Effects of Climate Change on the World Ocean

The fundamental role of the surface wave in the ocean and climate systems

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Outline

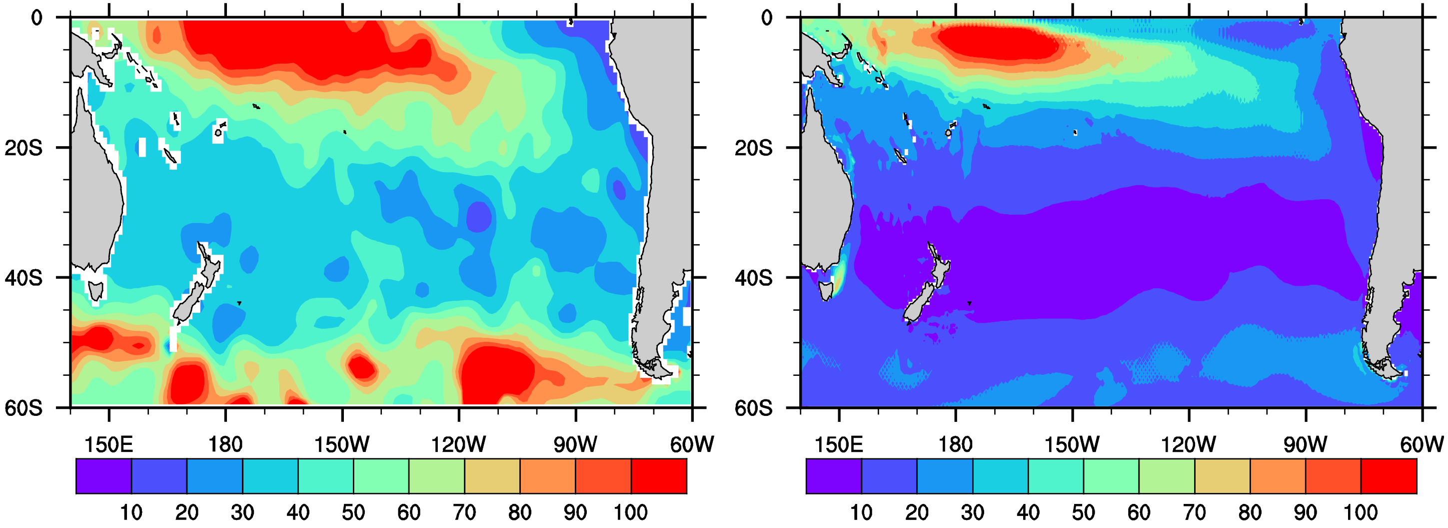
1. Background
2. Surface wave in ocean models
3. Surface wave in climate models
4. Summary

1. Background

Motivation

Common problems faced by OGCM:

(1) OGCMs: Simulated SST is overheating in summertime, and mixed layer depth is too shallow while the thermocline is too weak (Martin 1985, Kantha 1994, Ezer 2000, Mellor 2003).

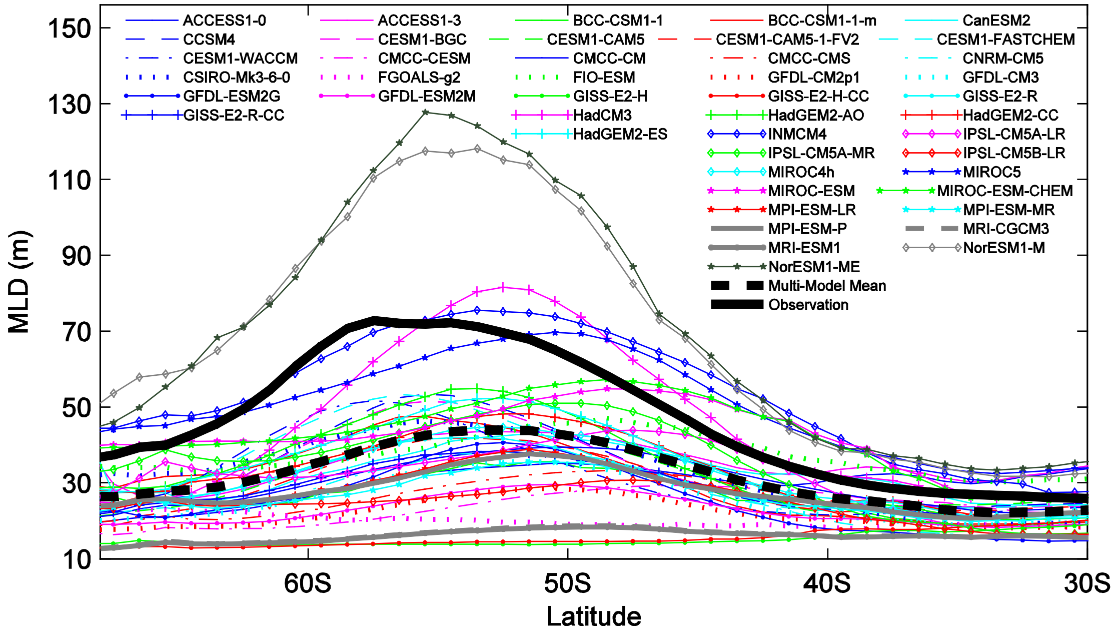


Observed (left) and simulated (right) MLD in Feb

Motivation

Common problems faced by climate models:

(2) Climate Models: Tropical bias for all CGCMs, such as too cold tongue, wrong Atlantic SST gradient and MLD



Observed ocean MLD (solid back) and 45 CMIP5 models MMM (dashed black)

Scientific clue: Lack of vertical mixing in the upper ocean

Ocean mixing is a problem of energy.

Surface wave: 60TW, while circulation is about 4TW.

Some related work: Breaking

1. Phillips, O. M. , 1961: "Although the use of potential theory has been very successful in describing certain aspects of the dynamics of gravity waves, it is known that in a real fluid the motion can not be truly irrotational". And Phillips (1974): **Wave is proved to be too feeble for any dynamic consequence**

2. Wave enhanced turbulence (Craig & Banner,1994; Terray, E.A. et al, 1996; Le Ngoc LY 2000; Burchard &Karsten, 2001; Mellor & Blumberg, 2004): Wave-breaking

3. Wave-current interaction (Xie et al 2002, 2003): 2-D

4. Mellor et al, 2003JPO, and 2008 J. Atmos. Ocean. Technol [wave breaking]

While these studies (wave-breaking) have shown some improvements in simulation, the surface wave effects are mostly limited to the top few meters, and too weak

Some related work: Non-breaking

5. In 2004, we proposed wave-induced vertical mixing, Bv, as the function of wave number spectrum.

6. In 2005 and 2006 (GRL), Alex Babanin: There is accumulating evidence that in absence of wave breaking, and even wind stress, turbulence still persists through the water column and not only the boundary layers.

7. The non-breaking wave-induced mixing was measured in Lab (Babanin et al, 2009, JPO; Dai et al, 2010, JPO; Savalyev et al, 2012, JGR) and in the ocean (Huang et al, 2010, 2012).

Separate the velocity field into averaged and fluctuation components

$$u_{zi} = U_i + u_i, \quad T_z = T + \theta, \quad S_z = S + s$$

Separate the fluctuation velocity into wave-related and current-related parts:

$$u_i = \boxed{u_{iw}} + u_{ic}$$

Reynolds stress

$$-\overline{u_i u_j} = \underbrace{-\overline{u_{iw} u_{jw}}}_{\text{Wave-induced stress}} \underbrace{\boxed{-\overline{u_{iw} u_{jc}} - \overline{u_{ic} u_{jw}}}}_{\text{Wave Effects}} \underbrace{-\overline{u_{ic} u_{jc}}}_{\text{Reynolds stress}}$$

$$-\overline{u_i\theta} = -\overline{u_{iw}\theta} - \overline{u_{ic}\theta}$$

$$-\overline{u_iS} = -\overline{u_{iw}S} - \overline{u_{ic}S}$$

Wave-induced

Circulation-related

$$B_V = \alpha \iint_{\vec{k}} E\left(\vec{k}\right) \exp\left\{2kz\right\} d\vec{k} \, \frac{\partial}{\partial z} \left(\iint_{\vec{k}} \omega^2 E\left(\vec{k}\right) \exp\left\{2kz\right\} d\vec{k} \right)^{1/2}$$

E(K) is the wave number spectrum which can be calculated from a wave numerical model. It will change with (x, y, t), so Bv is the function of (x, y, z, t).

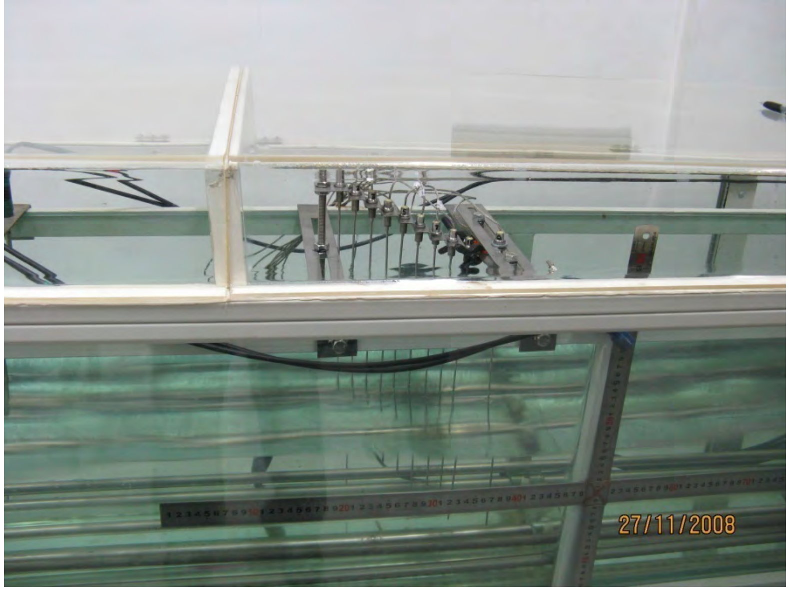
Qiao et al, GRL, 2004; OD, 2010

If we regard surface wave as a monochramatic wave,

$$B_v = \alpha A^3 k \omega \, e^{(-3kz)} = \alpha A \, u_s \, e^{(-3kz)} \; ,$$

Stokes Drift (Qiao AOS, 2008)

Bv is wave motion related vertical mixing instead of wave breaking.



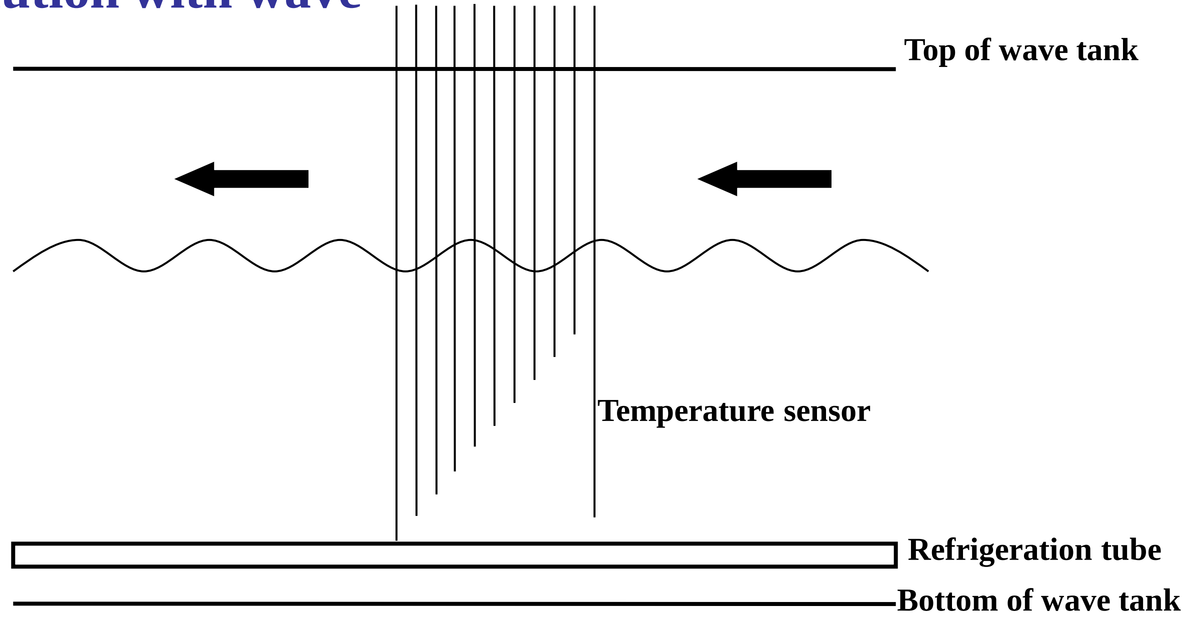
27/11/2008

Laboratory experiments:

Wave tank: 5m in length with height of 0.4m and width of 0.2m. To generate temperature gradient through bottom cooling of refrigeration tubes, and temperature sensors are self-recorded with sampling frequency of 1Hz.

(1) Temperature evolution in natural condition

(2) Temperature evolution with wave

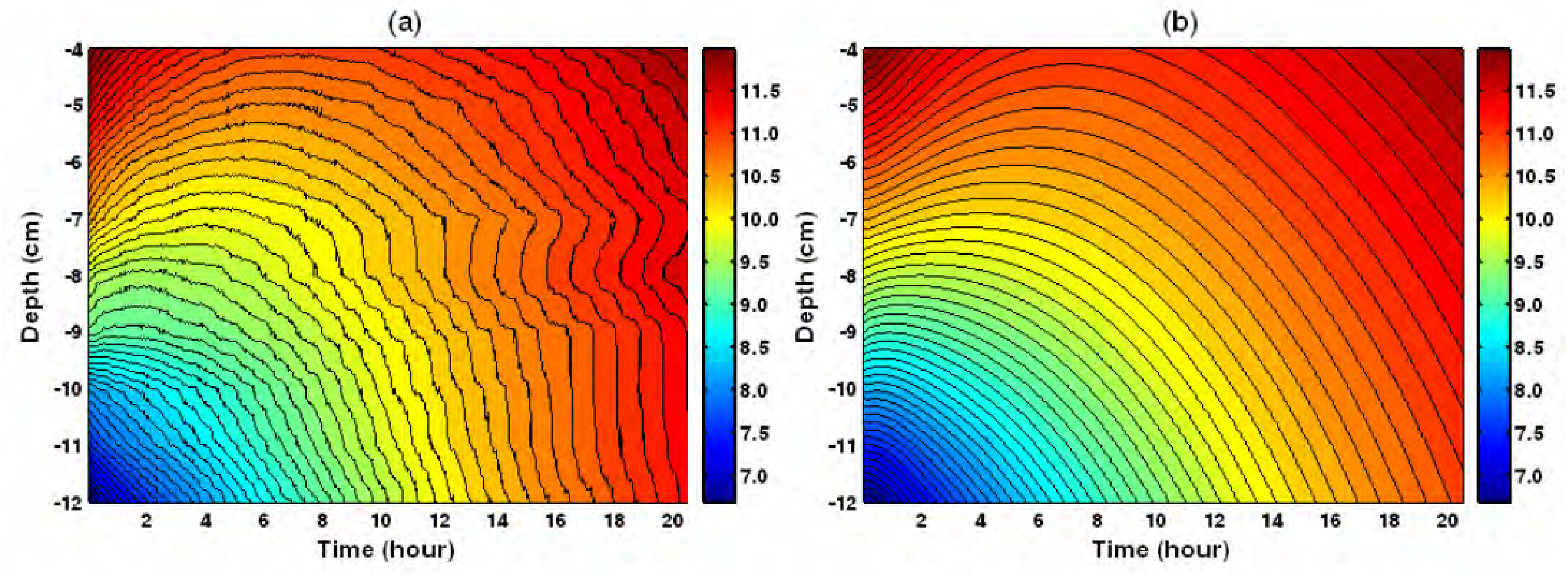


Dai et al, JPO, 2010

Experiment results without and with waves

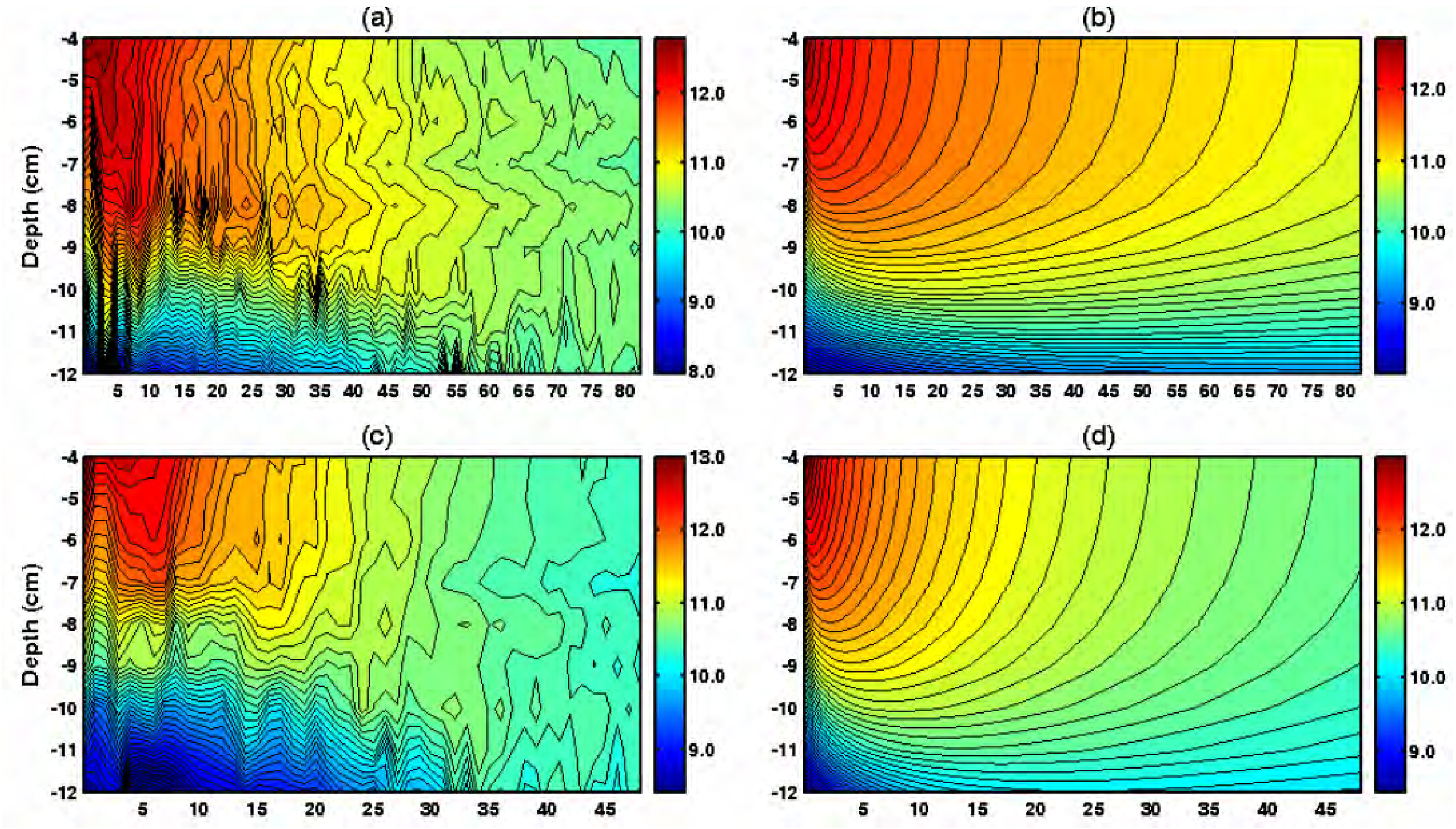
$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right)$$

kz=k0+Bv



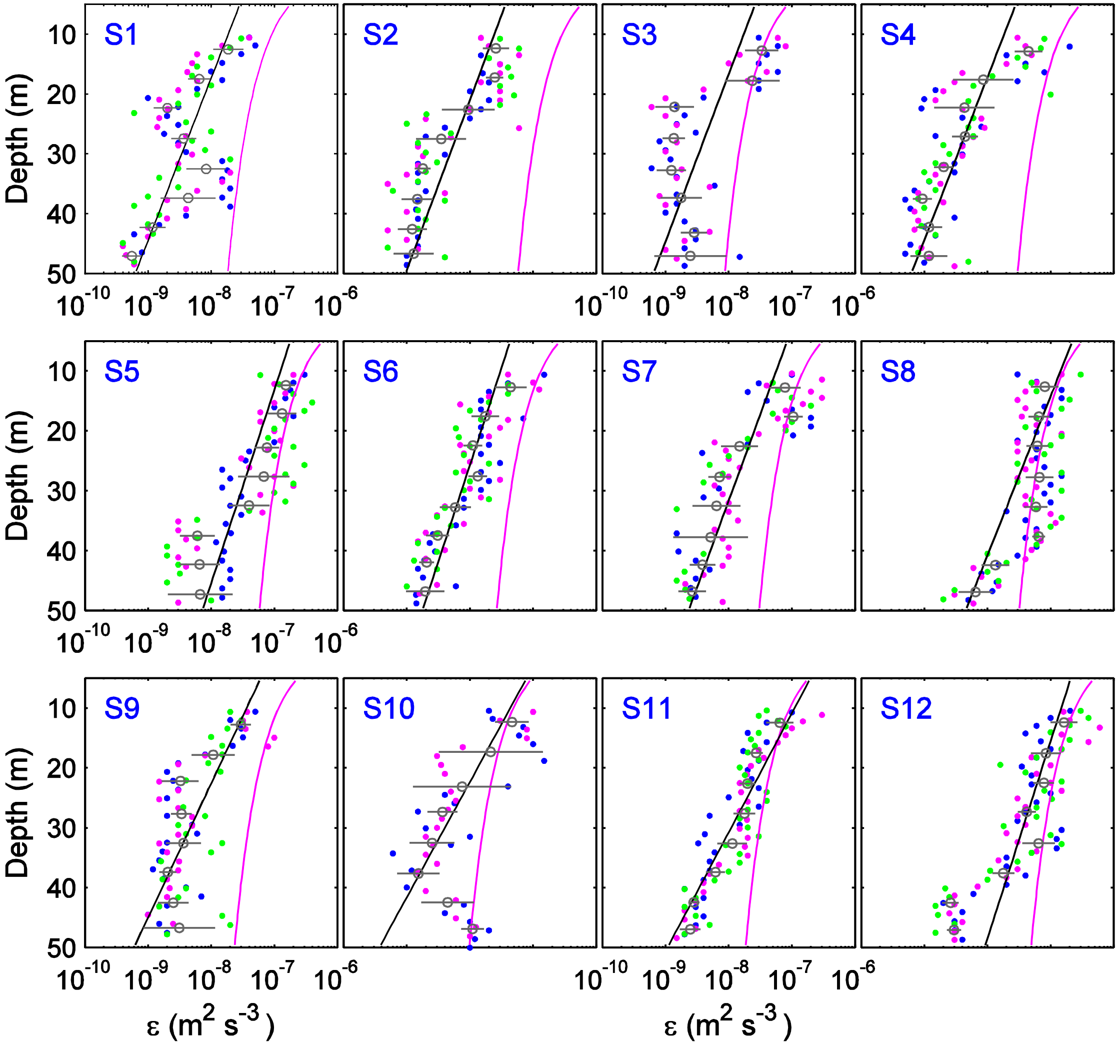
Evolution of water temperature without waves.
(a) Observation; (b) simulation.

Simulation results with waves



Evolution of water temperature with waves. Left: observation; right: simulation; (a,b) 1.0cm, 30cm; (c,d) 1.0cm, 52cm;

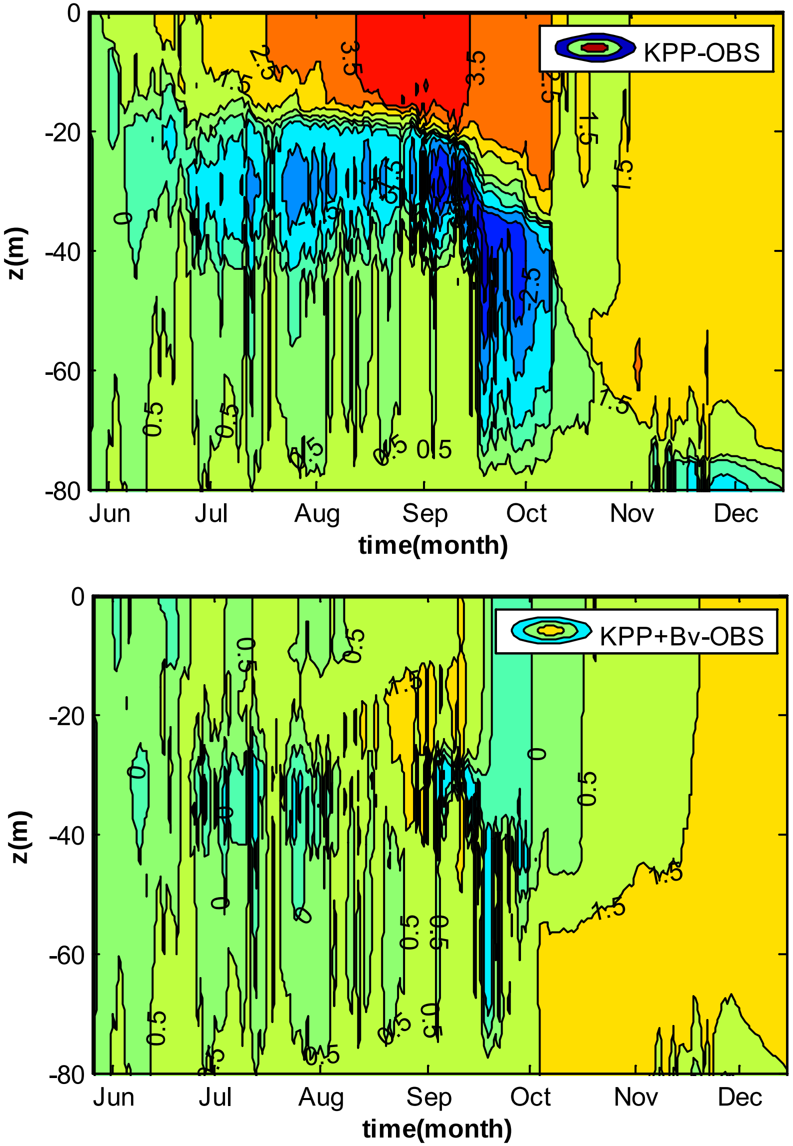
Observation evidences in deep water of SCS



Vertical profiles of the measured dissipation rates ε_m (dots), and those predicted by wave ε_{wave} (black lines) and the law of the wall ε_{wall} (pink lines) at Station S1~S12 (in m^2 s^{-3}). Observation is conducted in SCS during October 29 to November 10, 2010. Huang and Qiao et al, 2012, JGR

2. Surface wave in ocean models

1-D numerical models



KPP

KPP+Bv

The simulation deviation for Papa Station in 2007

3-D coastal circulation model (Special Issue on JGR, 2006 at http://www.agu.org/journals/ ss/CHINASEAS1/)

We apply Bv into:

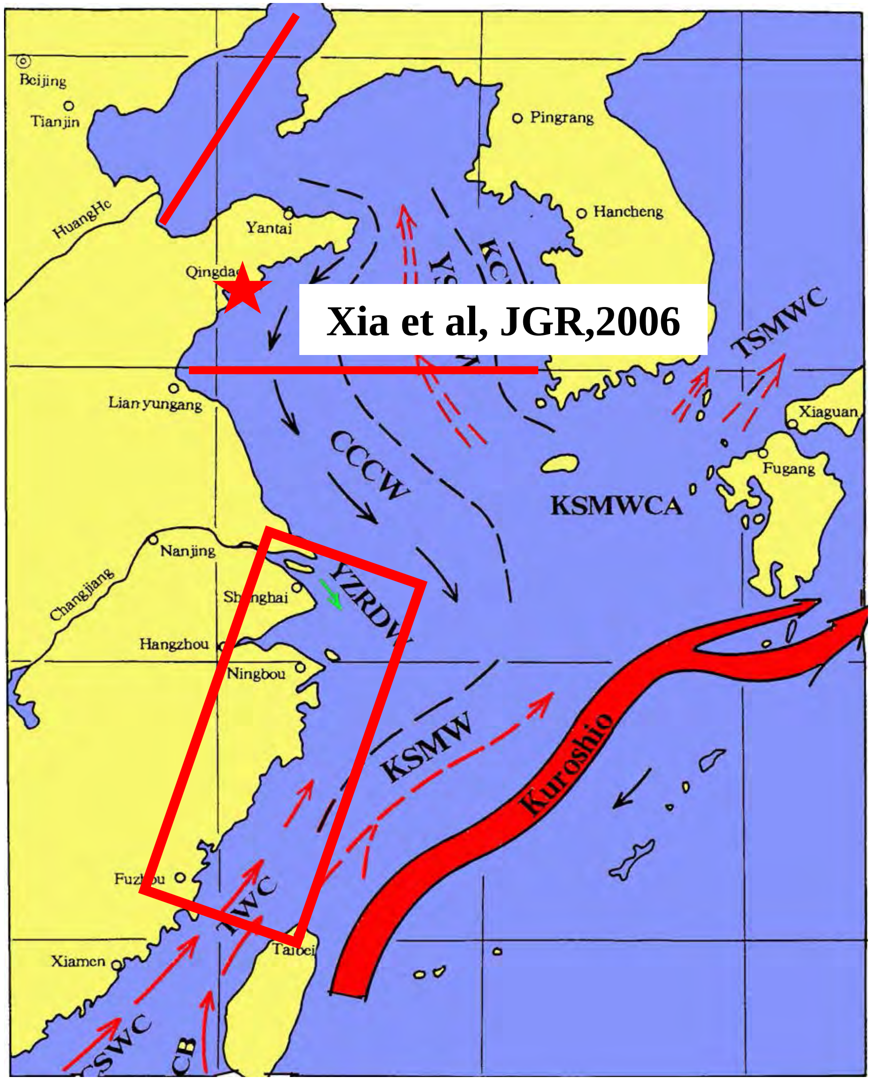
Bohai Sea

Yellow Sea

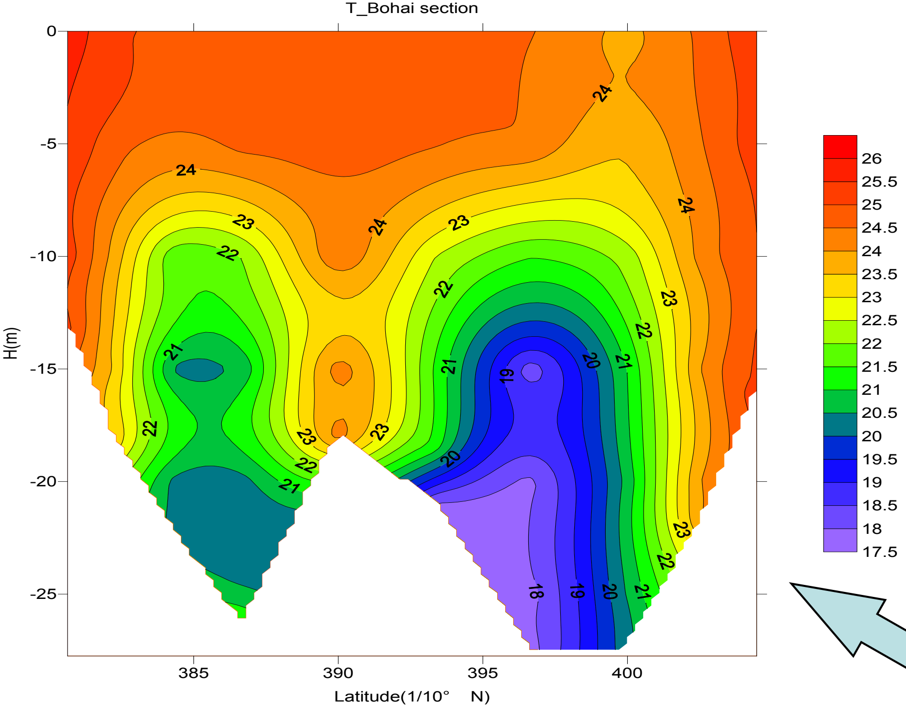
East China Sea

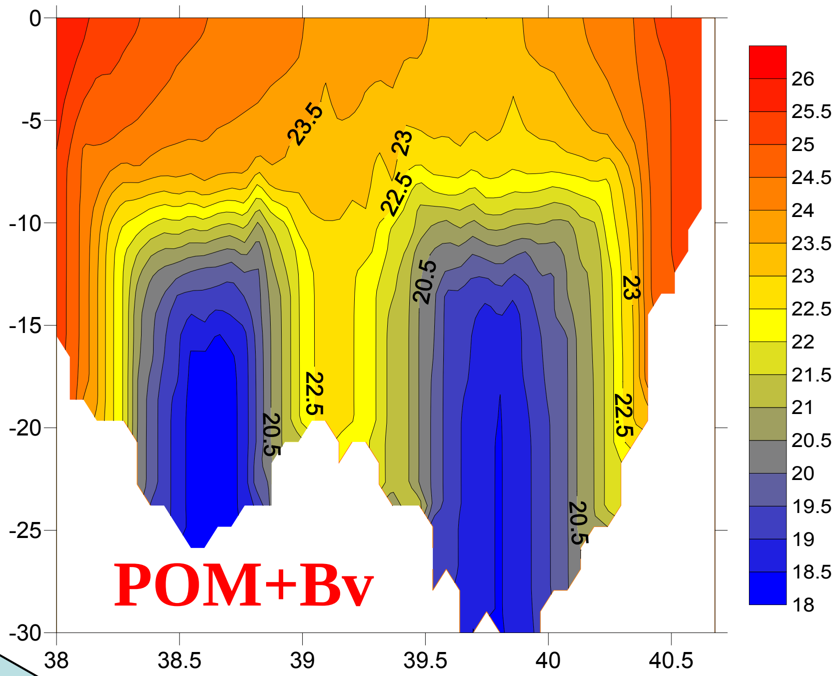
And

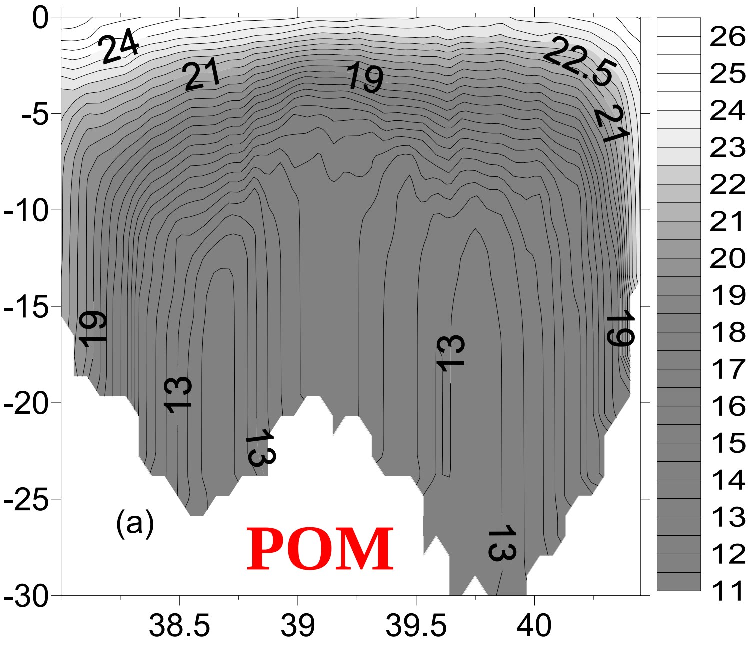
South China Sea



Xia et al, JGR,2006

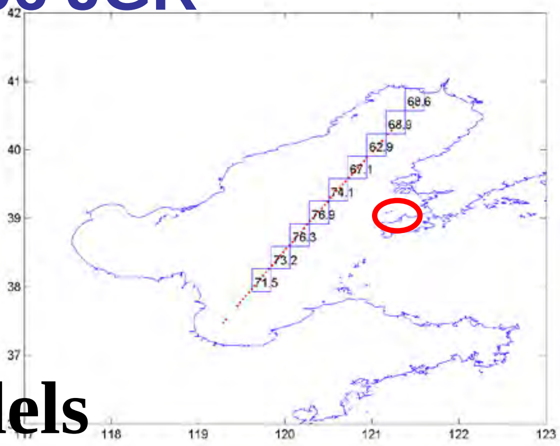






Observation in summer

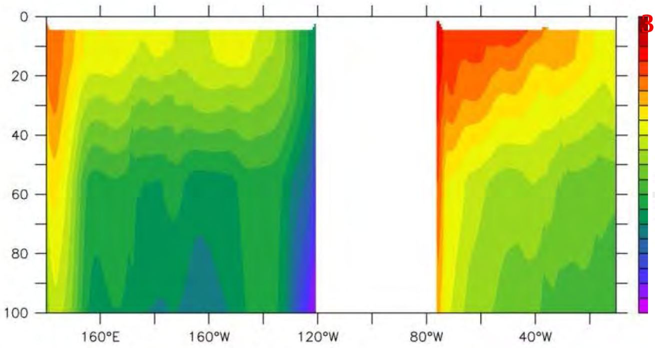
Lin et al, 2006 JGR



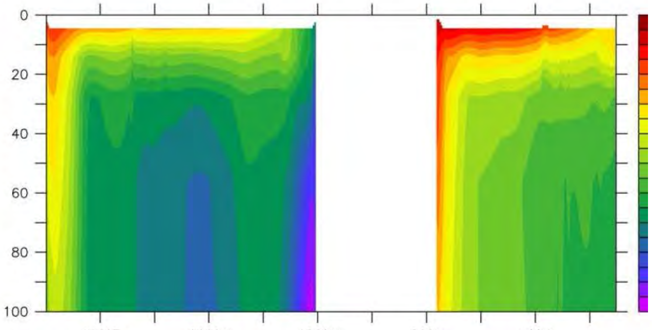
3-D coastal models

3-D global ocean circulation models

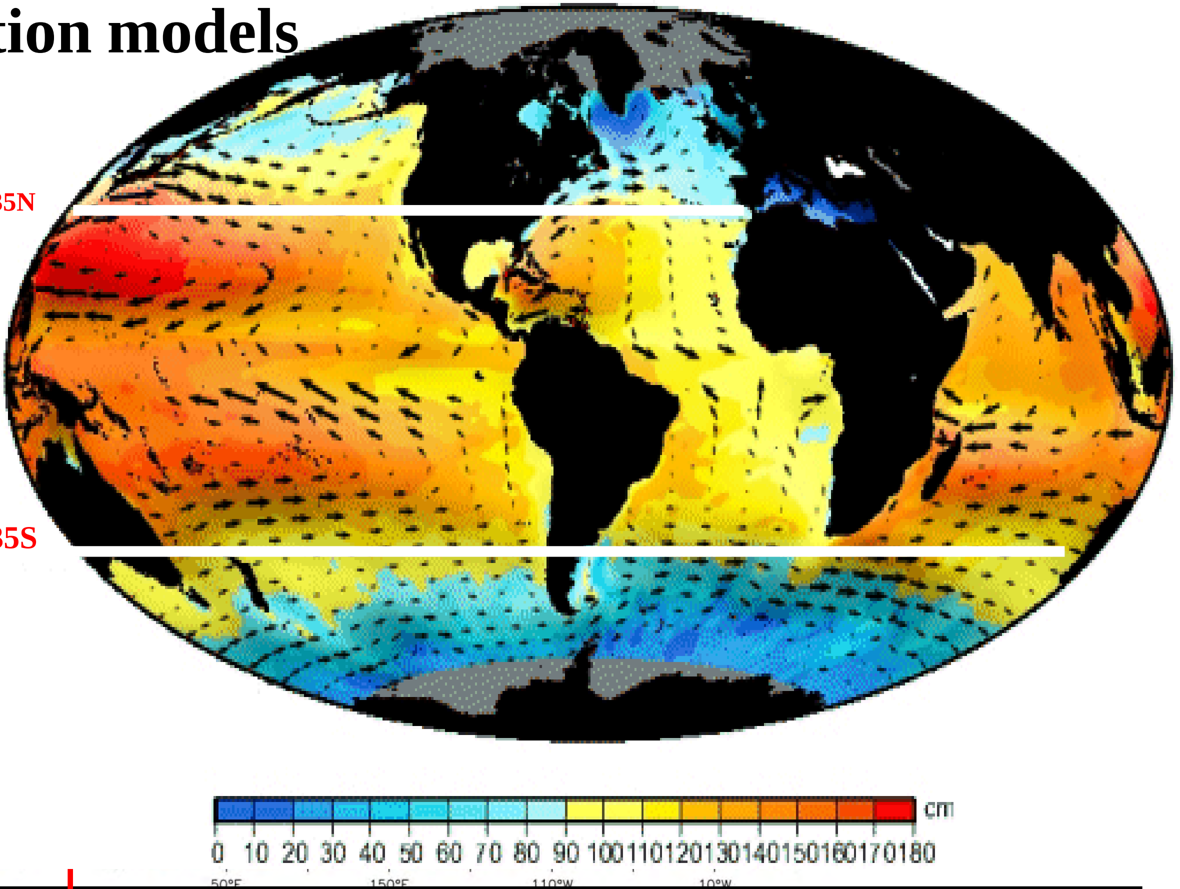
Pacific **Atlantic**

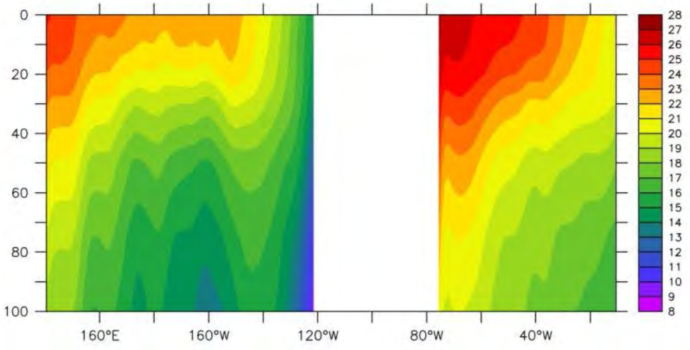


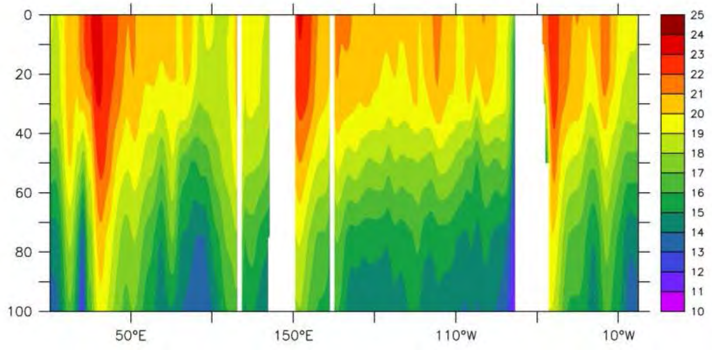
35N



35S







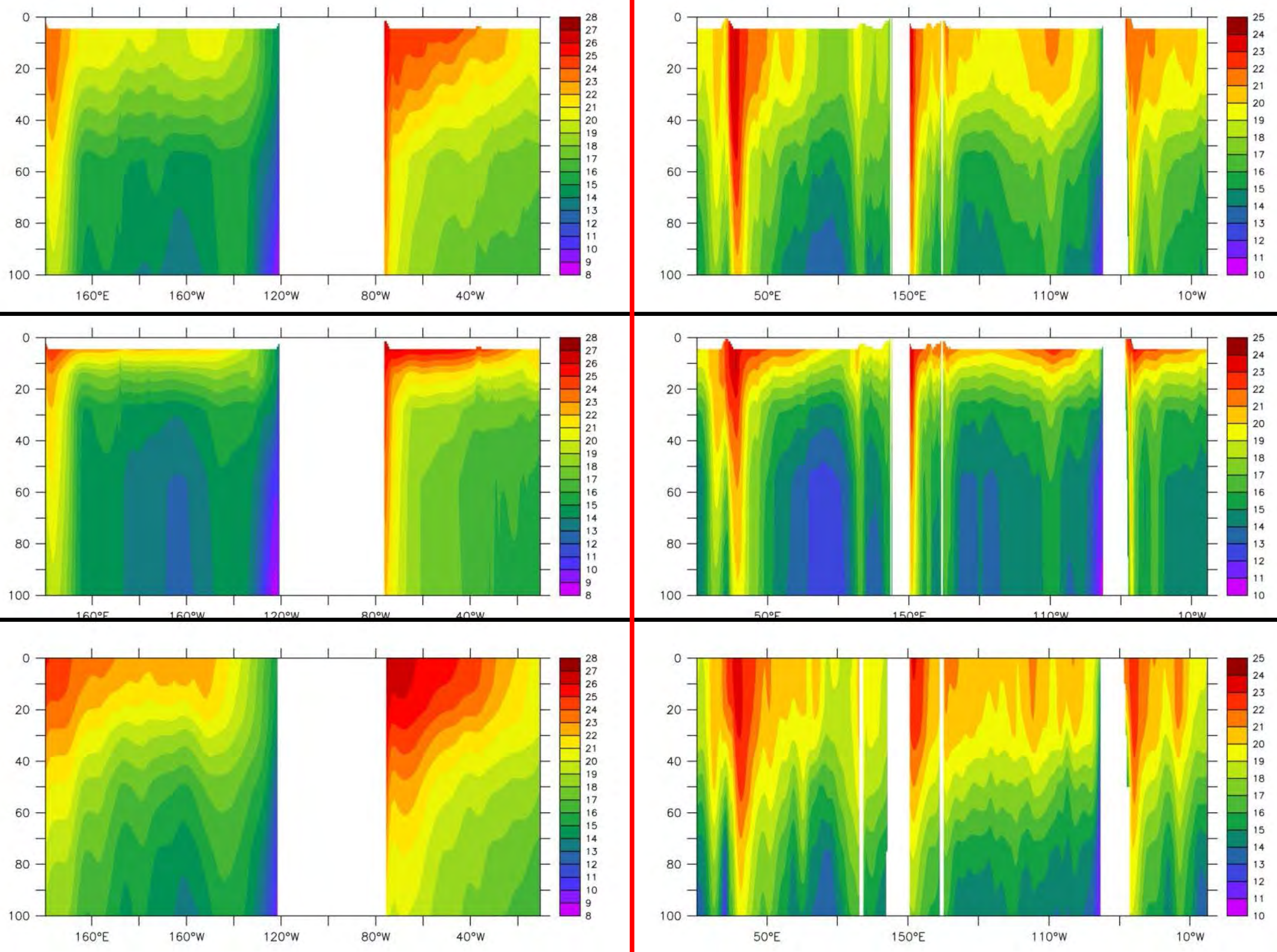
World Ocean Atlas

Along 35N transect in Aug.

Along 35S transect in Feb.

Vertical Temperature Distributions

Pacific **Atlantic** | **Indian** **Pacific** **Atlantic**



With
wave-induce mixing

Without
wave-induce mixing

World Ocean Atlas

Along 35N transect in Aug.

Along 35S transect in Feb.

How about to close the shear-induced mixing?

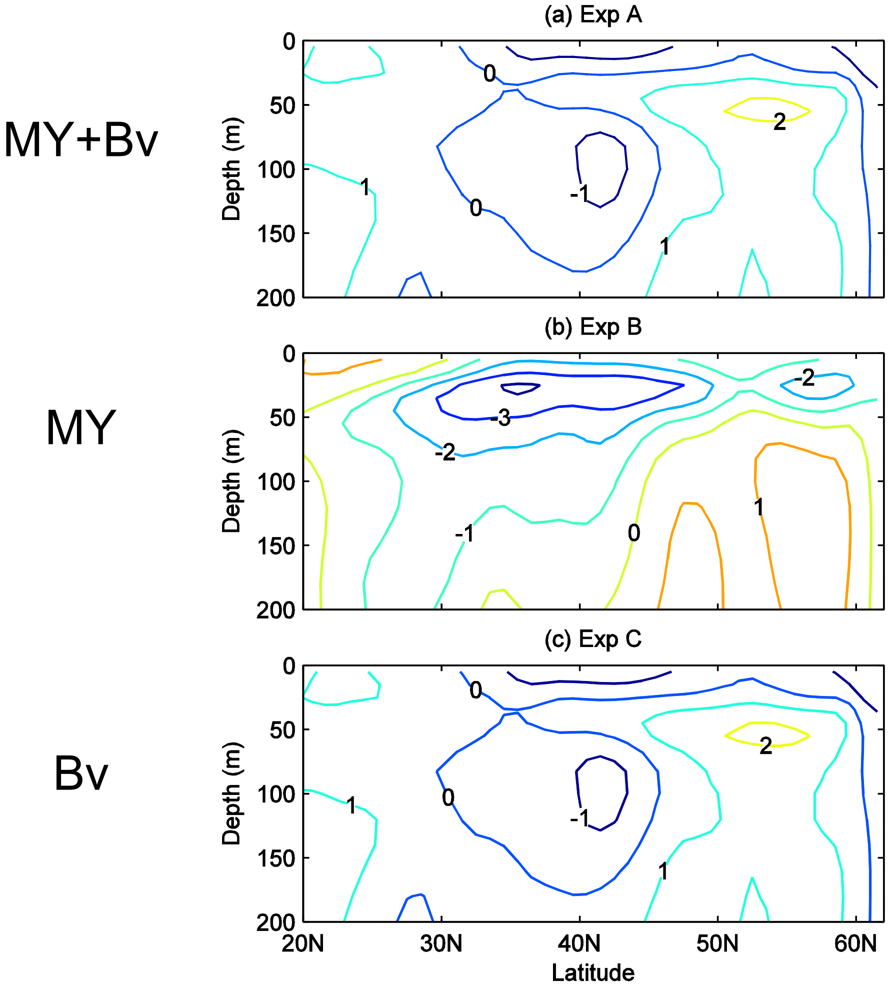
$$\frac{D}{Dt}\left(\frac{q^2}{2}\right) - \frac{\partial}{\partial z}\left[K_q \frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right] = P_S + P_b - \varepsilon,$$

(Mellor and Yamada, 1982)

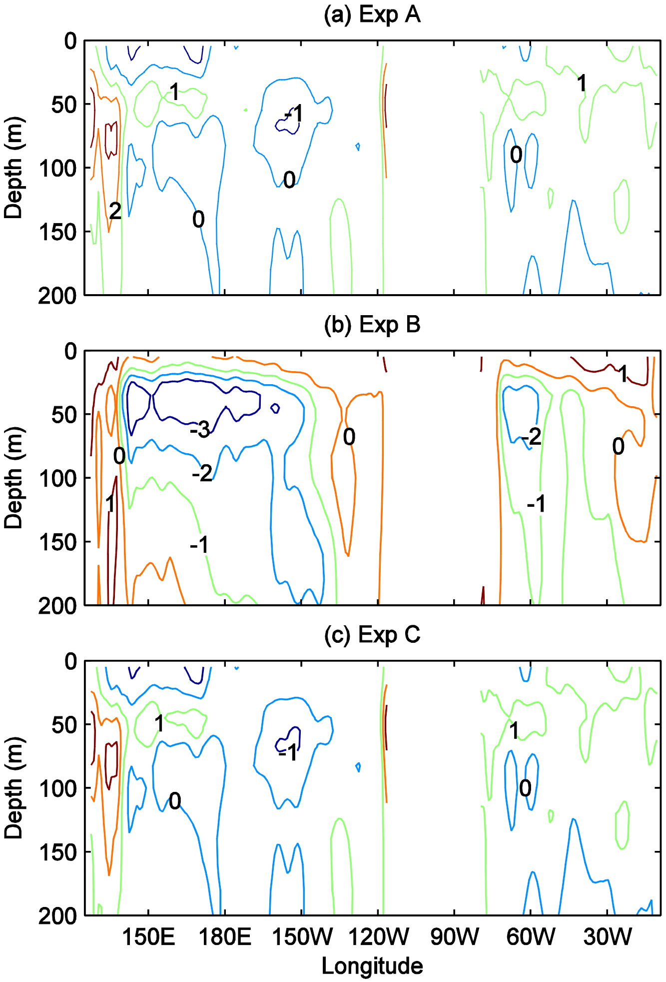
Numerical experiments for closing the shear-related vertical mixing
POM covering 72ºS -65ºN is selected;
Zonal resolution 1º, while meridional resolution is 1/3º between 10ºS-10ºN, and gradually increases to 1º by 20ºN and 20ºS;
32 sigma levels;
The background mixing of 1×10^{-4} m^2 s^{-1} (K_{m0}) for viscosity and 1×10^{-5} m^2 s^{-1} (K_{h0}) for diffusivity.

Experiment A: MY(Ps) + MY(Pb) + Bv + BG
Experiment B: MY(Ps) + MY(Pb) + BG
Experiment C: MY(Pb) + Bv + BG

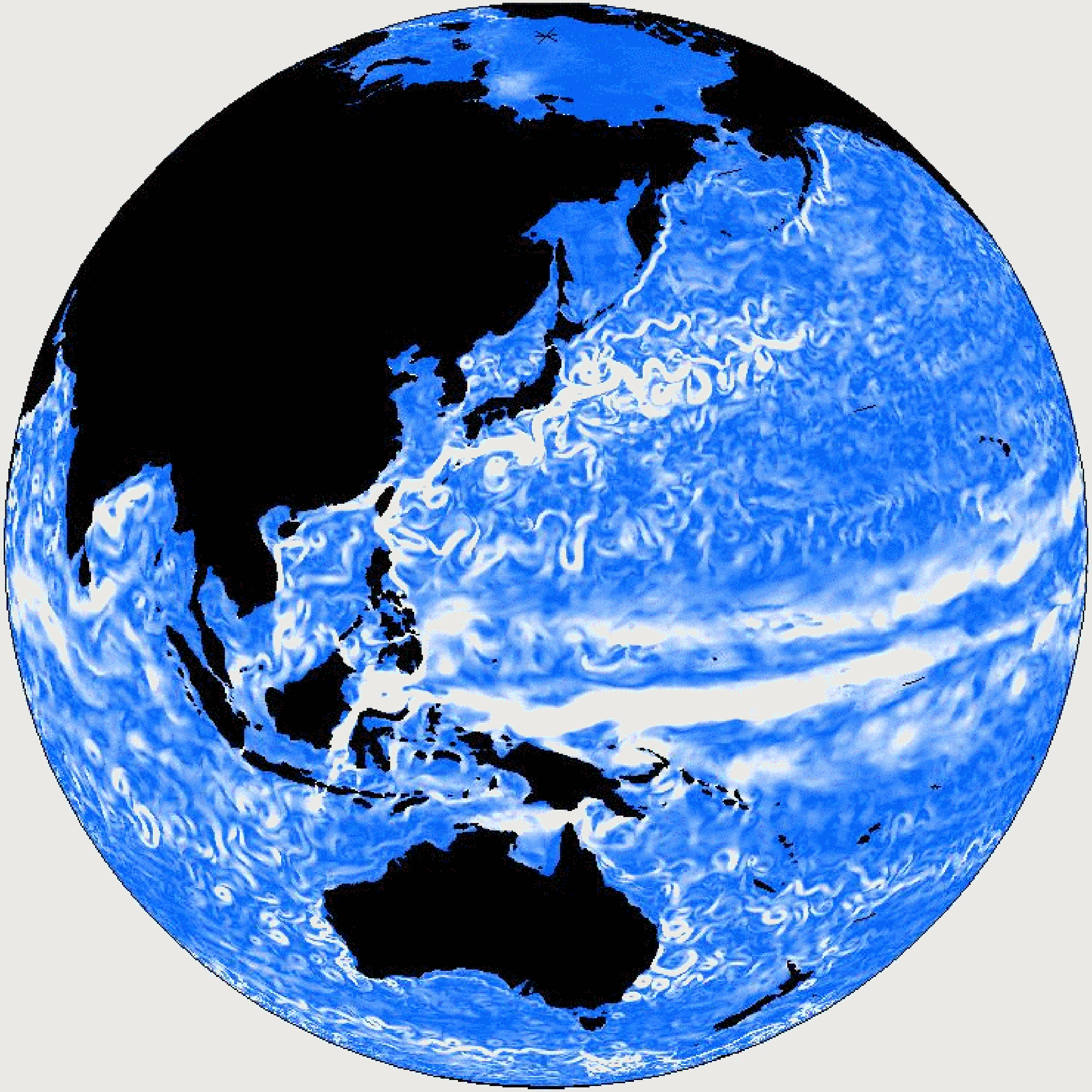
- Too cold subsurface temperature in Exp B
- Temperature difference in Exp C is very similar as that in Exp A



Temperature deviations from the climatology averaged in August along the dateline



Temperature deviationss from the climatology averaged in August along 30ºN



FIO wave-circulation coupled model with resolution of 0.1degree

3. Surface wave in climate models

In tropical area, Bv has no much improvements for the ocean circulation model compared with mid- and high latitudes. For full coupled climate model, it is a different story because of the feedback and nonlinearity.

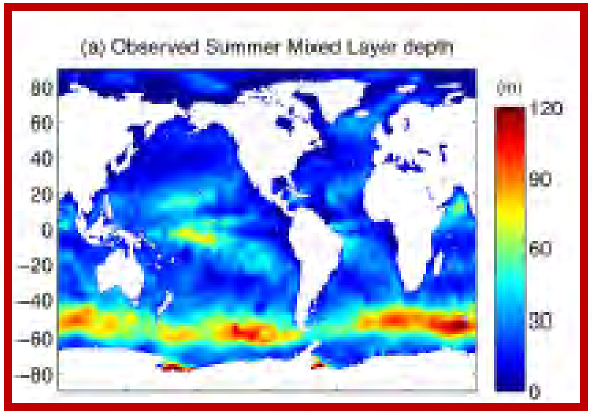
(1) FGCM0, LASG

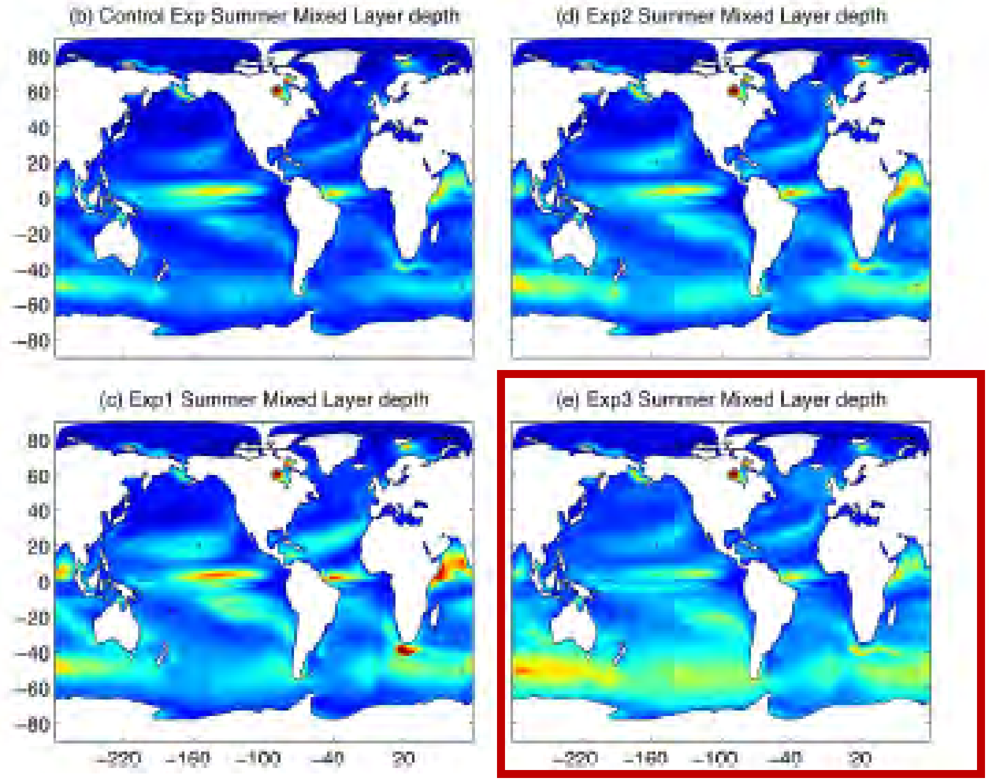
(2) CCSM3, NCAR

(3) FIO-ESM

Summertime oceanic mixed layers are biased shallow in both the GFDL and NCAR climate models (Bates et al. 2012; Dunne et al. 2012, 2013).

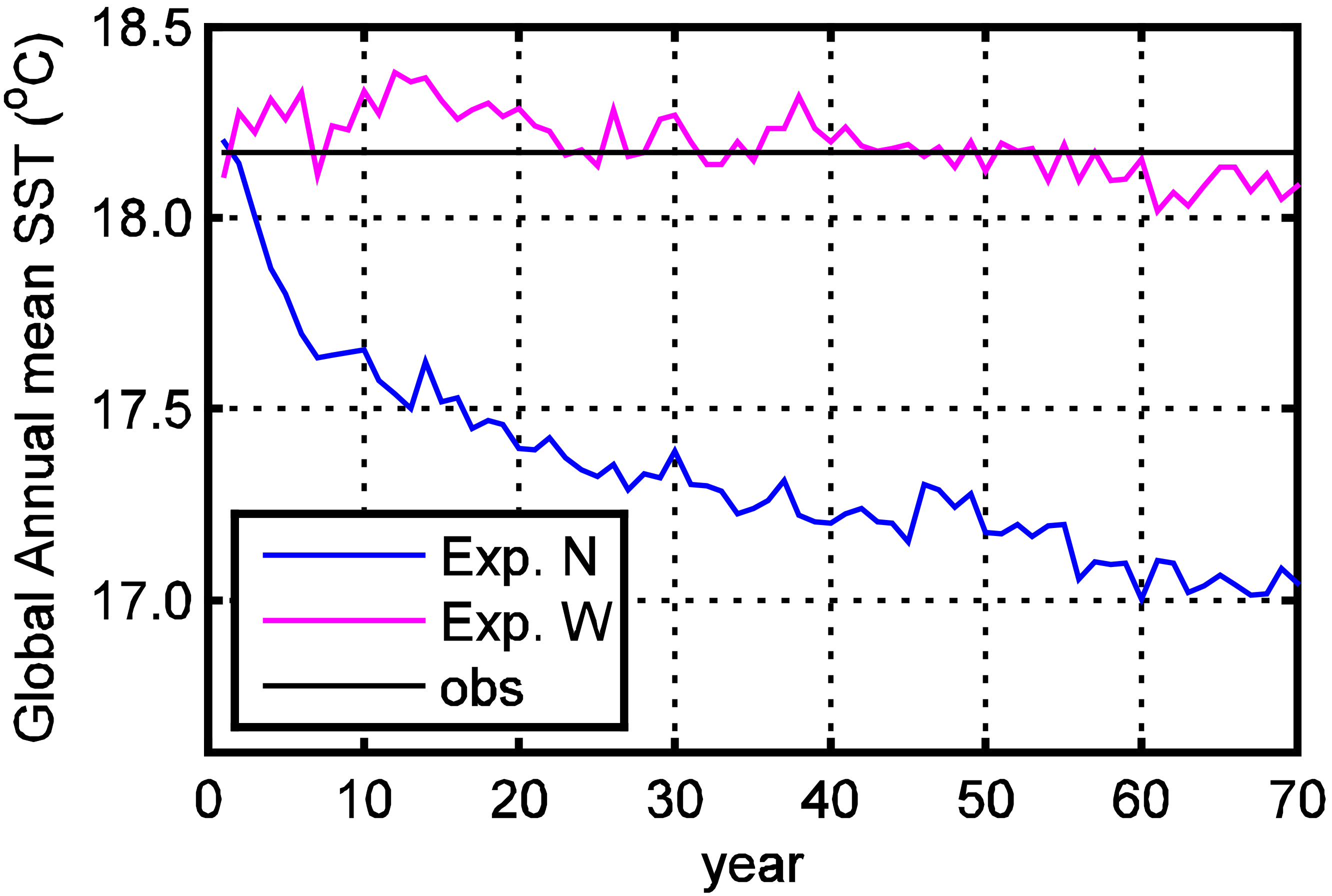
This scheme (Qiao et al., 2004) has most impact in our simulations on deepening the summertime mixed layers, yet it has minimal impact on wintertime mixed layers.





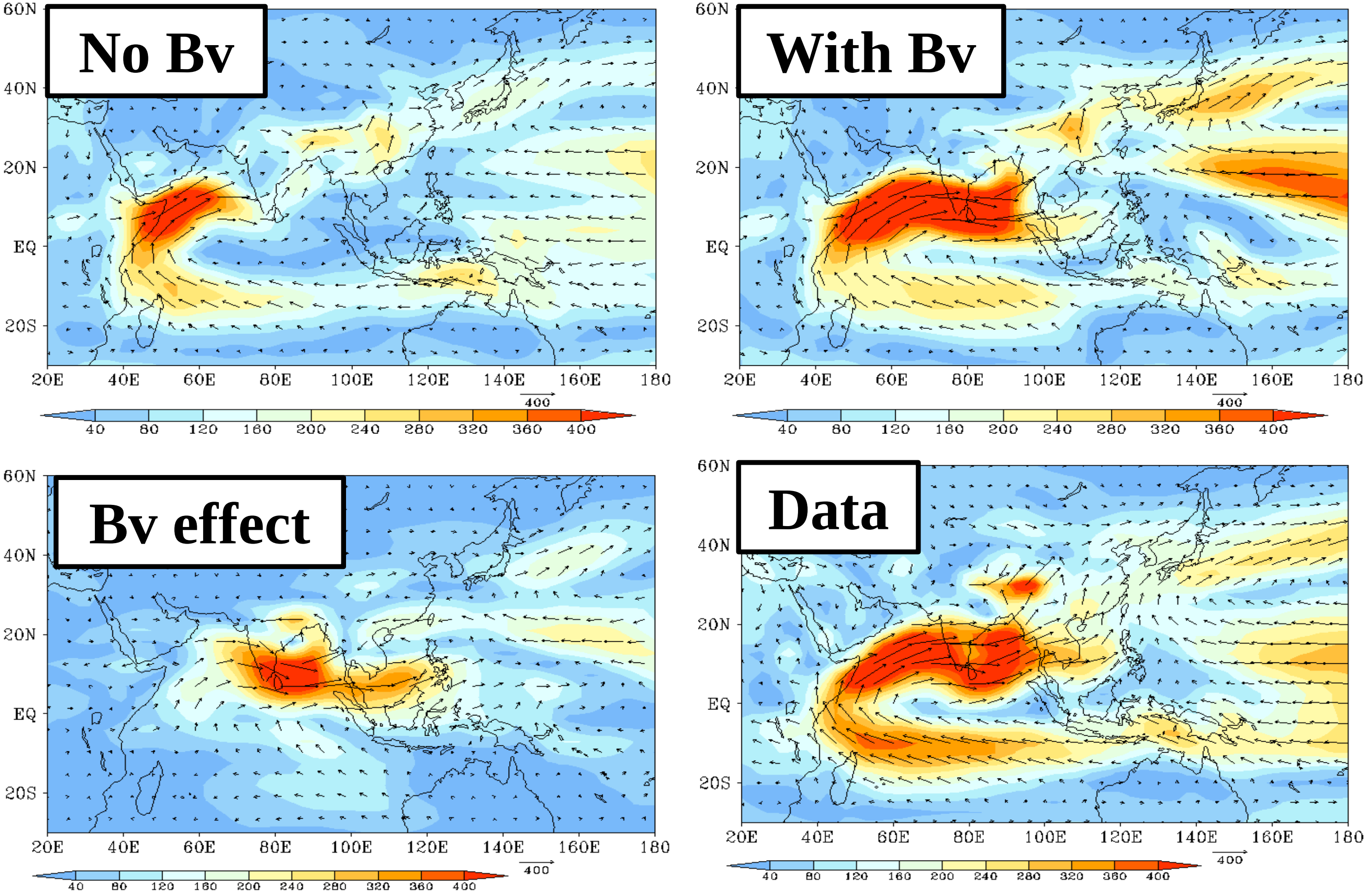
Yalin Fan, and Stephen M. Griffies, 2014, JC (Fig 3)

FGCM0



Time evolutions of global mean SSTs simulated in Exp. N (blue line for without Bv) and Exp. W (pink line for with Bv), and that from the WOA01 climatology (black line). Huang et al, AOS, 2008

Water vapor transport in Australian-Asian Monsoon area



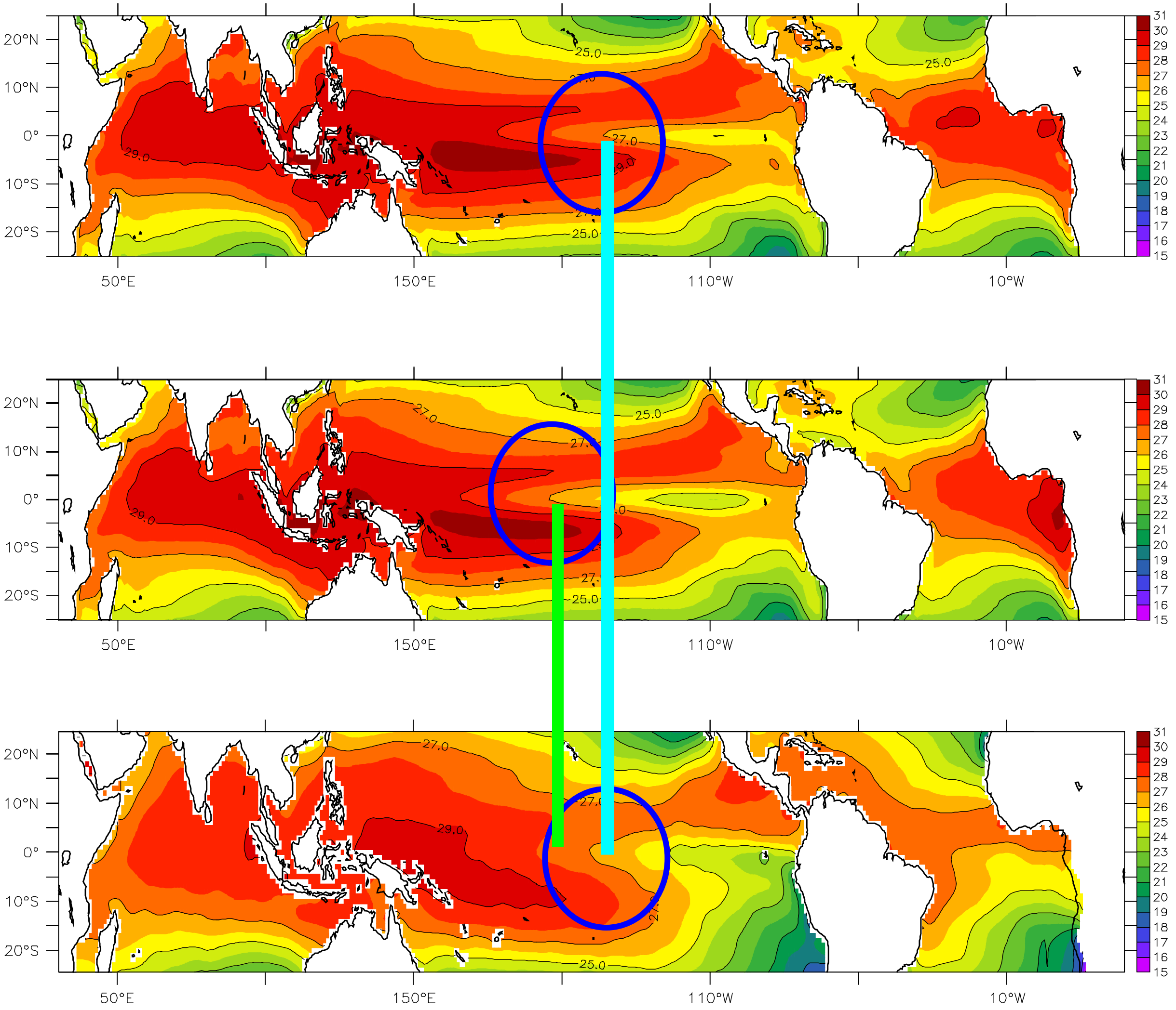
Song and Qiao et al, 2012, JAS

Tropical bias – too cold tongue (CCSM3)

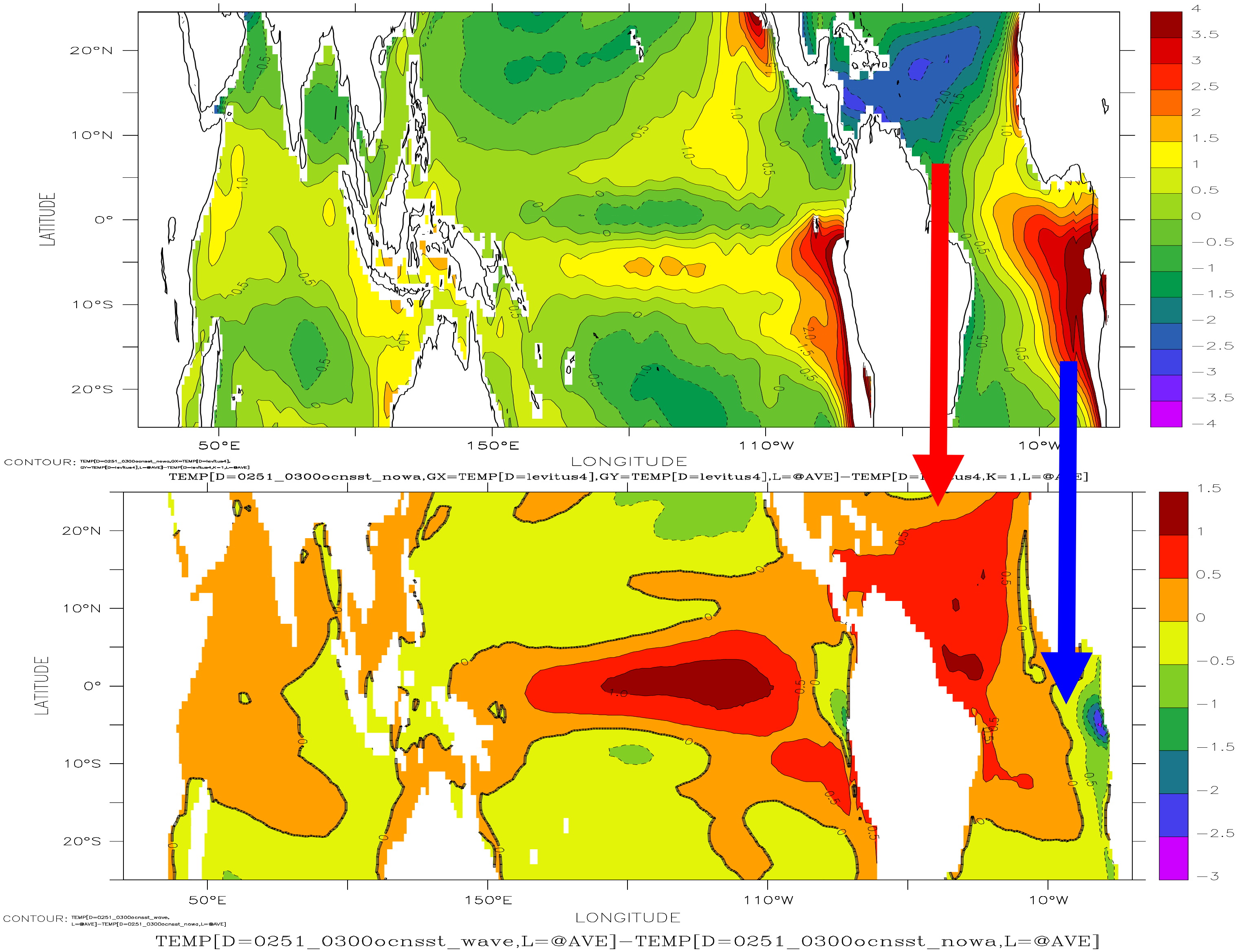
CCSM3+Waves

CCSM3: 251-300a

WOA



The isotherm of 27℃



Song et al, JGR, 2012

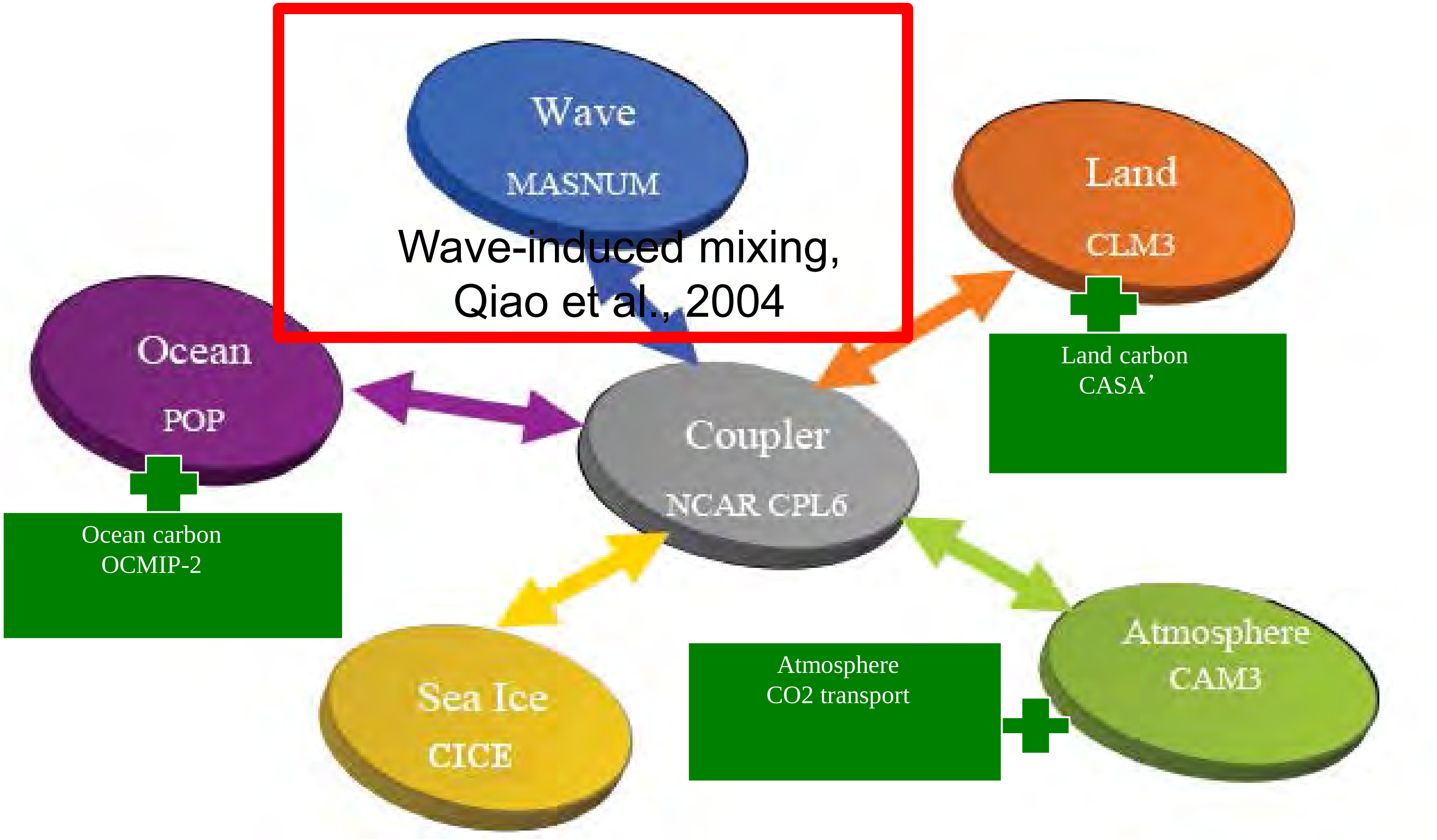
50a averaged SST (251-300a).

Up: Exp1-Levitus, Down: Exp2-Exp1

Exp1: CCSM3 without Bv

Exp2: with Bv

FIO-ESM for CMIP5 (Qiao et al, JGR, 2013**)**



Wave-induced mixing,
Qiao et al., 2004

Land carbon
CASA’

Ocean carbon
OCMIP-2

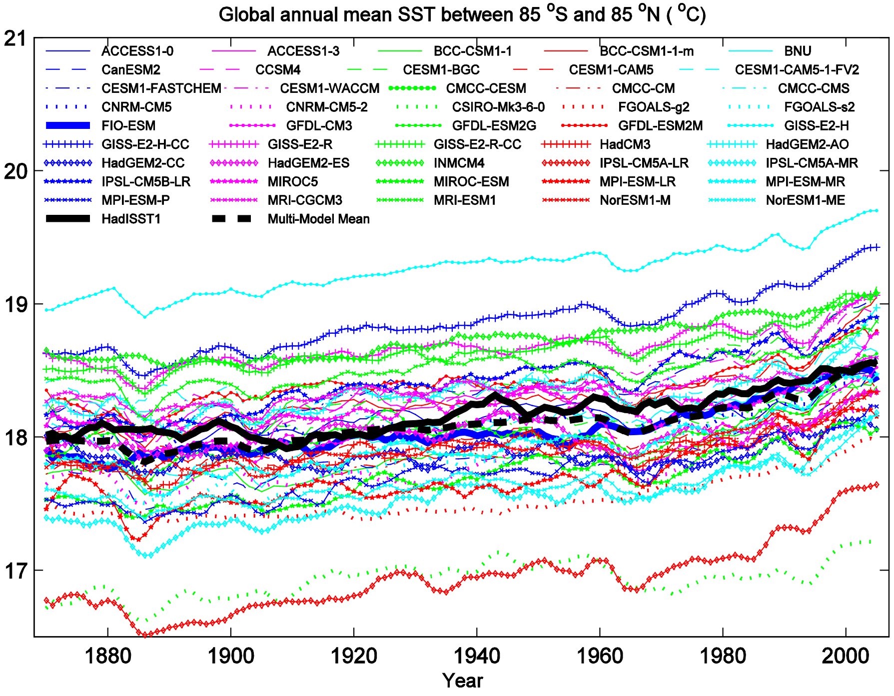
Atmosphere
CO2 transport

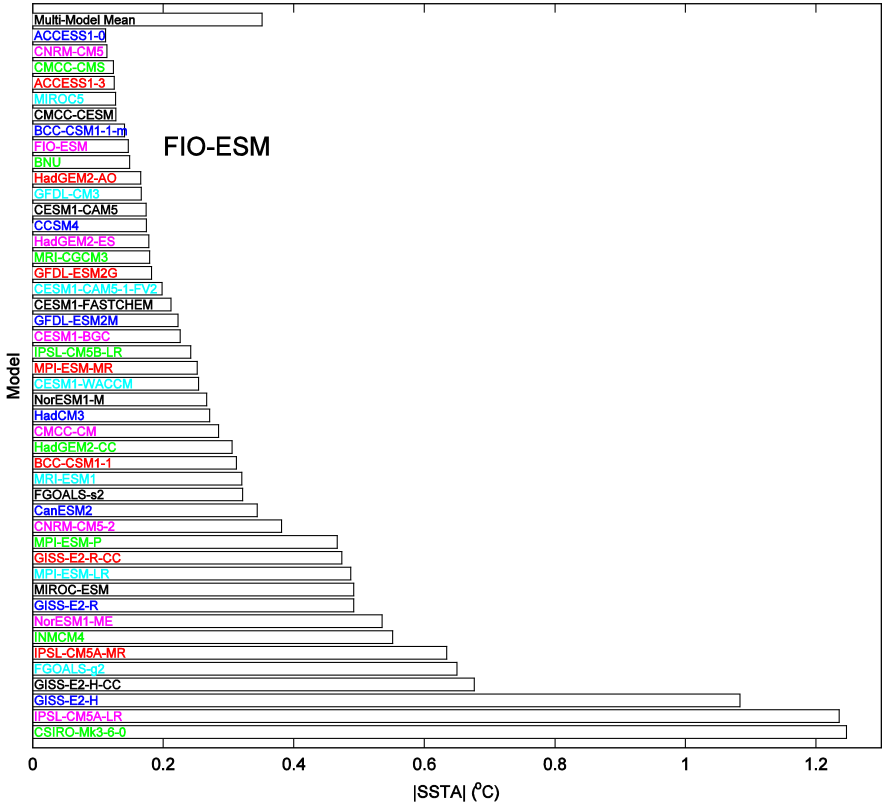
Descriptions of the FIO-ESM

Physical models

- ATM: CAM3.0, T42L26
- LND: CLM3, T42
- OCN: POP2, 1.1°*0.3~0.5°, 40 vertical layers
- ICE: CICE4, 1.1°*0.3~0.5°
- WAV: MASNUM wave model, 2°*2°
- Wave-circulation coupling: based on the wave-inducing mixing

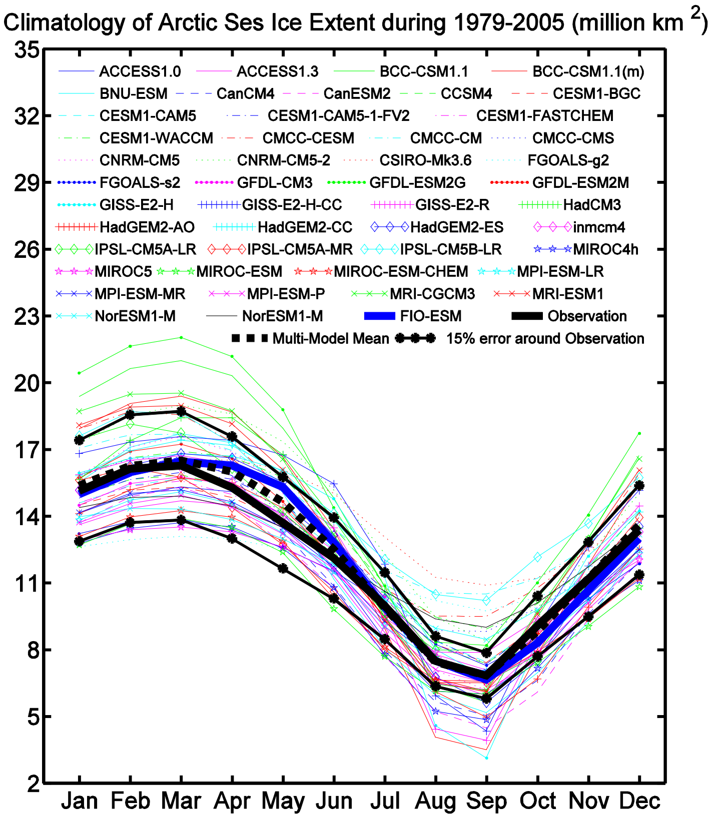
SST evolution in historical climate simulations during 1850-2005. 45 Models are compared with HadSST.

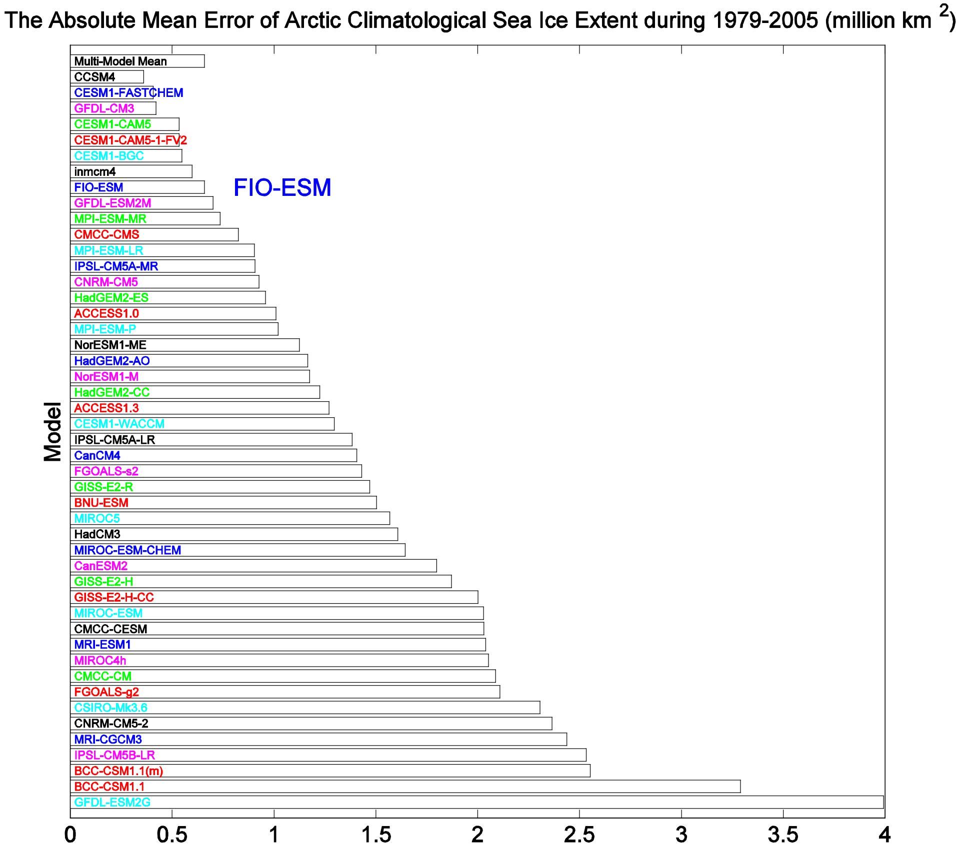

Global annual mean SST between 85 °S and 85 °N (°C)



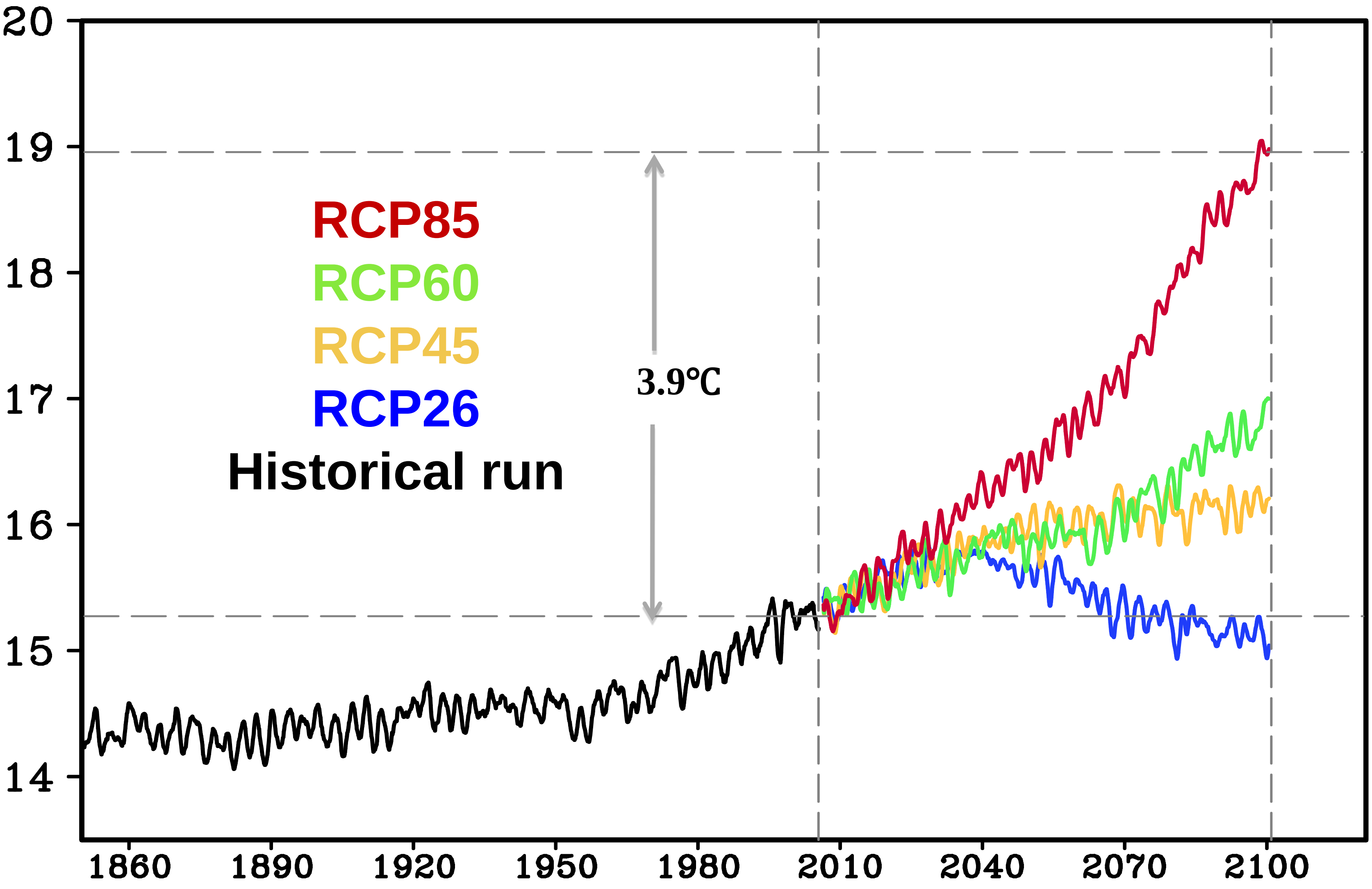
FIO-ESM

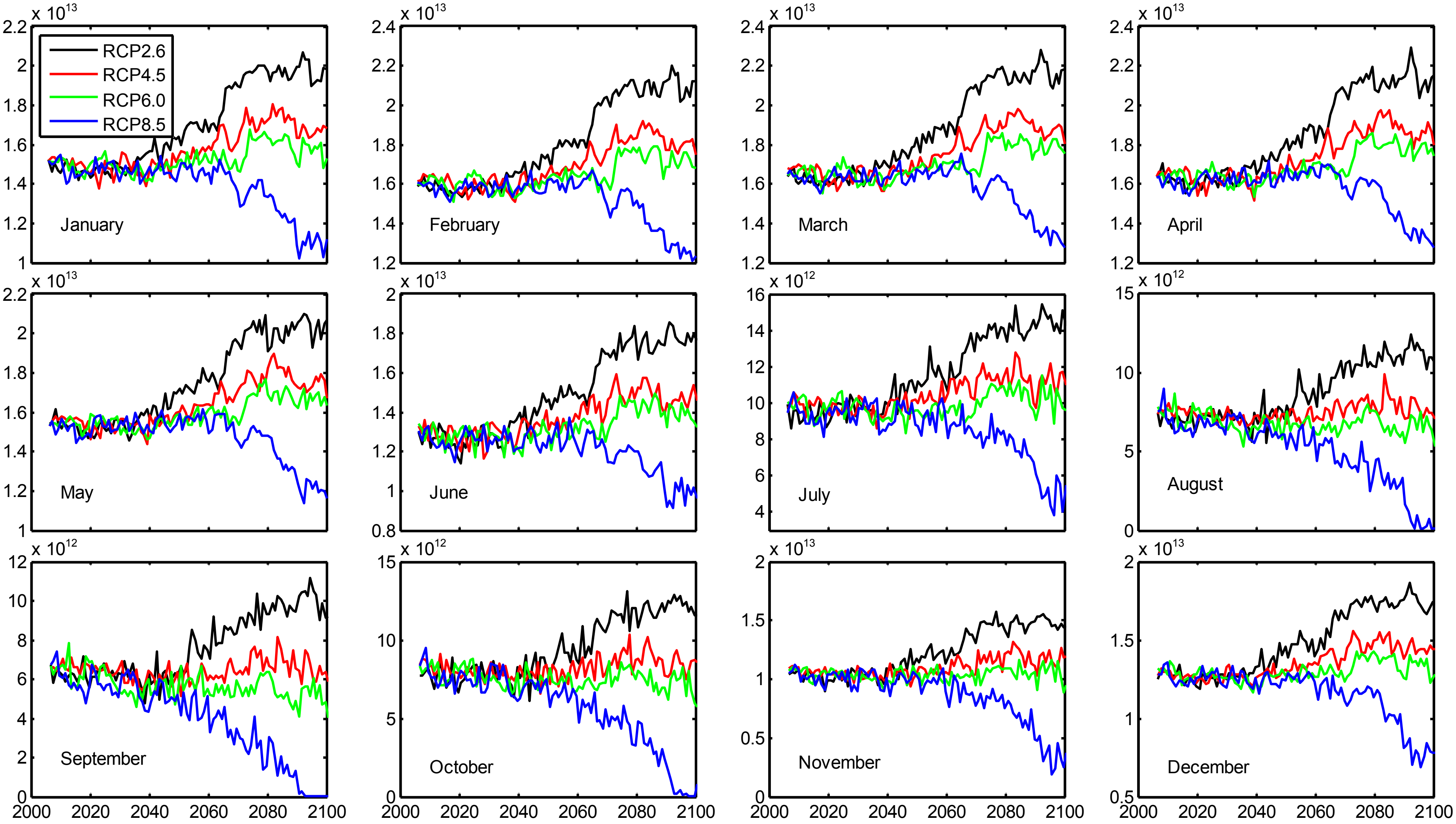
Arctic sea ice evolution in historical climate simulations during 1979-2005. 45 Models are compared with satellite data.


Climatology of Arctic Ses Ice Extent during 1979-2005 (million km ^{2})


The Absolute Mean Error of Arctic Climatological Sea Ice Extent during 1979-2005 (million km ^{2})

Centurial Future Projections





Time series of Arctic sea ice extent from RCP run.

Unit: m^2

Conclusions

- **The non-breaking surface wave-induced vertical mixing (Bv) plays a key role in improving OGCMs. Even excluding shear-induced mixing, ocean circulation model can work quite well, which suggests that Bv plays much more important role than that of shear-induced mixing.**
- **Bv can much improve the climate model. Our validations give us some confidence that surface waves, although so small scale, should be important for climate system.**

Thanks for your attention