tried to be as exhaustive and accurate as possible in documenting the available models. Table 1.1 includes all models listed in the table at http://cmip-pcmdi.llnl.gov/cmip5/availability.html.

Table 1.1 List of climate models available in the CMIP5 data archive.

Model name	Sponsoring organization	Host country	Ocean biogeochemistry
ACCESS1-0	Bureau of Meteorology / CSIRO	Australia	N
ACCESS1-3	Bureau of Meteorology / CSIRO	Australia	N
bcc-csm1-1	Beijing Climate Centre, China Meteorological Administration	China	Y*
bcc-csm1-1-m	Beijing Climate Centre, China Meteorological Administration	China	Y*
BNU-ESM	Beijing Normal University	China	Y*
CanCM4	Canadian Centre for Climate Modelling and Analysis	Canada	N
CanESM2	Canadian Centre for Climate Modelling and Analysis	Canada	Y
CCSM4	National Center for Atmospheric Research	United States	N
CESM1-BGC	National Center for Atmospheric Research	United States	Y
CESM1-CAM5	National Center for Atmospheric Research	United States	Y
CESM1-CAM5-1-FV2	National Center for Atmospheric Research	United States	Y
CESM1-FASTCHEM	National Center for Atmospheric Research	United States	Y
CESM1-WACCM	National Center for Atmospheric Research	United States	Y
CMCC-CESM	European Network for Earth System Modelling	Italy	Y
CMCC-CM	European Network for Earth System Modelling	Italy	N
CMCC-CMS	European Network for Earth System Modelling	Italy	N
CNRM-CM5-2	Centre National de Recherches Météorologiques	France	N
CNRM-CM5	Centre National de Recherches Météorologiques	France	Y
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation	Australia	N
EC-EARTH	EC-EARTH consortium	**	N
FGOALS-g1	Institute of Atmospheric Physics, Chinese Academy of Sciences	China	N
FGOALS-g2	Institute of Atmospheric Physics, Chinese Academy of Sciences	China	N
FGOALS-s1	Institute of Atmospheric Physics, Chinese Academy of Sciences	China	N
FGOALS-s2	Institute of Atmospheric Physics, Chinese Academy of Sciences	China	N

Table 1.1 Continued.

Model name	Sponsoring organization	Host country	Ocean biogeochemistry
FIO-ESM	First Institute of Oceanography	China	Y*
GFDL-CM2p1	NOAA Geophysical Fluid Dynamics Laboratory	United States	N
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory	United States	N
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	United States	Y
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	United States	Y
GISS-E2-H	NASA Goddard Institute for Space Studies	United States	N
GISS-E2-H-CC	NASA Goddard Institute for Space Studies	United States	Y
GISS-E2-R	NASA Goddard Institute for Space Studies	United States	N
GISS-E2-R-CC	NASA Goddard Institute for Space Studies	United States	Y
HadCM3	UK Met Office Hadley Centre	United Kingdom	N
HadGEM2-AO	UK Met Office Hadley Centre	United Kingdom	N
HadGEM2-CC	UK Met Office Hadley Centre	United Kingdom	N
HadGEM2-ES	UK Met Office Hadley Centre	United Kingdom	Y
inmcm4	Institute for Numerical Mathematics	Russia	Y*
IPSL-CM5A-LR	Institut Pierre Simon Laplace	France	Y
IPSL-CM5A-MR	Institut Pierre Simon Laplace	France	Y
IPSL-CM5B-LR	Institut Pierre Simon Laplace	France	Y
MIROC5	JAMSTEC / NIES / University of Tokyo	Japan	N
MIROC4h	JAMSTEC / NIES / University of Tokyo	Japan	N
MIROC-ESM	JAMSTEC / NIES / University of Tokyo	Japan	Y
MIROC-ESM-CHEM	JAMSTEC / NIES / University of Tokyo	Japan	Y
MPI-ESM-LR	Max Planck Institute for Meteorology	Germany	Y
MPI-ESM-MR	Max Planck Institute for Meteorology	Germany	Y
MPI-ESM-P	Max Planck Institute for Meteorology	Germany	N
MRI-CGCM3	Japan Meteorological Agency	Japan	N
MRI-ESM1	Japan Meteorological Agency	Japan	Y
NorESM1-M	EarthClim Consortium	Norway	N
NorESM1-ME	EarthClim Consortium	Norway	Y

* These models have highly parameterized ocean biogeochemistry and provide ocean surface pCO_2 and CO_2 flux but little else.
** EC-EARTH is a consortium of European countries, with no single host country or institution.

CMIP5 data consist of seven "realms" of which only four are of interest here: atmosphere, ocean, sea ice, and ocean biogeochemistry. Grids differ among realms: in most cases the atmosphere grid will be coarser than the ocean grid. Sea ice and ocean biogeochemistry fields are normally on the ocean grid. There is some nonuniformity in the CMIP5 dataset, *e.g.*, some models may have particular fields on the atmosphere grid that were generally on the ocean grid (*e.g.*, sea ice cover in CanESM2, air–sea CO_2 flux in MIROC-ESM).

To run a regional ocean model requires surface forcing and lateral boundary conditions. Surface forcing is normally specified in either a "flux" or "bulk formula" mode, the former specifying net heat and freshwater fluxes directly and the latter calculating them from the atmosphere state (air temperature, humidity, *etc*.). In CMIP5 models, these fields will be on the atmosphere grid in most cases. Sea ice cover is also potentially necessary for some regions of interest to PICES member countries (*e.g.*, the Bering Sea). Of course sea ice adds another dimension of complexity to the problem of how to specify surface fluxes.

Some fields are available on both atmosphere and ocean grids but do not necessarily represent exactly the same physical quantity in each case (Table 1.2). The variables tauuo and tauvo specifically represent wind stress on the ocean surface and therefore, are likely to be preferred to the more generic tauu and tauv by most users. Note that these are both priority 1 fields. A number of other ocean surface fields (mainly various subcomponents of the net heat, salt and freshwater fluxes) are priority 2 (Table 1.2) and therefore, may not be widely available. While both wind speed and wind stress variables are available on the atmosphere grid, wind speed may be needed to calculate air–sea gas exchange rates in biogeochemical models. While gas exchange coefficients and wind stress both scale approximately with the square of the wind speed, it can be difficult or impossible to estimate exchange coefficients from wind stress if the drag coefficient is not constant, and some groups may choose to use alternate gas flux parameterizations with different scaling (*e.g*., McGillis *et al*., 2004).

Table 1.2 List of surface forcing fields available in CMIP5 database.

Description	CMIP5 name[1]	Unit	Grid	Priority
Near-surface air temperature	tas	K	atmosphere	1
Surface air pressure[2]	ps	Pa	atmosphere	1
Precipitation	pr	kg m^{-2} s^{-1}	atmosphere	1
Snowfall	prsn	kg m^{-2} s^{-1}	atmosphere	1
Evaporation	evspsbl	kg m^{-2} s^{-1}	atmosphere	1
Near-surface specific humidity	huss	kg kg^{-1}	atmosphere	1
Surface upward latent heat flux	hfls	W m^{-2}	atmosphere	1
Surface upward sensible heat flux	hfss	W m^{-2}	atmosphere	1
Surface downwelling longwave radiation	rlds	W m^{-2}	atmosphere	1
Surface upwelling longwave radiation	rlus	W m^{-2}	atmosphere	1
Surface downwelling shortwave radiation	rsds	W m^{-2}	atmosphere	1
Surface upwelling shortwave radiation	rsus	W m^{-2}	atmosphere	1
Sea surface temperature	tso	K	atmosphere	1
Surface downward eastward wind stress	tauu	Pa	atmosphere	1
Surface downward northward wind stress	tauv	Pa	atmosphere	1

Table 1.2 Continued.

Description	CMIP5 name	Unit	Grid	Priority
Eastward near-surface wind speed	uas	m s^{-1}	atmosphere	1
Northward near-surface wind speed	vas	m s^{-1}	atmosphere	1
Surface downward eastward wind stress	tauuo	Pa	ocean	1
Surface downward northward wind stress	tauvo	Pa	ocean	1
Rainfall flux to ice-free ocean	pr	kg m^{-2} s^{-1}	ocean	2
Snowfall flux to ice-free ocean	prsn	kg m^{-2} s^{-1}	ocean	2
Water evaporation flux from ice-free ocean	evs	kg m^{-2} s^{-1}	ocean	2
Water flux into sea water from rivers	friver	kg m^{-2} s^{-1}	ocean	2
Water flux into sea water from icebergs	ficeberg	kg m^{-2} s^{-1}	ocean	2
Water flux into sea water due to sea ice thermodynamics[3]	fsitherm	kg m^{-2} s^{-1}	ocean	1
Water flux into sea water[4]	wfo	kg m^{-2} s^{-1}	ocean	2
Virtual salt flux into sea water due to rainfall	vsfpr	kg m^{-2} s^{-1}	ocean	2
Virtual salt flux into sea water due to evaporation	vsfevap	kg m^{-2} s^{-1}	ocean	2
Virtual salt flux into sea water from rivers	vsfriver	kg m^{-2} s^{-1}	ocean	2
Virtual salt flux into sea water due to sea ice thermodynamics[3]	vsfsit	kg m^{-2} s^{-1}	ocean	1
Virtual salt flux into sea water[4]	vsf	kg m^{-2} s^{-1}	ocean	2
Downward sea ice basal salt flux[3]	sfdsi	kg m^{-2} s^{-1}	ocean	1
Salt flux into sea water from rivers	sfriver	kg m^{-2} s^{-1}	ocean	2
Temperature flux due to rainfall expressed as heat flux into sea water	hfrainds	W m^{-2}	ocean	2
Temperature flux due to evaporation expressed as heat flux out of sea water	hfevapds	W m^{-2}	ocean	2
Temperature flux due to runoff expressed as heat flux into sea water	hfrunoffds	W m^{-2}	ocean	2

[1] See https://www.dkrz.de/up/services/data-management/projects-and-cooperations/ipcc-data/cmip5-variables for variable definitions.
[2] Surface air pressure is different from sea level pressure but the difference is small over the ocean.
[3] This was originally a priority 2 field but was raised to priority 1 at the request of the sea ice modelling community.
[4] This is further divided into a flux-correction and non-flux-correction component; we are assuming no flux correction.

Lateral boundary conditions will normally consist of temperature, salinity, and biogeochemical fields, including dissolved inorganic carbon (DIC), alkalinity, oxygen, and inorganic nutrients (nitrate, phosphate, silicate). In some cases it will also be necessary to specify current velocities or transports at the open boundaries. Most models will not have all of the biogeochemical fields, and in some cases (particularly phosphate and silicate) the number of CMIP5 models supplying them will be small. Particulates and plankton biomass variables have negligible sensitivity to initial and boundary conditions (*i.e.*, they reach internal equilibrium very quickly) and can normally be ignored at open boundaries. Dissolved organic carbon (DOC) is somewhere in between (mean turnover time of 1–2 years); a fair number of CMIP5 models include DOC but do not all define it in the same way (Anderson *et al.*, 2014). Ocean biogeochemistry fields are available only as annual means in CMIP5, except for two-dimensional fields such as surface nutrient concentrations and diagnostic quantities such as primary production. Ocean temperature (T), salinity (S), and horizontal velocities are available as three-dimensional monthly fields.

Table 1.3 lists the confirmed availability of ocean three-dimensional fields (excluding salinity and velocities) for the models shown in Table 1.1. It is assumed that if a particular experiment was conducted with a particular model, temperature, salinity and horizontal velocities (these are core outputs of any GCM, but not all experiments are run with all models) would be posted. Biogeochemistry fields, on the other hand, are highly model specific, so Table 1.3 lists all of the ones likely to be required for downscaling experiments. A few models are neglected because the differences from other model variants are negligible from an ocean perspective (*e.g.*, MIROC-ESM-CHEM is the same as MIROC-ESM but with active atmospheric chemistry).

Table 1.3 List of experiments and ocean biogeochemistry fields verified to be available via the Earth System Grid (ESG). If an experiment was posted, it is assumed that basic ocean fields (temperature, salinity, velocities) are available. Biogeochemistry fields vary from model to model; it is assumed that they do not vary among experiments within a particular model.

Model	**Grid**	**Experiment**				**Biogeochemistry fields**						
		hist	rcp26	rcp45	rcp85	dissic	talk	o2	no3	po4	silicate	dissoc
ACCESS1-0	I	×		×	×							
ACCESS1-3	I	×		×	×							
bcc-csm1-1	I	×		×	×							
bcc-csm1-1-m	I	×										
BNU-ESM	I	×			×	×	×	×		×		
CanCM4	C	×		×								
CanESM2	C	×	×	×	×	×	×		×			
CCSM4	I	×		×								
CESM1-BGC	I	×		×	×	×	×	×	×	×	×	×
CMCC-CESM	I	×			×	×	×	×	×	×		×
CMCC-CM	I	×		×	×							
CMCC-CMS	I	×		×	×							
CNRM-CM5	I	×	×	×	×	×	×	×	×	×	×	×
CSIRO-Mk3-6-0	C	×		×								
EC-EARTH	I	×		×								
FGOALS-g2	C	×	×		×							
FGOALS-s2	C	×	×		×							
FIO-ESM	I	×	×	×	×							
GFDL-CM2p1	I	×		×								
GFDL-CM3	I	×		×								

Table 1.3 Continued.

Model	Grid	Experiment				Biogeochemistry fields						
		hist	rcp26	rcp45	rcp85	dissic	talk	o2	no3	po4	silicate	dissoc
GFDL-ESM2G	I	×	×	×	×	×	×	×	×	×	×	×
GFDL-ESM2M	I	×	×	×	×	×	×	×	×	×	×	×
GISS-E2-H	C	×	×	×	×							
GISS-E2-H-CC	C	×		×	×	×			×		×	×
GISS-E2-R	C	×	×	×	×							
GISS-E2-R-CC	C	×		×	×	×			×		×	×
HadCM3	C	×		×								
HadGEM2-AO	C	×	×	×	×							
HadGEM2-CC	C	×		×		×	×	×	×		×	
HadGEM2-ES	C	×	×	×	×	×	×	×	×		×	
inmcm4	I	×		×	×	×						
IPSL-CM5A-LR	I	×	×	×	×	×	×	×	×	×	×	×
IPSL-CM5A-MR	I	×	×	×	×	×	×	×	×	×	×	×
IPSL-CM5B-LR	I	×		×	×	×	×	×	×	×	×	×
MIROC-ESM	C	×	×	×	×	×	×		×			
MIROC-ESM-CHEM	C	×	×	×	×	×	×		×			
MIROC5	C	×	×	×	×							
MIROC4h	C	×		×								
MPI-ESM-LR	I	×	×	×	×	×	×	×	×	×	×	×
MPI-ESM-MR	I	×	×	×	×	×	×	×	×	×	×	×
MPI-ESM-P	I	×										
MRI-CGCM3	I	×	×	×	×							
MRI-ESM1	I	×			×	×	×	×	×	×		×
NorESM1-M	I	×	×	×	×							
NorESM1-ME	I	×	×	×	×	×	×	×	×			×

I signifies irregular grid models; C signifies Cartesian grid.

See https://www.dkrz.de/up/services/data-management/projects-and-cooperations/ipcc-data/cmip5-variables for variable definitions.

Shading indicates that these models do not have ocean biogeochemistry, or no three-dimensional biogeochemistry fields were identified as available for the experiments listed here.

References

Anderson, T., Christian, J. and Flynn, K. 2014. Modeling DOM biogeochemistry, pp. 635–667 *in* Biogeochemistry of Marine Dissolved Organic Matter *edited by* D. Hansell and C. Carlson, Elsevier, Amsterdam.

Chen, D. and Cane, M. 2008. El Niño prediction and predictability. *J. Comput. Phys*. **227**: 3625–3640.

McGillis, W.R., Edson, J.B., Zappa, C.J., Ware, J.D., McKenna, S.P., Terray, E.A., Hare, J.E., Fairall, C.W., Drennan, W., Donelan, M., DeGrandpre, M.D., Wanninkhof, R. and Feely, R.A. 2004. Air-sea CO_2 exchange in the equatorial Pacific. *J. Geophys. Res.* **109**: doi:10.1029/2003JC002256.

Meehl, G., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J., Stouffer, R. and Taylor, K. 2007. The WCRP CMIP3 multimodel dataset – A new era in climate change research. *Bull. Amer. Meteor. Soc*. **88**: 1383–1394.

Moss, R., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F., Nakicenovic, N.Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P. and Wilbanks, T.J. 2010. The next generation of scenarios for climate change research and assessment. *Nature* **463**: 747–756.

Sen Gupta, A., Santoso, A., Taschetto, A.S., Ummenhofer, C.C., Trevena, J. and England, M.H. 2009. Projected changes to the Southern Hemisphere ocean and sea ice in the IPCC AR4 climate models. *J. Climate* **22**: 3047–3078.

Taylor, K., Stouffer, R. and Meehl, G. 2012. An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc*. **93**: 485–498.

2. *A Regional Climate Model simulation for the British Columbia continental shelf and offshore waters*

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Introduction

In this section we describe results from a future climate simulation for the British Columbia (BC) continental shelf and offshore waters. This research was supported by several agencies within Fisheries and Oceans Canada (see Acknowledgements) and greatly benefited from workshops organized by, and personal collaborations made possible through, Working Group 29. In particular, this work falls under the umbrella of the third Term of Reference of the Working Group, namely, "Continue the development of RCM implementations in the North Pacific and its marginal seas". As the results presented here are largely a summary of those in Foreman *et al*. (2014), the interested reader is referred to that publication for further details.

Our future simulation builds on the Masson and Fine (2012, henceforth MF12) application of ROMS (Regional Ocean Modeling System; Haidvogel *et al*., 2008) that was used to hindcast oceanic conditions for the period of 1995–2008. Morrison *et al.* (2014) described the approach for computing our initial and forcing conditions and Figure 2.1 shows the domain for MF12 and our model. The starting points of the Morrison *et al*. (2014) future fields were regional and global climate model simulations archived as part of the North American Regional Climate Change Assessment Program (NARCCAP, http://www.narccap.ucar.edu/). Though NARCCAP offers several regional/global model combinations and thus the possibility of forming ensemble averages, only those from the Canadian Global Climate Model 3 (CGCM3) and Canadian Regional Climate Model (CRCM) coupling have been used here. However, the NARCCAP projections were not used directly, as a comparison of winds over the contemporary period of 1971–2000 with the Faucher *et al*. (1999) and Foreman *et al*. (2011) re-constructed observations at buoys along the BC shelf revealed systematic biases in the timing of the spring and fall transitions and in particular, of the upwelling season. As the CRCM future winds generally displayed the same behaviour, employing them to directly force our future simulation would produce incorrect upwelling conditions and erroneous conclusions of their impact on future marine ecosystems. So instead, our future simulations were forced with fields that were the summation of those employed in the contemporary hindcast of MF12 and the future-minus-contemporary NARCCAP anomaly fields. Similar "pseudo-global warming" approaches for computing future projections have been used by Schär *et al*. (1996) and Hara *et al*. (2008).

In order to use the MF12 model for future projections, it need only be run with suitable future forcing and initial fields. In our case, the forcing anomalies are computed from the NARCCAP-defined "current" and "future" time periods of 1971–2000 and 2041–2070, respectively, with the future simulations assuming the A2 emissions scenario (no leveling off of greenhouse gases), the only scenario included in the NARRCAP archive. Though NARCCAP offers output from six regional climate models (RCMs) driven by up to four atmosphere–ocean general circulation models (AOGCMs), we chose to use the results from the CRCM forced by the CGCM3. This means that future water property and flow conditions along the BC shelf are essentially simulated by moving ahead the 1995–2008 sequence of events by 70 years. We acknowledge that our contemporary time period (1995–2008) only partially overlaps with the NARCCAP contemporary period of 1971–2000, thereby providing an inconsistency in this pseudo-projection. However, until Masson and Fine extend their hindcast back to 1971 or another high resolution model is developed for the region and run over a period that includes a standard climate multi-decadal period, this is the best alternative approach.

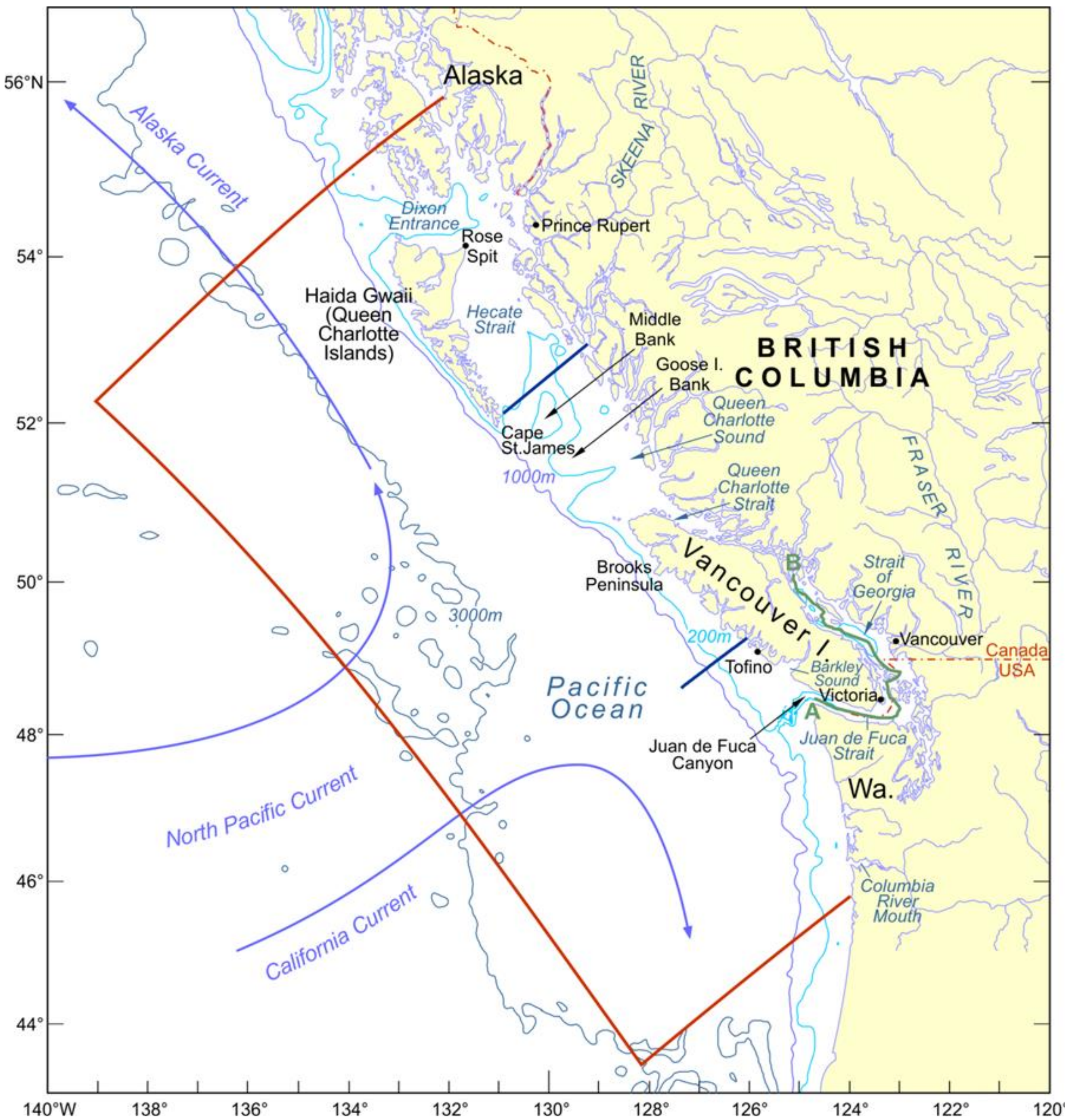

Fig. 2.1 Map of the British Columbia continental shelf showing bathymetric contours, place names, and average positions of major offshore currents. Solid red line denotes the outer boundary of the regional shelf model and the solid dark blue line north of Tofino denotes the transect used in Figure 2.8.

Changes in water properties

Figure 2.2 shows seasonally-averaged sea surface temperature (SST) anomalies with respect to their MF12 counterparts. Though the model initial conditions were computed by adding latitude-dependent temperature anomalies that ranged from about 1.5°C in the south to 1.8°C in the north to the MF12 values in January 1995, the resultant 14-year average SST anomalies have a more complicated structure that reflects changes in the model forcing fields and circulation patterns (*e.g*., eddies). All SST anomalies are positive, with those in the summer along the western Vancouver Island (VI) shelf being noteworthy in that they do not indicate a cooling due to an increase in the upwelling of colder subsurface water, at least not all the way to the surface. The December–February anomalies are generally largest and the June–August anomalies generally smallest, consistent with the surface air temperature anomalies seen in Figure 7 of Morrison *et al*. (2014). Even though the June–August river discharge temperatures have increased by a maximum of 2.5°C from those in MF12, there are relatively small SST increases (approximately 0.3°C) around the mouths of the Fraser and Columbia (not shown) rivers because of decreases in the summer discharge (Fig. 11, Morrison *et al*., 2014).

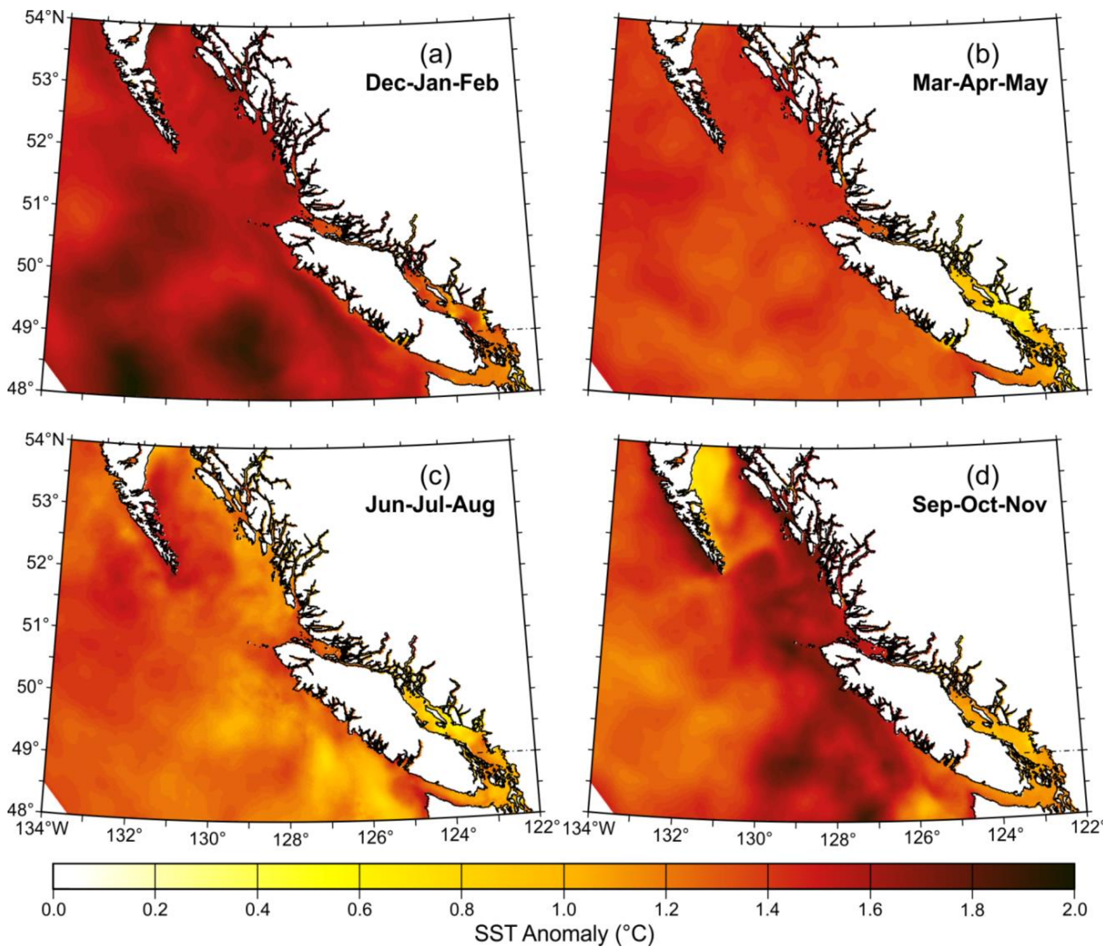

Fig. 2.2 Seasonally-averaged sea surface temperature anomalies (°C).

Figure 2.3 shows seasonally-averaged sea surface salinity (SSS) anomalies with respect to the MF12 hindcast. Though here also, the model SSS initial condition anomalies were only latitude-dependent, ranging from –0.25 psu in the south to –0.6 psu in the north, changes in the winds and circulation patterns arising from different monthly river discharges (Fig. 11, Morrison *et al*., 2014) have resulted in different seasonal SSS patterns. Though the generally smaller discharges from mid-June to mid-August have resulted in higher nearshore salinities at a few locations and seasons, SSS values are generally lower over most of the model domain, consistent with an overall increase in precipitation. Some of the local SSS anomalies, such as the winter positive anomaly emanating northwestward from Barkley Sound along the west coast of VI and the positive winter anomaly in the Strait of Georgia, arise from changes in the spatial distribution of freshwater plumes under changing forcing.

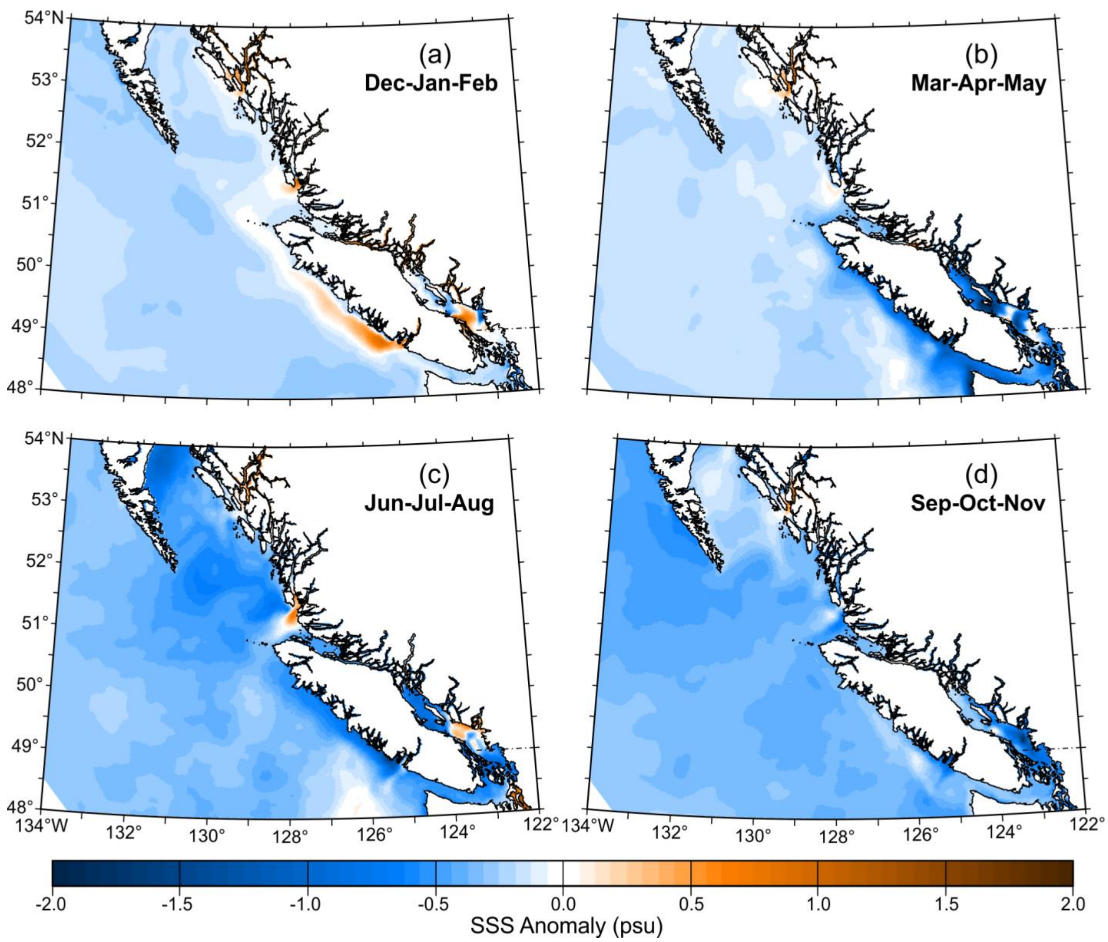

Fig. 2.3 Seasonally-averaged sea surface salinity anomalies (psu).

Figure 4 in Foreman *et al*. (2014) shows June contemporary salinities and future salinity anomalies along the Salish Sea thalweg during the annual peak Fraser River discharge. Consistent with the predicted increase in spring discharge (Fig. 11, Morrison *et al*., 2014), the surface salinity along the transect decreases by about 0.75 psu and by up to 2.0 psu near the mouth of the Fraser River. Below the surface, the salinity in the Strait of Georgia is uniformally reduced by about 0.5 psu, with the general salinity signature of the estuarine circulation projected to remain practically unchanged.

Changes in sea surface elevation

Figure 2.4 shows seasonally-averaged sea surface height (SSH) anomalies associated with changes in the regional ocean circulation. As described in the Bornhold and Thomson chapter of Christian and Foreman (2013), observed sea level rise also has contributions from: 1) the melting of glaciers and continental ice sheets, 2) volume expansions (or contractions) arising from temperature and salinity effects, and 3) vertical land motions arising from glacial rebound, tectonic processes (*e.g*., subduction) and compaction (sinking) in delta regions. (The interested reader is referred to Thomson *et al*. (2008) for thorough descriptions of the factors affecting, information gaps associated with, and estimates of sea level rise along the BC coast.) Apart from the extent to which our future river discharges reflect changes in the melting of BC glaciers (Morrison *et al*., 2011), none of these additional contributions are included here. ROMS assumes the ocean fluid is incompressible (*i.e*., the Boussinesq approximation) and thus does not capture volume expansions that, for example, would arise from warmer waters (Fig. 2.2). Though non-Boussinesq climate models (*e.g*., Kim *et al*., 2011) have been developed to include these expansions, the SSH anomalies computed here mostly arise from changes in the winds (set-up and set-down) and dynamic adjustments to changes in water density. In particular, most of these changes arise from forcing changes within the model domain rather than SSH signals entering via the lateral boundaries. (SSH anomalies were not directly included in the future lateral boundary forcing, though they would have developed via dynamical adjustments to the new density fields.) As illustrated in the small portion of the western boundary shown in Figure 2.4, the CGCM3 SSH anomaly along the western boundary was generally negative, with only portions rising above a cm in the fall and winter.

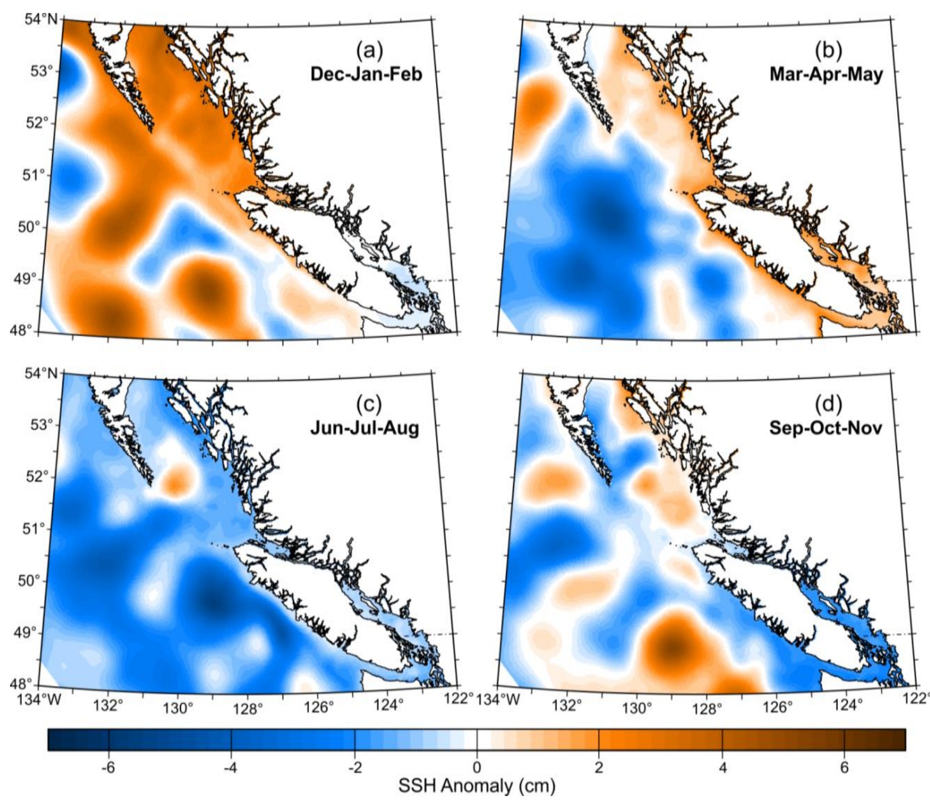

Fig. 2.4 Seasonally-averaged sea surface height anomalies (cm).

The generally higher SSH values on the shelf in the winter and spring (Fig. 2.4) are due to the stronger northwestward downwelling winds (set-up) and are projected to be as large as 4 cm in northern Hecate Strait in December–February. Analogously, the lower SSH values in almost all regions in June–August are generally a result of stronger southeastward upwelling winds. The negative September–November anomalies seen in southern BC shelf waters seem to be a continuation of those in June–August and thus may be mainly explained by the winds, while the slightly positive anomalies seen in portions of Queen Charlotte Sound and Hecate Strait are probably due to dynamic height increases arising from changes in salinity and temperature and an earlier and/or larger set-up from the stronger winter northwestward winds.

Though ROMS has the ability to incorporate SSH changes arising from atmospheric pressure, this was done neither in MF12 nor here. Therefore, the SSH changes shown in Figure 2.4 do not include any changes arising from the inverse barometer effect. Figure 9 in Foreman *et al*. (2014) shows monthly average differences between the NARCCAP CRCM-CGCM3 atmospheric pressures in 2041–2070 relative to those in 1971–2000. In addition to their impact on SSH, the gradients of these anomalies explain many of the wind changes described in Morrison *et al*. (2014). For example, a deepening of the Aleutian low pressure system in January combined with higher pressures over the continent is consistent with stronger northwestward winds over the BC shelf. Assuming a static inverse barometer correction to the sea levels associated with these pressures, the Prince Rupert January–July average range can be expected to increase by almost another 3 cm. However, these are only average SSH increases; storm events will certainly result in higher levels. Graham and Diaz (2001) showed that North Pacific winter storm intensity has increased over the last half of the 20th century while Abeysirigunawardena (2010) showed an increase in storm frequency at Prince Rupert over the same time period. The implication is that the surges and surface wave heights associated with these events can be expected to further exacerbate the flooding consequences of mean sea level rise.

It should be noted that there can be significant inter-decadal variations in sea level rise associated with patterns such as the Pacific Decadal Oscillation (PDO, Mantua *et al*., 1997) and they may over-ride those arising from greenhouse gas emissions (Overland and Wang, 2007). In particular, though sea levels have been rising at approximately 3 mm yr^{-1} globally (Cazenave and Nerem, 2004) since 1992, SSHs along the western North American coast have remained approximately stationary since 1980. Bromirski *et al*. (2011) showed that this could be explained by the dynamical steric response to changes in the North Pacific wind stress curl that arose when the PDO shifted from a cold to warm phase in the mid-1970s. They also cautioned that recent changes in wind stress along the Pacific eastern boundary "may be foreshadowing a persistent shift to the PDO cold phase" and a return to sea level rises in the region that could approach or exceed global values. It is therefore important to place the SSH results for the MF12 and our present study in the context of these inter-decadal variabilities. The average monthly value of the PDO over the 1995–2008 period of the MF12 hindcast (see http://jisao.washington.edu/pdo/graphics.html for a time series plot since 1900) is only slightly positive (+0.1). Consequently, SSH statistics arising from that hindcast and this subsequent future projection should not have been overly biased by the state of the PDO during these simulations.

Changes in the flow fields

Figure 2.5 shows contemporary and future eddy kinetic energy (EKE) within the model domain. Future higher values off the west coast of Haida Gwaii (Fig. 2.1) and northwest VI are predominantly winter features that arise from stronger northwestward winds. Haida Eddies are generated when counter-clockwise flows around Hecate Strait exit past Cape St. James (Crawford *et al*., 2002; Di Lorenzo *et al*., 2005) while similar flow separation arises when the northwestward Davidson Current passes Brooks Peninsula. A simulation where only the future wind forcing was replaced with contemporary values (*i.e.*, all other forcing fields included future anomalies) revealed this EKE increase was almost entirely due to increases in the winter winds. Animations further revealed that these future simulations do not produce more Haida Eddies — only that the eddy size increases. However, this result may be an artifact of our future wind forcing being formed by adding anomalies to the 1995–2008 winds. Were changes in storm frequency also included in the future winds, as suggested by the Abeysirigunawardena (2010) analysis, the number of Haida Eddies generated might also change. The animations also showed that not all the EKE off Haida Gwaii arose from Haida Eddies; some eddies were also generated further northward, perhaps from baroclinic instabilities similar to those described in Thomson and Gower (1998). Nevertheless, Haida Eddies do export coastal waters carrying nutrients and larvae offshore (Whitney and Robert, 2002) so changes in their magnitude may have important ecosystem consequences.

Figure 11 in Foreman *et al*. (2014) shows flows crossing a transect in southern Hecate Strait and further illustrates the Haida Eddy generation mechanism and how it is projected to change in the future. Contemporary, future and differences in the seasonally-averaged southern Hecate Strait flow fields at 20 m depth (Fig. 2.6) illustrate some of these patterns from a different perspective (20 m was chosen rather than the surface to reduce the effects of the wind.). Stronger currents are seen along the western flank of Middle Bank in all seasons and in the summer and fall they are accompanied by stronger flows on the eastern side, thereby strengthening the clockwise eddy. A similar but weaker eddy is also seen around Goose Island Bank and portions of its clockwise flows are also seen to change seasonally with larger scale patterns coming off northwestern VI or along the eastern side of Hecate Strait. Though both these eddies are partially generated by tidal rectification, it is changes in the larger scale wind and buoyancy-driven flow patterns that are causing the strengthening projected here. The major summer features seen in Figure 2.6 have been observed and were described in Crawford *et al*. (1995).

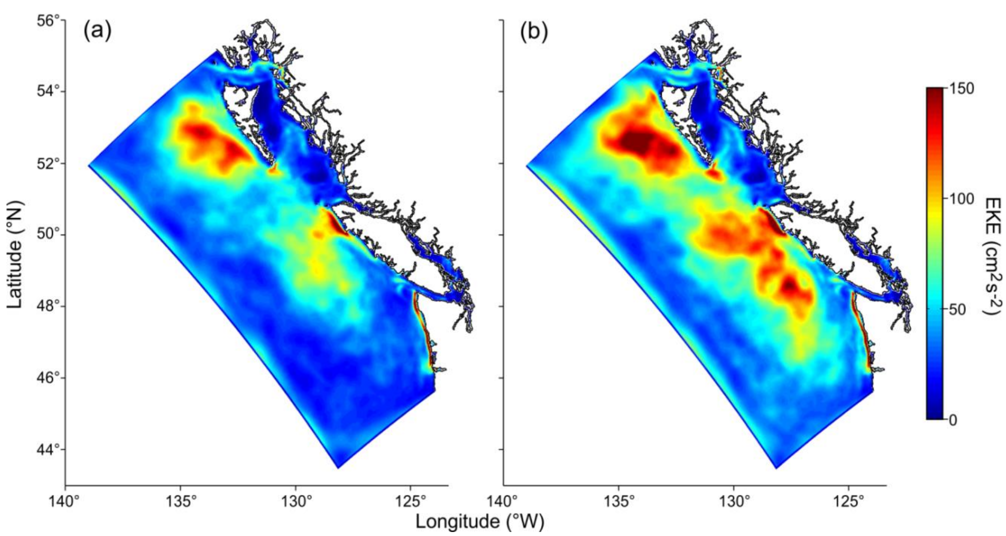

Fig. 2.5 Annually-averaged eddy kinetic energy (EKE; cm^2 s^{-2}) for the contemporary (from MF12) and future simulations.

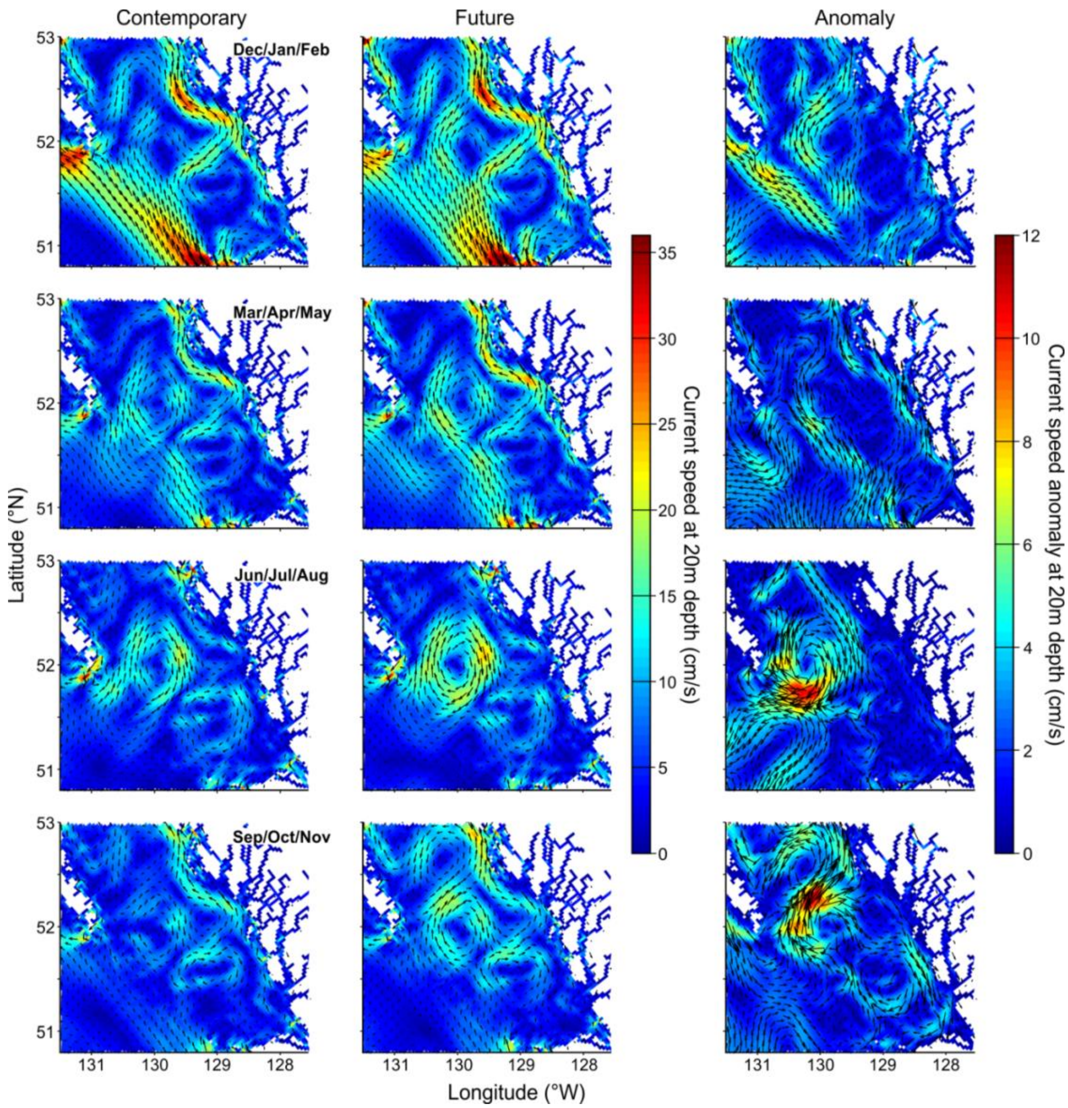

Fig. 2.6 Contemporary, future and differences in seasonally-averaged currents at 20 m depth in Queen Charlotte Sound. Note the colour scale change for the anomaly column.

Figure 13 in Foreman *et al*. (2014) shows analogous seasonally-averaged 20 m flows in northern Hecate Strait and Dixon Entrance. Here, the predominant patterns are the counter-clockwise Rose Spit Eddy (Crean, 1967) in Dixon Entrance and the northward flows along the eastern side of Hecate Strait. Both are seen to intensify in all seasons except summer, with the eddy position also varying seasonally. The northern edge of the eddy is seen to be an extension of the northward Hecate flows which, in turn, largely arise from river discharges and the wind.

Figure 2.7 shows analogous seasonally-averaged 20 m flows in the Salish Sea and off the southwest VI shelf. Stronger winter winds have generally increased the northwestward component of all December–February surface flows and in particular, the Davidson Current (Freeland *et al*., 1984) off the west coast of VI. The March–May surface currents have a similar pattern, and with the exception of stronger flows along the western Washington coast, are generally weaker. These latter flows arise from stronger winds and larger Columbia River discharges and either weaken the surface estuarine outflow in Juan de Fuca Strait or are sufficiently strong to cause reversals (Thomson *et al*., 2007). A weak Juan de Fuca Eddy (Freeland and

Denman, 1982) is also seen off the entrance of Juan de Fuca Strait in the March–May contemporary and future panels and more fully formed versions are seen in the following two seasons. These eddies are formed by a combination of upwelling winds, tidal mixing off Cape Flattery, and estuarine flows in Juan de Fuca Canyon and Strait (Foreman *et al*., 2008; MacFadyen and Hickey, 2010) and have important ecosystem impacts. However, unlike the more northerly Haida Eddies which move offshore after their generation, Juan de Fuca Eddies are similar to the Middle and Goose Island Bank Eddies and largely remain locked in place by underlying bathymetric features. Though the June–August anomaly panel in Figure 2.7 does suggest a small increase in the current magnitudes around the periphery of the Juan de Fuca Eddy, Figure 2.5 (and zoom-ins that are not shown) suggest very little difference in the future EKE in this region. Equally important to the magnitude of these eddies is the timing of their formation and disappearance, both of which are linked to the spring and fall transitions in alongshore winds. Attempts were made to determine if there was any change in these timings and, perhaps not surprisingly, given the lack of change in the winds described in Morrison *et al*. (2014), none were found. So, unlike the more northerly eddies described above, our future simulations do not suggest any significant changes to future Juan de Fuca Eddies.

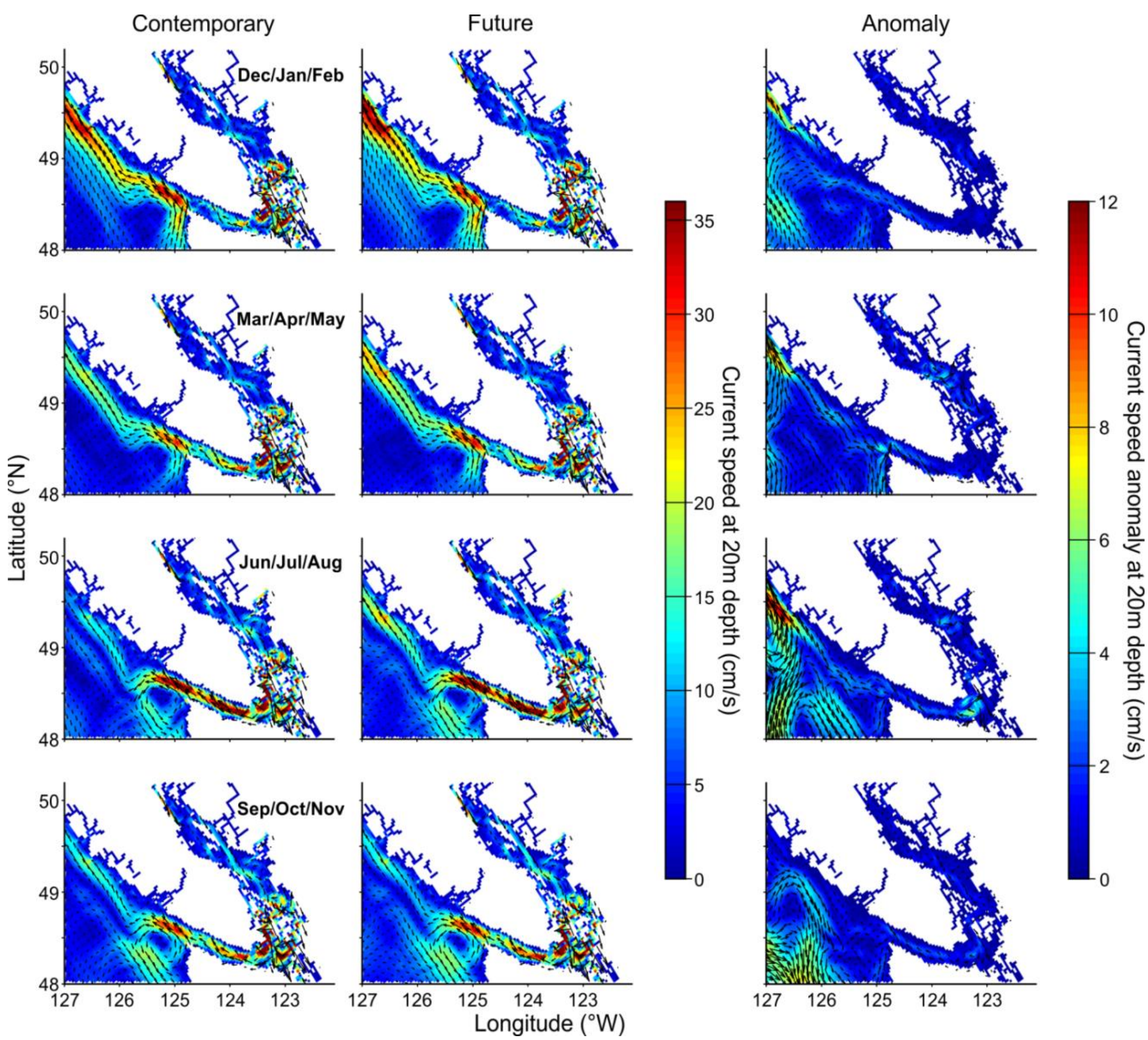

Fig. 2.7 Contemporary, future and differences in seasonally-averaged currents at 20 m depth in the Salish Sea and southwest Vancouver Island shelf. Note the colour scale change for the anomaly column.

However, the June–August anomaly panel in Figure 2.7 shows a stronger Vancouver Island Coastal Current (VICC, Thomson *et al*., 1989) arising from the stronger surface estuarine flows in Juan de Fuca Strait. The Shelf Break Current (SBC, Freeland *et al*., 1984) arising from upwelling winds is also evident in the June–August and September–November contemporary and future panels, and though the associated anomalies suggest magnitude increases, the patterns are not sufficiently distinct from those of the Juan de Fuca Eddy and an offshore eddy to permit definitive conclusions.

Figure 2.8 shows contemporary and future seasonal alongshore currents, isotherms, and isohalines along a transect crossing the mid-VI shelf. There are five main currents in this region, four of which are seen in the June–August contemporary and future panels. They are the northwestward buoyancy-driven VICC; the southeastward SBC which is further offshore, primarily wind-driven, and extends down the water column to approximately 150 m depth; the southeastward California Current that is even further offshore; and the northwestward California Undercurrent (CUC, Thomson and Krassovski, 2010; Hickey, 1979) which is centered at approximately 150–200 m depth along the continental slope. The SBC disappears when the winds reverse in the fall and is replaced by the Davidson Current which, as can be seen in the December–February panels, merges with the CUC and VICC to provide northwestward flow over the entire shelf and slope.

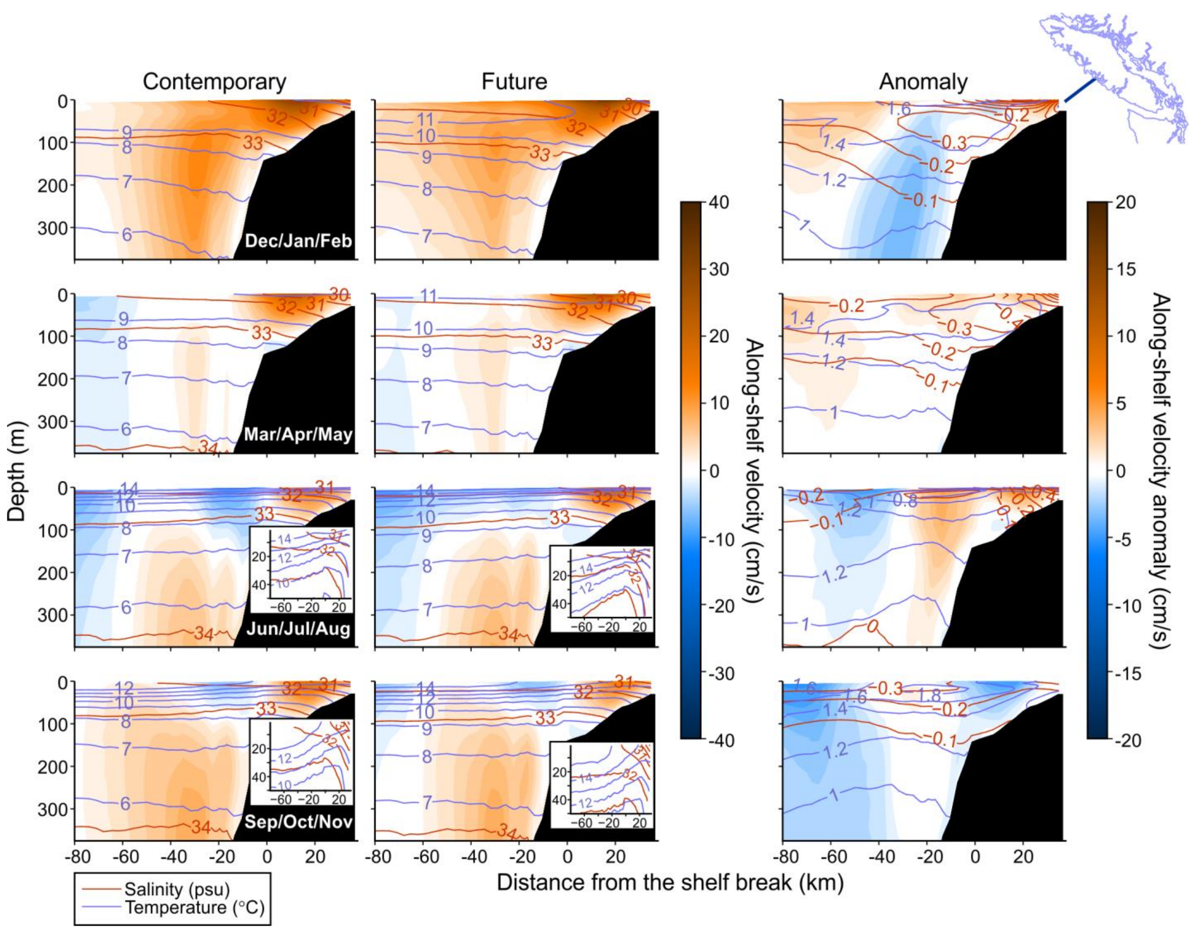

Fig. 2.8 Along-shelf currents crossing, and temperature (blue) and salinity (red) contours along, a transect off the mid-Vancouver Island shelf (see Figure 2.1). Redder (positive) shaded areas indicate greater flow to the northwest while darker blue regions indicate greater flow to the southeast.

The CUC is important for its roles in providing a conduit for the northward migration of fish species like hake (King *et al*., 2011) and being a source of nutrients and oxygen (Crawford and Peña, 2013) that are upwelled onto the VI shelf in summer. Though our results on future CUC changes could thus have important ecosystem consequences, we need to be cautious in their interpretation because the CUC does not originate within the model domain and its magnitude is strongly influenced by our southern boundary forcing. In particular, as the anomaly component of this boundary forcing was interpolated from oceanic temperatures, salinities, and currents in a model (CGCM3) that barely resolves the continental shelf, let alone slope, we do not have much confidence that these anomalies capture future changes accurately. Clearly, a global or regional climate model that has sufficient horizontal resolution (*e.g*., at least 10 km) to resolve the shelf and slope and that extends much further to the south (*e.g*., to Baja California) would be necessary to provide better estimates of changes to the CUC entering along the southern boundary of the model domain.

In that light, we must assign considerable uncertainty to the December–February projection that the CUC will be smaller in the future. On the other hand, the slight increases seen for the VICC and the off-shelf component of the Davidson Current are more credible as a future simulation wherein future wind forcing was replaced with contemporary values, demonstrating that both were due to increases in the wind. As seen in the March–May anomaly panel, relatively minor changes to the alongshore currents are projected for this time period. The VICC is seen to strengthen slightly, consistent with the lower salinities next to the coast. However, the June–August changes are more notable. Though the VICC is also stronger (and salinities smaller), a stronger CUC seems to have weakened the SBC. Though this might be interpreted as a consequence of weaker upwelling winds, the 0–50 m depth insets in the contemporary and future panels show isotherms (*e.g*., 10°C in contemporary *vs* 11°C in future) and isohalines (*e.g*., 32.5 psu) to be slightly steeper in the future case, suggesting more upwelling. This would also be consistent with stronger southeastward winds and the stronger California Current. Finally, the September–November panels indicate a weakening of the VICC and perhaps not so much strengthening of the California Current, but rather an eastward movement of its core. The CUC is essentially unchanged and the SBC is slightly weaker, possibly as a consequence of slight changes in the seasonally transitioning winds (*e.g*., Figure 5 in Morrison *et al*., 2014).

Summary and future work

The preceding presentation has described and interpreted results from a simulation for the BC continental shelf and offshore waters with an ocean-only regional climate model and the future forcing fields described in Morrison *et al*. (2014). In particular, the atmospheric and freshwater discharge forcing fields were downscaled and/or computed from CRCM-CGCM3 A2 scenario model output available on the NARCCAP archive (http://www.narccap.ucar.edu/) while the oceanic initial conditions and lateral boundary conditions were downscaled from the associated CGCM3 run. As the CRCM winds were shown to poorly capture average upwelling-favourable conditions over the baseline period of 1971–2000, a strategy of computing anomalous forcing and initial fields and adding them to the analogous values used in MF12 was adopted.

Seasonally-averaged sea surface temperatures were projected to increase by between 0.5 and 2.0°C while the analogous sea surface salinities were projected to decrease by as much as 2.0 psu, though there were some regions and periods in which small increases were projected. Stronger winter winds were seen to result in larger Haida Eddies and this can be expected to have important ecosystem consequences given the nutrients and larvae that they export offshore (Whitney and Robert, 2002). Though there were indications of slightly stronger upwelling along the VI shelf due to slightly stronger summer winds, no appreciable change was projected in the magnitude or formation timing of Juan de Fuca Eddies. However, increased flows were projected in some seasons for the Rose Spit, Middle Bank, and Goose Island Bank Eddies and these could also have important ecosystem impacts (*e.g*., Jamieson, 1985). Though changes were also projected for the California Undercurrent, limitations associated with the calculation of oceanic anomalies along the southern boundary of the model domain meant they had considerable uncertainty. Consequently, it is difficult to make definitive statements on how oxygen and nutrients upwelled from the California Undercurrent onto the VI shelf might change in the future.

However, except in summer, more precipitation over the watersheds emptying into coastal waters produced larger freshwater input and in particular, a stronger estuarine flow in Juan de Fuca Strait and a stronger Vancouver Island Coastal Current. Similar discharge increases along the central and north coasts also contributed to stronger flows in Queen Charlotte Sound, Hecate Strait, and Dixon Entrance.

Finally, seasonal wind and freshwater discharge increases along most of the coast meant that the winter minus summer range of sea surface height was generally projected to increase. An average projected range increase of 10 cm at Prince Rupert together with another 3 cm from average changes in the inverse barometer effect and event-specific storm surge and surface waves increases (Graham and Diaz, 2001; Abeysirigunawardena, 2010) certainly suggest a potential for increased flooding and damage to coastal structures.

Future work is planned to include the downscaling of forcing fields from analogous IPCC AR5 models that recently became available through the Coordinated Regional climate Downscaling Experiment (CORDEX, http://www.meteo.unican.es/en/projects/CORDEX). Work is also continuing (see the Peña *et al*. section in this WG 29 report) on coupling a variation of this BC RCM to a biogeochemical model in order to investigate the impacts that the afore-mentioned physical changes will have on future marine ecosystems.

Acknowledgments

We thank the Centre for Ocean Model Development for Application within Fisheries and Oceans Canada for the funding to support the development of the BC shelf model, and to purchase the 256 processor computer on which that model runs. We also thank the Climate Change Science Initiative, Ecosystem Research Initiative and Aquatic Climate Change Adaptation Services Program within Fisheries and Oceans Canada for their financial support, and Trish Kimber for assistance in producing the figures.

References

Abeysirigunawardena, D.S. 2010. Climate variability and change impacts on coastal environmental variables in British Columbia Canada. Ph.D. Dissertation, Geography, University of Victoria. 322 pp.

Bromirski, P.D., Miller, A.J., Flick, R.E. and Auad, G. 2011. Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration. *J. Geophys. Res*. **116**: doi:10.1029/2010JC006759.

Cazenave, A. and Nerem, R.S. 2004. Present-day sea level change: Observations and causes. *Rev. Geophys.* **42**: doi:10.1029/2003RG000139

Christian, J.R. and Foreman, M.G.G. 2013. Climate trends and projections for the Pacific large aqautic basin. Can. Tech. Rep. Fish. Aquat. Sci. 3032. 113 pp.

Crawford, W.R. and Peña, M.A. 2013. Declining oxygen on the British Columbia continental shelf. *Atmos.–Ocean* **51**: 88–103, DOI: 10.1080/07055900.2012.753028.

Crawford, W.R., Woodward, M.J., Foreman, M.G.G. and Thomson, R.E. 1995. Oceanographic features of Hecate Strait and Queen Charlotte Sound in summer. *Atmos.–Ocean* **33**: 639–681.

Crawford, W.R., J.Y. Cherniawsky, M.G.G Foreman, and J.F.R. Gower. 2002. Formation of the Haida-1998 oceanic eddy. J. *Geophys. Res*. **107(C7)6**: 1–14.

Crean, P.B. 1967. Physical oceanography of Dixon Entrance, British Columbia. *Bull. Fish. Res. Bd. Can.* 156, 66 pp.

Di Lorenzo, E., Foreman, M.G.G. and Crawford, W.R. 2005. Modelling the generation of Haida Eddies. *Deep-Sea Res. II* **52**: 853–873.

Faucher, M., Burrows, W.R. and Pandolfo, L. 1999. Empirical reconstruction of surface marine winds along the western coast of Canada. *Clim. Res*. **11**: 173–190.

Foreman, M.G.G., Callendar, W., MacFadyen, A., Hickey, B.M., Thomson, R.E. and Di Lorenzo, E. 2008. Modeling the generation of the Juan de Fuca Eddy. *J. Geophys. Res.* **113**: C03006, doi:10.1029/2006JC004082.

Foreman, M.G.G., Pal, B. and Merryfield, W.J. 2011. Trends in upwelling and downwelling winds along the British Columbia shelf. *J. Geophys. Res*. **116**: C10023, doi:10.1029/2011JC006995.

Foreman, M.G.G., Callendar, W., Masson, D., Morrison, J. and Fine, I. 2014. A model simulation of future oceanic conditions along the British Columbia continental shelf, Part II: Results and analyses. *Atmos.–Ocean* **52**: 20–38, doi:10.1080/07055900.2013.873014.

Freeland, H.J. and Denman, K.L. 1982. A topographically controlled upwelling center of southern Vancouver Island. *J. Mar. Res*. **40**: 1069–1093.

Freeland, H.J., Crawford, W.R. and Thomson, R.E. 1984. Currents along the Pacific coast of Canada. *Atmos.–Ocean* **22**: 151–172.

Graham, N.E. and Diaz, H.F. 2001. Evidence for intensification of North Pacific winter cyclones since 1948. *Bull. Amer. Meteor. Soc*. **82**: 1869–1893.

Haidvogel, D.B., Arango, H.G., Budgell, W.P., Cornuelle, B.D., Curchitser, E., Di Lorenzo, E., Fennel, K., Geyer, W.R., Hermann, A.J., Lanerolle, L., Levin, J., McWilliams, J.C., Miller, A.J., Moore, A.M., Powell, T.M., Shchepetkin, A.F., Sherwood, C.R., Signell, R.P., Warner, J.C. and Wilkin, J. 2008. Ocean forecasting in terrain following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System. *J. Comput. Phys*. **227**: 3041–3065.

Hara, M., Yoshikane, T., Kawase, H. and Kimura, F. 2008. Estimation of the impact of global warming on snow depth in Japan by the pseudo-global-warming method. *Hydrol. Res. Lett*. **2**: 61–64.

Hickey, B.M. 1979. The California Current system – Hypotheses and facts. *Prog. Oceanogr*. **8**: 191–279, doi:10.1016/0079-6611(79)90002-8.

Jamieson, G.S. 1985. Dungeness crab, *Cancer magister*, fisheries of British Columbia, pp. 37–60 *in* Proceedings of the symposium on Dungeness crab biology and management, Alaska Sea Grant Report 85-3, Alaska Sea Grant College Program, Fairbanks, Alaska.

Kim, D.-H., Woo, S.-B. and Lim, C.-W. 2011. Investigation on steric and nonsteric effect on sea level rise projections of the Northwestern Pacific Ocean, *in* Development and Application of Regional Climate Models, October 11–12, Seoul, Korea.

King, J.R., Agostini, V.N., Harvey, C.J., McFarlane, G.A., Foreman, M.G.G., Overland, J.E., Di Lorenzo, E., Bond, N.A. and Aydin, K.Y. 2011. Climate forcing and the California Current ecosystem. *ICES J. Mar. Sci.* **68**: 1199–1216.

MacFadyen, A. and Hickey, B.M. 2010. Generation and evolution of a topographically linked, mesoscale eddy under steady and variable wind-forcing. *Cont. Shelf Res*. **30**: 1387–1402.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc*. **78**: 1069–1079.

Masson, D. and Fine, I. 2012. Modeling seasonal to inter-annual ocean variability of coastal British Columbia. *J. Geophy. Res*. **117**: C10019, doi:10.1029/2012JC008151

Morrison, J., Foreman, M.G.G. and Masson, D. 2011. A method for estimating monthly freshwater discharge affecting British Columbia coastal waters. *Atmos.–Ocean* **50**: doi:10.1080/07055900.2011.637667.

Morrison, J., Callendar, W., Foreman, M.G.G., Masson, D. and Fine, I. 2014. A model simulation of future oceanic conditions along the British Columbia continental shelf, Part I: Forcing fields and initial conditions. *Atmos.–Ocean* **52**: 1–19, doi:10.1080/07055900.2013.868340.

Overland, J.E. and Wang, M. 2007. Future climate of the North Pacific Ocean. *Eos* **88**: 178–182.

Schär, C., Frei, C., Lüthi, D. and Davies, H.C. 1996. Surrogate climate-change scenarios for regional climate models. *Geophys. Res. Lett*. **23**: 669–672.

Thomson, R.E. and Gower, J.F.R. 1998. A basin-scale oceanic instability event in the Gulf of Alaska. *J. Geophys. Res*. **103**: 3033–3040.

Thomson, R.E. and Krassovski, M.V. 2010. Poleward reach of the California Undercurrent extension. *J. Geophys. Res*. **115**: C09027, doi:10.1029/2010JC006280.

Thomson, R.E., Hickey, B.M. and LeBlond, P.H. 1989. The Vancouver Island coastal current: Fisheries barrier and conduit, pp. 265–296 *in* Effects of Ocean Variability on Recruitment and an Evaluation of Parameters used in Stock Assessment Models *edited by* R. Beamish and G. McFarlane, Spec. Publ. Fish. Aquatic Sci. 108, Ottawa.

Thomson, R.E. Mihaly, S.F. and Kulikov, E.A. 2007. Estuarine versus transient flow regimes in Juan de Fuca Strait. *J. Geophys. Res*. **112**: C09022, doi:10.1029/2006JC003925.

Thomson, R.E., Bornhold, B.D. and Mazzotti, S. 2008. An examination of the factors affecting relative and absolute sea level in coastal British Columbia. Can. Tech. Rep. Hydrogr. Ocean Sci. 260, 49 pp.

Whitney, F. and Robert, M. 2002. Structure of Haida Eddies and their transport of nutrient from coastal margins into the NE Pacific Ocean. *J. Oceanogr*. **58**: 715–723.

3. *Regional climate coupled modelling for the Northwest Pacific: Preliminary results on sea surface temperature*

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Introduction

Today, extreme weather events and natural hazards associated with global warming are affecting human activities as well as ecosystems. In addition to the efforts of the international community, such as the United Nations Framework Convention on Climate Change, to reduce global warming, regional communities are taking various measures to adapt to climate change. In this light, the needs of local governments and industries for detailed information on future climate change are increasing. Global climate modelling, which is most widely used to project a future climate change, is still low in resolution due to the computational burden, making it difficult to meet the demand for detailed regional climate information. Instead, the use of dynamical downscaling methods using regional climate models is increasing as a practical solution.

As part of this dynamical downscaling approach, regional climate modelling has been actively used (*e.g.*, Di Luca *et al*., 2012; Seo *et al*., 2014; Xue *et al*., 2014; Rummukainen, 2016). However, many of these previous studies have used an atmosphere- or ocean-only model. When an atmosphere-only model is used, the ocean is mostly prescribed using observational or reanalysis sea surface temperature (SST) data, or is simulated with a simple one-dimensional ocean mixed layer model. Using the SST data as the surface boundary condition, the atmosphere-only model can maintain the ocean condition relatively close to reality, but air–sea interactions cannot be properly considered. On the other hand, air–sea interactions can be considered to some extent when using the one-dimensional ocean mixed layer model, but it is difficult to reproduce three-dimensional processes such as ocean currents adequately. To overcome these limitations, a regional ocean–atmosphere coupled model, or a regional climate coupled model (RCCM), has been developed and applied to many regional climate studies (*e.g.*, Artale *et al*., 2010; Zou and Zhou, 2013; Hong and Kanamitsu, 2014; Rockel, 2015).

In this study, we establish a RCCM for the Northwest Pacific, including the seas around the Korean peninsula, and present preliminary results on the SST over the Northwest Pacific. In order to analyze the effects of regional climate coupled modelling, three dynamical downscaling experiments were conducted and analyzed in comparison with a global model projection result.

Establishment of a regional climate coupled model and experimental design

Regional climate coupled model (RCCM) for the Northwest Pacific

Using the COAWST (Coupled Ocean–Atmosphere–Wave–Sediment Transport) modelling system (Warner *et al*., 2010) of the U.S. Geological Survey, we established a RCCM for the Northwest Pacific, including Korean waters. This RCCM consists of an ocean model, ROMS (Regional Ocean Modeling System)

(Shchepetkin and McWilliams, 2005), and an atmospheric model, WRF (Weather Research and Forecasting model) (Skamarock and Klemp, 2007). As a major physical parameterization, we selected the K-profile method (Large *et al*., 1994) for vertical mixing in the ocean model and Kain-Fritsch parameterization method (Kain, 2004) for moist convection in the atmospheric model. For the atmospheric model, to maintain a realistic large-scale wind field, we applied a spectral nudging every hour for the long waves with wave length over 1000 km. Data between the ocean and atmospheric models was exchanged every hour (Fig. 3.1) using MCT (Model Coupling Toolkit) (Larson *et al*., 2005) with SCRIP (Spherical Coordinate Remapping and Interpolation Package) (Jones, 1997).

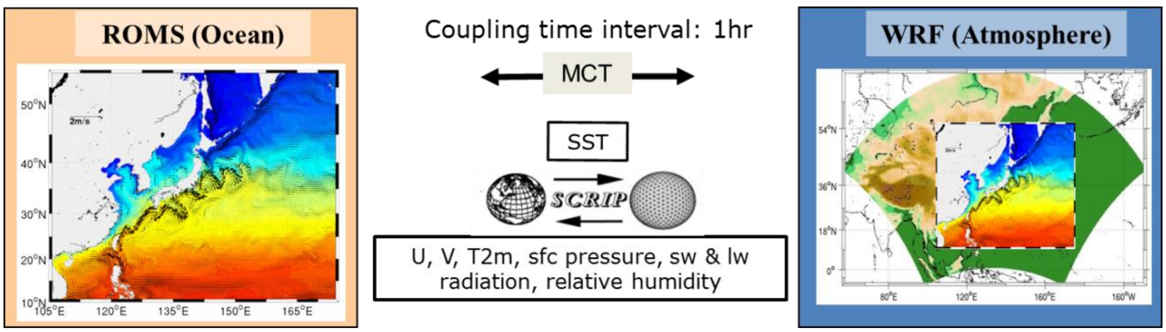

Fig. 3.1 Domain for the oceanic–atmospheric component model of the regional climate coupled model (RCCM) and the exchange variables between the component models on coupling.

While our target domain is a relatively small area, including Korean waters, we determined the model domain rather broad, spanning the Northwest Pacific, East Asia, and tropical heavy-rainfall area (Fig. 3.1). The ocean model domain was set to 10°N–55°N in latitude and 105°E–175°E in longitude, including the Kuroshio Extension region and the East Sea (also known as Japan Sea). The ocean model has a horizontal resolution of 1/12° (~10 km) and 30 vertical layers. The atmospheric model domain was set to have the meandering of the westerly jet passing through the Tibetan Plateau in the west and the northward propagation of mesoscale eddies generated from the deep convection over low latitudes in the south. The atmospheric model domain is similar to that of CORDEX-EA (Coordinated Regional climate Downscaling Experiment for East Asia), a regional model inter-comparison project sponsored by WCRP (World Climate Research Programme). The atmospheric model has a horizontal resolution of 50 km, the same as the CORDEX-EA protocol, and 26 vertical layers up to 50 hPa.

Experimental design

To distinguish the coupling effects from the downscaling effects, we conducted three different experiments: 1) the baseline experiment with an ocean-only model forced with global atmospheric reanalysis data, 2) a one-way coupling experiment with the ocean-only model forced with high-resolution atmospheric data obtained by dynamical downscaling with the atmospheric model, and 3) a two-way coupling experiment using the RCCM established for the Northwest Pacific. The two-way coupling experiment contained the downscaling effect of atmospheric forcing and the coupling effect between the ocean and atmospheric models. Thus we conducted a one-way coupling experiment to analyze the downscaling effects caused by using high-resolution atmospheric forcing data.

For a future climate projection, a pseudo-global warming method (Kawase *et al*., 2009) was applied to the three experiments. Following Jung *et al*. (2015), we used the CanESM2 historical and RCP 4.5 scenario outputs for the regional climate modelling to obtain an initial and boundary condition for a future climate. The CanESM2 was ranked as one of the best models among CMIP5 (Coupled Model Intercomparison Project-phase 5) global models for the East Asian summer monsoon (Jung *et al*., 2015). A pseudo-global warming experiment is to project a future climate by imposing a simulated climatological monthly change to a present-day climatology based on observational data so that a systematic model bias can be partly removed. Another advantage of the pseudo-global warming method is that by performing the model integration only for a certain period of the future, the computational burden can be reduced. Prior to the experiment, we performed a 100-year spin-up simulation using SODA (Simple Ocean Data Assimilation) reanalysis data of version 2.2.4 (Giese and Ray, 2011) and obtained an ocean initial and boundary condition for the Northwest Pacific. For the initial and boundary condition of the atmospheric model, we used ERA (European Centre for Medium-Range Weather Forecasts reanalysis) interim monthly data. In this study, we analyzed the 5-year averaged SST of the current climate (1981–1985) and the 5-year averaged SST of a future climate (2081–2085) and compared the preliminary results on future changes in the Northwest Pacific and in the seas around Korea.

Present climate SST

To verify the RCCM performance, we compared the SST climatology with observational data, OISST V2 (Optimum Interpolation Sea Surface Temperature version 2) and CanESM2 historical experiment results. Figure 3.2 presents the SST climatology in the boreal winter (February) and summer (August). The RCCM generally shows a spatial distribution and magnitude of SST closer to the observational data compared to the CanESM2, especially in the Yellow Sea and the East Sea. The RCCM shows the detailed structure of Liman and North Korean cold currents and mesoscale eddies which can be seen in the observational data. In the East China Sea and the area south of Japan, the RCCM considerably overestimates the summer SST.

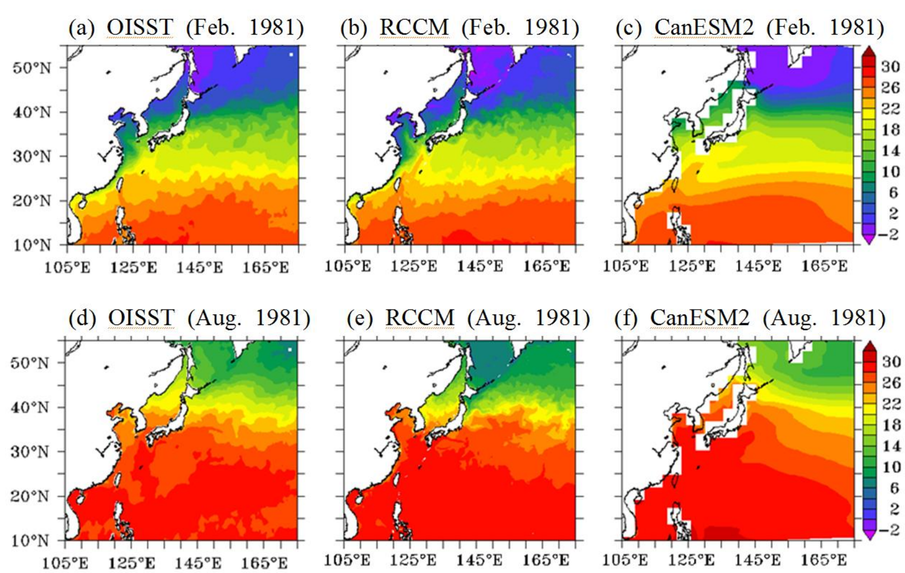

Fig. 3.2 Sea surface temperature (SST) in February (upper panels) and August (lower panels) in 1981: (a, d) OISST observational data, (b, e) results from the regional climate coupled model, and (c, f) those from the CanESM2 global model. Units are in °C.

A future projection of SST change

Projected SST changes in the Northwest Pacific

The SST in the Northwest Pacific is projected to increase according to the regional climate coupled models and the CanESM2 global model in the late 21st century compared to the late 20th century (Fig. 3.3). A notable, common feature of the SST projections is that the SST increase is larger in summer than in winter. The SST increase is also projected to be larger in middle latitudes than in low latitudes. Similar to the results presented in the previous section, the regional models, unlike the global model having a coarser resolution, show eddy-like structures in the ocean currents, especially in the Kuroshio Extension region.

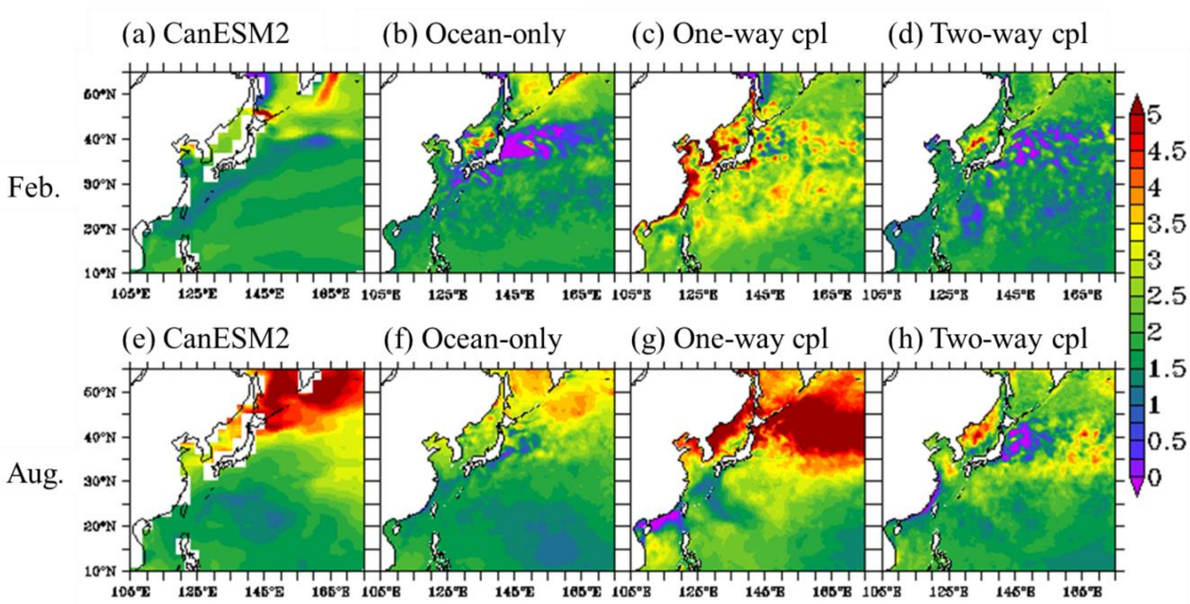

Fig. 3.3 Changes in sea surface temperature (SST) climatology from 1981–1985 to 2081–2085 in February (upper panels) and in August (lower panels) simulated by (a, e) the CanESM2 global model, (b, f) ROMS ocean-only model, (c, g) ROMS with atmospheric forcing from WRF (one-way cpl), and (d, h) ROMS-WRF regional climate coupled model (two-way cpl). Units are in °C.

Compared with the global model result, the RCCM and the ocean-only model project a smaller increase in SST in the Northwest Pacific region except for the East Sea and Okhotsk Sea during winter whereas the one-way coupled model projects a larger SST increase. The one-way coupled model shows a large SST increase in the Okhotsk Sea extended to the south during summer. In the mid-latitude Northwest Pacific, the one-way coupled model is more distinct from the ocean-only model in the regions such as the Kuroshio Extension and the coastal area of the Yellow and East China seas. This result suggests that even with the same ocean model, the resolution of atmospheric forcing can have a significant impact on air–sea interactions on a regional scale.

Projected SST changes in Korean waters

In order to analyze the SST in Korean waters, projected to significantly increase relative to other areas, we divided the waters into four regions having different characteristics (Fig. 3.4): the Yellow Sea, the East China Sea, and the northern and southern part of the East Sea. Figure 3.5 is a histogram showing the changes in SST collected from all grids within each region. The ocean-only model projects to increase from 1 to 3 degrees in the Yellow Sea, less than 3 degrees in the East China Sea, and less than 4 degrees in the northern and southern East Sea. The one-way coupled model simulates 2 to 3 degrees higher than the ocean-only model in all areas, suggesting that the future change in SST can be increased considerably by using atmospheric forcing in a higher resolution. On the other hand, the two-way coupled model projects the SST increase by 1 to 2 degrees higher than the ocean-only model, indicating that more realistic air–sea interactions on a regional scale can partly offset the changes caused by the one-way coupling. The two-way coupled model also projects that SST would be higher in the East Sea than in the Yellow Sea or the East China Sea, the same as the ocean-only model.

Figure 3.6 shows a seasonal change in SST increase in each of the four regions. The two-way coupled model, compared to the ocean-only model, shows a smaller increase in SST in the Yellow Sea during winter (February to March). Similar to the overall result for the Northwest Pacific, the ocean-only model and the two-way coupled model projects a larger increase in SST in summer than in winter. Such a larger warming in summer than in winter in the Northwest Pacific, including the Korean waters, can probably be explained by the intensification of the North Pacific High due to global warming that supplies warm and humid air to the regions. The one-way coupled model shows seasonal changes considerably different from the other two models, revealing an instability caused by a high-resolution atmospheric forcing. However, a more in-depth analysis is required to determine the exact cause.

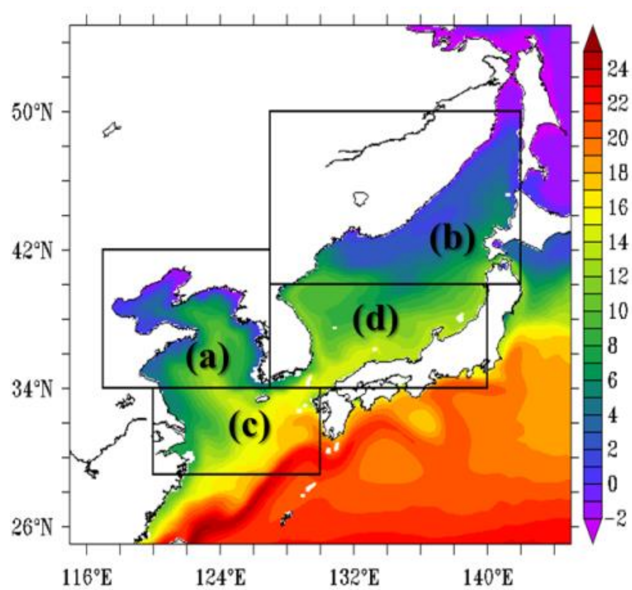

Fig. 3.4 Korean waters divided into (a) Yellow Sea, (b) northern East Sea, (c) East China Sea, and (d) southern East Sea.

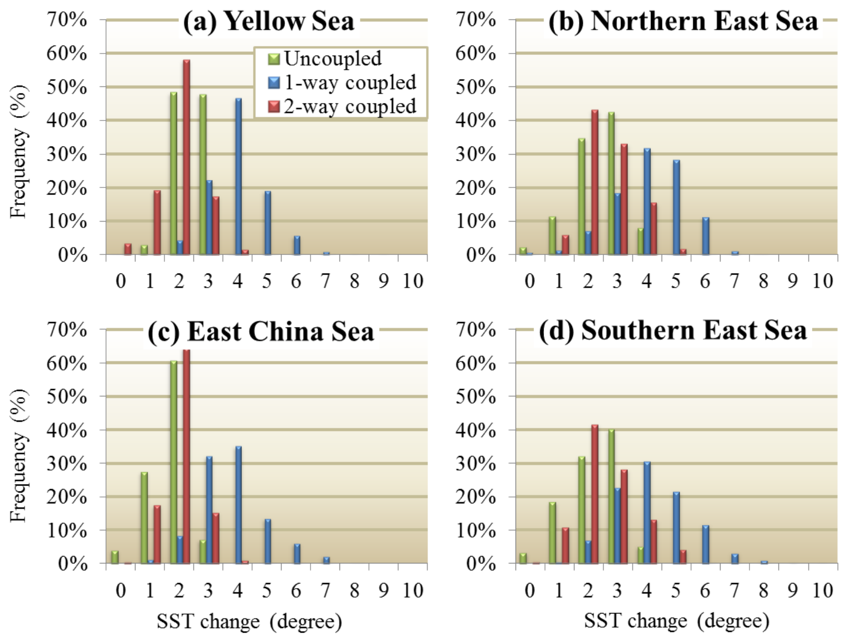

Fig. 3.5 Histogram of sea surface temperature (SST) change from the climatology for 1981–1985 to the climatology for 2081–2085 simulated by ROMS ocean-only model (uncoupled, green), ROMS with atmospheric forcing from WRF (1-way coupled, blue), and the regional climate coupled model (2-way coupled, red). Frequency distribution obtained from the grid cells within each for (a) Yellow Sea, (b) northern East Sea, (c) East China Sea, and (d) southern East Sea.

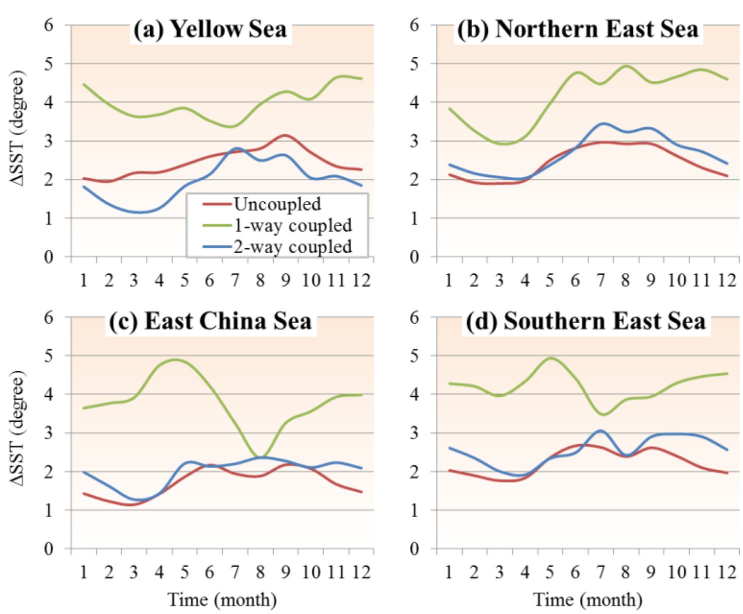

Fig. 3.6 Seasonal variations of the future changes in sea surface temperature (SST) averaged over each area: (a) Yellow Sea, (b) northern East Sea, (c) East China Sea, and (d) southern East Sea (see Fig. 3.4 for the domain for each area). Red lines represent the results from the ocean-only model forced with CanESM2 RCP 4.5 simulation data for the future climate change and ECMWF reanalysis data for the present climate, green lines for the results from the regional coupled climate model but with one-way coupling and without spectral nudging for atmosphere, and blue lines for the results from the regional climate coupled model with spectral nudging.

Conclusions

In this study, we have established a regional climate coupled model for the Northwest Pacific and attempted a future projection with detailed information of sea surface temperature by dynamical downscaling. In order to distinguish the effects of atmosphere–ocean model coupling on the future projection results from the effects of increasing the resolution of atmospheric forcing, a one-way coupled model experiment was performed separately with the ocean-only model and with the two-way coupled model. By performing these three experiments, we found that the atmospheric forcing resolution can have a significant impact on the simulation results, and the two-way coupled model, through more realistic air–sea interaction, can reduce the excessive errors seen in the one-way coupled model.

The two-way coupled model projected that the increase in sea surface temperature would be larger in the East Sea than in the Yellow Sea or East China Sea, and larger in summer than in winter, the same as the ocean-only model for the future changes in the seas around the Korean peninsula. However, the ocean-only model projects that the sea surface temperature will increase by about 2 degrees in the Yellow Sea during winter (February to March), while the two-way coupled model projects a smaller increase, by about 1 degree. These results indicate that the regional air–sea interaction can significantly change the climatological sea surface temperature of the Yellow Sea.

The regional climate coupled model developed for Korean waters for the first time through this study requires continual improvement in many aspects, but it basically allows more realistic air–sea interaction. The coupled model can be used to project future changes not only in Korean waters but for the coastal climate and fishery resources in the region. In addition, the regional model coupling technique acquired through this study can be applied to development of an integrated regional climate modeling system by adding component models of various fields such as the marine ecosystem.

Acknowledgement

This research was conducted as a part of the projects entitled “Development of coastal erosion control technology” funded by the Ministry of Oceans and Fisheries and “The future projection of marine ecosystem for the seas around Korea” funded by Korea Institute of Ocean Science and Technology.

References

Artale, V., Calmanti, S., Carillo, A., Dell’Aquila, A., Herrmann, M., Pisacane, G., Ruti, G., Sannino, G., Struglia, M.V., Giorgi, F. and Bi, X. 2010. An atmosphere–ocean regional climate model for the Mediterranean area: assessment of a present climate simulation. *Clim. Dyn*. **35**: 721–740.

Di Luca, A., de Elía, R. and Laprise, R. 2012. Potential for added value in precipitation simulated by high-resolution nested regional climate models and observations. *Clim. Dyn*. **38**: 1229–1247.

Giese, B.S., and Ray, S. 2011. El Niño variability in simple ocean data assimilation (SODA), 1871–2008. *J. Geophys. Res*. **116**: C02024, doi:10.1029/2010JC006695.

Hong, S. Y. and Kanamitsu, M. 2014. Dynamical downscaling: fundamental issues from an NWP point of view and recommendations. *Asia-Pacific J. Atmos. Sci*. **50**: 83–104.

Jones, P.W. 1997. A user’s guide for SCRIP: A spherical coordinate remapping and interpolation package. Los Alamos National Laboratory, Los Alamos, USA.

Jung, C.Y., Shin, H.-J., Jang, C.J. and Kim, H.J. 2015. Projected change in East Asian summer monsoon by dynamic downscaling: Moisture budget analysis. *Asia-Pacific J. Atmos. Sci*. **51**: 77–89.

Kain, J.S. 2004. The Kain–Fritsch convective parameterization: an update. *J. Applied Meteorol*. **43**: 170–181.

Kawase, H., Yoshikane, T., Hara, M., Kimura, F., Yasunari, T., Ailikun, B., Ueda, H. and Inoue, T. 2009. Intermodel variability of future changes in the Baiu rainband estimated by the pseudo global warming downscaling method. *J. Geophys. Res*. **114**: D24110, doi:10.1029/2009JD011803.

Large, W.G., McWilliams, J.C. and Doney, S.C. 1994. Ocean vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Rev. Geophys*. **32**: 363–403.

Larson, J., Jacob, R. and Ong, E. 2005. The Model Coupling Toolkit: A new Fortran90 toolkit for building multiphysics parallel coupled models. *Int. J. High Perf. Comp. App*. **19**: 277–292.

Rockel, B. 2015. The regional downscaling approach: a brief history and recent advances. *Current Clim. Change Rep.* **1**: 22–29.

Rummukainen, M. 2016. Added value in regional climate modeling. Wiley Interdisciplinary Reviews: Climate Change **7**: 145–159.

Seo, G.H., Cho, Y.K., Choi, B.J., Kim, K.Y., Kim, B.G. and Tak, Y.J. 2014. Climate change projection in the Northwest Pacific marginal seas through dynamic downscaling. *J. Geophys. Res*. **119**: 3497–3516.

Shchepetkin, A.F. and McWilliams, J.C. 2005. The Regional Ocean Modeling System (ROMS): A split-explicit, free-surface, topography-following coordinates ocean model. *Ocean Model.* **9**: 347–404.

Skamarock, W.C. and Klemp, J.B. 2007. A time-split nonhydrostatic atmospheric model for research and NWP applications. *J. Comput. Phys*. **277**: 3465–3485.

Warner, J.C., Armstrong, B., He, R. and Zambon, J.B. 2010. Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system. *Ocean Model.* **35**: 230–244.

Xue, Y., Janjic, Z., Dudhia, J., Vasic, R. and De Sales, F. 2014. A review on regional dynamical downscaling in intraseasonal to seasonal simulation/prediction and major factors that affect downscaling ability. *Atmos. Res*. **147**: 68–85.

Zou, L. and Zhou, T. 2013. Can a regional ocean-atmosphere coupled model improve the simulation of the interannual variability of the western North Pacific summer monsoon? *J. Clim*. **26**: 2353–2365.

4. *Downscaling of a future climate scenario to the Northwest Pacific marginal seas*

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Abstract

This report introduces a study on the future climate change projections in the Northwest Pacific (NWP) marginal seas using dynamic downscaling from global climate models (GCMs) over the period from 2001 to 2100. The model used forcing fields from three different GCM simulations to downscale the effect of global climate change. MIROC, ECHAM, and HADCM were selected to provide climate change signals for the regional climate model (RCM). These signals were calculated from the GCMs using Cyclostationary Empirical Orthogonal Function analysis and added to the present lateral open boundary and surface forcing. The RCM was validated by comparing the hindcast result with the observation. It was able to project detailed regional climate change processes that GCMs were not able to resolve. Relatively large increases in water temperature were found in the marginal seas. However, only a marginal change was found along the Kuroshio path. The RCM projection suggests that the temperature of the Yellow Sea Bottom Cold Water will gradually increase by 2100.

Introduction

Observed sea surface temperature (SST) increase in the Northwest Pacific (NWP) Ocean and its marginal seas is significantly higher than the global mean (Belkin, 2009). A rapid temperature change is expected to have a large impact on regional ecosystems (Lehodey and Maury, 2010). The NWP marginal seas are characterized by complex regional circulation and large variability, yet they are small enough for multiple numerical simulations to be economically feasible. The surface temperatures of the NWP marginal seas are largely influenced by major ocean currents such as the Kuroshio, the Tsushima Current (TC), the East Korean Warm Current (EKWC), and the Yellow Sea Warm Current (YSWC). These poleward currents provide a continuous supply of heat to the marginal seas from the subtropical ocean (Fig. 4.1).

Although Global Climate Models (GCMs) have provided future projections of large-scale distribution of heat and its impact on oceanic processes (Stock *et al*., 2011), changes in coastal and shallow water regions cannot be effectively investigated by GCMs. GCMs do not typically include relevant local shelf processes such as those due to tidal mixing or buoyancy input from rivers. A GCM with a relatively coarse resolution results in erroneously large or small transports through the straits. As a result, exchange of mass and energy between the open ocean and the semi-closed marginal seas tends to be inaccurate. An accurate rendition of mass and energy transports through the straits, of course, is an important factor for an accurate simulation of regional climate change. Several studies have investigated changes in temperature, transport and circulation in this region using numerical models (Cho *et al*., 2009; Seo *et al*., 2010; Cho *et al*., 2013; Kim *et al*., 2013).

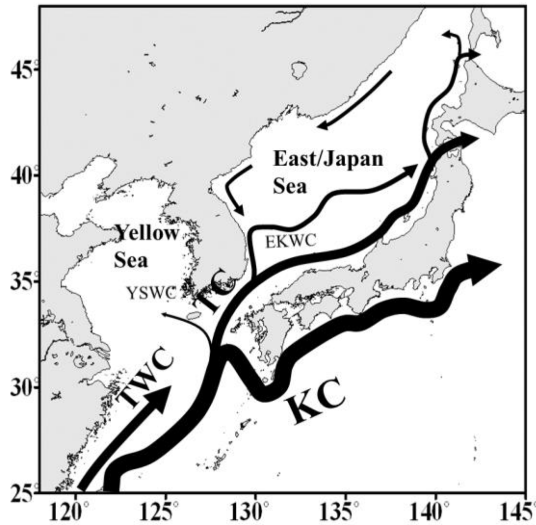

Fig. 4.1 Current system in the study area. KC, TWC, TC, EKWC, and YSWC represent the Kuroshio Current, Taiwan Warm Current, Tsushima Current, East Korean Warm Current, and Yellow Sea Warm Current, respectively.

This report introduces a study on the future climate change projections in the NWP marginal seas using dynamic downscaling from GCMs over the period from 2001 to 2100 (Seo *et al*., 2014). Dynamical downscaling technique adapted for a regional ocean circulation model is a useful strategy to capture local climate change in the marginal seas. In order to incorporate the effect of global climate change to a regional ocean model, the global warming signal together with its temporal and spatial patterns of change is extracted from each of the three GCM simulations: MIROC, ECHAM, and HADCM. Based on the extracted global warming signal, a dynamical downscaling strategy is developed.

Models

Global climate models

Three GCMs for regional downscaling were selected after evaluating the performance of available GCMs against the observations in the NWP and its marginal seas. The GCMs selected for our experiment are the MIROC-3.2 (HiRes) of the Centre for Climate System Research in Tokyo (K-1 Developers, 2004), the ECHAM5 of the Max Planck Institute for Meteorology in Hamburg (Roeckner *et al*., 2003), and the HadCM3 of the Hadley Centre in Reading (Johns *et al*., 1997). MIROC has the highest horizontal grid resolution among available GCMs. Reichler and Kim (2008) evaluated coupled GCMs and suggested that ECHAM and HADCM simulate better the present-day conditions. The Special Report on Emissions Scenario (SRES) A1B in the scenario of the 4th Assessment Report of the International Panel on Climate Change (IPCC) was selected for this experiment.

MIROC has a relatively fine horizontal grid resolution of 0.2° × 0.3°, whereas ECHAM and HADCM have resolutions of 1.0° × 1.0° and 1.25° × 1.25°, respectively. The coarse resolution of the GCMs results in an unrealistic transport through the Korea Strait, which is an important factor in determining heat transport in the NWP marginal seas. The mean seasonal variation of the transport through the Korea Strait, as calculated by GCMs from 2001 to 2010, was compared with that of the observed transport from 2001 to 2006 in

Figure 4.2 (Fukudome *et al*., 2010). A comparison shows that MIROC overestimates the transport of the Tsushima Current (TC) through the Korea Strait, whereas ECHAM and HADCM underestimate it.

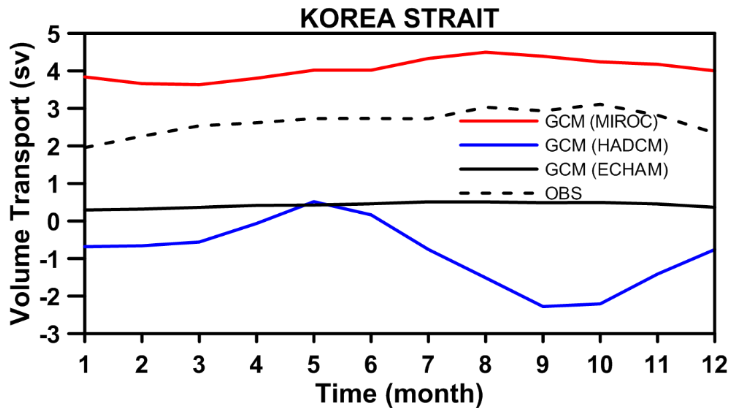

Fig. 4.2 Monthly mean transports through the Korea Strait from the GCMs and the observation. Transport from (red line) MIROC, (blue line) HADCM, and (black line) ECHAM are averaged over 2001–2010. The observation (dashed line) is averaged from 2001 to 2006 (Fukudome *et al*., 2010).

Regional model

The Regional Ocean Modelling System (ROMS) was used for the projection of climate change in the NWP marginal seas (Shchepetkin and McWilliams, 2005). ROMS is a free-surface, terrain-following, primitive equation ocean model discretized on the Arakawa-C staggered grid in the horizontal direction. The regional model domain includes the Northwest Pacific and its marginal seas (18°N to 49°N, 118°E to 155°E).

The horizontal grid spacing is approximately 10 km. In the vertical direction, 20 sigma (s-coordinate) levels are implemented to the scheme of Song and Haidvogel (1994), which enhances resolution towards the surface and the bottom. Daily mean surface ERA-Interim variables with 1.5° resolution were used to force the regional climate model (RCM); the ERA-Interim is the global atmospheric reanalysis produced by the European Center for Medium-Range Weather Forecasts (ECMWF; http://www.ecmwf.int/research/era). The daily mean forcing — mean sea level pressure, winds, air temperatures, specific humidity, downward longwave and shortwave radiation — represents the atmospheric condition in 2001. Ocean lateral boundary conditions derive from the monthly mean Simple Ocean Data Assimilation (SODA) global ocean reanalysis in 2001 (Carton *et al*., 2000a,b). A bulk flux algorithm is employed for the surface heat flux (Fairall *et al.*, 2003). Tides are included along the open boundaries using eight major tidal components (M2, S2, N2, K2, K1, O1, P1, and Q1) from TPXO7 in order to provide tidal mixing effects (Egbert and Erofeeva, 2002). Tides play an important role in mixing, which affects SST and the heat flux between the ocean and the atmosphere in the Yellow Sea (YS) and the East China Sea (ECS). Long-term mean monthly freshwater discharges from Changjiang (Yangtze) River and Huang He (Yellow) River were included in this study, which would affect surface mixing and salinity distribution.

Model validation

The spatial distribution of mean SST simulated by the regional model is compared with that of the satellite observation in winter and summer from 2001 to 2010 (Fig. 4.3). The satellite observation data were collected using the NOAA/AVHRR Pathfinder Version 5 and distributed by the Jet Propulsion Laboratory (http://poet.jpl.nasa.gov/) with a grid spacing of 4 km. The paths of the Kuroshio, the TC, and the East Korean Warm Current (EKWC) are characterized by warm SST signatures in winter. The Kuroshio can be clearly identified as warm water southwest of Japan in the simulation. The TC and the EKWC in the East/Japan Sea (EJS) are also relatively well defined as warmer water compared to the surrounding waters in the simulation.

The volume transport through the Korea Strait is important since it is a crucial factor for the distribution of heat and salinity in the EJS as well as in the ECS. An accurate simulation of the transport through the Korea Strait is a key element in accurately reproducing the circulation in the marginal seas of the NWP. Fukudome *et al*. (2010) estimated the transport based on currents measured from an ADCP mounted on a ferry boat. The observed transport as well as the regional model transport show remarkable seasonal variation during 2001–2006 (Fig. 4.4). The mean transport in the entire transport record is roughly 2.65 Sv. However, the transport of the SODA is about 1 Sv smaller than the observation and the regional model result. The unrealistic transport of the SODA might be due to the coarse grid resolution which is not sufficient in representing complicated topography and coastline in the study area.

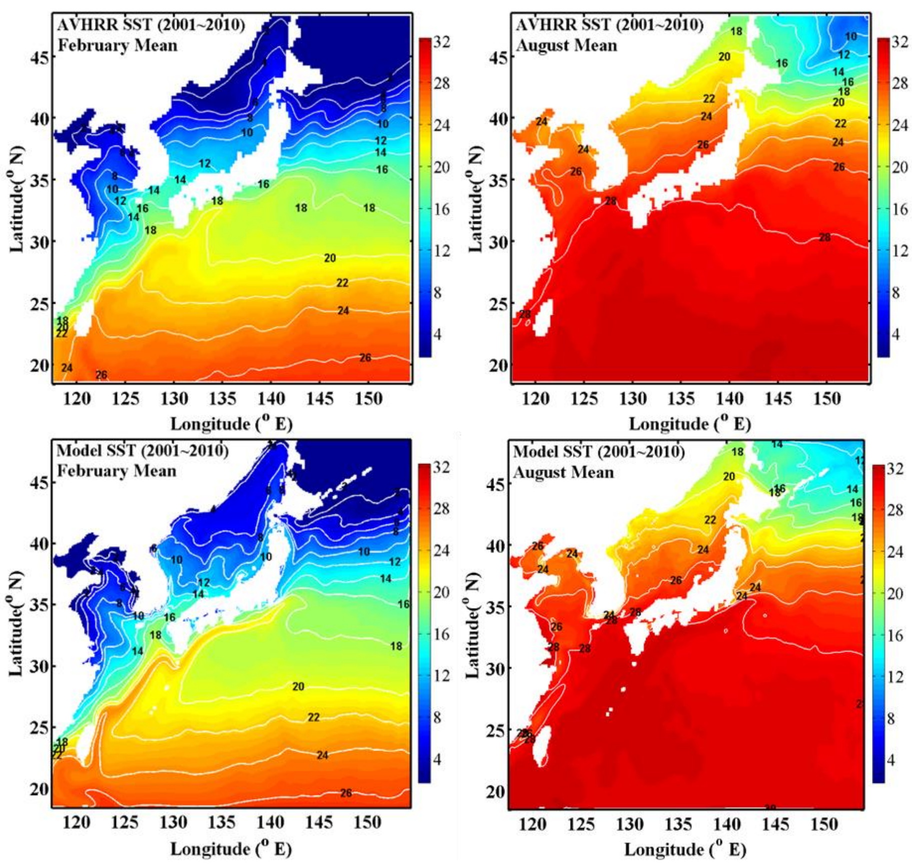

Fig. 4.3 Mean sea surface temperature (SST) from (upper) satellite observations and (lower) the regional ocean model (ROM) in (left) February and (right) August from 2001 to 2010.

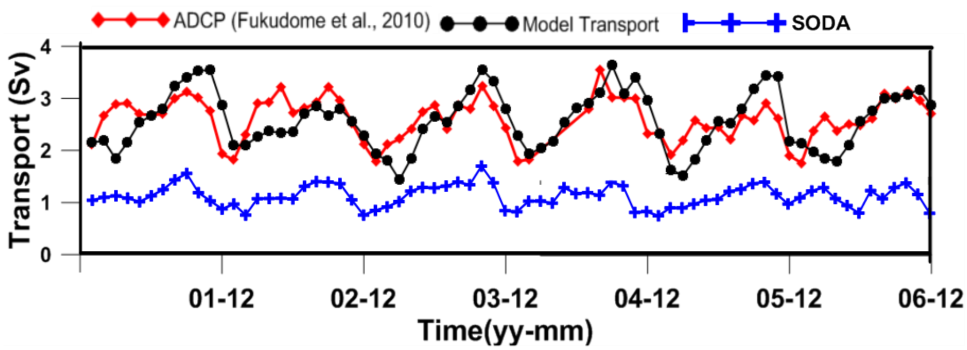

Fig. 4.4 Comparison of volume transports through the Korea Strait among the regional model (filled circles), the ADCP observation (filled diamonds; Fukudome *et al*., 2010), and the SODA reanalysis (crosses).

Transport from the Ocean General Circulation Model (OGCM) did not show significant seasonal variation (Fig. 4.2). While the regional model follows the observations closely (Fig. 4.4), the MIROC transport is about 1 Sv larger than the observations for the whole period. The ECHAM and HADCM transports also deviated from observations, with either close to zero or negative transports.

Warming trend from the GCM

The RCM is heavily influenced by local forcing induced by climate change. In order to incorporate the effect of climate change in an accurate manner, the long-term warming trend and its spatial distribution were calculated from the GCMs using CycloStationary Empirical Orthogonal Function analysis (CSEOF). The CSEOF analysis enables us to separate the anthropogenic warming trend from natural variability with diverse temporal and spatial scales. The CSEOF technique is useful for extracting physically evolving spatial patterns (Kim *et al.*, 1996; Kim and North, 1997).

Results and discussion

Surface current and temperature

Regional climate projection experiments were performed for the period from 2001 to 2100 by adding the warming signal to the present atmospheric forcing and lateral boundary condition. The similarities and differences of the surface current and temperature obtained from the GCMs and RCMs were compared in the NWP marginal seas.

The Kuroshio and the TC, which are prominent ocean currents in the NWP and its marginal seas, were properly resolved in the projected surface current and temperature in February 2100 by the regional model. On the other hand, GCMs are not able to adequately simulate these currents due to their coarse resolution (Fig. 4.5). The RCMs reproduce similar meanders of the Kuroshio despite the difference in GCM forcing. While GCM projections showed large differences in SST distribution in the marginal seas, RCMs showed consistent SST distribution over the marginal seas. In general, HADCM produces the coldest SST, and MIROC generates the warmest SST; RCMs do not result in large differences in SST distribution compared to GCMs.

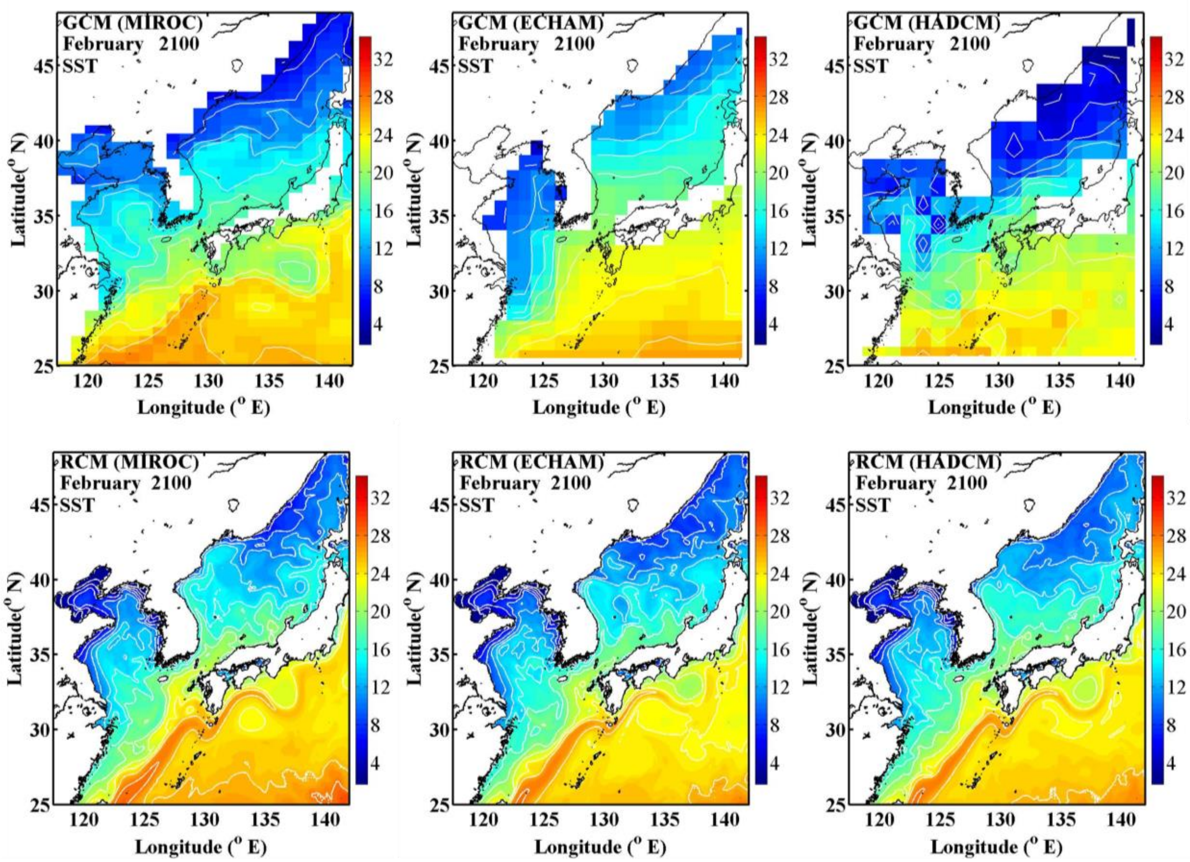

Fig. 4.5 Comparison of sea surface temperature (SST) between (upper) GCMs and (lower) RCMs in February 2100 for (left) MIROC, (middle) ECHAM, and (right) HADCM. Color indicates the SST and vector surface currents.

In summer, SST projections by the GCMs are colder than those by the RCMs (Fig. 4.6). The GCMs exhibit a larger area of cold water in the northern part of the EJS and in the center of the YS compared to the RCMs. In the southern EJS and in the Pacific, the distribution of SST from RCMs is similar to that of the GCMs. A close examination of GCM results shows that the Kuroshio and the TC are very weak. The Kuroshio together with its strong meander, however, is clearly expressed in the RCM results. In RCM simulations, SST in certain coastal regions of the YS reaches a maximum temperature of 30–32°C in August 2100.

To conduct detailed quantitative analysis, the spatial distribution of SST warming rates was calculated from GCMs and RCMs for the period 2010 to 2100 (Fig. 4.7). The spatial patterns of the warming trend are not quite consistent among the GCMs. On the other hand, RCMs produce similar patterns of SST warming rate despite having different GCM forcing. Relatively rapid warming is seen in the YS, while warming is sluggish along the Kuroshio path. The shallow and semi-enclosed YS might be sensitive to surface heating. The surface warming rate is greater in the northern area of the EJS compared to the southern region. The Kuroshio, which originates from the subtropical ocean, experiences relatively slow warming.

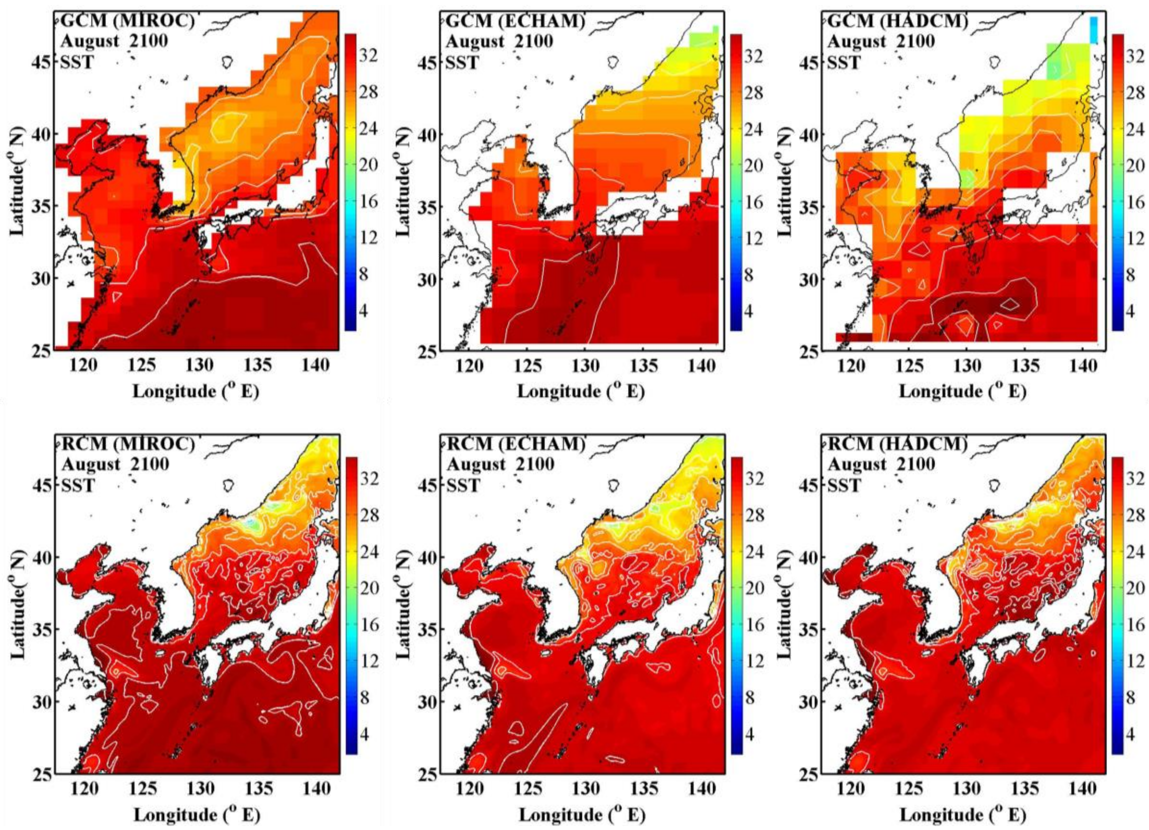

Fig. 4.6 As in Figure 4.5, except for August 2100.

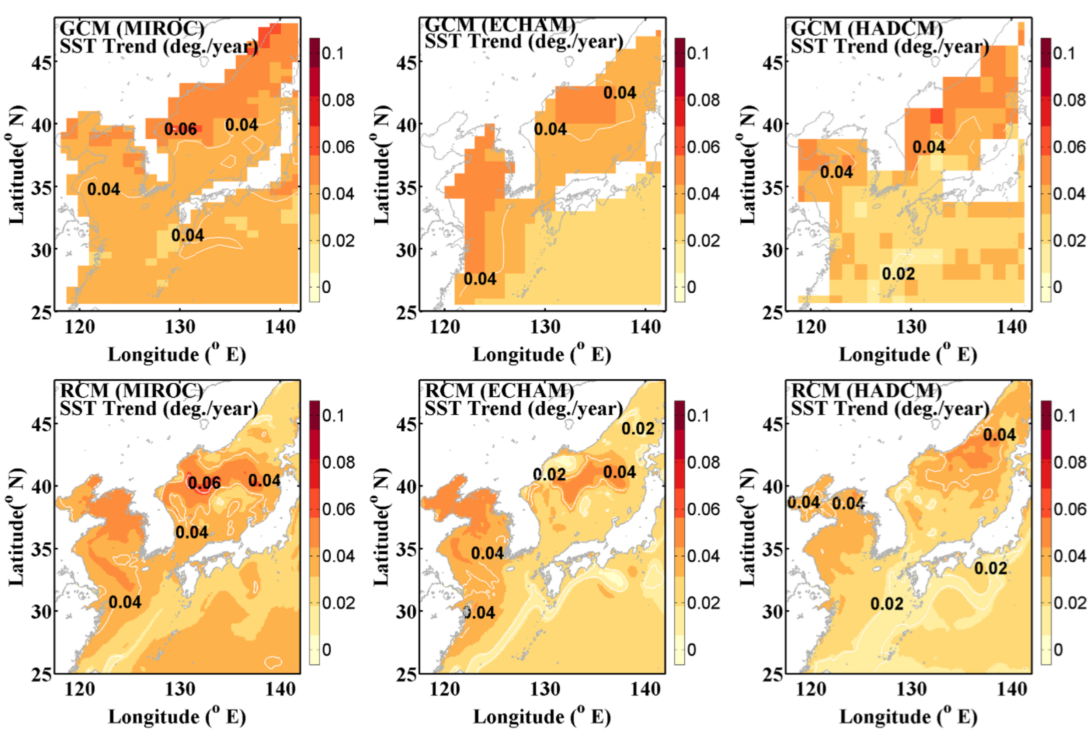

Fig. 4.7 Yearly mean sea surface warming trend from (upper) GCMs and (lower) RCMs from 2010 to 2100 for (left) MIROC, (middle) ECHAM, and (right) HADCM.

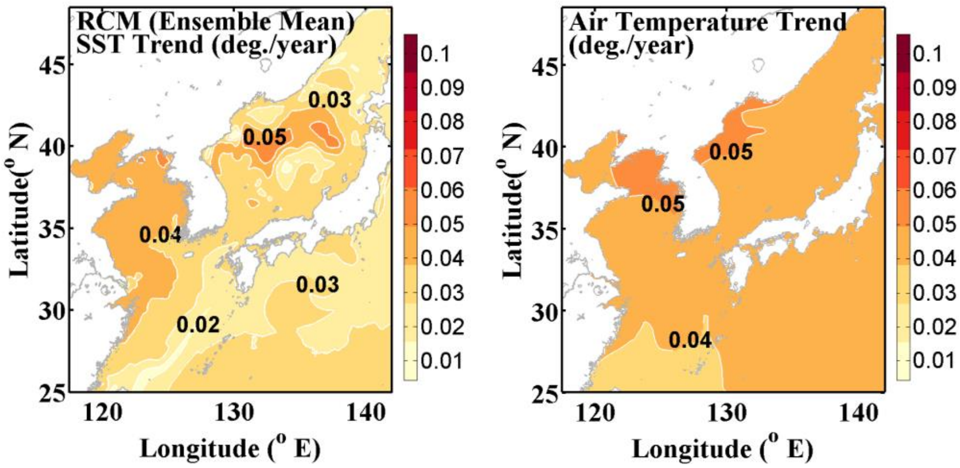

Fig. 4.8 Yearly mean warming trend of (left) the sea surface and (right) the air calculated by ensemble mean of RCMs from 2010 to 2100.

The ensemble mean of the surface warming trend was calculated from the RCMs and compared with the air temperature warming trend over the same period. The sea surface warming trend is weaker than that of air temperature over most of the study area (Fig. 4.8). SST exhibits a larger spatial difference (0.02–0.05ºC yr^{-1}) in warming rate than the air temperature (0.04–0.05ºC yr^{-1}). In the YS and in the Polar Front region in the EJS, the sea surface warming rate is greater than 0.04ºC yr^{-1}. The warming rate of the surface air is about two times greater than that of the sea surface in the Kuroshio area. However, the warming speed of the sea surface in the YS is almost the same as the air.

Yellow Sea Bottom Cold Water

There is a unique cold water mass below the thermocline in the YS in summer. It is called the Yellow Sea Bottom Cold Water (YSBCW) which is defined as cold water with temperature below 10ºC (Hur *et al*., 1999; Zhang *et al*., 2008; Park *et al*., 2011). The YSBCW is formed in winter and is stored in the lower layer below the strong thermocline during summer. Its spatial distribution can be identified in the bottom temperature distribution from the Oceanographic Atlas of the East Asian Seas (https://www.nodc.noaa.gov/OC5/regional_climate/EASclimatology/) in August (Fig. 4.9). The blue colored region in the middle of the YS represents the YSBCW which is 100–200 km in the longitudinal direction and about 500 km in the latitudinal direction.

GCMs cannot adequately simulate the characteristics of the YSBCW due to their coarse resolution and unrealistic topography. The bottom water temperature in August 2010 from MIROC and ECHAM shows cold water in the north and southwest, respectively (Fig. 4.10). HADCM shows bottom cold water less than 10°C in most of the YS. These results deviate from the observations shown in Figure 4.9. The YSBCW with temperature less than 10°C will disappear in the future according to the MIROC and ECHAM projections. Meanwhile, the bottom temperature of the YS as projected by HADCM will increase by a relatively small amount in future. The bottom depth of the YS in HADCM is greater than 200 m, whereas the maximum depth of the YS is less than 100 m. This unrealistic depth of the YS, as shown in HADCM, may have caused unrealistically large amounts of cold water in the YS in 2010 and 2100.

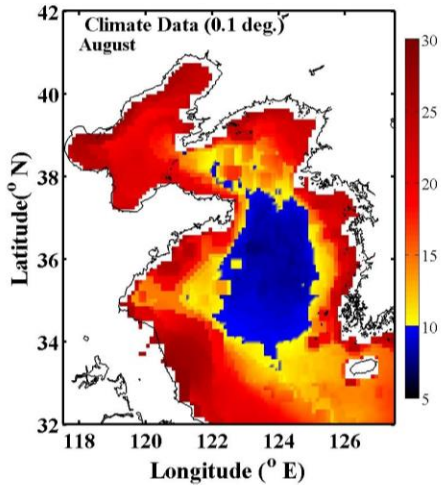

Fig. 4.9 Horizontal distribution of the bottom water temperature in August, from the oceanographic atlas of the East Asian Seas (https://www.nodc.noaa.gov/OC5/regional_climate/EASclimatology/). Blue represents the YSBCW colder than 10°C.

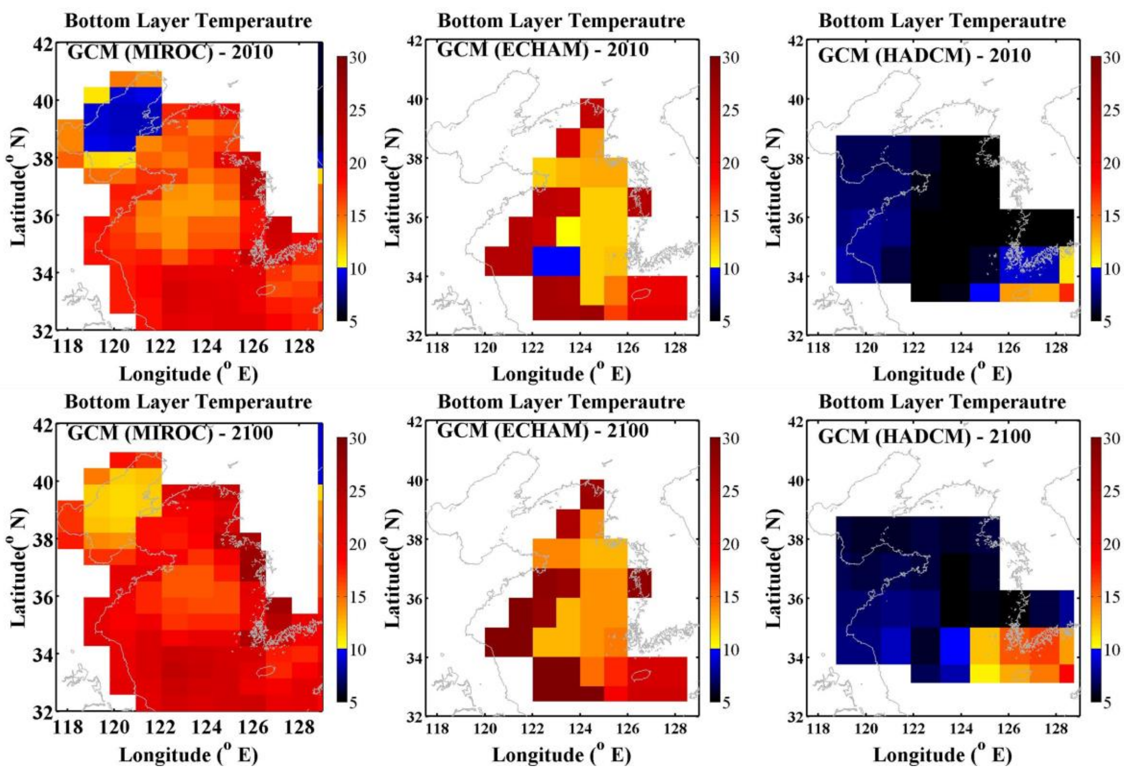

Fig. 4.10 Bottom temperature of GCMs in August (upper) 2010 and (lower) 2100 for (left) MIROC, (middle) ECHAM, and (right) HADCM.

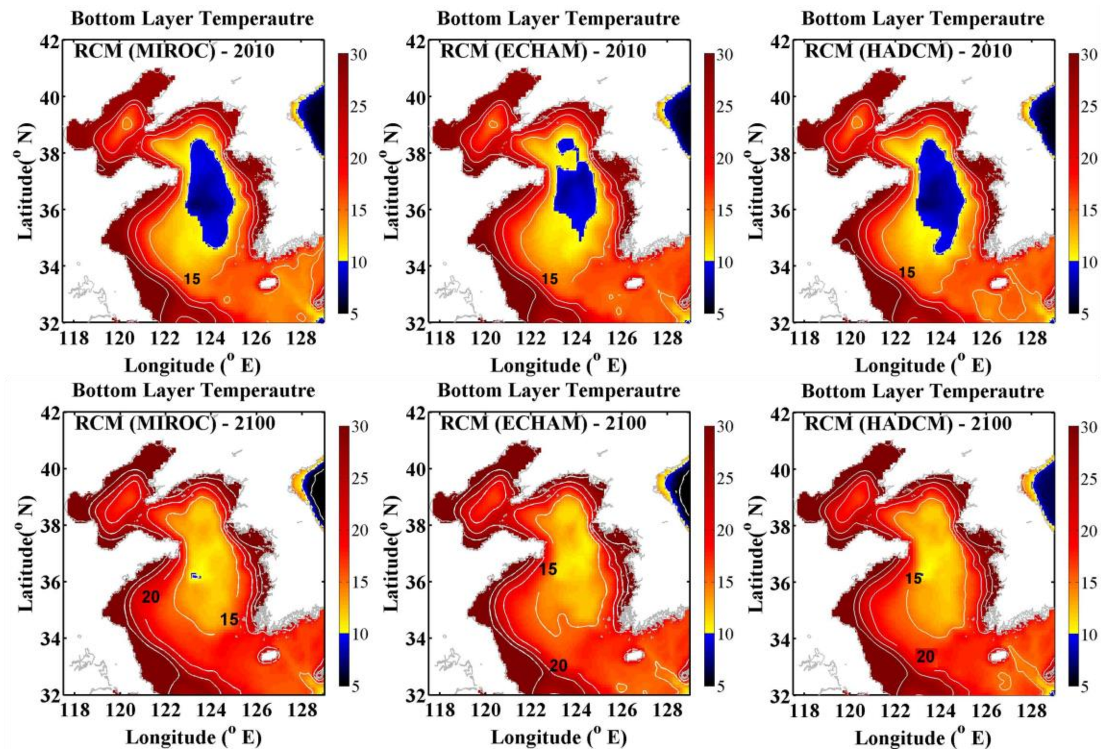

Fig. 4.11 As in Figure 4.10, except for RCMs.

Horizontal distributions of bottom temperatures simulated by RCMs in 2010 (Fig. 4.11) are comparable with those of the Atlas (Fig. 4.9), although the size of the YSBCW from the RCM is smaller. The difference, in part, may be due to the global warming. The Atlas was created using historical data, which includes observations from relatively colder periods, while the RCMs reflect the present conditions. The three RCMs show similar structure of the YSBCW in terms of its location and size, although the coverage of the YSBCW from ECHAM-RCM is slightly smaller than the others. All three RCMs consonantly predict the absence of the YSBCW colder than 10ºC in 2100. However, a small portion of the cold water remains in MIROC-RCM.

Conclusion

Forcing and boundary conditions for RCMs were dynamically downscaled from a GCM simulation in order to estimate regional climate change in the NWP marginal seas. Future forcing fields were generated by adding climate change components derived from GCMs to the present forcing fields. Similarly, future boundary conditions were produced by adding changes due to global warming to the present boundary conditions. Then, the resulting RCM was integrated to inspect the impact of global climate change in the marginal seas from 2010 to 2100. Climate change components of the surface forcing and open boundary data were derived from GCMs using the CSEOF technique. Regional model simulations that were dynamically downscaled from GCM simulations were validated by comparing the hindcast results with the observations with respect to the mean SST field, long-term trend of SST, and volume transport through the major straits.

The three RCM simulations with different GCM forcing results in similar spatial patterns of sea surface warming, whereas GCMs exhibit different patterns of sea surface warming trend. A relatively rapid increase in SST is seen in the YS, whereas a gradual increase is expected along the Kuroshio and the TC path.

GCMs do not properly reproduce the characteristics of the YSBCW, which is a unique water mass in summer due to the GCMs' coarse grid resolution and the unrealistic bottom topography in the YS. However, the location and the spatial coverage of the YSBCW simulated by RCMs are comparable to observations. All three RCM simulations predict that the YSBCW cooler than 10ºC will gradually decrease and the temperature of the YSBCW will increase by 3–4ºC by 2100.

References

Belkin, I.M. 2009. Rapid warming of large marine ecosystem. *Prog. Oceanogr*. **81**: 207–213, doi:10.1016/j.pocean.2009.04.011.

Carton, J., Chepurin, G. and Cao, X. 2000a. A simple ocean data assimilation analysis of the global upper ocean 1950–95: Part II. Results. *J. Phys. Oceanogr*. **30**: 311–326, doi:http://dx.doi.org/10.1175/1520-0485(2000)030<0311:ASODAA>2.0.CO;2.

Carton, J., Chepurin, G., Cao, X. and Giese, B. 2000b. A simple ocean data assimilation analysis of the global upper ocean 1950–95: Part I. Methodology. *J. Phys. Oceanogr*. **30**: 294–309 doi:http://dx.doi.org/10.1175/1520-0485(2000)030<0294:ASODAA>2.0.CO;2.

Cho, Y.-K., Seo, G.-H., Choi, B.-J., Kim, S., Kim, Y. and Dever, E.P. 2009. Connectivity among straits of the Northwest Pacific Marginal Seas. *J. Geophys. Res*. **114**: doi:10.1029/2008JC005218.

Cho, Y.-K., Seo, G.-H., Kim, C.-S., Choi, B.-J. and Shaha, D.C. 2013. Role of wind stress in causing maximum transport through the Korea Strait in autumn. *J. Mar. Syst*. **115**: 33–39, doi:10.1016/j.jmarsys.2013.02.002.

Egbert, G.D. and Erofeeva, S.Y. 2002. Efficient inverse modeling of barotropic ocean tides. *J. Atmos. Ocean. Technol*. **19**: 183–204, doi:http://dx.doi.org/10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2.

Fairall, C.W., Bradley, E.F., Hare, J.E., Grachev, A.A. and Edson, J.B. 2003. Bulk parameterization of air-sea fluxes: Updates and verification for the COARE algorithm. *J. Climate* **16**: 571–591, doi:http://dx.doi.org/10.1175/1520-0442(2003)016<0571:BPOASF>2.0.CO;2.

Fukudome, K.I., Yoon, J.H., Alexander, O., Takikawa, T. and Han, I.S. 2010. Seasonal volume transport variation in the Tsushima Warm Current through the Tsushima Straits from 10 years of ADCP observations. *J. Oceanogr*. **66**: 539–551, doi:10.1007/s10872-010-0045-5.

Hur, H.B., Jacobs, G.A. and Teague, W.J. 1999. Monthly variations of water masses in the Yellow and East China Seas. *J. Oceanogr*. **55**: 171–18, doi:10.1023/A:1007885828278.

Johns, T.C., Carnell, R.E., Crossley, J.F., Gregory, J.M., Mitchell, J.F., Senior, C.A. and Wood, R.A. 1997. The second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup and validation. *Clim. Dyn*. **13**: 103–134, doi:10.1007/s003820050155.

Kim, K.Y. and North, G.R. 1997. EOFs of harmonizable cyclostationary processes. *J. Atmos. Sci*. **54**: 2416–2427, doi:http://dx.doi.org/10.1175/1520-0469(1997)054<2416:EOHCP>2.0.CO;2.

Kim, K.Y., North, G.R. and Huang, J. 1996. EOFs of one-dimensional cyclostationary time series: Computations, examples, and stochastic modeling. *J. Atmos. Sci*. **53**: 1007–1017, doi:http://dx.doi.org/10.1175/1520-0469(1996)053<1007:EOODCT>2.0.CO;2.

Kim, C.-S., Cho, Y.-K., Choi, B.-J., Jung, K.-T. and You, S.H. 2013. Improving a prediction system for oil spills in the Yellow Sea: Effect of tides on subtidal flow. *Mar. Pollution Bull*. **68**: 85–92, doi:10.1016/j.marpolbul.2012.12.018.

K-1 Developers. 2004. K-1 coupled model (MIROC) description. K-1 Technical Report 1, Hasumi, H. and Emori, S. (Eds.), Center for Climate System Research, University of Tokyo, Tokyo, Japan, 34 pp.

Lehodey, P. and Maury, O. 2010. CLimate Impacts on Oceanic TOp Predators (CLIOTOP): introduction to the Special Issue of the CLIOTOP International Symposium, La Paz, Mexico, 3–7 December 2007. *Progr. Oceanogr*. **86**: 1–7, doi:10.1016/j.pocean.2010.05.001.

Park, S., Chu, P.C. and Lee, J.H. 2011. Interannual-to-interdecadal variability of the Yellow Sea Cold Water Mass in 1967–2008: characteristics and seasonal forcings. *J. Mar. Syst*. **87**: 177–193, doi:10.1016/j.jmarsys.2011.03.012.

Reichler, T. and Kim, J. 2008. How well do coupled models simulate today's climate? *Bull. Amer. Meteor. Soc*. **89**: 303–311, doi:http://dx.doi.org/10.1175/BAMS-89-3-303.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U. and Tompkins, A. 2003. The atmospheric general circulation model ECHAM 5. Part I: Model description. MPI Rep. 349, 127 pp.

Seo, G.-H., Choi, B.-J., Cho, Y.-K., Kim, Y.H. and Kim, S. 2010. Assimilation of sea surface temperature in the Northwest Pacific Ocean and its marginal seas using the ensemble Kalman filter. *Ocean. Sci. J*. **45**: 213–224.

Seo, G.-H., Cho, Y.-K., Choi, B.-J., Kim, K.-Y., Kim, B. and Tak, Y. 2014. Climate change projection in the Northwest Pacific marginal seas through dynamic downscaling. *J. Geophys. Res*. **119**: 3497–3516, doi:10.1002/2013JC009646.

Shchepetkin, A.F. and McWilliams, J.C. 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. *Ocean Model*. **9**: 347–404, doi:10.1016/j.ocemod.2004.08.002.

Song, Y. and Haidvogel, D. 1994. A semi-implicit ocean circulation model using a generalized topography-following coordinate system. *J. Comput. Phys*. **115**: 228–244, doi:10.1006/jcph.1994.1189.

Stock, C.A., Alexander, M.A., Bond, N.A., Brander, K.M., Cheung, W.W.L., Curchitser, E.N., Delworth, T.L., Dunne, J.P., Griffies, S.M., Haltuch, M.A., Hare, J.A., Hollowed, A.B., Lehodey, P., Levin, S.A., Link, J.S., Rose, K.A., Rykaczewski, R.R., Sarmiento, J.L., Stouffer, R.J., Schwing, F.B., Vecchi, G.A. and Werner, F.E. 2011. On the use of IPCC-class models to assess the impact of climate on living marine resources. *Prog. Oceanogr*. **88**: 1–27, doi:10.1016/j.pocean.2010.09.001.

Zhang, S.W., Wang, Q.Y., Lu, Y., Cui, H. and Yuan, Y.L. 2008. Observation of the seasonal evolution of the Yellow Sea Cold Water Mass in 1996–1998. *Cont. Shelf Res*. **28**: 442–457, doi:10.1016/j.csr.2007.10.002.

5. *Regional high-resolution ocean models in the western North Pacific and its marginal seas*

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Introduction

Japan is surrounded by the ocean and Japanese society is highly dependent on it. In addition, the surrounding ocean plays a role in regulating Japan's climate and weather. For example, the trajectories and intensities of typhoons and bomb cyclones, which occasionally cause serious damage to Japan, are influenced by sea surface temperature. Japan's coastline spans over 35,000 km and its Exclusive Economic Zone covers 4.47 million km^2. More than 99% of Japan's import and export materials are transported by ship (Trade Statics of Japan). The Japanese population is also highly dependent on protein consumption from marine products. The western North Pacific is very productive, with its structures influencing the formation of fishing grounds and its long-term ocean climate variabilities influencing fish stock fluctuations. Specifically, 25% of the marine global fishery catch is produced from the western North Pacific, despite covering only 6% of the global ocean according to the Food and Agriculture Organization (FAO, 2014).

The importance of the western North Pacific to the Japanese economy and society highlights the imperative of conducting nowcasts, forecasts, and seasonal predictions of the ocean state surrounding Japan. To this end, several operational ocean prediction systems have been developed composed of data collecting systems, data assimilation systems, and an ocean general circulation modelling system. In many cases, ocean general circulation models (and in some cases also data assimilation systems) have been applied for climate research. We refer to these models as regional ocean climate models. In this section, we collate and summarize the status of these regional ocean climate models for the waters surrounding Japan.

Background

In the western North Pacific, the western boundary currents of the subarctic and subtropical gyres (Oyashio and Kuroshio, respectively) form one of the most complicated ocean structures in the world (Kawai, 1972). The Kuroshio is a warm and oligotrophic current that separates at the Boso Peninsula (around 35.5°N, 140.5°E) and turns eastward as the Kuroshio Extension. The Oyashio is a cold and nutrient-rich current that turns to the east with a meandering called the First Oyashio Intrusion and the Second Oyashio Intrusion, based on the sequence from the coast, and forms the Oyashio Front as the southern boundary of the subarctic gyre. Therefore, the water temperature shows a strong meridional gradient and the Oyashio Front forms one of the strongest sea surface temperature (SST) gradients in the world (Nonaka *et al*., 2008). In addition, many meso-scale eddies (*e.g*., Itoh and Yasuda, 2010), streamers, jets (Isoguchi *et al*., 2006; Wagawa *et al*., 2014), and bifurcations (*e.g*., Mizuno and White, 1983) are generated from the meanders of both western boundary currents, and form a complex ocean structure, the mixed water region, between the Kuroshio Extension and Oyashio Front (Talley *et al.*, 1995; Yasuda *et al*. 2003; Kida *et al*., 2015).

In the western North Pacific, there are several marginal seas, including the western Bering Sea, Sea of Okhotsk, Sea of Japan and East China Sea. The local currents and water mass formation in these marginal seas add a unique character to the western North Pacific. The upstream Kuroshio branches in the East China Sea and flows into the Sea of Japan as the Tsushima Warm Current (Nitani, 1972; Ichikawa and Beardsley, 2002). Most of the Tsushima Warm Current flows out to the North Pacific as the Tsugaru Warm Current and to the Sea of Okhotsk as the Soya Warm Current. These warm currents also add to the complex water structures in the coastal environments around Japan.

In addition, disturbances formed by wind stress curl changes in the North Pacific propagate into the western North Pacific via Rossby waves. Since the Kuroshio and Oyashio are the western boundary currents in the subtropical and subarctic gyres, Rossby waves are integrated into the transports of these currents. Moreover, the response to the wind stress curl changes is especially manifested at the Kuroshio Extension (Sasaki and Schneider, 2011).

The complexity of the oceanography surrounding Japan requires representative ocean climate models to have: 1) high resolutions, both horizontally and vertically, to represent mesoscale phenomena and complicated structures in the western North Pacific and its marginal seas, and 2) total coverage of the North Pacific to represent the Rossby wave propagation signals from the east. To save computational costs, nesting approaches have been applied to the models to satisfy the above two requirements.

In this section we introduce five regional ocean climate models: MOVE/MRI.COM, JCOPE, DREAMS, JADE2, C-HOPE. There are two other well-known regional ocean climate models, FRA-ROMS (Fisheries Research and Educational Agency–Regional Ocean Modelling System) and COCO (CCSR (Center for Climate System Research) Ocean Component Model; Hasumi, 2006) used for the western North Pacific. Those models are reported in other sections of this scientific report.

MOVE/MRI.COM

The Japan Meteorological Agency (JMA) operates MOVE/MRI.COM (Meteorological Research Institute Multivariate Ocean Variational Estimation System / Meteorological Research Institute Community Ocean Model; Usui *et al*., 2006). The western North Pacific version of MOVE/MRI.COM (MOVE/MRI.COM-WNP) covers the region 117°E–160°W, 15°–65°N with a horizontal resolution of 0.1° around Japan and 54 vertical levels. The basic ocean general circulation model is MRI.COM (Ishikawa *et al*., 2005). The MOVE/MRI.COM-WNP is nested within the North Pacific version of MOVE/MRI.COM (MOVE/MRI.COM-NP), which is applied for the region 100°E–75°W, 15°S–65°N with a horizontal resolution of 0.5°. The MOVE system is based on a multivariate 3DVAR analysis scheme with a vertically coupled temperature-salinity (T-S) empirical orthogonal function (EOF) modal decomposition of a background error covariance matrix (Fujii and Kamachi, 2003). MOVE/MRI.COM-WNP successfully predicted the large meander of the Kuroshio in 2004/05 (Usui *et al*., 2011) and has been in operation since 2008. MOVE/MRI.COM has a global version, MOVE/MRI.COM-G, which is used to initialize the oceanic state of the seasonal forecasting system employing an atmosphere and ocean coupled model (JMA/MRI-CGCM2).

Recent development on MOVE/MRI.COM-WNP involves downscaling. A regional model for the Seto Inland Sea (MRI.COM-Seto), with a horizontal grid size of about 2 km (1/33° × 1/50°) and 50 vertical levels, has been developed to resolve small-scale coastal phenomena (Sakamoto *et al*., 2016). Another development is in the data assimilation method. A 4DVAR version of the MOVE system (MOVE-4DVAR) has been developed for MOVE/MRI.COM-WNP. In operation, MRI.COM-Seto is embedded within the 4DVAR version of MOVE/MRI.COM-WNP (MOVE/MRI.COM-Seto; Usui *et al*., 2015). MOVE-4DVAR has been also employed to produce a 30-year (1982–2012) reanalysis dataset for the western North Pacific Ocean (FORA-WNP30; Usui *et al*., 2016), which is the first-ever dataset covering the western North Pacific over three decades at eddy-resolving resolution.

JCOPE

The Japan Agency for Marine Science and Technology (JAMSTEC) operates the JCOPE (Japan Coastal Ocean Predictability Experiment) system. The domain of the first version of the western North Pacific version of JCOPE (JCOPE1) is 117°E–180°E, 12°N–62°N with a spatial grid resolution of 1/12° and 35 sigma levels (Kagimoto *et al*., 2008; Miyazawa *et al*., 2008). The western North Pacific high-resolution model is embedded in a low-resolution basin-wide model with a spatial grid of about 1/4° and 21 sigma levels using a one-way nesting method. The model has reasonably reproduced Kuroshio path fluctuations (Miyazawa *et al*., 2005). The Fisheries Research Agency (now known as the Fisheries Research and Education Agency, FRA) has operated JCOPE1 since April 2007 for the management of fishery resources off Japan (FRA-JCOPE). JAMSTEC has developed a second version of the system, JCOPE2, with enhanced model and data assimilation schemes (Miyazawa *et al*., 2009). FRA-JCOPE2, a reanalysis dataset covering 1993 to 2009 much used by scientists, has been updated using the latest available data (Soeyanto *et al*., 2014).

A much higher resolution model, JCOPE-T (Miyazawa *et al*., 2012, 2013; Varlamov *et al*., 2015), developed to include tidal effects, has been applied to the region 125°–148°E, 24°–48°N (another version covers 117°–150°E, 17°–50°N) with a spatial grid resolution of about 1/36° and 46 sigma levels. The model provides more realistic dissipation and velocity fields in narrow straits where dissipation hot spots are often formed than the 1/12° model. To evaluate potential electricity generation at several narrow regions, such as the Tokara Strait, JCOPE-T was downscaled to a spatial resolution of 1/500° (JAMSTEC, 2016). The results of the 1/500° resolution model resemble those of 1/36° resolution model since the upstream boundary condition dominates the main axis of the Kuroshio. However, when the main axis of the Kuroshio fluctuated out of the region, the results of the downscaled model showed higher velocity than that of the parent model (JAMSTEC, 2016).

DREAMS and JADE2

The Research Institute for Applied Mechanics (RIAM) of Kyushu University operates an ocean prediction system named Data assimilation Research of the East Asian Marine System (DREAMS). The dynamic driver of the prediction model is the RIAM Ocean Model: a free surface, z-coordinate, hydrostatic OGCM (Lee *et al*., 2003). DREAMS for the marginal seas (DR_M), with 1/12° × 1/15° and 40 vertical levels, is one-way nested in a lower-resolution basin-scale (DR_B) model for the western North Pacific. The DR_M model was designed to optimize the circulations and tidal variations in the Yellow Sea, East China Sea and Sea of Japan. The empirical parameters such as diffusion, viscosity coefficients, or meteorological and tidal boundary conditions have been calibrated using model Green's functions (Hirose, 2011; Moon *et al*., 2012) to produce better accuracy of prognostic integrations. The sequential corrections by approximate

Kalman filter keep the analysis fields of DR_B and M close to satellite measurements (Hirose *et al*., 2013). The interactive visualization tools on the DREAMS web site allows world-wide users to create images tailored to their demand (Fig. 5.1).

The DR_M model has been adopted as the main engine of the JADE2 (Japan Sea Data Assimilation Experiment 2) prediction system operated by the Japan Sea National Fisheries Research Institute, and thus contributes to fisheries research and assessments. For instance, the advection and diffusion processes of juvenile yellowtails are realistically simulated by numerical tracer experiments (Tsuji and Hirose, 2016). The model outputs have also been applied for a decadal prediction of plastic marine debris to be littered on a beach (Kako *et al*., 2014). Recently, finer resolution (1/60° × 1/75°) models have been developed and preliminary results are provided in the same web site (http://dreams-c.riam.kyushu-u.ac.jp/vwp/), mainly targeting the coastal applications.

For climate issues, the earlier version of DR_M was applied to investigate the influences of the Sea of Japan on the weather and climate around Japan. Hirose *et al*. (2009) statistically demonstrated the influence of the Tsushima Warm Current on the western Pacific (WP) teleconnection pattern, and hence on seasonal precipitation over the Japanese Islands. Yamamoto and Hirose (2011) used the data assimilation estimates to drive an atmospheric model to investigate the hypothesis of Hirose *et al*. (2009) and showed the possible influence of the East Asian marginal seas on Ferrel circulation.

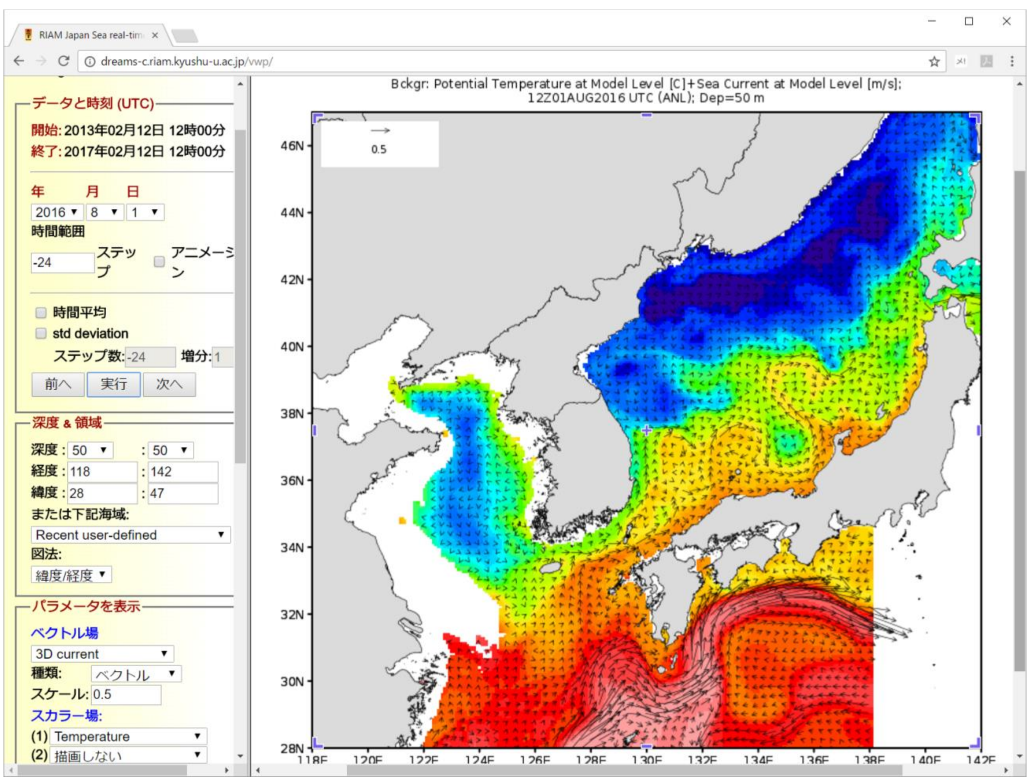

Fig. 5.1 Interactive visualization tools on the DREAMS web site (http://dreams-c.riam.kyushu-u.ac.jp/vwp/), which allows world-wide users to create images tailored to their demand.

C-HOPE for the western North Pacific

The Hamburg Ocean Primitive Equation model on a Curvilinear horizontal coordinate (C-HOPE; Wolff *et al*., 1997) was applied to the western North Pacific with spatial grid of 1/16° × 1/12° around Japan and 41 vertical levels (Komatsu *et al*., 2007). Data assimilation was conducted using the Tangent linear and Adjoint Model Compiler (TAMC; Giering, 1999). The model was coupled to a lower trophic ecosystem model NEMURO (North Pacific Ecosystem for Understanding Regional Oceanography; Kishi *et al*., 2007) which was developed by the PICES MODEL Task Team. The coupled ecosystem model has been applied to investigate plankton responses to the Kuroshio Extension meanders (Komatsu *et al*., 2007).

Recently, an ecosystem model has been developed to improve the resolution of finer plankton and microbial loop processes (eNEMURO; Yoshie *et al*., 2011). C-HOPE–eNEMURO has been applied to investigate fish growth response to future climate change (Ito *et al*., 2016). The output of data assimilation in 2000 was used as the initial condition and the model was driven by NCEP reanalysis atmospheric forcing from 2000 to 2010. After 2010, atmospheric forcing from MIROC-3.2 HiRes with the IPCC SRES-A1B scenario was used to drive the C-HOPE–eNEMURO until 2100. The average sea surface temperature (SST) in 2090–2100 showed higher values in the western North Pacific compared to 2000–2010. The SST in the mixed water region showed significant increases greater than 2.5°C (Fig. 5.2).

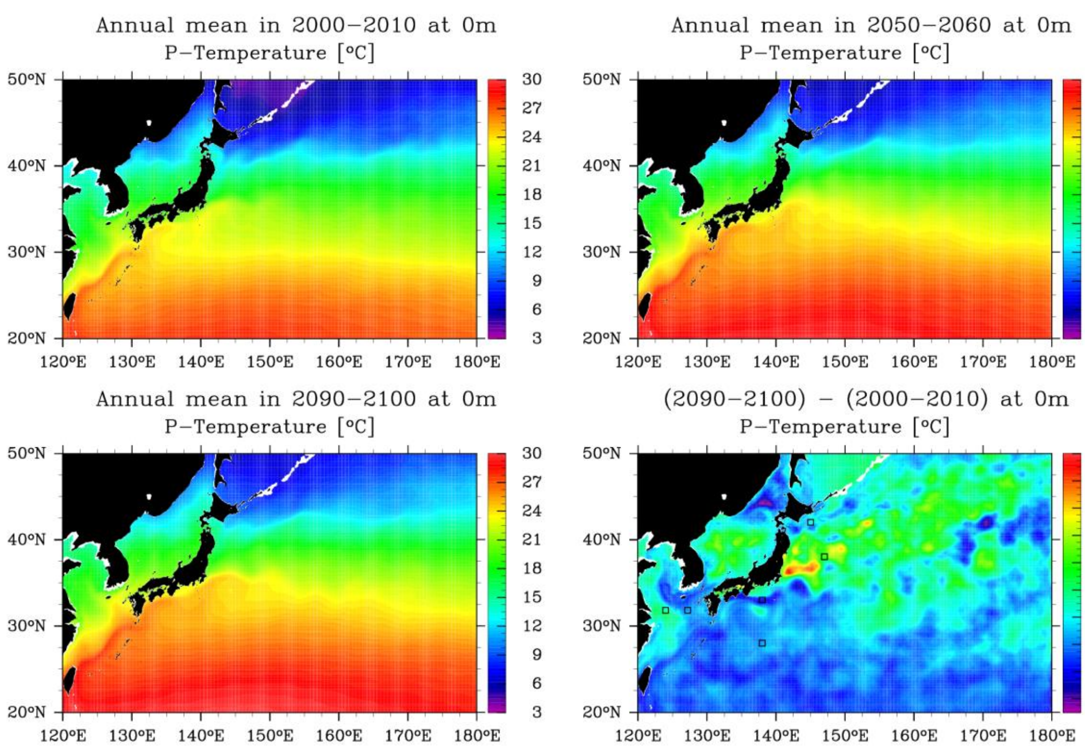

Fig. 5.2 Sea surface temperature (SST) distribution averaged for 2000–2010, 2050–2060, and 2090–2100 and SST difference between 2090–2100 and 2000–2010.

Phytoplankton concentrations decreased over almost the entire western North Pacific except for the coastal region from Hokkaido to the Kuril Islands in 2090–2100 compared with 2000–2010 (not shown). In eNEMURO, four types of phytoplankton compartments are included: small (pico-size representing cyanobacteria), medium (nano-size representing coccoliths and dinoflagellates), non-chaining large phytoplankton (micro-size non-chaining diatoms), and chain-forming large phytoplankton (micro-size chain-forming diatoms) (Fig. 5.3). While the small, medium, and non-chaining phytoplankton increased, chain-forming large phytoplankton decreased over almost the entire western North Pacific in 2090–2100. The ratio of chain-forming large phytoplankton decreased in the entire western North Pacific, especially in the Kuroshio Extension and mixed water region (Fig. 5.4). Similarly, small and medium size zooplankton decreased while large size and predatory zooplankton increased over almost the entire western North Pacific in 2090–2100 compared with 2000–2010 (not shown).

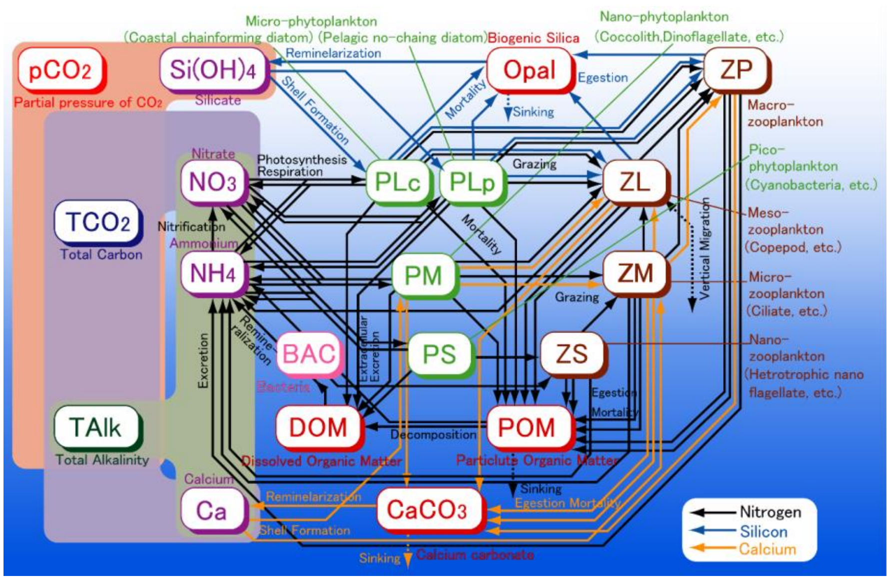

Fig. 5.3 Schematic flow chart of eNEMURO (modified from Yoshie *et al*., 2011).

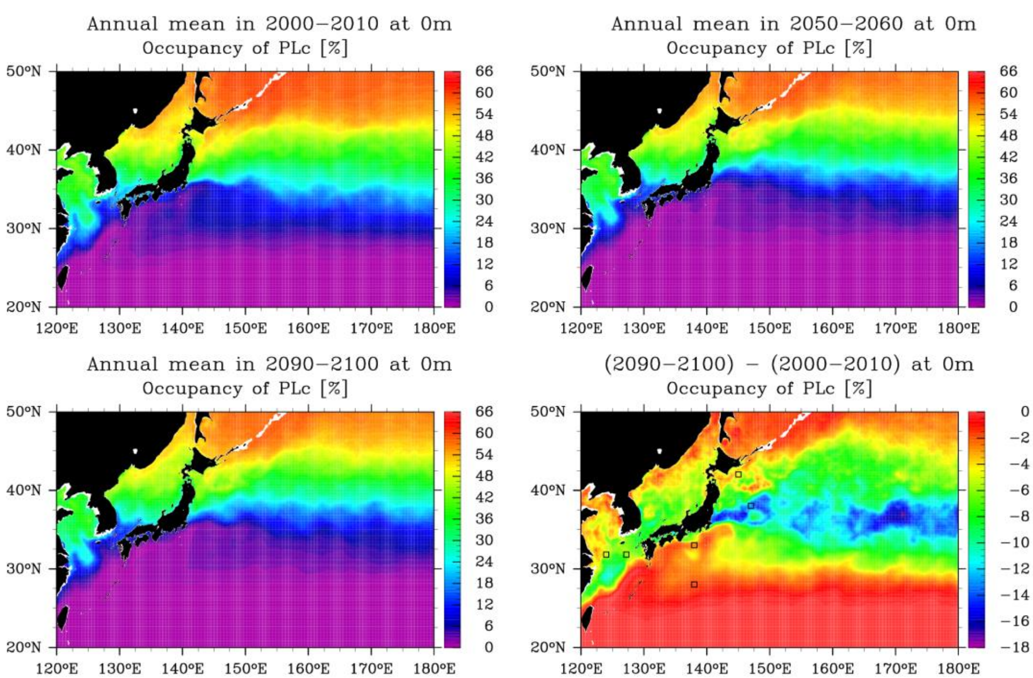

Fig. 5.4 Horizontal distribution of the ratio of chain-forming large phytoplankton in the surface layer averaged for 2000–2010, 2050–2060, and 2090–2100 and its difference between 2090–2100 and 2000–2010.

Coupled model with a marine ecosystem model

Similar to C-HOPE–eNEMURO, many regional ocean climate models have been coupled to lower trophic level ecosystem models (Table 1.5.1). For instance, COCO was coupled to NEMURO (Aita *et al.*, 2007; Sumata *et al.*, 2010). Ito *et al.* (2010) applied a data assimilation method to estimate optimal plankton model parameters and improved the performance of COCO-NEMURO. Hashioka and Yamanaka (2007) and Hashioka *et al.* (2009, 2013) applied COCO-NEMURO to investigate plankton responses to future climate change. Okunishi *et al.* (2012) extended the model to include Japanese sardine migration and growth and tested the responses of sardine to future climate change. COCO was also coupled to an improved version of NEMURO which includes iron limitation and optimum nutrient uptake kinetics of phytoplankton (MEM (Marine Ecosystem Model); Hirata *et al.*, 2013). MRI.COM was coupled to a NPZD model with CO_2 cycles (Nakano *et al.*, 2011). JADE and FRA-ROMS were also coupled to NEMURO. OFES (OGCM for the Earth Simulator; Sasaki *et al.*, 2008) is a global eddy-resolving model. MIROC is also a global climate model but is listed as a Japanese contribution in Table 1.5.1.

Table 5.1 Ecosystem-coupled regional ocean climate models used in Japan.

Model name	Compartment	Area	Resolution	Integration
COCO-N_$_{100}$P_$_{100}$ZDFe*	N2(N, Fe)-P100-Z100-Fish1	North Pacific	1/10°	climatology
OFES-NPZD	N1-P1-Z1-D1	Global North Pacific	1/10° 1/10° 1/30°	2000–2008 1995–2013 2002–2003
NPZD-CO_2-MRI.COM	N2-P1-Z1-D1-C2-DO	Global North Pacific	1/10° × 1/11° 1/2° × 1° 1° × 2°	1965–2007 CMIPS
MEM-CO_2-MRI.COM	N5-P2-Z3-POM3-DOM1-C4-DO	Global	1/2° × 1° 1° × 2°	1985–2007 1985–2100
JADE-NEMURO	N3-P2-Z3-POM2-DOM1	Sea of Japan	1/12°	2009–2012
FRA-ROMS-NEMURO	N3-P2-Z3-POM2-DOM1	North Pacific N-W Pacific	1/2° 1/10°	climatology
COCO(MIROC)-NEMURO(-FISH)	N3-P2-Z3-POM2-DOM1-(Fish1)	Global North Pacific	1/3.5° × 1/5.3°	1959–2004 1900s & 2100s
FRA-ROMS-eNEMURO	N3-P4-Z4-POM2-DOM1	North Pacific N-W Pacific	1/2° 1/10°	1990–2009
CHOPE-eNEMURO	N3-P4-Z4-POM2-DOM1	North Pacific	1/16°	1993–2010 1990–2100
CHOPE-eNEMURO-FISH	N3-P4-Z4-POM2-DOM1-Fishi1	North Pacific	1/16°	1990–2100
COCO-MEM	N5-P2-Z3-POM3-DOM1-C4-DO	–	–	–

* N_$_{100}$P_$_{100}$ZDFe denotes a model including one nutrient, 100 phytoplankton, 100 zooplankton, one detritus and one iron.

If we divide the ecosystem-coupled regional ocean climate models into objective oriented types, zooplankton-oriented models are limited (Fig. 5.4). This is not only a case for Japanese activities but is common globally since biogeochemists focus on carbon and primary production and fisheries scientists focus on fish (Ito *et al*., 2015). In addition, most of the ecosystem models in Japan are functional type models. Only the $N_{100}P_{100}$ZDFe model is a multi-adaptation model as there are few size-based modelling approaches in Japan (Fig. 5.5). Although the size-based modelling approach has limitations, it has several advantages including:

1. Coverage of the ecosystem is greater since size-based models can represent a continuous distribution of biota, from small phytoplankton to large top predator fish,
2. Species interactions are emergent (large species prey upon small ones),
3. It is possible to incorporate climate change impacts, and
4. It is useful for global assessment of climate change impacts on marine ecosystems since size-based models are generic and are able to be applied without local species composition (Ito *et al*., 2014).

In the near future, much more variety in models is essential in Japan to elucidate climate change impacts on marine ecosystems with quantitative uncertainties.

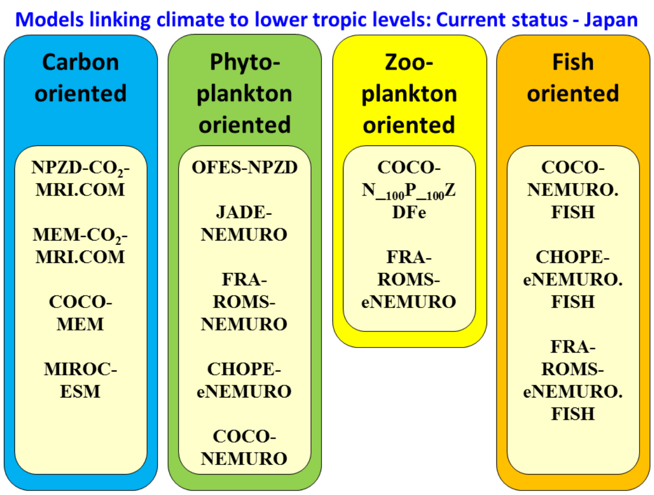

Fig. 5.4 Ecosystem-coupled regional ocean climate models applied in Japan. The models are divided into focal objectives.

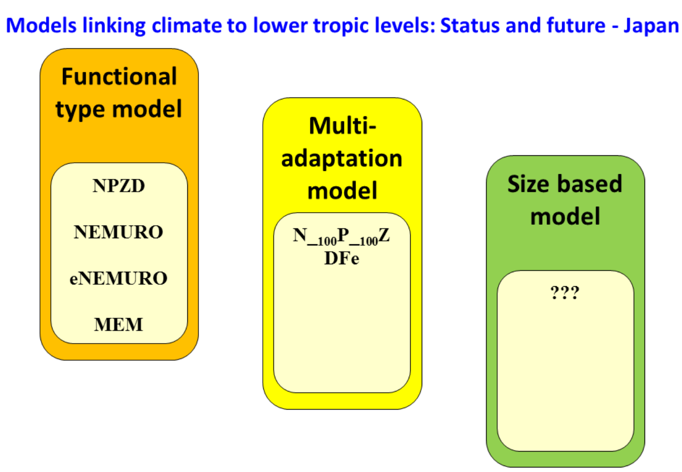

Fig. 5.5 Marine ecosystem models coupled to regional ocean climate models applied in Japan. The models are divided into model types.

Acknowledgements

This work was partly supported by the Japan Society for the Promotion of Science KAKENHI Grant Numbers JP15H05823 and JP26247076. This work was also partly supported by the Ministry of Agriculture, Forestry and Fisheries (MAFF) project "Development of mitigation and adaptation technologies to climate change in the sectors of agriculture, forestry and fisheries II" and the "Interdisciplinary Collaborative Research" of AORI (Atmosphere and Ocean Research Institute), The University of Tokyo.

References

Aita M.N., Yamanaka, Y. and Kishi, M.J. 2007. Interdecadal variation of the lower trophic ecosystem in the northern Pacific between 1948 and 2002, in a 3-D implementation of the NEMURO model. *Ecol. Modell.* **202**: 81–94.

FAO (Food and Agriculture Organization of the United Nations). 2014. The State of World Fisheries and Aquaculture 2014. Rome, 223 pp.

Fujii Y. and Kamachi, M. 2003. Three-dimensional analysis of temperature and salinity in the equatorial Pacific using a variational method with vertical coupled temperature-salinity EOF modes. *J. Geophys. Res*. **108**: 3297, doi:10.1029/2002JC001745.

Giering R. 1999. Tangent linear and adjoint model compiler. Users Manual version 1.4, 64 pp.

Hashioka T. and Yamanaka, Y. 2007. Ecosystem change in the western North Pacific associated with global warming obtained by 3-D NEMURO. *Ecol. Modell.* **202**: 95–104.

Hashioka T., Sakamoto, T.T. and Yamanaka, Y. 2009. Potential impact of global warming on North Pacific spring blooms projected by an eddy-permitting 3-D ocean ecosystem model. *Geophys. Res. Lett.* **36**: DOI: 10.1029/2009GL038912

Hashioka T., Vogt, M., Yamanaka, Y., Le Quéré, C., Buitenhuis, E.T., Aita, M.N., Alvain, S., Bopp, L., Hirata, T., Lima, I., Sailley, S. and Doney, S.C. 2013. Phytoplankton competition during the spring bloom in four plankton functional type models. *Biogeosciences* **10**: 6833–6850.

Hasumi H. 2006. CCSR Ocean Component Model (COCO) version 4.0. CCSR Report No. 25, 103 pp.

Hirata T., Saux-Picart, S., Hashioka, T., Aita-Noguchi, M., Sumata, H., Shigemitsu, M., Allen, I.J. and Yamanaka, Y. 2013. A comparison between phytoplankton community structures derived from a global 3D ecosystem model and satellite observation. *J. Mar. Syst*. **109-110**: 129–137.

Hirose N. 2011. Inverse estimation of empirical parameters used in a regional ocean circulation model. *J. Oceanogr*. **67**: 323–336.

Hirose N., Nishimura, K. and Yamamoto, M. 2009. Observational evidence of a warm ocean current preceding a winter teleconnection pattern in the northwestern Pacific. *Geophys. Res. Lett*. **36**: L09705, doi:10.1029/2009GL037448.

Hirose N., Takayama, K., Moon, J.-H., Watanabe, T. and Nishida, Y. 2013. Regional data assimilation system extended to the East Asian marginal seas. *Umi to Sora* **89**: 43–51.

Ichikawa, H. and Beardsley, R.C. 2002. The current system in the Yellow and East China Sea. *J. Oceanogr*. **58**: 77–92.

Ishikawa I., Tsujino, H., Hirabara, M., Nakano, H., Yasuda, T. and Ishizaki, H. 2005. Meteorological Research Institute Community Ocean Model (MRI.COM) Manual. Tech. Rep. Meteorol. Res. Inst., 47, the Meteorological Research Institute, 189 pp. (in Japanese). http://dx.doi.org/10.11483/mritechrepo.47.

Isoguchi O., Kawamura, H. and Oka, E. 2006. Quasi-stationary jets transporting surface warm waters across the transition zone between the subtropical and the subarctic gyres in the North Pacific. *J. Geophys. Res*. **111**: C10003. doi:10.1029/2005JC003402.

Ito S. 2016. History of lower trophic level marine ecosystem models and NEMURO. *Monthly Kaiyo* **48**: 291–301 (in Japanese).

Ito S., Yoshie, N., Okunishi, T., Ono, T., Okazaki, Y., Kuwata, A., Hashioka, T., Rose, K.A., Megrey, B.A., Kishi, M.J., Nakamachi, M., Shimizu, Y., Kakehi, S., Saito, H., Takahashi, K., Tadokoro, K., Kusaka, A. and Kasai, H. 2010. Application of an automatic approach to calibrate the NEMURO nutrient-phytoplankton-zooplankton food web model in the Oyashio region. *Prog. Oceanogr*. **87**: 186–200.

Ito S., McKinnell, S., Polovina, J., Hollowed, A. and Peck, M. 2014. Workshop on "*Comparison of Size-based and Species-based Ecosystem Models*". PICES Press, Vol. 22, No.1, pp. 9–11.

Ito S., Rose, K.A., Megrey, B., Schweigert, J., Hay, D., Werner, F.E. and Aita, M.N. 2015. Geographic variation in Pacific herring growth in response to regime shifts in the North Pacific Ocean. *Prog. Oceanogr*. **138**: 331–347.

Itoh S. and Yasuda, I. 2010. Characteristics of mesoscale eddies in the Kuroshio-Oyashio Extension region detected from the distribution of the sea surface height anomaly. *J. Phys. Oceanogr*. **40**: 1018–1034.

Kagimoto, T., Miyazawa, Y., Guo, X. and Kawajiri, H. 2008. High resolution Kuroshio forecast system - Description and its applications, pp. 209–234 *in* High Resolution Numerical Modeling of the Atmosphere and Ocean *edited by* W. Ohfuchi and K. Hamilton, Springer, New York.

JAMSTEC (Japan Agency for Marine Science and Technology). 2016. A report for "Ocean energy technology research and development: potential estimation".

Kako S., Isobe, A., Kataoka, T. and Hinata, H. 2014. A decadal prediction of the quantity of plastic debris littered on beaches of the East Asian marginal seas. *Mar. Pollut. Bull*. **81**: 174–184.

Kawai H. 1972. Hydrography of the Kuroshio Extension, pp. 235–352 *in* Kuroshio, Its Physical Aspects *edited by* H. Stommel and K. Yoshida, University of Tokyo Press, Tokyo.

Kida S., Mitsudera, H., Aoki, S., Guo, X., Ito, S., Kobashi, F., Komori, N., Kubokawa, A., Miyama, T., Morie, R., Nakamura, H., Nakamura, T., Nakano, H., Nishigaki, H., Nonaka, M., Sasaki, H., Sasaki, Y.N., Suga, T., Sugimoto, S., Taguchi, B., Takaya, K., Tozuka, T., Tsujino, N. and Usui, N. 2015. Oceanic fronts and jets around Japan: a review. *J. Oceanogr*. **71**: 469–497.

Kishi, M.J., Kashiwai, M., Ware, D.M., Megrey, B.A., Eslinger, D.L., Werner, F.E., Aita, M.N., Azumaya, T., Fujii, M., Hashimoto, S., Huang, D., Iizumi, H., Ishida, Y., Kang, S., Kantakov, G.A., Kim, H., Komatsu, K., Navrotsky, V.V., Smith, S.L., Tadokoro, K., Tsuda, A., Yamamura, O., Yamanaka, Y., Yokouchi, K., Yoshie, N., Zhang, J., Zuenko, Y.I. and Zvalinsy, V.I. 2007. NEMURO – a lower trophic level model for the North Pacific marine ecosystem. *Ecol. Modell*. **202**: 12–25.

Komatsu, K., Matsukawa, Y., Nakata, K., Ichikawa, T. and Sasaki, K. 2007. Effects of advective processes on planktonic distributions in the Kuroshio region using a 3-D lower trophic model and a data assimilative OGCM. *Ecol. Modell.* **202**: 105–119.

Lee, H.J., Yoon, J.-H., Kawamura, H. and Kang, H.-W. 2003. Comparison of RIAMOM and MOM in modeling the East Sea/Japan Sea circulation. *Ocean Polar Res*. **25**: 287–302.

Miyazawa, Y., Yamane, S., Guo, X. and Yamagata, T. 2005. Ensemble forecast of the Kuroshio meandering. *J. Geophys. Res*. **110**: C10026, doi:10.1029/2004JC002426.

Miyazawa, Y., Kagimoto, T., Guo, X. and Sakuma, H. 2008. The Kuroshio large meander formation in 2004 analyzed by an eddy-resolving ocean forecast system. *J. Geophys. Res*. **113**: C10015, doi:10.1029/2007JC004226.

Miyazawa, Y., Zhang, R., Guo, X., Tamura, H., Ambe, D., Lee, J.-S., Okuno, A., Yoshinari, H., Setou, T. and Komatsu, K. 2009. Water mass variability in the western North Pacific detected in a 15-year eddy resolving ocean reanalysis. *J. Oceanogr*. **65**: 737–756.

Miyazawa, Y., Masumoto, Y., Varlamov, S.M. and Miyama, T. 2012. Transport simulation of the radionuclide from the shelf to open ocean around Fukushima. *Cont. Shelf Res*. **50–51**: 16–29.

Miyazawa, Y., Masumoto, Y., Varlamov, S.M., Miyama, T., Takigawa, M., Honda, M. and Saino, T. 2013. Inverse estimation of source parameters of oceanic radioactivity dispersion models associated with the Fukushima accident. *Biogeosciences* **10**: 2349–2363.

Mizuno, K. and White, W.B. 1983. Annual and interannual variability in the Kuroshio Current system. *J. Phys. Oceanogr*. **13**: 1848–1869.

Moon, J.H., Hirose, N. and Morimoto, A. 2012. Green's function approach for calibrating tides in a circulation model for the East Asian marginal seas. *J. Oceanogr.* **68**: 245–354.

Nitani, H. 1972. Beginning of the Kuroshio, pp. 129–163 *in* Kuroshio, Its Physical Aspects *edited by* H. Stommel and K. Yoshida, University of Tokyo Press, Tokyo.

Nakano, H., Tsujino, H., Hirabara, M., Yasuda, T., Motoi, T., Ishii, M. and Yamanaka, G. 2011. Uptake mechanism of anthropogenic CO_2 in the Kuroshio Extension region in an ocean general circulation model. *J. Oceanogr*. **67**: 765–783.

Nonaka, M., Nakamura, H., Tanimoto, Y., Kagimoto, T. and Sasaki, H. 2008. Interannual-to-decadal variability in the Oyashio and its influence on temperature in the Subarctic Frontal Zone: An eddy-resolving OGCM simulation. *J. Clim*. **21**: 6283–6303.

Okunishi, T., Ito, S., Hashioka, T., Sakamoto, T., Yoshie, N., Sumata, H., Yara, Y., Okada, N. and Yamanaka, Y. 2012. Impacts of climate change on growth, migration and recruitment success of Japanese sardine (*Sardinops melanostictus*) in the western North Pacific. *Clim. Change* **115**: 485–503.

Sakamoto, K., Yamanaka, G., Tsujino, H., Nakano, H., Urakawa, S., Usui, N., Hirabara, M. and Ogawa, K. 2016. Development of an operational coastal model of the Seto Inland Sea, Japan. *Ocean Dyn*. **66**: 77–97.

Sasaki, Y. and Schneider, N. 2011. Decadal shifts of the Kuroshio Extension jet: Application of thin-jet theory. *J. Phys. Oceanogr*. **41**: 979–993.

Sasaki, H., Nonaka, M., Masumoto, Y., Sasai, Y., Uehara, H. and Sakuma, H. 2008. An eddy-resolving hindcast simulation of the quasi-global ocean from 1950 to 2003 on the Earth Simulator, pp. 157–185 *in* High Resolution Numerical Modeling of the Atmosphere and Ocean *edited by* W. Ohfuchi and K. Hamilton, Springer, New York.

Soeyanto, E., Guo, X., Ono, J. and Miyazawa, Y. 2014. Interannual variations of Kuroshio transport in the East China Sea and its relation to Pacific Decadal Oscillation and mesoscale eddy. *J. Geophys. Res*. **119**: 3595–3616, doi:10.1002/2013JC009529.

Sumata, H., Hashioka, T., Suzuki, T., Yoshie, N., Okunishi, T., Aita-Noguchi, M., Sakamoto, T., Ishida, A., Okada, N. and Yamanaka, Y. 2010. Effect of eddy transport on the nutrient supply into the euphotic zone simulated in an eddy-permitting ocean ecosystem model. *J. Mar. Syst*. **83**: 67–87.

Talley, L.D., Nagata, Y., Fujimura, M., Iwao, T., Kono, T., Inagake, D., Hirai, M. and Okuda, K. 1995. North Pacific intermediate water in the Kuroshio/Oyashio mixed water region. *J. Phys. Oceanogr*. **25**: 475–501.

Tsuji, T. and Hirose, N. 2016. Transport modeling of yellowtail juveniles in the East Asian marginal seas. *Monthly Kaiyo* **48**: 517–524.

Usui, N., Ishizaki, S., Fujii, Y., Tsujino, H., Yasuda, T. and Kamachi, M. 2006. Meteorological Research Institute multivariate ocean variational estimation (MOVE) system. *Adv. Space Res*. **37**: 806–822.

Usui, N., Tsujino, H., Nakano, H. and Fujii, Y. 2011. Decay mechanism of the 2004/05 Kuroshio large meander. *J. Geophys. Res*. **116**: C10010, doi:10.1029/2011JC007009.

Usui, N., Fujii, Y., Sakamoto, K. and Kamachi, M. 2015. Development of a four-dimensional variational assimilation system toward coastal data assimilation around Japan. *Mon. Weather Rev*. **143**: 3874–3892. DOI: 10.1175/MWR-D-14-00326.1.

Usui N., Wakamatsu, T., Tanaka, Y., Hirose, N., Toyoda, T., Nishikawa, S., Fujii, Y. Takatsuki, Y., Igarashi, H., Nishikawa, H., Ishikawa, Y., Kuragano, T. and Kamachi, M. 2016. Four-dimensional variational ocean reanalysis: a 30-year high-resolution dataset in the western North Pacific (FORA-WNP30). *J. Oceanogr*. **73**: 205–233, doi:10.1007/s10872-016-0398-5.

Varlamov, M.S., Guo, X., Miyama, T., Ichikawa, K., Waseda, T. and Miyazawa, Y. 2015. M2 baroclinic tide variability modulated by the ocean circulation south of Japan. *J. Geophys. Res*. **120**: 3681–3710, doi:10.1002/2015JC010739.

Yamamoto M. and Hirose, N. 2011. Possible modification of atmospheric circulation over the northwestern Pacific induced by a small semi-enclosed ocean. *Geophys. Res. Lett*. **38**: L03804, doi:10.1029/2010GL046214.

Yasuda, I. 2003. Hydrographic structure and variability of the Kuroshio-Oyashio Transition Area. *J. Oceanogr.* **59**: 389–402. DOI: 10.1023/A:1025580313836

Yoshie, N., Guo, X., Fujii, N. and Komorita, T. 2011. Ecosystem and nutrient dynamics in the Seto Inland Sea, Japan, pp. 39–49 *in* Interdisciplinary Studies on Environmental Chemistry – Marine Environmental Modeling and Analysis *edited by* M. Omori, X. Guo, N. Yoshie, N. Fujii, I.C. Handoh, A. Isobe and S. Tanabe, TERRAPUB, Tokyo, Japan.

Wagawa, T., Ito, S., Shimizu, Y., Kakehi, S. and Ambe, D. 2014. Currents associated with the quasi-stationary jet separated from the Kuroshio Extension. *J. Phys. Oceanogr*. **44**: 1636–1653.

Wolff, J.-O., Maier-Reimer, E. and Legutke, S. 1997. The Hamburg Ocean Primitive Equation model, HOPE. Max-Planck-Institut für Meteorologie. Technical Report No. 13, 98 pp.

6. *Nested-grid ocean modeling for the western North Pacific and Japan's coastal region*

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Background

The Atmosphere and Ocean Research Institute (AORI) and Japan Agency for Marine-Earth Science and Technology (JAMSTEC) are jointly developing an ocean general circulation model COCO (Hasumi, 2006) and a climate model MIROC (Hasumi and Emori, 2004) whose ocean component is COCO. MIROC is one of the contributors to CMIP5 and thus to IPCC AR5. We used two different setups of MIROC for CMIP5: a high resolution version (Sakamoto *et al*., 2012) and a medium resolution version (Watanabe *et al*., 2010). The horizontal grid spacing of the former is about 60 km for the atmosphere and about 20 km for the ocean, whereas that of the latter is about 150 km for the atmosphere and about 100 km for the ocean. The high resolution version directly resolves regional features of the present and future states of the ocean and climate to some extent, but some of the important oceanic and climatic structures are still biased at such resolution (Hasumi, 2014).

To further address regional ocean problems, we developed a two-way nested-grid ocean modeling system (Kurogi *et al*., 2013). Currently, we are applying this modeling system to physical and biogeochemical problems in the western North Pacific and Japan's coastal regions. This nested-grid ocean modeling system is also being applied to global climate modeling.

Western North Pacific modeling

For relatively long-term (over the decadal timescales) problems, we utilize two-level nesting where a western North Pacific model of $0.1° \times 0.1°\cos\phi$ (zonal and meridional, respectively, where ϕ is latitude) horizontal resolution is nested into a North Pacific model of $0.5° \times 0.5°\cos\phi$ horizontal resolution (Fig. 6.1). The model is applied to the meandering characteristics of the Kuroshio. The path of the Kuroshio south of Japan is known to take two different forms, large-meandering and non-large meandering, and each type of path persists for a few years to a decade (Hasumi, 2010). The path of the Kuroshio affects not only the climate over the Pacific region but also the Pacific fishery environment as it transports eggs and larvae of some fishery-important species. Its future change is of great concern for us. Even with high enough horizontal resolution to reproduce the Kuroshio separation from Japan's coast (~20 km), however, models tend to have problems in capturing its path and variability south of Japan.

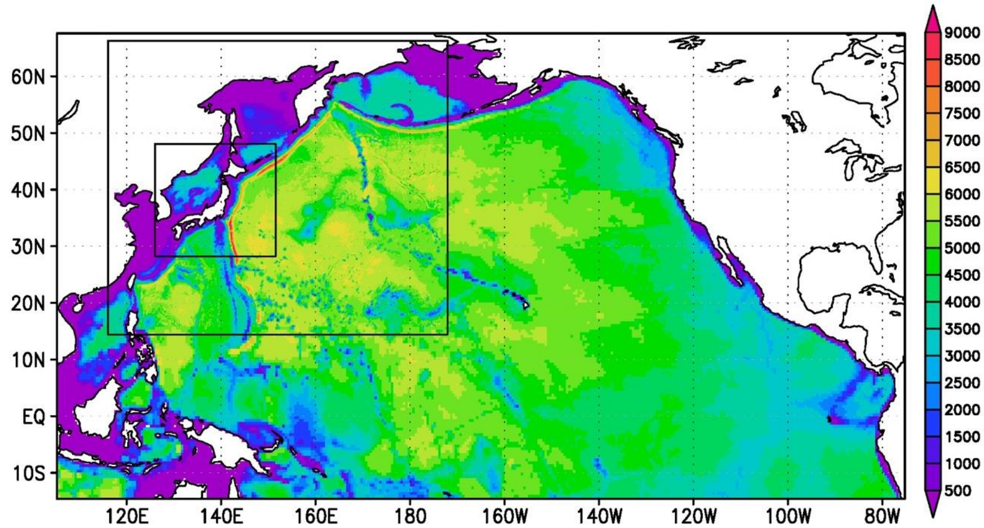

Fig. 6.1 Model domain of the three-level nesting system. The color scale indicates the depth (m) of the ocean floor.

When forced by the climatological annual cycle (*i.e.*, no interannual variation) of the surface air properties, the model exhibits repeated emergence of the two major types of the Kuroshio path south of Japan (Fig. 6.2). The duration of each path, a few years to a decade, is fairly realistic, and the transition processes characterized by the growth of the small meander and eddy separation are consistent with observed features. To our knowledge, this is the first successful simulation of spontaneous repetition of the two types of path. Some previous attempts succeeded in simulating the transition of the path from non-large-meandering to large-meandering and then back to non-large-meandering with realistic transition processes, but the duration of the large-meandering path was too short and only one transition event was simulated. It is demonstrated that the water column stretching of the upper layer due to the baroclinic structure of the current plays an important role in maintaining the large-meandering path (Kurogi *et al*., 2013). We are now applying this model to possible future changes of the meandering characteristics of the Kuroshio.

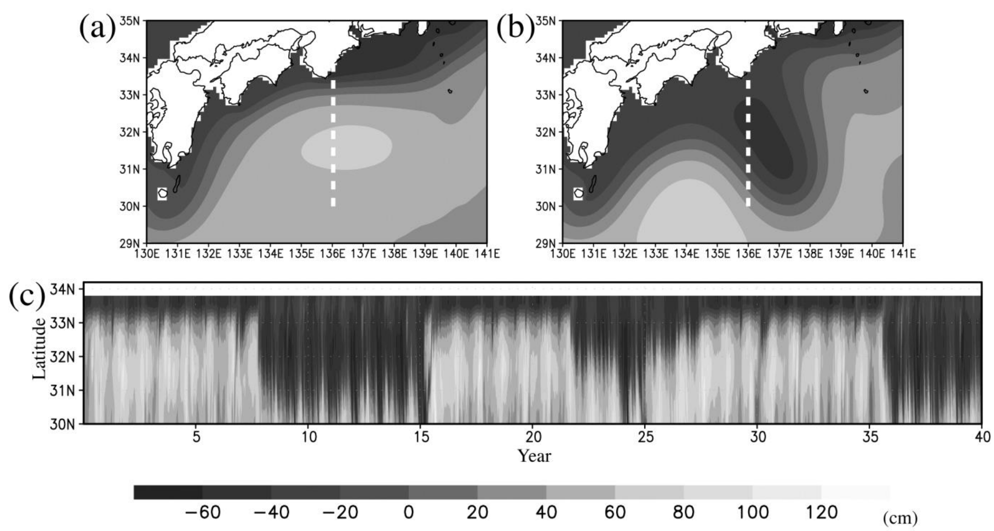

Fig. 6.2 (a) Sea surface height averaged from year 30 to 35 and (b) from year 36 to 40 of the two-level nesting simulation; (c) time evolution of the sea surface height along 136°E (dashed lines in (a) and (b)).

Japan's coastal regions modeling

For relatively short-term problems, we utilize three-level nesting where a model around Japan of 0.02° × 0.02°cosϕ horizontal resolution is further nested (Fig. 6.1). We are currently applying this model to Japan's coastal environment.

The coastal environment is, in general, heavily affected by riverine input of freshwater and dissolved substances. However, observations are too scarce to construct a reliable river discharge dataset covering the whole coast of Japan. Thus, previous modeling studies dealing with large-scale problems of Japan's coastal regions have often neglected river discharge. We utilized a product of a hydrological cycle model which calculates the river discharge from well-observed meteorological elements, and demonstrated the important influences of river discharge not only on coastal waters but also on offshore properties (Urakawa *et al*., 2015).

The coastal environment is also heavily affected by offshore currents. For example, the Sanriku ria coast, located on the Pacific side of northeastern Japan, is normally under the influence of Tsushima Warm Water, which originates in the Tsushima Warm Current and flows through the Tsugaru Strait and southward along the Sanriku ria coast, but cold core eddies originated in the Oyashio are known to come close to the coast occasionally. Aquaculture is intensively conducted in many small bays on the Sanriku ria coast, and intrusion of such a cold water could severely damage the aquaculture therein. Our three-level nesting succeeded in realistically simulating such a coastward approach of cold core eddies.

The above-mentioned three-level nesting is yet insufficient to deal with many of the problems in Japan's coastal regions. For example, the horizontal extent of the small bays on the Sanriku ria coast is mostly less than 10 km, so currents therein and exchange with offshore waters could only be well represented by ~100 m or finer horizontal resolution. We are currently conducting downscale modeling for Otsuchi Bay, on the Sanriku ria coast, with NPZD type ecosystem representation. The bay itself is resolved by ~18 m size horizontal grids, and that bay model is nested into a larger domain model of ~90 m size horizontal grid with the two-way method (Fig. 6.3). The boundary condition for the larger domain model is obtained from the inner-most model of the above-mentioned three-level nesting Pacific model. Its physical modeling is well established and validated (Sakamoto *et al*., 2017), and its application to ecosystem modeling is to appear shortly.

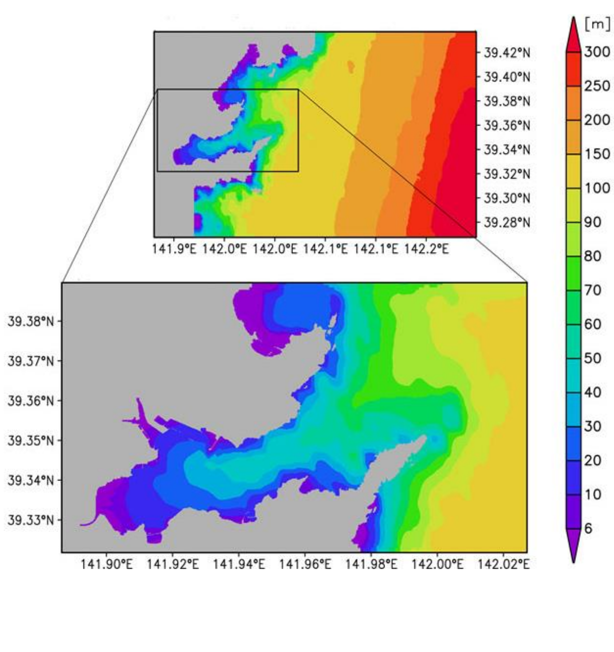

Fig. 6.3 Model domain for downscaling targeted at Otsuchi Bay, Sanriku ria coast.

Closing remarks

In oceanic phenomena, global and regional scales strongly interact with each other, especially when the time scale of interest is relatively long. So, if we intend to precisely know future changes of regional oceanic features under ongoing climate warming (over decadal or longer time scales), the one-way downscaling approach has a severe limitation. Although it is computationally costly, we need to step toward interactive (two-way) downscaling approaches. As for interaction, we have to take care of not only scales but also systems, *i.e.*, air–sea interaction and feedback.

We are developing a global climate modeling system with a two-level ocean nesting. Using this modeling system with high resolution in the western North Pacific region (Fig. 6.4), it is demonstrated that the oceanic variability in the Kuroshio Extension region and the associated air–sea interaction heavily affects the climatic features over the whole Pacific region even where the model resolution is not high enough (Tatebe *et al*., 2014), wherein a large-scale feedback in the coupled atmosphere–ocean system plays an important role (Tatebe *et al*., 2017).

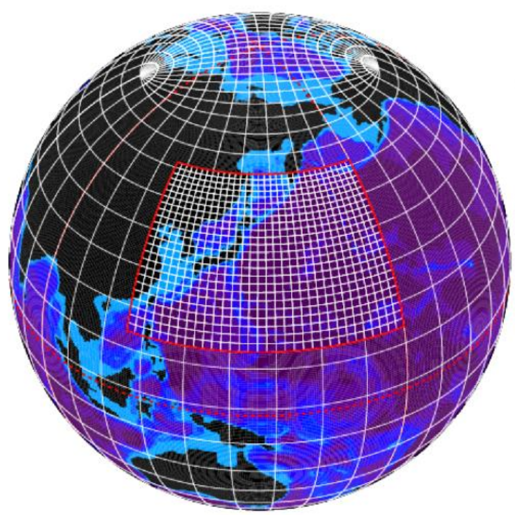

Fig. 6.4 Ocean model grid configuration for the global climate model with two-level nesting. White lines indicate grid cells (every twenty grid lines), and the high resolution model domain is bounded by red lines.

References

Hasumi, H. 2006. CCSR Ocean Component Model (COCO) version 4.0. CCSR Rep. No. 25, 103 pp.

Hasumi, H. 2014. A review on ocean resolution dependence of climate biases in AOGCMs. CLIVAR Exchanges, No. 65, Vol. 19, No. 2, pp. 7–9.

Hasumi, H. and Emori, S. 2004. K-1 coupled GCM (MIROC) description. K-1 Tech. Rep. No. 1, 34 pp.

Hasumi, H., Tatebe, T., Kawasaki, T., Kurogi, M. and Sakamoto, T.T. 2010. Progress of North Pacific modeling over the past decade. *Deep-Sea Res. II* **57**: 1188–1200.

Kurogi, M., Hasumi, H. and Tanaka, Y. 2013. Effects of stretching on maintaining the Kuroshio meander. *J. Geophys. Res*. **118**: 1182–1194.

Sakamoto, T.T., Komuro, Y., Nishimura, T., Ishii, M., Tatebe, H., Shiogama, H., Hasegawa, A., Toyoda, T., Mori, M., Suzuki, T., Imada, Y., Nozawa, T., Takata, K., Mochizuki, T., Ogochi, K., Emori, S., Hasumi, H. and Kimoto, M. 2012. MIROC4h – a new high-resolution atmosphere-ocean coupled general circulation model. *J. Meteorol. Soc. Japan* **90**: 325–359.

Sakamoto, T.T., Urakawa, L.S., Hasumi, H., Ishizu, M., Itoh, S., Komatsu, T. and Tanaka, K. 2017. Numerical simulation of Pacific water intrusions into Otsuchi Bay, northeast of Japan, with a nested-grid OGCM. *J. Oceanogr*. **73**: 39–54.

Tatebe, H., Kurogi, M. and Hasumi, H. 2014. MIROC5 with a nested ocean component focused on the western North Pacific. CLIVAR Exchanges, No. 65, Vol. 19, No. 2, pp. 49–52.

Tatebe, H., Kurogi, M. and Hasumi, H. 2017. Atmospheric responses and feedback to the meridional ocean heat transport in the North Pacific. *J. Climate* **30**: 5715–5728.

Urakawa, L.S., Kurogi, M., Yoshimura, K. and Hasumi, H. 2015. Modeling low salinity waters along the coast around Japan using a high-resolution river discharge dataset. *J. Oceanogr*. **71**: 715–739, doi: 10.1007/s10872-015-0314-4.

Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M., Takata, K., Yamazaki, D., Yokohata, T., Nozawa, T., Hasumi, H., Tatebe, H. and Kimoto, M. 2010. Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. *J. Climate* **23**: 6312–6335.

7. *The current status of an operational ocean forecast system "FRA-ROMS" and its community of models in the Japan Fisheries Research and Education Agency*

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Abstract

The Japan Fisheries Research and Education Agency (FRA) has developed an operational ocean forecast system, referred to as "FRA-ROMS", by coupling ocean general circulation models based on the Regional Ocean Modeling System (ROMS) with three-dimensional variational analysis schemes. This system aims primarily to nowcast and two-month forecast mesoscale variations in the Kuroshio–Oyashio region and to address many fisheries problems around Japan in relation to oceanographic conditions. In addition, other community models have been or are being developed on the basis of the FRA-ROMS, such as advanced marginal sea models with a higher accuracy for the East China Sea and the Okhotsk Sea, lower-trophic ecosystem models coupled with the FRA-ROMS, super-high-resolution models for the shelf–slopes and several coastal bays around Japan, and individual-based models (IBMs) for specific fishery resources or harmful organisms. This study briefly summarizes the current status and future perspective of our community efforts based on the FRA-ROMS in terms of regional ocean modeling and regional climate modeling.

Overview of the FRA-ROMS

The Japan Fisheries Research and Education Agency (FRA) developed its own operational ocean forecast system in April 2008 to comprehensively address many fisheries problems around Japan. This system was referred to as FRA-ROMS and has been in operation at weekly intervals since May 2012. The nowcast and two-month forecast are semi-automatically estimated and updated on the FRA-ROMS website (http://fm.dc.affrc.go.jp/fra-roms/index.html). The system consists of ocean general circulation models based on the Regional Ocean Modeling System (ROMS) of Rutgers University (Haidvogel *et al*., 2008) and three-dimensional variational (3D-var) analysis schemes. The 3D-var analysis schemes were not included in the ROMS default option but were developed in the FRA. Two ocean circulation models with a horizontal resolution of 1/2 and 1/10 degrees are connected by one-way nesting (Fig. 7.1a,b). The 1/2-degree coarse-resolution model covers most of the North Pacific, simulates basin-scale oceanographic variations associated with the Pacific Decadal Oscillation, North Pacific Gyre Oscillation and El Niño–Southern Oscillation, and imposes these basin-scale variations on the lateral boundaries of the 1/10-degree child model. The 1/10-degree model domain is limited to the Northwestern Pacific region around Japan and realistically simulates mesoscale variations dominant over the Kuroshio–Oyashio region. In this regard, however, it should be noted that tides, all river discharges except the Yangtze (Changjiang) River, and sea-ice processes are neglected in the current version of the FRA-ROMS. Details of the model configuration are summarized in Kuroda *et al*. (2013a, 2017).

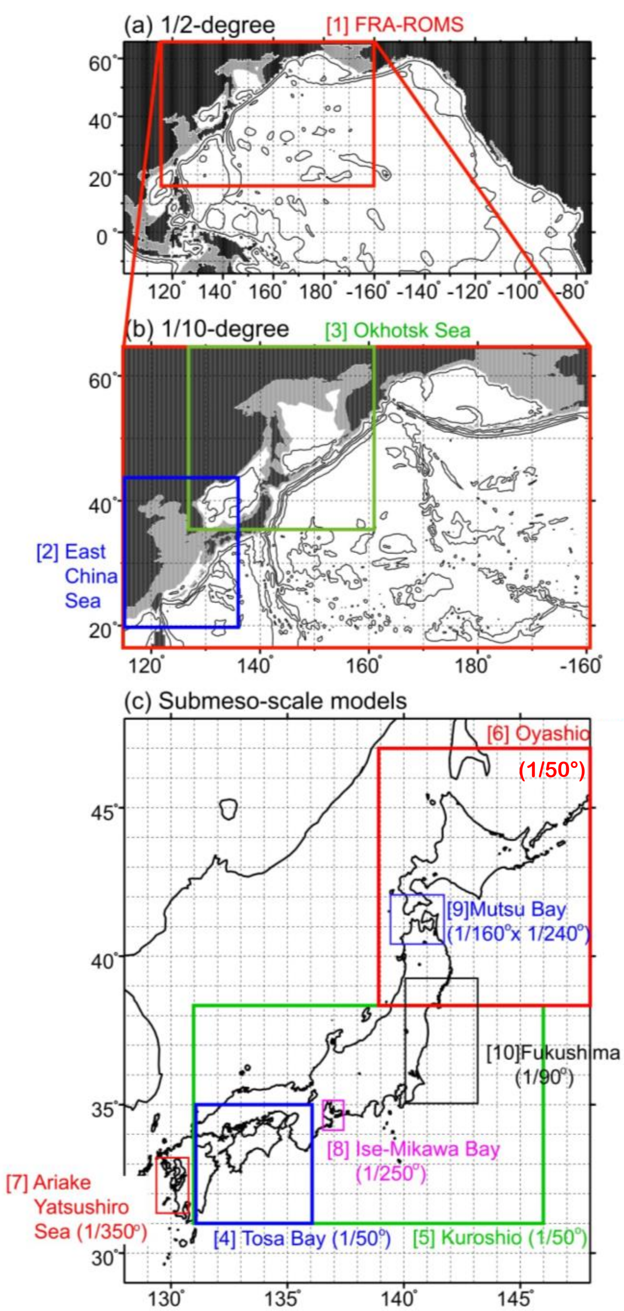

Fig. 7.1 Bathymetry and domain of (a) 1/2- and (b) 1/10-degree models. Contour interval is 2000 m and gray region emphasizes depths shallower than 500 m. (c) Model domain and horizontal resolution of submesoscale models with a horizontal grid size less than 1/50 degree.

The 3D-var analysis schemes were constructed using a technique similar to Multivariate Ocean Variational Estimation (MOVE), which is an operational ocean forecast system developed by the Meteorological Research Institute of the Japan Meteorological Agency (Usui *et al*., 2006). The 3D-var analysis schemes were originally developed for a z-coordinate ocean model, but they could be applied stably to a sigma-coordinate model such as the Princeton Ocean Model (Miyazawa *et al*., 2009). The schemes were thus expected to work robustly in coupling with S-coordinate ocean models, *i.e*., ROMS. Details of the 3D-var analysis schemes are explained in Kuroda *et al*. (2017). Altimetry-derived sea level anomalies, sea surface temperature, and *in situ* temperature–salinity profiles from vessels and Argo floats were assimilated into the FRA-ROMS using Increment Analysis Update with a weekly time window (Bloom *et al*., 1996). The assimilated product, called "reanalysis data", corresponding to nowcast, could then be analyzed as daily mean values (*i.e*., temperature, salinity, sea surface height, velocities, vertical mixing and diffusion) from January 1, 1993 to the present. The forecast product up to two months later could also be analyzed as daily mean values. The reproducibility of the reanalysis and forecast data was validated by FRA oceanographers through comparison with observed data. Its typical mesoscale reproducibility such as the Kuroshio axis, the Kuroshio Extension variability, and the southernmost latitude of the Oyashio intrusion are summarized in Kuroda *et al*. (2017).

The FRA-ROMS community models

Advanced marginal sea models

The reproducibility of the FRA-ROMS was not perfect, particularly for marginal seas because some physical elements such as tides, sea ice, and all discharges from the land were not taken into account. Two advanced marginal sea models, for the East China Sea (Setou *et al*., pers. comm.) and the Okhotsk Sea (Kuroda *et al*., 2012a), were developed separately (Fig. 7.1b) in order to provide model output more precise than the FRA-ROMS for fishery scientific projects (*e.g*., examination of the transport pathway of giant jellyfish generated in the East China Sea) to the test impacts of some physical elements or schemes on marginal sea models, and to incorporate essential elements into the FRA-ROMS as feedback in near future upgrades. Resolution and coordinates of the advanced regional models were identical to those of the 1/10-degree model in the FRA-ROMS, and the regional models were connected to the 1/10-degree model in the FRA-ROMS by one-way nesting (Fig. 7.1b). In the East China Sea model, tides and tidal currents were directly forced by sea level oscillations on the lateral boundary. In contrast, tidal mixing effects parameterized as diapycnal diffusivity were incorporated into the Okhotsk Sea model. This parameterization was based on internal tidal wave dissipation in the deep subsurface, which was originally estimated from energy conversion from barotropic to baroclinic tide by a barotropic tidal model (Jayne and St. Laurent, 2001; St. Laurent *et al*., 2002). A one-layer sea-ice model embedded in the developers' version of the ROMS was coupled with the Okhotsk Sea model. Moreover, freshwater discharge derived from the CORE (Coordinated Ocean-ice Reference Experiment) river runoff dataset was added to freshwater fluxes at the sea surface near land–sea grid points as precipitation, the similar method of which was frequently used in coarse-resolution climate models.

1/50-degree high-resolution models

Three kinds of 1/50-degree high-resolution models associated with submesoscale variation were developed (Fig. 7.1c). Initially, the 1/50-degree ocean model for the shelf and slope region inshore of the Kuroshio with the smallest area was developed in April 2008 in parallel with the development of the FRA-ROMS.

This model, called the "Tosa Bay model", was connected to the 1/10-degree model of the FRA-ROMS by one-way nesting. Tide and river discharge were included in the Tosa Bay model; tidal oscillations were directly forced on the lateral boundary, and discharge from all rivers was inferred by statistical relationships between river discharge and precipitation. Properties of submesoscale variations induced mainly by the Kuroshio were examined by analyzing the Tosa Bay model output in terms of climatological mean variability and heat budget within a winter mixed layer (Kuroda *et al*., 2013a; Kuroda *et al*., 2014a). The 1/50-degree Tosa Bay model was recently coupled with a simplified NPZD lower-trophic ecosystem model (Kuroda *et al*., 2015a, 2018a), discussed later.

The Tosa Bay model was extended to two larger model domains which covered most of the Japanese coastal waters: one covered the Kuroshio region south of Japan, the other the Oyashio region (Fig. 7.1c). Similar model configurations were adapted in the two models. These models are regarded as the next-generation FRA-ROMS. A simple scale-selective data assimilation method was adapted for initialization at the initial stage of the development. This method was essentially based on spectral nudging (Kuroda *et al*., 2012b; 2016) where mesoscale variations with spatial scales greater than about 100 km were modified by the FRA-ROMS reanalysis data without any modifications of submesoscale variations. The 1/50-degree Oyashio model was applied to a recovery project of local fisheries from the unparalleled huge tsunami disaster attributed to a mega earthquake (the Great East Japan Earthquake) on March 11, 2011 (Kuroda *et al*., 2018b). The 1/50-degree Kuroshio and Oyashio models have been already employed as oceanographic conditions in several individual-based models (IBMs). Moreover, the latest version of the 1/50-degree Oyashio model was coupled with the one-layer sea-ice model. Lateral boundary conditions with respect to sea-ice elements were prepared by the 1/10-degree Okhotsk Sea model (Fig. 7.1b). It should be borne in mind that the 1/50-degree Kuroshio and Oyashio models were unified to the single 1/50-degree model as the next-generation FRA-ROMS starting in April 2016 (Takahashi *et al*., 2017).

Super-high-resolution models

Several coastal models with super-high resolution of 1/90 to 1/350 degrees were developed for a specific shelf–slope region and semi-enclosed bays around Japan (Fig. 7.1c). These models were connected or connectable to the FRA-ROMS. Tidal currents and freshwater discharges from all the rivers into the model domain were taken into account. Aoki *et al*. (2012a) developed the 1/250-degree Ise-Mikawa Bay model to clarify the transport process of the jellyfish *Aurelia aurita sensu lato* in combination with particle-tracking experiments. Aoki *et al*. (2012b; 2016) constructed a 1/350-degree ocean model for the Yatsushiro Sea and Ariake Sea to study spatio-temporal variability of a harmful bloom of the raphidophycean flagellate, *Chattonella antiqua*. A useful utility method based on simplified momentum balance was also proposed by Aoki *et al*. (2014) to support monitoring the harmful bloom expansion. Moreover, Ito *et al*. (2013) developed the super-high-resolution Mutsu Bay model with a spherical grid size of 1/160 and 1/240 degrees to understand the mechanism of megadeath of aquacultured scallops, particularly in the autumn of 2010. Freshwater fluxes from the land were estimated using a hydrological model, namely, the Soil and Water Assessment Tool (SWAT). Recently, Ito *et al*. (2015) developed a 1/90-degree ocean model coupled with a wave, sediment and radioactivity material model related to Cesium-137, which leaked accidentally from the Fukushima Dai-ichi Power Plants (FDPP) after the tsunami generated by the 2011 Great East Japan Earthquake. The performance of the ocean–wave coupled model was validated by Aoki *et al*. (2015), focusing on a wind-induced event in Sendai Bay north of the FDPP. In addition, the spatio-temporal distribution of Cs-137 collected from five classes of sediments was compared with intensive moored observations, and simulated results of the Cs-137 sediments were analyzed by D. Hasegawa, K. Aoki, and others (pers. comm.).

Lower-trophic ecosystem models

Lower-trophic ecosystem models were also coupled with the FRA-ROMS. Kuroda *et al*. (2018a) incorporated a simplified NPZD (nutrient-phytoplankton-zooplankton-detritus) ecosystem model proposed by Oschiles (2001) into the ROMS code to elucidate the supply processes of nutrients onto the shelf–slope region facing the Kuroshio, southwest of Japan. The NPZD-coupled FRA-ROMS was further downscaled to the 1/50-degree Tosa Bay model (Fig. 7.1c). This study suggests that the 1/50-degree submesoscale variations associated with the Kuroshio frontal disturbances interacting with coastal topography play an essential role in the supply of nutrients onto the shelf and slope region. More sophisticated and complicated ecosystem models referred to as "eNEMURO" (Yoshie *et al*., 2011) were incorporated into the ROMS code and coupled with the FRA-ROMS by T. Okunishi, T. Setou and others (pers. comm.). The main purpose was to project fish food conditions under the global warming state, *i.e*., this examination can be regarded as a kind of regional climate modeling study. The coupled model could be implemented together with 3D-var analysis schemes, but the data assimilation was switched off for the future projection. Instead, using atmospheric forcings derived from climate models, the physical-biochemical state can be projected.

Individual-based models

A variety of IBMs, including a simple forward or backward particle-tracking model, was or is being developed based on the FRA-ROMS and its community of models, mainly in the Fisheries Agency's research projects to understand the processes of year-to-year variation in recruitment/stock of important commercial fish and to contribute to highly precise stock assessments in Japan, such as Japanese chub mackerel (*Scomber japonicus*) (Kuroda *et al*., 2015b; Okunishi *et al*., 2016), Japanese common squid (*Todarodes pacificus*) (Kuroda *et al*., 2013b), Japanese walleye pollock (*Theragra chalcogramma*) (Kuroda *et al*., 2014b), chum salmon (*Oncorhynchus keta*) (Azumaya *et al*., 2018), and yellowtail (*Seriola quinqueradiata*) (Setou *et al*., 2016a). Setou *et al*. (2016b) also studied the impact of changes in the spawning ground of yellowtail and their juvenile distribution under global warming by using output from the climate run of the FRA-ROMS.

The transport process and spatio-temporal distribution of harmful organisms have also been examined using simple IBMs combined with the FRA-ROMS or its community of models. As mentioned earlier, simulation of harmful organisms, such as jellyfish blooms and toxic algal blooms in coastal waters, were performed on the basis of super-high-resolution models (Aoki *et al*., 2012a,b). For the giant jellyfish (*Nemopilema nomurai*), which seriously affects the Japanese fishery in some summers, its transport process and pathway from the East China Sea to the waters of Japan have been investigated and predicted by particle-tracking experiments based on the reanalysis and forecast data of the FRA-ROMS (Setou *et al*., pers. comm.).

Near future perspective of the FRA-ROMS

There are some plans to upgrade the FRA-ROMS. The first modification will be to extend the model domains. For the 1/10-degree model, the eastern boundary and the southern boundary will be extended to the western coast of North America and 5–10°N, respectively. The 1/2-degree model domain will be also adjusted. A two-way nesting technique will be applied to connect the 1/2- and 1/10-degree models. In addition, several elements (*e.g*., tidal mixing, sea ice, and freshwater discharge from the land), which were neglected in the current version, will be incorporated. To unify the two 1/50-degree Kuroshio and Oyashio models, a single 1/50-degree high-resolution coastal model, which will cover almost the entire Japanese coastline, is being developed, as described above (Takahashi *et al*., 2017).

Acknowledgements

We express our deepest gratitude to Dr. M. Kamachi, Dr. N. Usui and Dr. Y. Fujii at the Meteorological Research Institute of the Japan Meteorological Agency for warm-hearted encouragement and technically supporting our model development. The FRA-ROMS was developed and implemented, with partial support from the Fisheries Agency, in 2008 by physical oceanographers in the FRA using vector and cluster supercomputing systems operated by the Agriculture, Forestry and Fisheries Research Information Technology Center (AFFRIT). The contents of this study do not necessarily reflect the views of the Fisheries Agency.

References

Aoki, K., Shimizu, M., Kuroda, H., Toyokawa, M. and Yamada, S. 2012a. Numerical study on the transport process of jellyfish *Aurelia aurita sensu lato* in Mikawa Bay, Japan. *Bull. Jpn. Soc. Fish. Oceanogr*. **76**: 9–17 (in Japanese with English abstract).

Aoki, K., Onitsuka, G., Shimizu, M., Kuroda, H., Matsuyama, Y., Kimoto, K., Matsuo, H., Kitadai, Y., Sakurada, K., Nishi., H. and Tahara, Y. 2012b. Factors controlling the spatio-temporal distribution of the 2009 *Chattonella antiqua* bloom in the Yatsushiro Sea. *Estuar. Coast. Shelf Sci*. **114**: 148–155.

Aoki, K., Onitsuka, G., Shimizu, M., Kuroda, H., Matsuo, H., Kitadai, Y., Sakurada, K., Ando, H., Nishi, H. and Tahara, Y. 2014. Variability of factors driving spatial and temporal dispersion in river plume and *Chattonella antiqua* bloom in the Yatsushiro Sea, Japan. *Mar. Pollut. Bull*. **81**: 131–139.

Aoki, K., Sugimatsu, K., Kuroda, H., Setou, T., Yagi, H., Kakehi, S., Hasegawa, D. and Ito, S. 2015. A multiple study for sudden temperature drop in Sendai Bay, Japan using mooring survey and coupled ocean-wave model. *J. Jpn. Soc. Civil Eng., Ser. B2 (Coastal Engineering)* **71**: 421–426 (in Japanese with English abstract).

Aoki, K., Shimizu, M., Kuroda, H., Yamatogi, T., Ishida, N., Kitahara, S. and Hirano, K. 2016. Numerical study for specifying the major origin of low salinity water associated with *Chattonella* (Raphidophyceae) blooms in Tachibana Bay, Japan. *J. Oceanogr*. **72**: 811–816.

Azumaya, T., Kuroda, H., Takahashi, D., Unuma, T., Yokota, T. and Urawa, S. 2018. Migration routes of juvenile chum salmon simulated with hydrodynamic model (submitted).

Bloom, S.C., Takacs, L.L., Da Silva, A.M. and Ledvina, D. 1996. Data assimilation using incremental analysis updates. *Mon. Weather Rev*. **124**: 1256–1271

Haidvogel, D.B., Arango, H., Budgell, W.P., Cornuelle, B.D., Curchitser, E., Di Lorenzo, E., Fennel, K., Geyer, W.R., Hermann, A.J., Lanerolle, L., Levin, J., McWilliams, J.C., Miller, A.J., Moore, A.M., Powell, T.M., Shchepetkin, A.F., Sherwood, C.R., Signell, R.P., Warner, J.C. and Wilkin, J. 2008. Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System. *J. Comput. Phys*. **227**: 3595–3624.

Ito, S., Seito, M., Yoshida, T., Takeuchi, K., Kakehi, S., Wagawa, T., Isoda, Y. and Kawamura, H. 2013. Water temperature forecasts to decrease megadeath of aquacultured scallops in Mutsu Bay, Japan. p. 13, Program and Abstracts PICES-2013, Communicating forecasts, uncertainty and consequences of ecosystem change, October 11–20, 2013, Nanaimo, BC, Canada.

Ito, S., Aoki, K., Kuroda, H., Setou, T., Takeuchi, K., Hasegawa, D., Kaeriyama, H., Ambe, D., Ono, T., Kakehi, S., Yagi, H., Sugimatsu, K. and Nakayama, A. 2015. Model developments to estimate movements of radioactive cesium with ocean sediment after the Fukushima Dai-ichi nuclear power plant accident. p. 178, Program and Abstracts PICES-2015, Change and sustainability of the North Pacific, October 14–25, 2015, Qingdao, China.

Jayne, S.R. and St. Laurent, L.S. 2001. Parameterizing tidal dissipation over rough topography. *Geophys. Res. Lett*. **28**: 811–814.

Kuroda, H., Takahashi, D., Setou, T., Azumaya, T. and Mitsudera, H. 2012a. Hindcast experiment for the Okhotsk Sea using the sea-ice-coupled Regional Ocean Modeling System. p. 243, Program and Abstracts PICES-2012, Effects of natural and anthropogenic stressors in the North Pacific ecosystems: Scientific challenges and possible solutions, October 12–21, 2012, Hiroshima, Japan.

Kuroda, H., Setou, T., Aoki, K., Hagiwara, Y. and Akabane, H. 2012b. A numerical study of "shirasu" fishing ground formation based on the Kuroshio submesoscale model, south of Japan. p. 226, Program and Abstracts PICES-2012, Effects of natural and anthropogenic stressors in the North Pacific ecosystems: Scientific challenges and possible solutions, October 12–21, 2012, Hiroshima, Japan.

Kuroda, H., Setou, T., Aoki, K., Takahashi, D., Shimizu, M. and Watanabe, T. 2013a: A numerical study of the Kuroshio-induced circulation in Tosa Bay, off the southern coast of Japan. *Cont. Shelf Res*. **53**: 50–62.

Kuroda, H., Yamashita, N., Kaga, T., Azumaya, T., Kuroda, H. and FRA-ROMS developers. 2013b: A study of interannual variation in passive transport process of larvae of Japanese common squid, *Todarodes pacificus*, reproduced by numerical particle-tracking experiments based on FRA-ROMS. Report of 2012 annual meeting on squid resources (in Japanese).

Kuroda, H., Hirota, Y., Setou, T., Aoki, K., Takahashi, D. and Watanabe, T. 2014a. Properties of winter mixed layer variability on the shelf-slope region facing the Kuroshio - Study of Tosa Bay, southern Japan. *Ocean Dyn*. **64**: 47–60.

Kuroda, H., Takahashi, D., Mitsudera, H., Azumaya, T. and Setou, T. 2014b. A preliminary study to understand the transport process for the eggs and larvae of Japanese Pacific walleye pollock *Theragra chalcogramma* using particle-tracking experiments based on a high-resolution ocean model. *Fish. Sci*. **80**: 127–138.

Kuroda, H., Takasuka, A., Hirota, Y., Aoki, K. and Setou, T. 2015a. Characteristics of winter mixed layer variability and nutrient supply processes onto the shelf-slope region facing the Kuroshio. *Bull. Coast. Oceanogr.* **53**: 3–9 (in Japanese with English abstract).

Kuroda, H., Shimizu, Y., Takahashi, M., Kawabata, A., Okunishi, T. and Setou, T. 2015b. Particle tracking experiments to specify hatching areas of the Pacific stock of chub mackerel off the southeastern coast of Japan. p. 250, Program and Abstracts PICES-2015, Change and sustainability of the North Pacific, October 14–25, 2015, Qingdao, China.

Kuroda, H., Toya, Y., Wagawa, T., Kuwata, A. and Setou, T. 2016. Development of a high-resolution ocean model around Hokkaido –To evaluate effects of the Okhotsk Sea on ecosystem in the North Pacific. *Low. Temp. Sci*. **74**: 1–11 (in Japanese with English abstract).

Kuroda, H., Setou, T., Kakehi, S., Ito, S., Taneda, T., Azumaya, T., Inagake, D., Hiroe, Y., Morinaga, K., Okazaki, M., Yokota, T., Okunishi, T., Aoki, K., Shimizu, Y., Hasegawa, D. and Watanabe, T. 2017. Recent advances in Japanese fisheries science in the Kuroshio-Oyashio region through development of the FRA-ROMS ocean forecast system: Overview of the reproducibility of reanalysis products. *Open J. Mar. Sci.* **7**: 62–90.

Kuroda, H., Takasuka, A., Hirota, Y., Kodama, T., Uchikawa, T., Aoki, K. and Setou, T. 2018a. Numerical experiments supply on the shelf-slope region off the southwestern coast of Japan. *J. Mar. Sys*. **179**: 38–54.

Kuroda, H., Toya, Y., Wagawa, T., Kakehi, S., Ito, S., Hasegawa, D., Kodama, T., Yamanome, T. and Naiki, K. 2018b. Extreme cold water events near the Sanriku coast, Japan: Linkage with the East Sakhalin Current and empirical prediction method (in prep.).

Miyazawa, Y., Zhang, R., Guo, X., Tamura, H., Ambe, D., Lee, J.-S., Okuno, A., Yoshinari, H., Setou, T. and Komatsu, K. 2009. Water mass variability in the western North Pacific detected in a 15-year eddy resolving ocean reanalysis. *J. Oceanogr*. **65**: 737–756.

Okunishi, T., Hasegawa, D., Kakehi, S., Kuroda, H., Setou, T., Ambe, D., Shimizu, Y., Takahashi, M. and Yoneda, M. 2016. Recruitment prediction of Japanese chub mackerel using the FRA-ROMS and its future perspective. *Fish. Biol. Oceanogr. Kuroshio* **17**: 4–5 (in Japanese).

Oschiles, A. 2001. Model-derived estimates of new production: New results point towards lower values. *Deep-Sea Res. II* **48**: 2173–2197.

Setou, T., Kuno, M., Kuroda, H. and Okunishi, T. 2016a. Simulation of transport of Yellowtail *Seriola quinqueradiata* juveniles in the North Pacific. Abstracts of the Joint Usage Research Meeting in Kashiwa campus by Atmosphere and Ocean Research Institute, the University of Tokyo, Role of drifting seaweed affecting recruitment and early survival of Yellowtail *Seriola quinqueradiata* during spring in East China Sea, February 18–19, 2016, Chiba, Japan (in Japanese).

Setou, T. Kuno, M., Kuroda, H. and Okunishi, T. 2016b. Projection of change in spawning ground of Yellowtail *Seriola quinqueradiata* under the global warming. Abstracts of the Joint Usage Research Meeting in Kashiwa campus by Atmosphere and Ocean Research Institute, the University of Tokyo, Role of drifting seaweed affecting recruitment and early survival of Yellowtail *Seriola quinqueradiata* during spring in East China Sea, February 18–19, 2016, Chiba, Japan (in Japanese).

St. Laurent, L.C., Simmons, H.L. and Jayne, S.R. 2002. Estimating tidally driven mixing in the deep ocean. *Geophys. Res. Lett*. **29**: doi:10.1029/2002GL015633.

Takahashi, D., Kuroda, H. and Setou, T. 2017. Seasonal and short-term variations in oceanographic condition around Japan simulated by a high-resolution ocean circultiaon model. *Fish. Biol. Oceanogr. Kuroshio* **18**: 39–43 (in Japanese).

Usui, N., Ishizaki, S., Fujii, Y., Tsujino, H., Yasuda, T. and Kamachi, M. 2006. Meteorological Research Institute Multivariate Ocean Variational Estimation (MOVE) system: some early results. *Adv. Space Res*. **37**: 806–822.

Yoshie, N., Guo, X., Fujii, N. and Komorita, T. 2011. Ecosystem and nutrient dynamics in the Seto Inland Sea, Japan, pp. 39–49 *in* Interdisciplinary Studies on Environmental Chemistry—Modeling and Analysis of Marine Environmental Problems, Vol. 5 *edited by* K. Omori, X. Guo, N. Yoshie, N. Fujii, I.C. Handoh, A. Isobe and S. Tanabe, TERRAPUB, Tokyo.

8. *A simulated circulation and its climate variability in the Primorye and Tsushima Current systems induced by atmospheric forcing, 1948–2009*

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Abstract

Based on numerical simulations, this study investigates the circulation in the northern Japan/East Sea (JES) and its climate variability induced by atmospheric forcing, from 1948–2009. We developed a model configuration based on an INMOM (Institute of Numerical Mathematics Ocean Model), which enables us to assess the influence of only atmospheric forcing on the circulation variability in the JES. Analysis of kinetic energy and total heat content in the JES obtained from our numerical simulations showed that the simulated circulation is in a quasi-steady state. We compared the simulated total heat content with that extracted from the SODA (Simple Ocean Data Assimilation) reanalysis and showed significant consistence between them. We established that the simulated circulation structure is very similar with that obtained from observations *in situ* in the intermediate layer in the JES.

Using empirical orthogonal function analysis, we studied the spatiotemporal variability of the relative vorticity in the intermediate and abyssal layers in the JES on interannual and decadal time scales. We found that the strengthening (weakening) of the cyclonic gyre occurs on the periods of 3, 4 and 5 years. On decadal time scales, we found a weakening of the cyclonic gyre from 1965 to 2001 and then its strengthening from 2001 to 2009. It is established that the strengthening (weakening) of the cyclonic gyre on interannual time scales of 3, 4 and 5 years is associated with positive wind stress curl variability on the same time scales. However, on decadal time scales, coupling between the wind stress curl over the JES and cyclonic gyre is not significant.

Introduction

In recent decades significant changes have been observed in the climate system of the Earth characterized by a quasi-linear increase in the total heat content of the World Ocean and its global sea level. These changes are heterogeneous both for space and for time and so the influence of these changes on regional climate will be diverse.

The Japan/East Sea (JES) is a semi-closed sea connected with the North Pacific Ocean and adjacent seas by means of shallow straits. Thermodynamic conditions of the JES have an impact on the regional climate of countries adjacent to the JES (Russia, Japan, and Korea). Analysis of temperature and heat content of the sub-surface layer in the JES (from sea surface to 300 m) has revealed their significant variability on the interannual and decadal time scales (Minobe *et al*., 2004; Na *et al*., 2012). Atmospheric forcing and water exchange between the JES and adjacent seas and the Pacific Ocean are considered the major factors responsible for the decadal variability in temperature of the JES, at least in its sub-surface layer. On the other hand, advection–diffusion processes are responsible for heat and salt redistribution for the entire JES basin. On spatial and temporal scales, the JES circulation was analyzed based on the observations *in situ* (Isobe and Isoda, 1997; Yanagimoto and Taira, 2003) and numerical simulations (Mooers *et al*., 2005). Most of these studies have considered the circulation in the sub-surface layer of the JES. Based on observations *in situ* Choi and Yoon (2010) showed that with depth, the JES circulation does not weaken and has significant seasonal variability. The basin-scale velocity field is dominated by a cyclonic gyre situated in the northern JES, with intense meso-scale eddies developing within the cyclonic gyre. Although the structure of basin-scale circulation in the JES in the sub-surface, intermediate and abyssal layers has been revealed, its climate variability has not been fully investigated.

In this study we present a model configuration based on a numerical ocean model INMOM (Institute of Numerical Mathematics Ocean Model), which enables us to investigate JES circulation variability in the intermediate and abyssal layers induced by only atmospheric forcing for the period 1948–2009. Using numerical simulations, we investigate the spatiotemporal variability of the cyclonic gyre based on analysis of the vertical component of the relative vorticity vector in the intermediate and abyssal layers in the JES. Moreover, we consider a relationship between the cyclonic gyre variability and wind stress curl over the JES on interannual and decadal time scales.

Model configuration description and model results

To analyze the climate variability of the cyclonic gyre observed in the northern JES and to reveal possible causes responsible for its variability, hindcast numerical simulations (from 1948 to 2009) of the JES circulation were carried out using a developed model configuration. The basic element of the model configuration is a numerical ocean model (INMOM) developed by the Institute of Numerical Mathematics (Gusev and Diansky, 2014). INMOM is a sigma-coordinate model based on the primitive equations of ocean dynamics, with hydrostatic and Boussinesq approximations. The major feature of our model configuration is a procedure formulating conditions for the simulated variables in the JES straits. According to this procedure, a free-slip condition for velocity is posed for all open boundaries, and for potential temperature and salinity in each strait of the JES, we reserve a grid space region where the nudging condition is applied from the sea surface to bottom with a time scale of about 3 hours. Using the procedure, we generate gradient currents in the JES straits (Tsushima/Korea Strait in the south and La Perouse/Soya Strait in the north), which transport heat and salt from south to north, respectively, in the JES.

We used a high spatial resolution (1/12° × 1/12° and 30-sigma levels), which allows for the influence of meso-scale eddies on the basin-scale circulation in the JES. Topography of the JES was extracted from the ETOPO2 dataset. On the sea surface, wind stress, net heat and salt fluxes as well as climatological runoff were set by using bulk formulae (Parkinson and Washington, 1979). Atmospheric parameters were extracted from the Coordinated Ocean-ice Reference Experiment (CORE phase II) (Large and Yeager, 2009). The CORE dataset was collected from 1948 to 2009 and contains the following atmospheric parameters: air temperature and humidity, wind velocity field at the height of 10 m, atmospheric pressure at the sea surface with time resolution of 6 hours and short and longwave radiation, daily. Simulated potential temperature and salinity averaged in the sub-surface layer with a depth of 50 m were relaxed to their climatological values. The relaxation coefficients for the averaged potential temperature and salinity were set to 1 and 3 months, respectively. The sub-grid scale dynamical processes were parameterized by the fourth order viscosity operator with a coefficient of 3.2×10^{10} m^4 s^{-1}. The horizontal diffusion of heat and salt were formulated along the geopotential surfaces and were parameterized by the second order viscosity operator with the coefficient of 4×10^2 m^2 s^{-1} for both variables. The vertical viscosity and diffusion coefficients were assessed from the turbulent closure model (Kochergin and Sklyar, 1992) at a background value of 5×10^{-6} m^2 s^{-1} and 10^{-4} m^2 s^{-1}, respectively. Convective mixing was parameterized by the maximal value of the diffusion and viscosity coefficients. Initial potential temperature and salinity equal to their climatological values corresponding to January (Conkright *et al*., 2002) and initial velocity field were set to null.

Validation of the model configuration was based on the comparison of the simulated circulation characteristics against the circulation characteristics extracted from the SODA (Simple Ocean Data Assimilation) reanalysis (Giese and Ray, 2011). We suppose that the JES circulation characteristic variations do not contain significant linear trends and their anomalies are small relative to their mean values. At first, we analyzed the kinetic energy (KE) of the JES, which was calculated by using the relation

$$KE = \iiint_V \bar{\rho} \frac{\bar{u}^2 + \bar{v}^2}{2} dV,$$

where $\bar{u}, \bar{v}$ are the monthly mean zonal and meridional velocity components, respectively, $\bar{\rho}$ is the monthly mean density and V is the volume of the JES basin.

Figure 8.1a shows the time series of annual mean KE obtained from the simulated velocity field and that extracted from the SODA reanalysis. The time series of the KE does not contain significant linear trends and can be characterized by significant interannual (time scale of 4–5 years) and decadal (time scale of 18–20 years) variability. A comparison of the simulated KE with that extracted from the SODA reanalysis indicates more intensive dynamics of the simulated circulation against the dynamics extracted from the SODA reanalysis. We suppose that this difference is induced by the coarse resolution used in the SODA reanalysis. During the climatological year the KE changes have a non-monotonic character. A maximum of the simulated KE is observed in autumn and winter and its minimum is observed in summer (Fig. 8.1b). Climatological-simulated KE changes are similar to those extracted from the SODA reanalysis. However, climatological KE extracted from the SODA reanalysis reaches its minimum in spring–summer. The standard deviation of the monthly mean anomalies of the KE is constrained by 50% relative to its climatological value for both the simulated velocity field and that extracted from the SODA reanalysis. We assessed total heat content (THC) in the JES by using the relation

$$THC = \iiint_V \bar{\rho}(T,S,0) c_p(T,S,0) \bar{T}(T,S,0) dV,$$

where $\bar{\rho}(T,S,0)$ is the monthly mean density of the JES sea water at a constant pressure, c_p is the heat capacity of the sea water at a constant pressure, and T and S are the monthly mean temperature and salinity of the JES water, respectively. Figure 8.1c shows the time series of annual mean THC obtained from the simulated data and the SODA reanalysis. Both time series do not contain significant linear trends, expect for the annual mean THC time series extracted from the SODA reanalysis, which contains a marginal linear trend from 1993 to 2009. During the climatological year, we observe a good agreement between the change of the simulated THC and that obtained from the SODA reanalysis (Fig. 8.1d). Analysis of monthly mean anomalies of the THC obtained from both datasets showed that their standard deviations are limited by 50% relative to their climatological values.

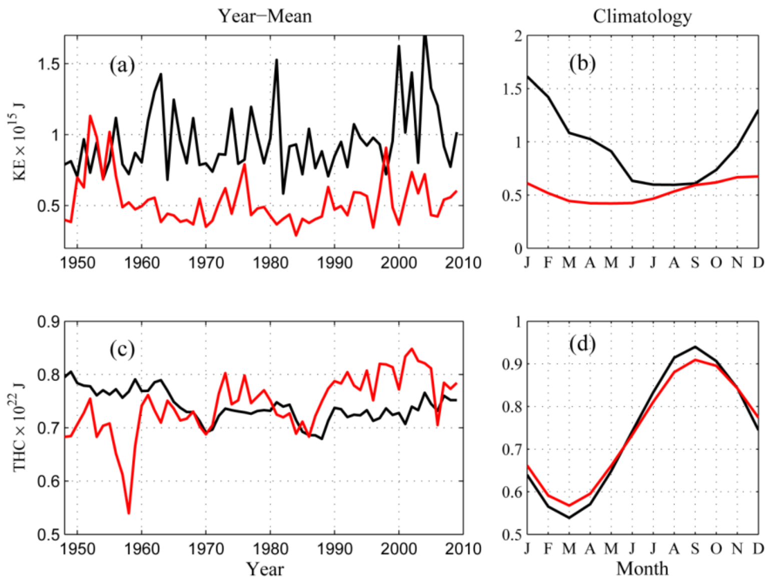

Fig. 8.1 Time series of kinetic energy (KE) in the JES, 1948–2009: (a) annual mean KE, (b) climatological KE. Time series of total heat content (THC) in the JES, 1948–2009: (c) annual mean THC, (d) climatological THC. The KE and THC calculated from the simulated data are shown by the black line and those calculated from the data extracted from SODA reanalysis are shown by the red line.

Based on the comparison of the simulated velocity and a vertical component of the relative vorticity vector (hereinafter a relative vorticity, RV) fields with those extracted from the SODA reanalysis, we will make a conclusion about the applicability of the presented model configuration to the study of the impact of only atmospheric forcing on cyclonic gyre variability in the JES. In order to calculate the RV field, we used the relation

$$\omega = \frac{1}{\cos\varphi}\left(\frac{\partial \bar{v}}{\partial \lambda} - \frac{\partial(\bar{u}\cos\varphi)}{\partial \varphi}\right) \Big/ Rf_0 ,$$

where R is the radius of the Earth and f_0 is the Coriolis parameter corresponding to a latitude of 43°5′N. According to Stokes theorem, the scales of the RV variability and those of the cyclonic gyre variability are similar. Figure 8.2 shows climatological-simulated velocity and RV fields in the sub-first layer (from 10 to 300 m) in the JES.

In winter, the cyclonic gyre dominates over the JES with an intensive south current near the western coast of Honshu Island representing the nearshore branch of the Tsushima Current, and an intensive north current along the Primorye coast representing the Primorye Current. In summer, the cyclonic gyre situated in the northern JES dominates both in the simulated velocity field and the velocity field extracted from the SODA reanalysis.

In the intermediate layer (from 500 to 1000 m), the velocity and RV fields are dominated by the cyclonic gyre both in the simulated velocity field and that extracted from the SODA reanalysis (Fig. 8.3). Comparison shows that the simulated cyclonic gyre covers more area than that extracted from the SODA reanalysis. We find that the simulated RV field of the cyclonic gyre is heterogeneous. Regions with a positive RV value (red color) alternate with regions with a negative RV value (blue color) in contrast to the

RV field obtained from the SODA reanalysis, which is quasi-homogeneous. The heterogeneity of the simulated RV field indicates an intensive meso-scale dynamics, which reaches the intermediate layer in the JES.

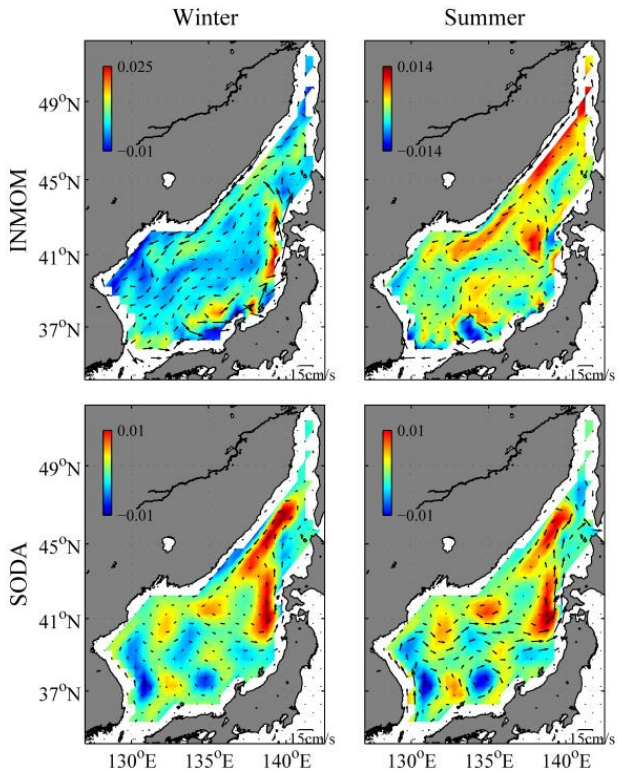

Fig. 8.2 Climatological velocity and relative vorticity (color) fields in the upper layer (from 10 to 300 m) in the JES. The upper row shows the simulated data and the lower row shows the data extracted from the SODA reanalysis.

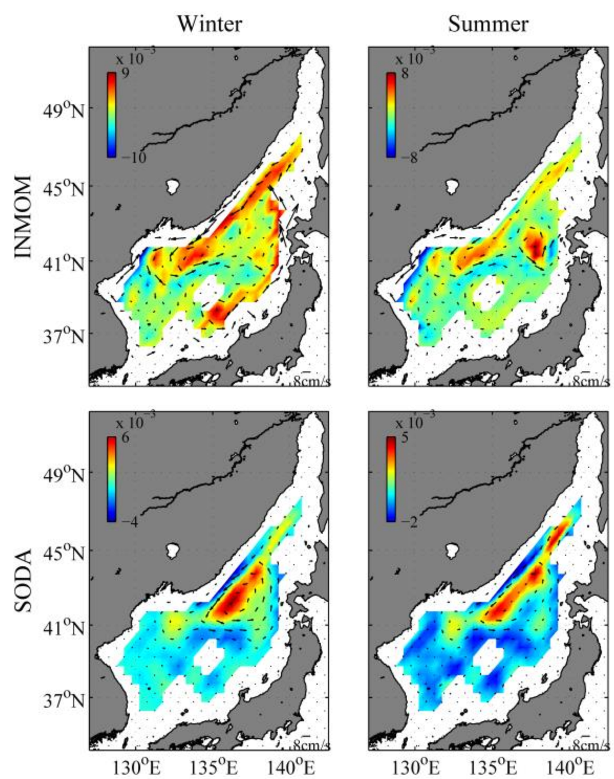

Fig. 8.3 Climatological velocity and relative vorticity fields (color), as in Figure 8.2, except in the intermediate layer (from 500 to 1000 m) in the JES.

In the abyssal layer (from 1000 to 2500 m), we do not observe significant changes in the velocity and RV fields relative to the intermediate layer. The cyclonic gyre dominates in the simulated velocity field and current velocities reach to 7 cm s^{-1} on its edge. The simulated RV field of the cyclonic gyre is heterogeneous.

Thus, we conclude that the simulated circulation contains the main components of basin-scale circulation of the JES, at least into the intermediate and abyssal layers. The features of the simulated velocity and RV fields and analysis of kinetic energy, as well as total heat content in the JES, indicate the applicability of the model configuration to investigate the impact of atmospheric forcing on the cyclonic gyre variability in the intermediate and abyssal layers in the JES from 1948 to 2009.

Interannual-to-decadal variability of the cyclonic gyre and its relationships with atmospheric forcing over the Japan/East Sea

In this section, we analyze the spatiotemporal variability of the cyclonic gyre based on the simulated RV in the intermediate and abyssal layers in the JES on interannual-to-decadal time scales. We use empirical orthogonal function (EOF) analysis of monthly mean RV anomalies. Preliminarily, they were subtracted from a linear trend and then were divided by the moving average with cutoff period at 6 years on interannual and decadal variations. The spatial structure of the *n*th EOF mode is presented as a homogeneous correlation map (HCM) (Wallace *et al*., 1992) showing the spatial distribution of a correlation coefficient between the monthly mean RV variations and the principal component (PC) of the *n*th EOF mode.

For intermediate and abyssal layers, the first two interannual EOF modes explain about 70% of the total variance and the interannual first EOF mode explains 50% of the total variance. The interannual third EOF mode accounts for less than 7% of the total variance. Analysis of the HCM corresponding to the interannual first EOF mode shows that large correlation coefficients (above 0.5) occur in the northern and the western Japan Basin and the Yamato Basin (Fig. 8.4a). The HCM corresponding to the interannual second EOF mode shows that positive correlation coefficients (about 0.3, red color) occur in the northern and southwestern Japan Basin and negative correlation coefficients (below –0.3, blue color) occur at the north edge of the Yamato Rise (Fig. 8.4b). We suppose that the intensive interannual variability of the RV of the cyclonic gyre is induced by the current instability along the continental slope and the cyclonic eddy variability in the northern Japan Basin (see Figs. 8.2–8.3, in summer).

The first PC time series is characterized by oscillations with periods of 3, 4 and 5 years (Fig. 8.4c). With depth we observe a phase synchronism among the oscillations of the first PC time series. Note that the amplitudes of these oscillations are not significantly decayed. The second PC time series is dominated by oscillations with a period of 4 years (Fig. 8.4d). With depth the phase synchronism among these oscillations is also observed and amplitudes of these oscillations are not significantly decayed.

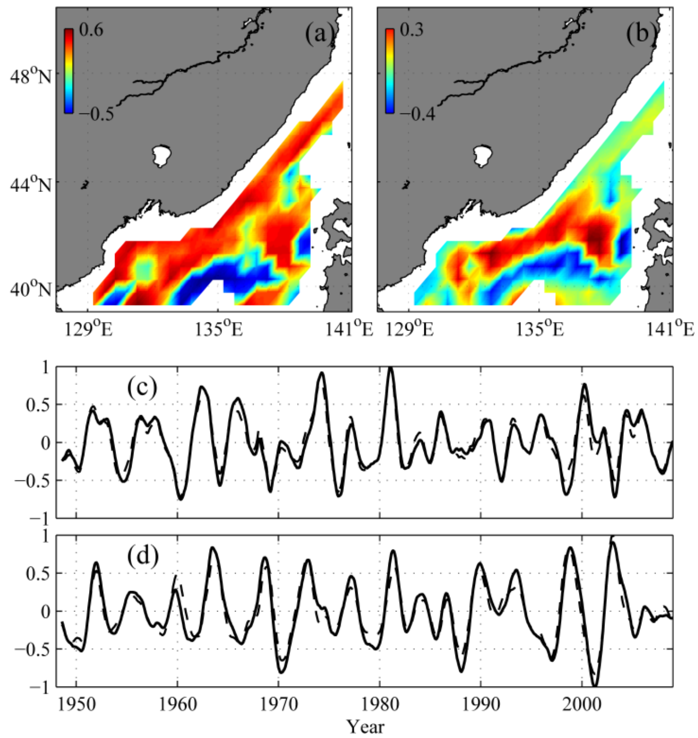

Fig. 8.4 Spatial patterns of interannual first (a) and second (b) EOF modes of relative vorticity, presented as homogenous correlation maps at 500 m depth. The principal components (PC) of interannual (c) first and (d) second EOF modes of relative vorticity at 500 m depth (black line) and 1500 m depth (dashed line). The PC is normalized by its maximum.

The decadal first EOF mode accounts for 49 to 65% of the total decadal variance and its contribution in decadal variance increases with depth. At the same time, the decadal second and third EOF modes explain 22% and 10% of the total decadal variance, respectively, and their contributions in the total decadal variance decrease with depth. The spatial structures of the HCM corresponding to the leading decadal EOF modes (Fig. 8.5) are very similar those corresponding to the leading interannual EOF modes (see Figure 8.4). Thus, intensive interannual and decadal variability of the RV occur mainly in the northern JES. Figure 8.5c and 8.5d show the PCs corresponding to the leading decadal EOF modes. From 1950 to 1968 and from 2000 to 2007 the positive variations of the decadal first PC are observed, and from 1968 to 2000 the negative variations dominate in the time series (Fig. 8.5d). The negative variations of the decadal second PC time series can be observed from 1955 to 1987 and its positive variations are observed from 1987 to 2007. With depth, the amplitudes of the decadal second PC variations are decayed in contrast to the amplitudes of the decadal first PC variations.

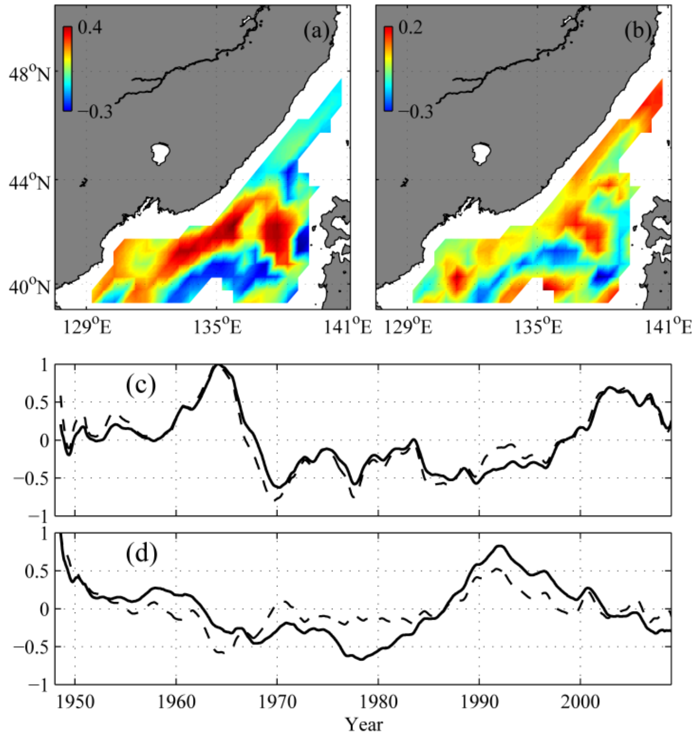

Fig. 8.5 As in Fig. 8.4, except for decadal leading EOF modes of relative vorticity.

Studies (Hogan and Hurlburt, 2005; Yoon *et al*., 2005) showed that wind stress curl (WSC) over the JES is one of the major atmospheric factors which governs the cyclonic gyre in the sub-surface layer in the northern JES. Based on the singular value decomposition (SVD) (Wallace *et al*., 1992) of a cross-correlation matrix of the WSC and RV monthly anomalies, we analyzed the relationship between them on interannual and decadal time scales. We found that the summarized square covariance fraction (SCF) of the two leading interannual SVD modes explains about 74% of the total square covariance and that the SCF is increased with depth. The correlation coefficient between the time series of the interannual first SVD mode expansion coefficients (EC), as an indicator of the strength of the coupling, equals approximately 0.86 and does not change with depth. Even though the SCF of the interannual second SVD mode is 15% of the total square variance, its strength of the coupling is very high (correlation coefficient of 0.8), which does not change with depth. Analysis of the HCMs corresponding to the interannual first SVD mode showed that large correlation coefficients corresponding to the RV (above 0.5) and the WSC (above 0.3) occur over the Japan Basin and in the central part of the JES, respectively. Note that a contribution of the coupling between the WSC and RV, corresponding to the interannual first SVD mode, in the WSC variations is less than that in the RV variations. The HCM corresponding to the interannual second SVD mode shows large correlation coefficients (above 0.3) corresponding to the RV in the northern and southwestern Japan Basin and the HCM corresponding to the WSC presents a dipole with positive correlation coefficients eastward of 135°E and negative correlation coefficients westward of this longitude. A contribution of the coupling between the WSC and RV, corresponding to the interannual second SVD mode, in the WSC anomalies is less than that in the RV anomalies. Time series of the ECs of the interannual first SVD mode are presented in Figure 8.6a. We observe strong coupling between the RV and WSC on the time scales of 3, 4 and 5 years and the strength of this coupling does not change with depth. According to the time series of the ECs corresponding to the interannual second SVD mode, a strong coupling between the RV and WSC manifests on the time scale of 4 years (Fig. 8.6b). Note that with depth small changes in the amplitudes of the EC time series correspond to the WSC and RV anomalies for both the interannual first SVD mode and interannual second SVD mode.

On decadal time scales, we find that the two first decadal SVD modes account for about 80% of the total square covariance and their summarized SFC increases with depth. The SCF corresponding to the decadal first SVD mode increases from 54% to 74%. At the same time, the SCF corresponding to the decadal second SVD mode decreases from 20% to 12% with depth. However, the strength of the coupling characterized by a correlation coefficient above 0.8 corresponding to the decadal second SVD modes is high and does not change significantly with depth. Analysis of the HCMs corresponding to the decadal first SDV mode shows that maximal correlation coefficients (above 0.3) corresponding to the RV occur in the southwestern and northern Japan Basin. Maximal correlation coefficients (above 0.15) corresponding to the WSC occur mainly in the northern Japan Basin. The spatial structure of the HCM corresponding to the decadal second SVD mode shows maximal coefficient correlations corresponding to the RV in the northern and southwestern Japan Basin, and does not significantly change with depth. The spatial structure of the HCM corresponding to the WSC presents a dipole with a quasi-zonal boundary.

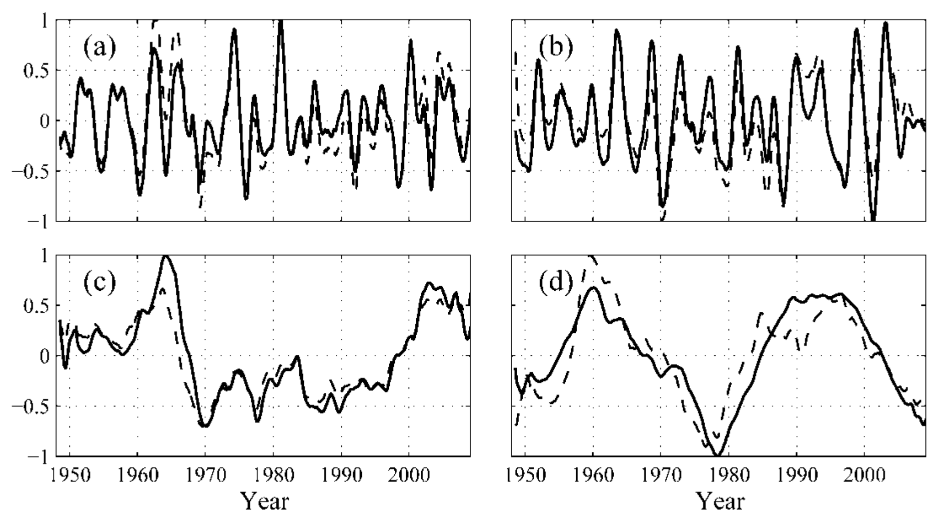

Fig. 8.6 Time series of expansion coefficients (EC) of the singular value decomposition (SVD) mode of relative vorticity (solid line) and wind stress curl (dashed line) over the JES: (a) interannual EC1 (correlation coefficient of 0.86), (b) interannual EC2 (correlation coefficient of 0.8), (c) decadal EC1 (correlation coefficient of 0.91), (d) decadal EC2 (correlation coefficient of 0.82). The EC is normalized by its maximum.

Positive correlation coefficients occur southeastward of this boundary and negative correlation coefficients occur northwestward. Note that correlation coefficients between the EC of the decadal second SVD mode and WSC anomalies are small (from –0.2 to 0.12). The time series of the ECs corresponding to the decadal first SVD mode are presented in Figure 8.6c. We find that the time series of the EC corresponding to the RV coincides with the PC of the decadal first EOF mode of the RV (see Figure 8.5c). The time series of the EC corresponding to the WSC coincides with that corresponding to the RV, with a time lag of 1 year. The time series of the ECs of the decadal second SVD mode are shown in Figure 8.6d. Events characterized by large variation amplitudes in the EC time series corresponding to the WSC are reflected in the EC time series corresponding to the RV with a time lag of 1 to 2 years, which is increased with depth.

Discussion and conclusions

This study investigated the cyclonic gyre observed in the intermediate and abyssal layers in the northern Japan/East Sea (JES) and its variability induced by atmospheric forcing for the period 1948–2009. Analysis was based on the results of the JES circulation numerical simulations carried out using a developed model configuration, which is based on INMOM. Atmospheric forcing included heat, salt and momentum fluxes across the sea surface, and atmospheric parameters were extracted from CORE phase II, 1948–2009.

In order to validate the developed model configuration, kinetic energy (KE) and total heat content (THC) of the simulated JES circulation were analyzed. We found that time series of annual mean KE does not contain significant linear trends and the ratio of standard deviation of the monthly mean KE anomalies to climatological value of the KE does not exceed 50% (see Figure 8.2). Moreover, we found that the time series of annual mean KE consists of oscillations with the periods of 3, 4 and 5 years and events with the time scale of 18–20 years. Our analysis of annual mean THC time series also did not show significant linear trends, and the ratio of standard deviation of the monthly mean THC anomalies to the climatological value of the THC does not exceed 50% (see Figure 8.3). We estimated the THC and revealed good agreement between the THC obtained from the numerical simulations and that extracted from the SODA reanalysis dataset. Analysis of climatological-simulated velocity and relative vorticity (RV) fields showed that a cyclonic gyre dominates in the basin-scale circulation in the intermediate and abyssal layers in the northern JES. The cyclonic gyre intensifies in winter and weakens in summer. Season variability of the cyclonic gyre is observed from the sub-surface layer up to the intermediate layer. Thus, we conclude that the presented model configuration allows us to consider the influence of only atmospheric forcing on the cyclonic gyre variability.

Based on the empirical orthogonal function (EOF) analysis of the monthly mean RV anomalies, we found that the strengthening (weakening) of the cyclonic gyre manifests on the time scales of 3, 4 and 5 years. Note that the oscillations with a period of 4 years dominate in the cyclonic gyre interannual variability (see Figure 8.4c and d). Decadal variability of the RV is most intense in the northern JES and over the northwestern edge of the Japan Basin. We found that decadal variations of the RV are characterized by a maximal amplitude in 1965, which is associated with a strengthening cyclonic gyre (see Figure 8.5c). Then, we observed a weakening period (up to 2000s) of the cyclonic gyre with significant variation in amplitude with a period of 10 years. After the year 2000, we observed an intensification of the cyclonic gyre up to 2009. At the same time, the decadal variability of the RV is characterized by a weakening (intensification) of the cyclonic gyre on the time scales of 20 to 25 years (see Figure 8.5d) in the northern Japan Basin.

Based on the singular value decomposition (SVD) analysis of the cross-correlation matrix of monthly mean wind stress curl (WSC) anomalies over the JES and monthly mean RV anomalies in the intermediate and abyssal layers of the JES, we considered the coupling between them on interannual and decadal time scales. We found that, on an interannual scale, strong coupling is observed between the RV over the Japan Basin and the WSC over the central part of the JES, with the period of 3, 4 and 5 years (see Figure 8.6a and b). On decadal time scales, we found a strong coupling between the RV anomalies in the northern and southwestern Japan Basin and the meridional gradient of the WSC over the JES (see Figure 8.6c and d). We establish that the significant increase in the RV associated with the intensification of the cyclonic gyre is governed by variability of a positive WSC over the central part of the JES. Intensification of the cyclonic gyre on time scales of 20 to 25 years and significant weakening of this gyre in 1980 is a result of meridional gradient WSC variability. We found that the contribution of decadal variability of the WSC is insignificant. So, we need to consider other atmospheric factors which can have an impact on decadal RV variability and thus, on decadal variability of the cyclonic gyre in the northern JES. This remains a subject for further study.

References

Choi, Y.J. and Yoon, J. 2010. Structure and seasonal variability of the deep mean circulation of the East Sea (Sea of Japan). *J. Oceanogr*. **66**: 349–361.

Giese, B.S. and Ray, S. 2011. El Niño variability in simple ocean data assimilation (SODA), 1871–2008. *J. Geophys. Res.* **116**: C02024, doi:10.1029/2010JC006695.

Conkright, M.E., Locarnini, R.A., Garcia, H.E., O'Brien, T.D., Boyer, T.P., Stephens, C. and Antonov, J.I. 2002. World Ocean Atlas 2001: Objective Analyses, Data Statistics, and Figures, CD-ROM Documentation. National Oceanographic Data Center, Silver Spring, MD, 17 pp.

Gusev, A. and Diansky, N.A. 2014. Numerical simulation of the World Ocean Circulation and its climatic variability for 1948-2007 using the INMOM. *Izv. Atm. Oceanic Phys*. **50**: 1–12.

Hogan, P.J. and Hurlburt, H.E. 2005. Sensitivity of simulated circulation dynamics to the choice of surface wind forcing in the Japan/East Sea. *Deep-Sea Res. II* **52**: 1464–1489.

Isobe, A. and Isoda, Y. 1997. Circulation in the Japan Basin, the northern part of the Japan Sea. *J. Oceanogr.* **53**: 373–381.

Large, W.G. and Yeager, S.G. 2009. The global climatology of an interannually varying air-sea flux data set. *Clim. Dyn*. **33**: 341–364.

Kochergin, V.P. and Sklyar, S.N. 1992. Semianalytical version of approximation of system of equations in the 'b-ε' turbulence mode. *Rus. J. Num. Anal. Math. Model*. **7**: 405–418.

Minobe, S., Sako, A. and Nakamura, M. 2004. Interannual to interdecadal variability in the Japan Sea based on a new gridded upper water temperature dataset. *J. Phys. Oceanogr.* **19**: 2382–2397, https://doi.org/10.1175/JPO2627.1.

Mooers, C., Bang, I. and Sandoval, F. 2005. Comparisons between observations and numerical simulations of Japan (East) Sea flow and mass fields in 1999 through 2001. *Deep-Sea Res. II* **52**: 1639–1661.

Na, H., Kim, K.Y., Chang, K.I., Park, J.J. Kim, K. and Minobe, S. 2012. Decadal variability of the upper ocean heat content in the East/Japan Sea and its possible relationship to northwestern Pacific variability. *J. Geophys. Res.* **117**: C02017, doi:10.1029/2011JC007369.

Parkinson, C.L. and Washington, W.M. 1979. A large-scale numerical model of sea ice. *J. Geophys. Res*. **84**: 311–337.

Wallace, J.M., Smith, C. and Bretherton, C.S. 1992. Singular value decomposition of wintertime sea surface temperature and 500-mb height anomalies. *J. Clim*. **5**: 561–576.

Yanagimoto, D. and Taira, K. 2003. Current measurements of the Japan Sea proper water and the intermediate water by ALACE floats. *J. Oceanogr.* **59**: 359–368.

Yoon, J.H., Abe, K., Ogata, T. and Wakamatsu, Y. 2005. The effects of wind-stress curl on the Japan/East Sea circulation. *Deep-Sea Res. II* **52**: 1827–1844, doi:10.1016/j.dsr2.2004.03.004.

9. *The development of an atmosphere-wave-ocean coupled regional climate model for the Asian–Australian monsoon region*

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Introduction

Global climate models (GCMs) are the most powerful tools for climate research. The horizontal resolution of GCMs is, however, usually too coarse to depict regional phenomena because of computational cost and physical uncertainty within mesoscale processes. There are mainly two ways to improve their performance on the regional scale (Giorgi and Gutowski, 2015). The first is to increase resolution. Consequently, the computational cost will increase nonlinearly due to a geometrical increase in the number of calculations involved. Generally, doubling the horizontal resolution needs more calculations of about 8 to 10 times the original one. The second way is to downscale by incorporating a Regional Climate Model (RCM) into the GCMs (Giorgi and Mearns, 1999). RCMs provide a valuable dynamic downscaling approach to bridge the gap between global and regional scales. It is widely recognized that RCMs are more skillful at resolving orographic climate effects than the driving GCMs, especially for near-surface variables due to more accurate orography and mesoscale physical processes (Leung and Qian, 2003; Han and Roads, 2004). RCMs have now been developed and are widely applied to regional climate research.

The regional climate in East Asia, which is regarded as one of the most vulnerable regions to global climate change (IPCC, 2012; Park *et al*., 2016), is attracting increasing attention. However, high-resolution RCMs are still a gap in the National Marine Environmental Forecasting Center (NMEFC) operational system. Therefore, an atmosphere-wave-ocean RCM has been developed as a stepping stone for the operational climate prediction system covering East Asia at NMEFC.

Model configuration

The atmosphere-wave-ocean RCM is developed from the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System produced by the United States Geological Survey (Warner *et al*., 2010). It is integrated by the Model Coupling Toolkit (MCT) to exchange data fields between the ocean model – Regional Ocean Modeling System (ROMS), the atmosphere model – Advanced Research Weather Research and Forecasting (WRF; ARW), the wave model – Simulating Waves Nearshore (SWAN), and the sediment capabilities developed as part of the Community Sediment Transport Modeling Project (Fig. 9.1). As shown in the figure, the atmosphere model provides 10-m surface winds to the wave model. The ocean model receives heat fluxes and momentum flux computed by the atmosphere model, and provides sea surface temperature (SST) to the atmosphere model. Meanwhile, the ocean model provides surface currents and free surface elevation to the wave model. The wave model provides significant wave height and wave length to the atmosphere and ocean models. The atmosphere model uses the wave variables to compute an enhanced sea surface roughness. The details can be found in Warner *et al*. (2010) and COAWST website (http://woodshole.er.usgs.gov/operations/modeling/COAWST/).

In this work, to reproduce East Asia climate features, the domain of the coupled model covers the Asian–Australian Monsoon region to reduce boundary effects (Fig. 9.2). The horizontal resolution of WRF is 0.3°, and it has 41 vertical layers to resolve atmospheric mesoscale processes reasonably. The horizontal resolution of ROMS is 0.15°, and it has 40 layers. The horizontal resolution of SWAN is the same as that of ROMS for fast transferring variables between them without grid interpolation. The data interchange frequency between the models is 3600 seconds according to the component model resolutions. The schemes of major physical and dynamic processes are adjusted for the regional climate simulation, including switching on the parameters for long-term simulation in WRF and ROMS, spectral nudging for WRF, boundary conditions for ROMS and SWAN, *etc*.

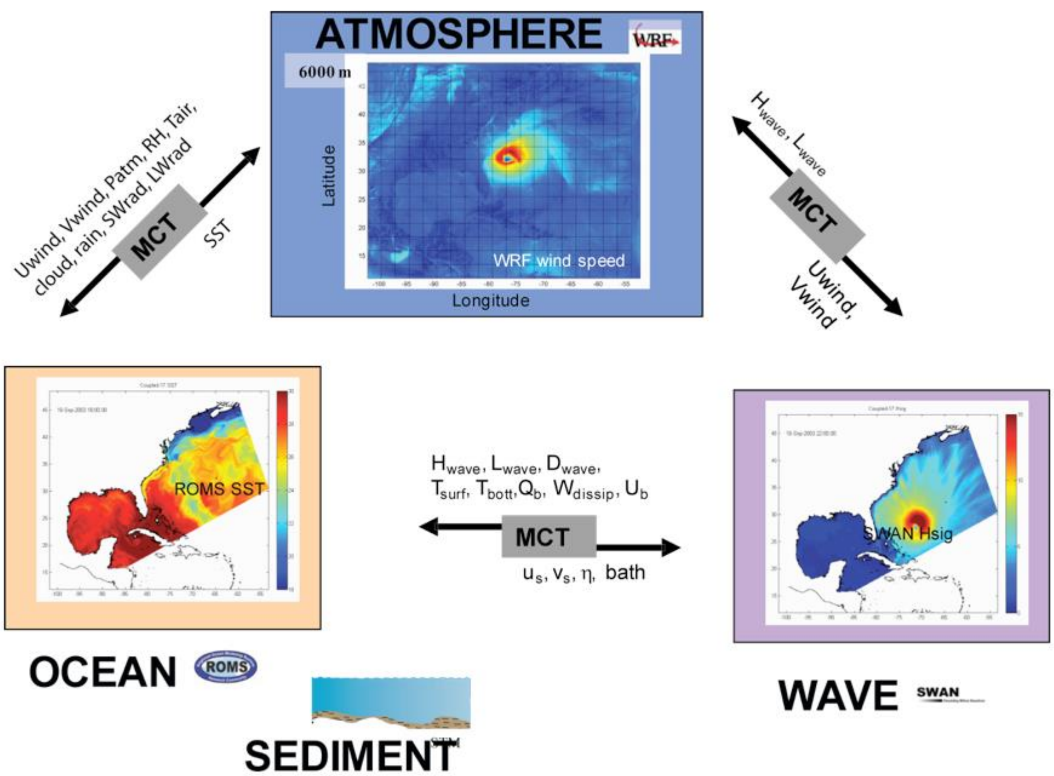

Fig. 9.1 Model schematic and data fields exchanged between component models.

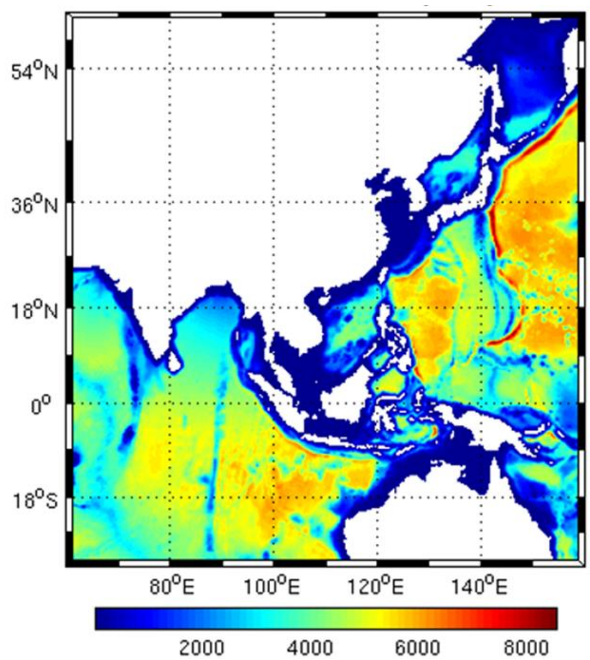

Fig. 9.2 ROMS and SWAN model domain and bathymetry (m) for the Asian–Australian monsoon region.

Results

Hindcast results

The hindcast experiment covering the period from 1991 to 2010 is conducted to evaluate the model prediction ability of the RCM. The initial conditions, lateral boundary conditions, atmospheric nudging data, and ocean climate data are from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data (Saha *et al*., 2010). To reduce spin-up effects, only model results from 2001 to 2010 are selected for analysis.

First, sea surface temperature (SST), a key variable of the climate system, is evaluated. Figure 9.3 shows regional-mean SST from 2001 to 2010 between model (red dashed line) and optimal interpolation SST (OISST) observation (black solid line) for the Asian–Australian monsoon region. We see that the coupling of the RCM can reproduce the seasonal variation of SST fairly well. The correlation coefficient between OISST and hindcast SST can reach 0.98, which indicates that the coupling of the RCM system is skillful enough to simulate the air–sea interaction reasonably. It should be noted that there is a small difference between the Climate Forecast System Reanalysis (CFSR) SST and simulated SST, which may be caused by the higher horizontal resolution and different physical processes in the coupling of the RCM.

Figure 9.4 shows the spatial patterns of averaged SST from 2001 to 2010. The patterns of simulated SST and observation are similar. The SST decreases from the tropical area to mid-high latitudes.

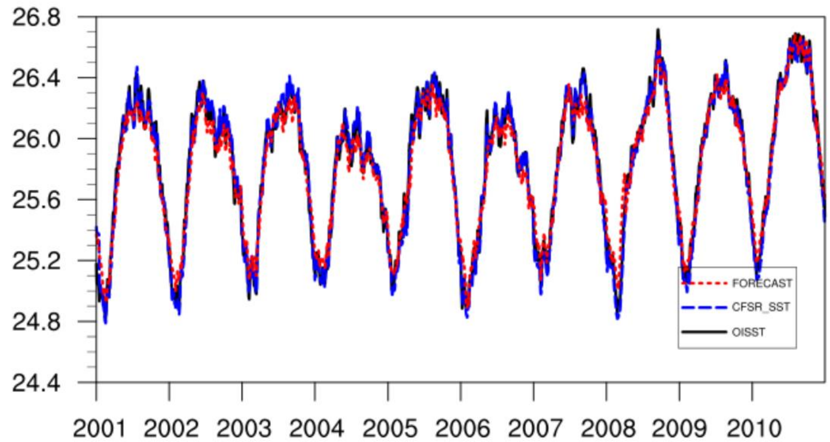

Fig. 9.3 Comparison of regional-mean daily SST (°C) among OISST (optimal interpolation SST), CFSR (Climate Forecast System Reanalysis) SST, and hindcast SST for the Asian–Australian monsoon region.

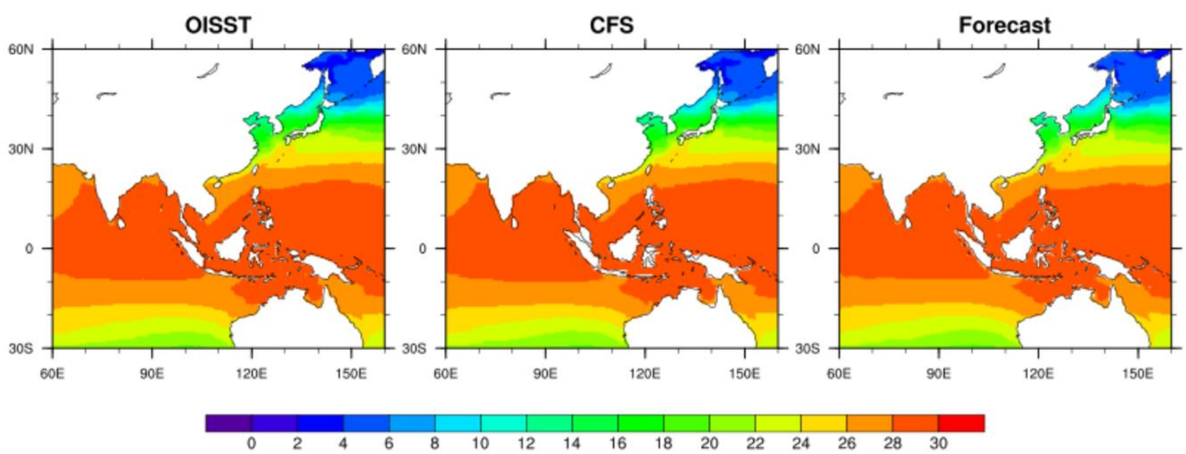

Fig. 9.4 The spatial patterns of averaged SST (°C) from 2001 to 2010 for OISST, CFS SST, and hindcast SST for the Asian–Australian monsoon region.

Forecast results

The aim of the coupled model development is to set up an operational regional climate prediction system. Therefore, a one-year (2015 A.D.) quasi-operational seasonal climate forecast experiment is conducted for evaluating the forecast skill. The initial conditions, lateral boundary conditions, atmospheric nudging data, and ocean climate data are, again, from the NCEP Climate Forecast System (CFS) (Saha *et al*., 2014) real-time forecast data.

Figure 9.5 compares the regional-mean SST for the Asian–Australian monsoon region in different seasons (winter: DJF, spring: MAM, summer: JJA, autumn: SON) between OISST, CFS and forecast. The trend of forecast SST matches well with the observation, and the average forecast bias is less than 0.5°C. The correlation coefficients between forecast results and OISST in the four seasons are 0.98 (DJF), 0.98 (MAM), 0.56 (JJA), and 0.82 (SON). The correlation coefficients show that the coupling of the RCM has different forecast skills in different seasons. In summer, the forecast skill is the lowest. A possible reason is the strong air–sea interaction during summer, which the coupling of the RCM cannot reproduce well. On the other hand, the forecast SST matches the CFS, which indicates the forecast skill of the RCM highly depends on the forecast skill of the CFS. Similar to the hindcast results, there also is a slight difference between CFSR SST and forecast SST which may be due to different horizontal resolution and physical processes in the RCM.

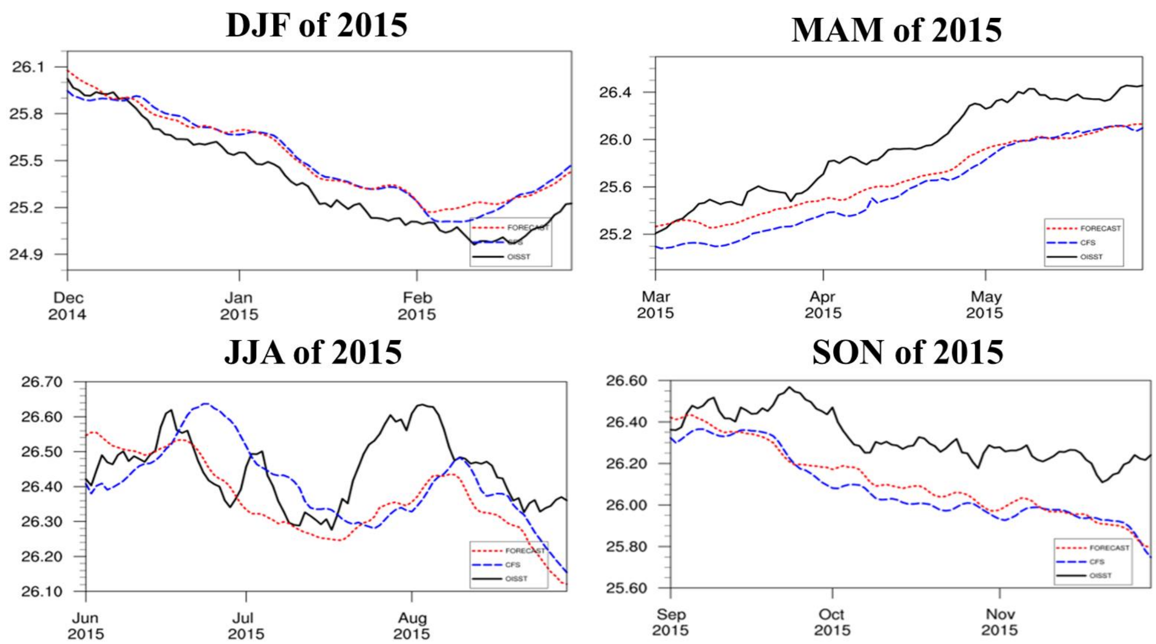

Fig. 9.5 Regional-mean SST (°C) in different seasons for the Asian–Australian monsoon region: black solid line is OISST, blue dashed line is SST of CFS and red dashed line is forecast SST.

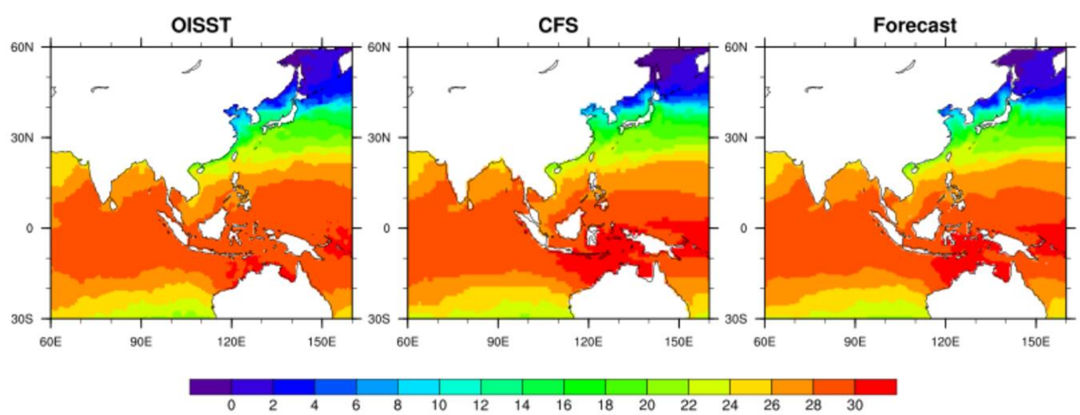

Fig. 9.6 Seasonal mean SST (°C) spatial patterns among OISST, CFS and RCM in winter (DJF).

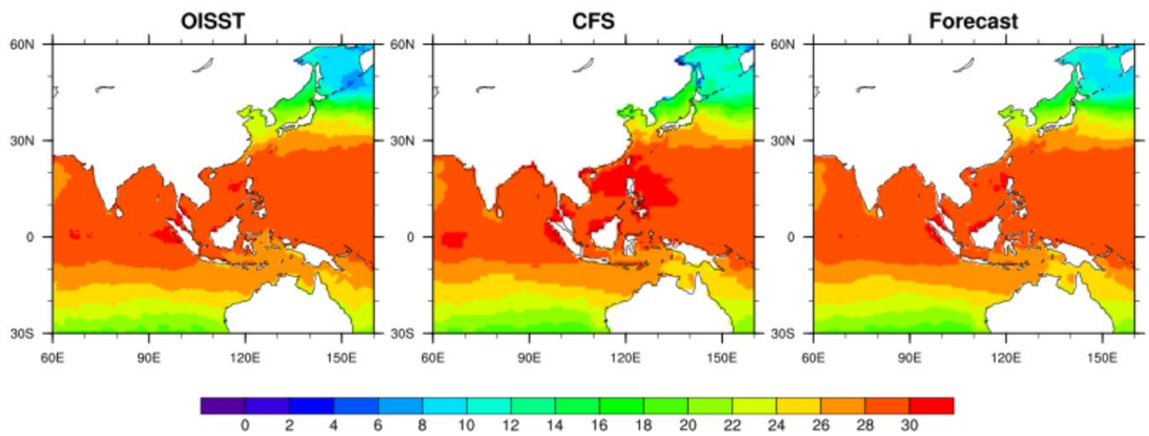

Fig. 9.7 Same as Figure 9.6, except in summer (JJA).

Figures 9.6 and 9.7 show the spatial patterns of winter and summer among OISST, CFS and RCM. These figures show the RCM can forecast the main patterns of SST in the model domain. Furthermore, the RCM can improve the SST forecast by comparing with the global CFS forecast, especially in the north and tropical area due to the higher model resolution and more accurate physical processes.

Summary and conclusions

This report introduces the development of a new atmosphere-wave-ocean RCM for the Asian–Australian monsoon region based on the COAWST model framework. The hindcast and forecast experiments showed that the RCM can reproduce and forecast well on the seasonal variation and spatial patterns of SST. In the future, we will analyze the results comprehensively to improve the RCM forecast skill and develop it into an operational system.

References

Giorgi, F. and Gutowski, W.J. 2015. Regional dynamical downscaling and the CORDEX Initiative. *Annu. Rev. Environ. Resources* **40**: 467–490, DOI: 10.1146/annurev-environ-102014-021217.

Giorgi, F. and Mearns, L.O. 1999. Introduction to special section: Regional climate modeling revisited. *J. Geophys. Res.: Atmos.* **104**: 6335–6352. doi: 10.1029/98JD02072.

Han, J. and Roads, J.O. 2004. U.S. Climate sensitivity simulated with the NCEP Regional Spectral Model. *Climatic Change* **62**: 115–154. doi: 10.1023/B:CLIM.0000013675.66917.15.

IPCC (Intergovernmental Panel on Climate Change). 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Field, C.B., Barros, V. , Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. and Midgley, P.M. (Eds.), Cambridge University Press, UK, 582 pp.

Leung, L.R. and Qian, Y. 2003. The sensitivity of precipitation and snowpack simulations to model resolution via nesting in regions of complex terrain. *J. Hydrometeorol.* **4**: 1025–1043.

Park, C., Min, S.K., Lee, D., Cha, D.H., Suh, M.S., Kang, H.S., Hong, S.Y., Lee, D.K., Baek, H.J., Boo, K.O. and Kwon, W.T. 2016. Evaluation of multiple regional climate models for summer climate extremes over East Asia. *Clim. Dyn.* **46**: 2469–2486. doi: 10.1007/s00382-015-2713-z.

Saha, S. *et al*. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. http://dx.doi.org/10.5065/D6513W89. Accessed 22 January 2018.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.T., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Peña Mendez, M., van den Dool, H., Zhang, Q., Wang, W., Chen, M. and Becker, E. 2014. The NCEP Climate Forecast System Version 2. *J. Climate* **27**: 2185–2208, doi:10.1175/JCLI-D-12-00823.1.

Warner, J.C., Armstrong, B., He, R. and Zambon, J.B. 2010. Development of a Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) Modeling System. *Ocean Model*. **35**: 230–244.

10. *Projected change in the East Asian summer monsoon by dynamic downscaling: Moisture budget analysis*

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This work is fully described in a paper by Jung *et al*. (2015) and summarized in this section.

Introduction

It is of considerable importance to understand and project a possible future change in the East Asian summer monsoon, as it affects the lives of millions of people in one of the most densely populated regions in the world. Although recent studies using a multi-model ensemble showed an overall increase in summer precipitation over East Asia, individual model results can significantly differ among themselves. Such an inter-model difference can be related to many factors, among them the inability of the global models to adequately capture regional features due to their relatively coarse resolution and insufficient treatment of small-scale processes. Hence, dynamical downscaling using a regional model is being widely used and is receiving even more attention to support the increasing demand from society for detailed information of regional climate change.

The purpose of this study is not only to investigate a possible change in the East Asian summer monsoon projected under the RCP4.5 global warming scenario, but also to understand its underlying mechanism by conducting a local moisture budget analysis. To simulate regional climate change, a pseudo global warming (PGW hereafter) method was used to reduce a global model's systematic bias for dynamical downscaling. For this PGW downscaling experiment, the CanESM2 model was selected among 16 CMIP5 models, based on an evaluation for the East Asian monsoon. We used NCEP/DOE (National Centers for Environmental Prediction/Department of Energy) reanalysis data for the present climate as the model's initial and boundary conditions and CanESM2's RCP4.5 scenario output for a future climate projection.

Experimental design and methods

Experimental design

The WRF (Weather Research and Forecasting) model version 3.4.1 (Skamarock *et al*., 2008) was used for dynamical downscaling in the PGW experiments. The spatial domain (Fig. 10.1) chosen for this study covers the entire East Asia region (10°S–60°N and 60°E–150°W). Details of the model configuration are given in Table 10.1.

As a baseline (CTRL hereafter) of the PGW experiment, NCEP/DOE global reanalysis data (Kanamitsu *et al*., 2002) was downscaled with WRF from 00 UTC of April 20 to 18 UTC August 31 every year for 10 years (1981–1990). A dynamical downscaling simulation for future climate projection was conducted based on the baseline period using the PGW method. A previous study using the PGW method suggests that the

PGW experiment results for a climate change projection may be sensitive to the projected climatological mean differences used as input rather than its baseline simulation period (Kawase *et al.*, 2009).

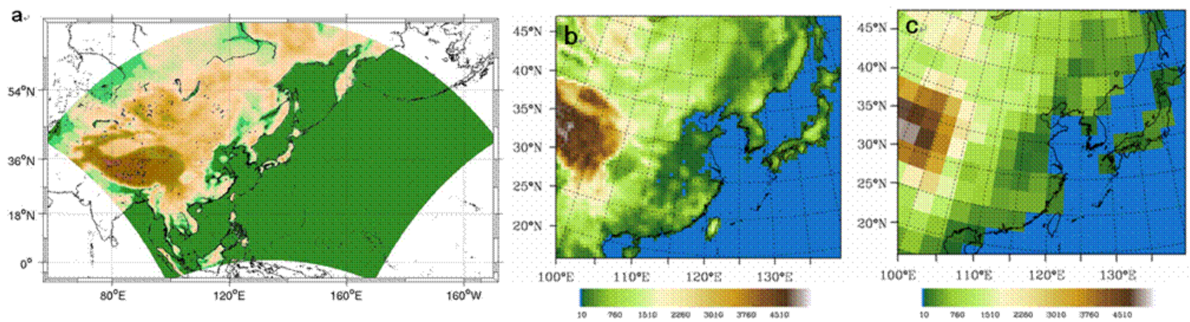

Fig. 10.1 (a) The experimental domain for dynamical downscaling with the WRF (Weather Research and Forecasting) model, and the model topography (in m) in our analysis domain for (b) WRF and (c) CanESM2.

Table 10.1 WRF version 3.4.1 model configuration and selected physical parameterization schemes used for dynamical downscaling.

Configuration	
Map projection	Lambert-conformal
Integration period	00 UTC April 20–18 UTC August 31
Horizontal resolution	50 km
Number of grids	215 × 155 × 27
Physical parameterization	
Moist convection	Kain-Fritsch (Kain, 2004)
Microphysics	WSM6 (Hong and Lim, 2006)
Boundary layer	YSU (Hong *et al.*, 2006)
Land surface model	Unified Noah (Ek *et al.*, 2003)
Shortwave radiation	Dudhia (Dudhia, 1989)
Longwave radiation	RRTM (Mlawer *et al.*, 1997)

Pseudo global warming experiment

For the downscaling of future climate projection, we calculated 6-hourly climatological mean differences between the CanESM2 (r1i1p1) RCP4.5 output for the years 2081 to 2100 and its corresponding historical output for years 1981 to 2000. The CanESM2 outputs were linearly interpolated to 6-hour intervals and regridded onto the WRF grids with a bi-linear method. By adding the CanESM2 climatological mean differences to the 6-hourly time series of NCEP/DOE reanalysis for years 1981 to 1990, we constructed a climatological projection dataset with a 10-year ensemble. The PGW downscaling experiment (PGW_CanESM2 hereafter) was then carried out for the 10 years from 1981 to 1990 using the climatological projection for the late 21st century climate. The CTRL and PGW_CanESM2 were carried out for an extended period of summer, from April 20 to August 31 (11 days for spin-up and 123 days from May to August for analysis) every year for the 10 years. A schematic diagram summarizing the PGW experimental design is shown in Figure 10.2.

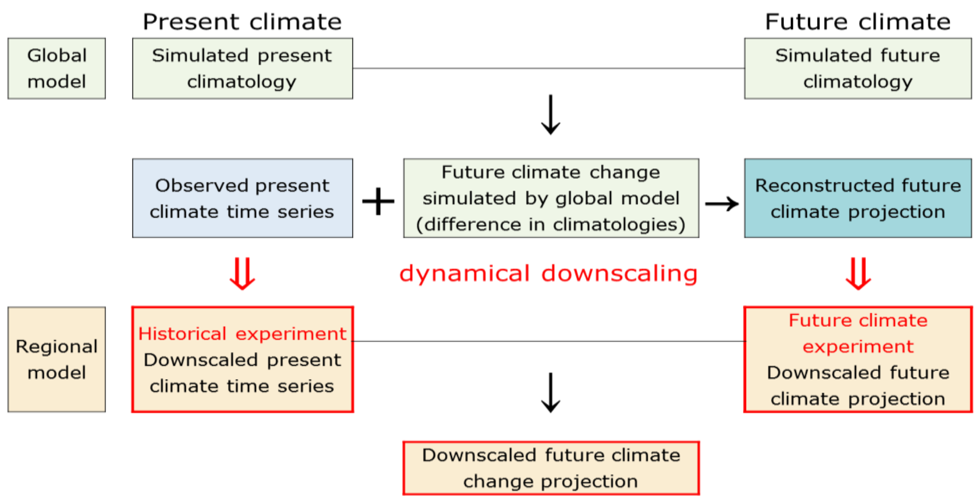

Fig. 10.2 A schematic diagram of the pseudo global warming experiment with dynamical downscaling for a future climate projection.

Since the PGW method takes only the climatological mean field to represent a climate change projection, one major limitation would be that the changes in temporal variabilities be excluded (Kawase *et al*., 2008). Thus, this constraint should be considered when planning a PGW experiment and interpreting the results.

Moisture budget equation

By ignoring the horizontal diffusion of moisture and the water in liquid and ice phases in the air, Trenberth and Guillemot (1995) used an air-column moisture budget equation for their global atmospheric water budget analysis given as

$$\frac{\partial W_A}{\partial t} + \vec{\nabla} \cdot \frac{1}{g} \int_{p_s}^{0} q\vec{V}\, dp = E - P \qquad (1)$$

where W_A is column-integrated water vapor (*i.e*., precipitable water), g the gravitational acceleration, p air pressure, $\vec{V}$ horizontal wind vector, q specific humidity, E and P evaporation and precipitation rate at the surface, respectively. The first term on the left side, a precipitable water tendency, is the atmospheric storage rate of column-integrated water vapor. This water vapor storage rate varies with season, but the rate is negligible on an annual mean basis or during a period of one season. A previous study that analyzed a moisture budget for the East Asian summer monsoon using CMIP5 global model data (Seo *et al*., 2013) ignored the storage rate and used monthly mean values to calculate the other terms in (1). They put aside all other contributing factors to the moisture budget and regarded them in total as the residual R. The residual thus includes submonthly contributions. Their simplified budget equation using monthly mean values is then

$$\langle \vec{\nabla} \cdot \left(\overline{q}\overline{\vec{V}}\right) \rangle = \overline{E} - \overline{P} + R \qquad (2)$$

where $\langle \overline{\vec{V}} \rangle$ denotes vertical integration within an air column and the overbar the monthly average.

Focused on the regional precipitation change and aimed to investigate the causal attributions of the change, we decomposed the flux form of moisture transport into the horizontal advection of moisture and the moisture flux by wind divergence as done by Hsu *et al*. (2013). To include transient effects in the moisture budget, we calculated the monthly mean values for each term with 3-hourly WRF outputs. Our budget equation is then

$$\overline{\langle \vec{V} \cdot (\vec{\nabla} q) \rangle} + \overline{\langle q \vec{\nabla} \cdot \vec{V} \rangle} = \overline{E} - \overline{P} + \varepsilon \quad (3)$$

where ε is a residual including horizontal diffusion and ε the budget error. By re-arranging the terms in (3) for the purpose of causal attribution, we get our budget equation for a future change (Δ) in precipitation as

$$\Delta\overline{P} = \Delta\overline{E} - \Delta\overline{\langle \vec{V} \cdot (\vec{\nabla} q) \rangle} - \Delta\overline{\langle q \vec{\nabla} \cdot \vec{V} \rangle} + \Delta\varepsilon. \quad (4)$$

Pseudo global warming experiment results

Precipitation and surface air temperature for the present climate

To validate the downscaling results, precipitation data based on observations from the APHRODITE (Asian Precipitation – Highly-Resolved Observational Data Integration Towards Evaluation water resources) model was used. The heavy precipitation pattern in CTRL (Fig. 10.3b) was similar to the NCEP/DOE reanalysis in Fig. 10.3d but with reduced overestimation over southern China. Thus, the mean bias averaged over land of the analysis domain was reduced as shown in Table 10.2. In the table, the spatial pattern correlation coefficient of the CTRL calculated with the APHRODITE climatology for land is 0.09 higher than NCEP/DOE reanalysis.

Climatological summer mean surface air temperature shows that downscaled CTRL presented more detailed regional structure of temperature pattern compared with the CanESM2 global model and NCEP/DOE reanalysis data in Figure 10.4.

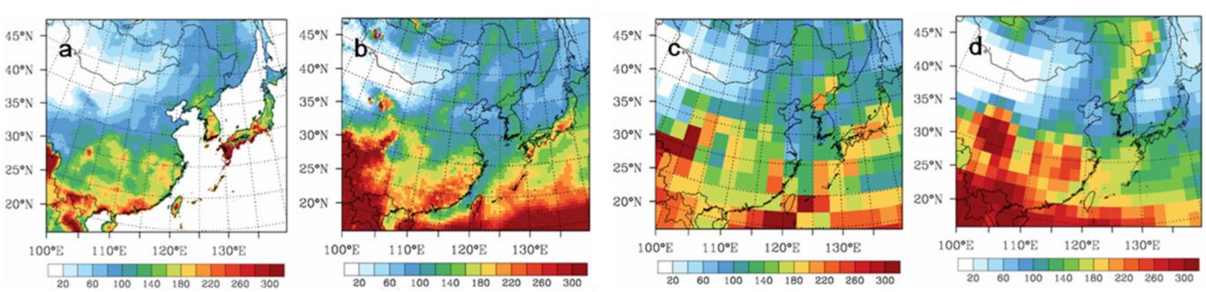

Fig. 10.3 Climatological summer (May to August) mean precipitation in mm month^{-1} for 1981 to 1990: (a) APHRODITE high-resolution observational data, (b) CTRL downscaling results with WRF, (c) CanESM2 CMIP5 historical output, and (d) NCEP/DOE reanalysis data used as input for the CTRL downscaling.

Table 10.2 Mean biases and spatial pattern correlation coefficients using summer (May to August) mean climatology for 1981 to 1990 over the land area of East Asia for surface air temperature and precipitation rate. The observational data consist of APHRODITE precipitation at a 1/4° and ERA-interim temperature at a 1/2°. Based on the observational dataset, the biases and correlations with CTRL-downscaled output using WRF, NCEP/DOE reanalysis used for the downscaling, and CanESM2 CMIP5 historical output have been calculated after regridding onto the CanESM2 resolution (~2.8° × 2.8°), which is coarsest among these data.

Variable	Data	Bias	Correlation
air temperature (°C) at 2 m	CTRL	0.03	0.99
	NCEP	0.70	0.98
	CanESM2	1.61	0.98
Precipitation rate (mm month^{-1})	CTRL	36.3	0.90
	NCEP/DOE	41.1	0.81
	CanESM2	11.3	0.83

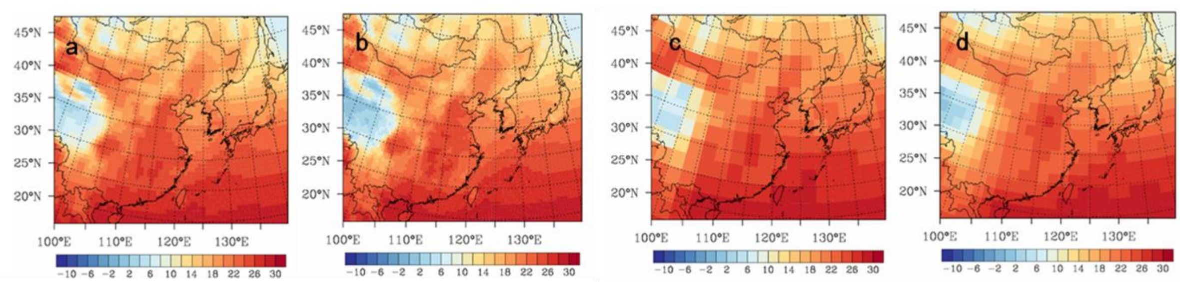

Fig. 10.4 Climatological summer (May to August) mean surface air temperature in °C for 1981 to 1990: (a) ERA-interim reanalysis data at a 1/2°, (b) CTRL downscaling results with WRF, (c) CanESM2 CMIP5 historical output, and (d) NCEP/DOE reanalysis data used as input for the CTRL downscaling.

Projected changes in precipitation and surface air temperature

PGW_CanESM2 (Fig. 10.5a, b), the differences from the CTRL results for the present climate (Fig. 10.5c, d) and the projected changes by CanESM2 (Fig. 10.5e, f) for climatological summer (May to August) mean precipitation and surface air temperature are shown in Figure 10.5.

The temperature change pattern shown in Figure 10.5d and f can be summarized as "warmer in high latitudes and in land with global warming". Such a warming pattern could possibly have contributed to the moistening of the low-level atmosphere as shown in Figure 10.6a and b, following the Clausius–Clapeyron relation (Held and Soden, 2006). This relation between surface warming and moistening may support the concept that less atmospheric warming by PGW_CanESM2 would have caused less moistening of the low-level atmosphere as compared with CanESM2, especially over land. Although the surface temperature change projected by CanESM2 was input for the PGW_CanESM2 downscaling simulation, the surface air temperature projected by PGW_CanESM2 could differ from the CanESM2 projection, affected by various factors such as changes in low-level pressure, regional circulation, and atmospheric stability.

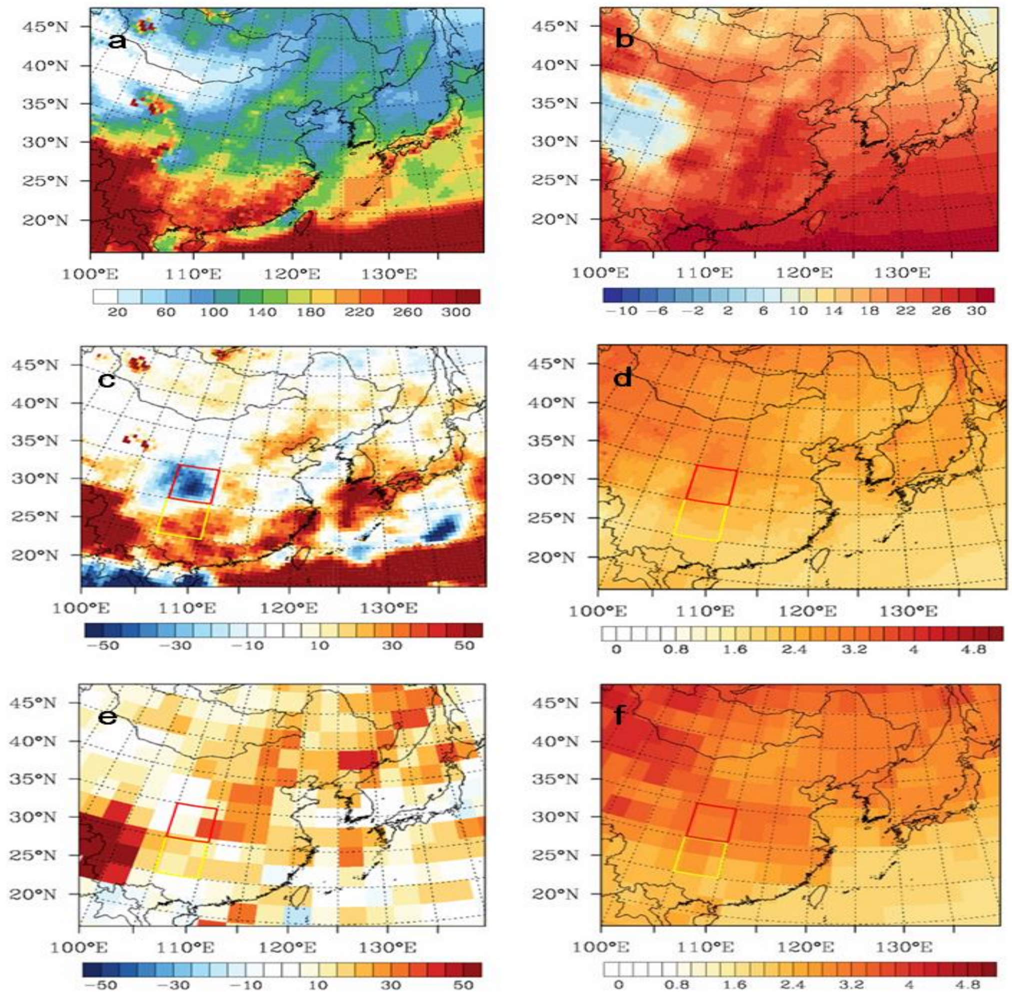

Fig. 10.5 Climatological summer (May to August) mean precipitation in mm month^{-1} (left) and surface air temperature in °C (right): (a, b) PGW_CanESM2 pseudo global warming experiment downscaling with WRF, (c, d) the difference in the PGW_CanESM2 and the CTRL downscaling outputs, and (e, f) the difference in CanESM2 CMIP5 RCP4.5 climatology for 2081 to 2100 and historical climatology for 1981 to 2000.

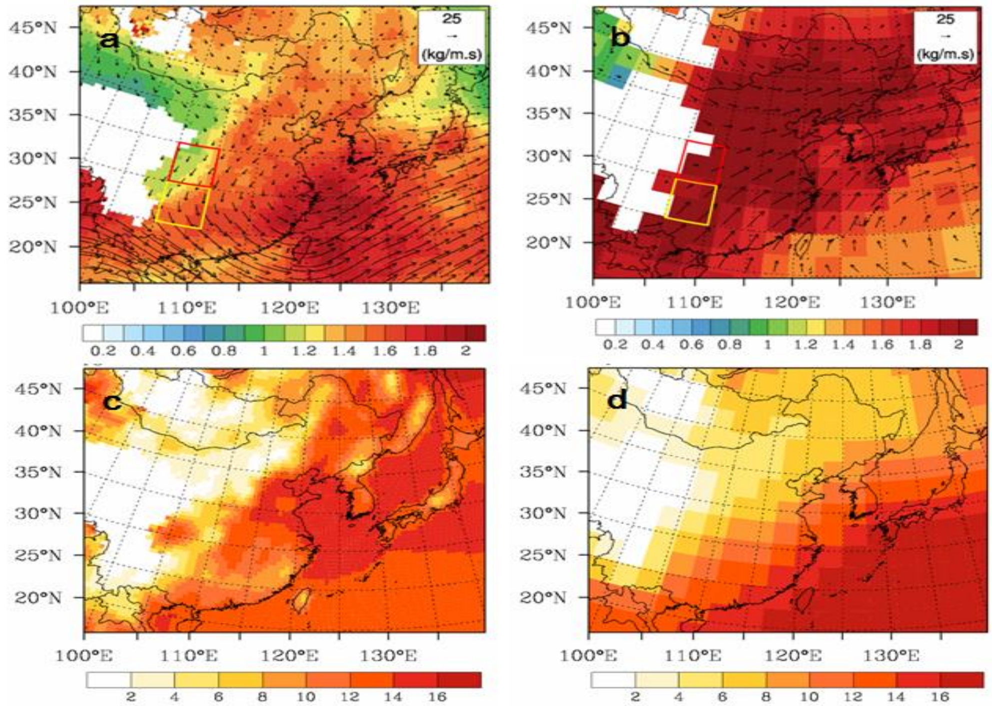

Fig. 10.6 Summer mean specific humidity (shaded colors) at 850 hPa in kg kg^{-1} and superimposed, vertically integrated moisture flux (arrows) in kg m^{-1} s^{-1} in the upper panels and geopotential height (shaded colors) at 850 hPa in m in the lower panels: (a, c) a future change obtained from the PGW_CanESM2 minus CTRL climatology on the left and (b, d) that from CanESM2 CMIP5 RCP4.5 minus historical climatology on the right. Non-colored area represents the area with terrain height above 850 hPa.

As for the projected precipitation change, both CanESM2 and PGW_CanESM2 increased the moisture flux passing over the East China Sea from the southwest, but the moisture flux in the CanESM2 result was more inland. As shown in the right panels of Figure 10.6, in CanESM2 the change in vertically-integrated moisture flux caused the increase in precipitation over East Asia due to an intensification of the subtropical North Pacific high and the southwesterly wind along the western boundary of the high. Unlike the overall increase simulated by CanESM2 (Fig. 10.5e), the precipitation is projected to be decreased in the northern area (indicated as a red box in Fig. 10.5) while it is projected to be increased in the southern area (indicated as a yellow box in Fig. 10.5) that the Yangtze (Changjiang) River runs through in PGW_CanESM2. The left panels in Figure 10.6 illustrate that in PGW_CanESM2, cold and dry air was transported from the northern continental area to the south and merged with hot and humid air from the subtropical Pacific. This cold and dry inflow from the north might have caused the precipitation decrease in the northern area. In addition, as the air passed over the Yangtze River, surface evaporation in the southern area would have been increased due to ventilation and water supply from the river. Because of this southward intrusion of continental flow, the moisture flux from the southwest along the subtropical North Pacific high appears to be confined to the East China Sea, having little influence over inland China. To further examine the contrast pattern, we analyzed an atmospheric moisture budget averaged over the local areas and present the results in the following section.

Moisture budget analysis for the regional precipitation change

We conducted a quantitative analysis calculating the area-averaged, vertically-integrated atmospheric moisture budget for each of the indicated areas to better understand the opposite changes in precipitation.

Figure 10.7 illustrates the moisture budget terms calculated as in (4). The precipitation decrease in the northern area, despite a slight increase in surface evaporation, can be attributed primarily to the horizontal advection of relatively dry air from the northern continental area as discussed above and secondarily to the divergent wind flow (Fig. 10.7a). In the meantime, the precipitation increase in the southern continental area, despite the dry air advection from the north, can be attributed to the increase in convergent wind flow and surface evaporation overly compensating the dry advection (Fig. 10.7b). A strengthened wind could drive more evaporation from the surface through ventilation and a convergent flow would make the water vapor stay locally. The evaporation increment in the southern area, more than twice as large as that in the northern area, can be explained by the geographic feature in which the Yangtze River could supply water vapor to the atmosphere.

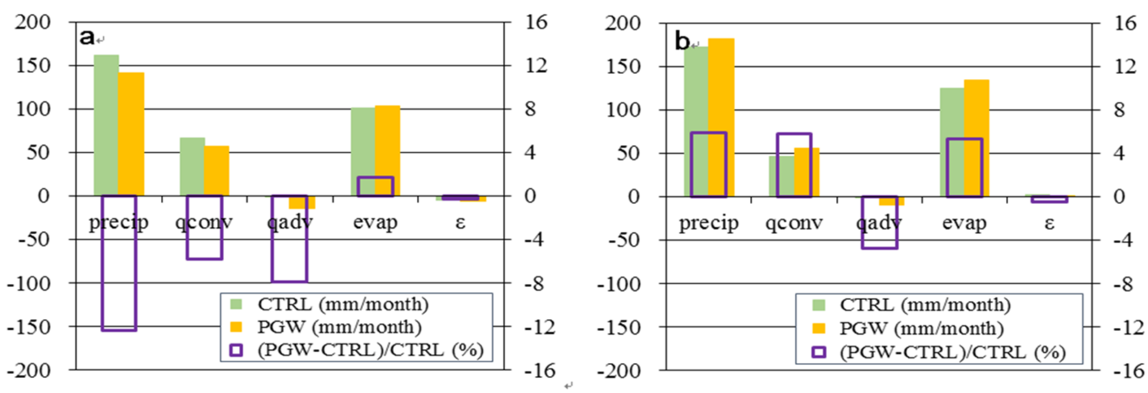

Fig. 10.7 Moisture budget terms calculated from the pseudo global warming experiments for a future climate averaged for 2081 to 2100 (PGW_CanESM2) and the downscaling result from NCEP/DOE reanalysis for the present climate averaged for 1981 to 2000 (CTRL): (a) results averaged over the northern continental area of 105°–110°E and 30°–35°N and (b) those averaged over the southern area of 105°–110°E and 25°–30°N. Green and orange bars, respectively, denote the CTRL and PGW_CanESM2 results in mm month^{-1} with the scale at left. Purple boxes denote their differences in percent with the scale at right.

Conclusion

The purpose of this study was to investigate summer precipitation change in East Asia projected under the RCP4.5 global warming scenario using the pseudo global warming (PGW) method and to understand its underlying mechanism. Unlike previous studies on the East Asian monsoon, we tried to identify the physical causes of the precipitation change under global warming by analyzing a local moisture budget. Focused on a significant contrast in precipitation change in Southwest China, the moisture budget analysis indicated that an increase in horizontally convergent wind and surface evaporation leads to a precipitation increase over the southern area and a horizontal advection of dry air from the northern continent leads to a precipitation decrease over the northern area.

This regionally contrasting change does not appear in the CanESM2 global model result or in other CMIP5 global model results (IPCC, 2013), indicating that such a regional-scale change may be poorly resolved by global models with low resolution. A dynamical-downscale simulation with a HadGEM3-RA regional model, however, revealed a similar contrasting pattern in precipitation change (NMIR, 2012). Yet, they did not mention the pattern and performed no in-depth analysis. Our analysis, with a local moisture budget, may provide an example of a quantitative approach to find the causal attributions for such hydrological changes on a regional scale.

References

Dudhia, J. 1989. Numerical study of convection observed during the winter monsoon experiment using a meso-scale two-dimensional model. *J. Atmos. Sci*. **46**: 3077–3107.

Ek, M.B., Mitchell, K.E., Lin, Y., Rogers, E., Grunmann, P., Koren, V., Gayno, G. and Tarpley, J.D. 2003. Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *J. Geophys. Res*. **108**: doi:10.1029/2002JD003296.

Held, I.M. and Soden, B.J. 2006. Robust responses of the hydrological cycle to global warming. *J. Clim*. **19**: 5686–5699.

Hong, S.-Y. and Lim, J.-O. 2006. The WRF single-moment microphysics scheme (WSM6). *J. Korean Meteorol. Soc*. **42**: 129–151.

Hong, S-Y., Noh, Y. and Dudhia, J. 2006. A revised vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev*. **134**: 2318–2341.

Hsu, P.-C., Li, T., Murakami, H. and Kitoh, A. 2013. Future change of the global monsoon revealed from 19 CMIP5 models. *J. Geophys. Res.: Atmos*. **118**: 1247–1260.

IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (Eds.), Cambridge University Press, Cambridge, 1535 pp.

Jung, C.Y., Shin, H.-J., Jang, C.J. and Kim, H.J. 2015. Projected change in East Asian summer monsoon by dynamic downscaling: Moisture budget analysis. *Asia-Pacific J. Atmos. Sci*. **51**: 77–89.

Kain, J.S. 2004. The Kain-Fritsch convective parameterization: An update. *J. Appl. Meteorol*. **43**: 170–181.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J.J., Fiorino, M. and Potter, G.L. 2002. NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteorol. Soc*. **83**: 1631–1643.

Kawase, H., Yoshikane, T., Hara, M., Ailikun, B., Kimura, F. and Yasunari, T. 2008. Downscaling of the climatic change in the Mei-yu rainband in East Asia by a pseudo climate simulation method. *SOLA* **4**: 73–76.

Kawase, H., Yoshikane, T., Hara, M., Kimura, F., Yasunari, T., Ailikun, B., Ueda, H. and Inoue, T. 2009. Intermodel variability of future changes in the Baiu rainband estimated by the pseudo global warming downscaling method. *J. Geophys. Res*. **114**: D24110, doi:10.1029/2009JD011803.

Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J. and Clough, S.A. 1997. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res*. **102**: 16,663–16,682.

NIMR (National Institute of Meteorological Research). 2012. Global climate change report corresponding to the IPCC fifth assessment report. National Institute of Meteorological Research 11-1360395-000341-10, Seoul, South Korea, 100 pp. (in Korean), http://www.climate.go.kr/home/cc_data/2013/climatechange_report_2012.pdf.

Seo, K.-H., Ok, J., Son, J.-H. and Cha, D.-H. 2013. Assessing future changes in the East Asian summer monsoon using CMIP5 coupled models. *J. Clim*. **26**: 7662–7675.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X-Y., Wang, W. and Powers, J.G. 2008. A description of the Advanced Research WRF Version 3. NCAR Technical Note NCAR/TN–475+STR, National Center for Atmospheric Research, Boulder, Colorado, USA, 123 pp. http://www.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf.

Trenberth, K.E. and Guillemot, C.J. 1995. Evaluation of the global atmospheric moisture budget as seen from analyses. *J. Clim*. **8**: 2255–2272.

11. *Water vapor transport over the Asian–Australia Monsoon region simulated by CMIP5 climate models*

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Introduction

The Asian–Australian (boreal) Summer Monsoon (AASM), characterized by an abrupt seasonal transition of general circulation, is an important climate system that influences the world's most populated region. Investigation of the monsoon system can help us to understand the mechanisms involved in climate variability and future climate projection. One of the major components of the AASM is water vapor transport (WVT) which greatly affects rainfall and the water budget during the monsoon season (Zhang, 2001). The onset time and arid–wet evolution of the monsoon are closely related to WVT variations (Cadet and Reverdin, 1981). Previous studies have mostly focused on the change in monsoon precipitation. However, our understanding of the characteristics and spatiotemporal changes of the WVT during the summer monsoon season remains insufficient. Observed results show that the large-scale pattern of summer mean WVT in the AASM region is characterized by a westward WVT in the southern Indian Ocean, the Somalia Jet, and an eastward WVT from the Arabian Sea to the South China Sea, which then turn northward and bring sufficient water vapor to East Asia (Cadet and Nnoli, 1987).

Coupled atmosphere–ocean general circulation models (AOGCMs) are effective tools to reproduce past climate systems and predict future climate change, but it remains a big challenge for AOGCMs to simulate realistically the frequency, intensity and temporal variability of monsoon systems (Wang, 2008) as well as the WVT (Zhou *et al*., 2001). Obvious errors in the simulation of monsoon systems indicate the deficiencies of climate models in describing the complex physical processes of monsoons (Wang, 2008). In this paper, the 20th century historical simulations and future projections resulting under different Representative Concentration Pathway (RCP) scenarios, including RCP2.6, RCP4.5, RCP6.0 and RCP8.5, from 22 AOGCMs were used to investigate summer mean characteristics of water vapor fluxes. All these models were from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor *et al*., 2009) which has contributed to the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). In order to realistically understand monsoon behavior in global warming experiments, we selected several models known to perform better in WVT historical simulations for multi-model projection studies.

The climatological mean results were constructed by the June–July–August (JJA) data in the period 1979–2005. WVT, shown as water vapor flux, was calculated from the surface to 300 hPa, as expressed by

$$Q = \frac{1}{g}\int_{p_S}^{p_T} q\mathbf{V}dp \qquad (1)$$

where Q is the water vapor flux and g represents the acceleration of gravity. The product of specific humidity (q) and the velocity vector (V) was integrated from the surface level (p_S) to 300 hPa (p_T).

Results

Figure 11.1 compares the boreal summer mean spatial patterns of WVT among National Centers for Environmental Prediction (NCEP) reanalysis data and the 22 AOGCMs. Here, we focus on the Asian–Australian monsoon region from 30°E to 160°E and from 30°S to 60°N, where the strongest air flow in the world, named the Somalia Jet, locates. The results show that most of the models can generally reproduce the observed pattern of climatological WVT in summer, including the westward water vapor transportation in the southern Indian Ocean, the cross-equator part under the force of the Somalia Jet, and the eastward WVT in the Northern Hemisphere that brings large amounts of water vapor to the Asian area. Three components of the WVT from the southern Indian Ocean, the Australian–Indonesian region and the northwestern Pacific converge in the South China Sea, then propagating northward, have a significant influence on the East Asian Monsoon. The largest intensity of the WVT is up to 300 kg m^{-1} s^{-1} along the coast of Somalia, and can be produced by most of the AOGCMs.

Most of the models are able to simulate the pattern of the three branches of the WVT and water vapor convergence in East Asia. However, considerable simulated biases still exist when we make comparisons between NCEP reanalysis data and each simulation of the AOGCMs. Considering the WVT over the Indian Ocean, as shown in Figure 11.2, many of the AOGCMs, such as BCC-CSM1-1, BNU-ESM, CanESM2, FGOALS-s2, FIO-ESM, GFDL-ESM2G, HadGEM2-AO, MIROC4h, and MPI-ESM-LR produce a weaker water vapor flux over the southern Indian Ocean and a stronger water vapor flux over the low latitudes of the northern Indian Ocean. It is clear that there is an obvious negative bias over the northern region of the Arabian Sea and Bay of Bengal. HadGEM2-CC, HadGEM2-ES, GISS-E2-H and GISS–E2–R produce a WVT that is too weak over the Indian Ocean. An obvious negative water vapor bias occurs along the transport belt in both the Southern and Northern Hemisphere MME (multi-model ensemble mean) compared with NCEP reanalysis data. There is still a substantial negative anomaly in existence around the Tibetan Plateau, indicating that topographic forcing described in the model has an important influence on simulation of the WVT. Most of the models cannot reproduce the effect of topography blocking water vapor transport. For the WVT over the northwestern Pacific, the pattern is driven by the summer subtropical high. Several models (*e.g.*, BNU-ESM, FIO-ESM, MIROC4h, MIROC-ESM, MIROC-ESM-CHEM, and NorESM1-M) simulate too strong a water vapor flux over the northwestern Pacific. However, CCSM4 and MRI-CGCM3 yield weaker WVT patterns, and this simulated bias is closely related to the simulation of the subtropical high over the Pacific. The intensity of the WVT branch over the Australian–Indonesia region is relatively weak so that the simulated biases are not as obvious as those in other regions. Generally, MME results considerably overestimate the water vapor flux in the tropical northern Indian Ocean and northwestern Pacific. In contrast, HadGEM2-CC and HadGEM2-ES show a poor capability in their simulation of the WVT, with quite a difference in spatial distribution.

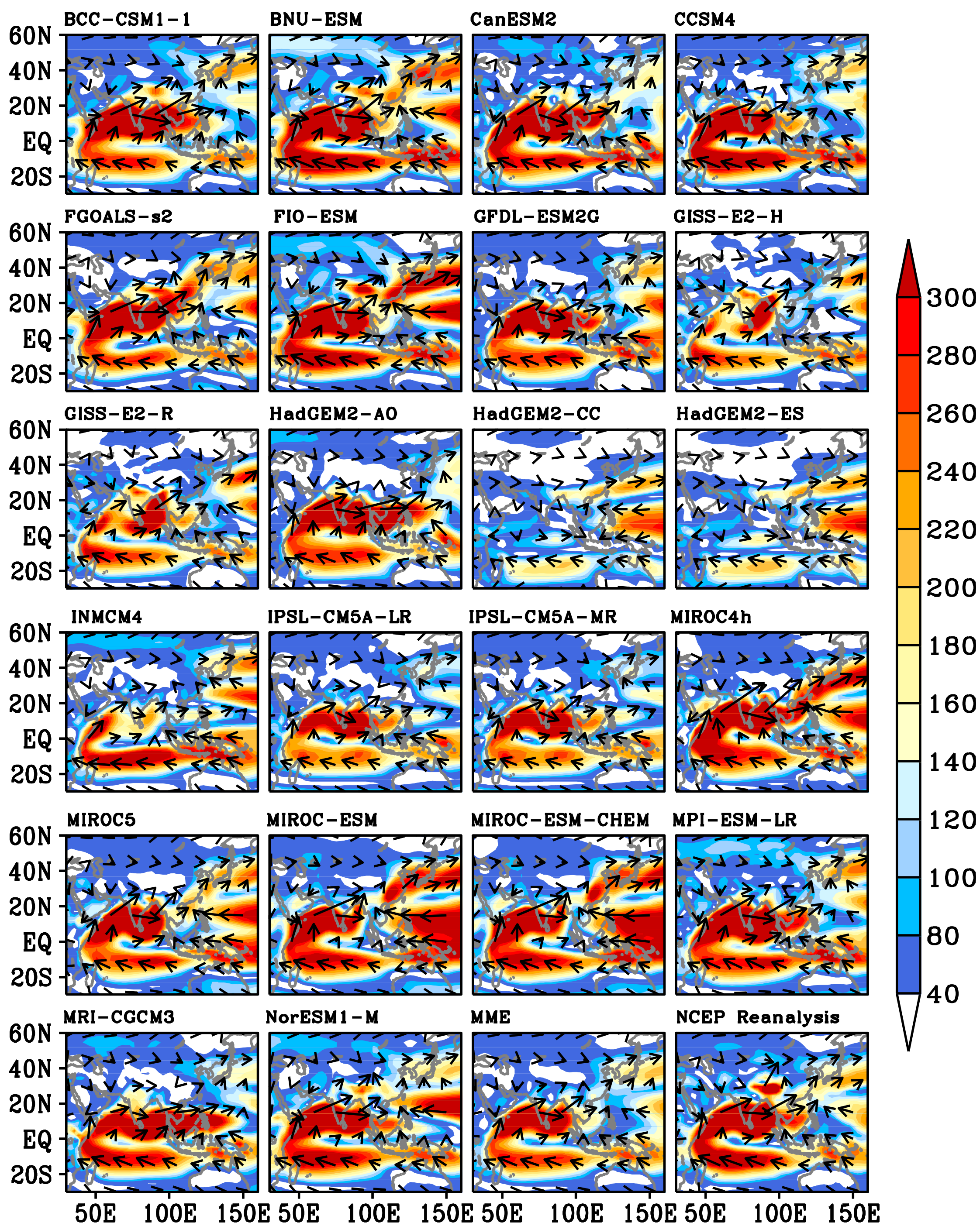

Fig. 11.1 Summer mean (June–August, 1979–2005) WVT climatology (units: kg m^{-1} s^{-1}) integrated from the surface to 300 hPa in historical simulations by 22 coupled models and NCEP reanalysis data for the Asian–Australian monsoon region.

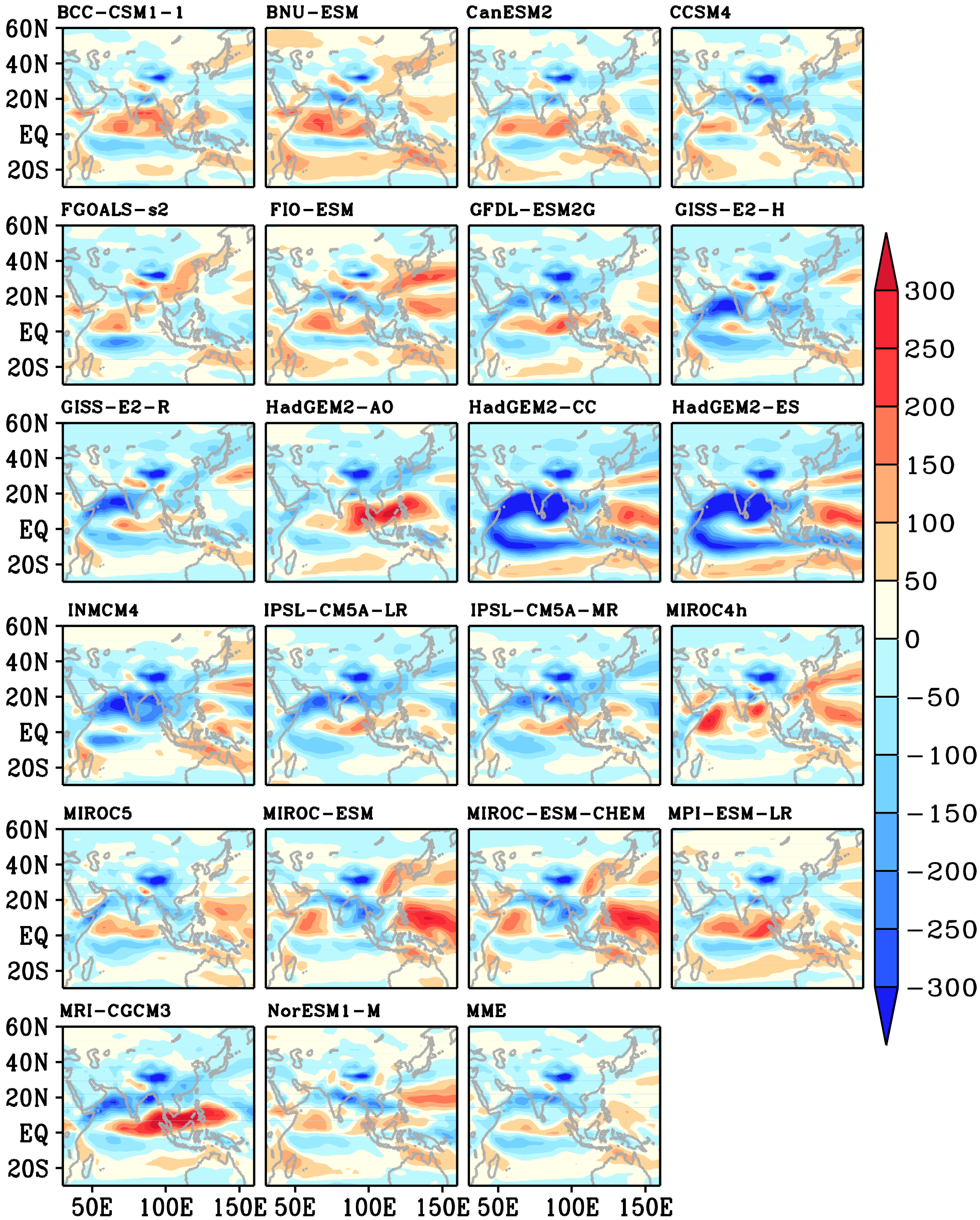

Fig. 11.2 Difference in summer mean (June–August, 1979–2005) WVT (units: kg m^{-1} s^{-1}) between historical simulations and NCEP reanalysis data for the Asian–Australian monsoon region.

Taylor diagrams of the 22 AOGCM simulations provide a concise statistical summary on how well the AOGCMs produce water vapor flux in terms of correlation and standard deviation (STD) (Taylor, 2001). We classify the WVT as having three components: the southern Indian Ocean WVT (SI-WVT; 30°–100°E, 30°S–25°N); the Australian–Indonesian WVT (AI-WVT; 100°–160°E, 30°S–10°N) and the northwestern Pacific WVT (NP-WVT; 120°–160°E, 10°–60°N). The pattern of each branch and WVT over the whole region is judged by the Taylor diagram. As shown in Figure 11.3, the distance between any two points represents the STD between two models. All statistics are calculated based on summer mean data after interpolating model results to the same grid as observed data. The results show that AOGCMs differ widely in their ability to produce the spatial distributions of summer-averaged WVT. In Figure 11.3a–d, MME with the highest correlation coefficient shows better performance in terms of WVT simulation than any single climate model. Eighteen of 22 models have correlation coefficients between 0.7 and 0.9, and the STDs of 10 models among these are near the reference line (Fig. 11.3a). For the three components of the WVT, the AOGCMs show different simulation abilities. For SI-WVT, most of the models can reasonably reproduce the distribution patterns, and the difference between the two model points is not too large (Fig. 11.3b). However, for AI-WVT and NP-WVT, the loosely scattered points in Figure 11.3c and d, respectively, suggest that the models differ greatly in their simulation ability. Some of the correlation coefficient and STD values are even out of figure range. For AI-WVT, most of the models have larger STDs. For NP-WVT, only six of 23 models have a correlative coefficient between 0.7 and 0.9. The simulation abilities of AOGCMs for NP-WVT still need to be improved.

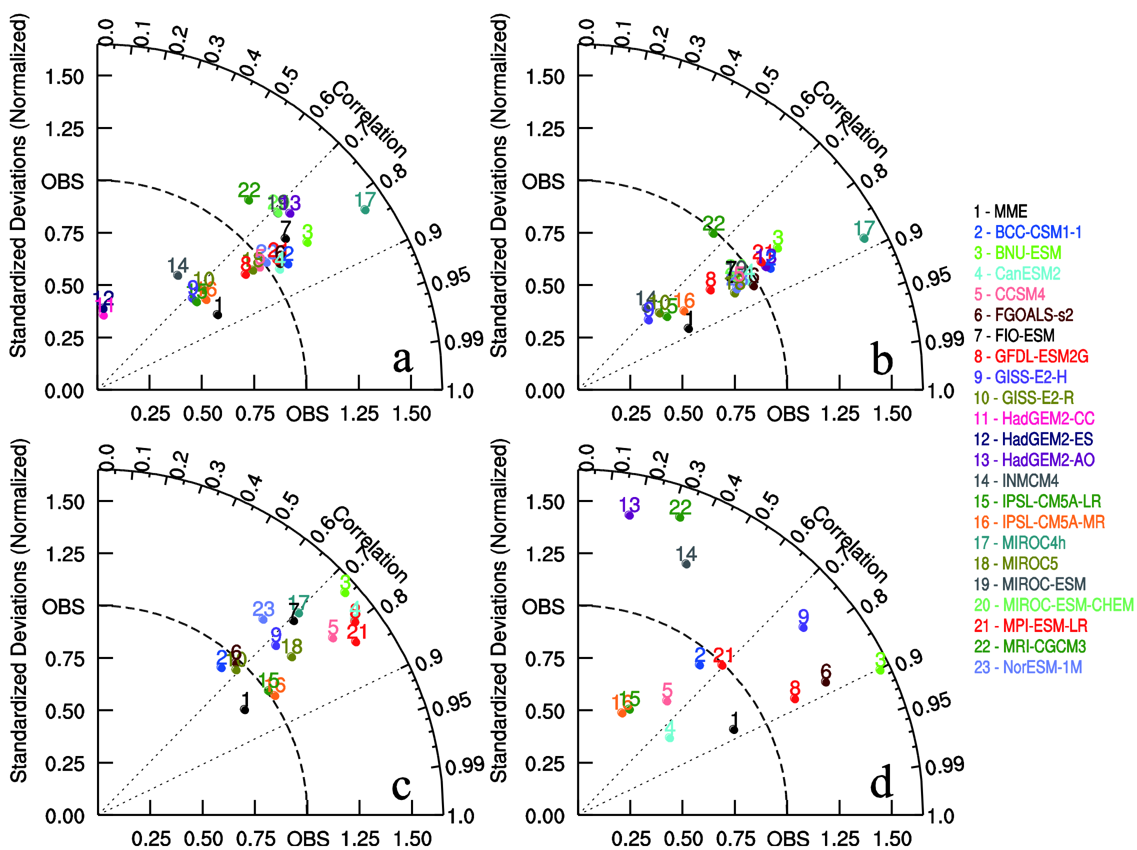

Fig. 11.3 Taylor diagrams for summer mean climatological WVT in the Asian–Australian monsoon region. Different colored dots represent different models. (a) WVT for all areas, (b) SI-WVT, (c) AI-WVT, and (d) NP-WVT.

As shown in Fig. 11.3a, there were 10 models with relatively high correlation coefficients and STD of realistic mean WVT patterns. These models, including BCC-CSM1-1, BNU-ESM, CanESM2, CCSM4, FGOALS-s2, FIO-ESM, GFDL-ESM2G, MIROC5, MPI-ESM-LR, and NorESM1-M were selected to project WVT variation under the scenario of global warming. The linear ensemble mean method was applied to obtain more persuasive results. From RCP2.6 to RCP8.5, it is obvious that the WVT will be strengthened under global warming, especially the SI-WVT component in the Arabian Sea and Bay of Bengal (Fig. 11.4). Compared to RCP runs with historical simulations, it is obvious that the WVT will be weaker over the AASM region for RCP2.6 (Fig. 11.4a) and RCP4.5 (Fig. 11.4b). The simulated results for RCP2.6 show that the large negative anomalies are distributed from the eastern part of the Arabian Sea to the Bay of Bengal. Meanwhile, in the RCP4.5 experiment, the most remarkable changes of the WVT with negative biases are over the lower latitudes of the northern Indian Ocean. In RCP6.0 (Fig. 11.4c) and RCP8.5 (Fig. 11.4d), the models simulate an enhanced SI-WVT in the Arabian Sea, over India, and in the Bay of Bengal, meaning the WVT will be stronger under global warming. The intensity variation of up to 60 kg m^{-1} s^{-1} in RCP8.5 is much stronger than that of RCP6.0. However, in the lower latitudes of the northern India Ocean, the mean of 10 AOGCMs produced a weaker WVT in RCP6.0 and RCP8.5. In addition, the NP-WVT component in the western Pacific in four RCP scenario experiments is enhanced. The variation of the WVT has a close relationship with atmospheric temperature.

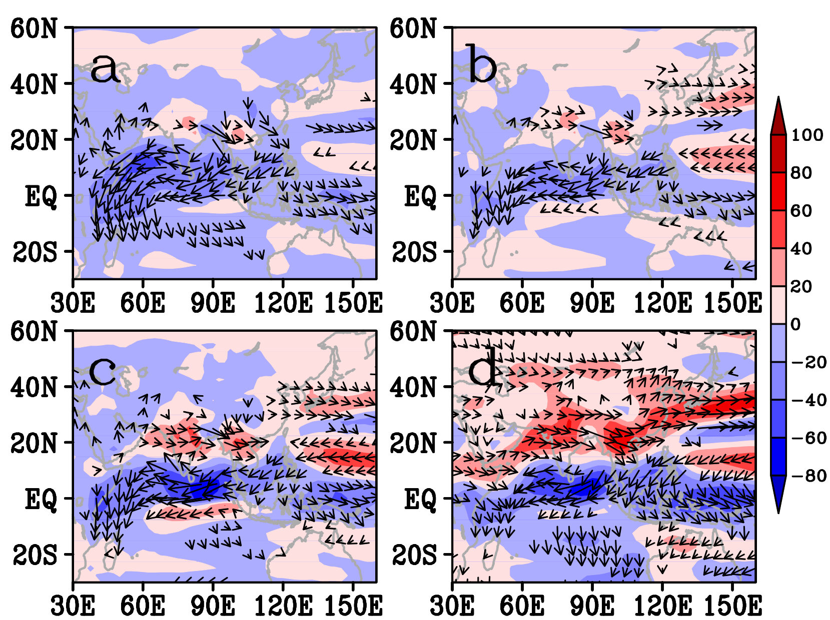

Fig. 11.4 The difference in summer mean WVT (2081–2100; units: kg m^{-1} s^{-1}) between the future scenario runs and historical experiments in the Asian–Australian monsoon region for (a) RCP2.6, (b) RCP4.5, (c) RCP6.0, and (d) RCP8.5.

Conclusions

Climatological variations of the WVT have been investigated based on monthly data from 20th century historical simulations and future projection experiments of the newest generation of 22 AOGCMs that participated in CMIP5. Compared with NCEP reanalysis data, the observed spatial patterns of WVT can be reasonably reproduced by most of the models. The MME results can produce a better distribution of the

WVT with high correlation coefficients and small STD. Some models, especially BCC-CSM1-1, BNU-ESM, CanESM2, CCSM4, FGOALS-s2, FIO-ESM, GFDL-ESM2G, MRIOC5, MPI-ESM-LR, and NorESM1-M, reproduce more reasonable WVT patterns, and so these 10 models were selected to project the change of WVT under global warming scenarios. Analysis based on future projection experiments for RCP2.6, RCP4.5, RCP6.0, and RCP8.5 showed that global warming forced by different RCP scenarios results in an enhanced WVT over India and the western Pacific and a weakened WVT over the tropical Indian Ocean. The different spatial variations of WVT under the four RCP scenarios need further analysis.

References

Cadet, D. and Nnoli, N. 1987. Water vapour transport over Africa and the Atlantic Ocean during summer 1979. *Quart. J. Roy. Meteorol. Soc.* **113**: 581–602.

Cadet, D. and Reverdin, G. 1981. Water vapour transport over the Indian Ocean during summer 1975. *Tellus* **33**: 476–487.

Taylor, K.E. 2001. Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.: Atmos.* **106**: 7183–7192.

Taylor, K.E., Stouffer, R.J. and Meehl, G.A. 2009. A summary of the CMIP5 experiment design. PCDMI Rep., 33 pp. (Available at http://cmip-pcmdi.llnl.gov/cmip5/experiment_design.html.)

Wang, B. 2008. Thrusts and prospects on understanding and predicting Asian monsoon climate. *Acta Meteorol. Sinica* **22**: 383–403.

Zhang, R. 2001. Relations of water vapor transport from Indian monsoon with that over East Asia and the summer rainfall in China. *Adv. Atmos. Sci.* **18**: 1005–1017.

Zhou, T., Yu, R., Zhang, X., Yu, Y., Li, W., Liu, H. and Liu, X. 2001. Features of atmospheric moisture transport, convergence and air-sea freshwater flux simulated by the coupled climate models. *Chinese J. Atmos. Sci.* **25**: 596–608.

12. *Modeling of marine ecosystem variability in the East Asian Marginal Seas: Preliminary results*

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Introduction

East Asian Marginal Seas (EAMS), lying in the northwestern Pacific Ocean, form one of the largest marginal seas in the world (Fig. 12.1). The EAMS include the Yellow Sea (embracing the Bohai Sea), the East China Sea, the East Sea (Sea of Japan; East Sea henceforth), and the Okhotsk Sea. Observations and climate simulations show the dramatic changes in the marine ecosystem, which are under acceleration in the EAMS through various anthropogenic pressures on top of natural variabilities. How can we understand past marine ecosystem changes and associated dynamics in conjunction with climate change and other environmental factors? How will the future EAMS marine ecosystem be different from today under multiple pressures such as global warming, ocean acidification, and oxygen depletion? To address these critical questions is very challenging and needs long-term, steady research activities. As an initial effort to tackle this problem, we established a Marine System Model (MSM) based on the coupling of physical and biogeochemical models, which can be one of the best tools for the synoptic understanding of spatial and temporal variabilities of the lower-trophic marine ecosystem as well as its future change projection. In this study, we introduce a MSM hindcast experiment for the EAMS and preliminary results of model performance assessment.

Marine System Model

The MSM in this study is based on POLCOMS (Proudman Oceanographic Laboratory Coastal Ocean Modelling Systems; Holt and James, 2001) for the ocean circulation model and ERSEM (European Regional Seas Ecosystem Model; Blackford *et al*., 2004) for the lower-trophic biogeochemical model. POLCOMS is a three-dimensional, Arakawa B-grid type, shelf seas oriented hydrodynamic model developed at POL (since April 2010, part of the UK National Oceanography Centre). The model solves the momentum and scalar transport equations for oceanographic applications, with realistic bathymetry and forcing. The underlying hydrodynamics in POLCOMS are the shallow water equations with hydrostatic and Boussinesq approximations. Since the first development of POLCOMS for the studies of frontal dynamics in the North Sea, it has been widely developed both as a hydrodynamic and a multi-disciplinary model, including use of its sediment transport module, coupled to the Los Alamos Sea Ice model (CICE, http://oceans11.lanl.gov/trac/CICE) as well as to ERSEM. It has also been coupled to the General Ocean Turbulence Model (GOTM, Burchard *et al*., 1999; http://www.gotm.net/) to allow for a range of improved turbulence models and the third generation of WAve Model (WAM, The WAMDI group, 1988).

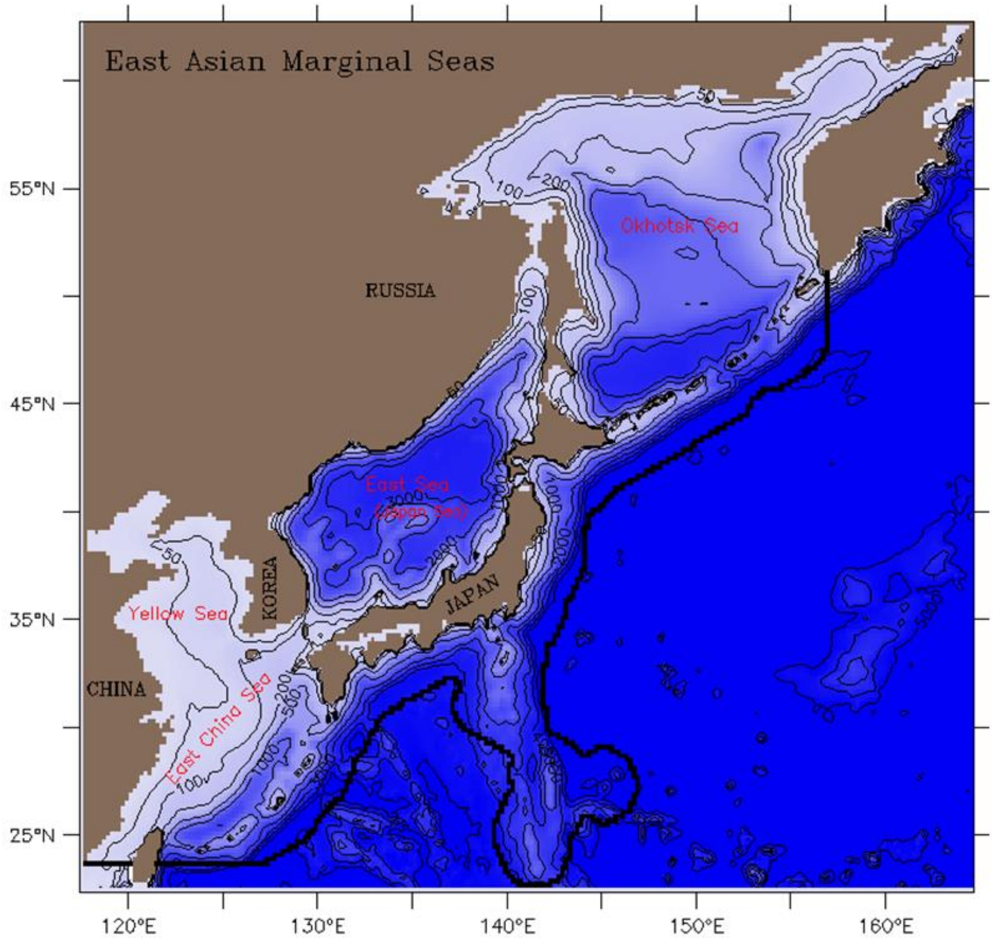

Fig. 12.1 The domain of the Marine System Model (MSM) covering most of the East Asian Marginal Seas including the Yellow Sea, East China Sea, East Sea (Japan Sea) and Okhotsk Sea. Contours represent water depths (m). Model open boundaries, depicted by solid black squares, are extended to 200 km beyond the edge of the continental shelf at around 800 m depth and include the regions of the major oceanic currents, the Kuroshio and the Oyashio. The maximum depth inside the open boundaries is 5500 m.

ERSEM is one of the most complicated carbon-based Nutrients-Phytoplankton-Zooplankton-Detritus (N-P-Z-D) models. Phytoplankton functional types are classified by diatoms and non-diatoms, based on whether they need silicate uptake. The non-diatoms are further classified by their size such as pico-phytoplankton, nano-phytoplankton and micro-phytoplankton. Three zooplankton functional types based on size fraction comprise nano-zooplankton, micro-zooplankton, and meso-zooplankton. There are three size classes of particulate organic matter and two types of dissolved organic matter (labile and semi-labile). Three nutrients (nitrate, phosphate and silicate) as well as carbon are explicitly tracked within the model functional types, and bacteria complete the microbial loop connecting the dissolved organic matter and the inorganic nutrients pool (Fig. 12.2). A salient feature of ERSEM is that the carbonate chemistry is also included in the model connecting the inorganic carbon flow in the water (Artioli *et al.,* 2012).

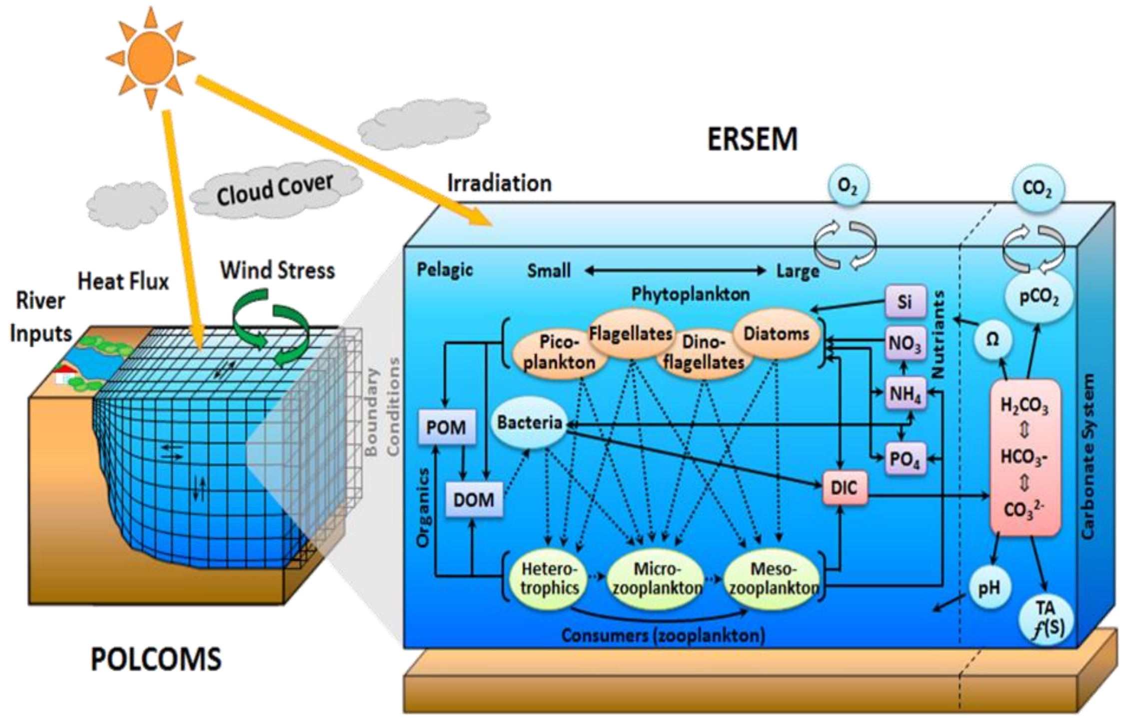

Fig. 12.2 Schematic of the regional MSM coupling the hydrodynamic ocean circulation model (POLCOMS; Proudman Oceanographic Laboratory Coastal Ocean Modelling System) and the lower trophic ecosystem model (ERSEM; European Regional Seas Ecosystem Model).

There have been many applications, based on the regional POLCOMS–ERSEM coupled model (Fig. 12.1; Holt and James, 2001; Holt *et al*., 2009a), to project the physical state of the ocean, the biogeochemistry and lower trophic levels of the marine food web. Our MSM is based on one particular domain of global coastal ocean modelling efforts done by Holt *et al*. (2009b).

The model domain covers most of the East Asian Marginal Seas including the Yellow Sea, East China Sea, East Sea and Okhotsk Sea (117°–165°E, 22°–63°N, Fig. 12.1). The major oceanic currents, the Kuroshio and the Oyashio, strongly affecting these marginal seas, are included in the model domain, and the open boundary regions are extended to 200 km beyond the edge of the continental shelf at around 800 m depth. The model uses a rectangular grid with horizontal resolution of 0.2° (18–22 km) and 40 s-coordinate vertical levels distributed according to bottom topography flattening beyond 5500 m depth.

Initial temperature and salinity fields as well as physical conditions at the open ocean boundary, including sea surface height, and zonal and meridional currents were derived from the 1/12° global NEMO (Nucleus for European Modelling of the Ocean) model output (ORCA0083-N01; http://gws-access.ceda.ac.uk/public/nemo/, Duchez *et al*., 2014) conducted by the National Oceanographic Centre Southampton, UK. A total of 8 tidal constituents (K2, S2, M2, N2, K1, P1, O1, Q1) from the TPXO 7.2 (http://volkov.oce.orst.edu/tides/global.html) result were imposed at the open boundary to include tidal forcing. Nutrient initial conditions were derived from the January climatology of World Ocean Atlas data (Garcia *et al*., 2010, https://www.nodc.noaa.gov/OC5/woa13/) and their monthly mean values were relaxed at the open boundary.

At the ocean surface boundary, the model was forced using 6-hourly and daily output from the ERA-interim atmospheric reanalysis data (http://www.ecmwf.int/en/research/climate-reanalysis/era-interim). A total of 30 annual-mean flows as well as monthly mean flows of the Changjiang River were imposed at the model river mouths from the Global Runoff Data Center (GRDC, http://www.bafg.de/GRDC/EN/Home/homepage_node.html). Concentrations of nitrate, phosphate, silicate, dissolved organic carbon/nitrogen/phosphate, particulate organic carbon, particulate nitrogen/phosphate at the river mouths were also imposed from the Global NEWS2 data (http://nutrientchallenge.org/press-release/global-news-data-available).

Volume transport in the Korea Strait

One of the key factors for model evaluation of the EAMS is the Tsushima Warm Current (TWC) volume transport across the Korea Strait located between Japan and Korea. The TWC flows into the East Sea through the Korea Strait and flows out to the Pacific Ocean through the Tsugaru and the Soya straits. According to the analysis of Acoustic Doppler Current Profiler (ADCP) data obtained by the ferryboat *Camellia* during 1997–2007, the mean volume transport of the TWC is estimated as 2.65 Sv (Takikawa *et al*., 2005; Fukudome *et al*., 2010). The average volume transport of corresponding 10-year model results is 2.30 Sv, which is comparable with the observational estimation (Fig. 12.3). Though the winter transport of the model is somewhat lower than that of the observation, the seasonal cycle of volume transport depicted by the summer to autumn high, as well as the winter low, is well simulated. It is also encouraging that the standard deviations of the TWC volume transports estimated by those two different methods are similar to each other (0.55 Sv for model and 0.42 Sv for observation).

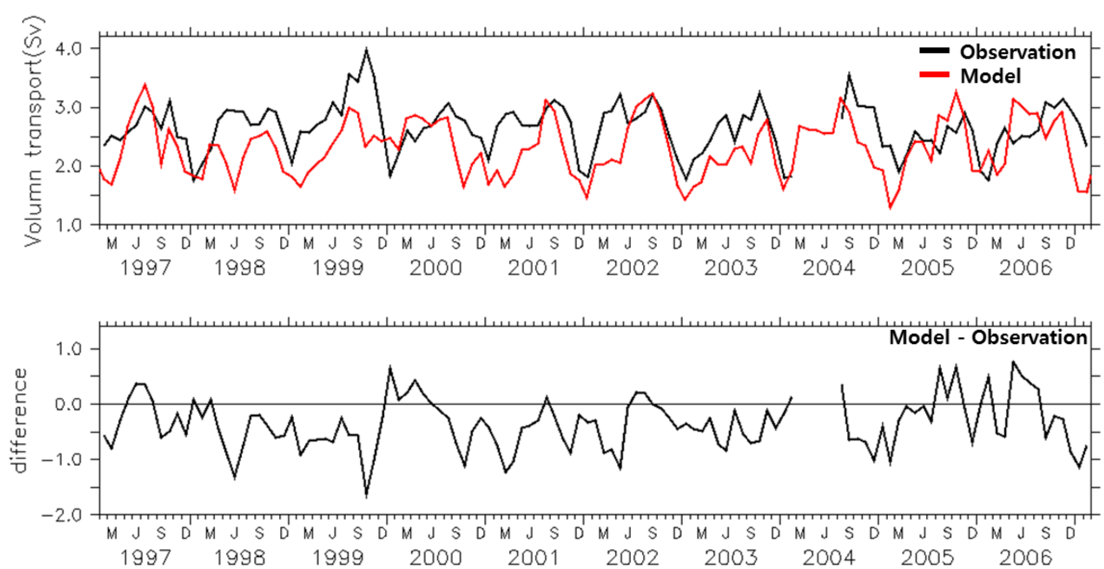

Fig. 12.3 Time series of monthly-mean Tsushima Warm Current (TWC) volume transports of model (red) and observational estimation (black) using ferryboat-mounted ADCP data (Takikawa *et al*., 2005; Fukudome *et al*., 2010). Lower pane shows the time series of monthly mean differences (model minus observation).

Temperature, salinity and nutrients around the Korean peninsula

The National Institute of Fisheries Science (NIFS) of Korea has been leading bimonthly observations of marine environment variables such as temperature, salinity, dissolved oxygen, nitrate, phosphate, silicate as well as plankton since 1961 (Fig. 12.4d) and distributes them through the Korea Oceanographic Data Center website (KODC; http://www.nifs.go.kr/kodc/soo_list.kodc). In this section, we compare five-day averaged MSM output variables with these observations point by point according to horizontal and vertical locations for the period 1995–2010.

Seasonal temperature and salinity distributions in each marginal sea area are compared on the T-S diagram as shown in Figure 12.4. It is noticeable that the model salinity in the eastern part of the Yellow Sea is systematically higher than observations regardless of the season. The temperature range, however, is well matched with the observations all year round. In the East Sea, the model salinity range is comparable with observations but model temperature in the whole water column is slightly higher than observations during the year. The overestimation of East China Sea salinity is not as high as in the Yellow Sea and not as low as in the East Sea. Low salinity water in the upper ocean during the summer in the East China Sea, which is a consequence of Changjiang River discharge, is not well resolved. This may be because the salinity imposed to the mixed water at the grid designated for the river mouth is too high in the model rather than to less freshwater flux.

To assess overall model performance, we introduced target diagrams (Fig. 12.5) showing the normalized mean bias error, normalized unbiased RMSE (Root Mean Square Error) and the correlation coefficient according to Jolliff *et al*. (2009). Normalization of each variable is based on its observational range. As described in the previous paragraphs, we find that the mean biases of the Yellow Sea salinity and the East Sea temperature are positive. The symbol colors in each diagram represent a one-to-one correlation between the model results and observations (the darker the higher the correlation, and red (blue) for positive (negative) correlation. The correlations of temperature and salinity are relatively higher than other variables and that of dissolved oxygen is low though the mean bias and RMSE are not the worst. Silicate in the Yellow Sea is the poorest estimated variable with a large mean bias error as well as a large RMSE. Positive RMSE of silicate means the standard deviation of model silicate is larger than that of observed silicate. The source of the unrealistic high silicate concentration in the Yellow Sea might be related to insufficient understanding of the dynamics of diatoms or wrong parameterization of a simple benthic return scheme. The latter seems to be more plausible because of the overall shallower depth of the Yellow Sea compared to the other seas.

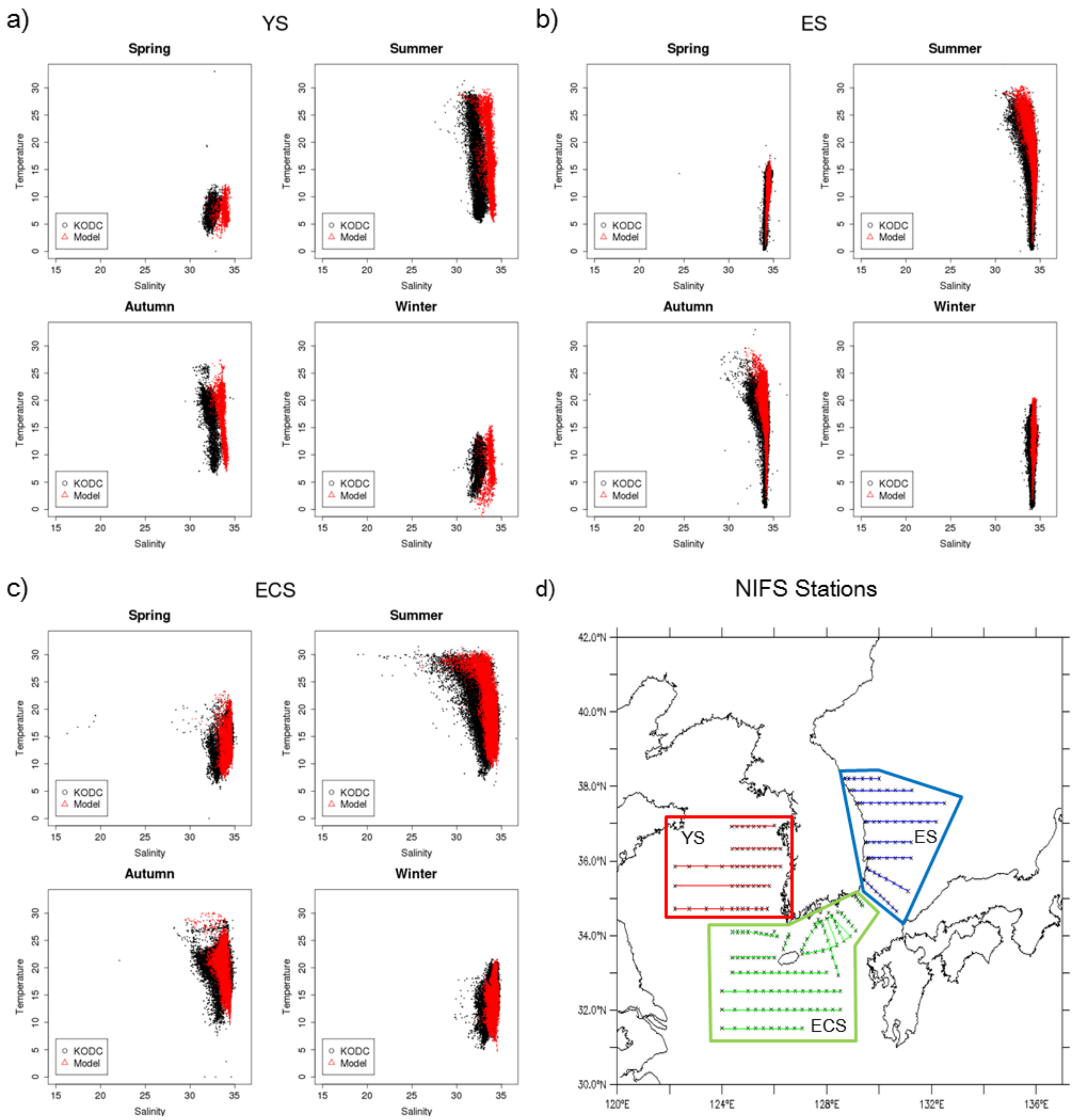

Fig. 12.4 Comparisons of temperature and salinity on the T-S diagram in the waters around the Korean peninsula. Observations (black) and corresponding model data (red) in the (a) Yellow Sea, (b) East Sea, and (c) East China Sea. Stations of bimonthly observations from 1995 to 2010 by the National Institute of Fisheries Science (NIFS) of Korea are depicted in (d).

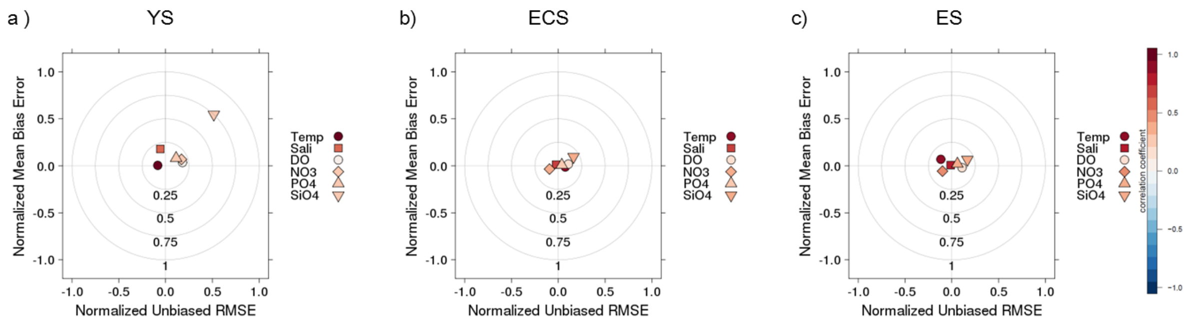

Fig. 12.5 Target diagrams of six variables (temperature, salinity, dissolved oxygen, nitrate, phosphate, and silicate) in each marginal sea: (a) Yellow Sea, (b) East China Sea, and (c) East Sea. Reference data are from the bimonthly observations by NIFS, depicted in Figure 12.4. Normalization is based on the range of each observation. The *y*-axis shows the mean bias error (positive means overestimation of model) and *x*-axis shows the Root Mean Square Error (RMSE) multiplied by the sign of the Standard Deviation (SD) difference (positive means the SD of the model is higher than the SD of observations). Symbol colors show the one-to-one linear correlation between the model results and the reference observations.

Surface chlorophyll-a

Surface chlorophyll-a (Chl-*a*, henceforce) data were compared with the monthly mean satellite-derived Chl-*a* database of the Ocean Colour Climate Change Initiative (OCCCI; Hollmann *et al*., 2013; http://www.esa-oceancolour-cci.org) as shown in Figure 12.6. In February, model and OCCCI show a similar Chl-*a* concentration in the Yellow Sea and the western East China Sea. Chl-*a* concentration in the model, however, is considerably overestimated in other areas, especially in the Kuroshio and Oyashio region as well as in southern part of the East Sea. On the contrary, Chl-*a* concentration in the northern part of the East Sea and the Okhotsk Sea seem to be underestimated. In April, the model produces very high Chl-*a* concentrations in the central Yellow Sea, northern part of the East Sea, and central Okhotsk Sea. In June, the spatial patterns of surface Chl-*a* distributions are similar in model and satellite except for the higher concentration in the Okhotsk Sea and the northern part of the East Sea in the model. In August, Chl-*a* concentrations of model and satellite are similar except that model Chl-*a* in the East Sea is much lower than OCCCI, implying much more depletion of surface nutrients in the model. In October, the autumn bloom in the southern part of the East Sea is too strong while the northern part is too weak. An anti-correlated pattern between the coastal area and the offshore region is shown in the Okhotsk Sea as well. In December, the eastern part of the East China Sea as well as southern part of the East Sea, including the region around the Kuroshio and Oyashio currents, show high Chl-*a* concentrations in the model compared to OCCCI.

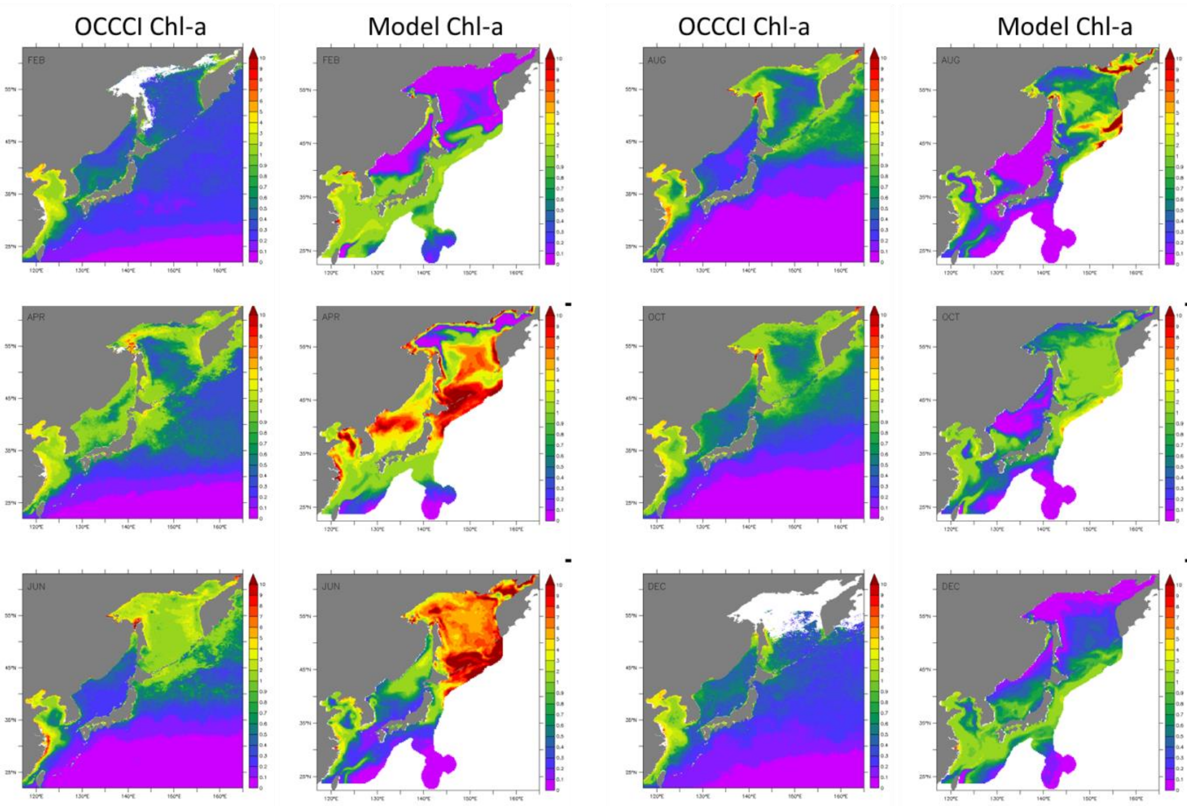

Fig. 12.6 Comparisons between the satellite-derived monthly climatological surface chlorophyll-a (Ocean Colour Climate Change Initiative (OCCCI) version 2; Hollmann *et al*., 2013; http://www.esa-oceancolour-cci.org) and model climatology.

Summary and future work

The simulation results of EAMS physical and biogeochemical variables using a POLCOMS–ERSEM based MSM have been assessed by comparing with available observations or derived data by other methods. The volume transport of the Tsushima Warm Current across the Korea Strait is similar to ferryboat-mounted ADCP results in terms of long-term mean transport and seasonal cycle. Comparisons with bimonthly observed temperature, salinity, dissolved oxygen, nitrate, phosphate, and silicate shows MSM performance is generally good though the scores are different variable by variable. Target diagrams showing mean bias error, RMSE and correlation appear to be useful to assess the performance of the MSM. Satellite-derived surface Chl-*a* is also very useful to evaluate the model skill in the EAMS even though it is not sea truth. In spite of the encouraging performance of the MSM simulation in the EAMS, it is still far from the reality and much more effort is needed to improve performance. Since the similarity between model and observation is different area by area and by time, careful investigation and better tuning of model parameters and dynamics are important to improve the MSM.

To upgrade the current MSM, sensitivity tests for the initial and boundary conditions are also necessary. The rivers play a crucial role for the freshwater and nutrient supply to the EAMS. Benthic coupling is important, especially in the shallow region. Parameters and numerical schemes in the physical and biogeochemical models should be improved continuously, based on more observational evidence.

Future work using the MSM developed in this study includes the climate change projection in the EAMS. To reduce the uncertainty of the future projections, suitable future forcing anomalies and initial fields are critical (Holt *et al*., 2012). CMIP5 (Coupled Model Intercomparison Project Phase 5) model results as well as downscaled regional climate model results are the crucial sources to develop forcing and boundary conditions. Connecting the simple global biogeochemical model variables to the complicated regional ecosystem model variables is also a challenging subject.

Model intercomparison as well as reference data sharing among the nations around the EAMS are very important to improve our understanding of past marine ecosystem changes. Information sharing with stakeholders, policy makers, and the public by providing periodical future projections and knowledge-based guidance of marine ecosystem preservation can be prompted through an internationally collaborative and coordinated program.

Acknowledgments

This study is supported by the in-house project (E99494) of Korea Institute of Ocean Science and Technology (KIOST) titled "The future projection of marine ecosystem for the seas around Korea I – Development of a pilot atlas for the past change and future projection of marine ecosystem in the seas around Korea".

References

Artioli, Y., Blackford, J.C., Butenschön, M., Holt, J.T. and Wakelin, S.L. 2012. The carbonate system in the North Sea: Sensitivity and model validation. *J. Mar. Syst*. **102–104**: 1–13.

Blackford, J.C., Allen, J.I. and Gilbert, F.J. 2004. Ecosystem dynamics at six contrasting sites: a generic modelling study. *J. Mar. Syst*. **52**: 191–215.

Burchard, H., Bolding, K. and Villarreal, M.R. 1999. GOTM – A general ocean turbulence model. Theory, applications and test cases. Tech. Rep. EUR 18745 EN, European Commission.

Duchez, A., Frajka-Williams, E., Castro, N., Hirschi, J. and Coward, A. 2014. Seasonal to interannual variability in density around the Canary Islands and their influence on the Atlantic meridional overturning circulation at 26°N. *J. Geophys. Res*. **119**: 1843–1860, 10.1002/2013JC009416.

Fukudome, K-I., Yoon, J-H., Ostrovskii, A., Takikawa, T. and Han, I-S. 2010. Seasonal volume transport variation in the Tsushima Warm Current through the Tsushima Straits from 10 years of ADCP observations. *J. Oceanogr*. **66**: 539–551, doi:10.1007/s10872-010-0045-5.

Garcia, H.E., Locarnini, R.A., Boyer, T.P., Antonov, J.I., Zweng, M.M., Baranova, O.K. and Johnson, D.R. 2010. World Ocean Atlas 2009, Volume 4: Nutrients (Phosphate, Nitrate, Silicate) *edited by* S. Levitus (No. NOAA Atlas NESDIS 71), U.S. Government Printing Office, Washington, DC.

Hollmann, R., Merchant, C.J., Saunders, R., Downy, C., Buchwitz, M., Cazenave, A., Chuvieco, E., Defourny, P., de Leeuw, G., Forsberg, R., Holzer-Popp, T., Paul, F., Sandven, S., Sathyendranath, S., van Roozendael, M. and Wagner, W. 2013. The ESA climate change initiative: satellite data records for essential climate variables. *Bull. Amer. Meteorol. Soc*. **94**: 1541–1552.

Holt, J.T. and James, I.D. 2001. An *s* coordinate density evolving model of the northwest European continental shelf: 1 model description and density structure. *J. Geophys. Res*. **106**: 14,015–14,034.

Holt, J., Wakelin, S. and Huthnance, J. 2009a: Downwelling circulation of the northwest European continental shelf: A driving mechanism for the continental shelf carbon pump. *Geophys. Res. Lett*. **36**: L14602, doi:10.1029/2009GL038997.

Holt, J., Harle, J., Proctor, R., Michel, S., Ashworth, M., Batstone, C., Allen, I., Holmes, R., Smyth, T., Haines, K., Bretherton, D. and Smith, G. 2009b. Modelling the global coastal ocean. *Phil. Trans. Roy. Soc. A* **367**: 939– 951.

Holt, J.T., Butenschön, M., Wakelin, S.L., Artioli, Y. and Allen, J.I. 2012. Oceanic controls on the primary production of the northwest European continental shelf: model experiments under recent past conditions and a potential future scenario. *Biogeosciences* **9**: 97–117.

Jolliff, J., Kindle, J.C., Shulman, I., Penta, B., Friedrichs, M.A.M., Helber, R. and Arnone, R.A. 2009. Summary diagrams for coupled hydrodynamic-ecosystem model skill assessment. *J. Mar. Syst*. **76**: 64–82.

Takikawa, T., Yoon, J.-H. and Cho, K.-D. 2005. The Tsushima Warm Current through Tsushima Straits estimated from ferryboat ADCP data. *J. Phys. Oceanogr*. **35**: 1154–1168.

The WAMDI Group. 1988. The WAM Model – A third generation ocean wave prediction model. *J. Phys. Oceanogr*. **18**: 1775–1810.

13. *Towards climate change projections of biogeochemical conditions along the British Columbia coast*

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Introduction

The British Columbia (BC) shelf along the Pacific coast of Canada is in the transition zone between coastal upwelling to the south and downwelling to the north. The southern coast is within the domain of the northern California Current System (CCS), and is characterized by seasonal upwelling with winds being upwelling-favourable in summer and downwelling-favourable in winter. A unique oceanographic characteristic of this region is that low oxygen and high carbon content are found at shallow depths (Crawford and Peña, 2013). Summer upwelling not only injects nutrients into surface waters that stimulate phytoplankton growth and make this region very productive, but also advects low-oxygen and carbonate-poor waters across the slope and shelf, decreasing the near-bottom oxygen and pH on the continental shelf (Feely *et al*., 2008). In addition, large amounts of freshwater enter the BC coast that affect coastal circulation by enhancing near-surface stratification and also through buoyancy-driven coastal currents, such as the northward-flowing Vancouver Island Coastal Current (VICC) (Thomson *et al*., 1989). The VICC brings waters of high nutrients to the ocean surface along the southwest coast of Vancouver Island and forms a barrier impeding upwelled high carbon and low oxygen waters from penetrating the inner shelf (Bianucci *et al*., 2011). Year-to-year variability in wind forcing causes large changes in intensity, duration and timing of upwelling and downwelling (*e.g*., Foreman *et al*., 2011) whereas lower-frequency climate variability, such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and North Pacific Gyre Oscillation (NPGO) cause significant changes in oceanographic properties. This region, like many other marine ecosystems, is expected to experience alterations associated with climate change as well as from changes in ocean carbonate chemistry due to the continuing increase of CO_2 in the atmosphere.

Coupled atmospheric–oceanic general circulation models (AOGCMs) are effective tools to reproduce past climate systems and predict future climate change at a global scale, but they do not typically resolve adequately coastal ocean processes that play significant roles in coastal ecosystems (*e.g*., upwelling, fresh water influence). For example, Fiechter *et al*. (2014) used a suite of physical–biogeochemical models to investigate the impact of horizontal resolution on air–sea CO_2 fluxes in the CCS. They found that the width of the outgassing region is largely overestimated when horizontal resolution is not eddy resolving, showing the importance of model resolution in resolving the complex dynamics of the region. Along the west coast of the U.S., regional model simulations project a rapid progression of ocean acidification from 1995 to 2050 indicating that this region is particularly vulnerable to future ocean acidification (Gruber *et al.*, 2012; Hauri *et al*., 2013). In these studies, the physical part of the model is forced with present-day climatological boundary conditions whereas the lateral and surface boundary conditions for the carbon systems are from future CO_2 scenarios. However, biogeochemical cycles will not only be altered directly by the rising partial pressure of carbon dioxide ($p\text{CO}_2$) in the atmosphere, but also by indirect effects, such as higher temperatures and changes in wind strength and patterns (*e.g*., Bakun, 1990). A regional ocean circulation model simulation of future ocean conditions along the BC shelf (Foreman *et al*., 2014) projects an increase in sea surface temperature, decrease in sea surface salinity, and larger Haida Eddies but not appreciable changes to the cross-shelf upwelling. These changes could alter biogeochemical properties and have important ecosystem consequences. Thus, a regional model of the BC coast capable of resolving relevant physical and biogeochemical processes needs to be developed to project future conditions in biological production and the biogeochemistry of the region. This model is also needed to evaluate the potential risk (likelihood) for the development of hypoxia events and corrosive conditions.

In this section, we describe current efforts to develop a regional coupled physical–biogeochemical model of the BC coastal ocean to predict possible future climate conditions using dynamic downscaling from regional climate models (RCMs) and/or global climate models (GCMs) output under the RCP8.5 global warming scenario. This work is in progress and has benefited from workshops organized by Working Group 29 and discussions among its members.

Model description

Regional ocean circulation–biogeochemical model

The regional model couples a high resolution (3 km in the horizontal and 42 vertical levels) ocean circulation model to a plankton–biogeochemical model. The model domain extends from south of the Columbia River in northern Oregon to the Alaska Panhandle (Fig. 13.1a). The circulation model is based on the Masson and Fine (2012) implementation of ROMS (Regional Ocean Modeling System) that was successfully used to hindcast oceanic conditions for the period of 1995–2008. The vertical resolution was increased from 30 to 42 levels so that the surface layer thickness ranges from a minimum of 0.3 m in the shallowest areas (7 m deep) to ~1.6 m at the deepest depth (~3800 m deep), allowing a reasonable representation of the mixed layer and the euphotic zone everywhere in the domain. The plankton–

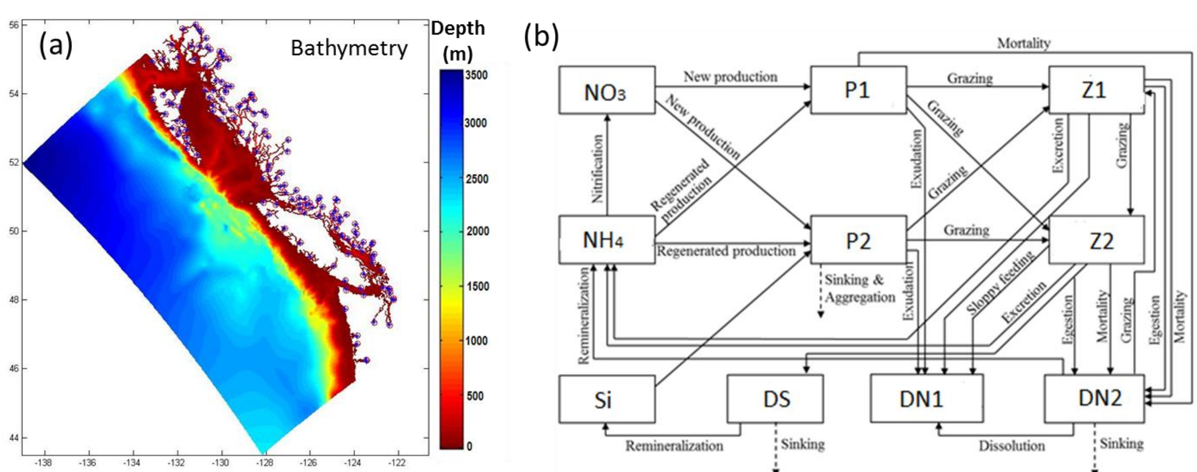

Fig. 13.1 (a) Model domain and bathymetry (m) showing river input locations (o) and the location of the vertical cross-section used in Figure 13.7, and (b) schematic diagram of the nitrogen-based NPZD plankton ecosystem model. Boxes represent the state variables and arrows indicate flows of matter through the system (solid arrows) or out of the system (dashed arrows).

biogeochemical model is a modified version of the nitrogen-based NPZD model described by Peña *et al*. (2016), along with a carbon and an oxygen cycle component. The NPZD (nutrient-phytoplankton-zooplankton-detritus) model was modified to include two pools of detritus (a small one that sinks slowly and a large one that sinks fast) and a sediment layer that accumulates particulate organic matter reaching the seafloor where it is subject to aerobic remineralization at a specified rate. The model (Fig. 13.1b) consists of sixteen compartments: nitrate (NO_3), ammonium (NH_4), silicate (Si), flagellates (P1), diatoms (P2), herbivorous zooplankton (Z1), omnivorous zooplankton (Z2), small and large nitrogen detritus (DN1 and DN2), small and large carbon detritus (DC1 and DC2), silicon detritus (DS), dissolved inorganic carbon (DIC), alkalinity (Alk), mineral $CaCO_3$ ($DCaCO_3$), and oxygen (O_2). The carbon and oxygen cycles are coupled to the plankton ecosystem model via fixed C:N:O Redfield ratios, but different remineralization rates for detritus nitrogen (DN1 and DN2) and carbon (DC1 and DC2) allow departures from Redfield C:N ratios. The exchange of O_2 and CO_2 across the air–sea interface is parameterized following Wannikhof (1992) and the inorganic ocean carbon cycle is based on the Ocean Carbon Cycle Model Intercomparison Project (OCMIP) standard routines (Najjar and Orr, 1999).

The model was run for a 30-year hindcast (1981–2010) forced by eight major tidal components (M2, S2, N2, K2, K1, O1, P1, and Q1) along the open boundaries, freshwater discharge, and atmospheric forcing. The latter is derived from NARR (North American Regional Reanalysis), and consists of 3-hourly wind stress and daily atmospheric parameters at 32 km spatial resolution. Monthly freshwater discharges from 153 rivers affecting the study area, derived as in Morrison *et al*. (2002), are included. Salinity and temperature initial and lateral ocean boundary conditions are derived from monthly mean Simple Ocean Data Assimilation (SODA) global ocean reanalysis, whereas nutrients and oxygen conditions are derived from monthly climatological means of the World Ocean Atlas 2013. Initial and boundary conditions for the inorganic carbon system (DIC and TA (total alkalinity)) are based on the PACIFic ocean Interior CArbon (PACIFICA) Database. A seasonal cycle was added to the annual mean DIC and TA boundary conditions using a monthly climatology of pCO_2 (Takahashi *et al*., 2014) and monthly TA values computed from sea surface temperature and salinity using an empirical parameterization (Lee *et al*., 2006). Initial and boundary conditions for all other biogeochemical variables were set to low constant values (≤ 0.05 mmol-N m^{-3}). To reduce spurious signals along the open boundaries, a sponge layer was added by increasing horizontal mixing near the boundaries.

An extensive validation of the physical model indicates that it is able to reproduce salient features of the seasonal and interannual variability of the region (Masson and Fine, 2012). Also, the simulated distribution of nutrients and chlorophyll, as well as the simulated seasonal cycle and inter-annual variability of mixed layer depth, compare reasonably well with *in-situ* and satellite observations. In order to use this model to project impacts of future climate change on biological production and biogeochemistry, it needs only to be run with suitable future forcing and initial fields.

Global climate model projections

While most GCM projections for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) do not include biogeochemical components, simulations from coupled physical–biogeochemical models were used for the fifth assessment report (IPCC AR5). There are large differences in the number of state variables and parameterization of the biogeochemical components in these models. For example, the biogeochemical component ranges from simple NPZD models (*e.g.*, Canadian Centre for Climate Modelling and Analysis (CCCMA) model, CanESM2) to more than 30 prognostic tracers (*e.g.*, NOAA Geophysical Fluid Dynamics Laboratory model, GFDL-ESM2M). Increased complexity of the ocean biogeochemical component might improve realisms but could also increase uncertainty and not necessarily lead to better results. Results from the AR5 new generation of global climate models are available through the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (Taylor *et al*., 2012). CMIP5 uses a new set of emissions scenarios known as Representative Concentration Pathways (RCPs) that assume policy actions will be taken to achieve certain emission targets. Within the core set of runs, there are two future projections simulations consistent with a high emissions scenario (RCP8.5) and a mid-range mitigation emissions scenario (RCP4.5). In the RCP8.5 scenario, radiative forcing increases throughout the 21st century before reaching a level of ~8.5 W m^{-2} at the end of the century.

To better characterize projected climate changes at regional scales, it is necessary to downscale the output from several models to produce an ensemble of simulations. The spread of results found will provide some perspective concerning uncertainty or some measure of how much confidence might be placed on the projected impacts of climate change. In CMIP5, ocean temperature, salinity and horizontal velocities are available as three-dimensional monthly fields whereas ocean three-dimensional biogeochemical fields (NO_3, Si, DIC, Alk and O_2) are available only as annual means.

The required atmospheric forcing can be obtained by applying downscaling techniques to output from AOGCMs and/or RCMs. The increased resolution of RCMs is able to better capture spatial variations in oceanic winds and heat fluxes. For our model domain, the North American Regional Climate Change Assessment Program (NARCCAP) provides RCM data at a finer horizontal resolution than AOGCMs for AR4 results. Similarly, the Coordinated Regional Climate Downscaling Experiment (CORDEX) aims to provide high-resolution (25 and 12 km) "downscaled" climate data based on CMIP5 simulations analogous to the NARCCAP AR4 results. However, regional downscaled projections for North America are not presently available within the CORDEX archive. Thus, only simulations that result from forcing and initializing with the Canadian Regional Climate Model (CanRCM4) forced by the Canadian Earth System Model (CanESM2) are presented.

Climate forcing

The regional ocean physical–biogeochemical model was forced by initial and lateral boundary conditions dynamically downscaled from CanRCM4/CanESM2 RCP8.5 scenario model output available on the CCMA archive (http://www.cccma.ec.gc.ca/data/data.shtml). The atmospheric-only CanRCM4 has a resolution of 22 km and the CanESM2 of about 1.41° longitude and 0.94° latitude and 40 vertical levels. Regional climate projections were performed for the period from 2041 to 2070 using future forcing fields that were generated by adding monthly average differences between future (2041–2070) and current (1981–2010) scenarios derived from CanRCM4/CanESM2 to the contemporary hindcast (1981–2010) forcing fields. This approach for computing future projections has been applied in previous studies (*e.g.*, Hara *et al*., 2008; Foreman *et al*., 2014). Future freshwater discharges along the BC coast were computed from CanRCM4 following the method of Morrison *et al*. (2002), as for the hindcast run.

Figure 13.2 shows monthly-averaged surface air temperature anomalies from CanRCM4 used to force the regional model. Warming occurs throughout the region, with temperature anomalies being larger over land than over the ocean. The largest anomalies over the ocean occur from August to October and the smallest from May to July. Similar fields were computed for winds, precipitation, sea level pressure, humidity, and shortwave and long-wave radiation.

Temperature, salinity and perpendicular velocity anomalies downscaled from the CanESM2 model at the lateral boundaries are shown in Figure 13.3. All temperature anomalies are positive (range from 0.8 to 2.8°C), while all salinity anomalies are negative (range from –0.5 to 0) in the upper 500 m. For the biogeochemistry fields, NO_3, DIC and Alk anomalies at the lateral boundaries were computed from CanESM2 but because this model does not have Si and O_2, it was not possible to compute their anomalies so the boundary condition for these variables were left unchanged from the hindcast run.

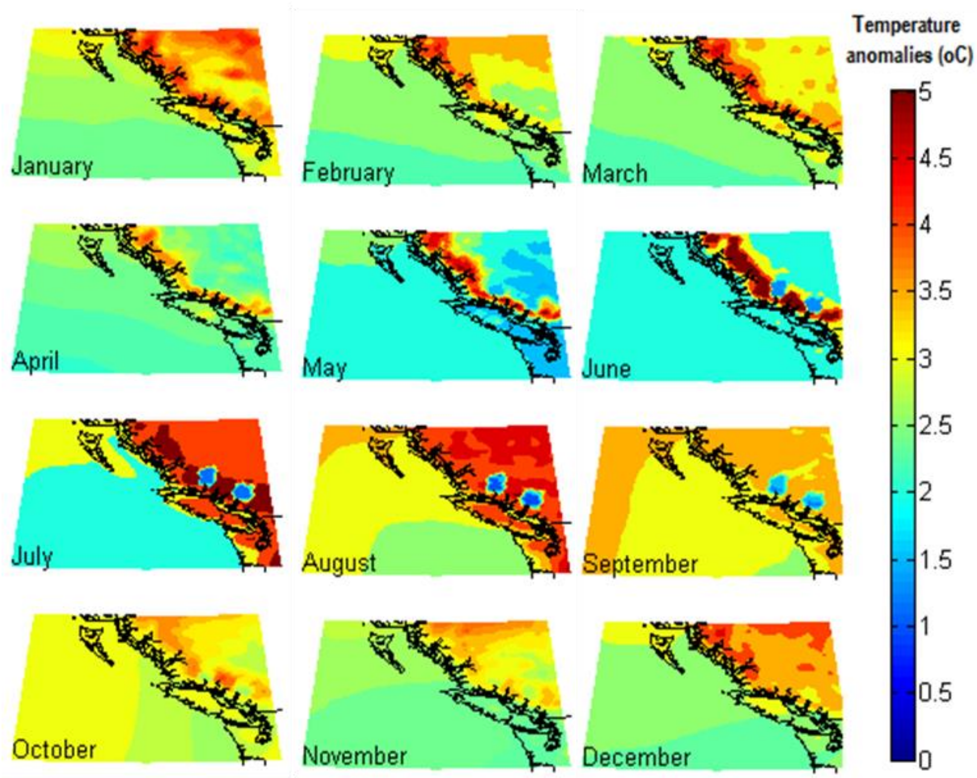

Fig. 13.2 CanRCM4 monthly-averaged surface air temperature anomalies (°C) for the period 2041–2070 minus 1981–2010.

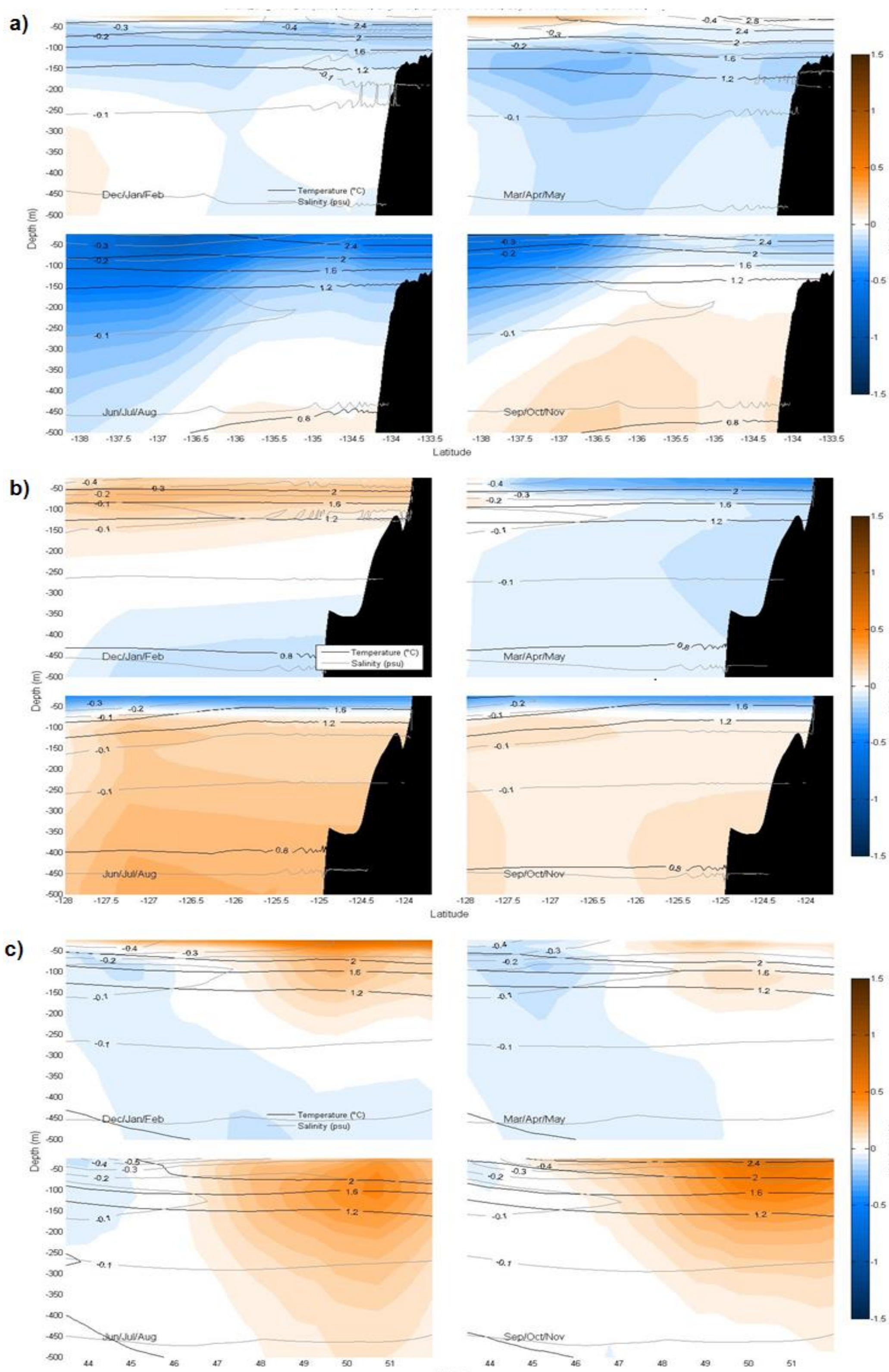

Fig. 13.3 Seasonally-averaged changes in temperature (black lines), salinity (grey lines) and perpendicular velocity (colour contours) for the (a) northern, (b) southern, and c) western grid boundaries. Positive velocities denote flow into the ROMS domain along the western and southern boundaries and out of the domain along the northern boundary.

Results

The model projects increases in sea surface temperature (SST) of between 0.8 and 3°C (Fig. 13.4). Averaged seasonal SST anomalies are generally higher during the summer and fall, consistent with air temperature anomalies (Fig. 13.2). However, SST anomalies are more variable, showing the lowest increase in SST along the western Vancouver Island and Washington coast during summer and fall, respectively. In comparison, seasonally-averaged sea surface salinity (SSS) is projected to decrease by as much as 1 on Dogfish Banks in Hecate Strait during the summer (Fig. 13.5). In all seasons there is a positive SSS anomaly nearshore, reaching as much as 0.9 off the Washington coast in winter. Smaller negative SSS anomalies are found offshore, especially during the summer.

Seasonal average surface chlorophyll anomalies (2041–2070 minus 1981–2010) decrease by as much as 2 (mg m^{-3}) in spring along the continental shelf (Fig. 13.6). In summer, surface chlorophyll increases by as much as 3 (mg m^{-3}) along the west coast of northern Vancouver Island and Hecate Strait but decreases by 2.3 (mg m^{-3}) further south. Changes in surface chlorophyll concentration are lowest in winter.

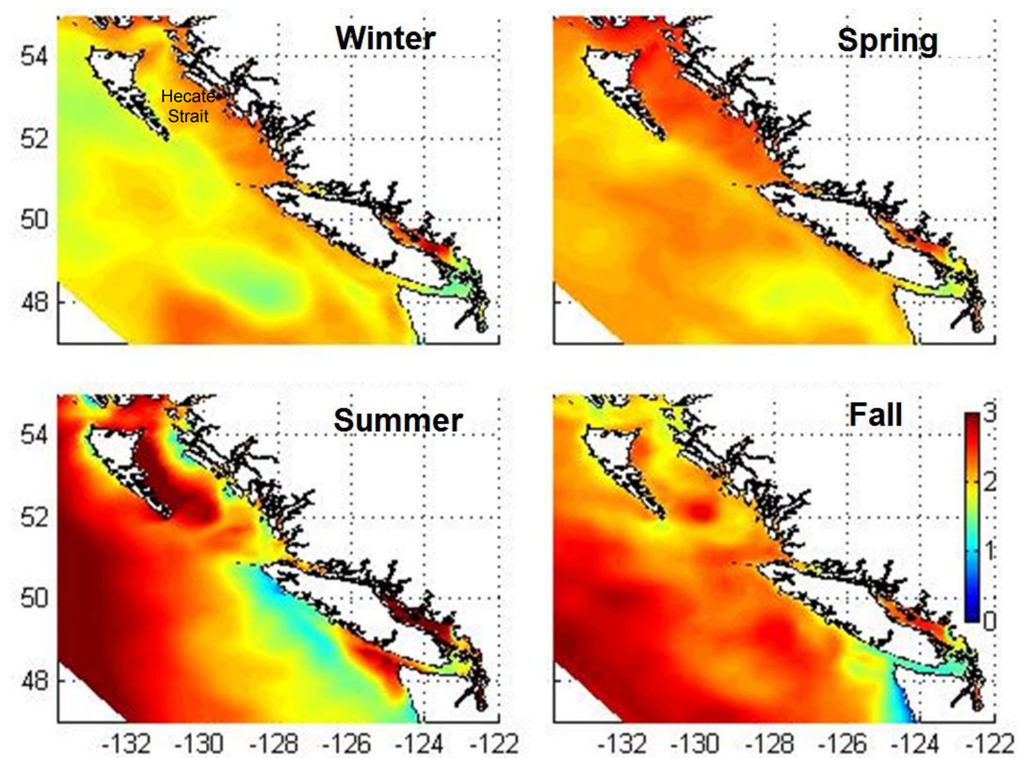

Fig. 13.4 Seasonal average SST (°C) anomalies (2041–2070 minus 1981–2010).

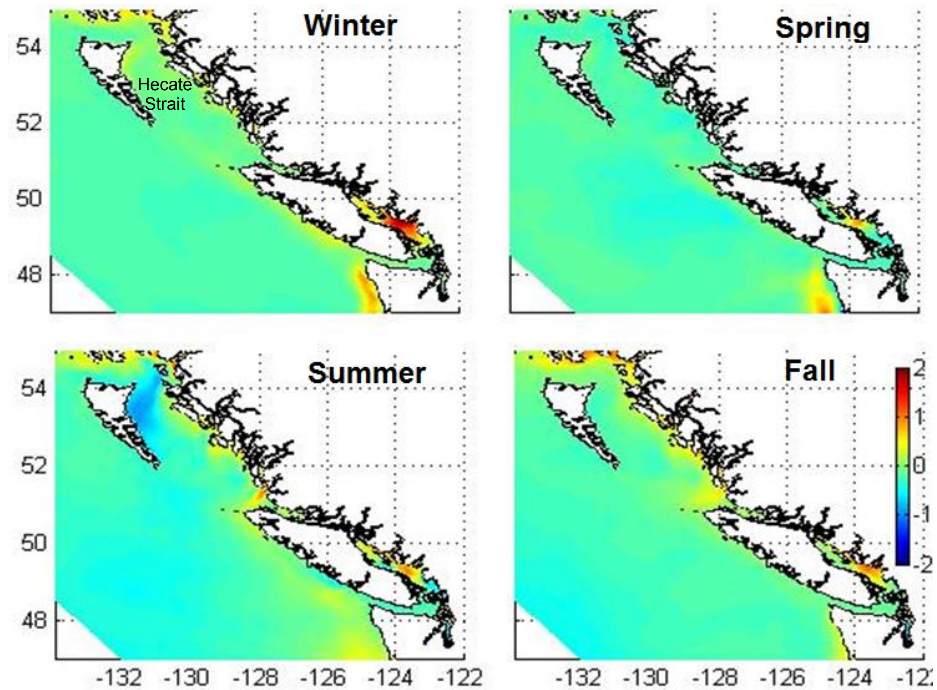

Fig. 13.5 Seasonal average SSS anomalies (2041–2070 minus 1981–2010).

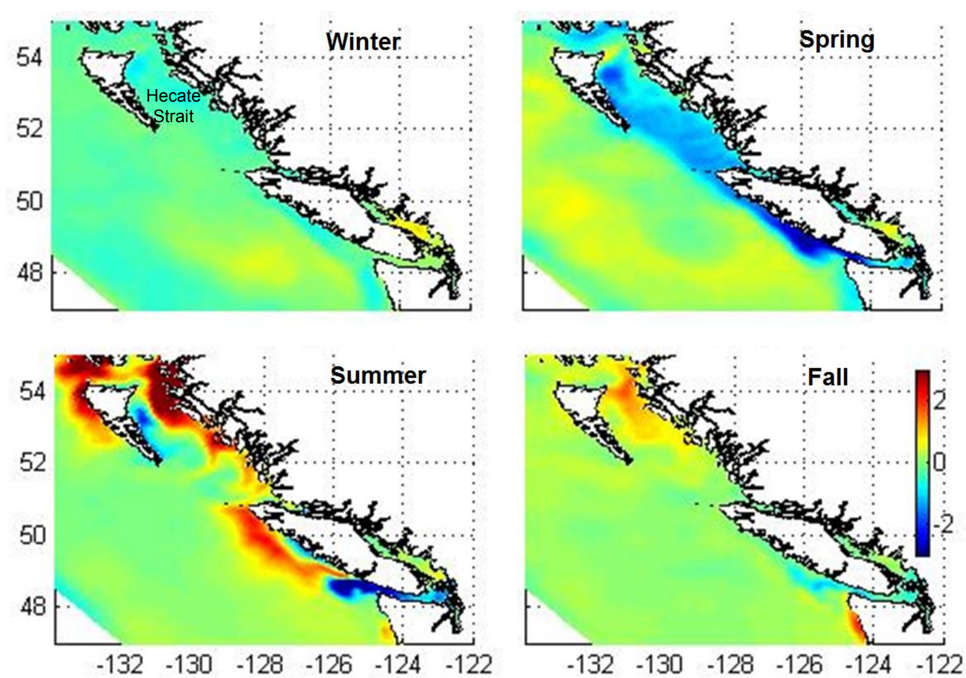

Fig. 13.6 Seasonally average surface chlorophyll concentration (mg m^{-3}) anomalies (2041–2070 minus 1981–2010).

Figure 13.7 shows contemporary and future summer average salinity and nitrate concentration along a transect crossing the shelf off Vancouver Island (see Figure 13.1 for location). Contemporary and future salinity and nitrate show an uplift of contours near the shelf break and an increase in values with depth. The anomaly panels show an increase in salinity and nitrate concentration over the shelf-break, indicating stronger upwelling. Previous studies have proposed that increasing greenhouse gas concentrations would force intensification of upwelling-favourable winds in eastern boundary current systems (Bakun, 1990). Our preliminary analysis supports this hypothesis. Changes in upwelling conditions would influence biological productivity in the area, as well as ocean acidification and deoxygenation.

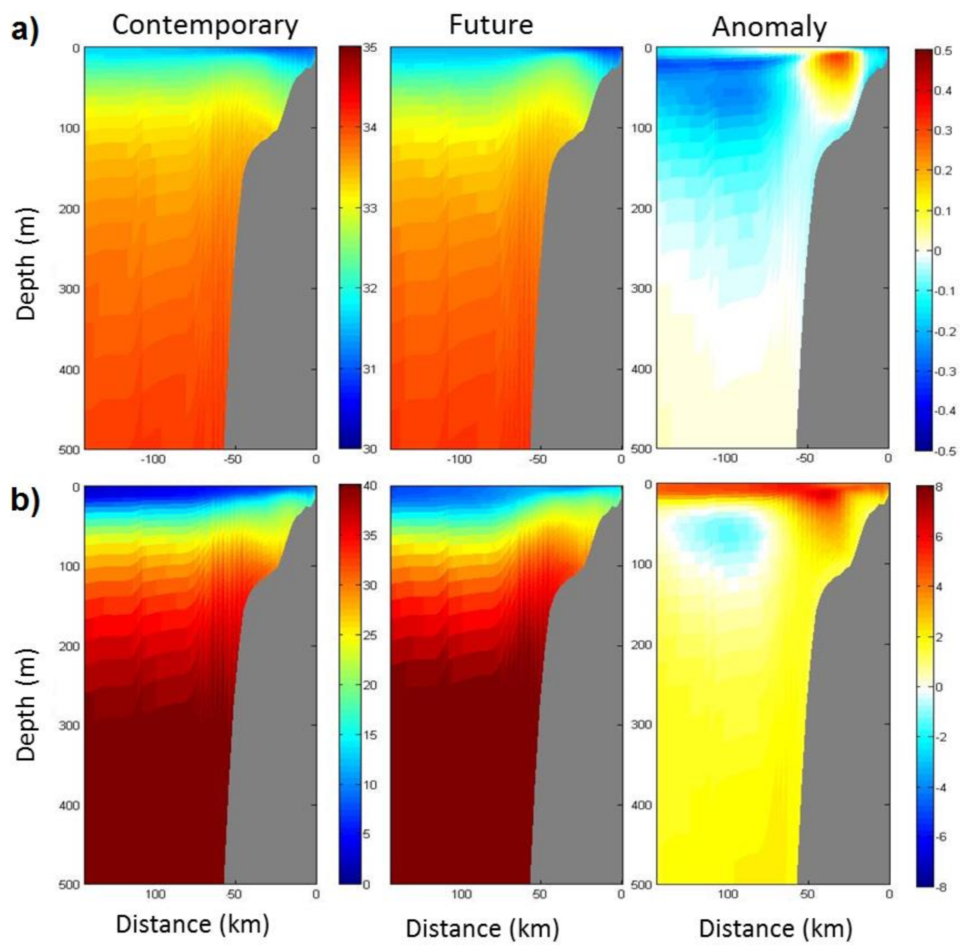

Fig. 13.7 Vertical sections of contemporary (1981–2010), future (2041–2070) and anomaly (future minus present) in summer-averaged (a) salinity and (b) nitrate concentration (mg m^{-3}) in the upper 500 m along a transect off the mid-Vancouver Island shelf (see Figure 13.1).

Summary and future work

A regional coupled physical–biogeochemical model of the BC coastal ocean was developed to predict possible future climate conditions, using dynamic downscaling from RCMs and/or GCMs output. After describing the model, we presented results from a simulation of future ocean conditions along the BC coast under the RCP8.5 global warming scenario that resulted from forcing and initializing with the Canadian

Regional Climate Model (CanRCM4) forced by the Canadian Earth System Model (CanESM2). Future forcing fields were generated by adding monthly average differences between future (2041–2070) and contemporary (1981–2010) scenarios derived from CanRCM4/CanESM2 to the contemporary hindcast (1981–2010) forcing fields. Initial analysis of model results shows that averaged seasonal SST is projected to increase by 0.8 to 3°C whereas averaged seasonal SSS anomalies vary from –1 to 1. These changes are stronger during the summer. Seasonal sea surface chlorophyll concentration is projected to decrease in spring but to increase during the summer by ~2.5 (mg m^{-3}). Future salinity and nitrate concentration along a transect crossing the shelf off Vancouver Island show an enhanced uplift of contours, suggesting an increase in upwelling over the shelf break of Vancouver Island. More analyses are underway and their results will be summarized in a manuscript that will be submitted to a peer-reviewed journal.

Next, we will extend our analysis by carrying out multiple simulations of future changes in biogeochemistry using downscaling of forcing fields from several other RCM/GCM models. The outputs from these models will be compared and analyzed to determine consistent future trends. Our imperfect knowledge and model description of biogeochemical processes represent a critical source of uncertainty when performing climate projections. Thus, ensembles of simulations are needed to characterize uncertainties with more confidence.

Acknowledgements

We thank the Aquatic Climate Change Adaptation Services Program (ACCASP) and the Centre for Ocean Model Development and Application (COMDA) within Fisheries and Oceans Canada for supporting the development of the biogeochemical BC coastal model. We also thank Mike Foreman for useful discussions and John Morrison for assistance in preparing atmospheric forcing fields.

References

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. *Science* **247**: 198–201.

Bianucci, L., Denman, K.L. and Ianson, D. 2011. Low oxygen and high inorganic carbon on the Vancouver Island Shelf. *J.Geophys. Res*. **116**: C07011, doi:10.1029/2010JC006720.

Crawford, W.R. and Peña, M.A. 2013. Declining oxygen on the British Columbia continental shelf. *Atmos.–Ocean* **51**: 88–103, DOI: 10.1080/07055900.2012.753028.

Feely, R.A., Sabine, C.L., Hernandez-Ayon, J.M., Ianson, D. and Hales, B. 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science* **320**: 1490–1492, doi:10.1126/science.1155676.

Fiechter, J., Curchitser, E.N., Edwards, C.A., Chai, F., Goebel, N.L. and Chavez, F.P. 2014. Air-sea CO_2 fluxes in the California Current: Impacts of model resolution and coastal topography. *Global Biogeochem. Cycles* **28**: 371–385, doi:10.1002/2013GB004683.

Foreman, M.G.G., Pal, B. and Merryfield, W.J. 2011. Trends in upwelling and downwelling winds along the British Columbia shelf. *J. Geophys. Res*. **116**: C10023, doi:10.1029/2011JC006995.

Foreman, M.G.G., Callendar, W., Masson, D., Morrison, J. and Fine, I. 2014. A model simulation of future oceanic conditions along the British Columbia continental shelf. Part II: Results and analyses. *Atmos.–Ocean* **52**: doi:10.1080/07055900.2013.873014.

Gruber, N., Hauri, C., Lachkar, Z., Loher, D., Frolicher, T.L. and Plattner, G.-K. 2012. Rapid progression of ocean acidification in the California Current System. *Science* **337**: 220–223.

Hara, M., Yoshikane, T., Kawase, H. and Kimura, F. 2008. Estimation of the impact of global warming on snow depth in Japan by the pseudo-global-warming method. *Hydrological Res. Lett*. **2**: 61–64.

Hauri, C., Gruber, N., Vogt, M., Doney, S.C., Feely, R.A., Lachkar, Z., Leinweber, A., McDonnell, A.M.P., Munnich, M. and Plattner, G.-K. 2013. Spatiotemporal variability and long-term trends of ocean acidification in the California Current System. *Biogeosciences* **10**: 193–216.

Lee, K., Tong, L.T., Millero, F.J., Sabine, C.L., Dickson, A.G., Goyet, C., Park, G.-H., Wanninkhof, R., Feely, R.A. and Key, R.M. 2006. Global relationships of total alkalinity with salinity and temperature in surface waters of the world's ocean. *Geophys. Res. Lett*. **33**: L19605, doi:10.1029/2006GL027207.

Masson, D. and Fine, I. 2012. Modeling seasonal to interannual ocean variability of coastal British Columbia. *J. Geophys. Res*. **117**: C10019, doi:10.1029/2012JC008151.

Morrison, J., Foreman, M.G.G. and Masson, D. 2002. A method for estimating monthly freshwater discharge affecting British Columbia coastal waters. *Atmos.–Ocean* **50**: doi:10.1080/07055900.2011.637667.

Najjar, R.G. and Orr, J.C. 1999. Biotic-HOWTO. Internal OCMIP Report, LSCE/CEA Saclay, Gif-sur-Yvette, France, 15 pp.

Peña, M.A., Masson, D. and Callendar, W. 2016. Annual plankton dynamics in a coupled physical–biological model of the Strait of Georgia, British Columbia. *Prog. Oceanogr*. **146**: 58–74.

Takahashi, T., Sutherland, S.C., Chipman, D.W., Goddard, J.G., Newberger, T. and Sweeney, C. 2014. Climatological Distributions of pH, pCO_2, Total CO_2, Alkalinity, and $CaCO_3$ Saturation in the Global Surface Ocean. ORNL/CDIAC-160, NDP-094. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. doi: 10.3334/CDIAC/OTG.NDP094.

Taylor, K., Stouffer, R. and Meehl, G. 2012. An overview of CMIP5 and the experiment design. *Bull. Amer. Meteorol. Soc*. **93**: 485–498.

Thomson, R.E., Hickey, B.M. and LeBlond, P.H. 1989. The Vancouver Island Coastal Current: Fisheries barrier and conduit, pp. 265–296 *in* Effects of Ocean Variability on Recruitment and an Evaluation of Parameters used in Stock Assessment Models, Vol. 108, *edited by* R. Beamish and G. McFarlane, Special Publication of Fisheries Aquatic Sciences, Ottawa.

Wanninkhof, R. 1992. Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res*. **97**: 7373–7382.

Appendix 1

WG 29 Terms of Reference

WG 29 term: 2011–2015
Parent Committees: BIO and POC

1. Assemble a comprehensive review of existing regional climate modeling efforts;
2. Assess the requirements for regional ecosystem modeling studies (*e.g.*, how to downscale the biogeochemistry);
3. Continue the development of RCM implementations in the North Pacific and its marginal seas;
4. Convene special sessions and inter-sessional workshops dedicated to the RCM topic;
5. Publish report and/or review paper on best practices for regional coupled modeling;
6. Establish connections between PICES and climate organizations (*e.g.*, CLIVAR) and global climate modeling centers (*e.g.*, NCAR, JAMSTEC, CCCMA);
7. Collaborate with other PICES expert groups such as WG 27, S-CCME and the FUTURE Advisory Panels possibly by producing “Outlooks”;
8. Publish a final report summarizing results.

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Appendix 3

Meeting Reports and Topic Session/Workshop Summaries from Past Annual and Inter-sessional Meetings Related to WG 29

International Workshop
Development and Application of Regional Climate Models[2]
October 11–12, 2011, Seoul, Korea

Global oceans including the North Pacific and Atlantic Oceans together with their marginal seas have experienced pronounced climatic and environmental changes from the 20th century due to global warming and its associated thermodynamic consequences. Scientific understanding of these climate changes has advanced notably in recent years owing to the development of global climate models (GCMs). Current GCMs, however, have mainly been focused on simulating global climate features based on coarse horizontal and vertical grid resolutions. As a result, these models lack some key processes that occur at regional scales. Thus, it is important on the one hand to assess the performance of GCM products and to identify uncertainties for those regional key processes by comparing the model results with long-term observations. On the other hand, the development of regional climate models has become more and more important to fill the gap between the GCMs and the growing demand of climate predictions and scenarios on highly-resolved spatio-temporal scales, since the GCMs are usually not successful in doing such a job.

Regional ecosystem study based on numerical modeling is an emerging field. An international workshop on *Development and Application of Regional Climate Models* was held at the Mayfield Hotel, Seoul, Korea on October 11–12, 2011. This two-day workshop aimed to provide a platform to discuss various aspects of regional coupled or ocean climate modeling such as different approaches, downscaling, parameterizations, and coupling to the GCMs. It also encompassed the coupling of regional climate models (RCMs) to ecosystem models. The workshop was co-sponsored by PICES, ICES, Research Institute of Oceanography/Seoul National University, and Ministry of Land, Transport and Maritime Affairs, Korea. Workshop conveners were Kyung-Il Chang (Korea, POC/PICES), Michael Foreman (Canada, POC/PICES), Chan Joo Jang (Korea, POC/PICES), Myron Peck (Germany, ICES), and Angelica Peña (Canada, BIO/PICES). About 65 marine scientists and postgraduate students from 8 countries (Canada, China, Germany, Japan, Korea, Norway, U.K., U.S.A.) participated in the workshop. Eighteen oral presentations including those from 12 invited speakers, and 10 posters were presented. The workshop consisted of four scientific sessions: Global and RegionalCoupled Models, Regional Ocean Projections, Analysis of Climate Models, and Ecosystem Modeling. The following provides the highlights of each of the oral presentations followed by a summary of the discussion section. A number of general recommendations emerged from this workshop and are listed in the final section.

SESSION 1
Global and Regional Coupled Models

Hiroyasu Hasumi – *Development of a coupled climate model with a two-way nested ocean component*

- Eddy resolution is needed to generate a realistic path and separation point of the Kuroshio Extension (KE);
- Nested ocean grids are effective to simulate critical current areas (only have 2 to 3 times increased cost as opposed to increasing total model resolution);
- Increased temperature suppressed meandering of KE;
- Non-nested variance estimates were over-estimated (41% *versus* 21.5%).

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[2] See PICES Press article on a second Regional Climate Modeling Workshop, page 174.

Hyun-Suk Kang – *Global and regional climate projections based on the RCP emission scenarios for IPCC AR5*

- Only 3 figures in all of IPCC AR4 were based upon RCM or downscaled products;
- Precipitation as well as evaporation need to be considered (soil moisture has decreased);
- Intense warming in the East Sea (critical to project changes in runoff and stratification);
- Lack of good boundary conditions is a problem.

Tianjun Zhou – *Air-sea interaction and Northwestern summer monsoon variability: Comparison of AGCM & regional ocean-atmosphere coupled model simulations*

- 2 regional atmospheric and 2 ocean models (POM, LICOM);
- Warm and cold bias within the same model (POM);
- When threshold value (RH70) was used to suppress convection, agreement was much better;
- Coupling atmospheric and oceanic models improved Pacific rainfall and wind field (anti-cyclonic circulation);
- This is likely a region-specific correction. Does one need far-field coupling?

Hyodae Seo – *Regional coupled downscaling: mesoscale air-sea interaction and regional climate change*

- In the equatorial Atlantic, large tropical instability waves (TIWs) influence SST (*e.g.*, latitudinal troughs associated with 2.5°C SST differences);
- Eddy advection is important to the heat flux;
- Enhanced current shears = stronger dynamic instability and TIWs (30% increase in eddy kinetic energy). Intensified eddy temperature advection;
- GCMs might capture heat budget but lack critical processes (get the right result for the wrong reason);
- Upwelling requires a coupled ocean-atmosphere system to resolve dynamics;
- There are pros and cons of downscaling GCMs that contain mean bias errors.

SESSION II

Regional Ocean Projections

Bjorn Adlandsvik – *Dynamical downscaling of future climate in the Barents and North Seas*

- GCMs lack resolution needed for shelf seas (coastline, bathymetry, exchange of deep-water, river run-off, eddies, frontal zones and mixing);
- Sea ice is an important problem for GCMs and reason for downscaling;
- Objective is to get "sufficient realism";
- Downscaling = added value (*e.g.*, sea ice cover, hydrographic structure of the water column, and current dynamics such as inflow into North Sea were all better represented).

Cheo-Ho Kim – *Comparison of the sea surface height distribution in the different grid resolution circulation models*

- Realistic sea surface height needed to examine the potential effect of global warming on sea level rise;
- Compared GCM 1° × 1°, 110 yrs; GCM 0.5° × 0.5°, 30 years; NP_0.5 (0.5° × 0.5°) 100 yrs;
- Different temporal evolution of SSH among high and low resolutions;
- Realistic air-sea boundary layer is critical to apply for the convergence / divergence of water mass through the lateral boundary for the realistic simulation of SSH in the RCM;
- Question was posed: Is it always better to use higher-resolution models?

Dong-Hoon Kim – *Steric and non-steric effect on sea level rise projections of the Northwestern Pacific Ocean*

- Previous simulations showed that CO_2 doubling increased SST by 1.5°C leading to a 10 cm increase in SSH from the steric effect;
- Compared MIROC3.2H *vs* HADCM3, and 2 scenarios;
- A1B gets 3°C and 35 cm SSH increase *vs* 2°C and 25 cm in series B1;
- The two model systems predicted differences of about 1°C and 10 cm SSH;
- Spatial estimates differ for CM2.1 *versus* ReMOM (due to differences in water circulation patterns);
- Steric effect projected to be driver in some areas while non-steric effect predicted to be more important in other areas.

Mike Foreman – *A regional climate model for the British Columbia continental shelf*

- Coarse resolution of the GCM cannot represent the spatial structure of temperature in this (and other) coastal region(s);
- Seasonality in river discharge water is critical and model-dependent feature;
- GCMs predict area to be fresher and warmer in the future, but magnitude displays spatio-temporal variability;
- Forcing with anomalies because projections are not trusted;
- Upwelling is coming later than before but it is stronger when it occurs. Also, downwelling is stronger. Both timing and magnitudes are critical for production cycles.

Enrique Curchitser – *Up- and down-scaling effects of upwelling in the California Current System*

- Upwelling areas are poorly described in GCMs;
- There are local and remote climate effects of eastern boundary upwelling system;
- If models are not run long enough, results may reflect only internal variance in the model results which are falsely interpreted as climate signals;
- Avoid making projections that ignore feedbacks between regional and larger-scale models because each one is evolving different mean climates;
- Coupled system has local, regional, and global scale consequences.

Yang-Ki Cho – *Development of a regional ocean climate model for Northwest Pacific marginal seas*

- Simulation with ROMS (10 km grid, 20-z layers, daily wind forcing, and discharge of major rivers);
- Mean SST and STD compared well with observations of SST from satellites and *in situ* measurements;
- The 100-year trends of SST in the East Sea from the regional model are similar (greater warming in north than in south) to those from a GCM, but the regional models have a weaker trend, particularly in northern areas of model domain.

SESSION III

Analysis of Climate Models

Inkweon Bang – *Climate change in the Northwestern Pacific seen in CSEOF analysis of SRES A1B simulations of AR4 models*

- Simulations compared (2011–2100), 12 atmospheric variables, and 5 oceanic variables examined using cyclostationary EOF (mode detection);
- Analysis allows you to decompose the variance components and understand the processes of warming / climate signal coming from the model both spatially and temporally;

- Oceanic variables including dynamic height and cyclonic and anti-cyclonic circulation cells associated with KE – strong westward flow (strengthening of extension), no change in the position.

Chan Joo Jang – *Evaluation of regional ocean simulation from CMIP3 models: a case for the North Pacific Ocean mixed layer depth*

- Mixed layer depth (MLD) is expected to change with climate warming;
- Decrease MLD in the KE is mainly due to decreased wind stress during the wintertime. Increased MLD in the Oyashio is created by a northward shift of KE;
- South of KE, MLD (ensemble average) is 120 m too deep while it is ~ 40 m too shallow to the north;
- Taylor diagram indicates that phenology is OK, but the amplitude of seasonal changes is too small;
- Resolution (Kuroshio too wide and too weak) – surface wind stress bias – western winds are too strong (estimates of MLD may improve when using higher resolution models).

SESSION IV
Ecosystem Modeling

Myron Peck – *New ICES PICE working group on integrative physical-biological and ecosystem modelling*

- There is a movement towards establishing a working group to develop end-to-end models and apply biophysical models to practical management applications;
- Topics to be addressed might include dynamic model coupling – feedbacks, effects of biology on physics, micro-, meso- to basin-scale issues;
- Opportunity also exists to establish an ICES-PICES working group on Regional Climate Modelling and dynamic downscaling (likely via strategic initiative on climate change);
- Current issues / challenges facing individual-based models for marine fish early life stages (illustrative of challenges facing many different models).

Icarus Allen – *Regionally downscaled climate modeling: physics to fisheries*

- ERSEM coupled model is a good example;
- Variety of issues facing models of productivity of key ecosystem players;
- Important feedback exists between physical and biological aspects and climate which are not well represented in many models;
- Sources of model uncertainty change with time, particularly when scenarios are being used;
- Devise skill assessment by removing physics from the system (*e.g.*, using empirical relationships between chlorophyll and size-class).

Angelica Peña – *Development of a regional plankton ecosystem model for the Pacific coast of Canada*

- Complex dynamics between physical, chemical and biological processes;
- Accurate hydrography is essential to capture features of primary and secondary production;
- Response of ecosystem depends upon the physical forcing utilized. (*e.g.*, very sensitive to differences in freshwater input, winds, tides and mixing scheme);
- Major (biological) issue is the ability to understand adaptive capacity of ecosystems that will require reliable estimates of physical processes that, over time, may gradually change.

Corinna Schrum – *Climate change downscaling to marine ecosystems, lessons learned from exercises with AR4 and AR5 GCM scenarios*

- North Sea and Baltic Sea have very different physical processes (*e.g.*, exchange times of 0.3 *versus* 30 yrs);
- Wind field and shortwave radiation have largest effects on primary production estimates;
- Re-analysis data and climate models have large differences in the wind speeds (nearly a factor of 2). All climate models tested predicted region to be significantly wetter;
- The ability to change the variability in forcing is also a topic that needs to be addressed (weakness, you lack the dynamic consistency);
- Nutrient dynamics very important to consider (only included in the earth system models).

SESSION V
Wrap-up and Recommendations

Current Challenges Facing Regional Climate Modelling

Spatio-temporal differences in the sensitivity of different areas to climate warming exist and current GCM estimates are too coarse in coastal/shelf sea regions and too poor at high latitudes to provide robust estimates of future climate. For these, and other reasons, downscaling of GCMs using RCMs will be necessary. There was a general consensus that, although developing regional coupled (atmosphere–ocean) model systems is very time-consuming, in many cases this will be required for proper treatment of climate system dynamics. This is particularly clear in near-coastal areas such as upwelling zones where most of ocean/fish productivity occurs.

Despite the ongoing development of GCMs with higher resolution, regional downscaling will be required. Benefits include:

i) A reduction of GCM biases,
ii) The usefulness of downscaled products for ecosystem applications, and
iii) An ability to provide more highly resolved estimates needed for regional impact studies.

One opinion was expressed that regional downscaling cannot be avoided because, regardless of GCM spatial resolution, increasing computer power will be taken as an opportunity for increasing the resolution of existing regional models.

Assessing impacts on marine systems will require an amalgamation of both climate and anthropogenic drivers. Thus, scenario definition is critical. Some differences exist between AR4 and AR5 GHG emission scenarios. The choice of scenarios will depend upon the targets of the research – and targets may be unique to the audience with which one is working (*e.g.*, the worst case scenario needed for risk assessments). Moreover, one may not need to use a range of scenarios but to merely prescribe different boundary conditions (*e.g.*, different greenhouse gas concentrations).

Resolving the issues with physical (climate) models and choosing the correct scenarios to run is only part of the challenge facing environmental scientists charged with projecting climate effects on living marine resources and ecosystems. Bottom-up factors do not always control the system. In some cases, anthropogenic pressures such as fishing can be more important than bottom-up factors and must be incorporated alongside regionally downscaled climate estimates into biological models. There is a general need to separate "physics" and "biology" within coupled biophysical models to gain a better representation of key biological processes. When biological models are viewed in isolation, much can be learned by perturbing the systems – whether motivated by climate or not. This will lead to the development of more robust biological models that can link to physical/biogeochemical models and make use of regionally downscaled products.

Issues Emphasized by Workshop Participants

1) Climate drift can occur after some time within models due to numerical artefacts. There are ways to control it with spectral nudging, *etc*. The magnitude of the problem may vary for different models.
2) There should be a unified treatment of the dynamics between RCM and GCMs and the metrics needed for evaluating uncertainties in both modelling approaches. Uncertainty can be decomposed into different classes (internal variability, parameter uncertainty, scenario variability), all of which should be quantified (see Hawkins and Sutton, 2009, *BAMS*, 90(8), pp. 1095–1107).
3) RCMs and GCMs should be analyzed for inherent differences in their parameterizations to test for potential mismatches prior to downscaling.
4) Two-way interactions allowing feedback between an RCM and GCM are needed (a uni-directional coupling from GCM to RCM is normal but not sufficient). Examples are up-welling and the potential impacts of clouds on GCM radiative forcing.
5) Land–ocean coupling is needed (freshwater discharge, nutrient and carbon fluxes). This is a large topic that was not sufficiently addressed in the talks.
6) For downscaling from GCMs with known biases in their projections, utilizing anomalies to present-day simulations was thought to be a better approach. One pitfall discussed is that you are not capturing the variability by utilizing anomalies.
7) The ensemble approach is powerful – this can also include the choice of scenarios. How can this be addressed properly (particularly with regard to wind)?
8) Testing whether projected changes in the ocean are due to "real" climate effects or are these merely due to internal dynamics of the model may require that models be run for a very long periods of time (150 + years).

Future Prospects for Collaboration

A Strategic Initiative on Climate Change Effects on Marine Ecosystems is proposed for PICES and ICES. A group that focuses on regional downscaling could be formed under this umbrella. Care should be taken not to overlap with activities of other groups. A report was just submitted from PICES' Working Group on *Evaluations of Climate Change Projections* (WG 20) focusing on historical simulations and skill assessment of RCMs. A second ToR of WG 20 was the development of RCMs. There was support to create a new "parent group" for this type of activity. Both ICES and PICES are focusing on climate projections in marine ecosystems and RCMs will be needed for this. Prof. Chang can bring this forward to the PICES Science Board and Myron Peck will talk with the ICES SCICOM. Regional climate modelers are also encouraged to attend the new ICES Working Group on Integrative Physical-biological and Ecosystem Modelling (WGIPEM), particularly for discussions with End-to-End models dealing with future climate.

A question was posed as to whether this group would like to collaborate with CORDEX (Coordinated Regional Downscaling Experiment) – a world-wide effort to produce regionally downscaled atmospheric models. There is no ocean component in that effort (only the atmospheric component). Although there is a strong case for the need for an active ocean underneath the atmosphere, the CORDEX community may not be the easiest route towards creating such coupled models. There is a large community of meteorologists that would be willing to collaborate that may not be part of this established community. A second group that could be interested in these activities is CLIVAR. Its work is focused on global ocean models. However, they may be leveraged to fund some of the regional workshops.

After the Workshop

The PICES 2011 Annual Meeting followed the RCM Workshop, beginning on October 14 in Khabarovsk, Russia. During the Annual Meeting, Drs. Enrique Curchitser and Michael Foreman, participants of the Workshop, prepared a proposal for a new working group on regional downscaling and Dr. Curchitser presented the proposal at the POC Meeting. A possible linkage with the new ICES working group (WGIPEM) was considered but since the theme of the WGIPEM is end-to-end modeling, not regional downscaling of physical environments and low-trophic level ecosystems, it was decided not to pursue formal linkage. The POC Committee proposed the group to Science Board and Governing Council as the Working Group on *Regional Climate Modeling* (WG 29).

Important issues included in the ToRs of WG 29 are:

i) Assembling a comprehensive review of existing regional climate modeling efforts;
ii) Assessing the requirements for regional ecosystem modeling studies (*e.g.*, how to downscale the biogeochemistry);
iii) Continuing the development of RCM implementations in the North Pacific and its marginal seas;
iv) Collaborating with other PICES expert groups such as the Working Group on *North Pacific Climate Variability and Change* (WG 27), the Section on *Climate Change Effects on Marine Ecosystems* (S-CCME), and the FUTURE Advisory Panels possibly by producing “Outlooks”, and also establishing connections between PICES and climate organizations (*e.g.*, CLIVAR) and global climate modeling centers (*e.g.*, NCAR, JAMSTEC, CCCMA). Within ICES, S-CCME is known as SICCME, the Strategic Initiative on Climate Change Effects on Marine Ecosystems.

PICES Twenty-first Annual Meeting (PICES-2012)
October 12–21, 2012, Hiroshima, Japan

Working Group 29 on *Regional Climate Modeling*

The first business meeting of Working Group (WG 29) on *Regional Climate Modeling* (RCM) was held in Hiroshima, Japan on October 13, 2012 during the PICES Annual Meeting. With 16 members and observers in attendance (*WG 29 Endnote 1*), the agenda (*WG 29 Endnote 2*) included an introduction to the objectives of WG 29 by Co-Chairman, Dr. Enrique Curchitser. Co-Chairman, Dr. Chan Joo Jang, gave a brief overview of national activities in RCM. After short presentations by Working Group members, discussion moved to emerging issues in RCMs, plans and schedule of future activity.

AGENDA ITEM 2
Overview of national RCM activities

Dr. Curchitser described the motivation for WG 29, including its terms of reference (TOR; *WG 29 Endnote 3*), future schedule and plans. Dr. Jang gave a short presentation showing each PICES member country's RCM information (model domain, grid size, *etc.*) based on responses to a questionnaire distributed to WG 29 members prior to the Hiroshima meeting.

AGENDA ITEM 3
Presentations on topics relevant to terms of reference

As the main agenda item of the meeting, participating members described their research activities that are relevant to the TOR.

Michael Foreman: *An update on the IOS Regional Climate Model for the British Columbia (BC) continental shelf*

Dr. Foreman described the development and preliminary results of an RCM (ocean only) for the BC continental shelf. Future forcing and initial field anomalies were computed from the NARCCAP CRCM/CGCM fields. Runs were done with combinations of future and contemporary forcings to understand the nature of changes. Future plans include the following:

- To develop projections using other NARCCAP AR4 RCM combinations and AR5 RCM anomalies;
- To update an NPZD-type ecosystem model to include cycling of several biogeochemical elements (N, C, $Si(OH)_4$ and O_2), two types of phytoplankton and of zooplankton, multiple limiting nutrients, dynamic chlorophyll compartments, and temperature dependence of physiological rates;
- To couple the NPZD and marine geochemical ecosystem model (Angelica Peña);
- Boundary conditions for ecosystem projections will be based on nutrients only (not plankton).

Kyung-Il Chang: *Ocean climate change: Analyses, projection, adaptation*

Prof. Chang described RCM activities focusing on future projection for seas around Korea. Better surface boundary conditions are essential for RCM projections: present climate + climate change mode. The plan is to extract climate change modes from global simulations and use these to force RCM models. Cyclostationary EOF analysis was used to identify the modes. Projections will be made for marginal seas for 2100 based on A1B and RCP4.5. The projected SST changes in marginal seas around Korea show more warming in the northern region.

Andrei Krovnin: *Introductory presentation of the INM Ocean Model (INMOM)*

Dr. Krovnin provided a short description of INMOM and numerical simulation results for the Japan/East Sea and North Pacific Ocean. INMOM uses a sigma-coordinate system with primitive governing equations. Numerical simulations of the Japan/East Sea and North Pacific Ocean circulations are performed by using INMOM and real atmospheric forcing CORE and ERA-Interim databases. The JES version had a resolution of 1/20 deg. with 40 levels. The simulation suggested that the decadal variability is likely caused by the variability of the Siberian High, whereas interannual variability is determined by the geographical features of the Japan Basin. Decadal-scale variation of total Russian salmon catches (Kotenev *et al.*, 2010) was introduced.

Hiroyuki Tsujino: *Regional ocean-climate modeling effort in JMA-MRI*

Dr. Tsujino reported on nested regional ocean-climate models in use at JMA-MRI:
- Global–Western North Pacific (WNP) model,
- Global–WNP - near Japan (JPN) model,
- Global atmosphere–Global Ocean–WNP model,
- Global–Western North Pacific (WNP) model.

<u>Purpose</u>: long-term variability, carbon cycle and bio-geochemical processes of the western North Pacific Ocean
Global model: global tri-pole model developed for CMIP5,
Western North Pacific regional model: embedded within the global model, two-way transfer,
Global-WNP-near Japan model,
Focus: sub-mesoscale processes around the oceanic front,
1/33° × 1/50° (2 ~ 3 km horizontal resolution), integration with and without tide,
Global atmosphere –Global Ocean–WNP model,
Oceanic Global–WNP model is coupled with a global AGCM as a possible next generation climate model of JMA-MRI,
WNP model improvement: Change southern boundary of the Subtropical gyre (12°N) – put the southern BC at 10°N.

Hiroshi Kuroda: *Regional ocean modeling around Japan based on an operational ocean forecast system of the Fisheries Research Agency (FRA-ROMS)*

FRA has developed a climate modeling and downscaling subsystem around Japan (FRA-ROMS). It is used as an operational ocean forecast system with a 2 month horizon, updated weekly. The ROMS-3D VAR system is a basin-scale model with ½° horizontal resolution and nesting at one tenth of a degree. Higher resolution (1/50 deg. Horizontal) is used for a Tosa Bay, Hokkaido coastal model, while a one tenth degree horizontal resolution model coupled to a sea-ice model is used in the Okhotsk Sea.

Shin-ichi Ito: *NEMUROMS and eNEMUROMS*

The North Pacific model comes in two forms:
1) NEMUROMS: ROMS ($dx = dy$ = ½°, 48 levels) + NEMURO
2) eNEMUROMS: ROMS ($dx = dy$ = ½°, 48 levels) + eNEMURO (extended North Pacific Ecosystem Model for Understanding Regional Oceanography)

The specifications of the western North Pacific model are:
1) NEMUROMS: ROMS ($dx = dy$ = 1/10 deg., 48 levels) + NEMURO
2) eNEMUROMS: ROMS ($dx = dy$ = 1/10 deg., 48 levels) + eNEMURO

Model parameters were optimized by PEST (adjoint method software) with a box mode and observational data. Estimating the model parameters from observational data improved the simulation results. Iron is not included. A high-resolution (1/160° × 1/240° × 25 levels) version of the model was used to investigate a recent problem of megadeaths of scallops in the Mutsu Bay.

Olga Trusenkova: *Regional patterns of interannual sea level variability: Case of the Japan/East Sea*

Dr. Trusenkova described how variation in sea level trends around the basin are forced substantially by the throughflow. Eddy Kinetic Energy (EKE) indicates that mesoscale variability is caused by instability of mean currents and their interactions with bathymetry. EKE is highest from October to November and lowest in March to April, which is the same as the seasonal variation of the circulation strength. Shear instability is important. There were no interannual counterparts of the EKE Instability Mode or SLA Gradient Mode stability of the meridional density gradient despite the large variability of the transport in the Korea Strait. The main remaining questions to be answered are: Will regional climate models reproduce this variability? What should be the change in transport in the Korea Strait for destabilizing meridional density gradient and substantially changing circulation patterns and mesoscale energetics? What are mechanisms behind the relationship with PDO? Will the east–west seesaw be maintained on the 5 year or longer time scales?

Chan Joo Jang: *A regional ocean–atmosphere coupled climate model has been developing for hindcast and future projection in the seas around Korea*

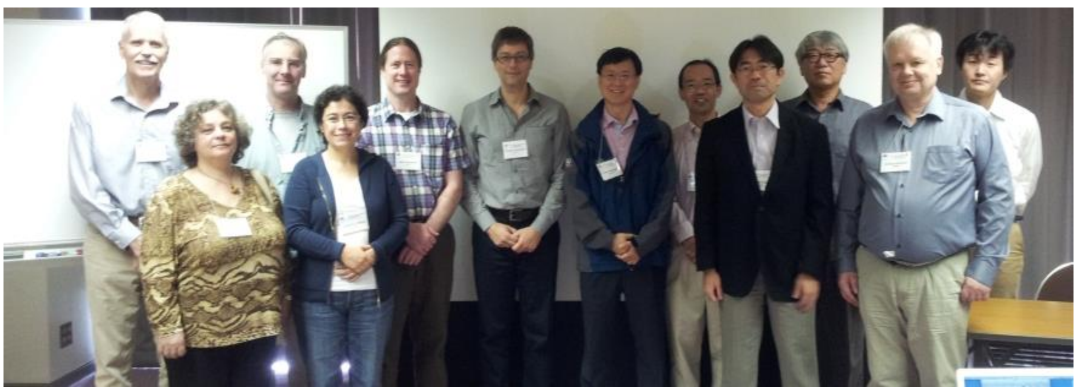
Dr. Jang reported that mixed layer changes from the fifteen CMIP5 models were analyzed and the preliminary results were given. Projected changes in the mixed layer depth (MLD) in the North Pacific Ocean have similar patterns with those of CMIP3, with considerable model-to-model difference in terms of magnitude of change. An overall decrease in MLD in the Kuroshio Extension region and an increase in the Oyashio region. The relationship between the PDO and ENSO is projected to intensify in the future, possibly due to enhanced atmospheric teleconnection between equator and the mid-latitudes.

AGENDA ITEM 4
Discussion of emerging issues and schedule of upcoming activities

After the presentations, the Working Group discussed some emerging issues related with RCM development and its application to climate change studies. These included:
1. Placement and implementation of boundary conditions.
2. Downscaling of biogeochem: Worry about nutrients and less about plankton.
3. Force regional models with ensemble mean, or individual members?
4. Sea level variability issues in regional models.

5. How to estimate uncertainty in regional models.
6. How to choose which model to use for boundary conditions.
7. One- *vs* two-way boundary conditions.
8. Different ways to force model.
9. Overlay future anomalies on hindcast products *vs* "pure" products.
10. Use (cyclo-stationary) EOF analysis to extract climate modes from global model and use that to force models.
11. Mean *vs* variability: accounting for changes in variability in projections.
12. Which climate mechanisms to look for in regional models.
13. What variables (from CMIP5 models) should we provide to the rest of PICES community: T, S, MLD?
14. Where/who will analyze CMIP5 data?
15. What additional information do we need for each member's RCM activity?

WG 29 reviewed the TORs and assigned leadership roles to each (*WG 29 Endnote 4*) before developing a plan of action for the upcoming year (*WG 29 Endnote 5*). The Co-Chairs adjourned the meeting and thanked all participants for their presentations, discussion, and commitment to conducting research directed at specific TORs.



Participants of the first meeting of WG 29 at PICES-2012. Left to right: Michael Foreman, Olga Trusenkova, Jim Christian, Angelica Peña, Seth Danielson, Enrique Curchitser, Chan Joo Jang, Shin-ichi Ito, Hiroyuki Tsujino, Kyung-Il Chang, Andrei Krovnin, and Hiroshi Kuroda

WG 29 Endnote 1

WG 29 participation list

Members

Kyung-Il Chang (Korea)
James Christian (Canada)
Enrique Curchitser (USA, Co-Chairman)
Michael Foreman (Canada)
Shin-Ichi Ito (Japan)
Chan Joo Jang (Korea, Co-Chairman)
Andrey S. Krovnin (Russia)
Hiroshi Kuroda (Japan)
Angelica Peña (Canada)
Olga Trusenkova (Russia)
Hiroyuki Tsujino (Japan)

Observers

Rongshuo Cai (China)
Seth Danielson (USA)
Skip McKinnell (PICES)
Sun Peng (China)
Elena Ustinova (Russia)

WG 29 Endnote 2

WG 29 meeting agenda

1. Welcome and self-introductions
2. Introduction to WG 29 (Curchitser) and national RCM overview (Jang)
3. Brief presentations for research topics relevant to TORs from each member
4. Discussion for some emerging issues, specific plans and schedule

WG 29 Endnote 3

WG 29 Terms of Reference

1. Assemble a comprehensive review of existing regional climate modeling efforts;
2. Assess the requirements for regional ecosystem modeling studies (*e.g.*, how to downscale the biogeochemistry);
3. Continue the development of RCM implementations in the North Pacific and its marginal seas;
4. Convene special sessions and inter-sessional workshops dedicated to the RCM topic;
5. Publish report and/or review paper on best practices for regional coupled modeling;
6. Establish connections between PICES and climate organizations (*e.g.*, CLIVAR) and global climate modeling centers (*e.g.*, NCAR, JAMSTEC, CCCMA);
7. Collaborate with other PICES expert groups such as WG 27, S-CCME and the FUTURE Advisory Panels possibly by producing “Outlooks”.
8. Publish a final report summarizing results.

WG 29 Endnote 4

Terms of reference: Members' involvement

1. Collect and summarize the current status of each member country's regional climate modeling efforts. (Contributing members: Jang, Curchitser)
2. Exchange information of each member country's RCM development and related research activities, and discuss some immerging issues related with RCM development and its climate application (Contributing members: all members)
3. Discuss what variables from CMIP5 models need to be available to other PICES experts group (Contributing members: Curchitser, Jang, Foreman, and other members)
4. Collect and analyze CMIP5 data focusing on North Pacific Ocean. (Contributing members: Christian, Jang)
5. Convene workshops for exchange and summarizing RCM activity. (Contributing members: Chang, Curchitser, Jang, Peña)

WG 29 Endnote 5

Action items for 2012–2013

TOR 1, 2 and 3: Dr. Curchitser will review three requirements for RCM studies including biogeochemistry downscaling. Dr. Jang will collect and summarize information of RCM development from each member country.

TOR 4: Drs. Curchitser and Jang will contribute to a Topic Session at PICES-2013 on "*Recent trends and future projections of North Pacific climate and ecosystem*" (see below). Dr. Chang will organize the 2nd RCM workshop in September 2013, and the Co-Chairmen will also serve as Co-convenors for the workshop.

TOR 5: Both Co-Chairmen, together with other members, will publish a review paper for RCM efforts, through activities related with TOR 1–3.

TOR 6 and 7: Many members including Drs. Curchitser, Christian, and Peña will contribute to establish connections between PICES and climate organizations, and collaborate with other PICES expert groups by providing some basic data, *e.g.* mixed layer depth) for ecosystem studies.

Proposal a 1-day Topic Session on
"*Recent trends and future projections of North Pacific climate and ecosystem*" at PICES-2013

The North Pacific Ocean experiences change on a range of timescales, and is among the most difficult regions of the world ocean in which to detect secular climate trends associated with anthropogenic forcing against the background of natural variability. Understanding impacts on ecosystems and the human communities dependent on them requires understanding of the magnitudes of climate variability and change. Sustained observations of past and present states, modeling of future states with global climate models (GCMs), and downscaling of GCM projections to the regional scale are all key components of the scientific effort to understand impacts and inform adaptation efforts. Downscaling efforts are likely to include a variety of methods, both statistical and dynamical, including high-resolution regional ocean circulation models with embedded ecosystem/biogeochemical models, statistical models relating local population statistics to climate forcing or climate indices, and multi-species models forced by temperature or oxygen anomalies from regional or global models. This session invites papers on time-series of observations of the North Pacific Ocean in the context of recent climate variability and change, and future projections of changes including statistical and dynamical downscaling.

Sponsoring Committees/Program: BIO/POC/TCODE/MONITOR/FUTURE

Convenors: James Christian (Canada), Enrique Curchitser (USA), Chan Joo Jang (Korea) and Angelica Peña (Canada), Jack Barth (USA)

PICES Twenty-second Annual Meeting (PICES-2013)
October 11–20, 2013, Nanaimo, Canada

Report of Working Group 29 on *Regional Climate Modeling*

The second business meeting of Working Group (WG 29) on *Regional Climate Modeling* (RCM) was held in Nanaimo, Canada, on October, 12, 2013 preceding the PICES Annual Meeting. With 17 members and observers in attendance (*WG 29 Endnote 1*), the meeting agenda included an introduction to WG 29 by Co-Chairmen, Drs. Enrique Curchitser and Chan Joo Jang's brief overview to each member nation Regional Climate Modeling (RCM) activity. After short presentations by the RCM Working Group members, the members discussed some emerging RCM issues, plans and schedule of future activity and preparation of the group's final report. Below are the agenda items (*WG 29 Endnote 2*) and the corresponding discussion of the meeting.

AGENDA ITEM 1
Welcome and self-introductions

1. Pre-meeting social to allow members to interact.
2. Introduction to WG 29 activities by Drs. Jang, Curchitser, and Chang.
3. Everyone introduced themselves (including new WG 29 members Drs. Panjun Du (China) and Young Ho Kim (Korea) (attendee sheet was circulated).

AGENDA ITEM 2
WG 29 activities

Dr. Curchitser reviewed WG 29's terms of reference and first meeting in Hiroshima, Japan (2012) after which the group discussed emerging issues arising from that meeting.

Regional Climate Modeling 2nd workshop

Dr. Kyung-Il Chang reported on the second Regional Climate Modeling workshop held September 10–12, 2013 in Busan, Korea. Dr. Skip McKinnell has distributed a draft article of the workshop which will be published in the PICES Press newsletter (Vol. 22, No. 1, Winter 2014). The 3-day workshop was attended by more than 40 participants and comprised 9 mesoscale and sub-mesoscale presentations on Day 1, 9 RCM presentations on Day 2, 3 climate variability presentations on Day 3, and 7 posters.
Important discussions:

- At what resolution do models converge?
- How useful are idealized models?
- How important are sub-mesoscale processes for climate?
- What can be learned from1-way nesting?
- RCM-3 could focus on physical-biological and ocean-atmosphere coupling.

WG 29 proposals for 2014 FUTURE Open Science meeting and 2014 PICES Annual Meeting

WG 29's proposal for a Topic Session on "*Regional climate modeling in the North Pacific*" to be convened by Drs. Curchitser and Jang, was accepted by the OSM SSC and will be held on Day 1 of the FUTURE Open Science Meeting (April 15–18, 2014, Kohala Coast, Hawaii). A proposal for a Topic Session (*WG 29 Endnote 3*) by the same name was submitted by Dr. Jang for PICES-2014 (October 17–26, 2014, Busan, Korea).

AGENDA ITEM 3

Updates on national RCM activities

1. ***Panjun Du (China):*** *Forecasting activities and issues in the East China Sea*

Dr. Du described the modeling activities relating to the East China Sea and the issues relating to forecasting there. In particular he described:

- Storm surge and wave forecasting carried out by six regional divisions,
- Data availability from buoy and coastal observing systems,
- Regional ocean model applications using FVCOM:
  - mariculture application; tide and sandbar forecasting,
  - Shanghai – saltwater intrusion into Yangtse River in the dry season,
  - Storm surges around Zhou Shan Island – high resolution unstructured grid,
  - Temperature rise in Xiangshan harbour (power stations),
  - Future work and improvements.

2. ***Hiroshi Kuroda (Japan):*** *regional ocean model forecasting and hindcasting around Japan*

Dr. Kuroda described the modeling activities with the FRA implementation of the ROMS model. Specifically he described:

- ½ and 1/10 degree resolution implementations for the western Pacific; some finer 1/50 degree (sub-mesoscale) for Kuroshio and Hokkaido, 3DVar and scale-selective data assimilation – spectral nudging (for spatial scales > 100 km) for large domain model,
- The various models are also being applied for fisheries science.

3. ***Shin-ichi Ito (Japan):*** *Water temperature forecasts for cultured scallops in Mutsu Bay, Japan*

Dr. Ito spoke about water temperature forecasts for cultured scallops in Mutsu Bay.

- In 2010 record high temperatures resulted in high scallop mortality,
- Anti-estuary circulation due to anomalous winds was responsible for the mortality,
- A ROMS nested model was implemented down to 1/160 and 1/240 degrees and used to identify conditions that resulted in the anti-estuarine circulation.

4. ***Chan Joo (Korea):*** *RCM development around Korea and CMIP5 analysis*

Dr. Joo discussed the following topics in his presentation:

- Large resource (personnel and computing) requirements are required,
- Coupled atmosphere–ocean model used for NW Pacific; NPZD model for EJS,
- MLD analyses: CanESM2, RCP4.5 so far but more models to come,
- Multi-bias analysis suggests no improvement with CMIP5.

5. ***Young Ho Kim (Korea):*** *climate and regional ocean reanalysis from data assimilation system of KIOST*

- Ensemble optimal interpolation is used for DA (computational demands not as high as other approaches),
- Compared with global climatology, SST in Nino3.4 region, TS cross-sections along 160° and 180°E,
- New open boundary conditions for their model, MOMp1,
- Plan to set up regional ocean forecasting system.

6. ***Jerome Fiechter (USA):*** *Role of Eastern Boundary Current regions in global carbon cycles*

Dr. Fiechter presented results from recent work with a coupled bio-physical regional model for the California Current System. His presentation focused on the model implementation and some early results from that work that included:

- California Current System: ROMS + NEMURO,
- Effect of different horizontal resolutions,
- OCMIP air–sea CO_2 exchange,
- Shelf *vs* offshore regions,
- More detailed talk on Wednesday (S4),
- Sees daily variability,
- Outgasing in upwelling zone,
- 30 km resolution bad, 10 km ok, 3 km good,
- Map of outgassing *vs* equilibrium,
- Coastal representation (capes) and bathymetry important,
- Differences in northern and southern CCS for carbon budget.

7. ***Dimitry Stepanov (Russia):*** *Numerical study of low frequency variability in JES circulation*

- Ocean model used is INMOM,
- Showed mean circulation at 500 m and 1500 m; relative vorticity.

8. ***Michael Foreman (Canada):*** *Regional ocean climate model projection for the British Columbia continental shelf*

Dr. Foreman discussed the results from two papers that were accepted in *Atmosphere-Ocean* which focus on regional projections for the British Columbia coast.

9. ***Kyung-Il Chang (Korea):*** *WG 29 FUTURE contributions*

- 4 (Julie Hall, Manuel Barange, Phillip Mundy, Hiroaki Saito) out of 6 potential members were in place for the FUTURE Evaluation Team that will meet immediately after the Open Science Meeting to evaluate FUTURE’s progress.
- FUTURE products are important, so:
  - How to link WG 29 products to other expert groups?
  - How to identify gaps in FUTURE beyond 2014?
  - In WG 29 final report, need to add summary on how we addressed FUTURE questions.
  - Can we prepare database of future projections (same scenario?):
    - ✓ Perhaps for California Current region (Curchitser), Korea (Jang and/or Chang), Japan (Ito and Kuroda), BC (Foreman)
    - ✓ Need to talk to TCODE (Shevchenko)

The 3rd International Symposium on "*Effects of climate change on the world's oceans*" will take place March 23–27, 2015, in Santos, Brazil. The deadline for symposium theme session and topic suggestions is October 2013. ICES currently has proposed over a dozen topics. Dr. Shoshiro Minobe suggested two topics on:

- impact of climate variability and change on nutrient distributions,
- validation and utilization of earth system models to RCMs.

It was also suggested that a third RCM workshop (RCM3) be held in conjunction with the symposium (jointly with ICES).

AGENDA ITEM 4
WG 29 final report

Dr. Joo presented ideas for a final WG report and along with specific section assignments, will email them to the members. Also discussed was the strategy for data archiving model results that would be available to PICES users:

- What would it entail? Could it be hosted by PICES/TCODE?
- Produce monthly average 3D T, S, velocity, contemporary and future fields? (FUTURE outlooks),
- Do we adopt a unified format and create scripts to facilitate export (would require a lot of work, who?), or do we re-direct users to portals (Japanese, Korean, *etc*.) for each set of output?
- Important parameters (MLD, nutrients) can come from CMIP5 (Chan Joo Jang, Shoshiro Minobe, Jim Christian already producing), RCM values.

AGENDA ITEM 5
WG 29 term extension

The last item proposed by the Co-Chairs and discussed by the group was whether to request a one-year extension to the Working Group. The main reason for the extension is to be able to participate in the upcoming PICES/ICES/IOC symposium in Brazil, where a session on regional modeling was proposed. With the group's agreement, the Co-Chairs agreed to present the request in the POC Committee meeting.

WG 29 meeting participants (left to right): Hiroshi Kuroda, Arthur Miller, Emanuele Di Lorenzo, Shin-ichi Ito, Young Ho Kim, Xingrong Chen, Panjun Du, Angelica Peña, Enrique Curchitser, Elena Ustinova, Kyung-Il Chang, Dmitry Stepanov, Chan Joo Jang, Michael Foreman, Hal Batchelder, and Jerome Fiechter.

WG 29 Endnote 1

WG 29 participation list

<u>Members</u>

Kyung-Il Chang (Korea)
James Christian (Canada)
Enrique Curchitser (USA, Co-Chairman)
Panjun Du (China)
Jerome Fiechter (USA)
Michael Foreman (Canada)
Shin-ichi Ito (Japan)
Chan Joo Jang (Korea, Co-Chairman)
Young Ho Kim (Korea)
Hiroshi Kuroda (Japan)
Angelica Peña (Canada)
Dmitry V. Stepanov (Russia)

<u>Observers</u>

Harold (Hal) Batchelder (USA)
Xingrong Chen (China)
Emanuele Di Lorenzo (USA)
Arthur Miller (USA)
Elena Ustinova (Russia)

WG 29 Endnote 2

WG 29 meeting agenda

1. Welcome and self-introductions including introduction of new WG 29 members (Drs. Panjun Du (China) and Young Ho Kim (Korea)) (Co-chairs)
2. Introduction to WG 29 activity (Jang, Curchitser, Chang)
   a. Brief introduction of WG 29 including Terms of Reference (Jang)
   b. Review of the first meeting of WG 29 in Hiroshima, Japan (Curchitser)
   c. Report on the Regional Climate Modeling 2nd workshop in Busan, Korea (Chang)
   d. Report on WG29 workshop proposals for 2014 Open Science meeting and for 2014 PICES Annual Meeting (Jang)
3. Short update by each member of their nation RCM activity (WG 29 members)
4. Discussion on preparation and timeline of WG 29 final report, and specific plans and schedule (Co-Chairs)
5. WG 29 term extension

WG 29 Endnote 3

Proposal for a 1-day Topic Session on
"*Regional climate modeling in the North Pacific*" at PICES-2014

Regional climate models are a key scientific tool for understanding climate change at regional to local scale, which is highly relevant to considerations for many socio-economic impacts. Despite the apparent limitations associated with errors in forcing fields and uncertainties in downscaling techniques, regional climate models continue to provide critical information for regional climate change by filling the gap between projections by global climate models and demand for developing adaptation and mitigation strategies at highly resolved scales. This session calls for papers addressing the recent efforts for regional climate modeling such as developing novel approaches for dynamic downscaling, comparison between regional and global climate model results, detection and evaluation of regional climate changes in the North Pacific Ocean simulated by regional and global climate models, assessment of their uncertainty, and coupling of regional climate models with other Earth system model components such as biogeochemical and ecological models. The session aims to assemble and share existing expertise in recent efforts to regional climate models by providing a platform to discuss their limitations and reliability.

Sponsoring Committees/Program: POC/TCODE/FUTURE

Convenors: Chan Joo Jang (Korea), Enrique Curchitser (USA), Michael Foreman (Canada), Kyung-Il Chang (Korea), Shin-ichi Ito (Japan), Angelica Peña (Canada), Hyodae Seo (USA)

Extracted from:

Summary of Scientific Sessions and Workshops at PICES-2013

BIO/POC/TCODE/MONITOR/FUTURE Topic Session (S6)
Recent trends and future projections of North Pacific climate and ecosystems

Co-Convenors: *Jack Barth (USA), James Christian (Canada), Enrique Curchitser (USA), Chan Joo Jang (Korea) and Angelica Peña (Canada)*

Invited Speakers:
Jason Holt (National Oceanography Centre, UK)
William Merryfield (Canadian Centre for Climate Modelling and Analysis, Environment Canada)

Background

The North Pacific Ocean experiences change on a range of timescales, and is among the most difficult regions of the world ocean in which to detect secular climate trends associated with anthropogenic forcing against the background of natural variability. Understanding impacts on ecosystems and the human communities dependent on them requires understanding of the magnitudes of climate variability and change. Sustained observations of past and present states, modeling of future states with global climate models (GCMs), and downscaling of GCM projections to the regional scale are all key components of the scientific effort to understand impacts and inform adaptation efforts. Downscaling efforts are likely to include a variety of methods, both statistical and dynamical, including high-resolution regional ocean circulation models with embedded ecosystem/biogeochemical models, statistical models relating local population statistics to climate forcing or climate indices, and multi-species models forced by temperature or oxygen anomalies from regional or global models. This session dealt with papers on time-series of observations of the North Pacific Ocean in the context of recent climate variability and change, and future projections of changes including statistical and dynamical downscaling.

Summary of presentations

Overall the session was extremely well subscribed and well attended, and the quality of the science was very good. An S6 presenter, Dr. Youngji Joh (Korea), received the MONITOR Best Oral Presentation award for a MONITOR-sponsored Topic Session. There was good representation from almost all of the PICES countries (two presenters from China withdrew in August due competing commitments). At most times there were in excess of 50 people present. The session was extended from a full day to an additional half day to accommodate all of the presenters.

Dr. Jason Holt (National Oceanography Centre, UK) started off the session with an invited talk about how to downscale global climate model predictions to the scale of shelf seas in order to get the shelf ecosystem response right. He reviewed how shelf seas differ from the deep ocean in their response to climate change projections, including that shallow shelf seas are more in thermal equilibrium with the atmosphere than is the deep ocean and that horizontal fluxes are particularly important in shelf seas, especially those contributing to ocean–shelf exchange. Dr. Holt pointed out that isolated seas are vulnerable to single drivers and concluded by reinforcing the need to compare the model results with long time series that are available from the European shelf seas.

Two speakers reviewed the use of regional climate models for both the western (Dr. Chul Min Ko, Korea) and eastern (Dr. Michael Foreman, Canada) North Pacific. They both pointed out that global climate models don't get the regional dynamics right and that downscaling was necessary. They both used the "pseudo global warming" technique where future-minus-contemporary anomalies were added to the initial and forcing fields of their regional models. Dr. Foreman pointed out that summertime winds off the British Columbia coast are not projected to be very different in the future and that global models do not resolve the California Undercurrent, which carries nutrient-rich, oxygen-poor waters from the south.

Dr. Ryan Rykaczewski (USA) used a suite of IPCC models to examine the Bakun (1990) hypothesis that winds off the U.S. west coast should become stronger with global warming. He found no evidence for this in the models and noted that the atmospheric pressure gradient between ocean and land does not increase as hypothesized by Bakun. Dr. William Crawford (Canada) showed how subsurface dissolved oxygen concentrations across the eastern North Pacific exhibit coherent interdecadal variation, with increases from the 1950s to the 1980s and a decline after the 1980s.

Two speakers demonstrated the importance of getting the details of the regional circulation correct in order to understand interannual and interdecadal variability in the Japan/East Sea. Dr. Dmitry Stepanov (Russia) focused on the deep circulation in the Japan Basin as influenced by the basin geography and Dr. Yuri Oh (Korea) described how nutrient fluxes through the Korea Strait influenced productivity in the southern Japan/East Sea (JES). Dr. Joo-Eun Yoon (Korea) further addressed this topic later in the day with an analysis of the mechanisms controlling interannual variability of primary production in the JES over 1998–2007 and the importance of Tsushima Current transport.

The second invited speaker, Dr. William Merryfield (Canada) reviewed the (very new) science of seasonal-to-interannual and decadal climate prediction, the areas of North Pacific climate that are amenable to prediction, and the particular challenges encountered in the North Pacific relative to other ocean areas. Dr. Youngji Joh (Korea) reviewed the ability of CMIP5 models to simulate the PDO, ENSO, and mechanisms underlying tropical-extratropical teleconnections, and found them substantially improved over CMIP3. Dr. James Christian (Canada) discussed the challenge of detecting an anthropogenic signal in ocean biogeochemical data, illustrated by sampling CMIP5 model simulations. Dr. Vera Pospelova (Canada) showed how dinoflagellate cysts can be used as an index of past primary productivity, using data mostly from the California Current region. Dr. Sanae Chiba (Japan) discussed the effects of climate variability on the mean size of the copepod community using over 10 years of CPR data, noting that there is a size dependence of the efficiency of trophic transfer to higher trophic levels. The copepod community showed significant interannual-to-interdecadal variability over this period, which was different in the eastern and western North Pacific.

The second day was equally well attended and again featured speakers from most of the PICES countries. Dr. Taeki An (Korea) discussed seasonal shifts of ecosystem structure in the JES, which show coherent fluctuations across trophic levels from phytoplankton to fish. Dr. Neil Banas (USA) considered similar shifts of ecosystem structure in the Bering Sea, and suggested that future climates will likely be unfavourable for pollock due to reduced production of large copepods. Dr. Andrei Krovnin (Russia) considered the effect of climate variability on pollock and pink salmon recruitment and noted that North Pacific climate variability may also be related to the Arctic and North Atlantic oscillations. Dr. Hae Kun Jung (Korea) considered records of a variety of fisheries around Korea in relation to multiple climate indices over 1960–2010, concluding that there are multiple ‘cold’ and ‘warm’ periods that are relatively, but not entirely, consistent across indices and in their effects on fisheries. Dr. Tony Koslow (USA) examined CalCOFI icthyoplankton survey data from 1950–2010, and found that mesopelagic fishes have coherent fluctuations across ecotypes that are correlated with subsurface oxygen concentration. He further noted that advection (California Current transport) and water mass structure are important factors in climate control of fish and plankton assemblages.

List of papers

Oral presentations

Jason Holt, Icarus Allen, Yuri Artioli, Laurent Bopp, Momme Butenschon, Heather Cannaby, Ute Daewel, Bettina Fach, James Harle, Dhanya Pushpadas, Baris Salihoglu, Corinna Schrum and Sarah Wakelin (Invited)
Physical processes mediating climate impacts in shelf sea ecosystems

Chul Min Ko, Chan Joo Jang, Chun Yong Jung and Cheol-Ho Kim
A Regional Climate Coupled Model for the western North Pacific: Assessment of a present climate simulation

Michael Foreman, Wendy Callendar, Diane Masson, John Morrison and Isaak Fain
Regional ocean climate model projections for the British Columbia continental shelf

Ryan R. Rykaczewski, John Dunne, Charles A. Stock, William J. Sydeman, Marisol García-Reyes, Bryan A. Black and Steven J. Bograd
Investigating the upwelling intensification hypothesis using climate-change simulations

William Crawford and Angelica Peña
Decadal changes in dissolved oxygen concentration in the thermocline of the Northeast Pacific

Dmitry V. Stepanov, Victoriia I. Stepanova and Nikolay A. Diansky
Interdecadal variability of circulation in the northern Japan/East Sea based on numerical simulations

Yuri Oh, Chan Joo Jang, Sinjae Yoo and Chul Min Ko
Effects of nutrient transport through the Korea Strait on the seasonal and interannual variability in the East Sea (Japan Sea) ecosystem

William Merryfield (Invited)
How predictable is the North Pacific?

Youngji Joh, Chan Joo Jang, Minho Kwon, Ho-Jeong Shin and Taewook Park
An improvement of reproducibility of Pacific decadal oscillation in CMIP5

James R. Christian
Detection of anthropogenic influences on ocean biogeochemistry in the North Pacific

Vera Pospelova
Environmental and primary productivity change in coastal waters of the eastern North Pacific revealed from the sedimentary phytoplankton record

Joo-Eun Yoon, Young Baek Son and Sinjae Yoo
Primary productivity and its interannual variability in the East Sea, 1998-2007

Sanae Chiba, Sonia Batten, Tomoko M. Yoshiki, Tadafumi Ichikawa and Hiroya Sugisaki
Climate induced variation in the basin scale zooplankton community structure in the North Pacific

William T. Peterson and Jennifer L. Fisher
The influence of ten El Niño events on pelagic ecosystem structure in the northern California Current

Hiroshi Kuroda, Taku Wagawa, Yugo Shimizu, Shin-ichi Ito, Shigeho Kakehi, Takeshi Okunishi, Sosuke Ohno, Hiromi Kasai and Akira Kusaka
Interdecadal decreasing trend of the Oyashio on the continental slope off the southeastern coast of Hokkaido, Japan

Taeki An, Hyun Je Park, Jung Hyun Kwak, Chung Il Lee, Hae Won Lee, Kangseok Hwang, Jung Hwa Choi and Chang-Keun Kang
Seasonal shift of ecosystem structure around the Ulleung Basin of the East/Japan Sea

Elena I. Ustinova and Yury D. Sorokin
Recent trends of air and water temperature and ice cover in the Far-Eastern Seas

Neil S. Banas, Robert G. Campbell, Carin Ashjian, Evelyn Lessard, Alexei Pinchuk, Evelyn Sherr, Barry Sherr and Jinlun Zhang
Linking sea-ice retreat and increasing water temperature to plankton community structure and function in the eastern Bering Sea

Andrei Krovnin, Boris Kotenev and George Moury
Climatic variability in the Northwest Pacific: Regimes, mechanisms, trends, impact on commercial fish populations

Hae Kun Jung, Chang-Keun Kang and Chung Il Lee
Regional differences in the response of ocean environment and fisheries resources in Korean waters to the North Pacific regime shift and possible mechanisms

J. Anthony Koslow, Peter Davison, Ana Lara-Lopez and Mark D. Ohman
Epipelagic and mesopelagic fishes in the southern California Current System: Ecological interactions and oceanographic influences on their abundance

Poster presentations

Sayaka Yasunaka, Yukihiro Nojiri, Tsuneo Ono, Shin-ichiro Nakaoka and Frank A. Whitney
Monthly maps of sea surface nutrients in the North Pacific: Basin-wide distribution and seasonal to interannual variations

Minwoo Kim, Cheol-Ho Kim and Chan Joo Jang
Effects of grid refinement in the global ocean circulation experiments

Cheol-Ho Kim, Chan Joo Jang and Minwoo Kim
Sea level projection of the North Pacific Ocean using a non-Boussinesq ocean-sea ice model in the SRES A1B scenario

Olga Trusenkova and Dmitry Kaplunenko
Patterns of interannual to decadal sea level variability in the Japan/East Sea

SM M. Rahman, Chung Il Lee and Chang-Keun Kang
Regional differences in oceanic and fisheries variability in the East/Japan Sea related to north Pacific climate-ocean variability

Allison R. Wiener, Marisol García-Reyes, Ryan R. Rykaczewski, Steven J. Bograd and William J. Sydeman
Statistical downscaling of an ensemble of Global Climate Models output for the California upwelling region

Wu Shuangquan, Gao Zhigang, Yang Jinkun and Yu Ting
Numerical simulation of ocean ecological dynamics in Taiwan Strait

PICES Twenty-third Annual Meeting (PICES-2014)
October 16–26, 2014, Yeosu, Korea

Report of Working Group 29 on *Regional Climate Modeling*

The third business meeting of Working Group (WG 29) on *Regional Climate Modeling* (RCM) was held in Yeosu, Korea, on October 17, 2014. With 10 members and observers in attendance (*WG 29 Endnote 1*), the meeting began with an introduction to Working Group activities, and progress and plans by Co-Chairmen, Drs. Enrique Curchitser and Chan Joo Jang. After short presentations by the RCM Working Group members, a brief introduction was given by Japanese member, Dr. Shin-ichi Ito, focusing on items relevant to WG 29. Finally, the members discussed some emerging RCM issues, plans and schedule of future activity and preparation of the group's final report, and next phase of the Working Group. Below are the agenda items (*WG 29 Endnote 2*) and the corresponding discussions during the meeting.

AGENDA ITEM 2
WG 29 activities

Dr. Jang overviewed WG 29's activities including convening relevant sessions and workshops, including the second meeting in Nanaimo, Canada (2013) and Open Science Meeting in Hawaii (April 15–18, 2014). In addition, Dr. Curchitser introduced the third 3rd PICES/ICES/IOC Symposium on "*Effects of climate change on the world's oceans*" (Santos, Brazil, March 21–27, 2015) and the RCM session therein.

WG 29 proposals for PICES-2015

WG 29's proposal for a 1-day Topic Session on "*Past, present, and future climate in the North Pacific Ocean: Updates of our understanding since IPCC AR5*" (*WG 29 Endnote 3*) to be convened mostly by WG 29 members including Drs. Jang, was accepted for PICES-2015 (October 15–25, 2015, Qingdao, China).

AGENDA ITEM 3
Updates on national RCM activities

1. ***Michael Foreman (Canada):*** *Regional ocean climate model projections and their ecosystem implications for British Columbia, Canada*

Dr. Foreman discussed the results from two papers that were published in *Atmosphere–Ocean* and focus on regional projections for the British Columbia coast. His presentation was closely linked to WG 29 TOR #3:

- The RCM projects stronger eddy kinetic energy, stronger Vancouver Island coastal current, and little change in upwelling in the coast;
- The Haida Eddies, an important contributor to ecosystem changes, are projected to become stronger.

2. ***Angelica Peña (Canada):*** *A regional ocean climate model with biogeochemistry for the British Columbia continental shelf*

Dr. Peña presented one-way downscaling of physics and biogeochemistry on the British Columbia continental shelf for detecting, understanding, and projecting climate change impacts on plankton productivity, nutrient supply, oxygen and carbon content, as well as for evaluating the potential risk (likelihood) for the development of hypoxia events and corrosive conditions. Specifically she talked about:

- A coupled physical–biogeochemical model that has been used in which ROMS was implemented as a circulation model. The biogeochemical model includes NPZD, O_2, DIC and Alkalinity;
- Future projections experiments are planned by using CRCM or CGCM forcing and increasing atmospheric $p\mathrm{CO_2}$ and DIC at the lateral boundaries.

3. ***Shin-ichi Ito (Japan):*** *RCM developments in Japan*

Dr. Ito spoke about the status of RCM development in Japan, including MRI models, AORI model, CHOPE-eNEMURO, eNEMUROMS, and Mutsu Bay modeling. He also mentioned the possibility of providing simulation data from each RCM to PICES.

4. ***Hiroshi Kuroda (Japan):*** *Recent update of regional ocean modeling: Lower-trophic ecosystem modeling*

Dr. Kuroda described the modeling activities with the FRA implementation of the ROMS model coupled with eNEMURO or a NPZD model. Specifically he described:

- An operation ocean forecast system (FRA-ROMS) for mesoscale variation over the Kuroshio–Oyashio region;
- The importance of nutrient supply by submesoscale eddies for enhanced chlorophyll concentration on the shelf–slope region.

5. ***Yang-Ki Cho (Korea):*** *Climate change projection in the Northwest Pacific marginal seas through dynamic downscaling*

Dr. Cho showed future climate change for seas around Korea using dynamic downscaling with a ROMS model forced with three different GCM forcings from three CMIP3 global models. Main results are as follows:

- The RCM projects a rapid warming in the Yellow Sea in contrast to a slow warming along the Kuroshio path;
- Future work includes dynamical downscaling forced with CMIP5 models, and inclusion of ecosystem modelling.

6. ***Chan Joo Jang (Korea):*** *CMIP5 analysis: preliminary results*

Dr. Jang presented results from CMIP5 analysis focusing upper-ocean processes including sea surface temperature (SST), mixed layer depth (MLD), and Pacific Decadal Oscillation (PDO), as described below:

- Horizontal resolution of most of the CMIP models is about 1–1.5° for ocean components and 1.5– 2° for atmosphere components, indicating almost no improvement compared with CMIP3 models. (Dr. Peña suggested investigating changes in vertical levels of CMIP5 models, which might be more influential on simulation of biogeochemical processes by CMIP5 models.);
- Common SST biases: a cold bias in the North Pacific and a warm bias in the Southern Ocean;

- MLD biases in CMIP5 show nearly the same patterns as in CMIP3, indicating almost no improvement in MLD simulation by CMIP5 models compared with CMIP3 models;
- CMIP5 models seem to improve the PDO spatial pattern mainly due to a better simulated atmospheric link between tropics to extra-tropics.

7. ***Young Ho Kim (Korea):*** *Data assimilative modeling system of KIOST*

Dr. Kim introduced the KIOST climate model focusing on the ocean data assimilation system (DASK):
- Ensemble Optimal Interpolation – Cost effective System;
- Compared with global SST and SSS climatology and heat content;
- Data released through KIOST LAS/OpenDAP server (http://las.kiost.ac).

8. ***Enrique Curchitser (USA):*** *Multi-scale modeling of boundary currents*

Dr. Curchitser extended his RCM implementation to serveral boundary current regions, including the California coast, Northwest Atlantic and the Benguela region to reduce significant SST biases from GCMs. He discussed the role of wind interpolation and some difficulties with land–sea masks when embedding a high-resolution model within a global framework.

9. ***Dimitry Stepanov (Russia, presented by Dr. Olga Trusenkova):*** *Numerical modeling of circulation in the Okhotsk Sea: Preliminary results*

- The ocean model (INMOM) is a 3-dimensional, sigma coordinate model of 1/20 degree horizontal resolution;
- INMOM was applied to the Okhotsk Sea and simulated some prominent features, including two branches of the East Sakhalin Current.

AGENDA ITEM 4
FUTURE evaluation report

Dr. Ito reviewed the report of the FUTURE Evaluation Team, focusing on some issues relevant to WG 29. Suggestions were to include:
- Ecosystem modelling in climate forecasting to investigate climate change impacts on commercial fisheries;
- Short-term (seasonal to inter-annual) forecasting.

AGENDA ITEM 5
WG 29 final report, and specific plans and schedule

Dr. Curchitser presented ideas for a final WG report and, along with specific section assignments, will email them to the members.
- Each member needs to submit about a 5–10 page summary;
- Experts outside the WG 29 members can be invited if needed;
- Possible topics for the next phase of WG 29 could be related to the role of eddies and upwelling, which are associated with biological activity.

WG 29 meeting participants (left to right): Shin-ichi Ito, Enrique Curchitser, Young-Ho Kim, Hal Batchelder, Olga Trusenkova, Michael Foreman, James Christian, Angelica Peña, Hiroshi Kuroda, Chan Joo Jang

WG 29 Endnote 1

WG 29 participation list

Members

James Christian (Canada)
Enrique Curchitser (USA, Co-Chairman)
Michael Foreman (Canada)
Shin-Ichi Ito (Japan)
Chan Joo Jang (Korea, Co-Chairman)
Young Ho Kim (Korea)
Hiroshi Kuroda (Japan)
Angelica Peña (Canada)
Olga Trusenkova (Russia)

Observers

Harold (Hal) Batchelder (PICES)

WG 29 Endnote 2

WG 29 meeting agenda

1. Welcome and self-introduction (Co-Chairs)
2. Introduction to WG 29 activity (Jang, Curchitser)
   a. Brief introduction of WG activities, progress, and plans (Jang)
   b. Introduction to the third 3rd PICES/ICES/IOC Symposium on "*Effects of climate change on the world's oceans*" in Brazil, 2015 (Curchitser)
3. Short update by each member of their nation RCM activity (WG 29 members)
4. Brief introduction of FUTURE evaluation report (Ito)
5. Discussion on preparation and timeline of WG 29 final report, and specific plans and schedule (Curchitser)

WG 29 Endnote 3

Proposal for a 1-day POC/BIO/TCODE Topic Session on "*Past, present, and future climate in the North Pacific Ocean: Updates of our understanding since IPCC AR5*" at PICES-2015

Co-Convenors: Chan Joo Jang (Korea), Ho-Jeong Shin (Korea), Zhenya Song (China), Sukgeun Jung (Korea), Anne Hollowed (USA), Kyung-Il Chang (Korea), Angelica Peña (Canada), Shin-ichi Ito (Japan)

Climate has been changing and is highly likely to have been influenced by human activities. These changes, which have greatly affected the Earth's environment, have been manifested in oceanic ecosystems. Social demands for information on future projections are increasing the need to adapt to and mitigate climate change. The objective of this session is to update our understanding since IPCC AR5 on the past, present and future climate for the North Pacific Ocean and its marine ecosystems, focusing particularly on climatic change in ecosystem-relevant upper ocean and atmospheric variables. Climate change and its impact have been widely investigated using global climate models, while adaptation and mitigation issues have been studied using mostly regional climate models. While this session invites papers on various topics related to both climate simulations and observations, we also encourage presentations on the development and results of regional climate models (RCMs) and Earth System Models (ESMs), and assessment of hindcast simulations and their application to the projection of future climate or marine ecosystems using coupled general circulation models (CGCMs) in the North Pacific Ocean. Future projections of the North Pacific Ocean and its ecosystems, as obtained from global climate models (including CMIP5 standard experiment data for comparison with RCM results) will also be an important contribution to this session.

Extracted from:

Summary of Scientific Sessions and Workshops at PICES-2014

POC/TCODE FUTURE (S10)
Regional climate modeling in the North Pacific

Co-Convenors: *Chan Joo Jang (Korea), Kyung-Il Chang (Korea), Enrique Curchitser (USA), Michael Foreman (Canada), Shin-ichi Ito (Japan), Angelica Peña (Canada), Hyodae Seo (USA)*

Invited Speakers:
Enrique Curchitser (Rutgers University, USA)
Eun Soon Im (Singapore-MIT Alliance for Research and Technology (SMART), Singapore/USA)
Hyun-Suk Kang (National Institute of Meteorological Research, Korea)
Hyoun-Woo Kang (KIOST-PML Science Office, UK)
Kei Sakamoto (Meteorological Research Institute, Japan)
Hyodae Seo (Woods Hole Oceanographic Institution, USA)

Background

Regional climate models are a key scientific tool for understanding climate change at regional to local scale, which is highly relevant to considerations for many socio-economic impacts. Despite the apparent limitations associated with errors in forcing fields and uncertainties in downscaling techniques, regional climate models continue to provide critical information for regional climate change by filling the gap between projections by global climate models and demand for developing adaptation and mitigation strategies at highly resolved scales. This session called for papers addressing the recent efforts for regional climate modeling such as developing novel approaches for dynamic downscaling, comparison between regional and global climate model results, detection and evaluation of regional climate changes in the North Pacific Ocean simulated by regional and global climate models, assessment of their uncertainty, and coupling of regional climate models with other Earth system model components such as biogeochemical and ecological models. The intent of the session was to assemble and share existing expertise in recent efforts to regional climate models by providing a platform to discuss their limitations and reliability.

Summary of Presentations

About 40 people attended and 15 presentations were made. Unfortunately, two presentations from China and Russia were cancelled, and four other countries' members contributed the oral presentations. In addition, three poster presentations were made. The session started with a brief introduction of the session by Dr. Chan Joo Jang: needs of regional climate models to investigate the current and future states of coastal ocean and marine ecosystems.

The first invited talk by Enrique Curchitser showed three examples (two eastern boundary upwelling systems and one western boundary current) of the NCAR Community Earth System Model (CESM) application using the nested high-resolution ROMS model. The examples demonstrated the need for better representation of oceanic mesoscale processes such as the coastal upwelling and the local ocean currents for the improved simulation of regional and global climate. The presentation also discussed the issue related to the interpolation of near-shore wind in the coupled model along the eastern boundary upwelling zones to which the coastal upwelling is sensitive. The second invited talk by Hyodae Seo showed an excellent model application to investigate effects of eddy–wind interactions in the California Current System on the eddy kinetic energy and Ekman pumping. Interactions between eddy current and wind showed quite large damping impacts on the eddy activity in the California Current System, and this was nearly entirely due to the eddy-induced surface current effect on wind stress as opposed to the eddy-induced surface temperatures. The third invited talk by Hyun-Suk Kang introduced the current status and the future perspective of the upcoming Coordinated Regional Downscaling Experiment (CORDEX) and its achievements for the East Asia domain. CORDEX is a WCRP-sponsored research program that aims to provide a coordinated regional model evaluation framework, a climate projection framework, and an interface to the applicants of the climate simulations in climate change impact, adaptation, and mitigation studies. The fourth invited talk by Eun-Soon Im introduced another CORDEX participating model: the MIT Regional Climate Model (MRCM). The talk showed the importance of the improved schemes for atmospheric deep convection and clouds and coupling of a biosphere simulator in MRCM for the simulation of precipitation in the Maritime Continent and the West African Monsoon. The fifth invited talk by Hyoun-Woo Kang showed an application of a regional marine system model on the northwestern Pacific and the variability of Yellow and the East China Seas, with the emphasis on the impacts of tides and river discharge on the biogeochemistry. The sixth invited talk by Kei Sakamoto showed an example of a high resolution operational model in Seto-Inland-Sea and its extension to the around Japan model. There were many excellent contributed talks dominated by young scientists especially from the Republic of Korea. The contributions of young Korean scientists gave us perspectives of further and continuing developments of regional climate modeling.

List of papers

Oral presentations

Climate—Boundary current interactions: Stories from East and West (Invited)
Enrique Curchitser, Justin Small, William Large, Raphael Dussin, Katherine Hedstrom and Brian Kaufman

Regional coupled modeling of the eddy-wind interactions in the California Current System (Invited)
Hyodae Seo

Climate change projection for the western North Pacific Ocean by dynamical downscaling
Chul Min Ko, Chan Joo Jang, Ho-Jeong Shin and Yong Sun Kim

Regional climate change projection for the northwest Pacific marginal seas
Gwang-Ho Seo, Yang-Ki Cho, Byoung-Ju Choi and Kwang-Yul Kim

CORDEX and its recent progress for East Asia (Invited)
Hyun-Suk Kang, S. Hong, J.-Y. Jung, M.-S. Suh, S.-K. Oh, D.-H. Cha and S.-K. Min

Introducing the MIT Regional Climate Model (MRCM) and its application to climate studies worldwide (Invited)
Eun-Soon Im and Elfatih A.B. Eltahir

Projected change in the East Asian summer monsoon from dynamical downscaling: Moisture budget analysis
Chun-Yong Jung, Chan Joo Jang, Hyung-Jin Kim and Ho-Jeong Shin

An assessment of ocean climate reanalysis by the Data Assimilation System of KIOST
Young Ho Kim, Chorong Hwang and Byoung-Ju Choi

Application of a regional marine system model on the northwestern Pacific and the variability of the yellow and the East China Seas (Invited)
Hyoun-Woo Kang, Hanna Kim, Jae Kwi So, Momme Butenschon and Icarus Allen

Development of a Seto-Inland-Sea model toward operational monitoring and forecasting (Invited)
Kei Sakamoto, Goro Yamanaka, Hiroyuki Tsujino, Hideyuki Nakano, Norihisa Usui and Shogo Urakawa

A biogeochemical model for the British Columbia continental shelf
Angelica Peña, Diane Masson and Michael Foreman

Transport of *Todarodes pacificus* winter cohort into the Yellow Sea in the early life states
Ji-Young Song, Joon-Soo Lee, Jung-Jin Kim and Ho-Jin Lee

Impact of horizontal model resolution on air-sea CO_2 exchange in the California Current
Jerome Fiechter, Enrique Curchitser, Christopher Edwards, Fei Chai, Nicole Goebel and Francisco Chavez

Seasonality and linear trend of circulation around Korea derived from multi-platform observations
Sung Yong Kim

Regime-dependent nonstationary relationship between the East Asian winter monsoon and North Pacific Oscillation
Gyundo Pak, Young-Hyang Park, Frederic Vivier, Young-Oh Kwon and Kyung-Il Chang

Poster presentations

Characteristics of physical elements during a typical algae bloom in the Yellow Sea
Xu Shanshan, Dong Mingmei, Yu Ting and Miao Qingsheng

Regional efficacy of ocean heat uptake under a CO_2 quadrupling
Ho-Jeong Shin, Ken Caldeira, Chan Joo Jang and Yong Sun Kim

Analysis of HadGEM2-AO historical and climate forecasting experiments
Haejin Kim, Cheol-Ho Kim and Hong-Ryeol Shin

The 3rd International PICES/ICES/IOC Symposium on "*Effects of climate change on the world's oceans*" March 23–27, 2015, Santos, Brazil

Theme Session S4

Regional models for predictions of climate change impacts: methods, uncertainties and challenges

Convenors:
Shoshiro Minobe (Hokkaido University, Japan)
Enrique N. Curchitser (Institute of Marine and Coastal Science, Rutgers University, USA)

Plenary Speaker:
Arne Biastoch (GEOMAR Helmholtz Centre for Ocean Research, Germany)

Invited Speaker:
Shin-ichi Ito (FRA, Japan)

Predicting climate change impacts on regional ocean processes and marine ecosystems is challenging because it (1) involves advanced and high-resolution models for the ocean and its resources, (2) has concrete consequences in terms of regional and national management of ecosystem services, and (3) aims to provide direct scientific support in the implementation of the Ecosystem Approach to Fisheries Management. A number of practical and conceptual challenges occurring at the regional scale will be highlighted in this session.

First, regional projections are subject to uncertainties that arise from the baseline global climate projections, the downstream modelling tools and in combining models. Regional models (RM), including regional air-sea coupled models or regional ocean models, are the starting points for understanding and projecting climate change on a regional scale. While global climate models are capable of capturing the large-scale mean climate behavior, they have limitations for regional assessments due to their coarse spatial resolutions. We welcome papers addressing the downscaling of global climate models to regional scale, including a variety of methods, both statistical and dynamical, such as high-resolution regional ocean circulation models with embedded biogeochemical models, and statistical models relating local population statistics to climate forcing or climate indices.

Secondly, expanding the RM projections to predicting climate change impacts on regional ecosystems in combination with other drivers such as fishing, requires the integration of ecosystem processes and knowledge on the ecosystem functioning, though a combination of multiple models. The use of multiple models can be three fold: (1) using several multidisciplinary models to build end-to-end models from the physics to the high trophic levels and their exploitation; (2) using multiple models to address uncertainty of the projections due to model structure and processes (*e.g.*, envelope approach, or comparative approach across models); and (3) using multiple hybrid approaches to integrate most of available information and data such as a combination of climate statistical niche models and foodweb models. We welcome papers addressing the challenges and uncertainties in combining multiple models for regional global change impacts on ecosystems, and provide the opportunity for papers that combine different modelling approaches in order to improve the projections of global change, including climate change in combination with other stressors such as fishing and pollution.

List of papers

Shin-ichi Ito, Takeshi Okunishi, Taketo Hashioka, Takashi T. Sakamoto, Naoki Yoshie, Kosei Komatsu and Akinori Takasuka (Invited)
Regional models for projections of climate change impacts on small pelagic fishes in the western North Pacific

Charles A. Stock, John P. Dunne and Jasmin G. John
Trophic amplification of ocean productivity trends in a changing climate

Edson J.R. Pereira and Ilana Wainer
Downscaling the 1990-2100 ocean climate projections for the Arabian Gulf

Angelica Peña, Diane Masson and Mike Foreman
A regional biogeochemical climate model for the British Columbia continental shelf

Rodrigo S. Martins
Reviewing the use of computer-based modelling to study squid larval dispersal: Experiences from South Africa and Brazil

Illarion Mironov and Alexander Demidov
Comparison numerical models results and hydrographic data in the Atlantic Ocean

Jonathan Tinker, Jason Lowe, Jason Holt and Rosa Barciela
Marine climate projections for the NW European shelf seas: Dynamically downscaling a perturbed physics ensemble to explore climate uncertainty and temporal response

Ivonne Ortiz, Kerim Aydin and Al Hermann
Fish movement and distribution drivers in a climate to fisheries model for the Bering Sea

Tarumay Ghoshal and Arun Chakraborty
ROMS hindcast experiments on BOB's extreme events with daily forcing input

Fedor N. Gippius, Alisa Yu. Medvedeva, Elena A. Malyarenko, Victor S. Arkhipkin, Stanislav A. Myslenkov and Galina V. Surkova
Wind wave regime of eastern European seas

AOGS 2015: 12th Annual Meeting of the Asia Oceania Geosciences Society

August 2–7, 2015, Singapore

Theme Session AS27-23

Recent advances in regional climate modeling: Development challenges and applications

Convenors:
Eun-Soon Im (Singapore-MIT Alliance for Research and Technology, Singapore)
Ho-Jeong Shin (Korea Institute of Ocean Science and Technology, Korea)
Chan Joo Jang (Korea Institute of Ocean Science and Technology, Korea)
Srivatsan Raghavan (National University of Singapore, Singapore)
Hung Soo Kim (Inha University, Korea)

Invited Speakers:
Venkata Ratnam Jayanthi (Japan Agency for Marine-Earth-Science and Technology, Japan)
Liong Shie-Yui (Tropical Marine Science Institute, National University of Singapore)

As a potential way to effectively utilize climate information at regional to local scales, dynamical downscaling with a regional climate model (RCM) has been performed across worldwide. Many studies have demonstrated that a RCM can be a key scientific tool for understanding climate processes and assessing the climate changes and their impacts on a regional scale. In this regard, this session invites diverse research activities associated with RCM development and applications from the atmospheric or oceanographic perspective, and aims to share recent advances and to provide a platform to discuss the progress and limitation. We are particularly interested in topics addressing 1) development and its challenges of an integrated modeling system that coupled climate subsystems such as atmosphere, ocean, and biosphere, 2) improvement of the model physics and dynamics, 3) sensitivity of climate system to human influences such as land use, aerosols and greenhouse gases, 4) new approaches for model evaluation and uncertainty assessment, and 5) interdisciplinary applications of downscaled climate data to various impact assessment studies (*e.g*. agriculture, hydrology).

PICES Twenty-fourth Annual Meeting (PICES-2015)
October 15–25, 2015, Qingdao, China

Working Group 29 on *Regional Climate Modeling*

The fourth and final business meeting of working group (WG 29) on *Regional Climate Modeling* (RCM) was held on October 16, 2015 in Qingdao, China. With 11 members and observers in attendance (*WG 29 Endnote 1*), the members focused on discussion on preparation of the group's final report including its contents and schedule, and on next phase of the working group. Finally, the members presented a short update for each member's RCM development activity. Below are the agenda items (*WG 29 Endnote 2*) and the corresponding discussions during the meeting.

AGENDA ITEM 1
Welcome

1. Pre-meeting social to allow members to interact.
2. Introduction to WG 29 activities and plans by Drs. Chan Joo Jang and Enrique Curchitser.

AGENDA ITEM 2
WG 29 final report (FR), specific plans and schedule

Dr. Jang presented ideas for a final WG report (structure, specific section assignments) and members agreed upon the content and future schedule, as follows:

- Each member will submit about a 5- to 10-page summary;
- Experts outside of WG 29 can be invited to contribute, if needed;
- Possible topics for the next phase are related to the role of eddies and upwelling, which are associated with biological activity;
- FR schedule:
  - Titles of each member's contribution, RCM info (domain, grid size, purpose, *etc*.), titles of papers and conference presentations (Nov. 1, 2015);
  - Short draft summary (5–10 pages including figures) for each country's RCM development efforts (Jan. 15, 2016);
  - FR Draft (Feb. 2016).

AGENDA ITEM 3
Possible topics for WG 29 next phase

Members discussed possible topics for a next phase of WG 29 and terms of reference for the most likely working group:

- Possible working groups on:
  - High resolution earth system RCM,
  - Sub-mesoscale eddies,

- Ecosystem in upwelling regions,
- Ocean–atmosphere coupled RCM,
- Local-regional nested RCM,
- Physical–biological coupled RCM,
- RCM: decadal hindcast and prediction,
- COCEAN (ocean version of CORDEX).

▪ Suggested Working Group on 'Regional Bio-physical Predictions and Projections':
Terms of reference to include:
- Seasonal-to-interannual predictability assessment,
- Downscaling of climate change projections,
- Changes in meso and sub-mesoscale eddies,
- Regional projection intercomparison,
- Trends in upwelling,
- Climate projection from RCMs.

AGENDA ITEM 4

Updates on national RCM activities

1. Chan Joo Jang (Korea): *Dynamical downscaling of climate change by using RCMs*

Dr. Jang presented results from CMIP5 evaluation analysis and regional climate modeling for the western North Pacific Ocean focusing on the seas around Korea:

- Analyzing all CMIP5 models for certain variables (ex. SST) is too demanding because many model simulations are available: for example, more than 50 different models from 24 institutes of 13 countries contributed to historical run output of SST. This factor, in addition to computing resources, limits the number of CMIP5 model simulations that can be used for dynamical downscaling of climate change projection.
- Most of the CMIP5 models have more than 40 vertical levels, compared with CMIP3 models mostly having less than 40 levels, indicating that CMIP5 models slightly improved their horizontal resolution. This improvement might be more influential on simulations of biogeochemical processes by CMIP5 models.
- CMIP5 models still show significant common SST biases and MLD biases, while their PDO spatial pattern appears to be improved, mainly due to a better simulated atmospheric link between the tropics to extra-tropics.
- Regional climate coupled models (RCCM) projected greater surface warming in summer than in winter in the seas around Korea, possibly due to earlier westward expansion or intensification of the North Pacific High Pressure system.
- Two-way coupling of regional modeling can considerably modify SST projected changes in Korean waters.

2. Tiejun Ling (China): *Regional coupled climate model application*

Dr. Ling introduced a typhoon (Muifa) simulation using a region coupled model (COAWST) with a 15 km horizontal resolution:

- Results showed that precipitation was better resolved, probably due to improved SST simulation;

- The next step is to integrate the model for 20 years and extend the model domain to the Asian-Australian Monsoon region.

3. Hiroshi Kuroda (Japan): *The current status of an operation ocean forecast system "FRA-ROMS" and its community models in FRA*

Dr. Kuroda detailed on-going efforts for developing the Fisheries Research Agency (FRA) forecast system with data assimilation and community models:

- The operation ocean forecast system (FRA-ROMS) produces a nowcast and 2-month forecast with a 1-week update, which are publically available through the website (http://fm.dc.affrc.go.jp/fra-roms/index.html);
- The FRA-ROMS system is evolving into a community model including a lower-tropic ecosystem model, a sea-ice model, and an individual based model.

4. Dmirty V. Stepanov (Russia): *Modelling the circulation and its variability in the Japan/East Sea*

Dr. Stepanov reported on modelling studies with the INMOM model for the Japan/East Sea and the Okhotsk Sea. The main results are as follows:

- A simulated cyclonic gyre in the northern Japan/East Sea shows predominant 4-year variability;
- Tidal effects can contribute to sea ice concentration in the Okhotsk Sea.

AGENDA ITEM 5

Adjourn meeting

WG 29 Endnote 1

WG 29 participation list

Members

James Christian (Canada)
Enrique Curchitser (USA, Co-Chairman)
Shin-Ichi Ito (Japan)
Chan Joo Jang (Korea, Co-Chairman)
Hiroshi Kuroda (Japan)
Tiejun Ling (China)
Angelica Peña (Canada)
Fangli Qiao (China)
Dmitry V. Stepanov (Russia)

Observers

Ying Bao (China)
Daisuke Hasegawa (Japan)

WG 29 meeting participants (left to right): Ying Bao, Shin-ichi Ito, Fangli Qiao, Enrique Curchitser, Angelica Peña , James Christian, Dmitry V. Stepanov, Chan Joo Jang, Tiejun Ling, Hiroshi Kuroda, Daisuke Hasegawa

WG 29 Endnote 2

WG 29 meeting agenda

1. Welcome and self-introduction (Co-Chairs)
2. Discussion on timeline and contents of WG 29 final report (Jang and WG 29 members)
3. Possible following working groups (Jang and WG 29 members)
4. Short update by each member of their national RCM activity (WG 29 members)

Extracted from:

Summary of Scientific Sessions and Workshops at PICES-2015

POC/BIO/TCODE Topic Session (S7)
Past, present, and future climate in the North Pacific Ocean: Updates of our understanding since IPCC AR5

Co-Convenors: *Chan Joo Jang (Korea), Ho-Jeong Shin (Korea), Zhenya Song (China), Sukgeun Jung (Korea), Anne Hollowed (USA), Kyung-Il Chang (Korea), Angelica Peña (Canada), Shin-ichi Ito (Japan)*

Invited Speakers:
Jacquelynne R. King (Pacific Biological Station, Fisheries and Oceans Canada, Canada)
Shoshiro Minobe (Hokkaido University, Japan)
Yongqiang Yu (State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, China)

Background

Climate has been changing and is highly likely to have been influenced by human activities. These changes, which have greatly affected the Earth's environment, have been manifested in oceanic ecosystems. Social demands for information on future projections are increasing the need to adapt to and mitigate climate change. The objective of this session was to update our understanding since IPCC AR5 on the past, present and future climate for the North Pacific Ocean and its marine ecosystems, focusing particularly on climatic change in ecosystem-relevant upper ocean and atmospheric variables. Climate change and its impact have been widely investigated using global climate models, while adaptation and mitigation issues have been studied using mostly regional climate models. While this session invited papers on various topics related to both climate simulations and observations, presentations were encouraged on the development and results of regional climate models (RCMs) and Earth System Models (ESMs), and assessment of hindcast simulations and their application to the projection of future climate or marine ecosystems using coupled general circulation models (CGCMs) in the North Pacific Ocean. Future projections of the North Pacific Ocean and its ecosystems, as obtained from global climate models (including CMIP5 standard experiment data for comparison with RCM results), were also important contributions to this session.

Summary of presentations

Dr. Chan Joo Jang (co-convenor, Korea) introduced the goals and objectives of the topic session. He noted that this session included oral presentations from 3 invited speakers, 12 contributed talk, and 11 posters. The talks were organized into three overarching sub-themes: climate change from a global perspective (4 talks); marine ecosystem and biogeochemistry (6 talks); and ocean dynamics (5 talks). Dr. Jacquelynne King (Canada, invited) introduced climate change from a global perspective sub-theme with an overview of the key findings from the 3rd PICES/ICES/IOC Symposium on "*Effects of climate change on the world's oceans*" which was held in Santos, Brazil, in March 2015. The following 3 talks emphasized the importance of maintaining and improving the ocean observation system, the role of heat storage in the global heat budget; and the performance of CMIP5 models in reconstructing air–sea fluxes in the equatorial Pacific. Dr. Shoshiro Minobe (Japan, invited) introduced the marine ecosystem and biogeochemistry sub-theme by demonstrating how output from CMIP5 models can be used to project range shifts of Pacific salmon. His work suggested that sockeye salmon will be vulnerable to climate change. Dr. Anne Hollowed reported on an international coordinated research program by S-CCME (PICES/ICES Section on *Climate Change Effects on Marine Ecosystems*). The following 5 talks addressed a framework for projecting the implications of climate change on marine ecosystems through innovative modeling approaches. Dr. Yongqiang Yu (China, invited) introduced the ocean dynamics sub-theme with a review of the impacts of external forcing on decadal variability in CMIP5 simulations. The following 4 talks focused on the mechanisms underlying specific ocean features including the genesis of tropical cyclones, seasonal differences in long-term trends in sea surface temperature, and observed patterns of circulation variability. Dr. Shin-ichi Ito (co-convenor, Japan) closed the session by thanking the speakers. He acknowledged the value of interdisciplinary topic sessions and encouraged continued collaborations within the PICES research community.

List of papers

Oral presentations

Report from Brazil: Effects of climate change on the world's oceans (Invited)
Jacquelynne King

The latest progress on global Argo observations
Jianping Xu and Zenghong Liu

The CMIP5 ocean heat storage and temperature
Ho-Jeong Shin and Chan Joo Jang

Evaluation on air-sea CO_2 fluxes in the equatorial Pacific simulated by CMIP5 models
Lei Wang, Yong Luo and Jianbin Huang

SST habitat and food change projections for Pacific salmon (*Oncorhynchus* spp.) in the North Pacific and adjacent seas based on CMIP5 climate models (Invited)
Shoshiro Minobe, Hiromichi Ueno, James R. Irvine, Alexander V. Zavolokin, Katherine W. Myers, Mio Terada, Mitsuho Oe and Skip McKinnell

S-CCME's international coordinated research program to project climate change impacts on fish and fisheries by 2019
Anne B. Hollowed, Kristin Holsman, Shin-ichi Ito, Myron Peck, John Pinnegar and Cisco Werner

Climate-change driven range shifts of chub mackerel (*Scomber japonicus*) projected by bio-physical coupling individual based model in the western North Pacific
Sukgeun Jung, Ig-Chan Pang, Joon-ho Lee, Lee Kyunghwan, Tae Hoon Kim, Hwa Hyun Lee, Kyung-Su Kim and Suam Kim

Potential effect of climate change for copepods distribution in western North Pacific Ocean
Hiroomi Miyamoto, Kazuaki Tadokoro, Takeshi Okunishi, Hiroya Sugisaki, Kiyotaka Hidaka, Yuichi Hirota, Tsuneo Ono, Kou Nishiuchi, Satoshi Kitajima, Takahiko Kameda, Haruyuki Morimoto and Tadafumi Ichikawa

Near future lower-trophic ecosystem projection in the seas around Korea
Hyoun-Woo Kang, Hanna Kim, Jae Kwi So, Momme Buttenschon, Icarus Allen and Ok Hee Seo

Future changes of nutrient dynamics and biological productivity in California Current System
Fei Chai, Peng Xiu and Enrique N. Curchitser

Impacts of external forcing on the decadal climate variability in CMIP5 simulations (Invited)
Yongqiang Yu and Yi Song

A genesis potential index for tropical cyclone using oceanic parameters
Min Zhang, Lei Zhou and Dake Chen

Seasonal characteristics of the long-term sea surface temperature variability in the Yellow and East China Seas
Yong Sun Kim, Chan Joo, Jang Jin, Yong Jeong and Yongchim Min

Effects of atmospheric forcing on circulation variability in the northern Japan/East Sea in 1948 to 2010
Dmitry V. Stepanov, Victoriia I. Stepanova and Anatoly V. Gusev

Anomalous tropical cyclone activity in the northwestern Pacific in 2014
Lei Yang, Dongxiao Wang, Xin Wang and Ke Huang

Poster presentations

Effects of CO_2-driven ocean acidification (OA) on early life stages of marine medaka (*Oryzias melastigma*)
Jingli Mu, FeiJin, JuyingWang, Nan Zheng and Yi Cong

Features of the circulation structure in the Okhotsk Sea based on high-resolution numerical simulation in 1979 to 2000
Dmitry V. Stepanov, Vladimir V. Fomin and Nikolay A. Diansky

Development of a regional climate coupled model for the seas around Korea
Hee Seok Jung, Chan Joo Jang and Ho-Jeong Shin

The effects of runoff forcing on the summer monsoon onset in a climate model
Yajuan Song, Fangli Qiao and Zhenya Song

Change of beginning and duration of the first stage of Far-Eastern summer monsoon on the southern coast of Primorye
Lyubov' N. Vasilevskaya, Tatiana A. Shatilina and D.N. Vasilevskiy

10th WESTPAC International Scientific Conference
Advancing Ocean Knowledge, Fostering Sustainable Development From the Indo-Pacific to the Globe
April 17–20, 2017, Qingdao, China

Sub-theme D: ***Enhancing knowledge of cross-cutting and emerging issues***
D19: Ocean and climate model development and applications

Co-convenors:
Fangli Qiao (First Institute of Oceanography, SOA, China)
Chan Joo Jang (Korean Institute of Ocean Science and Technology, Republic of Korea)
Fredolin Tangang (Universiti Kebangsaan Malaysia, Malaysia)
Mohd Fadzil Mohd Akhir (Institute of Oceanography and Environment, Universiti Malaysia Terengganu, Malaysia)

Ocean and climate models are key tools in the management of marine resources and mitigation of marine hazards, forecast of typhoons and prediction of climate. In this session, to identify challenges and advances in ocean and climate models, we encourage scientists to submit their works related to development of ocean and climate models, operational ocean forecasting systems, model validation, data assimilation, and different kinds of applications including dynamic research based on models. Downscaling of climate models to regional scale, parameterization of ocean mixing and air-sea interaction, typhoon model development and prediction of Monsoons are especially welcomed.

List of Presentations

Ho-Jeong Shin
An assessment of CMIP5 climate models for the ocean temperature and salinity

Bin Xiao
The effects of ocean tide in global ocean general circulation models

Kok Poh Heng
Prediction of potential upwelling region in the southern Kalimantan and its interaction with the east coast of Peninsular Malaysia by using numerical model and satellite data

Biao Zhao
The development of regional atmosphere-ocean-wave coupled model for typhoon

Chang Zhao
Simulation of the distribution of 137Cs in the ocean from nuclear tests

Nurul Rabitah Daud
Dynamic of El-Niño Southern Oscillation (ENSO) towards upwelling and Thermal Front Zone in the East Coast Peninsular Malaysia

Xunqiang Yin
The development of EAKF-ODA system and its application in climate models

Xiaodan Yang
Evaluation of three sublayer temperature profile schemes for the diurnal cycle of SST simulation in an ocean general circulation model

Wonkeun Choi
An assessment of the surface winds simulated over the seas around the Korean Peninsula by CMIP5 global and CORDEX regional climate models

Meng Wei
Attribution analysis for the failure of CMIP5 climate models to simulate the recent global warming hiatus

Ho-Jeong Shin
Interannual variability in surface circulation of the East/Japan Sea: Three-dimensional numerical model simulations

Yajuan Song
Improvement of the summer monsoon onset over the Bay of Bengal in a CGCM

Huiqin Hu
Assessing the impact of data assimilation cycling frequencies on fog forecasting via the extended WRF 3DVAR: An OSSE study

Changshui Xia
Case study on the three-dimensional structure of meso-scale eddy in the South China Sea based on a high-resolution model

Liping Yin
Establishing and applying of a coupled individual based model of edible jellyfish (*Rhopilema esculentum* Kishinouye) releasing in the Liaodong Bay

Huiling Qin
Numerical simulation of a subseasonal SST warming event in the Bay of Bengal in pre-monsoon season, 2010

Yiding Zhao
Prediction skill of North Pacific SST and precipitation in FIO-ESM

Qi Shu
The development and application of a global eddy-resolving surface wave-tide-circulation coupled model

Appendix 4

PICES Press Articles Related to WG 29

2012 Yeosu Workshop on "Climate Change Projections"

by Enrique Curchitser and Icarus Allen

A 2-day workshop on "*Climate change projections for marine ecosystems: Best practices, limitations and interpretations*" was held on May 13–14, 2012, preceding the 2nd International Symposium on "*Effects of Climate Change on the World's Ocean*" convened in Yeosu, Korea. The goal of the workshop was to explore different approaches to modeling the impacts of climate change and variability on marine ecosystems and to highlight their strengths and limitations. A significant motivation was to bring together both global and regional modelers whose communities often work separately. A particular interest of the convenors (co-authors of this article) was to insure that the definition of an ecosystem included higher trophic levels and both direct and indirect anthropogenic influences. The tone for the workshop was set by the opening remarks of Icarus Allen (Plymouth Marine Laboratory, UK) who discussed the scientific interest in understanding how ecosystems respond to climate change, the propagation of the climate signal through an ecosystem, difficulties in making future projections, issues with downscaling, whole ecosystem approaches, and anthropogenic effects questions of how to deal with uncertainty. The need to take risks in our approaches to these problems was indicated.

Over the two days, about 40 scientists participated in the workshop. Invited talks by Villy Christiansen and William Cheung (University of British Columbia, Canada), Jason Holt (National Oceanographic Centre, UK), Charles Stock (NOAA's Geophysical Fluid Dynamics Laboratory, USA dealt with research using both global and regional climate models coupled with marine ecosystem models. Together with submitted contributions, a range of models was presented which included global and regional coupled physics, fish and fishers.

Dr. Christiansen started the workshop with a talk about the NEREUS project led by the University of British Columbia. The work is motivated by the question of "Will there be fish for coming generations?" and the realization that many fisheries have collapsed across the globe. The project takes a global approach and models the ecosystem from biogeochemistry to the market. It includes on the order of 1000 fish species and nearly 250 fishing fleets (Fig. 1). NEREUS is also a leader in outreach activities, producing visualizations of model data for the public at large.

Dr. Holt tackled the topic of climate drivers on coastal marine ecosystems. His emphasis was on downscaling global climate models to the broad continental shelves of northern Europe and exploring the physical mechanisms (the interplay of turbulence, mixing and nutrient supply) that exert controls over phytoplankton growth. He presented several considerations for the treatment of uncertainty in complex coupled bio-physical models.

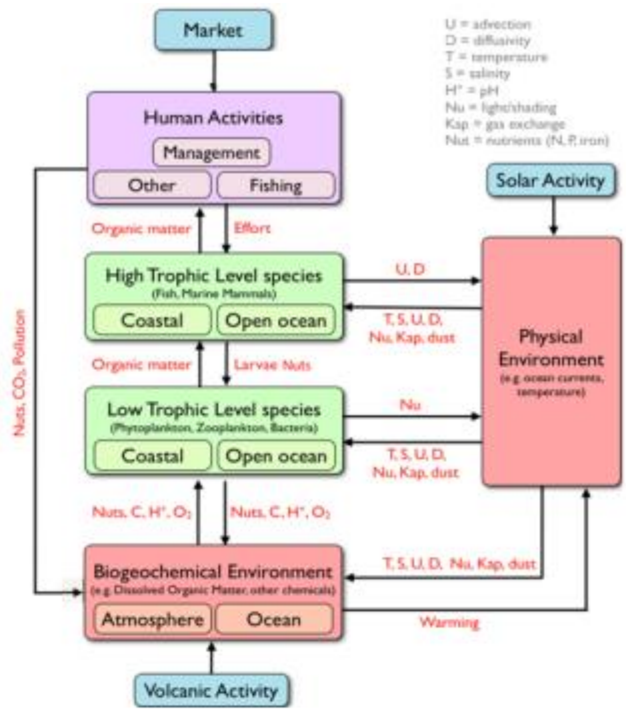


Fig. 1 Schematic diagram of the Nereus modeling framework. The model is being used to concurrently study the effects of climate change and human activity (such as fishing) on global fish stocks. Nereus takes a global approach to the problem simultaneously modeling 1000 species of fish and over 250 different fishing fleets (see http://www.nereusprogram.org/ for details).

Dr. Stock described his work on using IPCC-class models to assess the impact of climate change on living marine resources. He described some of the challenges of using global models: resolution, separating variability and trends and the fact that these models were not designed to address marine ecosystems, in particular on regional scales (Fig. 2). However, an understanding of the functioning of coupled global climate models and the careful design of ecosystem models can yield insight into ecosystem functioning under projected climate change scenarios.

Dr. Cheung focused on the modeling of large-scale effects of global change on marine ecosystems and fisheries. The motivating issues were ocean warming, de-oxygenation, acidification and overfishing. His presentation dealt with the question of the combined effect of these issues on fisheries

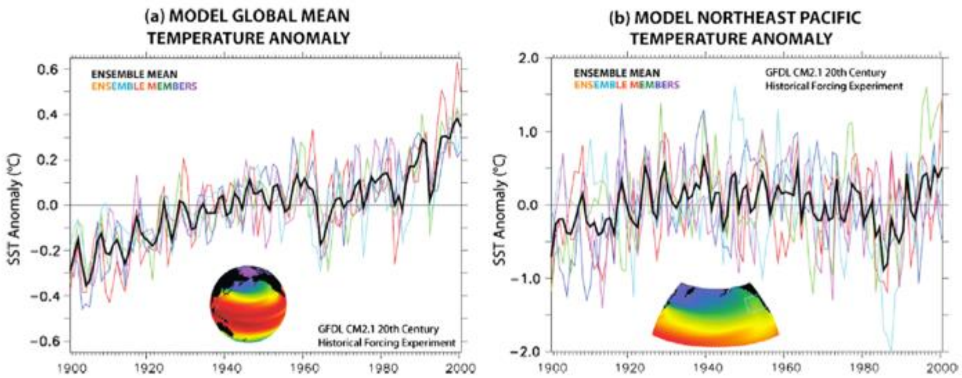


Fig. 2 Temperature anomalies from an ensemble of future projections using the GFDL CM2.1 model. Left: Global mean, Right: Northeast Pacific. This figure illustrates the difference in global and regional variability in the climate model suggesting needed caveats when evaluating global models on a regional basis and interpreting regional ecosystem responses to a global climate signal. Stock et al., 2011. Prog. Oceanog. 88, 1–27.

and explored the sensitivity of model results to projected climate scenarios. His model results suggest that by 2050 warming may cause regions in the tropics to lose catch potential, while high-latitude regions may gain. However, global catch potential is predicted to decrease.

Further presentations at the workshop discussed various approaches to linking climate and ecosystem models, and several threads emerged from these presentations:

- How useful these models are for management, planning and policy purposes,
- The need, advantage and issues of downscaled climate solutions, and
- The validity of regional interpretations of global climate model results.

The topic of model resolution and the multi-scale nature of the problem (both in physics and biology) permeated throughout the presentations and the ensuing discussions. In particular, the participants articulated the needs of coastal ecosystem research that are not necessarily well served by global climate models. A significant amount of time was devoted to a discussion on the communication of model results and model uncertainty to a variety of constituents. The challenge of taking research models and developing them to be useful tools for operational oceanography or management strategy evaluation was also discussed (Fig. 3).

It was recognized at the workshop that as we move forward in trying to make projections of future ecosystem health under likely climate change, it is important for the regional ecosystem and global climate communities to continue working together. Current modeling capacities are inadequate for some of the questions that are being posed. In particular, the challenge of making policy-relevant predictions over the next 2 or 3 decades in the face of a modeled climate signal, which is indistinguishable from the natural variability of the system, was noted. The participants agreed that at present, the community is not ready to describe "best practices", but enough different approaches exist that we can contrast "current" practices. A review manuscript on state-of-the-art approaches highlighting their strengths and weaknesses for making projections of particular ecosystems is expected as the outcome from the workshop.

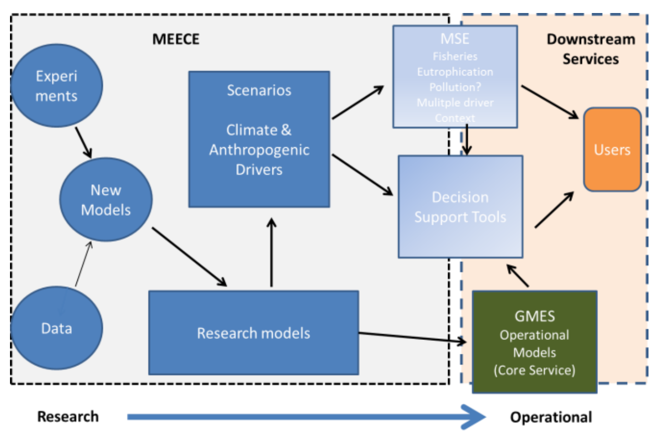


Fig. 3 Schematic of the model development process illustrating the challenge of building research models and pulling them through to operational and decision support tools.

Dr. Enrique Curchitser (enrique@marine.rutgers.edu) is an Associate Professor at Rutgers University (USA). His main research interests are at the intersection of climate and ecosystems. His current projects range from downscaled coupled bio-physical modeling of the California Current and Bering Sea, the impact of climate change on coral bleaching in the Coral Triangle and the role of the Gulf Stream in the climate and social systems of the northeast U.S. Within PICES, he is a member of the Physical Oceanography and Climate Committee and Working Group 27 on Climate Variability and Change in the North Pacific, and co-chairs Working Group 29 on Regional Climate Modeling.

Dr. J. Icarus Allen (jia@pml.ac.uk) is Head of Science for marine ecosystem modelling at the Plymouth Marine Laboratory (UK). His main research interests are the response of marine ecosystem to combinations of climatic and anthropogenic change, ecosystem model skill assessment and operational oceanography. He is a member of the ICES Working Group on Integrative Physical-Biological and Ecosystem Modelling (WGIPEM) and leads the EC FP7 Marine Ecosystem Evolution in a Changing Environment (MEECE) project.

Second Regional Climate Modeling Workshop

by Kyung-Il Chang, Enrique Curchitser, Chan Joo Jang and Kelvin Richards

Participants of the second Regional Climate Modeling Workshop (September 10–12, 2013, Busan, Korea).

A second Regional Climate Modeling Workshop (RCM-II) took place from September 10–12, 2013, in Busan, Korea. The workshop was co-organized by PICES, Seoul National University and the Korean Ministry of Oceans and Fisheries. Drs. Kyung-Il Chang (Seoul National University, Korea), Enrique Curchitser (Rutgers University, USA), Chan Joo Jang (Korea Institute of Ocean Science and Technology, Korea) and Kelvin Richards (International Pacific Research Center, USA) served as co-convenors. The first workshop (RCM-I) was held in 2011, in Seoul, Korea.

Workshop participants were given a warm welcome to the beautiful seaside city of Busan by Mr. Song-Hack Lim, Director for Marine Environment Policy Division of the Ministry of Oceans and Fisheries. In his remarks, Mr. Lim drew attention to the work of the Intergovernmental Panel on Climate Change (IPCC) and the concern for global society that IPCC reports have generated during the last 25 years. The Korean peninsula has experienced significant increases in temperature and changes in marine biology in its adjacent seas. Fishes from the subtropical oceans, for example, are replacing many of the native species of fish in the southern sea of Korea near Jeju Island. Mr. Lim pointed out that rapid physical and ecological changes in regional seas are a great concern and an ability to develop accurate projections of future climate change is of utmost importance for the Korean government, and encouraged participants to engage in vigorous discussions that will lead to more accurate regional climate models. Following Mr. Lim, Dr. Skip McKinnell (PICES Deputy Executive Secretary), introduced the activities of PICES Working Group 29 on *Regional Climate Modeling* (2011–2014) and described how international workshops like RCM-II are contributing to the goals of this expert group.

Workshop presentations were grouped on a thematic basis beginning with *Mesoscale and Sub-mesoscale Motions* on the first day, then *Regional Climate Projections* on the second day, and finishing with *Climate Variability in the North Pacific* on the final day. The full program of the workshop and extended abstracts can be downloaded from WG 29's webpage.

Invited speakers at the workshop supported by PICES included Drs. Shoshiro Minobe (Hokkaido University, Japan) and Michael Foreman (Institute of Ocean Sciences, Canada). Dr. Minobe presented on "*Regional influence of basin-scale wind stress variability via jet-trapped Rossby waves in the western North Pacific*". His main point was that jet-trapped Rossby waves are newly discovered features that are not yet captured by regional climate models whose zonal domain and spatial and temporal resolutions are insufficient to realize the jet. Model spatial resolution must be increased, perhaps by an order of magnitude. One consequence of missing this feature (in the Kuroshio Extension) is that jet-trapped waves create a different sea level anomaly pattern around Japan compared to linear long Rossby waves. Dr. Foreman spoke on "*Regional ocean climate projections for the British Columbia continental shelf*" and showed how regionally downscaled climate models were being used to support regional climate projections for the coast of British Columbia, Canada.

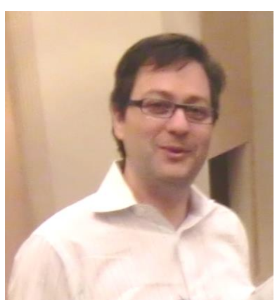
On the last day, a discussion session was moderated by Drs. Kelvin Richards and Enrique Curchitser. Questions stimulated by the workshop included: How useful are idealized process models? At what spatial resolution do results converge? How important are sub-mesoscale processes in a global sense? Is it possible to simply parameterize the impact of the sub-mesoscale? How much can be learned from one-way nesting? How to quantify the impact of global warming? What is the way forward – Limited area *versus* basin scale models?

The relative importance of sub-mesoscale processes sparked considerable interest and discussion. Dr. Jason Holt (National Oceanography Centre, UK) believed that they must be parameterized in global models and that super-parameterization might be a route to go. Dr. Richards suggested embedding downscaled models within global models. Dr. Paulo Calil (Universidade Federal do Rio Grande, Instituto de Oceanografia, Brazil) noted that when trying to understand the carbon cycle, for example, the parameterization must be based on physical understanding, and he emphasized a need to understand the influence of small-scale structures. Drs. Christopher Edwards (University California Santa Cruz, USA) and Kelvin Richards indicated that our ability to parameterize processes in large-scale models is limited because the processes are too complicated. That led to a question whether we can be clever enough to parameterize all of the important sub-mesoscale processes. "Probably not" was the response. Process studies though are useful to understand the sub-mesoscale approach. A question was also raised if sub-mesoscale processes need to be resolved in regional models and, if yes, then what resolution is needed? It was noted that: the response must consider distinguishing shelf seas from the open ocean (Dr. Holt), the decision probably depends on the context (Dr. Minobe), and we are not at a point yet to quantify the overall impact of sub-mesoscale processes and need to assess their importance (Dr. Richards).

Dr. Annalisa Brocco (Georgia Institute of Technology USA) expected that the next IPCC assessment will use higher resolution without adding greater complexity. Dr. Richards reminded participants of Dr. Clara Deser's paper suggesting that 40 ensemble members are needed so that, at the present time, it might not be possible to afford higher resolution although it could be useful to have higher resolution for southern ocean winds, for example.

On discussing the need for RCM-III, there was a suggestion that it could be important to attract atmospheric and land surface modelers to the workshop. Recognizing that Korea was the host of RCM-I and RCM-II and may also be a host of RCM-III, Dr. Foreman asked about modeling issues of greater interest to Korea? Dr. Chang re-iterated what Mr. Lim had said in his welcome address – that sea level rise and ecosystem change are the two issues of greatest interest to the Korean government. He suggested that RCM-III might focus on physical/biological coupling, although noted that no one in Korea is doing ocean/atmosphere coupling. Dr. Minobe proposed the idea of a workshop or session on regional climate modeling that might include the scientists working in the Atlantic, possibly in conjunction with the 3rd International Symposium on "*Effects of climate change on the world's oceans*" (March 23–27, 2015, Santos, Brazil).

Dr. McKinnell closed the workshop with some encouraging words on the need for, and value of, regional climate models. It is not uncommon to find that GCMs are not capturing variability at the scales that are of interest to scientists working at regional scales.

Dr. Kyung-Il Chang (kichang@snu.ac.kr) is an Associate Professor at the Seoul National University (SNU, Korea), working on various aspects of physical oceanography of the East Sea: deep circulation and currents, hydrography and currents in Korea Strait, and interaction of near-inertial waves with mesoscale eddies. In PICES, he has been a member of the Physical Oceanography Committee (POC) since 2006 and a member of the CREAMS/PICES Advisory Panel since 2009, and he is currently serving his second term as Chairman of POC.

Dr. Enrique Curchitser (enrique@marine.rutgers.edu) is an Associate Professor at Rutgers University (USA). His main research interests are at the intersection of climate and ecosystems. His current projects range from downscaled coupled bio-physical modeling of the California Current and Bering Sea, the impact of climate change on coral bleaching in the Coral Triangle and the role of the Gulf Stream in the climate and social systems of the northeast U.S. Within PICES, he is a member of POC and Working Group 27 on Climate Variability and Change in the North Pacific, and co-chairs Working Group 29 on Regional Climate Modeling.

Dr. Chan Joo Jang (cjjang@kordi.re.kr) is a Research Scientist at the Korea Institute of Ocean Science and Technology (KIOST). His research interests include climate change analysis and modeling, observation and modeling for ocean turbulence mixing, and physical-biogeochemical couple models. In PICES, he co-chairs WG 29 on Regional Climate Modeling, and is a member of POC and WG 27.

Dr. Kelvin Richards (rkelvin@hawaii.edu) is a Professor at the Department of Oceanography and International Pacific Research Center, University of Hawai'i at Manoa. His research interests include ocean processes and dynamics, ocean/atmosphere interactions, and ecosystem dynamics. In the early 2000s he chaired the CLIVAR Pacific Panel and helped organize two PICES/CLIVAR workshops.

FUTURE OSM Session on "*Regional climate modeling in the North Pacific*"

by Enrique Curchitser and Chan Joo Jang

A one-day session exploring regional climate modeling in the North Pacific was convened on April 15, 2014, at the FUTURE Open Science Meeting (on the Big Island of Hawaii) to report progress made towards the goals of FUTURE science program. The session was an opportunity for members of the PICES Working Group on *Regional Climate Modeling* (WG 29) to summarize their activities and develop links to other FUTURE efforts.

The topic of regional climate models has generated interest in the PICES community since it recognizes the need to both explore the implications of the global IPCC-class models for PICES member countries and assess state-of-the-science techniques for downscaling global models. Regional downscaling—effectively running models with higher spatial resolution in target areas—of global models is a means of representing climate on time and space scales more appropriate for socio-economic and coastal ocean studies. WG 29 has been focusing on ocean processes and the implications to marine ecosystems.

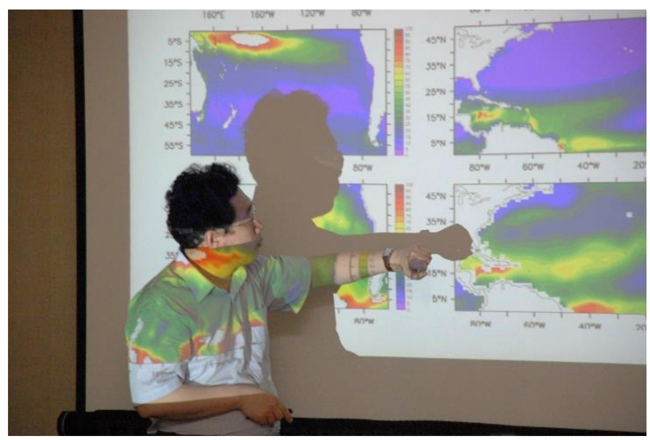
The session was co-convened by Drs. Enrique Curchitser (Rutgers University, USA) and Chan Joo Chang (KIOST, Korea) and had three invited speakers, Drs. Michael Foreman (Institute of Ocean Sciences, Canada), Arthur Miller (Scripps Institution of Oceanography, USA) and Takashi Mochizuki (JAMSTEC, Japan) and a total of 11 contributed papers. In the first invited presentation, given at the plenary session, Dr. Foreman described new techniques for downscaling climate projections for coastal, coupled physical–biological studies. The technique relies on bias correction of winds from global-scale future projections based on seasonal historical patterns. He demonstrated an application of this technique to the coast of British Columbia where both wind magnitude and direction are crucial to determining the patterns of coastal circulation.

Co-Convenor, Dr. Chan Joo Jang (KIOST, Korea), introducing the list of presentations for the theme session.

Dr. Miller presented results from a coupled ocean–atmosphere regional model of the Kuroshio Extension region, which is characterized by energetic oceanic eddies and fronts. He explored mechanisms for air–sea coupling of high-resolution components and highlighted the important role of the ocean in forcing the atmosphere on regional scales.

Dr. Mochizuki discussed the role of internal model variability to future projections using global models, in particular for the coming decades. He concluded that accurate initial and boundary conditions are essential for developing reliable decadal-scale climate projections.

Other abstracts in the session considered diverse topics and approaches: Downscaled projections of future climate in the California Current (Dr. Francisco Werner); the role of model resolution on the air–sea CO_2 exchange (Dr. Jerome Fiechter *et al.*); regional biogeochemical downscaling in coastal British Columbia (Dr. Angelica Peña *et al.*); ensemble regional predictions in the Bering Sea (Dr. Albert Hermann *et al.*); Dynamical downscaling of global models in the western Pacific (Dr. Chan Joo Jang); the role of a wave mixing parameterization in improving projections (Dr. Fangli Qiao) and a look at a global 1/10° model.



Dr. Fangli Qiao (First Institute of Oceanography, State Oceanic Administration, China) comparing mixed layer depths of two different oceans with and without wave effects.

Overall, the presentations can be categorized into three main topics: 1) additional value (*e.g.*, addressing known biases, coastal currents, *etc*.) derived from regional climate models, 2) regional projections of future climate and 3) applications of regional downscaling to ecosystem studies.

The main topic during the open discussion period focused on the question of what resolution is desirable in regional studies. The participants noted that the answer may depend on the region and dynamics of interest. Furthermore, it may be necessary to adjust model resolution after an initial exploratory investigation. Another topic during the discussion was on the need and future of ensemble modeling in regional settings and the unique challenges that could emerge. Of note was the conversation on the expected number of ensemble members and the need for multi-model ensembles. Finally the participants discussed the topic of bias propagation from global to regional models and from physics to biogeochemistry. The discussion focused on ways to identify and quantify model biases in the different model components.

Dr. Enrique Curchitser (enrique@esm.rutgers.edu) is an Associate Professor at the Department of Environmental Sciences and the Institute of Marine and Coastal Sciences at Rutgers University, USA. His main research interests are at the intersection of climate and ecosystems. His current projects range from downscaled coupled bio-physical modeling in the California Current and Bering Sea, the impact of climate change on coral bleaching in the Coral Triangle and on the role of the Gulf Stream in the climate and social systems of the northeast U.S. He is a member of the PICES Physical Oceanography and Climate Committee, Working Group 27 on Climate Variability and Change in the North Pacific and co-chairs Working Group 29 on Regional Climate Modeling.

Dr. Joo Chan Jang (cjjang@kiost.ac) has been a Principal Research Scientist in the Ocean Circulation and Climate Research Division of the Korea Institute of Ocean Science and Technology since 2011. His research interests include analysis and modeling of climate change in the North Pacific Ocean, focusing on Korean waters, circulation–ecosystem couple modeling, and turbulence modeling. He is a member of the PICES Physical Oceanography and Climate Committee, Working Group 27 on Climate Variability and Change in the North Pacific and co-chairs Working Group 29 on Regional Climate Modeling.

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Jamieson, G. and Zhang, C.-I. (Eds.) 2005. Report of the Study Group on Ecosystem-Based Management Science and its Application to the North Pacific. **PICES Sci. Rep. No. 29**, 77 pp.

Brodeur, R. and Yamamura, O. (Eds.) 2005. Micronekton of the North Pacific. **PICES Sci. Rep. No. 30**, 115 pp.

Takeda, S. and Wong, C.S. (Eds.) 2006. Report of the 2004 Workshop on *In Situ* Iron Enrichment Experiments in the Eastern and Western Subarctic Pacific. **PICES Sci. Rep. No. 31**, 187 pp.

Miller, C.B. and Ikeda, T. (Eds.) 2006. Report of the 2005 Workshop on Ocean Ecodynamics Comparison in the Subarctic Pacific. **PICES Sci. Rep. No. 32**, 103 pp.

Kruse, G.H., Livingston, P., Overland, J.E., Jamieson, G.S., McKinnell, S. and Perry, R.I. (Eds.) 2006. Report of the PICES/NPRB Workshop on Integration of Ecological Indicators of the North Pacific with Emphasis on the Bering Sea. **PICES Sci. Rep. No. 33**, 109 pp.

Hollowed, A.B., Beamish, R.J., Okey, T.A. and Schirripa, M.J. (Eds.) 2008. Forecasting Climate Impacts on Future Production of Commercially Exploited Fish and Shellfish. **PICES Sci. Rep. No. 34**, 101 pp.

Beamish, R.J. (Ed.) 2008. Impacts of Climate and Climate Change on the Key Species in the Fisheries in the North Pacific. **PICES Sci. Rep. No. 35**, 217 pp.

Kashiwai, M. and Kantakov, G.A. (Eds.) 2009. Proceedings of the Fourth Workshop on the Okhotsk Sea and Adjacent Areas. **PICES Sci. Rep. No. 36**, 305 pp.

Jamieson, G., Livingston, P. and Zhang, C.-I. (Eds.) 2010. Report of Working Group 19 on Ecosystem-based Management Science and its Application to the North Pacific. **PICES Sci. Rep. No. 37**, 166 pp.

Pakhomov, E. and Yamamura, O. (Eds.) 2010. Report of the Advisory Panel on Micronekton Sampling Intercalibration Experiment. **PICES Sci. Rep. No. 38**, 108 pp.

Makino, M. and Fluharty, D.L. (Eds.) 2011. Report of the Study Group on Human Dimensions. **PICES Sci. Rep. No. 39**, 40 pp.

Foreman, M.G. and Yamanaka, Y. (Eds.) 2011. Report of Working Group 20 on Evaluations of Climate Change Projections. **PICES Sci. Rep. No. 40**, 165 pp.

McKinnell, S.M., Curchitser, E., Groot, C., Kaeriyama, M. and Myers, K.W. 2012. PICES Advisory Report on the Decline of Fraser River Sockeye Salmon *Oncorhynchus nerka* (Steller, 1743) in Relation to Marine Ecology. **PICES Sci. Rep. No. 41**, 149 pp.

Takeda, S., Chai, F. and Nishioka, J. (Eds.) 2013. Report of Working Group 22 on Iron Supply and its Impact on Biogeochemistry and Ecosystems in the North Pacific Ocean. **PICES Sci. Rep. No. 42**, 60 pp.

Shaw, C.T., Peterson, W.T. and Sun, S. (Eds.) 2013. Report of Working Group 23 on Comparative Ecology of Krill in Coastal and Oceanic Waters around the Pacific Rim. **PICES Sci. Rep. No. 43**, 100 pp.

Abo, K., Burgetz, I. and Dumbauld, B. (Eds.) 2013. Report of Working Group 24 on Environmental Interactions of Marine Aquaculture. **PICES Sci. Rep. No. 44**, 122 pp.

Hollowed, A.B., Kim, S., Barange, M. and Loeng, H. (Eds.) 2013. Report of the PICES/ICES Working Group on Forecasting Climate Change Impacts on Fish and Shellfish. **PICES Sci. Rep. No. 45**, 197 pp.

Ross, P.S. (Ed.) 2013. Report of the Study Group on Marine Pollutants. **PICES Sci. Rep. No. 46**, 49 pp.

Trainer, V.L. and Yoshida, T. (Eds.) 2014. Proceedings of the Workshop on Economic Impacts of Harmful Algal Blooms on Fisheries and Aquaculture. **PICES Sci. Rep. No. 47**, 85 pp.

Kestrup, Åsa M., Smith, D.L. and Therriault, T.W. (Eds.) 2015. Report of Working Group 21 on Non-indigenous Aquatic Species. **PICES Sci. Rep. No. 48**, 176 pp.

Curtis, J.M.R. (Ed.) 2015. Report of the Study Group on Biodiversity Conservation. **PICES Sci. Rep. No. 49**, 61 pp.

Watanuki, Y., Suryan, R.M., Sasaki, H., Yamamoto, T., Hazen, E.L., Renner, M., Santora, J.A., O'Hara, P.D. and Sydeman, W.J. (Eds.) 2016. Spatial Ecology of Marine Top Predators in the North Pacific: Tools for Integrating across Datasets and Identifying High Use Areas. **PICES Sci. Rep. No. 50**, 55 pp.

Uye, S.I. and Brodeur, R.D. (Eds.) 2017. Report of Working Group 26 on Jellyfish Blooms around the North Pacific Rim: Causes and Consequences. **PICES Sci. Rep. No. 51**, 221 pp.

Makino. M. and Perry. R.I. (Eds.) 2017. Marine Ecosystems and Human Well-being: The PICES-Japan MAFF MarWeB Project. **PICES Sci. Rep. No. 52**, 235 pp.

Trainer, V.L. (Ed.) 2017. Conditions Promoting Extreme *Pseudo-nitzschia* Events in the Eastern Pacific but not the Western Pacific. **PICES Sci. Rep. No. 53**, 52 pp.

Jang, C.J. and Curchitser, E. (Eds.) 2018. Report of Working Group 29 on Regional Climate Modeling. **PICES Sci. Rep. No. 54**, 177 pp.

PICES Scientific Reports

Hargreaves, N.B., Hunter, J.R., Sugimoto, T. and Wada, T. (Eds.) 1993. Coastal Pelagic Fishes (Report of Working Group 3); Subarctic Gyre (Report of Working Group 6). **PICES Sci. Rep. No. 1**, 130 pp.

Talley, L.D. and Nagata, Y. (Eds.) 1995. The Okhotsk Sea and Oyashio Region (Report of Working Group 1). **PICES Sci. Rep. No. 2**, 227 pp.

Anonymous. 1995. Report of the PICES-STA Workshop on Monitoring Subarctic North Pacific Variability. **PICES Sci. Rep. No. 3**, 94 pp.

Hargreaves, N.B. (Ed.) 1996. Science Plan, Implementation Plan (Report of the PICES-GLOBEC International Program on Climate Change and Carrying Capacity). **PICES Sci. Rep. No. 4**, 64 pp.

LeBlond, P.H. and Endoh, M. (Eds.) 1996. Modelling of the Subarctic North Pacific Circulation (Report of Working Group 7). **PICES Sci. Rep. No. 5**, 91 pp.

Anonymous. 1996. Proceedings of the Workshop on the Okhotsk Sea and Adjacent Areas. **PICES Sci. Rep. No. 6**, 426 pp.

Beamish, R.J., Hollowed, A.B., Perry, R.I., Radchenko, V.I., Yoo, S. and Terazaki, M. (Eds.) 1997. Summary of the Workshop on Conceptual/Theoretical Studies and Model Development and the 1996 MODEL, BASS and REX Task Team Reports. **PICES Sci. Rep. No. 7**, 93 pp.

Nagata, Y. and Lobanov, V.B. (Eds.) 1998. Multilingual Nomenclature of Place and Oceanographic Names in the Region of the Okhotsk Sea. **PICES Sci. Rep. No. 8**, 57 pp. (Reprint from MIRC Science Report, No. 1, 1998)

Hollowed, A.B., Ikeda, T., Radchenko, V.I. and Wada, T. (Organizers) 1998. PICES Climate Change and Carrying Capacity Workshop on the Development of Cooperative Research in Coastal Regions of the North Pacific. **PICES Sci. Rep. No. 9**, 59 pp.

Freeland, H.J., Peterson, W.T. and Tyler, A. (Eds.) 1999. Proceedings of the 1998 Science Board Symposium on The Impacts of the 1997/98 El Niño Event on the North Pacific Ocean and Its Marginal Seas. **PICES Sci. Rep. No. 10**, 110 pp.

Dugdale, R.C., Hay, D.E., McFarlane, G.A., Taft, B.A. and Yoo, S. (Eds.) 1999. PICES-GLOBEC International Program on Climate Change and Carrying Capacity: Summary of the 1998 MODEL, MONITOR and REX Workshops, and Task Team Reports. **PICES Sci. Rep. No. 11**, 88 pp.

Lobanov, V.B., Nagata, Y. and Riser, S.C. (Eds.) 1999. Proceedings of the Second PICES Workshop on the Okhotsk Sea and Adjacent Areas. **PICES Sci. Rep. No. 12**, 203 pp.

Danchenkov, M.A., Aubrey, D.G. and Hong, G.H. 2000. Bibliography of the Oceanography of the Japan/East Sea. **PICES Sci. Rep. No. 13**, 99 pp.

Hunt, G.L. Jr., Kato, H. and McKinnell, S.M. (Eds.) 2000. Predation by Marine Birds and Mammals in the Subarctic North Pacific Ocean. **PICES Sci. Rep. No. 14**, 168 pp.

Megrey, B.A., Taft, B.A. and Peterson, W.T. (Eds.) 2000. PICES-GLOBEC International Program on Climate Change and Carrying Capacity: Report of the 1999 MONITOR and REX Workshops, and the 2000 MODEL Workshop on Lower Trophic Level Modelling. **PICES Sci. Rep. No. 15**, 148 pp.

Stehr, C.M. and Horiguchi, T. (Eds.) 2001. Environmental Assessment of Vancouver Harbour Data Report for the PICES MEQ Practical Workshop. **PICES Sci. Rep. No. 16**, 213 pp.

Megrey, B.A., Taft, B.A. and Peterson, W.T. (Eds.) 2001. PICES-GLOBEC International Program on Climate Change and Carrying Capacity: Report of the 2000 BASS, MODEL, MONITOR and REX Workshops, and the 2001 BASS/MODEL Workshop. **PICES Sci. Rep. No. 17**, 125 pp.

Alexander, V., Bychkov, A.S., Livingston, P. and McKinnell, S.M. (Eds.) 2001. Proceedings of the PICES/CoML/IPRC Workshop on "Impact of Climate Variability on Observation and Prediction of Ecosystem and Biodiversity Changes in the North Pacific". **PICES Sci. Rep. No. 18**, 210 pp.

Otto, R.S. and Jamieson, G.S. (Eds.) 2001. Commercially Important Crabs, Shrimps and Lobsters of the North Pacific Ocean. **PICES Sci. Rep. No. 19**, 79 pp.

Batchelder, H.P., McFarlane, G.A., Megrey, B.A., Mackas, D.L. and Peterson, W.T. (Eds.) 2002. PICES-GLOBEC International Program on Climate Change and Carrying Capacity: Report of the 2001 BASS/MODEL, MONITOR and REX Workshops, and the 2002 MODEL/REX Workshop. **PICES Sci. Rep. No. 20**, 176 pp.

Miller, C.B. (Ed.) 2002. PICES-GLOBEC International Program on Climate Change and Carrying Capacity: Report of the PICES 2002 Volunteer Observing Ship Workshop. **PICES Sci. Rep. No. 21**, 38 pp.

Perry, R.I., Livingston, P. and Bychkov, A.S. (Eds.) 2002. PICES Science: The First Ten Years and a Look to the Future. **PICES Sci. Rep. No. 22**, 102 pp.

Taylor, F.J.R. and Trainer, V.L. (Eds.) 2002. Harmful Algal Blooms in the PICES Region of the North Pacific. **PICES Sci. Rep. No. 23**, 152 pp.

Feely, R.A. (Ed.) 2003. CO_2 in the North Pacific Ocean (Working Group 13 Final Report). **PICES Sci. Rep. No. 24**, 49 pp.

Aydin, K.Y., McFarlane, G.A., King, J.R. and Megrey, B.A. (Eds.) 2003. PICES-GLOBEC International Program on Climate Change and Carrying Capacity: The BASS/MODEL Report on Trophic Models of the Subarctic Pacific Basin Ecosystems. **PICES Sci. Rep. No. 25**, 93 pp.

McKinnell, S.M. (Ed.) 2004. Proceedings of the Third Workshop on the Okhotsk Sea and Adjacent Areas. **PICES Sci. Rep. No. 26**, 275 pp.

Kishi, M.J. (Ed.) 2004. Report of the MODEL Task Team Second Workshop to Develop a Marine Ecosystem Model of the North Pacific Ocean including Pelagic Fishes. **PICES Sci. Rep. No. 27**, 49 pp.

King, J.R. (Ed.) 2005. Report of the Study Group on the Fisheries and Ecosystem Responses to Recent Regime Shifts. **PICES Sci. Rep. No. 28**, 162 pp.

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Front cover figure

Domains and resolutions of the regional climate models developed by PICES member countries.