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MODELLING OF THE SUBARCTIC NORTH PACIFIC CIRCULATION
(*Report of Working Group 7*)

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EXECUTIVE SUMMARY

This review focuses on modelling ocean circulation and its variability in the subarctic North Pacific; it addresses issues specific to that region, and not the subject of ocean modelling in general. The performance of existing models is assessed in relation to observations in the upper ocean, intermediate waters and deep/abyssal waters. Not surprisingly, the quality of model results is generally found to match that of the observations. Models of surface circulation, where data are most abundant, reproduce many observed features, while the reliability of model results at greater depths remains more problematic. In general, model results are found too coarse and insufficiently reliable for many of the applications towards which they have been developed (fisheries, pollution, climate...) and significant improvements are required.

We have identified a number of gaps in physical understanding and supporting data which need be filled to improve model performance. Many of these apply to ocean modelling in general, but some, particularly with respect to the influence of marginal seas (Bering, Japan, Okhotsk), are specific to the subarctic North Pacific. Recommendations address ways of filling these gaps and using international collaboration within PICES to foster development of better ocean circulation models in the subarctic North Pacific.

1.0 INTRODUCTION

Numerical modelling has become the primary tool for analysis and design in many areas of fluid mechanics. This is also true of atmospheric and oceanic flows, where numerical models are used to explore the subtleties of flow dynamics, examine the consequences of changes in physical parameters and develop flow patterns for domains of complex geometry under realistic forcing conditions. Numerical modelling has also become a tool to guide observations, identifying areas where the most revealing measurements should be made and which data in turn should be assimilated into predictive models (Smith, 1991). Hydrodynamic models are readily extended, at least in principle, to include chemical properties of ocean waters and the lower trophic levels of oceanic biology. Modelling opens a window into the future by simulating conditions resulting from different scenarios and policies; it similarly offers a tool for the exploration of past conditions.

Numerical simulation represents a step comparable to the invention of calculus in the analysis and understanding of nature. It will play an increasingly important role in ocean science and its applications. In view of its highly technical nature and rapid development, it is important that progress and prospects in the modelling of the oceans be frequently reviewed.

Working Group 7 of PICES has been charged with reviewing the state of modelling efforts of the circulation of the subarctic Pacific. Our terms of reference, presented in Appendix 1, also require that we identify areas where progress may be made through enhanced data coverage and improved physical understanding, and that we comment on the consequences of current deficiencies in modelling the circulation on other kinds of models pertaining, for example, to the climate, ecosystems, and material transports. Key scientific questions arising in the oceanography of the subarctic North Pacific have been summarized in an earlier report by Working Group 6 of PICES (Hargreaves and Sugimoto, 1993). The success and challenges of modelling the circulation and ocean properties of our area may be assessed in terms of the ability of models to answer these key questions.

We first define the scope of the review, identifying the spatial and temporal scales of relevant oceanic phenomena. We follow with an overview of the state of the art of existing models, assessed in terms of their ability to reproduce observations in areas of special interest. We continue with a discussion of improvements thought to be required in understanding and modelling physical processes. The role of marginal seas and improvements required in linking their circulation with that of the open ocean are discussed next, followed by a discussion of the need for additional data sources and quality. Finally, we discuss the consequences of the perceived deficiencies of North-Pacific circulation models on the modelling of other properties. Specific recommendations for achieving required improvements are also presented.

2.0 SCOPE OF REVIEW

In approaching a topic as vast as ocean modelling, it is important to clearly define the scope of our review. Our topic of interest is the subarctic North Pacific, defined as that area north of 30°N, and not the world ocean, nor ocean modelling in general, which have been reviewed elsewhere (see for example Marotzke, 1994; Weaver and Hughes, 1994; WOCE 1994; McWilliams, 1996). Furthermore, we understand circulation to mean fairly large-scale, slowly varying motion. Although of great practical interest, phenomena such as waves, tides, tsunamis and similar high-frequency motions will not be discussed here, unless they happen to have some effect in the longer term. We are interested, however in mesoscale eddies, their strength, position and variability. Similarly, the modelling of coastal basins on the continental shelf, where great progress has been made in developing practical simulation and decision-making tools, will not be included in our review. Only major coastal regions, also known as marginal seas, will be considered of interest, and then only because of their influence on large-scale oceanic properties, mainly through buoyancy fluxes and processes of water mass formation.

The smallest oceanic processes (surface and internal wave breaking, turbulent entrainment, shear instability, double diffusion...) take place over scales of centimeters to tens of meters, well below the resolution of large-scale models. The effect of these processes must perforce be parameterized, and the appropriateness and accuracy of such parameterizations is a general concern in ocean modelling. (cf. for example Bryan, 1987; Cummins et al., 1990; Danabasoglu, 1994; Gargett and Holloway, 1992; Large et al., 1994). Our review addresses issues of sub-grid-scale parameterization only in as much as they are identified as being particularly pertinent to our area of interest, the subarctic North Pacific.

The smallest horizontal scale considered of interest in open-ocean models is the Rossby radius of the first internal mode, of the order of 20 km in length over most of the area of interest (Emery et al., 1984). Models capable of resolving mesoscale eddies, which occur on that scale, are said to be "eddy-resolving". A resolution of 1/8th of a degree seems to be sufficient to resolve most features of interest. In complicated areas, like the Kuroshio-Oyashio confluence zone, a higher resolution is needed to model dynamic and bathymetric interactions. Enhanced resolution is also necessary in coastal regions, where smaller scales are often imposed by the boundary geometry and by the punctual nature of buoyancy sources, such as rivers. The problem of matching relatively coarse open-ocean models to finer-scale marginal sea models is important in the subarctic North Pacific, as in other ocean areas. In the vertical, a higher level of resolution is often required to resolve critical topographic details or the structure of important transitions. In modelling the evolution of the seasonal thermocline, and the processes through which energy, momentum and mass are exchanged between the atmosphere and the ocean, special attention must be paid to the dynamics of the mixed layer, in the upper 200-300 metres of the ocean, so that the finest vertical resolution must be applied to that region.

An extremely important consideration in modelling is verification against observations. Ocean modelling has not reached the level of sophistication of operational atmospheric weather modelling, where extensive verification is possible against a rich observational network. Perhaps that degree of sophistication will come some day, when model results can be routinely compared at an eddy-resolving level against satellite altimetry and temperature data (cf. Hurlburt, 1984 for a review of this topic, and Carnes et al., 1995, for a recent application to the North Pacific). At this point, it was agreed that models should be judged on their ability to reproduce some key features correctly, and part of the Working Group's discussion focused on the identification of these features, in specific areas.

3.0 REVIEW OF EXISTING MODELS

In terms of circulation patterns and general water property structure, one may recognize four superposed layers in the subarctic North Pacific. The uppermost, near-surface layer, is subject to direct atmospheric interactions, and is clearly the most energetic and variable layer of the ocean. It includes the wind-mixed Ekman layer and the cooling convection layer to the pycnocline (~ 500 m). This is arguably the layer of greatest interest to human needs and activities, and also that which has been observed in most detail. This layer has received the most modelling attention and will be discussed in greatest detail. Below it (in the range 500 - 1,500 m), we find an intermediate layer, which is particularly important in the subarctic Pacific because of the presence of the North Pacific Intermediate Water, a water mass of relatively low salinity which extends over much of the region. The lower part of this later includes flow associated with the northward spread of Antarctic Intermediate Waters. Further down (1,500 - 4,000 m), we recognize a slow deep circulation, which may be considered as a return flow to the abyssal circulation (4,000 m to bottom) associated with inflow of the mixed Antarctic Bottom Water and North Atlantic Deep Water steered by bottom topography. Because so little is known about these two deepest layers, they will be lumped together in our discussion.

While the region of interest is the subarctic North Pacific, it is impossible to consider the circulation in one area in complete isolation from the rest of the ocean. Vigorous flow from the south enters the region in the west (the Kuroshio); the influence of El Niño penetrates the ocean from the east as variability in seasonal to decadal time scales. There is also evidence, mostly in the distribution of water properties, of important meridional transport at depth. For example, Bingham and Lukas (1994) have detected the presence of North Pacific Intermediate Water near the Philippines, where it appears to contribute to the Indonesian Throughflow (Gordon, 1995) and hence to the return branch of the main thermohaline conveyor belt circulation. Most models of the subarctic North Pacific circulation have been, and will continue to be parts of models concerned with the entire Pacific Ocean and, increasingly, the whole World Ocean.

3.1 Surface circulation

3.1.1 General Features

The surface circulation is that about which we know the most and where modelling efforts have also been most intense. Models have been developed for wind-forcing, or thermohaline forcing, or both. In simplified form, the surface circulation of the North Pacific consists of a clockwise subtropical gyre in the south and a counter-clockwise subpolar gyre in the north (Fig. 1). The subtropical gyre consists of a strong western boundary current in the west, the Kuroshio, and a more diffuse return circulation over the rest of the ocean. Similarly, the subarctic gyre has strong flows on western boundaries which, probably because of their geographical configuration, partly break up the larger gyre in sub-gyres: the Alaskan Gyre, the Bering Sea Gyre, the Western Subarctic Gyre and a gyre within the Sea of Okhotsk. (Ohtani, 1991). There is much variability in the area bordering on the Aleutian Island chain and some uncertainty in the degree of connection, partly through the Bering Sea, between the Alaskan Gyre in the east and the Western Subarctic Gyre in the west. The region considered here includes all the subarctic gyres and the northern part of the subtropical gyre.

Existing circulation models readily reproduce some of the gross features of the near-surface circulation. For example, the Cherniawsky and Holloway (1991) simplified upper-ocean model, driven by wind-stress and surface heat and fresh-water fluxes, yields an Alaskan Gyre, a Western Subarctic Gyre and an Okhotsk Sea Gyre (Fig. 2). The absence of the Aleutian Island chain in the model of course makes any comparison with the observed circulation impossible in that area.

State-of-the-art eddy-resolving models of the whole ocean (Semtner and Chervin, 1988,

1992) or of the Pacific (Hurlburt et al., 1992, 1995) or some of its parts (Cummins and Freeland, 1993) typically include a number of vertical layers (6 to 20) and a resolution of 1/2 to 1/16 of a degree (although higher resolution models have been developed for restricted regions). Such models, driven by observed winds, do reproduce the main features of the circulation seen in Fig. 1, and also exhibit considerable mesoscale eddy activity, occurring where it is actually observed, near Sitka (southeast Alaska), the Queen Charlotte Islands, the Alaskan Stream and in the Kuroshio extension region. Examples are shown in Fig. 3 -5.

A more critical comparison of model results with observations must focus on areas of sufficient data density, where specific features are clearly recognized. We have identified four such regions: the Kuroshio path south of Japan; the Kuroshio-Oyashio confluence; the Kuroshio extension; and the Alaskan Gyre.

3.1.2 Specific regions

a. The Path of the Kuroshio

South of Japan, the Kuroshio takes different paths, changing between them on an interannual basis (Fig. 6). The two most frequent paths are the "straight path", also referred to as N-type (normal) and a "large-meander path", also called A-type (abnormal). These two states persist for periods of several months to several years. The next most persistent path is the "C-type", which takes a detour south of Hachijo Island (Izu Ridge). Two other paths (B and D) are transient features observed during the transition period from one stable path to another. The predominantly bimodal path characteristics of the Kuroshio south of Japan are peculiar to this region and are not observed in the Kuroshio extension, to the east, or in other major western boundary currents. Path variations and duration have a strong effect on fisheries, marine transportation and climate along the southern coast of Japan. There is a practical need for understanding path dynamics and for a predictive model of path selection.

From a physical point of view, four kinds of models of Kuroshio paths have been put forward; all include the influence of ocean bathymetry in the area south of Japan.

Boundary-value problem model. Kozlov (1986) has reviewed theoretical investigations of the bi-modality of the Kuroshio south of Japan. The first model is an inflow-outflow type of model within the Shikoku Basin, where inflow and outflow positions are constrained by the bathymetry and the shape of the coastline. Inflow takes place through Tokara Strait in the Nansei Island chain south of Kyushu; outflow is through the deeper portions of the Izu-Ogasawara Ridge, between Miyake and Hachijo Islands (Fig. 6).

As originally pointed out by White and McCreary (1976), the presence of a standing Rossby wave (and hence of one or more meanders) of length $\lambda = (U/\beta)^{1/2}$ in a north-eastward inertial jet size within a basin of given size is related to the flow velocity U and to the rate of change of the Coriolis parameter β. Masuda (1982) presented analytical solutions of Warren's (1968) path equations for a nonlinear boundary-value problem. He showed the dependence of the path on inflow velocity, hysteresis phenomena in path selection, and the presence of multiple equilibrium states of the straight and large meander paths for the same parameter values. Yasuda et al. (1985) confirmed Masuda's results with a barotropic model of the area south of Japan. In both of these models, a straight path generally occurs at a relatively high inflow velocity and a large meander path at a slower inflow velocity. Inclusion of a Munk layer in which viscous dissipation takes place near the coast allows a straight path also to occur at low inflow velocity.

Yoon and Yasuda (1987) also investigated the dependence of model results on the shape of the northern boundary. With the northern boundary running at 23° north of east, rather than zonally, a viscous straight path occurs at low inflow velocity and a large meander path at a high velocity, while at intermediate velocities both paths can occur for the same parameter values (Fig. 7). Chao (1984) and Akitomo et al. (1991) obtained similar results in different model configurations. Masuda (1989) confirmed the existence of multiple equilibrium states as well as the effects of topography in laboratory experiments.

Geometry-forced meander model. A second type of model considers the nature of the path of the Kuroshio to arise from a steady wave of the stream forced by local coastal geometry, for example, the Kyushu Peninsula, or the Kii Peninsula. White and McCreary (1976) examined a lee-wave meander downstream of a coastal bump corresponding to Kyushu. Charney and Flierl (1980) analytically examined interactions between a jet and periodic coastal bumps and suggested the possibility of multiple equilibrium paths. Yamagata and Umatami (1987, 1989) also studied such interactions and proposed and inlet-velocity/meander amplitude diagram similar to that of Yasuda et al. (1985).

Bottom control path model. The third type of model is that of a straight path controlled by bottom topography. Robinson and Taft (1972) examined path characteristics and effects of bottom topography using path equations. In their model, the path which escapes bottom control becomes a free inertial jet and forms a large meander. Taft et al. (1973) suggested, on the basis of observations, that the straight path could not be entirely controlled by bottom topography. Sekine (1988a, b, c; 1990) studied the effects of bottom topography in a two-layer inflow and outflow model with realistic bottom topography in the lower layer, confirming the importance of topography. Martynov and Moiseev (1988) also studied topographic control of the Kuroshio path.

Eddy-resolving basin-scale Pacific model. Recently, it has become feasible to investigate the path of the Kuroshio south of Japan using eddy-resolving basin-scale Pacific models (Fig. 4). Using a 1/8°, 6-layer Pacific Ocean model north of 20° S with realistic geometry and bottom topography, Hurlburt et al. (1996) were able to simulate spontaneous transitions between meander and straight paths south of Japan when the model was forced by the Hellerman and Rosenstein (1983) monthly wind-stress climatology year after year. When they allowed interannual variations in the amplitude of the wind forcing, they found that path selection shows little sensitivity to Tokara Strait transport (transport south of Kyushu) over the range simulated (36-72 Sv in yearly means). The mean Tokara Strait transport for straight paths and meander paths differed by only 2 Sv. However, interannual increases in wind forcing or in Tokara Strait transport gave rise to a predominant meander path while decreases yielded a predominant straight path. Like Yoon and Yasuda (1987) they found that baroclinic instability is an important element of meander path formation. They also found that a seamount complex west of the Izu Ridge enhances the fraction of time that the Kuroshio spends in the meander path.

Transition from straight to meander path. This transition usually occurs as follows: a small "trigger" meander, generated south of Kyushu, propagates eastward and develops into a large meander (Yoshida, 1961; Shoji, 1972; Sekine,1992). Such a small meander is generated in early spring almost every year and in the fall of some years when the Kuroshio surface velocity increases (Sekine and Toba, 1981a; Sekine, 1992). These small meanders however do not necessarily develop into a large and persistent meander path. A detailed analysis (Matsumoto, 1994) shows that only those small meanders generated from February to August and propagating eastward with a velocity below a critical value actually developed into large meanders. A number of authors (Sekine and Toba, 1981b; Yoon and Yasuda, 1987; Kubokawa, 1989) have examined nonlinear vorticity dynamics of meanders in that region and the effects of topography and stratification on their stability.

Comparison with observations of bimodality. Following from the above models, a number of diagnostic diagrams relating path type to Kuroshio volume transport have been proposed. It remains impossible to choose between these various diagrams because of the lack of sufficient observations.

Volume transport by the Kuroshio is reported to be small during periods of large meander paths south of Japan (Taft, 1972; Nitani, 1972; Sekine et al., 1991). In contrast, the transport is large in the East China Sea during the same periods (Nishizawa et al., 1982). This behaviour is confirmed by transport measurements across 137°E (Qiu and Joyce, 1972), and by cross-stream sea-level differences (measured between Naze and Nishinoomote Islands) representative of inflow into Tokara Strait (Kawabe 1980).

These latter observations seem to support the results of Yoon and Yasuda (1987) which predict, for a two-layer, realistic coastal geometry model, a straight Kuroshio path for low inflow velocity and a multiplicity of possible states for larger velocity. However, these models do not reproduce the "C-type" path which emerges in the transition from a large meander to a straight path.

Seasonal variability. Geostrophic transports calculated from hydrographic sections south of Japan indicate maximum transports in summer and minimum values in the winter (Pavlova, 1964; Masuzawa, 1965; Nitani, 1972; Taft, 1972, 1978; Minami et al., 1979). Sea-level differences across Tokara Strait indicate the same seasonal variation (Blaha and Reed, 1982; Kawabe, 1988). This observed seasonal pattern is opposite to the seasonal response expected from a Sverdrup balance to applied wind-stress fields. However, Greatbatch and Goulding (1989, 1990), using a steady-state barotropic model forced by monthly wind stress and including realistic bathymetry, found that about half of the sea-level difference could be explained by a local Sverdrup balance. Sekine and Kutsuwada (1994), also pointed out that the volume transport south of Japan is actually a maximum in the winter, as expected from a Sverdrup balance, while the vertical shear, which is what was estimated from hydrographic data, is maximum in the summer. On the other hand, Qiu (1992), using a combination of satellite altimetry and hydrographic data, showed that the eastward flowing jet is strongest in July and August and that the seasonal change is caused by the change in intensity of the recirculation gyre south of Japan.

While models have shed light on many of the mechanisms which may be responsible for the path taken by the Kuroshio, there is still much to be learned in this complex area. Further understanding of the Kuroshio south of Japan will clearly require more accurate measurements of Kuroshio transport and additional improvements in numerical models. Predictive ability will be reached only when variations in the strength and path of the Kuroshio can also be predicted... perhaps in relation to some index of meteorological forcing.

b. The Kuroshio-Oyashio Confluence

Another area of great interest is the Kuroshio-Oyashio confluence region, east of northern Japan. The details of the circulation in that complex region have been studied extensively (Kawai, 1972; Kozlov, 1971, 1972; Mizuno and White, 1983; Qiu et al.1991; Yasuda et al. 1992; Yasuda, 1995; Yasuda et al. 1995; Talley et al., 1995; Hurlburt et al., 1996). The complexity of the circulation is illustrated by the various patterns used to represent it (Fig. 8). Overall, one may characterize the region as one of extreme variability, with rings and meanders appearing, drifting and vanishing in a transition zone between the Kuroshio and Oyashio frontal regions. The positions and properties of these features are of great importance to regional fisheries, navigation and climatology and, as for the region previously discussed, predictive numerical modelling could become an extremely useful tool.

A prominent feature of the Kuroshio-Oyashio confluence region is a double front system which consists of the Kuroshio front and the subarctic (Oyashio) front. The Kuroshio front borders on the Kuroshio Extension, with current speeds up to 3 m/s. The Oyashio front is a water-mass front between cold, low-salinity subarctic waters and warm, saline subtropical waters (Zhang and Hanawa, 1992). Temperature and salinity differences across that front compensate in their influence on the density; horizontal density gradients are small and so is the velocity at the front (Roden, 1972, 1977).

Numerical model results should at least resemble the kind of flow pattern seen in Fig. 8. They should ensure detachment of the Kuroshio at the correct latitude, include a branch of the Oyashio along the coast of Japan, reproduce the double front structure, and transfer warm water across the frontal zone well east of the Japanese coast.

Semtner and Chervin's (1992) global 1/2° eddy-resolving, 20-level model gave a more realistic output than previous coarser resolution models. It showed a bifurcated Kuroshio Extension similar to observations. Frontal analyses comparing model products with observations however put the Kuroshio Extension about 5° south of observations (Garzoli et al., 1992) and yielded unrealistically strong currents at the subarctic front. The Oyashio coastal southward flow is not reproduced in that model and northward flow from the Kuroshio Extension is instead dominant near the east coast of Japan. Variability in the Kuroshio Extension was not consistent with GEOSAT observations, although model kinetic energy levels were comparable to that of observations (Garaffo et al., 1992). Semtner and Chervin (1992) concluded that their model resolution was insufficient to reproduce the details of the circulation in that area. The 3.5 layer, 1/2° resolution wind-driven model of Metzger et al. (1992) also exhibits the required double front structure, but was not compared in detail with observations in this region. In observations (Fig. 8) the northward flow from the Kuroshio Extension to the Oyashio (subarctic front) is separated from the east coast of Japan, a feature simulated by Hurlburt et al. (1992, 1996), and shown in Fig. 4 and Fig. 9. Hurlburt et al. (1996) find that this occurs because the bottom topography reduces the separation between the Oyashio and the Kuroshio Extension. However, baroclinic instability, and hence an eddy-resolving model, is essential for the upper-ocean topographic coupling that allows this to occur.

The Oyashio coastal branch is an important feature of the Kuroshio/Oyashio confluence region. The cold and relatively fresh waters which it carries southwards are thought to be important in the formation of North Pacific Intermediate Waters (Yasuda et al., 1995). The coastal environment on the northeast coast of Japan is significantly influenced by the presence of the coastal Oyashio branch. There is important seasonal and interannual variability in the southernmost latitude reached by this current (Ogawa et al., 1987). There is evidence for decadal-scale fluctuations and a 3-4 year cycle possibly linked to ENSO events (Takasugi and Yasuda, 1994). There are also years of extreme cold waters, observed in the spring (Okuda, 1986). In spite of the importance of the Oyashio coastal branch, no model fully reproduces its presence and variability, although the Hurlburt et al. (1996) 1/8° and 1/16° models represent significant progress in explaining these phenomena.

c. Kuroshio Extension

The Kuroshio Extension is that part of the Kuroshio travelling eastward after detachment from the Japanese coast. It is an area of great meandering and eddying motion, at the southern edge of the Kuroshio/Oyashio confluence region. This region has received modelling attention in the past and has recently been the focus of intense efforts through the Kuroshio Extension Regional Experiment (Hogan et al., 1992; Hurlburt et al.,1992, 1996; Jacobs et al., 1995; Mitchell et al., 1995) and the Megapolygon Experiment, conducted by Russian scientists in 1987 (Ivanov, 1992). Typical results, shown in Fig. 9, show that eddy-resolving models do produce circulation patterns which are generally consistent with what is observed. General statistical comparisons would include the latitude of maximum current and of maximum eddy activity. It would also include simulation of the mean meanders east of Japan shown in Figs. 1, 4 and 8. Because the meandering and eddy generation associated with the Kuroshio Extension is due to flow instabilities and is not a determininstic response to atmospheric forcing, a detailed comparison of synoptic flow patterns would require model initialization using observational data which can resolve mesoscale features such as those in Fig. 9. Carnes et al. (1995) have attempted to do this using satellite altimeter data, front and eddy locations from satellite infra-red imagery and 4-D data assimilation. Problems associated with this kind of exacting comparison are discussed under the section **Variability** below.

Hurlburt et al. (1996) find that the latitude of the Kuroshio Extension is associated with the winter-time zero wind stress curl. Both the

Hellerman and Rosenstein (HR) monthly wind-stress climatology and a monthly climatology derived from the European Centre for Medium-range Weather Forecasts (ECMWF) 1000 mb winds have been used to drive their 1/8° 6-layer Pacific model. East of about 150°E the two wind climatologies give a mean latitude for the Kuroshio Extension in the model which differ by about 3° of latitude: approximately 34°N for the HR winds (Fig. 4) and 37°N for ECMWF winds (Fig. 30). The observed latitude is 35°N. In addition, Hurlburt et al. (1996) find that the mean meanders east of Japan are associated with the trench and seamounts east of where the Kuroshio separates from the coast. Again, the upper ocean-topographic coupling is achieved via baroclinic instability.

d. The Alaskan Gyre

Another region of special interest is the northeast Pacific, where the West Wind Drift bifurcates into the Alaska Gyre and the California Current. Model results (see Figs. 4 and 5) do, of course, reproduce the bifurcation. There is also considerable seasonal variability in the current systems of the eastern boundary area. Surface current patterns have been traditionally linked to large-scale seasonal wind variations. During summer months, coastal upwelling conditions prevail north from California as far north as the Queen Charlotte Islands; during winter months, upwelling no longer occurs and the Davidson Current is found inshore of the main subtropical gyre.

The Gulf of Alaska is also a region characterized by abundant precipitation. Strong fresh water runoff, from the Columbia River northward, contributes to a coastal buoyancy-driven current which gradually joins the anticyclonic Alaska Gyre (Royer, 1981; Hickey et al., 1991). The fresh water inflow is partly recirculated within the Alaska Gyre and contributes to the relative freshness of subarctic North Pacific waters and the strong halocline found especially in the east.

Regional models of the northeast Pacific (Cummins, 1989, 1991; Cummins and Mysak, 1988; Cummins and Freeland, 1993; Lee et al., 1992) have explored links between variability of the Alaska Gyre, wind-forcing and bathymetry. Mesoscale eddy activity is much weaker than in the western North Pacific, but eddies are nevertheless present (Matthews et al., 1992; Thomson et al., 1990). Some features, like the Sitka Eddy (Tabata, 1982; Swaters and Mysak, 1985), may be related to bottom topography; others may arise from the generation of Rossby waves on the coast of North America (Cummins et al., 1986; Jacobs et al., 1993; Melsom et al., 1995).

Measurements made on the continental shelf have illustrated the richness of variability associated with direct wind forcing, shelf waves and runoff pulses in an eastern boundary layer (e.g., Mooers and Smith, 1968; Huyer et al., 1975; Hsieh, 1982; Hickey et al., 1991). Early models often focussed on recognition of particular types of wave or instability phenomenon; efforts have also been made at explaining observed variability in terms of these phenomena and of local as well as distant forcing (Gill and Schuman, 1974; Hickey and Hamilton, 1980; Halliwell and Allen, 1984; Federiuk and Allen, 1995).

Coastal temperatures are deemed to be strongly influenced by El Niño (Mysak, 1986). The high resolution North Pacific model of Jacobs et al. (1994) does reveal the propagation of coastal Kelvin waves northwards from the equator along the North American coast, as have earlier studies (e.g., Johnson and O'Brien, 1990). There has long been discussion as to whether coastal temperature changes are associated mainly with local perturbations in atmospheric forcing or with the effect of these Kelvin waves (Hamilton and Emery, 1985). Recent calculations using the 1/8° model of Hurlburt et al. (1996), show that interannual fluctuations of sea level off southern Alaska (Fig. 10) are well reproduced by the model and that enhanced mesoscale activity in the Gulf of Alaska (such as the Sitka Eddy) follows upon El Niño activity (Melsom et al., 1995).

While the sharp surface halocline of the Alaskan gyre is a strong obstacle to ventilation, Van Scoy et al. (1991) have suggested that wintertime forcing might sometimes be strong enough to overcome the potential energy of the halocline and that the 26.8 density surface might outcrop in the Alaskan gyre, either in multiple small areas in response to storm forcing or infrequently in large areas in response to interannual fluctuations of the wind stress. Using time series of tritium concentration at Station P, Van Scoy and Druffel (1993) suggest that ventilation to the density of the NPIW occurs within the Alaskan gyre during El Niño years.

3.1.3 Variability

As we have already indicated in some instances, what is most poorly understood and modeled in all areas is the variability of the circulation. Understanding of the extent and nature of the variability in turn affects interpretation of the data and the definition of the mean circulation. We distinguish three types of variations in ocean properties and circulation: (i) - changes directly related to atmospheric forcing, with time-scales on the order of a week and spatial scales of hundreds of kilometers; (ii) - smaller scale features, with time scales of weeks to months: eddies, rings and meanders; (iii) - longer term, seasonal and interannual variations which shift the axes of currents and modify their strength and their water properties.

Weather forcing consists of the response of the upper ocean to momentum and energy exchange across the sea surface. This response may be represented through local effects in so-called upper-layer models (Large et al., 1994) or incorporated directly as input to more complex three-dimensional models. We are not discussing here the high-frequency inertial oscillations associated with the passage of storms and changes in wind speed and direction. On the scale of atmospheric weather systems, the ocean responds by moving under the wind's influence and by changing its surface properties in response to mixing and heat exchange with the atmosphere. Predicting the meteorologically forced ocean response is clearly limited in time by the skill of weather forecasting. However, the effect of free waves initiated by atmospheric forcing may be predictable on much longer, perhaps decadal time scales (Jacobs et al., 1994).

Eddies and meanders. Mesoscale variability is mostly, but not exclusively, associated with regions of strong shear. We have already noted the presence of large meanders in the path of the Kuroshio and of eddies and meanders in the Kuroshio extension and in the Oyashio. The Alaskan Stream region, off the Aleutian Islands, is another region of intense eddy activity, as is the Kamchatka Current. We have noted above that mesoscale eddies are also found in a region of weaker currents, in the Gulf of Alaska.

It is one thing to model the mean circulation, it is another to actually reproduce the eddies and meanders. All models with sufficient resolution do reproduce zones of high eddy kinetic energy generally where it is observed in nature. As a first test of the ability of models to reproduce the appropriate level of eddy kinetic energy, one may compare statistics of their eddy-generating ability to observations. The most suitable data sets for comparison are those of satellite altimetry, as used by Hogan et al. (1992) and Hurlburt et al. (1992, 1995b, 1996), who showed some compatibility between one model and some observations in the Kuroshio Extension region.

As noted earlier in our discussion of the path of the Kuroshio, the exact shape of meanders and eddies is sensitive to a variety of physical effects and to the details of model structure. Furthermore, the actual eddies observed at any one time are partially the result of the recent history of the upstream flow pattern: there is a strong dependence, in the model as in the ocean, on initial conditions. Fig. 11 illustrates the dependence of the spatial variability on various physical parameters.

The task of correctly predicting the evolution of mesoscale oceanic variability (e.g. of individual meanders, eddies and eddy-shedding events) is analogous to that of atmospheric weather prediction. The difference is that the time and space scales of oceanic mesoscale variability are quite different from those of the atmosphere. With spatial scales of tens of kilometres, much greater spatial resolution is required to model oceanic mesoscale variability. Time scales of weeks to months offer a wider prediction window than in the atmosphere, provided the effects of direct meteorological forcing are not dominant. Satellite remote sensing can, in some cases, provide sufficiently dense information for data assimilation into ocean models and operational prediction. A number of attempts have shown that sea surface altimetry can indeed be successfully assimilated into high-resolution models of active eddying regions, like the Gulf Stream (De Mey and Ménard, 1989) and the California current (White et al., 1990). A recent evaluation of forecast skills by Fox et al. (1993) shows that Gulf Stream forecasts of up to two weeks are possible. Lai et al. (1994) in their assessment of forecasting success, emphasized the importance of starting with the right initial conditions, assimilating data correctly and successfully parameterizing sub-grid scale phenomena. Early attempts to apply similar techniques to the Pacific Ocean have yielded encouraging results (Carnes et al., 1995). Sometimes, under clear skies, high resolution sea surface temperature maps may also be used to enhance the data base. This is an area of rapid and important development in marine modelling.

Seasonal and Interannual Variability. The path of the Kuroshio, the extension of the Oyashio coastal branch, the latitude of the Alaska - California Current bifurcation and the strength of the Alaskan Gyre are all subject to longer term variability. In the upper layer, some of this variability is found to be closely linked with direct meteorological inputs at seasonal and interannual to interdecadal scales. Recent climate modelling studies are convincing us that long-term oceanic variation is one of the active components of the global air-sea coupled system, as apparent in interdecadal scale climate variations (Trenberth and Hurrell, 1994). We refer to this link in a later section.

Connections with the ENSO phenomenon have already been mentioned above. Recent numerical simulations (Jacobs et al., 1994) suggest that the influence of the 1982/83 El Niño may perhaps extend over more than a decade in the North Pacific, propagating up the east coast of 27 the ocean as a Kelvin wave and travelling westward as baroclinic Rossby waves. Decadal and interdecadal variations are important in the atmosphere (Kitoh, 1991), in the sea-surface temperature (Yukimoto et al., 1995) and in the temperature and salinity of the upper 500 m of the ocean (Watanabe et al., 1994). Hurlburt et al. (1996) simulate a decadal time scale flow instability in the Kuroshio Extension that requires an eddy-resolving basin-scale model. The first EOF of the observed long-term sea surface temperature (SST) shows that both on the ENSO time scale and on a decadal time scale there are clear signals on a pan-Pacific scale (Fig. 12). Kitoh (1991) indicated in his atmospheric general circulation model (AGCM) simulation that the interannual and interdecadal variations of the intensity of the Aleutian Low, and consequently the cyclonic surface wind stress on the sea surface, are mostly results of teleconnections with similar variations of the central tropical Pacific associated with ENSO. Miller et al. (1994) simulated such oceanic variations in middle to high latitudes using observed wind stress and heat flux anomalies. The study of the impact of this type of climatic variations on ocean dynamics and on oceanic heat transport is an active field of research in ocean modelling.

A key criterion for climate change modelling, which is concerned with statistical properties rather than synoptic details, is not the predictive skill of the model for interannual variability, but whether a model has a realistic spatial and temporal spectrum of variability at these time scales. Global ocean-only models have shown realistic modes of interannual variability when forced with observed forcing (e.g. Chao and Philander, 1993; Jacobs et al., 1994; Zhang and Endoh, 1994), though it is clear that a model must possess adequate resolution in the tropical region in order to avoid distorting the important equatorial Kelvin and Rossby waves. There are also many additional areas of concern (Stockdale et al., 1993). Philander et al. (1992) noted that low-resolution ocean models may not be capable of representing the important mechanisms of ENSO, though in coupled systems they do possess distinctive modes of oscillation. Recent hypotheses suggest that decadal variability in the Pacific may be either linked to the El Niño/La Niña signal in the equatorial Pacific (Trenberth and Hurrell, 1994) or to midlatitude air-sea instabilities (Latif and Barnett, 1994).

A useful summary of the nature and predictability of oceanic variability is reproduced as Table 1 (from Hurlburt, 1984).

3.1.4 Water properties

The subarctic North Pacific is characterized by the presence of a rather brackish, approximately 100 m deep, upper layer. This layer extends south to a broad front which defines the subarctic boundary region eastward of the western boundary current region (Fig. 1). The brackish upper layer owes its existence to the excess of precipitation over evaporation over the subarctic North Pacific as well as to the inflow of freshwater from many coastal rivers. In addition, the upper layer is subject to seasonal thermal stratification. The northern marginal seas (Bering, Okhotsk) are also the site of extensive ice formation. Buoyancy fluxes through lateral boundaries (including marginal seas) and the sea surface are the main factors in determining near-surface water properties over most of the subarctic north Pacific. Advection plays an important role in spatially limited, but nevertheless very important areas, such as the Kuroshio/Oyashio confluence area, where strong horizontal mixing occurs.

Extensive modelling of the seasonal thermocline has focussed on subarctic North Pacific waters (Denman and Miyake, 1973; Martin, 1985; Gaspar et al., 1990; Thomas et al., 1993). A common technique, which has often been found satisfactory, has been to ignore advection entirely and to describe the evolution of the thermocline by using a 1-D model which includes air-sea exchanges and a parameterization of vertical mixing. This kind of model could then be attached to a 3-D ocean model to describe the evolution of its upper layer temperature. Large et al. (1994) have reviewed the limitations of upper layer models, which they find generally inadequate, even in areas of weak advection.

When advection is important, it must be included in the evolution of upper layer properties. Cherniawsky and Holloway (1991, 1993) have examined various effects on the details of water property distributions in the Kuroshio/Oyashio extension region, using a 2.5 layer primitive-equations model with resolution of 1° in latitude and 1.5° in longitude. Cherniawsky et al. (1990) coupled a sea-ice model to the above to extend the realism of the model. The circulation which results is not quite realistic, particularly in not yielding a coastal branch of the Oyashio.

Existing models are thought not to do very well with respect to the distribution and generation of water properties, most markedly in the Kuroshio-Oyashio region. Improvements in model resolution, in the specification of atmospheric forcing, in the understanding of the exchange with neighbouring, especially coastal, basins and in mixed-layer physics are necessary to improve the situation. We will return to this point in our discussion of intermediate-water formation and circulation.

3.2 Intermediate circulation

The intermediate waters of the subarctic Pacific may be defined with reference to T-S properties shown in Fig. 13. An examination of this figure reveals several important properties of the North Pacific. First, there are two main parts to the T-S diagram. Subpolar gyre stations show a T-S relation that begins in shallow water with relatively low salinities, near 33.0, and low temperatures, near 4°C, and extends to very cold (1°C) and saline (34.7) water in the deepest portions of the water column. Subtropical gyre stations, on the other hand, show relatively warm and saline surface waters (34.2, > 10°C), a mid-depth salinity minimum near potential density of 26.8, and deeper water similar to that of the subpolar gyre. The subtropical salinity minimum defines the water usually called the North Pacific Intermediate Water (NPIW). The mechanism of formation of this minimum observed in the subtropical gyre is not well-understood, but it seems clear that it is related somehow to the mixing of subpolar water across the subtropical-subpolar frontal boundary in the western North Pacific, followed by advection and diffusion into the subtropical gyre interior.

A number of studies (i.e., Talley, 1993) show that isopycnal surfaces at potential densities greater than 26.6 are not generally in contact with the atmosphere in the open North Pacific at any time of the year, effectively eliminating direct air-sea interaction as a possible agent in the formation of the subtropical salinity minimum. (Although, as we have noted earlier, there has been some suggestion of ventilation within the Alaskan gyre). Furthermore, at potential densities greater than about 27.4 the T-S characteristics of the subpolar and subtropical gyres become virtually indistinguishable. For this reason, a useful definition of the intermediate layer of the North Pacific is the layer lying between potential densities of 26.7 and 27.4. A useful map of the salinity on the central NPIW surface within this layer is given in the classic work of Reid (1965) (Fig. 14). Modelling of the intermediate circulation of the subarctic North Pacific thus includes a strong emphasis on the formation and distribution of the NPIW.

During most of the year the minimum salinity in the subpolar water column is at the sea surface, mainly due to the relatively low evaporation rate at the surface of the North Pacific compared to other oceans (Warren, 1983), while in the subtropical gyre the minimum salinity in the water column is generally located in the intermediate layer, near sigma-theta of 26.8. As noted above, however, the two gyres must be connected at that level, since the water in the subtropical salinity minimum clearly at least partially originated in the subpolar gyre (this was already represented in Sverdrup et al, 1942; Fig. 15). The present generation of numerical models does not adequately reproduce these large-scale T-S features, and indeed many existing models do not produce a subtropical salinity minimum at all. Modelling the distributions of ocean properties, like temperature and salinity, which affect density and hence circulation is a pre-requisite to the development of models which can follow tracers and pollutants. Building accurate models of the North Pacific that produce the gross large-scale characteristics of both the subtropical and subpolar gyres, and the interaction between them, is clearly a high priority for the future of Pacific Ocean modelling.

The formation mechanism of the NPIW has puzzled oceanographers for a long time (Sverdrup et al., 1942; Hasunuma, 1978; Talley, 1993) and Talley et al. (1995) have reviewed recent ideas on the process of formation of NPIW, in the area which encompasses the Kuroshio/Oyashio confluence, northeast of Japan. Fig. 16 shows a schematic diagram of the currents and features involved in the process, whereby waters advected from the Oyashio, the Kuroshio and from the Sea of Japan through Tsugaru Strait mix, under atmospheric forcing, to create NPIW.

Modelling the formation of NPIW is a major challenge! Fukasawa et al. (1992) developed an inverse model which uses Levitus's data (1982) to estimate transport on isopycnal surfaces at intermediate depths (Fig. 17). Results show a basin-scale circulation, as expected, and a source in the Oyashio-Kuroshio mixing region. Two source regions have however been suggested for the origin of the low salinity water which forms the core of the NPIW: the first is the Oyashio/Kuroshio mixing region (Talley and Nagata, 1993; Yasuda et al., 1995); the other is a process of direct spontaneous ventilation of sigma-theta 26.8 water in the Alaskan gyre (Van Scoy et al., 1991). Yamanaka et al.'s (1995) model shows that water supplies from both the Bering and the Okhotsk Seas are necessary to create the salinity minimum structure and support the first region as a more likely source. Qiu (1995) has presented a local model which tries to explain the salinity minimum structure in terms of the surrounding water masses. There is not universal agreement on the reliability of model results and a need for better resolution and better control of diffusion parameters has been expressed. Models developed do not exhibit the sharp sub-polar/sub-tropical front seen in nature. There is also little confidence in the amounts of NPIW produced. It is suggested that additional tracers (beyond salt) should be used to test the intermediate circulation; freons, for example, might provide useful information of water age and path.

There is more to the intermediate circulation than the spreading of NPIW. Yamanaka et al. (1994) have performed experiments with an Ocean General Circulation Model with and without surface wind forcing for the same surface climatological temperature and salinity conditions. In the absence of the wind stress, the remaining thermohaline circulation is only 10 to 20% of what is found in the presence of wind forcing. This result shows that the NPIW is at a depth where wind forcing circulation is still important in determining the circulation.

3.3 Deep and bottom circulation

Available information indicates that one should think of the circulation in the subarctic North Pacific as consisting of at least four layers: surface, intermediate, deep and bottom. The layer below the main pycnocline needs to be divided into deep and bottom layers because most of the northward flowing water (Lower Circumpolar Water) returns southward as a mid-depth flow of Pacific Deep Water (Fiadeiro, 1982; Johnson and Toole, 1993).

When discussing the deep and bottom circulation, exchanges with more southerly areas of the Pacific and with other oceans become extremely important, since at those depths, the primarily thermohaline circulation is linked to the global "conveyor belt" whose structure remains mysterious in many areas, and which is perhaps better represented through a more complicated diagram than a simple "belt", such as that shown in Fig. 18. Schmitz (1995) provides a recent summary of observational knowledge of the global thermohaline circulation. An interpretation of deep flows into the North Pacific, at 4,000 m and 5,000 m, by Kawabe and Taira (1995) is shown in Fig. 19. This figure clearly reveals the general western boundary current nature of the deep circulation and the channeling influence of the large scale bathymetry. The absence of any information over wide areas is also striking.

Exchanges between the Pacific and the Southern Ocean have been discussed in global model results (Gill and Bryan, 1971; Cox, 1989; Semtner and Chervin, 1992; Ishikawa et al.,1993; Toggweiler and Samuels, 1993, Ishizaki, 1994; Shriver and Hurlburt, 1995) and are still not well enough understood. Model results from Ishizaki (1994), seen in Fig. 20, do however show some general similarity with what is known of the flow. Exchanges across the equatorial Pacific have been modelled by Suginohara and Fukasawa (1988) and Suginohara and Aoki (1991), whose results exhibit a complex vertical structure of "stacked jets" along the equator whose nature remains controversial (Wang, 1995) and which seem difficult to reconcile with observations such as those of Firing (1989).

Models suggest that the combined effects of baroclinic instability and bottom topography are very important in the Kuroshio/Oyashio extension region (Hurlburt et al., 1995b, c, 1996). The bottom topography is an important factor in steering deep flows and regulating the distribution and intensity of baroclinic instability. The baroclinic instability drives abyssal flows, including eddy-driven deep mean flows, which are then constrained to follow **f/h** contours of the bottom topography (with f the Coriolis parameter and h the ocean depth). The abyssal flow in turn tends to steer the upper ocean flow, including the mean path of the Kuroshio/Oyashio extension. Eddy-driven deep mean flows from the model are consistent with mean abyssal currents measured in the Kuroshio Extension Regional Experiment in the region where the Kuroshio separates from the coast of Japan (Hallock and Teague, 1995).

The influence of unresolved eddies on bottom interactions has been discussed by Holloway (1992) and Eby and Holloway (1994). Their method for including such "topographic stresses" yields considerably different circulation patterns at depth. We shall return to this point when discussing possible improvements to model physics.

3.4 Assessment

It is tempting to be impressed by the results of models such as those depicted in Fig. 9, which reproduce the main features of the subarctic North Pacific circulation and considerable realistic detail of the circulation in some of the most complex areas within the domain. While the achievements of state-of-the-art, eddy resolving models are impressive, they nevertheless are just beginning to reproduce characteristic features of the western boundary currents and their region of interaction, such as the latitude of detachment of the Kuroshio and the frontal region of the Kuroshio Extension. They are still incapable of properly simulating water mass properties of the upper layer and the properties and positions of important fronts in vigorous mixing regions such as the Oyashio-Kuroshio confluence. Model results for the deeper and abyssal circulation are difficult to assess since there are few measurements at great depths.

Circulation modelling has made rapid progress in recent years, and in particular, the results of the high resolution models described, for example, by Hurlburt et al. (1996) are very encouraging and suggest that many of the deficiencies currently identified in model results will soon be corrected. These deficiencies are associated with the representation of physical processes, atmospheric forcing, boundary conditions at contacts with marginal seas, and other data deficiencies. These we shall consider in turn.

For convenience a list of physical models of large-scale circulation and their general characteristics is presented in Table 2.

4.0 PHYSICAL PROCESSES

While ad-hoc, correlative models may sometimes do a good job at predicting some natural phenomena, experience in atmospheric sciences and in oceanographic modelling shows clearly that better physics yields better and more reliable results. We have already alluded to a number of situations where physical understanding is lacking. These will now be discussed in more detail.

Model physics include first a correct formulation of the basic physical principles which control fluid motion and the changes in fluid properties. Difficulties in arriving at a correct formulation start with the discretization of the computational domain, which forces the representation of unresolved physical phenomena through some kind of parameterization. Even in eddy-resolving models, there remain sub-grid-scale phenomena, such as salt-fingering, cabelling, waves, tides, turbulence, inertial motions, sharp fronts, etc...which are either completely neglected or included into some exchange parameter such as an "eddy-viscosity". Sometimes, a more complicated scheme is used, which attempts to relate the state of the modeled flow and that of smaller scale properties through some closure hypothesis.

Because such problems are an important challenge to ocean modelling, they were very much on the mind of members of Working Group 7. Nevertheless, because of their generic nature, they will receive only passing attention here, focusing on a few points of particular pertinence to the subarctic North Pacific. We return briefly to numerical techniques in the last section of this chapter.

Resolution

As discussed earlier, problems of resolution are particularly important where strong flows interact with bottom topography. Another situation is the eastward penetration of inertial jets such as the Kuroshio Extension and their associated high variability. This is illustrated in Fig. 21 by a comparison of simulations at 1/8° and 1/16° resolution. It has been argued that mesoscale resolution in the probable formation region of NPIW (and perhaps in other areas) is not sufficient to identify and characterize major mixing processes. Increasing the resolution is one way to deal with this problem. The development of bigger and faster supercomputers has allowed great progress in this direction. In an area such as the subarctic North Pacific, where marginal seas, shelf regions and boundary currents are important and need to be modeled at a greater resolution, there is a need for techniques which can provide variable resolution. Possible classes of techniques in this regard include the nesting of different grid meshes (Spall and Holland, 1991) and the use of unstructured gridding techniques such as finite and spectral finite elements (Iskandarani et al, 1994). The enhanced-resolution capabilities of these new techniques will be particularly significant for programs, such as GLOBEC and others, which emphasize regional physical/chemical/biological interactions. The other way to deal with inadequate resolution is to improve the parameterization of sub-grid scale phenomena, particularly mixing, to which we return below.

High vertical resolution is required in regions where important physical phenomena take place on small vertical scales: in the upper, wind-influenced layer, and in some areas where sharp pycnoclines occur. Particular cases include the fitting of upper layer models to the top of large scale ocean models, an issue already raised above; and ice modelling.

Partial models

What we call a "partial model" is a model which focuses on a range of depths or densities: the upper, wind-influenced layer, or the salinity-minimum layer, and does not solve for the whole thickness of the ocean. (This is an unusual terminology, but one which does not raise confusion with "layer" and "level" models.) This kind of model requires boundary conditions at its upper or lower boundary, or both, from ocean layers above or below it.

Because of the need for enhanced resolution near the surface, a detailed upper-layer model which handles the physics of air-sea interactions is sometimes matched to a semi-passive deeper ocean or to an active fully three-dimensional model. Cherniawsky and Holloway (1991, 1993) have examined the response of the upper layer of the North Pacific to a variety of surface forcing regimes using this kind of approach. Sterl and Kattenberg (1994) have embedded a mixed-layer model into an ocean general circulation model of the Atlantic. This kind of approach is important and requires further experimentation, especially where air-sea interface fluxes are important.

Large-scale upwelling associated with Ekman suction is important in the eastern and the western subarctic Pacific, due to the influence of the prevailing atmospheric systems, such as the Aleutian low. Gradual nutrient replenishment associated with this process, as well as direct wind mixing, is thought to be important in determining marine productivity. However the situation is complicated; both upwelling and downwelling occur over the subarctic region. Judging from oxygen distributions, upwelling seems to be significant only in the upper layers. Distributions of other tracers, such as CFC's and tritium may also shed light on vertical water movements and need to be better understood (Van Scoy et al., 1991).

Modelling the intermediate layer circulation requires information about flows into it from above and below, which may perhaps be obtained from a meteorologically driven upper-layer above; there is however no good information on the distribution and variability of the large scale deep upwelling velocity below.

Ice modelling

The mechanical and thermodynamic processes which regulate the growth and retreat of sea ice are inadequately represented in current large-scale ocean circulation models. Although some success has been reported in coarse-resolution coupled ice/ocean modelling of, for example, the Arctic Ocean (Fleming and Semtner, 1991), available ice models have known deficiencies at the higher resolutions necessary to resolve processes in partially ice-covered regions such as the Japan, Okhotsk and Bering Seas. Alternate treatments of sea ice dynamics and thermodynamics need exploration, both in idealized settings and in fully coupled high-resolution basin-scale models of the North Pacific. In particular, small scale prediction of ice cover is extremely important for navigational purposes in the marginal sea areas.

Topographic stress

There is always a practical limit to increasing resolution. Holloway (1992) has pioneered a different approach, which considers interactions between unresolved eddies and the bathymetry in terms of statistical principles. Holloway (1992) and Eby and Holloway (1994) suggested that relaxation of flows towards a statistical highest entropy state rather than towards a state of rest might lead to more realistic representations of topographic stress. Fig. 22 shows a comparison between currents at a depth of 2,880 m obtained in the usual fashion and those obtained when imposing relaxation to a statistical state. The deep currents are much stronger in the second case and, in some areas, in different directions. The Deep Western Boundary Current in the Shikoku Basin, off Japan, is much stronger in the second model and more in keeping with the measurements of Fukasawa et al. (1986). While this approach is relevant to all ocean models, it is also a clear example of the need for further work in representing ocean physics in numerical models, and especially in modelling deep currents.

Mixing processes

Many problems of small scale physics identified as relevant to the subarctic North Pacific relate to the parameterization of mixing of water properties at sub-grid scales, a point which we have already alluded to earlier. The idea of isopycnal diffusion is based on movement of water particles carrying their salinity and temperature by steady subgrid-scale geostrophic neutral eddies. An unstable or decaying eddy mixing (also double diffusion) has a diapycnal component. Accurate modelling of diapycnal fluxes (across isopycnal surfaces) is a necessary pre-requisite for the representation of thermohaline processes, including water mass formation and conversion. It seems that the representation of the diffusivity tensor as being diagonal with respect to principal axes lying in local isopycnal surfaces is necessary for meeting this requirement. (The diapycnal and along-isopycnal diffusivities differ by many order of magnitudes.) While this can be done in fixed-level coordinate models, the necessary introduction of horizontal numerical diffusion cancels the effects of diffusivity tensor rotation and re-introduces a spuriously high effective diapycnal diffusivity, especially where isopycnal surfaces slope strongly, as in strong boundary currents (Redi, 1982; McDougall and Church, 1988). A more natural vehicle for representing diapycnal diffusive processes in the ocean is the isopycnal-layer model, in which potential density, or some other suitable variable, is used as a vertical coordinate in place of the geometric depth (deSzoeke and Bennett, 1993; deSzoeke, 1995). In a numerical model based on isopycnal coordinates the diapycnal diffusion can be very accurately controlled. This feature is a necessary requirement for developing models of water mass formation and transformation. Gent and McWilliams (1990) have discussed the same situation in terms of an "eddy-induced transport velocity" which arises from the skew-symmetric component of a 3x3 tensor which parameterizes the effect of oceanic eddy motions. Gent et al. (1995) have shown that this parameterization yields results consistent with observed meridional heat transport.

Vortex interactions

The energetic regions east and south of Japan are areas where meanders form and travel along the Kuroshio and the Oyashio, and where rings are created and transport water masses across frontal zones (Yasuda et al., 1992; Yasuda, 1995). Even in models where these features are resolved, there is a lack of clear practical understanding of the dynamics of ring and vortex interactions and of their interaction with stratification and frontal zones. Further analysis of such features and their interactions would shed light on the behaviour of these complex regions.

Numerical Methods

Model configuration (multi-level, multi-layer; spectral; sigma-coordinates...) discretization methods (finite differences, elements, irregular or nested grids...) and numerical techniques can have a strong influence on the quality of the solutions of geophysical hydrodynamic problems. The solutions obtained should be as physically faithful as possible, without numerical artifacts of, for example, dispersive, diffusive or advective nature; they should also be robust and stable in the face of parameter changes and forcing variations. For operational applications, speed of calculation is also an important factor. Methods most suitable in one area, such as the deep ocean, may not be appropriate in coastal areas; models ideal for the representation of some processes, say Rossby wave propagation, may fail miserably in some other regard. Experimentation is a necessary and important aspect of model development.

At this stage of ocean modelling, it is essential to foster independent experimentation among different groups in different PICES countries; it is equally important to facilitate frequent exchange of ideas and comparisons of models results between these various groups so that they may learn from each other and that independent work may contribute to progress for all.

5.0 MARGINAL SEAS

Three important semi-enclosed marginal seas surround the subarctic North Pacific: the Sea of Okhotsk, the Sea of Japan and the Bering Sea. These areas are the site of more extreme thermohaline forcing than the open Pacific. Runoff, cooling and ice formation in the marginal seas contribute to water mass modifications which affect the surface and intermediate water properties of the subarctic North Pacific.

The Sea of Okhotsk

The oceanography of the Sea of Okhotsk has recently been extensively reviewed by Talley and Nagata (1995). This sea has extensive shallow areas as well as deeper basins in the middle and the south (Fig. 23). The circulation during the warm season consists of a cyclonic gyre, with more intense currents along the coasts and significant input from the Sea of Japan through Soya Strait. (Fig. 24). There is also thought to be important inflow of water from the Pacific through the passes of the Kuril Archipelago. Pacific Ocean waters circulating through the Sea of Okhotsk are cooled and diluted with fresh water. Waters exiting the Sea at its southeastern end mix with Oyashio waters and are thought to be an important contributor to the formation of NPIW.

There have been few publications on models of the Okhotsk Sea; Luchin (1993), as quoted in Talley and Nagata (1995), mentions only his own modelling efforts (Luchin, 1982), where he applied Sarkisyan's D1/18/ model (Sarkisyan, 1977) to calculate summer currents using available water density information and atmospheric pressure fields described by Timofeeva. More recently, Kuzin et al. (1995) have reported on diagnostic and one-month prognostic calculations of the circulation in the Sea of Okhotsk.

The exchanges between the Pacific and the Sea of Okhotsk through the Kurile Islands occur in the vicinity of major anticyclonic eddies of great persistence (Zyryanov, 1974). The origin, nature and role of these features remain poorly understood, and need to be clarified in order to understand the exchange between the Sea of Okhotsk and the Pacific. The complex interactions suggested by Bobkov's (1993) interpretation of the circulation near the southern boundary of the Sea of Okhotsk (Fig. 25) present a significant challenge to modelers. Improved numerical modelling will certainly prove to be an important tool to unravel the subtleties of the interactions of the Sea of Okhotsk with the Pacific.

The Sea of Japan

The Sea of Japan is a deep basin, connected to the rest of the Pacific by shallow sills (Fig. 26). Overviews of its oceanography and circulation have been presented by Ichiye (1984) and Takano (1991). Overall circulation (Fig. 27) is driven by winds, runoff and temperature differences, and by inflow in the south through Tsushima Strait with outflow through Tsugaru and Soya Straits.

There have been extensive theoretical and numerical modelling studies of the Japan Sea (Kawabe, 1982; Yoon, 1982a, b, c; Sekine, 1986, 1991; Kang, 1988; Seung and Kim, 1989, 1993; Seung, 1992; Yoon, 1995; and Holloway et al., 1995). Some recent simulations in the Sea of Japan (Hurlburt et al., 1995b) have demonstrated the sensitivity of the abyssal circulation to horizontal resolution and shown the importance of going to a very high resolution (1/32°) to reproduce the separation latitude of the East Korea Warm Current. The state of modelling in that area is well developed but still subject to the general limitations regarding physical processes and data support stated elsewhere in this report (cf. also Vasilyev and Makashin, 1992; Kozlov et al., 1995).

As far as the circulation in the subarctic North Pacific is concerned, the Sea of Japan is important because it contributes water to the Pacific through Tsugaru Strait, south of Hokkaido, and through Soya Strait and along the north shore of Hokkaido, into the Kuroshio/Oyashio confluence region and the area of formation of the

North Pacific Intermediate Water (Vasilyev and Dudka, 1994).

The Bering Sea

The Bering Sea includes a very wide shallow shelf as well as a deep basin in the south (Fig. 28). Extensive ice formation during winter is a dominant feature of its surface layer. Alaskan Stream waters flows into the Bering Sea through Aleutian passes in the east and participates in the dominant cyclonic circulation which exits southwards as the East Kamtchatka current (Fig. 1). There has been extensive international study of the Bering Sea (Arsenyev, 1967; Takenouti and Ohtani, 1974; Sayles et al., 1979; Stabeno and Reed, 1994; Verkhunov, 1995). Recent modelling (Overland et al. 1994) efforts reproduce some of the features of this circulation (Fig. 29).

As seen in Fig. 1, the general surface circulation of the subarctic north Pacific includes flow through the Bering Sea and Sea of Okhotsk gyres. These two marginal seas thus participate in the general cyclonic circulation of the subpolar gyre and play an important role in meridional transport of surface waters and their properties. Contributions from the Bering Sea to the Oyashio and from flow having passed through the Sea of Okhotsk are important to the formation of the NPIW and thus to thermohaline forcing of the surface and intermediate circulations.

Overall, temperature and salinity distributions within the marginal seas and mass transport through them and out at their boundaries are not sufficiently well documented to provide reliable boundary conditions for ocean-scale models. No satisfactory modelling of the subarctic North Pacific is possible without including these fluxes. Because these basins are much smaller than the whole subarctic North Pacific, they may be easier to model with a degree of resolution sufficient to reproduce all relevant features and may be used as test areas for new developments.

6.0 DATA REQUIREMENTS

A broad observation, arising from our review of models of the subarctic North Pacific circulation, is that the quality of the models is generally similar to that of the observations in the area, or layer modeled. For example, models of the upper layer, about which most is known, are better and more reliable than those of the deep ocean. The quality and density of data available in an area determine the level of knowledge of that area and hence set the standards for modelling. As a general principle, one could then state that the best way to improve the quality of models is to improve the quality and quantity of oceanographic data. Since data are much more expensive than model results, some careful thought has to be given to gathering those data which will lead to the greatest degree of model improvement.

Bathymetry

The simplest area of data improvement, which may be done once for all, is in the description of bottom topography. A precise specification of bottom topography is essential for accurate modelling of processes in shallow areas, especially at the junction of marginal seas with the deep ocean. The importance of topographic accuracy is also felt strongly where the Kuroshio closely approaches the Japanese coast, before it flows over the Izu ridge. In that region, baroclinic interactions with bottom slopes and other vorticity effects are particularly important and strongly affect the separation latitude and the subsequent fate of the Kuroshio and of its meanders.

ETOPO5 (NOAA, 1986), the industry-standard bottom topography file for ocean modelling is thought to be unreliable in some areas below 200 m. The Kurile Island region in particular is very poorly defined in ETOPO5 and there are some doubts about the accuracy of sill depths in that region. Nearshore bathymetric information is usually available in national files, and the problem may be resolved by ensuring general access to all sources of bathymetric information within PICES partners.

Atmospheric forcing

Accurate characterization of the wind field and of surface buoyancy flux constituents is crucial for reliable modelling of the subarctic north Pacific. A comparison of results obtained by a high-resolution ocean model using respectively Hellerman-Rosenstein (climatological data from ship observations) and ECMWF (output from ECMWF weather forecasting model with assimilation of observations) wind forcing is shown in Fig. 30. There are significant differences in the path of the Kuroshio between the two simulations. In their model of the Kuroshio/Oyashio confluence region mentioned above, Cherniawsky and Holloway (1991, 1993) and Cherniawsky et al. (1990) found a significant sensitivity of the Oyashio front to wind-stress and to buoyancy inputs. These examples point out the need for the best local wind measurements and analysis as inputs to ocean models. Long-term (many decades), high quality fields of winds and surface fluxes are needed to anchor studies of the sensitivity of ocean property and circulation variability to these fluxes. A first step would be for PICES to initiate a review of the status of these fields. It is suspected that the biggest weakness is the surface freshwater fluxes [i.e. evaporation - precipi-tation]. The suggested review would be an important step in deciding "... the kinds of observations and other information needed to improve circulation models".

Re-analysis of atmospheric forcing functions is now underway at a number of agencies and will yield higher quality input to ocean models and to coupled ocean atmosphere models. These efforts are designed to provide consistently-analyzed atmospheric fields through time using state-of-the art data assimilation techniques. This will reduce the inconsistencies due to operational changes found in time-series analyses from operational products at weather forecast centres.

Accurate modelling of the surface circulation also depends critically on the availability of winds measured as closely as possible to the sea-surface. In this respect, the availability of satellite scatterometer wind information is particularly important. Support should be expressed for the continuation of programs, such as the Japanese ADEOS mission which carry out this function.

Ocean properties

Oceanographic data are necessary for initialization, boundary conditions, assimilation and verification. Information necessary to specify sea-surface fluxes is thought to be a weak point, especially in thermohaline models (precipitation and evaporation at sea). More detailed climatologies than that of Levitus are necessary, especially in complicated regions. PICES should exert its influence on member states to increase the accessibility to local data sets collected by fisheries, defense and other agencies. It is also thought to be important to continue to collect satellite data (altimetry, ocean color, scatterometry, infra-red radiation): PICES should also push for continuation of "Earth Observation" programs in member countries. The Oyashio region east of the Kuriles is poorly sampled, especially in the winter [40-50°N, 145-170°E]; more information is required in that area to understand water properties leading to intermediate water formation. Finally, acoustic monitoring of ocean properties promises to yield large- scale information about ocean climate and perhaps ocean circulation. PICES countries should keep an interest in such methods as a means of monitoring some aspects of the subarctic North Pacific.

Currents

Sufficiently long-lasting direct current measurements, both at fixed moorings and by tracked drifters, are sorely lacking in many areas of the subarctic Northern Pacific. Their absence makes critical comparison with model results difficult. Long-lasting drifters, which can follow the flow at controlled depths (or density levels), offer a particularly attractive means of comparing data and model results below the surface. The results recently reported by Riser (1995) and Taira et al. (1995), using respectively RAFOS and SOFAR floats, in intermediate and deep waters of the western Pacific are an especially satisfying beginning in this respect and provide direct information over long periods of time on deep motions. Satellite altimetry is already being used to infer geostrophic flows from sea-level slopes (e.g. Fox, 1993) and will develop into an operational tool to monitor surface currents and for data assimilation into prognostic models of ocean currents. Every encouragement should be given by PICES to the deployment of drifters, especially at depth, and to satellite missions carrying altimeters.

7.0 APPLICATIONS OF MODELLING

Oceanographers wish to know about the ocean's circulation because they will then know where water goes, where it carries heat and materials away, how it affects ocean productivity, etc... Knowing the circulation may be a goal in itself, but it also has numerous practical consequences.

Navigation

Knowledge of ocean currents is useful to plan the most effective shipping routes at sea: this was precisely the motivation for Benjamin Franklin to publish the earliest map of the Gulf Stream, off new England. While modern shipping is less sensitive to ocean currents, there remains an area where ocean models can be extremely helpful to shipping. This is in ice-covered regions where winds and ocean currents move sea-ice around, alternately hindering or favouring navigation. Coupled atmospheric-ocean-ice models in the Sea of Okhotsk and the Bering Sea may still bring benefits in planning navigation in those areas.

Ocean Pollution

The spread of noxious substances dissolved in or carried by ocean waters is a growing global concern. Radioactive substances, dissolved gases and fine particulate matter might pose threats to ecosystems or unexpectedly catalyze geobiochemical reactions; on the other hand, they may also provide information on mixing and advection in the oceans. The interests of PICES members in maintaining high ocean productivity within a clean environment already clash with their own polluting industrial activities in near-shore areas; they may soon also be causes of friction between member countries. A good understanding of ocean circulation and its variability is essential for the management of marine pollution. Existing ocean models can only provide broad guidance on contamination levels and paths taken by pollutants.

Material floating at the surface of the ocean (flotsam) is a special kind of pollutant which often travels long distances to accumulate on distant shores. Because of the visibility of flotsam, there has been wide concern about its fate at sea (Shaw and Day, 1994). In the absence of predictive models capable of describing surface currents on a day-to-day basis over wide ocean areas, imaginative short cuts have been developed to satisfy immediate needs. Wakata and Sugimori (1990) used average monthly ship-drift data to estimate the trajectories and average density distributions of floating debris in the North Pacific. Kubota (1994) derived climatic monthly values of surface drift using COADS data (for calculating Stokes and Ekman drift) and climatic averages of water properties to estimate the monthly-mean geostrophic component of the surface flow. The need for better temporal resolution of surface drift led Ingraham and Miyahara (1988, 1989) to develop the OSCURS (Ocean Surface CURrents Simulation) model which uses daily winds in combination with a climatological geostrophic current field to prescribe a surface drift velocity. This model has been applied with some success to tracking drifting objects (Ebbesmeyer and Ingraham, 1992, 1994) and to explore possible effects of ocean currents on salmon migration (Thomson et al., 1992, 1994). OSCURS of course cannot include mesoscale eddies. Comparisons between OSCURS calculations and the drift rate of satellite-tracked WOCE drifters, drogued at 15 m, show considerable similarity, but also reveal that OSCURS speeds often exceed WOCE drifter speeds by 50% or more (Fig. 31). This result reminds us of the presence of strong shears near the ocean surface and the sensitivity of surface drifter motion to direct wind action.

Climate

Under climate change, we understand large-scale changes in ocean properties on time scales exceeding that of the ENSO phenomenon. There is evidence for interdecadal shifts in ocean properties (the 1976-88 shift, for example: cf. Trenberth and Hurrell, 1995) in the subarctic North Pacific. There is also evidence for longer term changes in near-surface ocean temperature and salinity (Thomson and Tabata, 1989). Whether observed changes are of anthropogenic origin or part of long-term natural fluctuations is a question of pressing and continuing relevance. Recognizing long-term oceanic climate variability and understanding its causes requires global models of great reliability.

Secular trends in ocean properties are small, of the order of 0.1°C/ decade or less (Thomson and Tabata, 1989) and could arise from a heat flux imbalance of the order of 1 W m^{-2}. This is much smaller than the routine accuracy of surface flux measurements, although high-quality process experiments, such as the TOGA COARE experiment, have attained this level of accuracy over limited areas and short times. This being the case, the interpretation of long time scale modelling exercises must be subject to great caution and it may be that ocean circulation models run over decadal time scales should be used to study the sensitivity of the ocean to small changes in surface fluxes; they may also be useful for identifying causal patterns and linkages between modeled changes and subtle forcing modifications.

In addition to natural inter-decadal fluctuations one should also be concerned with changes associated with modified ocean conditions under global warming scenarios associated with a doubling and a quadrupling of atmospheric CO_2 levels. Some studies (e.g. Manabe and Stouffer, 1994) indicate a very strong response in the North Atlantic, where the thermohaline circulation collapses, mostly due to the greatly increased excess of precipitation and runoff over evaporation following atmosphering warming. The situation in the Pacific is more linear, with increasing atmospheric CO_2 leading to increasing temperature (Weaver, 1993). Knutson and Manabe (1994) have performed a relevant simulation with a global coupled ocean-atmosphere general circulation model with global warming induced by a 4 x CO_2 atmosphere and a control 1 x CO_2 atmosphere. Despite a 5°C warming in the equatorial Pacific and a 50% increase in time-mean atmospheric water vapour in the 4 x CO_2 simulation, they found no intensification of the ENSO-like sea-surface temperature fluctuations, but rather a slight decrease in their magnitude. Any coupled ocean-atmosphere models should successfully represent ENSO in order to represent interdecadal variability in the North Pacific circulation. This is another strong justification for extending North Pacific models to equatorial regions.

Ocean productivity

There is growing interest in fisheries management in understanding large-scale variations in ocean productivity and in the carrying capacity of commercially important species, especially anadromous fish (e.g. Hinch et al., 1995; Kuznetsov, 1995). Modelling ocean productivity consists of imbedding food-web models within physical circulation and ocean property models. There is already great interest in modelling various parts of the ecosystem (e.g. Frost, 1993; SUPER, 1993; Sugimoto and Hargreaves, 1993). Exploration and proper representation of the links between wind and boundary mixing, Ekman pumping and productivity, especially their interannual variability, which are important physical factors on the biology, require high quality wind-driven models, and in turn high quality winds. The re-analysis of winds mentioned earlier is a welcome development in this respect.

Marginal seas and shelf areas are also areas of high biological productivity. Variations in the production of commercial species of greatest interest often depend on phenomena and interactions occurring on scales well below those now resolved by ocean wide and regional models. A major challenge for fishery oceanographers will be to find a way to use the results of large scale models within the scope of more local interests.

Interannual variations in circulation and water mass patterns may have unexpected results on carrying capacity that will require coupled physical-biological models to quantify and test hypotheses regarding mechanisms of cause and effect. For example, in the vicinity of Hawaii, in the central North Pacific subtropical gyre, the 1991-92 ENSO event appeared to create a more stable surface layer. Karl et al. (1995) documented a resulting increase in relative abundance of nitrogen-fixing microalgae such that the food-web shifted from nitrogen-limitation to phosphorus-limitation, with accompanying changes in food-web structure and trophic flows.

CO_2 exchange

At this point, we cannot reliably estimate the ocean-atmosphere CO_2 transfer rate. Both ecosystem and CO_2 system studies will require explicit mixed layers embedded in Ocean General Circulation Models. These models will have to represent adequately fluxes at the based of the mixed layer [the Large et al. (1994), kind of model]. Current GCM models of the CO_2 system contain highly constrained biology (e.g. Maier-Reimer, 1993), although Drange (1994) has developed a version of the Miami isopycnic model (Black et al., 1989) of the North Atlantic for the CO_2 system that includes a 7-compartment ecosystem module. No doubt similar attempts will be made in the subarctic North Pacific in the next few years.

Wallace (1995), in his discussion of monitoring carbon inventories emphasizes the need for further measurements and better models to understand the uptake of tracers (including CO_2) and interpretation of tracer results.

Fish migration and distribution

The distribution and migrations of fish populations are influenced by ocean properties. It has long been a goal of fisheries oceanographers to discover reliable links between routinely measured ocean properties and the distribution of commercially exploited fish stocks. More recently there has arisen a broad concern about the effects of climate change and its effect on the carrying capacity of the ocean (Beamish, 1995).

Once some relation has been established between fish habitat and ocean properties, modelling can help by keeping track of the location and extent of waters having these properties. Forecasting of mesoscale variability may assist in directing fishing activity; seasonal and interannual variability may affect stock assessment; long-term climate variations may lead to significant changes in carrying capacity and in migration routes. For example, in the northwest Pacific, a relationship between oceanographic conditions and saury fishing grounds has been found, suggesting that inter-decadal oceanographic variations may lead to significant changes in migration routes (Yasuda and Watanabe, 1994; Yasuda and Kitagawa, 1995). Welch et al. (1995) have recently discovered significant temperature limits to salmon habitat in the subarctic North Pacific. Prospects of global warming threaten to reduce the extent of this habitat.

Fish migration studies require not only ocean property distributions, but also currents. In studying the effects of ocean currents on the homing migration of sockeye salmon to the Fraser River, Thomson et al. (1991, 1993) and Dat et al. (1995) used surface current vectors from the OSCURS model. Francis and Hare (1994) used the same model in their bioenergetic studies. There is a clear need for better models of surface currents, and a comparison of the Hurlburt et al. (1996) model with WOCE drifter paths and OSCURS results would be in order.

Fisheries are an important economic activity of PICES countries and a better, more quantitative knowledge of the influence of ocean conditions on fish habitat and fish migrations is necessary to improve planning and management of fishing activities. Existing circulation models are neither detailed enough nor reliable enough to follow fish habitat and predict migrations.

Weather prediction

The influence of ocean temperatures on weather needs little discussion and is indeed the original source of interest of meteorological agencies in the oceans. Better long-term weather prediction in North America relies in part on a better predictive knowledge of sea surface temperature in the North Pacific. Refinement of Ocean-Atmosphere Coupled General Circulation Models is already a goal of Meteorological Agencies in member countries and it is important for PICES to maintain close contact with these agencies as well as with ocean-oriented bodies.

Ocean prediction

Prediction of ocean properties in real time, using methods similar to those of atmospheric weather prediction, is possible only with a good understanding of physics, powerful modelling tools and extensive data. Dense sampling over a wide area is necessary to initiate a model and assimilate data into a prediction scheme. Coupling satellite altimetry with high-resolution models could allow predictive modelling of surface flows and their variability in regions of particular interest. Preferred application would be to areas where rapid knowledge of the varying position of fronts, eddies or other features is thought to be relevant to economic activity, such as fishing, or to public safety, as in weather prediction. Because of the limits of resolution (now at best +/- 2 cm) of the altimetry, the technique is currently applicable only in regions of sufficiently high eddy kinetic energy. The development of ocean predicting systems has been reported by Robinson et al. (1989), Glen et al. (1991) and Miller et al. (1995). Fox et al. (1993) and Lai et al. (1994) have described operational applications in the Atlantic; Carnes et al. (1995) reported on efforts to apply similar methods to the North Pacific. In all discussions of ocean prediction, one should recall earlier comments about ocean predictability, as summarized in Table 1.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Our review has clearly shown that modelling of the circulation of the subarctic North Pacific is an area of intense scientific activity and that great progress has been made in recent years. This activity is taking place in the broader context of ocean modelling in general and often as a geographical component of pan-Pacific or even global models. Progress has been driven by need for a better understanding and predictability of weather, climate, fisheries, navigation and environmental protection; it has been facilitated by technological developments in numerical modelling techniques and computing technology.

A comparison of model results with available information on ocean currents and properties shows that, although models reproduce some of the main features of the circulation, many important features remain poorly modeled and indeed unexplained.

It is noteworthy that models have received the most attention and yield their best performance in areas where the observations are most detailed: Model results are also most detailed and closest to observations in the upper ocean, where data are most abundant. Results at great depths are less reliable, if only because there are fewer observations to compare them to.

Confidence in model results thus continues to be established in relation to observations. There are still too many difficulties in representing oceanic physics on coarsely discretized grids to believe model results simply on the basis of the physics which they contain; furthermore, there remain many contentious points about how well the physics are represented in existing models. For example, we still don't know to what extent boundary layer versus interior mixing governs large scale dynamics.

Existing circulation models are still incapable of providing reliable explanations of variations in large-scale ocean productivity or in regional oceanographic features pertinent to fisheries. There has nevertheless been significant progress made in high-resolution modelling of the North Pacific circulation, particularly in modelling high-latitude El Niño effects, which suggests that further progress is to be expected in that area. Because of current difficulties in modelling the mechanisms and rate of production of North Pacific Intermediate Water, and the lack of sufficient observations, it is not yet possible to assess the rate of ventilation of the subarctic North Pacific and its rate of uptake of carbon dioxide. The unreliability of deep circulation models remains an obstacle to connecting the subarctic North Pacific to global ocean models.

While predictive modelling of the response of the ocean to meteorological forcing remains limited by the predictability of atmospheric circulation, longer-term predictability is possible in situations where a large component of variability is associated with internal dynamics, such as in the evolution of Kuroshio meanders, or of El Niño effects. Ocean model predictive skills thus depend on the phenomena under consideration, as well as on model structure and the use of data assimilation techniques (Hurlburt, 1984). Proposals for improvements in ocean modelling capability must take careful account of such considerations. Furthermore, given current developments in coupled ocean-atmosphere modelling, ocean predictive modelling on climatological time scales will soon be merged with ENSO models, North Pacific mid-to-high latitudes ocean and atmosphere system prediction and global warming models. Ocean models will then be an internal component of climate models.

All the above problems are however characteristic of ocean modelling in general: similar difficulties are encountered in other oceans. Some would argue that since 20 years of intense modelling efforts have still left a number of important deficiencies in models of the North Atlantic, a smaller ocean, it might be unwise in the short term to strive for full representation of subarctic North Pacific features in eddy-resolving models, and that the emphasis should focus on a better understanding of the physics of specific processes (such as formation of the North Pacific Intermediate Water). Others disagree with this opinion and would insist that detailed observational comparisons are as important in the Pacific as in the Atlantic. Recent high-resolution models of the North Pacific (Hurlburt et al., 1995) have been more successful at describing the separation position of the Kuroshio and its interaction with topography than similar attempts with the Gulf Stream. However, computing facilities will remain for some time one of the limiting factors in the development of high-resolution models of the Pacific Ocean circulation.

Numerical ocean modelling will continue to develop, driven by the needs of those who would apply its results as well as by the scientific ambition of modelers. Academic and operational models will continue to be improved as physical and computational understanding is refined and the machinery's power increases. What is of concern to this Working Group is what can be done by PICES to facilitate the improvement of circulation models in the subarctic North Pacific and to bring the greatest benefits to participating countries. Our recommendations will address these issues.

In keeping with our observation that the best models are developed where the best data are available, our first set of recommendations addresses the continuing need for information about the ocean to stimulate model development and permit verification. Fundamentally, the more we know about the ocean, especially about those aspects in which we are most interested, the better our models will become. Ocean modelling is still, and will long remain, at a stage where model results cannot replace data. One of the most effective means for PICES to assist in improving models of the circulation of the subarctic North Pacific is to recommend action to fill data gaps and to make data available to modelers of all participating countries.

Recommendation 1. PICES should press for filling data gaps seen by the Working Group as impediments to model development in the following areas:

1.1 - ocean bathymetry, currently available in files such as ETOPO5, with 5-minute resolution, is inadequate for coastal models, marginal seas, and flow-topography interactions. General availability of geo-referenced high resolution (1 km or better) bathymetry is required for reliable modelling in those circumstances. PICES should mandate a small group with the responsibility of making this information available to its members.

1.2 - extensions of ocean property atlases to finer spatial and temporal resolution are desirable, especially in areas of active mixing (Kuroshio/Oyashio confluence) and strong air-sea exchanges (Bering and Okhotsk Seas). PICES should create, or stimulate within one of its members, the creation of a group of people devoted to the formulation and accomplishment of that task.

1.3 - ocean-atmospheric exchanges are a dominant forcing of oceanic models; high-resolution, re-analyzed atmospheric heat flux, freshwater flux and wind stress fields are essential for modelling of upper layer properties and circulation. PICES should initiate, or stimulate, a detailed review of the quality and availability of time-series of all meteorological forcing fields over the subarctic North Pacific as a step towards improving the reliability of models.

1.4 - high spatial and temporal resolution of ocean properties, especially sea-level height (through satellite altimetry), is essential for documenting the circulation and facilitating model verification. PICES should express strong support for national and international satellite missions for observation of the oceans.

Recommendation 2. PICES should express support for the development of the Ocean Observing System and offer assistance in coordinating its implementation in the subarctic North Pacific.

Recommendation 3. Data are useful only when available. PICES should encourage the development of avenues of rapid, informal as well as formal, data exchange between agencies, institutions and individual scientists in participating countries, so that collaboration may be enhanced and model development hastened.

A second set of recommendations aims at encouraging development of models for the benefit of PICES countries. Although we have indicated a number of areas in which improvements are needed in physics and in computing, we do not attempt to be prescriptive of details: progress will be accelerated by means of providing modelers with information, equipment and challenges.

Recommendation 4. To encourage development of modelling, PICES should sponsor or support interdisciplinary, international workshops concerned with modelling specific geographical areas or addressing specific fundamental issues. These workshops should be carefully focussed, identifying needs, state-of-the-art, challenges and suggestions for improvements.

Suggested geographical areas could be: the Kuroshio/Oyashio confluence; the Kuroshio extension; Bering Sea - Pacific Ocean exchange, etc.... Modelling topics could be: matching marginal sea to the deep ocean; the deep and abyssal circulation; data assimilation and its application to circulation models as well as to other, not exclusively physical, ocean properties.

Recommendation 5. To enhance the utility of models to a broad community of ocean scientists and decision makers of countries with different languages and scripts, PICES should encourage the development of visualization methods applicable to large (the whole subarctic North Pacific domain) as well as small scale (e.g. Kuroshio path simulations) situations and capable of carrying impactful insight about all kinds of ocean phenomena. A competition for the most successful visualization satisfying these criteria could be a feature of PICES meetings, with appropriate prizes.

9.0 TABLES AND FIGURES

Table 1. Predictability of Oceanic Phenomena (adapted from Hurlburt, 1984).

CLASS	EXAMPLE	IMPLICATIONS
1. Strong, rapid (less than a week), and direct	Upper mixed layer, surface waves, upwelling (both coastal and equatorial processes), storm surges	Forecasts are short range; limited by atmospheric predictive skill, less sensitive to errors in initial state; more sensitive to errors in forcing
2. Slow (weeks to months) and indirect	Mesoscale eddies, meandering currents, frontal locations, features related to low instabilities on the mesoscale	Forecasts may have range of month or more; more sensitive to initial state; less sensitive to errors in forcing; statistics may be predicted via simulation; requires operational oceanographic data; altimeter data promising
3. Slow (weeks to years) and direct	El Nino; much of the tropical ocean circulation; gyres; patterns associated with geometric constraints, i.e., med. circulation	Long range forecasts possible; sensitive only to errors in forcing on long time scale; “Nowcasting” and forecasting feasible using ocean models with sparse ocean data

Table 2. Specifications for physical models of large-scale circulation.

	Predicting Variables and Equations	Physical Implications	Examples in Text
1. Layer Model	Horizontal velocities and layer depth. Horizontal momentum equation averaged in an isopycnal layer and equation of mass conservation for layer depth. Layer depth and velocities are defined on horizontal grids	Water mass exchange between layers is parameterized as dia-pycnal mass flux. Temperature and salinity are jointly expressed in thickness of isopycanl layers.	Yoon and Yasuda (1987)
2. Level Model (often called as OGCM)	Prognostic equation of horizontal momentum and temperature/salinity equations with the equation of state (for water density from temperature, salinity and pressure). Vertical velocity is daignostically estimated by mass continuity equation.	Heat flux and water flux at the sea surface are explicitly incorporated. Widely known as Bryan-Cox (GFDL) type model. Although depth of a vertical grid point is often fixed in time, isopycnal vertical coordinate is sometimes adopted. For explicit treatment of tidal currents, a free surface version of OGCM is developed.	Eby and Holloway (1994)
3. Eddy Resolving Model for 1 & 2	Prognostic equations of horizontal momentum and pressure/density fields with horizontal grid size, pressure/density fields with horizontal grid size, typically less than ¼ degrees or 1/6 degrees.	Explicit prediction of meso-scale eddy motion. Isopycnal diffusion associated with meso-scale eddies is included.	Hurlburt et al. (1996), Semtner and Cherbin (1992)
4. Diagnostic Model (Inverse Model)	Determine horizontal and vertical velocities with a diagnostic method, given the density field and/or under constraints of conservation of water mass and any other water properties and chemical tracers.	The model is called an inverse model when the equations are non-predictive (no time change). When predictive temperature and salinity in an OGCM 2 are restored to the given T and S (i.e., density field) with sufficiently short time, it is called a robust diagnostic model.	Fukasawa et al (1992) One from robust models?
5. Coupled Atmosphere and Ocean Model	Prediction of physical variables with OGCM 2 and Atmospheric GCM, exchanging sea surface momentum-, heat-, and water- fluxes. For longer time-scale climate change, such as global warming, a sea-ice model is additional	A tool for study of mechanism of global climate change such as ENSO and the interdecadal climate shift, Coupled O-A layers model 1 are also employed in ENSO study.	Philander et al. (1992), Latif et al (1994)

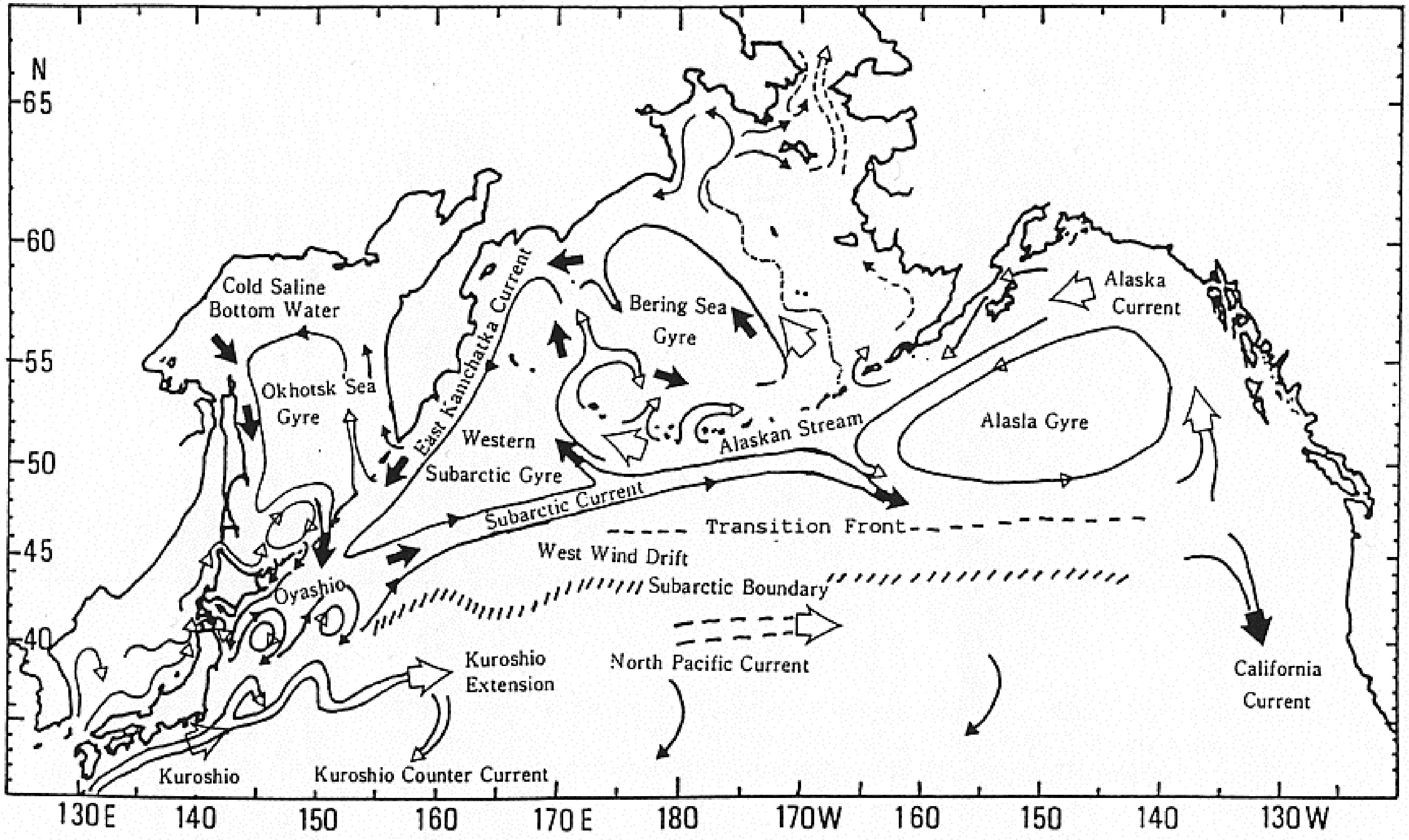

Fig. 1. General surface circulation in the subarctic North Pacific Ocean. (after Dodimead et al., 1963; Favorite et al., 1976; as revised by Ohtani, 1991)

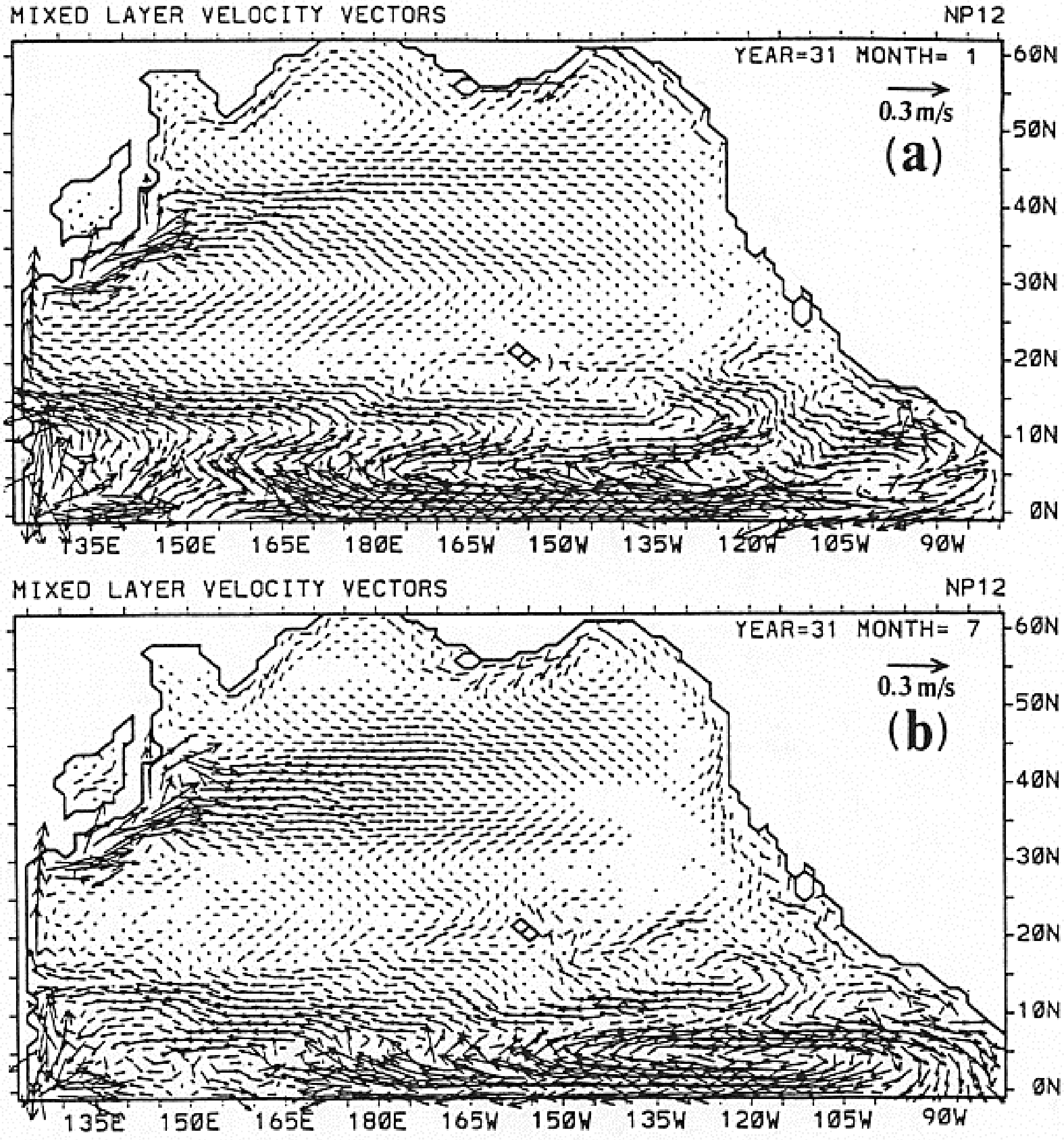

Fig. 2. Upper layer velocities in the simplified upper ocean model of Cherniawsky and Holloway (1991) in a) January and b) July. Resolution in this model is 1° latitude by 1.5° longitude; the model is driven by wind-stress and fluxes of heat and salt. It consists of only two layers in the vertical. For clarity, every second vector and vectors < 0.01 m/s are deleted and vectors > 0.3 m/s are truncated to 0.3 m/s. Note the seasonal variability.

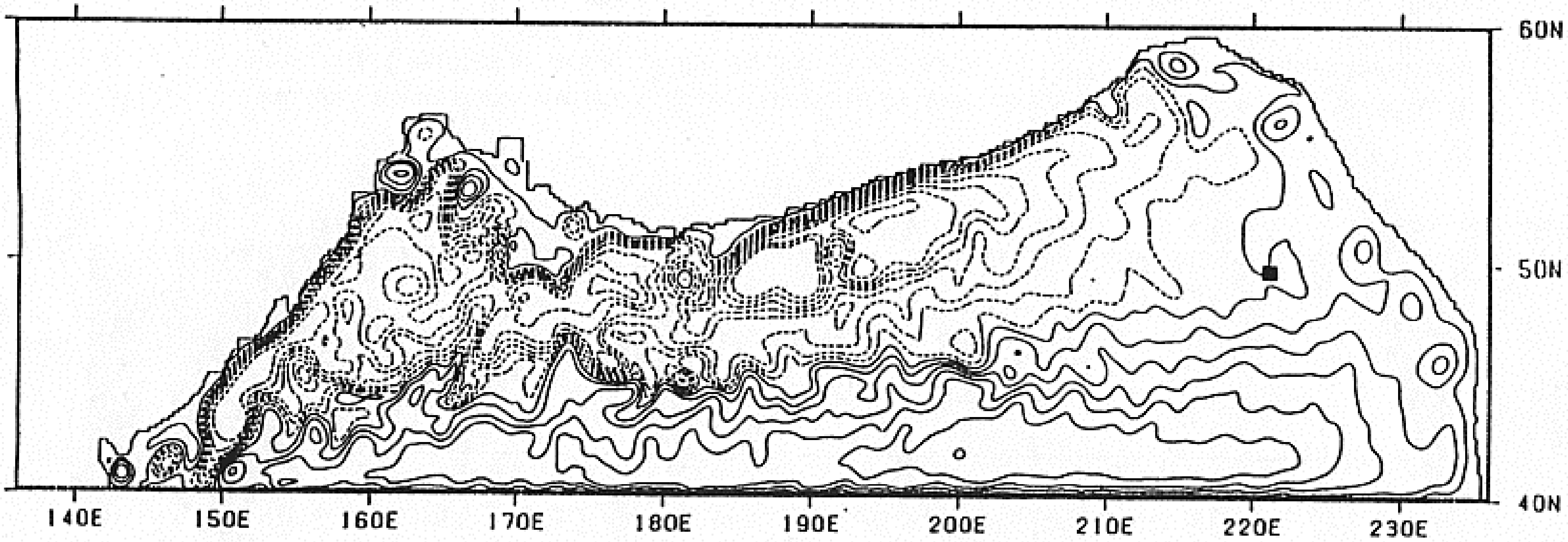

Fig. 3. Instantaneous streamfunction in the top layer of the three-layer, quasi-geostrophic, 1/6° resolution model of Cummins and Freeland (1993). The contour interval is 7500 m2s-1. Note the presence of the Alaskan Stream as a coherent flow along the slanting northern boundary which separates from the coast at about 185°E. This model does not include any of the marginal seas: Bering, Japan, Okhotsk.

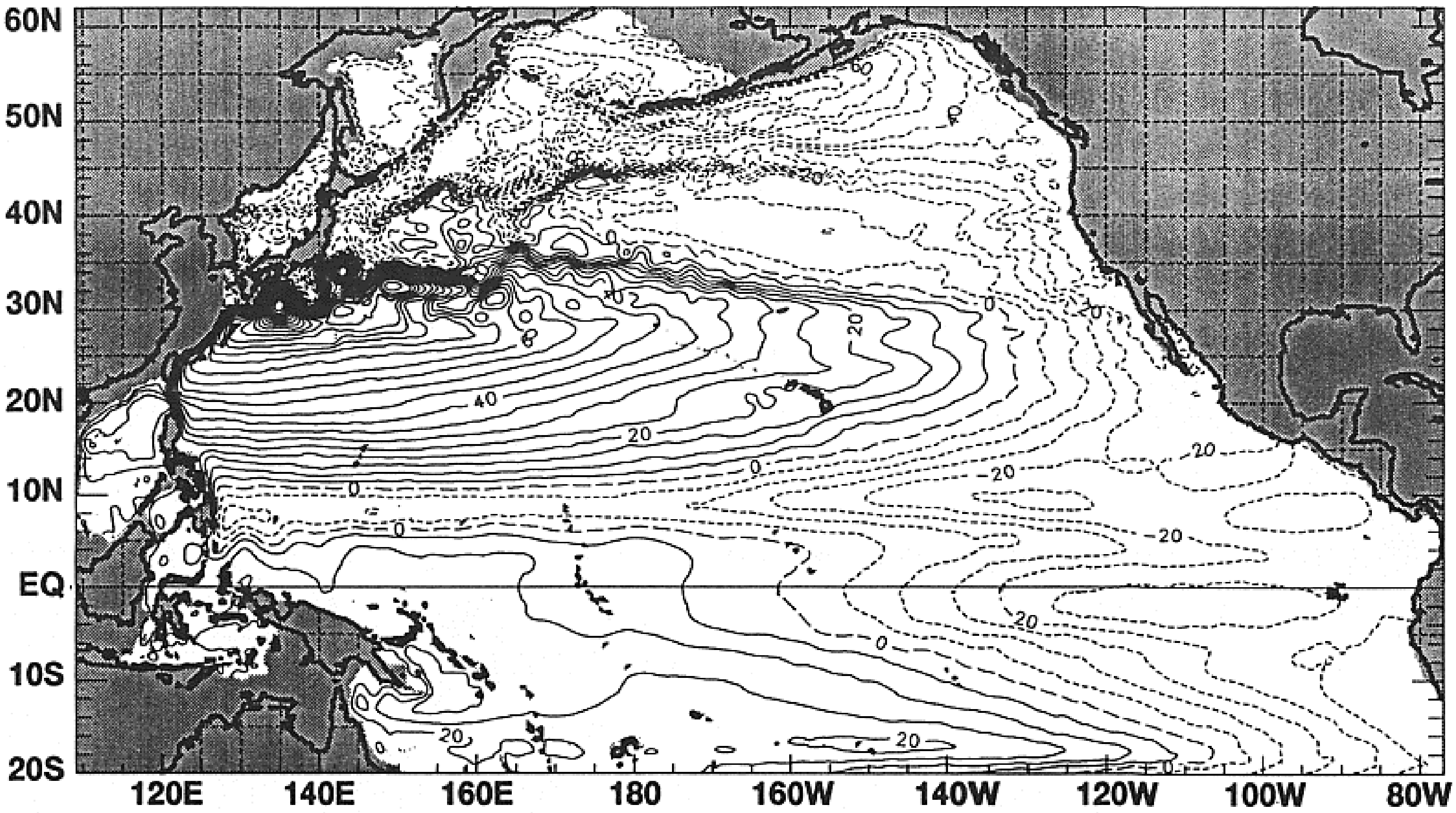

Fig. 4. Simulated upper ocean current systems as depicted by average sea-surface height from the NRL 6-layer, 1/16° resolution model of the Pacific Ocean north of 20°S. Positive contours above the reference level are solid lines; negative contours are dashed lines (Minimum = -80.18 cm; Maximum = 144.60 cm). The model was forced by the Hellerman and Rosenstein (1983) monthly wind stress climatology. From Hurlburt et al. (1995a).

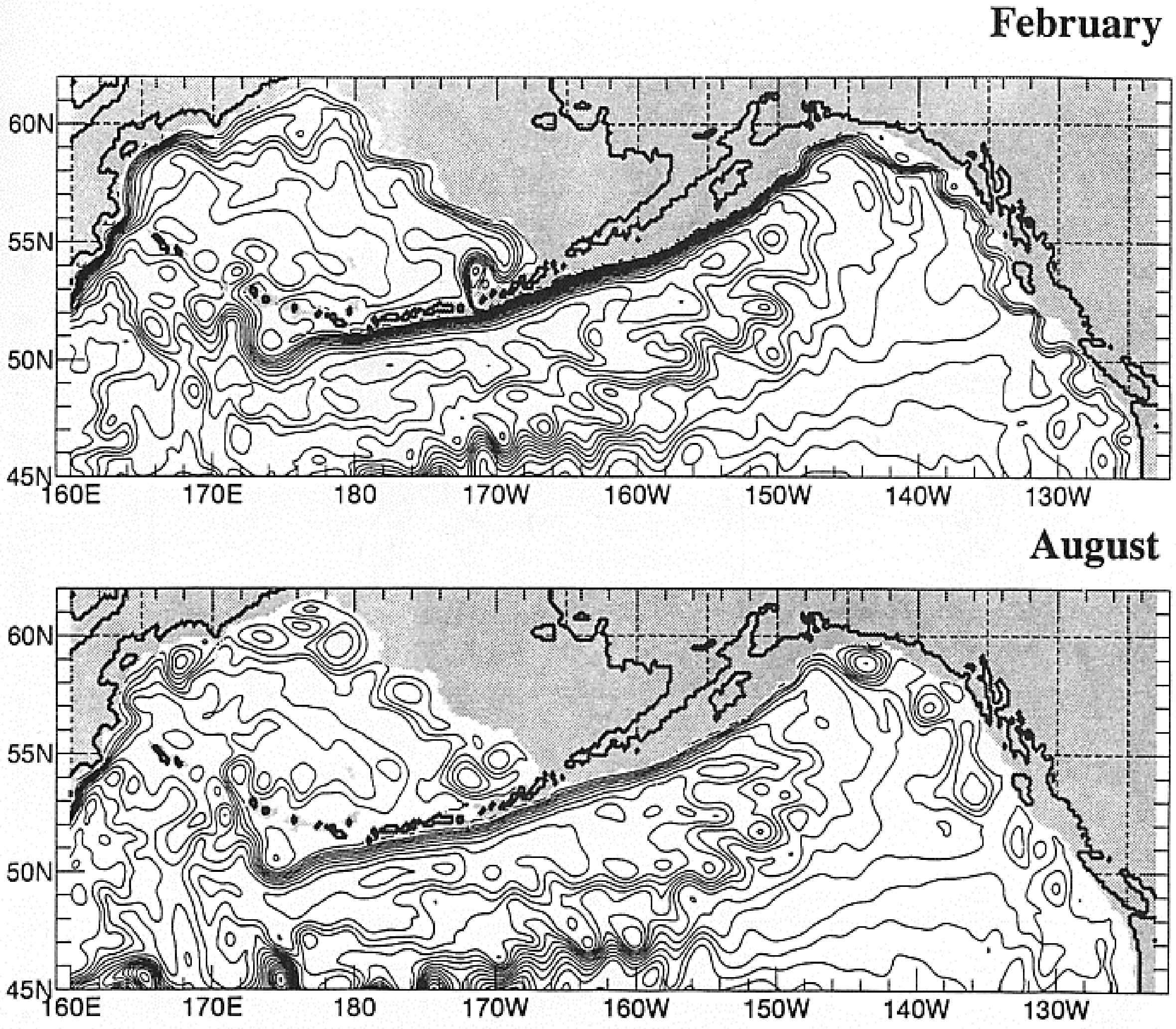

Fig. 5. Snapshots of sea surface heights in the subarctic North Pacific portion of the NRL 6-layer 1/8° resolution Pacific Ocean model. (Courtesy of H. Hurlburt).

The model successfully depicts the main features of the circulation such as the subpolar and Alaska gyres, the Alaska Stream and the Kamchatka Current. Strong seasonal variations occur near the eastern boundary of the Alaska Gyre and the deep part of the Bering Sea. In February, northward eastern boundary currents are found in both regions. By August, they have given way to large eddies that have started to propagate off shore. Such eddies have been observed, the best known being the Sitka Eddy. The model was forced from rest to statistical equilibrium at 1/4 degree resolution and then continued at 1/8 degree (0.125 x 0.176 degrees lat, long for each variable). The atmospheric forcing was provided by the European Centre for Medium Range Weather Forecasts (ECMWF) 1000 mb winds averaged monthly over the period 1981-1991. This simulation was done in support of the ARPA/SERDP funded project, Global Acoustic Mapping of Ocean Temperature (GAMOT).

ARPA/SERDP = Advanced Research Projects Agency/ Strategic Environmental Research and Development Program.

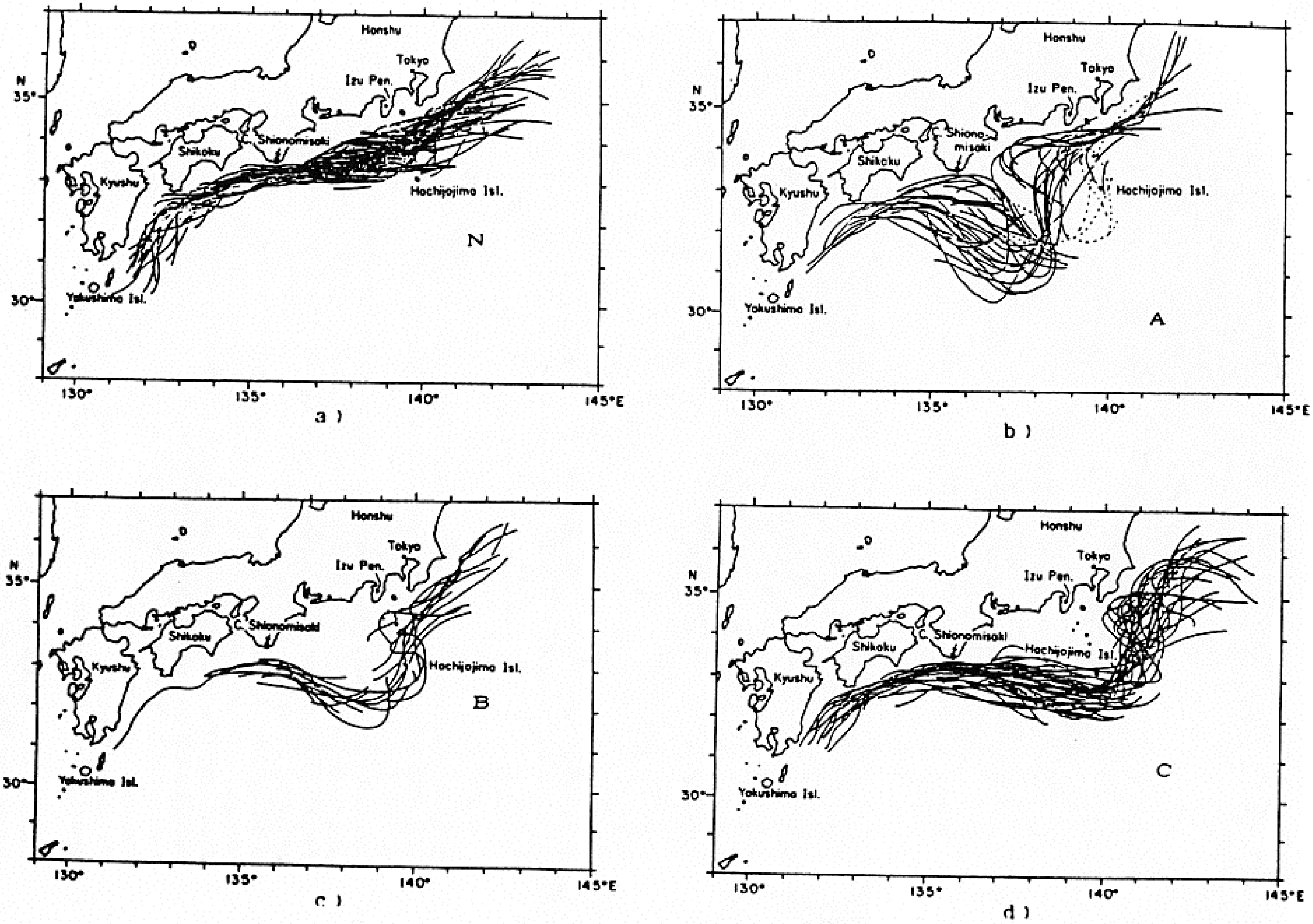

Fig. 6. Stream axes (15°C isotherm at 200m) of four typical states of the Kuroshio during the period 1955-84. (from Yoon and Yasuda, 1987).

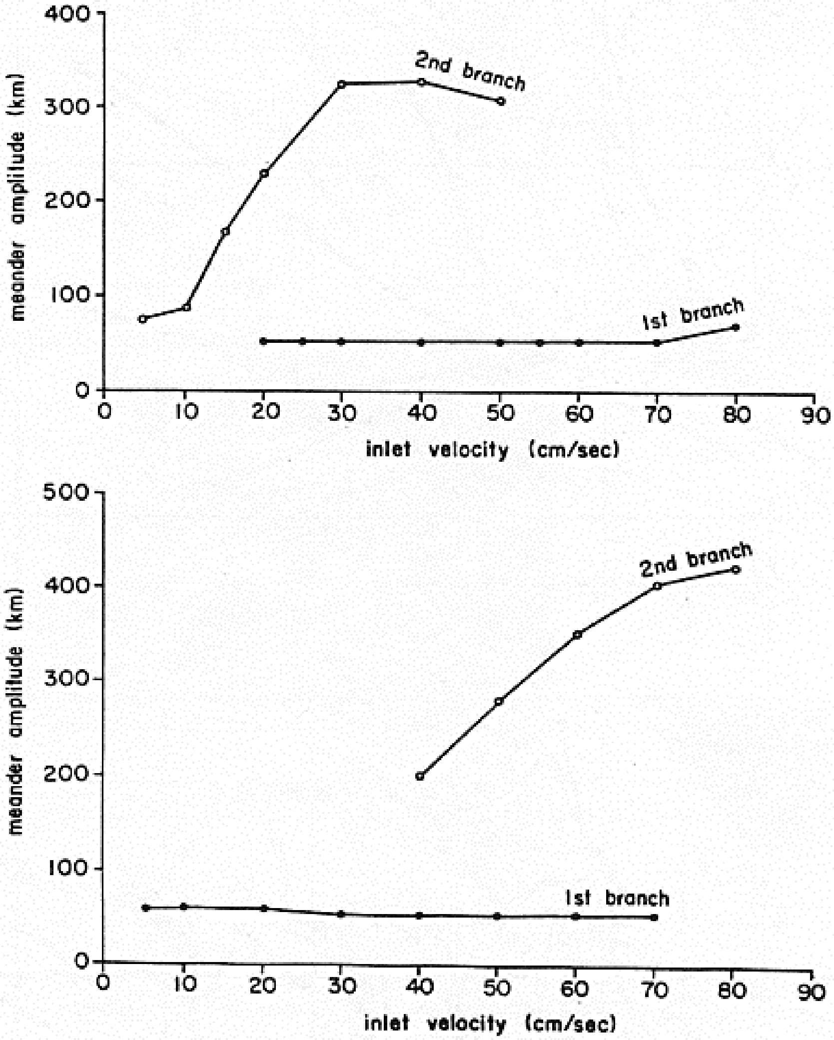

Fig. 7. Path selection as a function of inflow velocity in a model of the Kuroshio path with sloping coastline. The upper panel corresponds to an angle of 12° north of east; the second panel to an angle of 23°. The "1st branch" corresponds to the linear (N) flow pattern; the "2nd branch" is the meander path (A). (from Yoon and Yasuda, 1987).

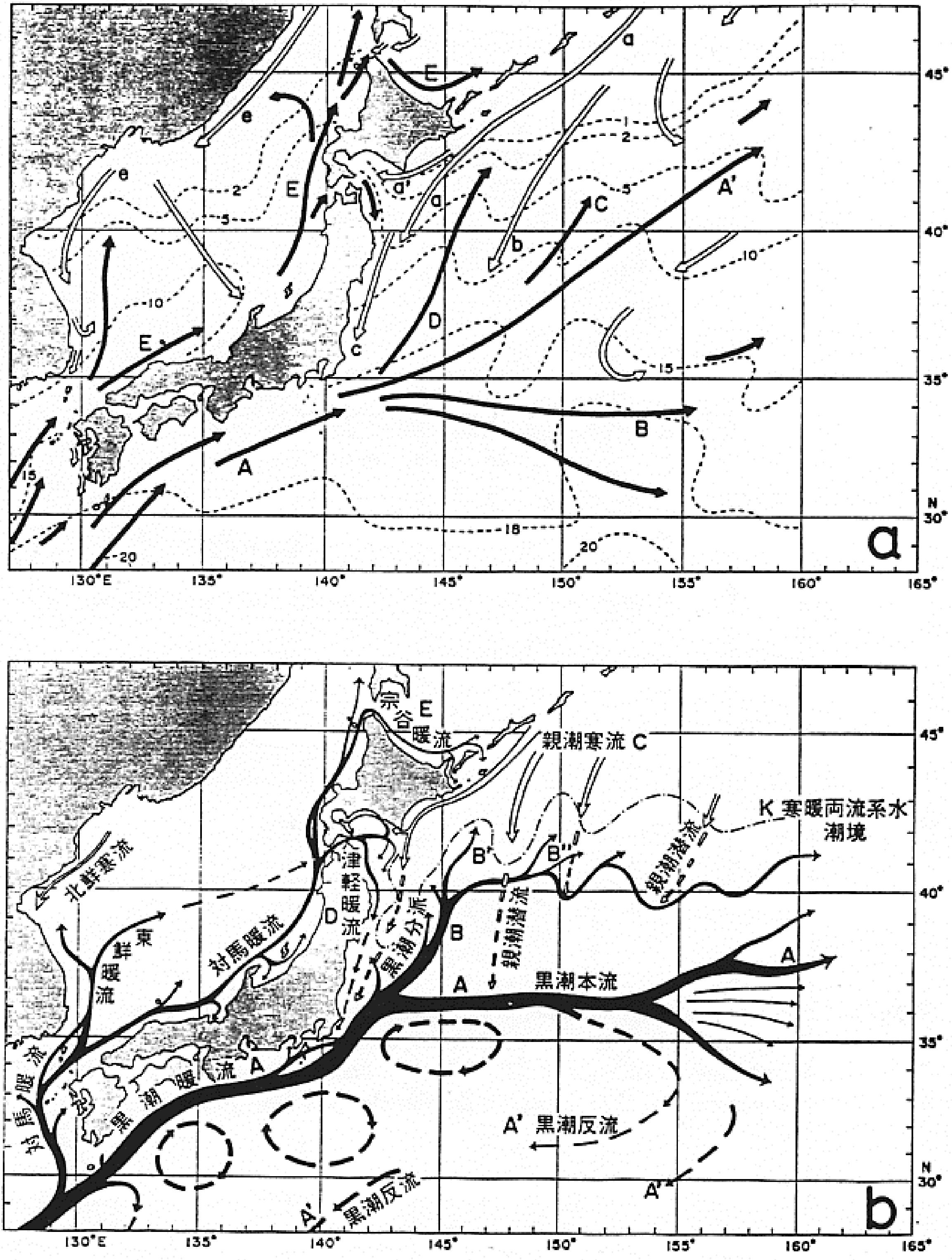
a
b
A
A'
B
C
D
E
a
b
c
d'
e
1
2
5
10
15
18
20
宗谷暖流 E
親潮寒流 C
K 寒暖両流系水潮境
親潮潜流
北鮮寒流
東鮮暖流
対馬暖流
津軽暖流 D
黒潮分流
B
B'
B''
A 黒潮本流
黒潮暖流 A
A' 黒潮反流
A'
130°E
135°
140°
145°
150°
155°
160°
165°
N 30°
35°
40°
45°

Fig. 8 (a) & (b).

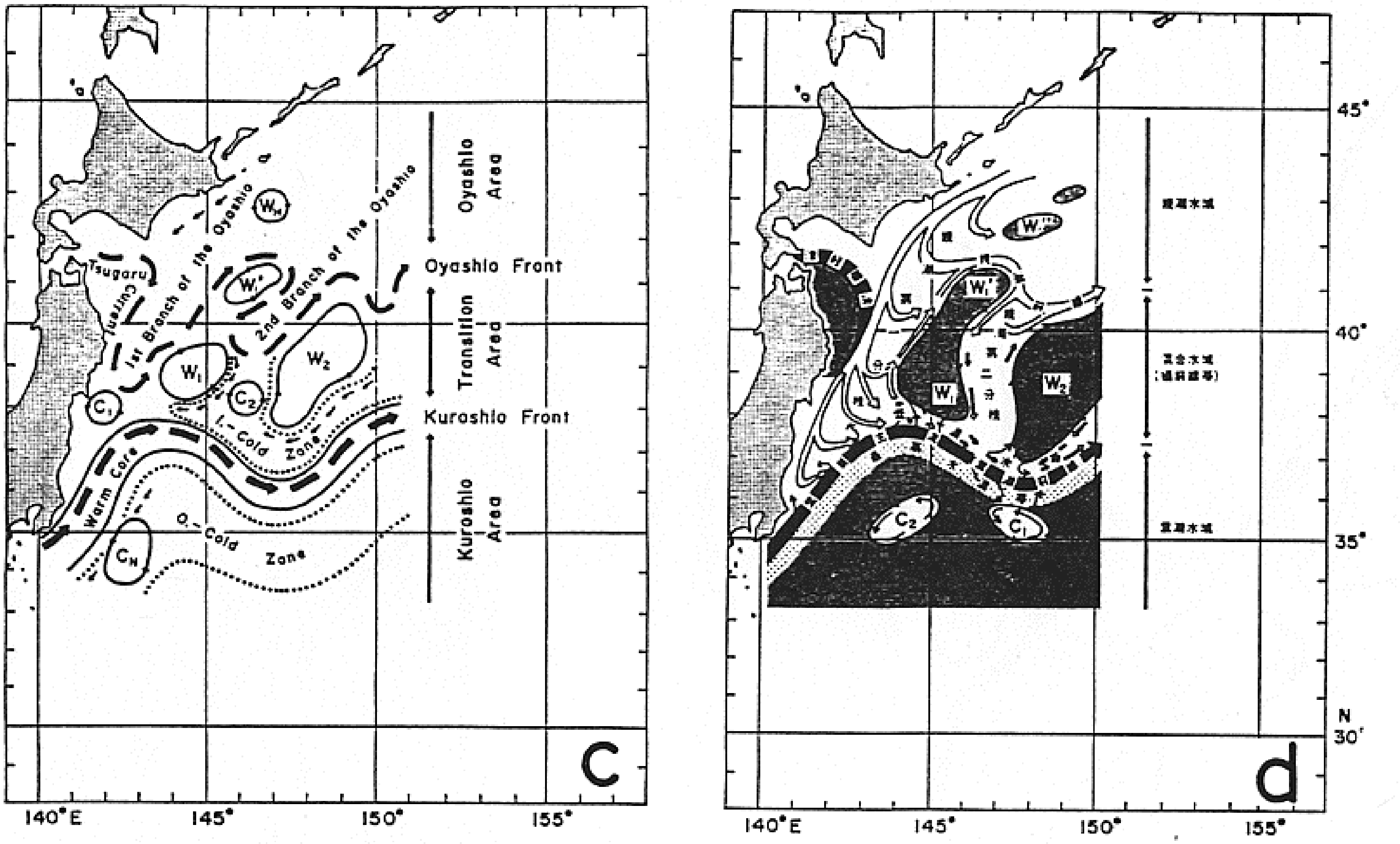
Tsugaru Current
1st Branch of the Oyashio
2nd Branch of the Oyashio
W₁
W₂
W₁'
W_H
C₁
C₂
C_H
I.- Cold Zone
O.- Cold Zone
Warm Core
Oyashio Area
Oyashio Front
Transition Area
Kuroshio Front
Kuroshio Area
c
d
W₁'''
140°E
145°
150°
155°
45°
40°
35°
N 30°

Fig. 8 (c) & (d).

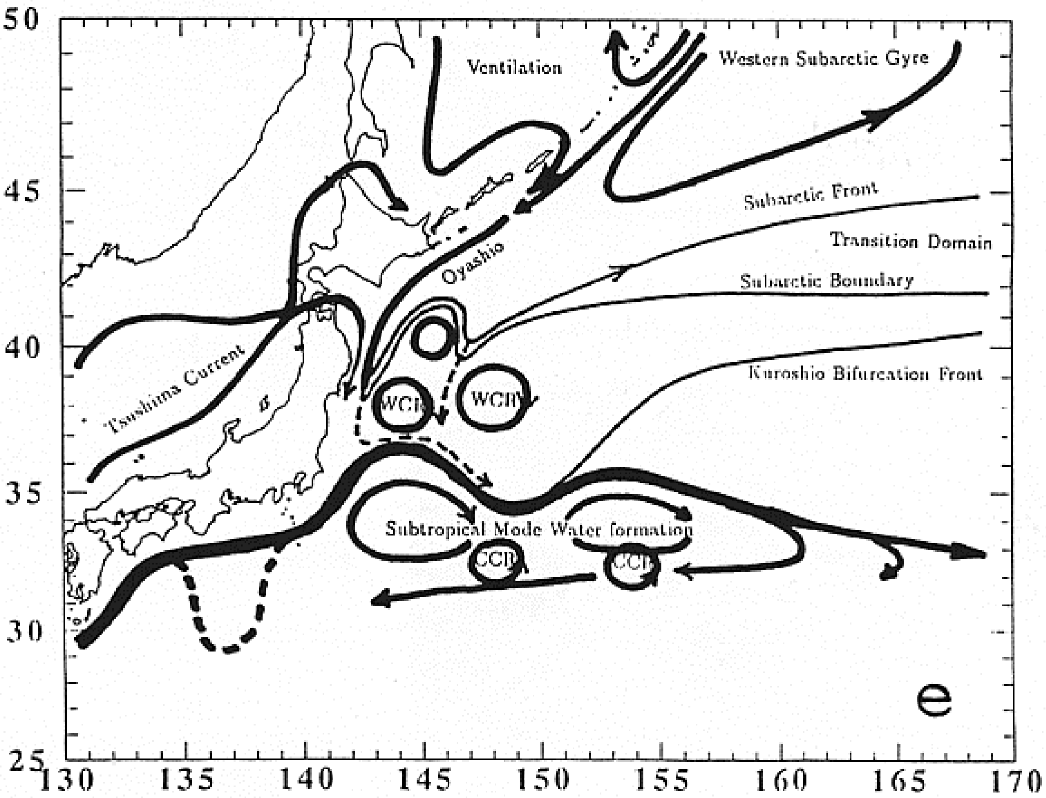

Fig. 8 (e).

Fig. 8. Interpretations of circulation patterns in the Kuroshio-Oyashio confluence and Kuroshio extension region, near Japan.

Parts a-d are reproduced from Kawai (1972) and represent various interpretation proposed at that time (original sources in reference).

a - Alternatively meshed current fingers, with dashed lines showing water temperature (°C) in February;

b - is an interpretation in terms of fork-like currents, without confluence;

c - is a double front system, with streaks and eddies;

d - is a modified double front system.

Part e is the circulation pattern inferred by Yasuda et al. (1995), with warm core (WCR) and cold core (CCR) rings.

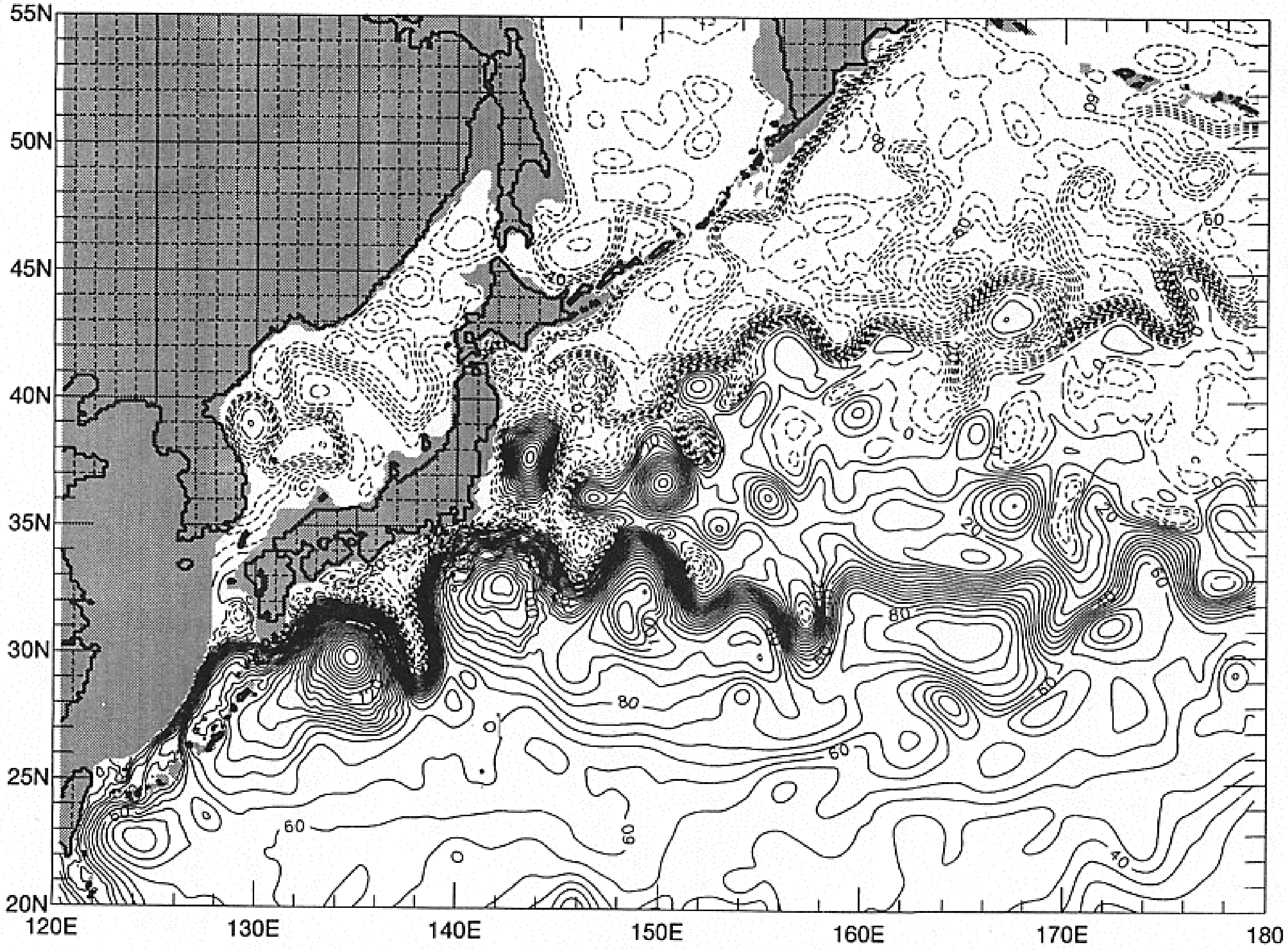

Fig. 9. January snapshot of sea surface height in the northwest Pacific as simulated by the NRL 6-layer, 1/16° resolution Pacific Ocean model of Hurlburt et al.(1995a). Note the general similarity with the double front systems of Fig 8. Contour interval is 5 cm.

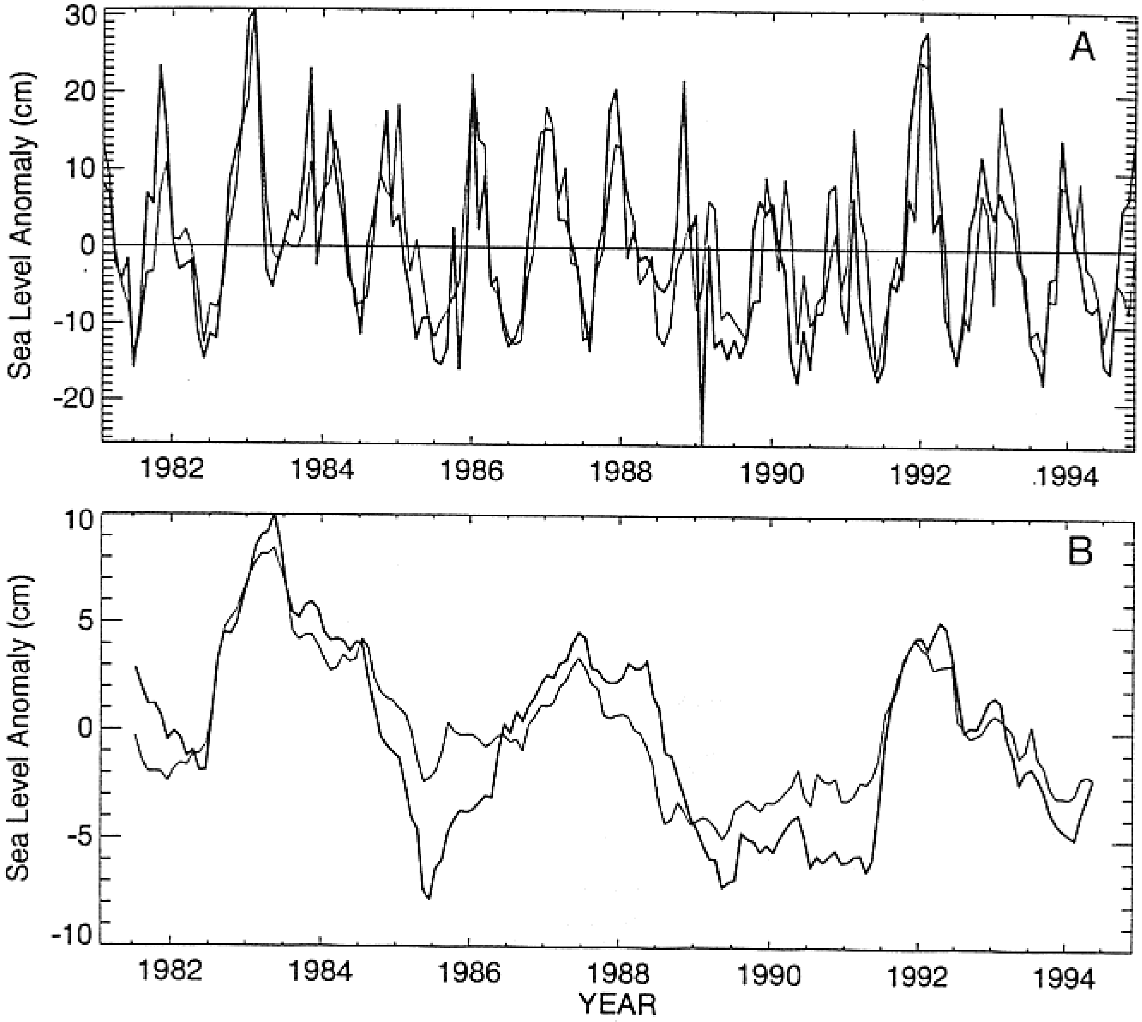

Fig. 10. A comparison of sea level observed at Sitka, Alaska, with sea level in the NRL 1/8° 6-layer Pacific Ocean model. Thick line is from the IGOSS data at Sitka; thin line is model result.

A - 30-day means of sea-level anomaly which emphasizes seasonal variability.
B - One year running means to show interannual variability including the 82-83, 86-87 and 91-92 El Niños. After Melsom et al. (1995).

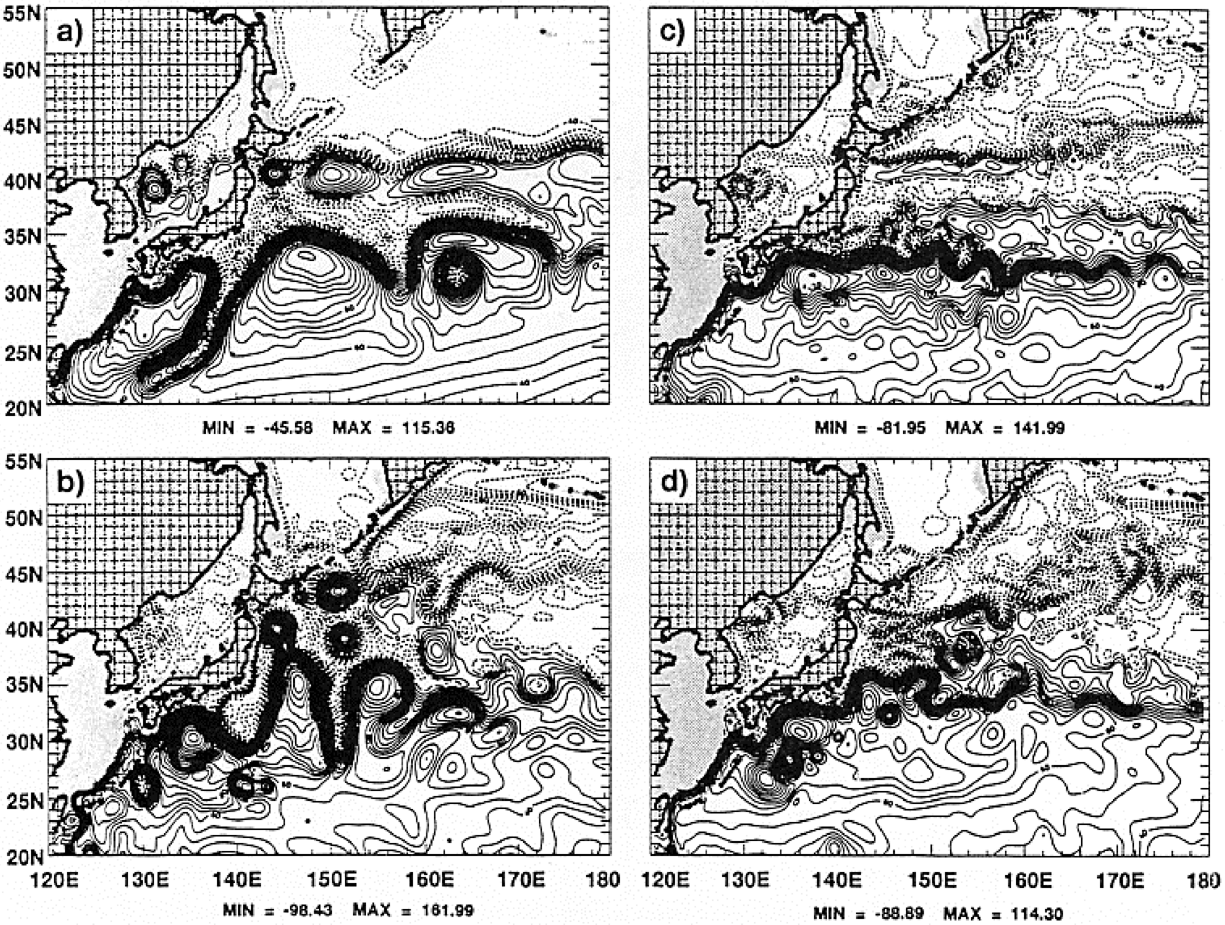

Fig. 11. Snapshots of sea surface height off Japan in the northwest Pacific portion of 1/8° simulations, showing the sensitivity of model results to model structure: a) 1.5 layer reduced gravity simulation; b) 5.5 layer reduced gravity simulation; c) 6-layer flat bottom simulation; d) 6-layer with realistic bottom topography. (From Hurlburt et al., 1995a)

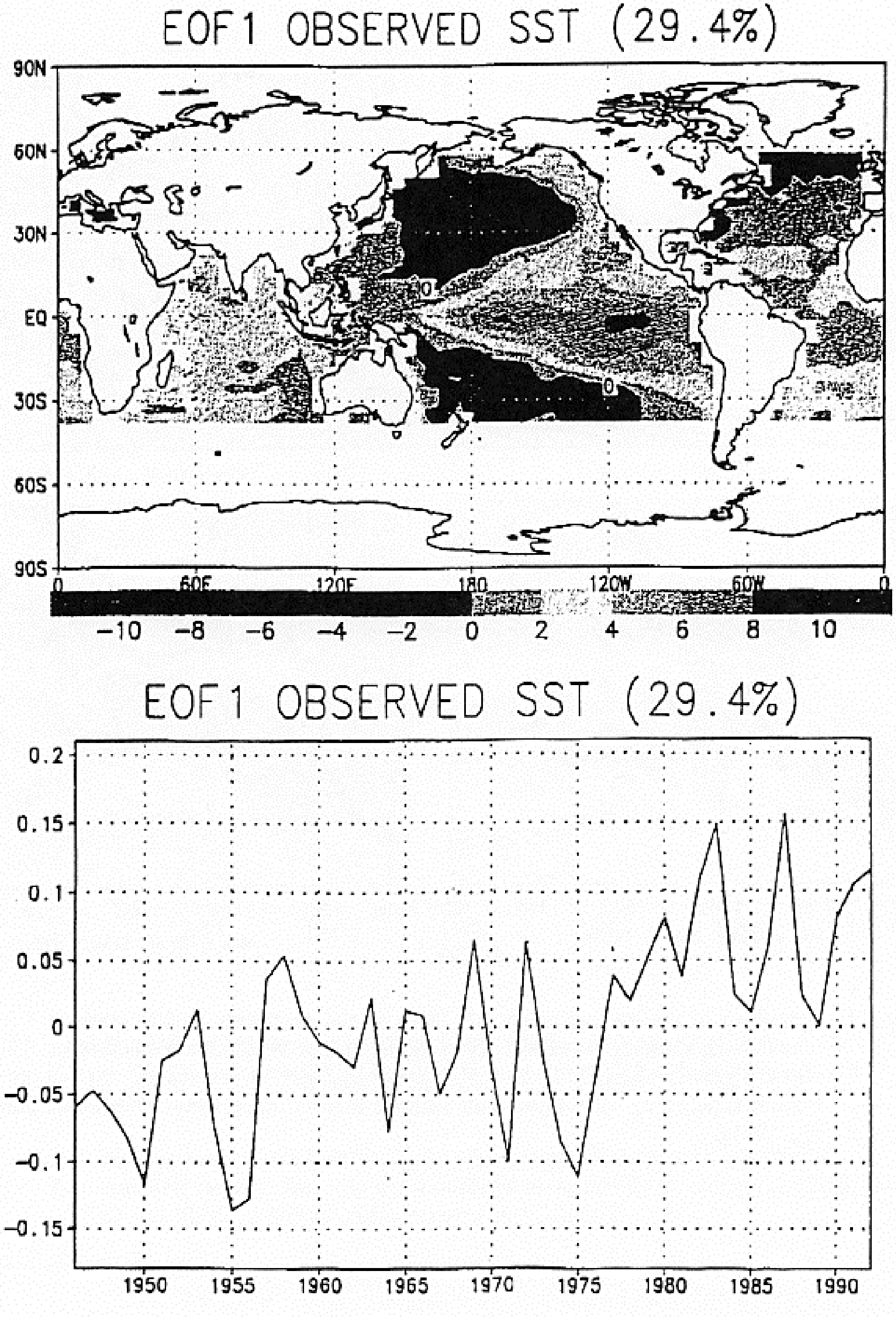

Fig. 12. Spatial pattern (upper panel) and time coefficient (lower panel) of the first EOF for the observed sea surface temperature (60°N to 40°S; 1945-1992). From Yukimoto et al., 1995.

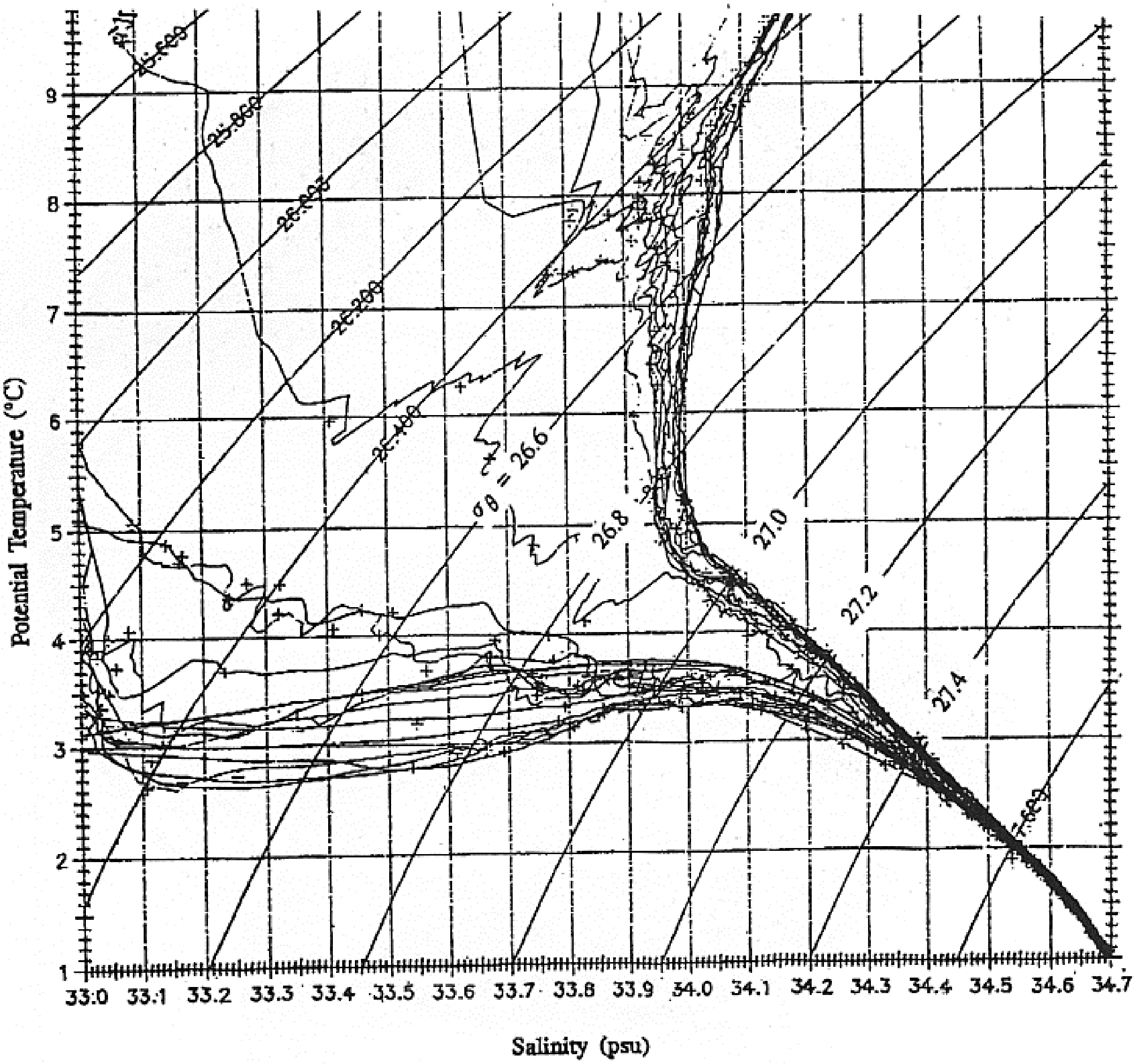

Fig. 13. Temperature-salinity data from a US WOCE cruise from Dutch Harbor, Alaska, to Fiji, essentially along the International Date Line, during the summer of 1993. The subarctic front occurs at the transition between the low surface salinity T-S curves to the high surface salinity curves. The North Pacific Intermediate Water is characterized by the salinity minimum around potential density 26.8 in those T-S curves with higher surface salinity and temperature. (courtesy of Gunnar Roden, University of Washington)

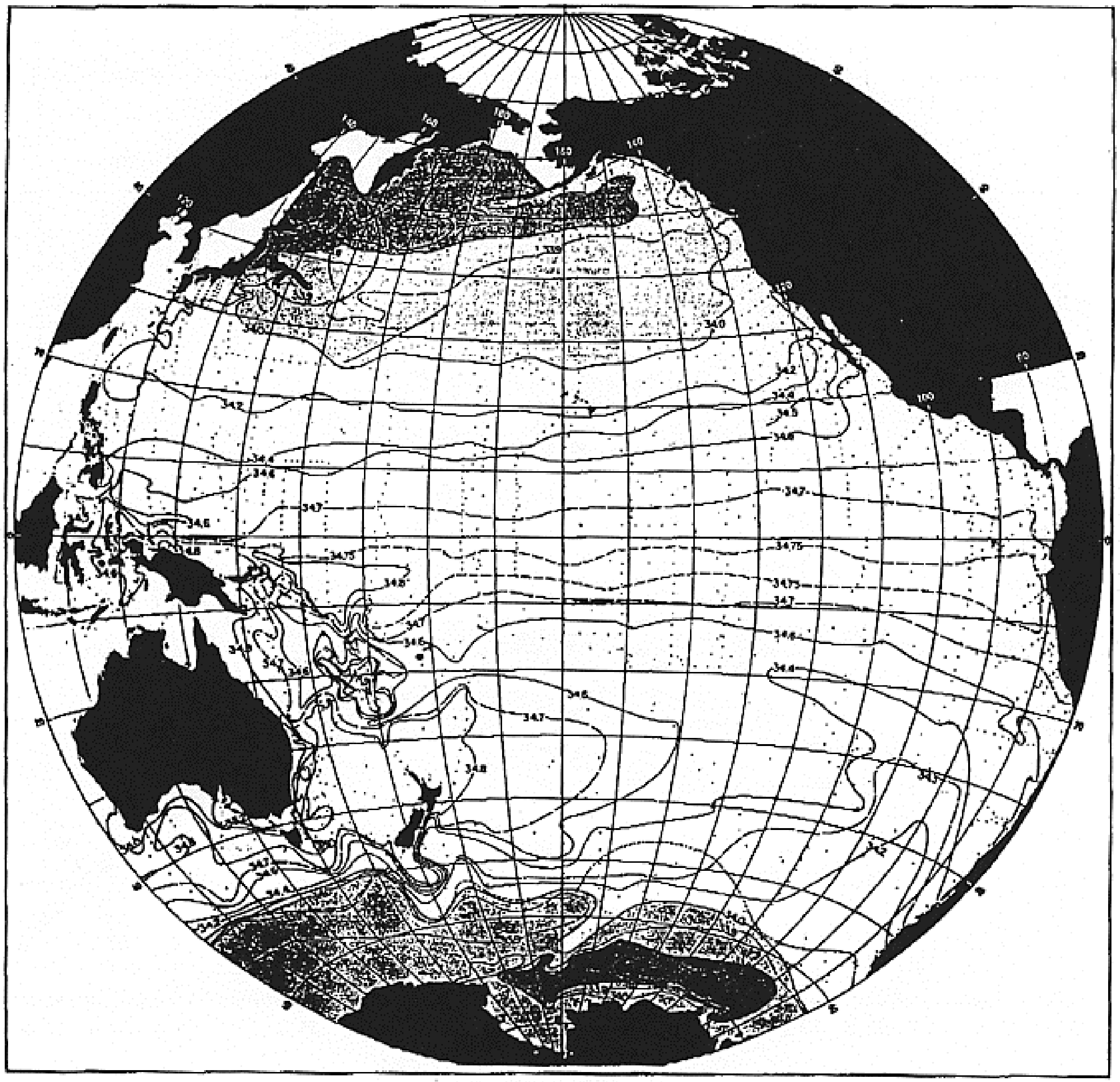

Fig. 14. Salinity on the delta-T = 125 cl/ton surface, showing the spreading of the NPIW in the North Pacific (From Reid, 1965).

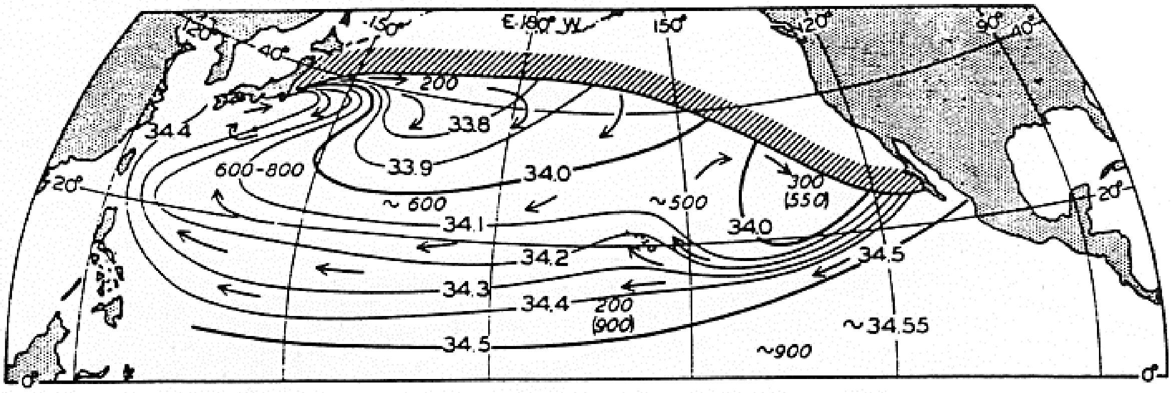

Fig. 15. Salinity in the layer of minimum salinity of the North Pacific, with inferred flow direction indicated by arrows and the depth of the minimum in meters indicated. (From Sverdrup et al., 1942.)

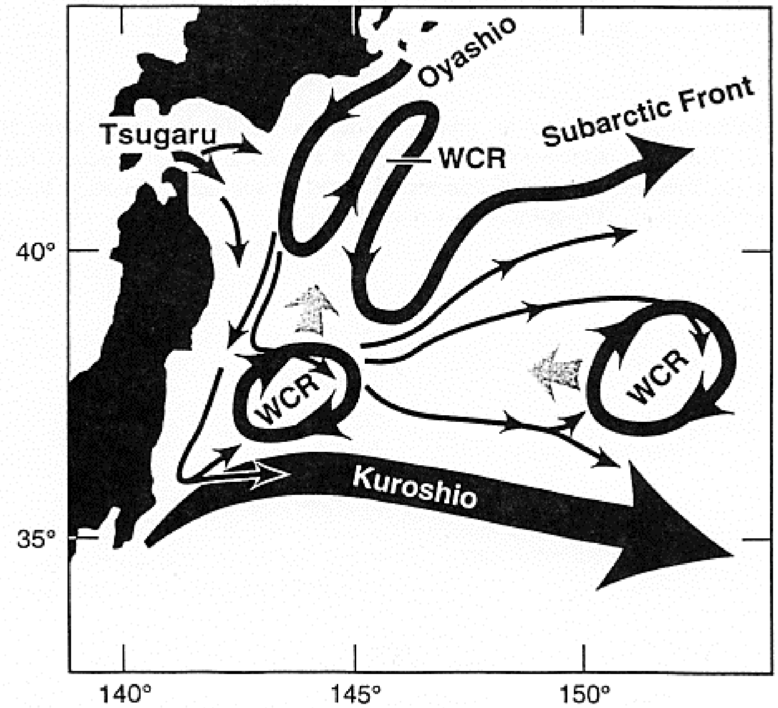

Fig. 16. Schematic diagram proposed by Talley et al. (1995) in their discussion of the formation of North Pacific Intermediate Water. This figure is to be compared to similar diagrams shown in Fig. 8. The heavy arrows are the major currents and the lighter curves are general directions of water movement, including intrusions into the warm core rings (WCR) and the Kuroshio. The region is extremely variable and each of the features shown is continuously changing.

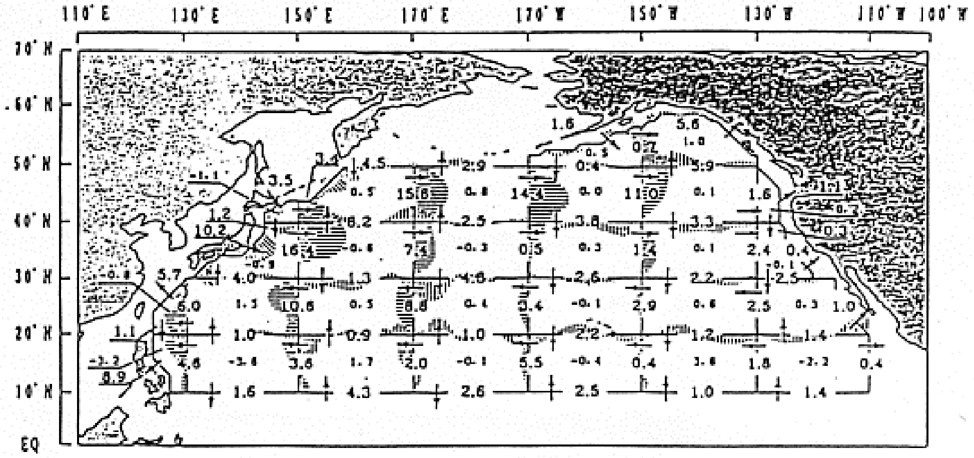

Fig. 17. Circulation inferred from an inverse model for the density range sigma-theta 26.5 - 27.5. Numerals attached to arrows denote a volume transport across the sides of a box (in Sverdrups). Small numerals located at the center of each box denote the mass imbalance. (From Fukasawa et al. 1992).

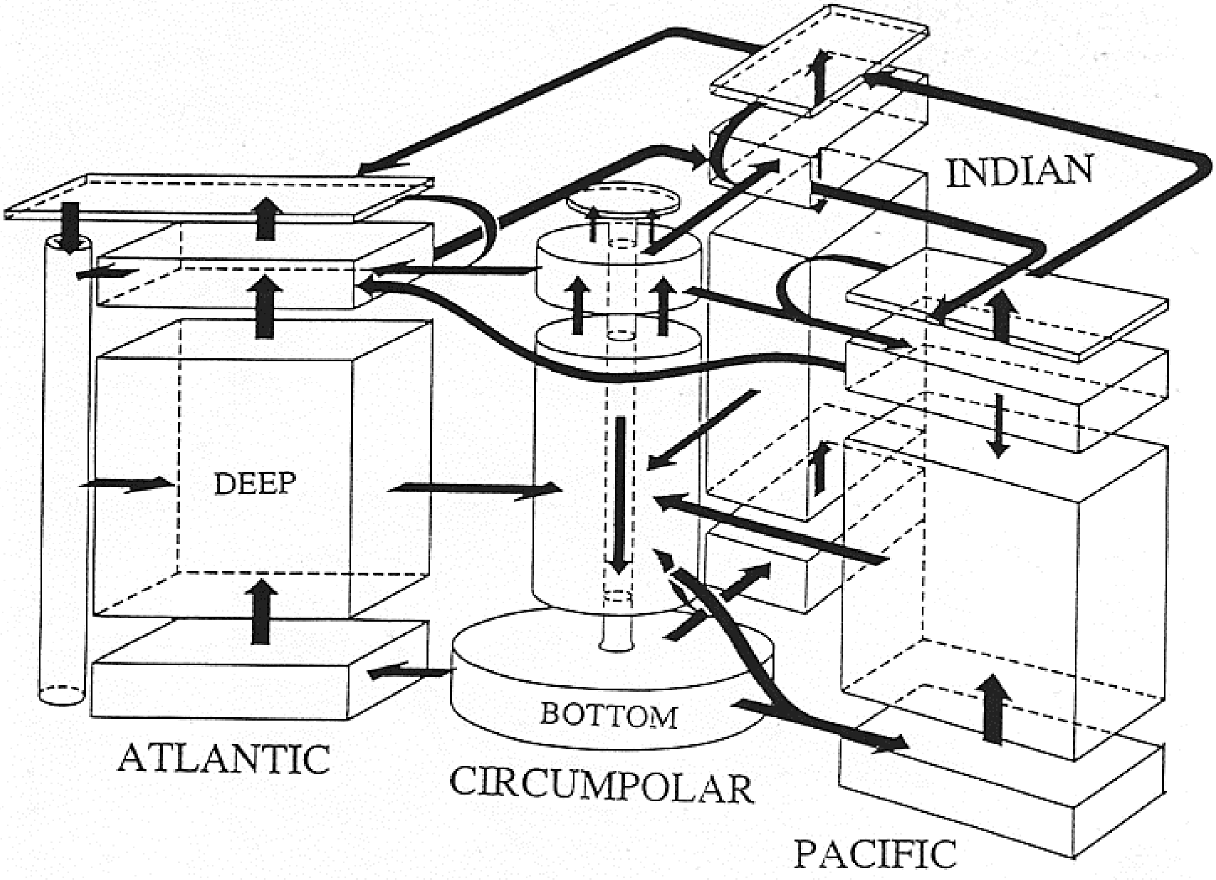

Fig. 18. A schematic box model of the world ocean circulation (after N. Suginohara, as presented by Y. Nagata, 1995.)

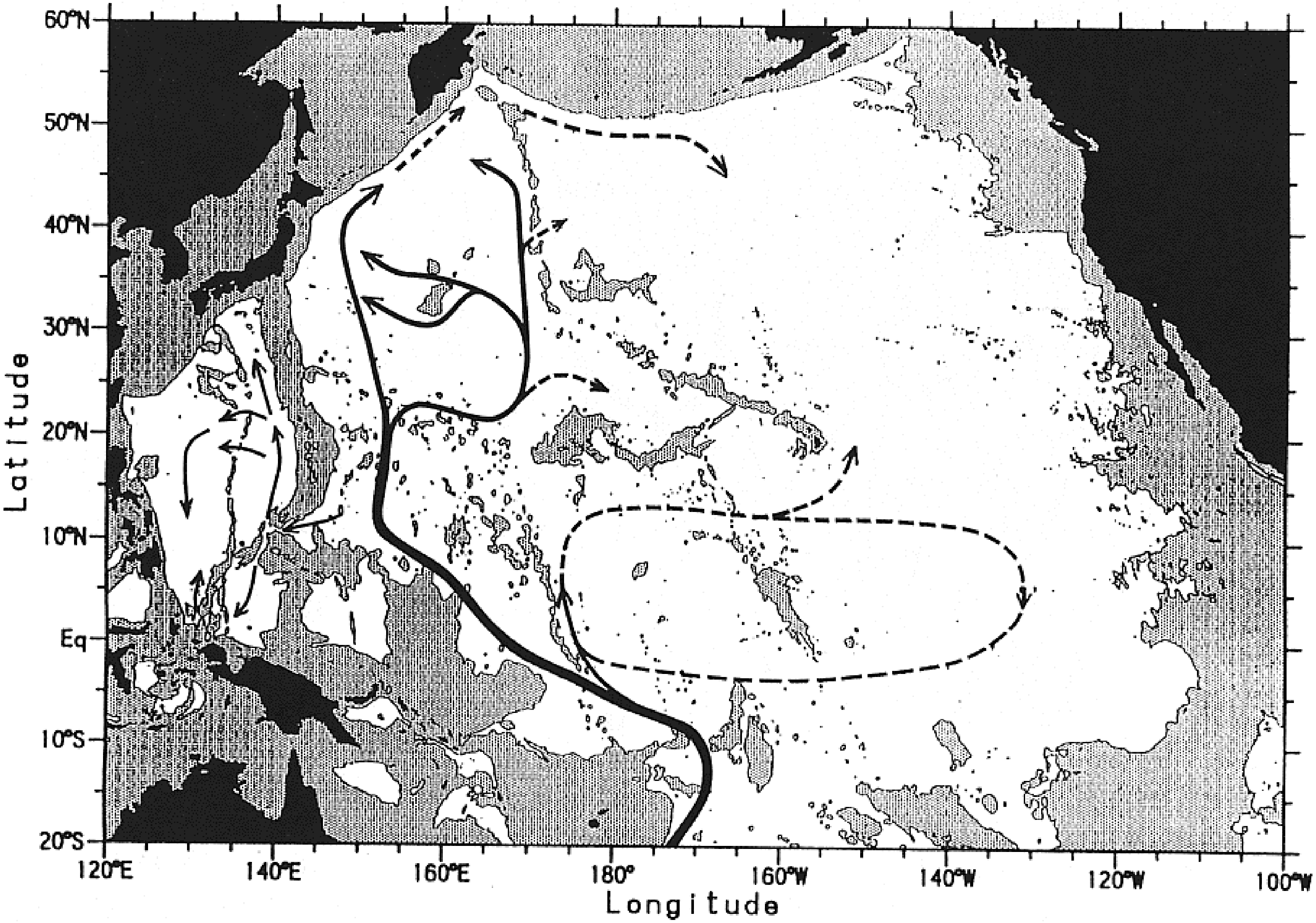

Fig. 19A.Deep circulation in the North Pacific as inferred from available observational evidence. A - at 4,000 m. (From Kawabe and Tarai, 1995).

A

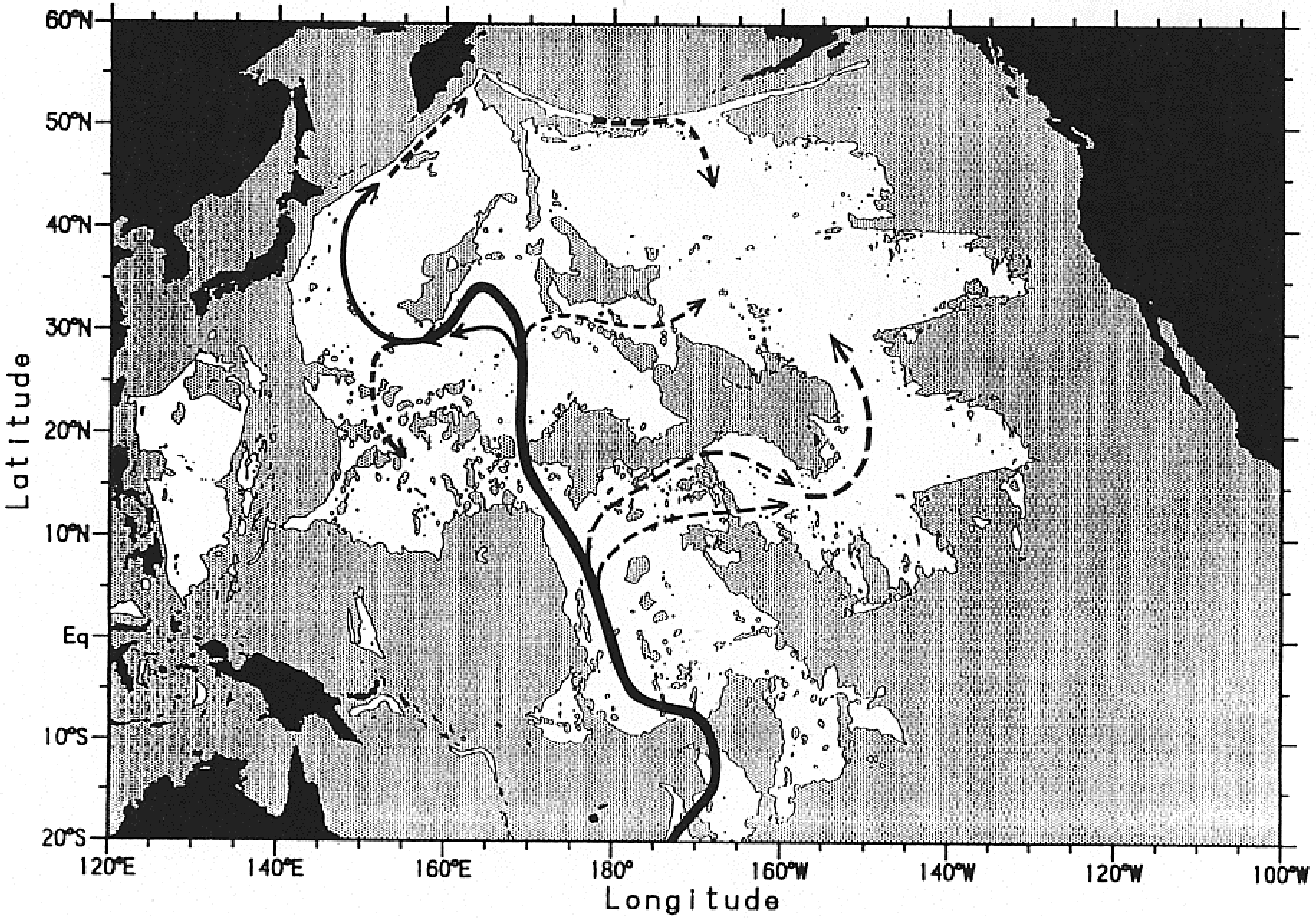

Fig. 19B. Deep circulation in the North Pacific as inferred from available observational evidence. B - at 5,000 m. (From Kawabe and Tarai, 1995).

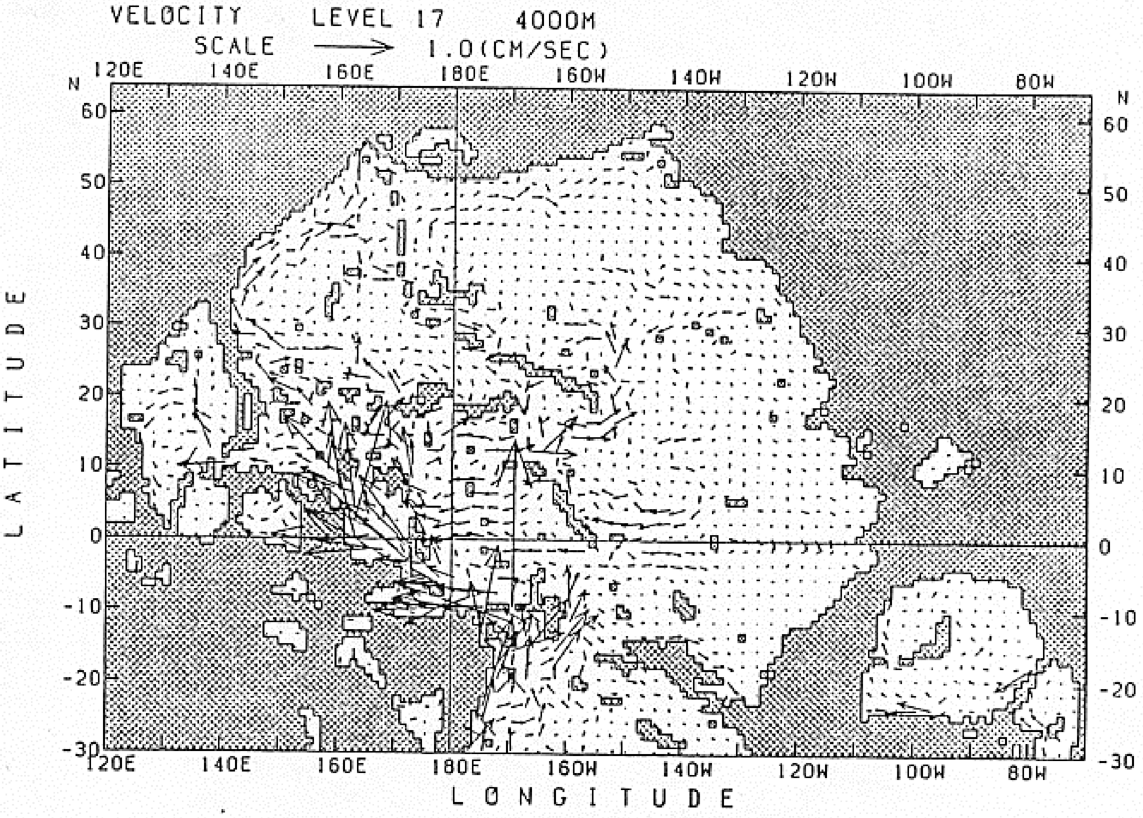

Fig. 20. Simulated deep flows in the North Pacific (from Ishizaki, 1994).

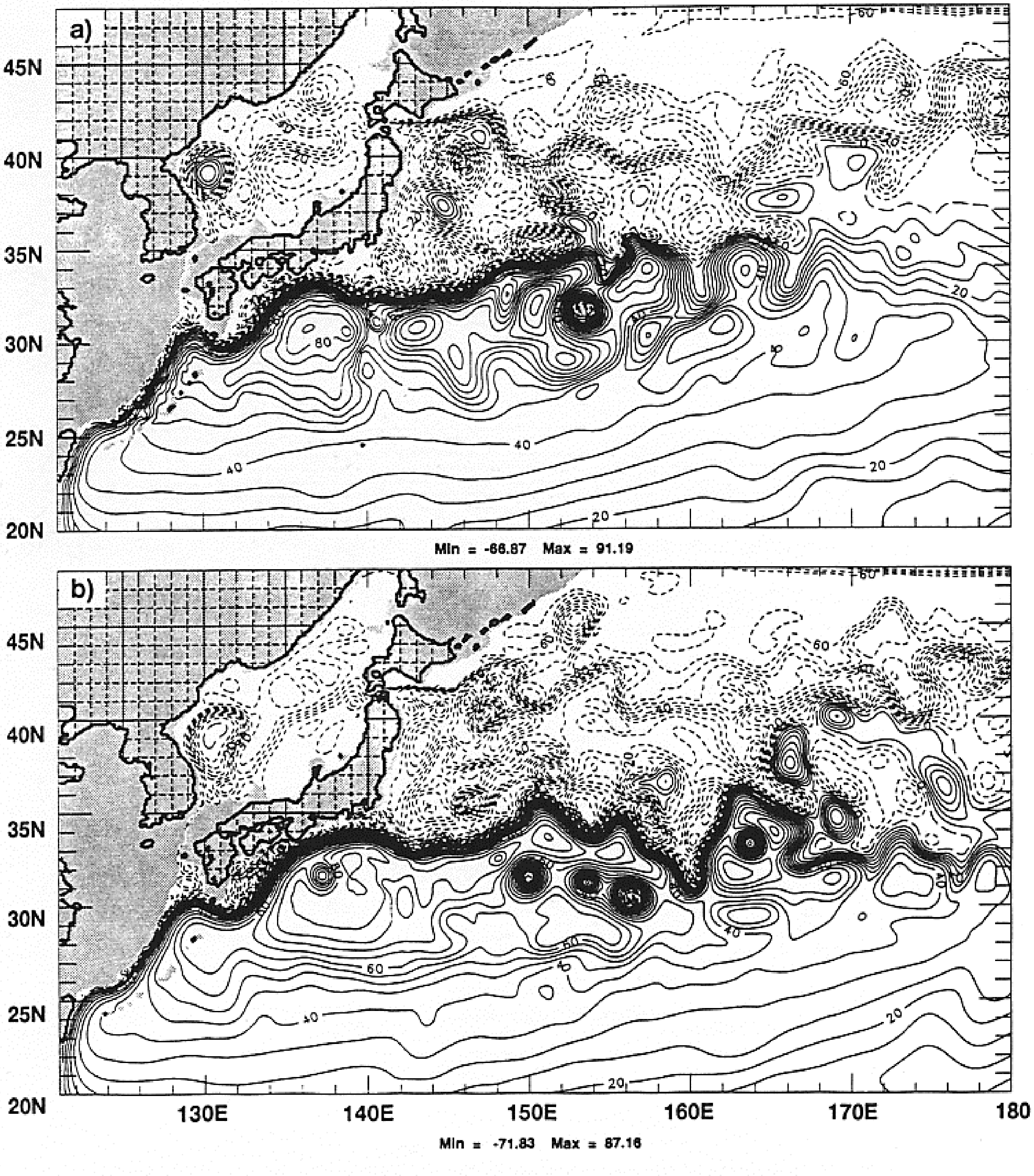

Fig. 21. A comparison of two snapshots of sea-surface height contours in the northwest Pacific from two-layer models of the subtropical gyre with realistic bottom topography: **a** - 1/8° resolution; **b** - 1/16° resolution. The sea surface height contours depict upper ocean currents and eddies. (From Hurlburt et al., 1995a)

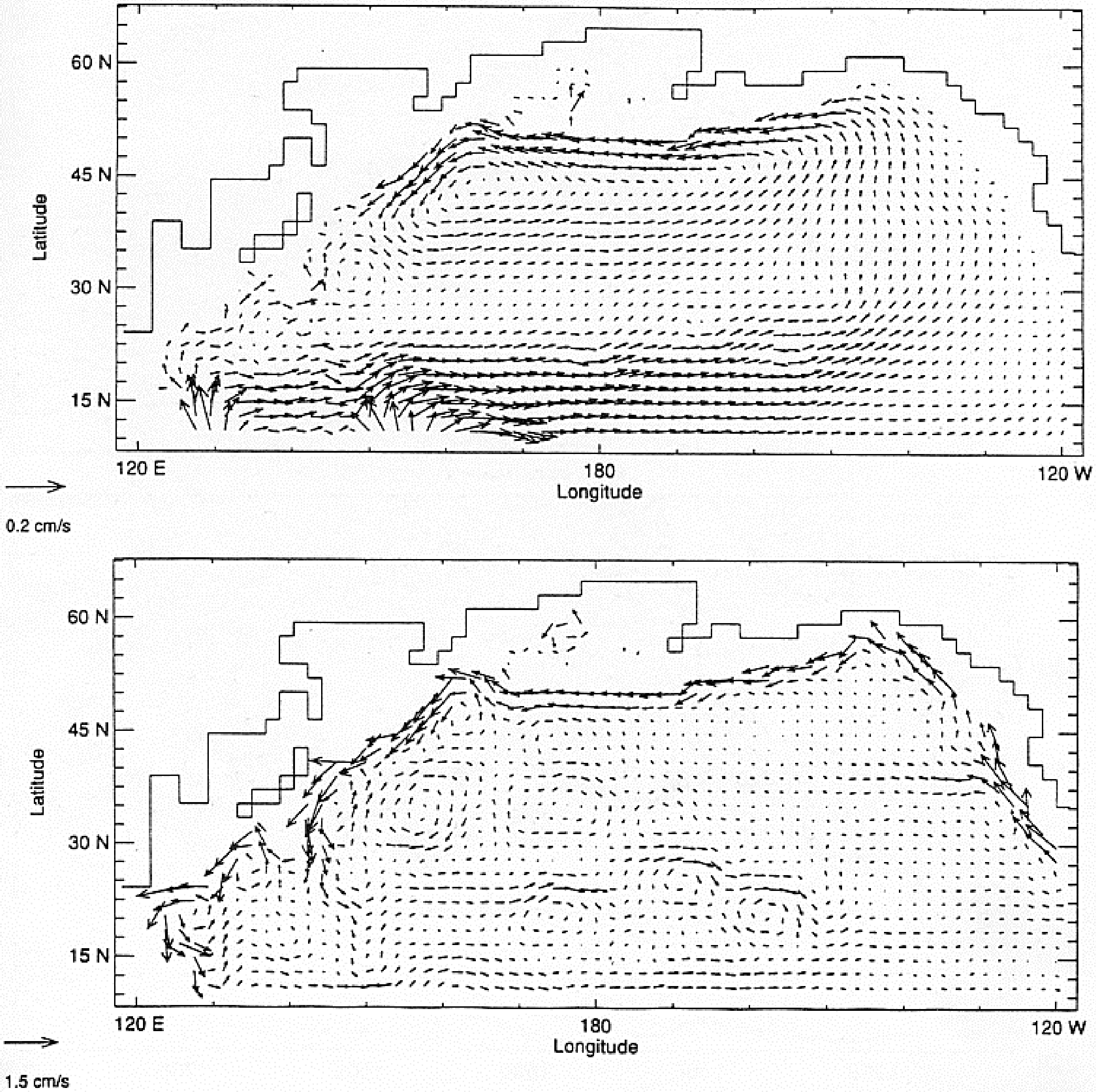

Fig. 22. A comparison of currents at a depth of 2880 m calculated using the GFDL Modular Ocean Model in the usual fashion (above) and with relaxation to a statistical steady state (from Eby and Holloway, 1994).

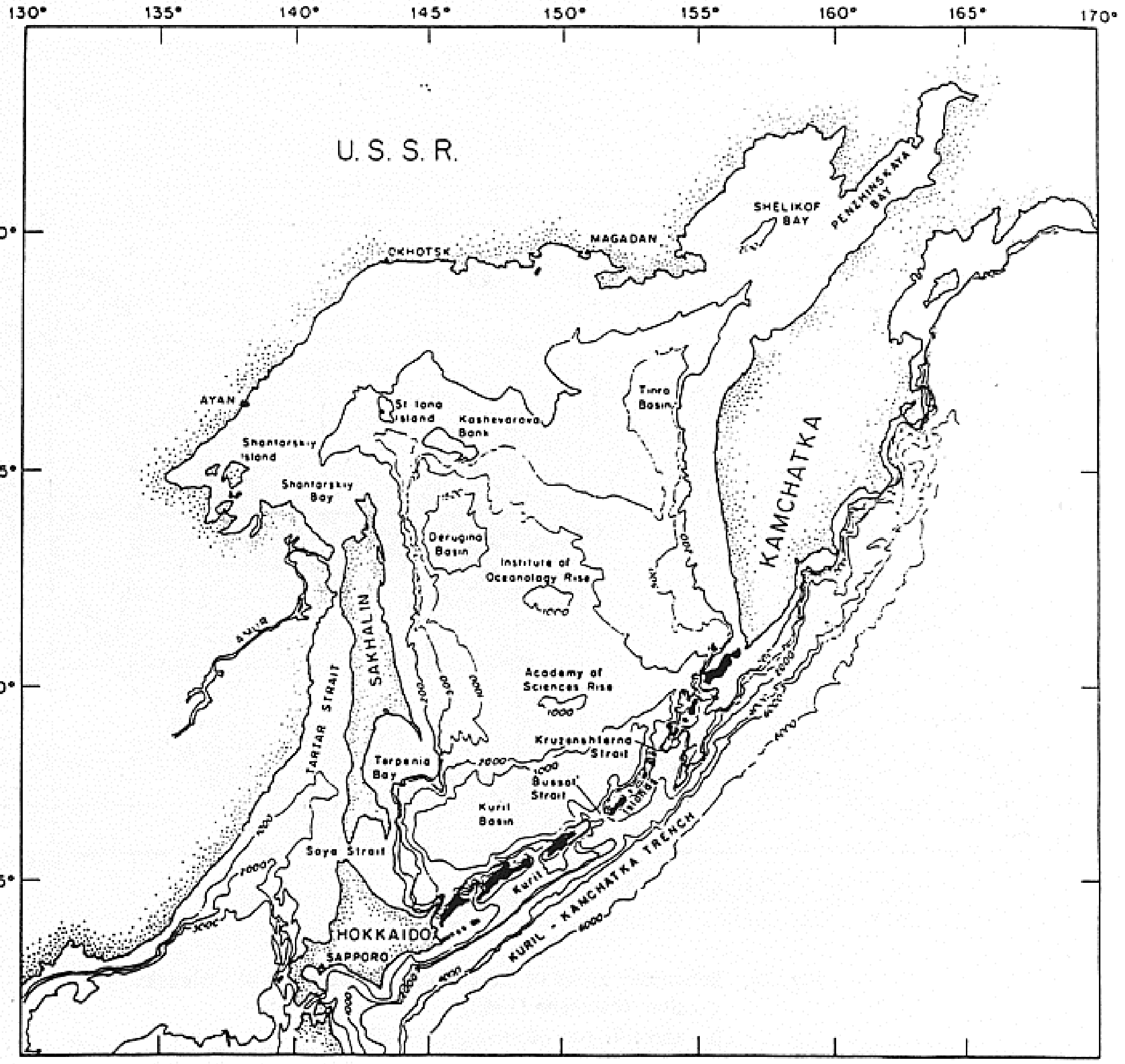

Fig. 23. The bathymetry of the Sea of Okhotsk

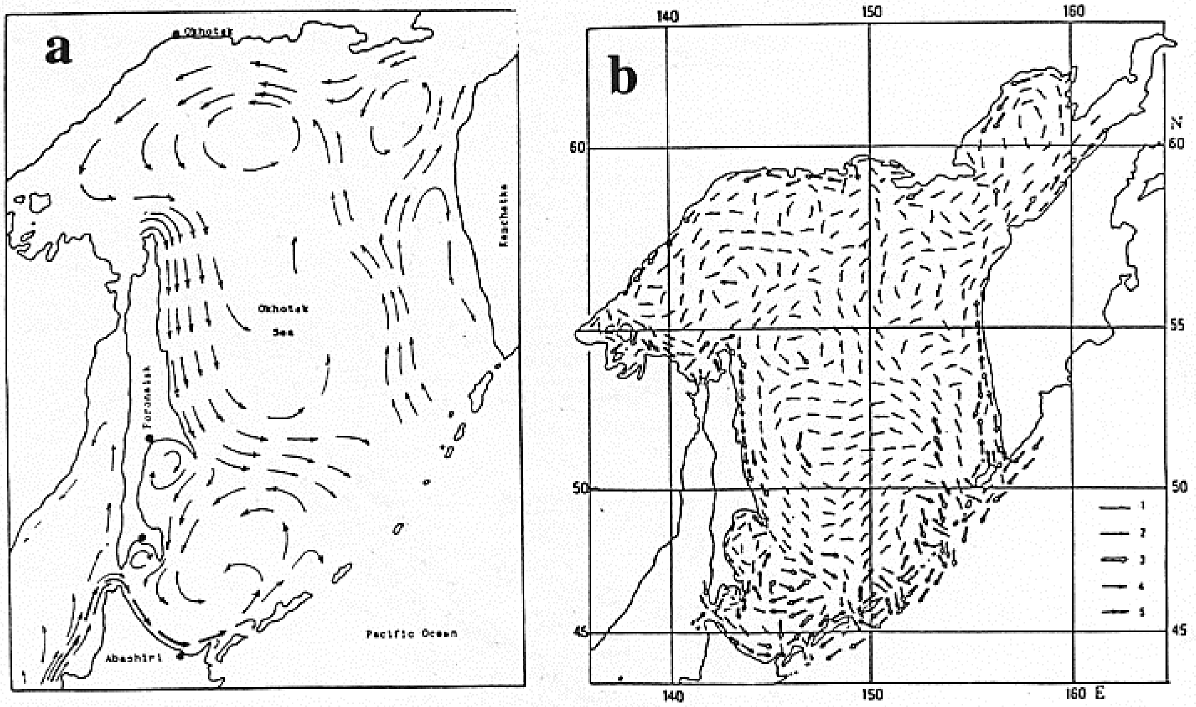

Fig. 24. Schematic views of the circulation in the Sea of Okhotsk:
a - after Watanabe (1963);
b - according to Moroshkin (1964).

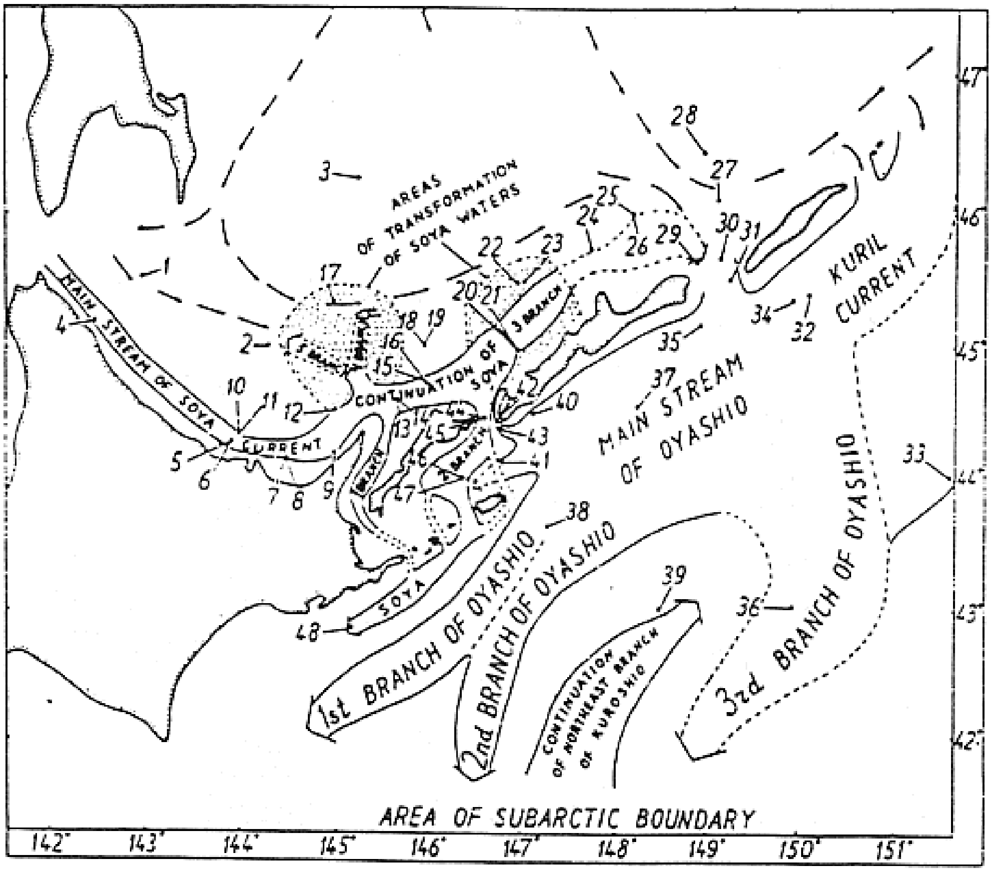

Fig. 25. Details of exchanges between the Sea of Japan (through Soya Strait), the Sea of Okhotsk and the Pacific around Hokkaido. (After Bobkov, 1993).

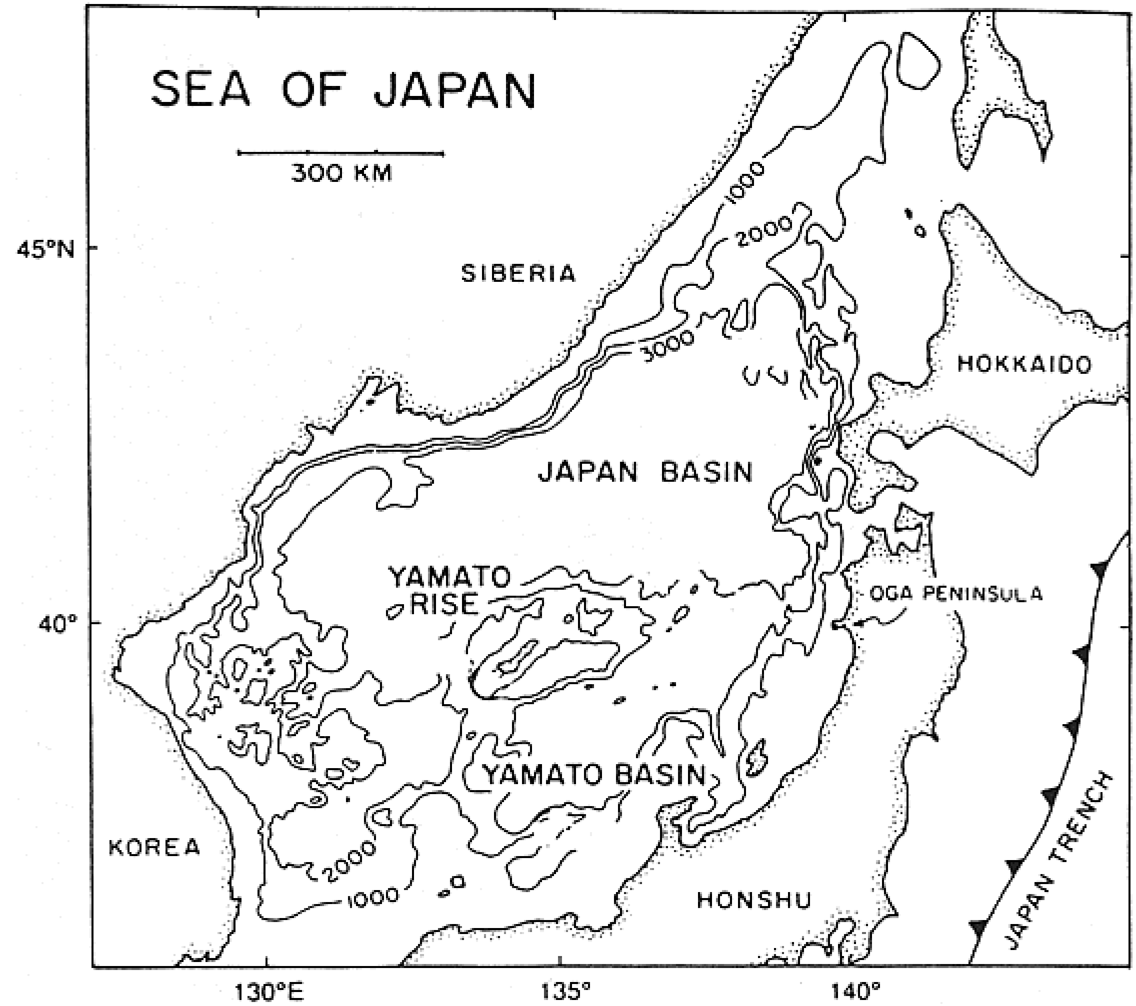

Fig. 26. The bathymetry of the Sea of Japan.

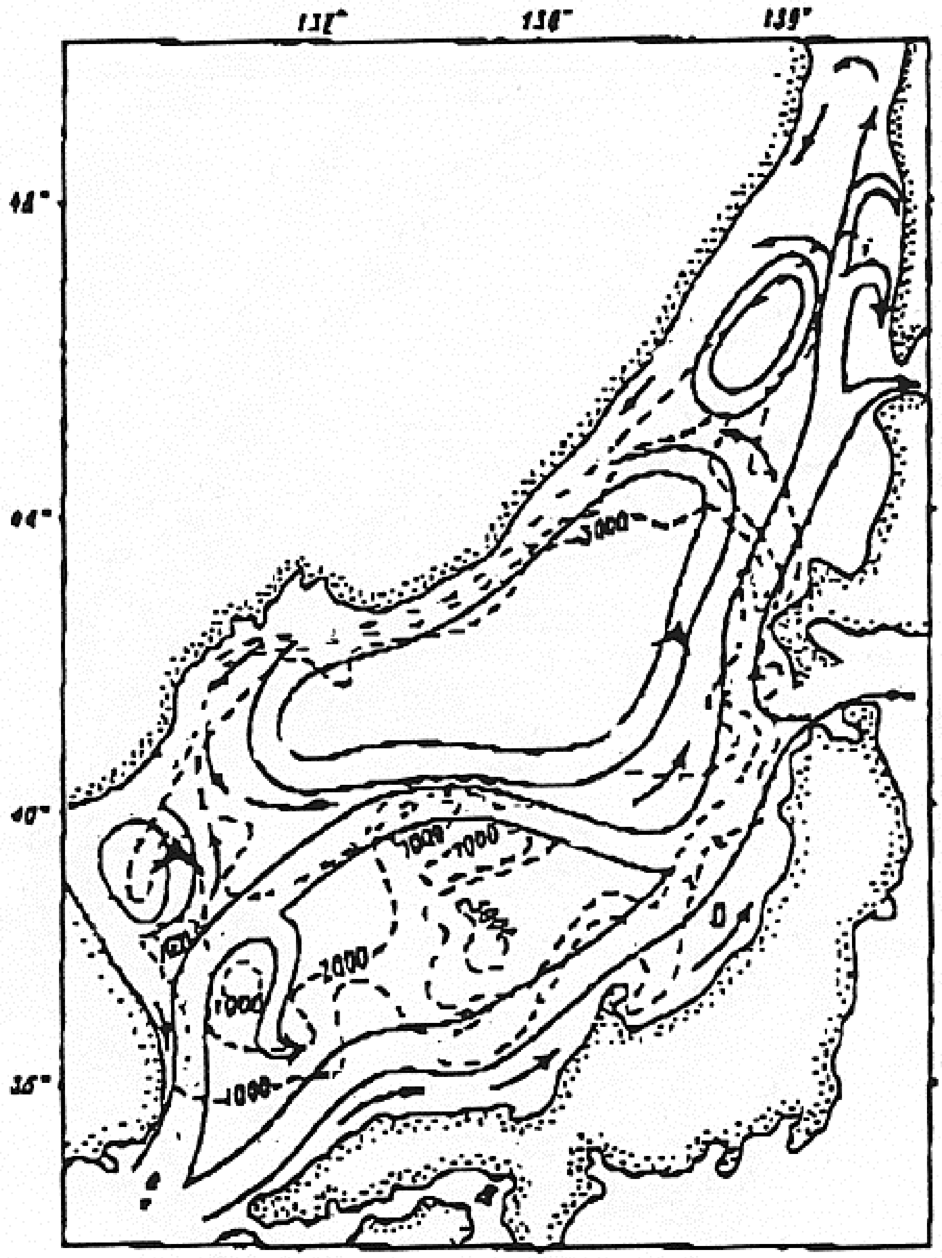

Fig. 27. Schematic circulation in the Sea of Japan (from Yoon, 1995; adapted from Yarichin, 1980).

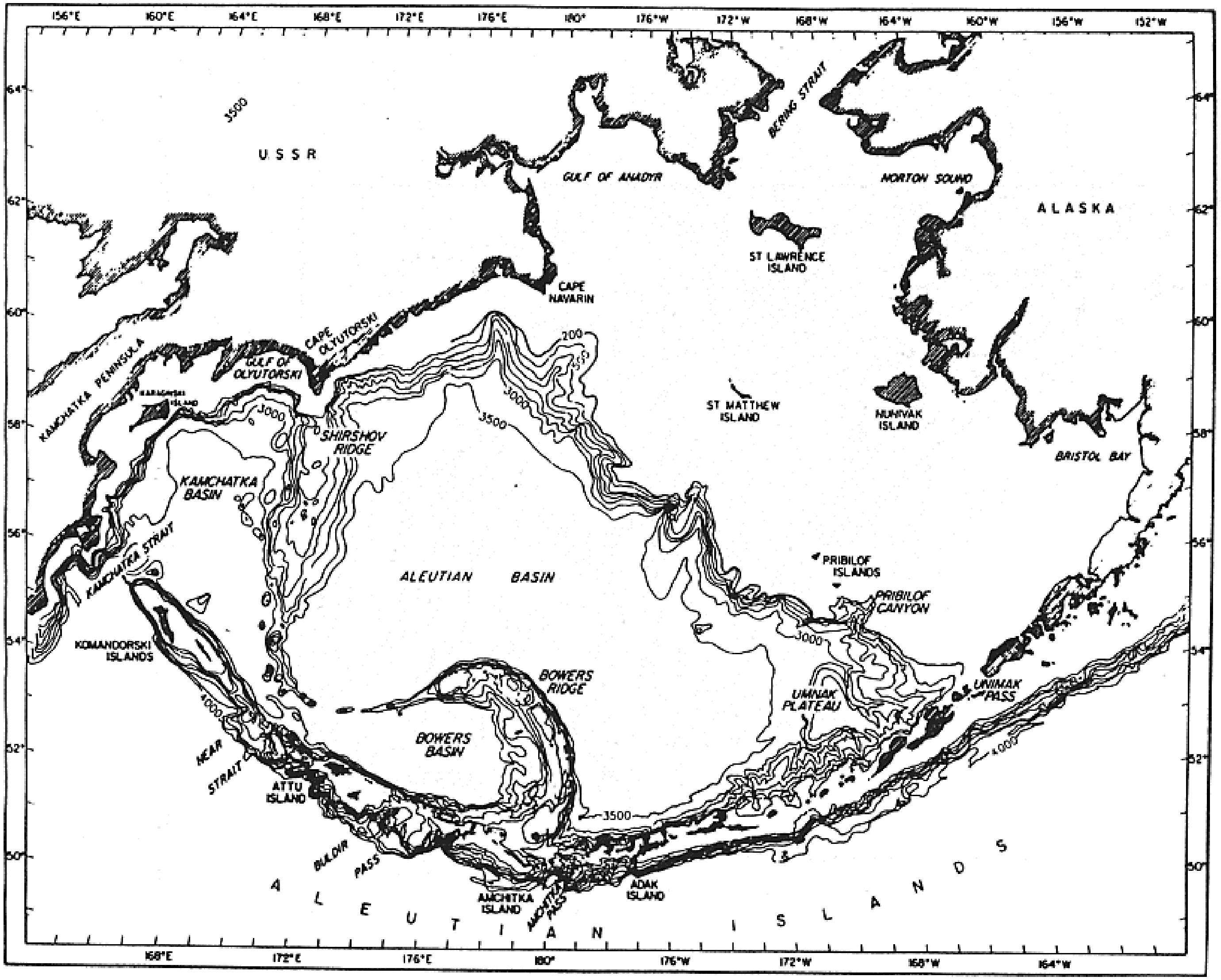

Fig. 28. The bathymetry of the Bering Sea.

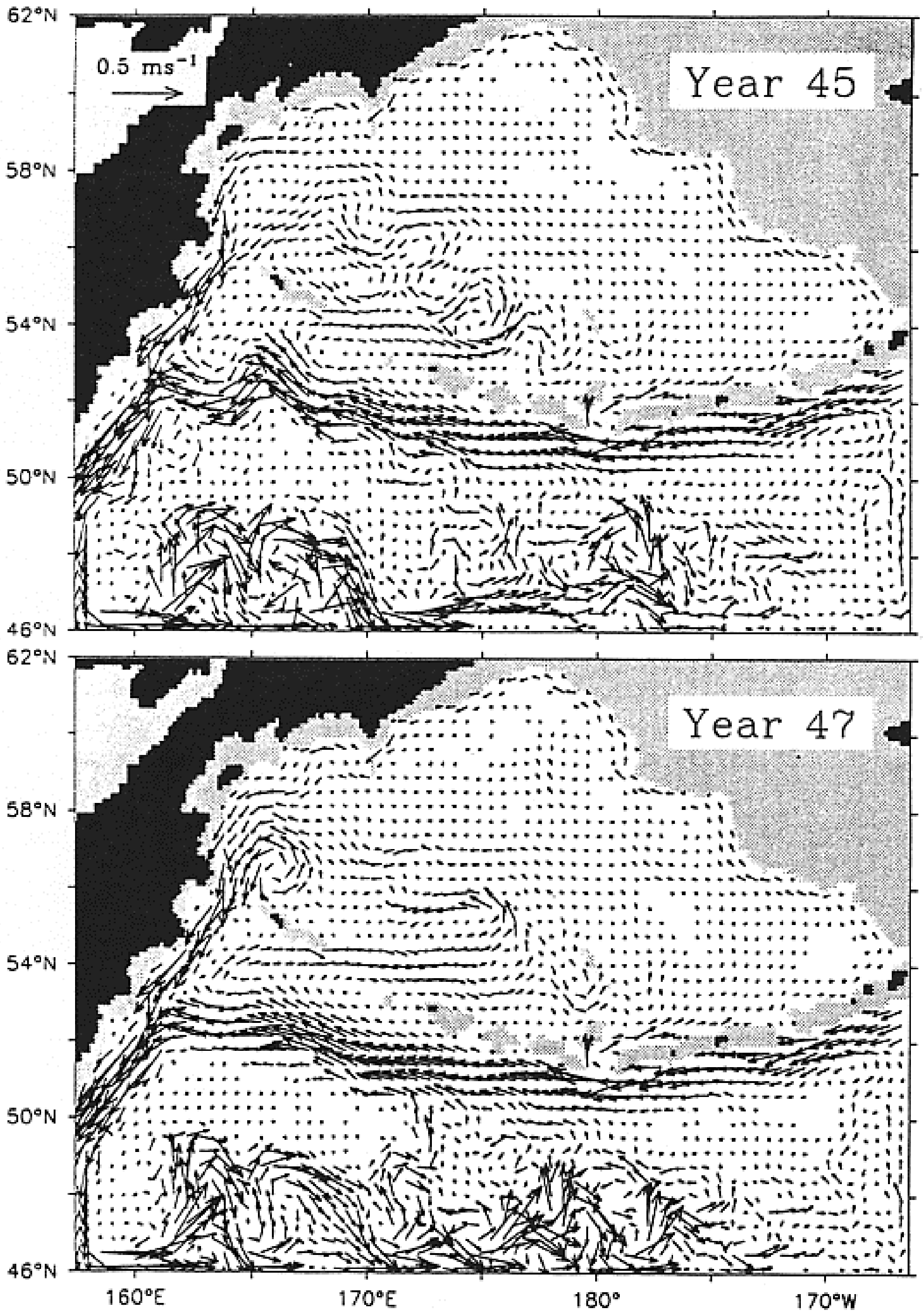

Fig. 29. Snapshots of upper-layer currents in a numerical model of the Bering Sea circulation at integration years 45 and 47. Internannual differences are attributed to flow instabilities. (From Overland et al. 1994).

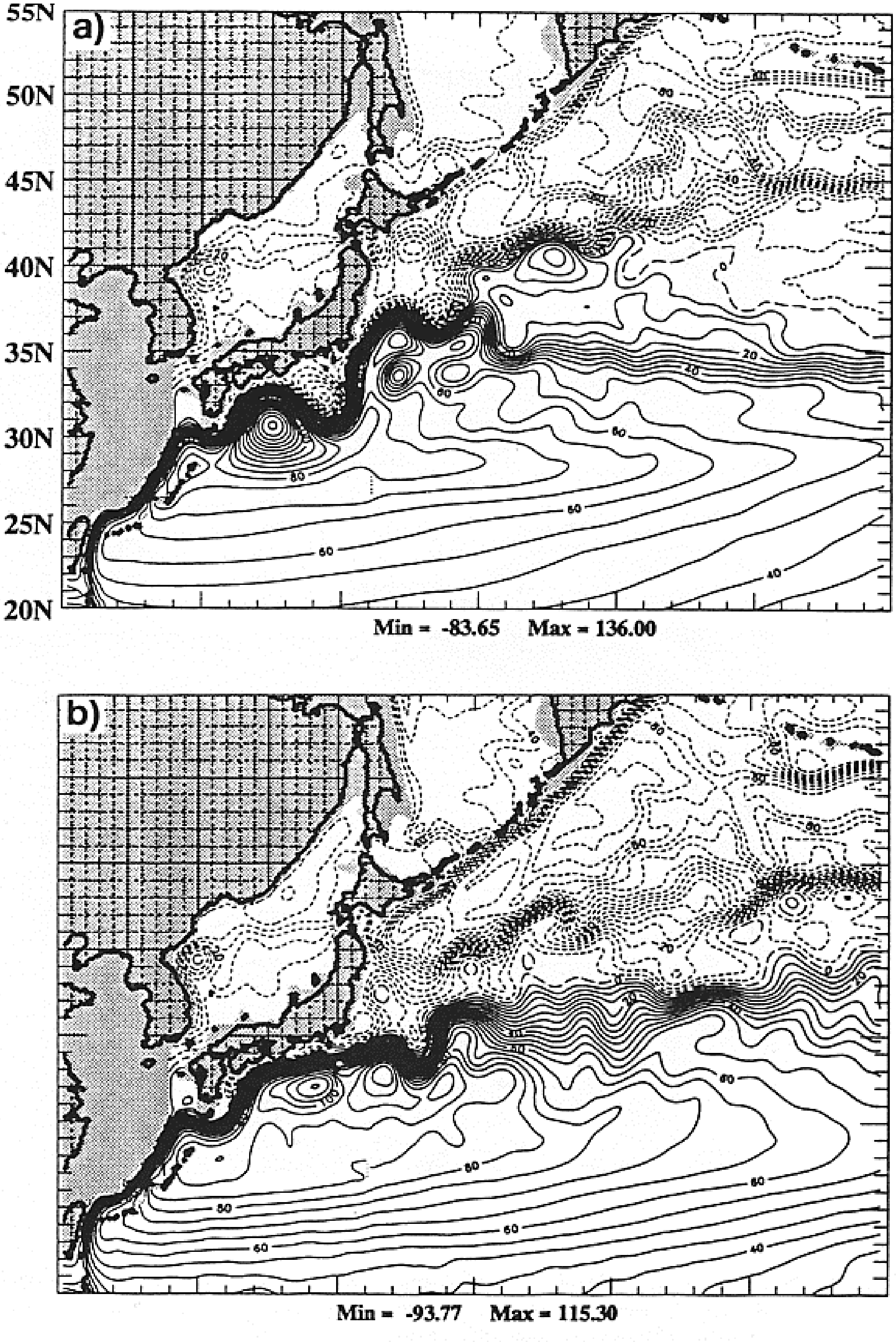

Fig. 30. Mean sea surface height contours from the NRL 1/8° 6-layer Pacific Ocean model north of 20°S driven in **a** - by Hellerman and Rosenstein (1983) monthly wind stress, and in **b** - by ECMWF 1000 mb wind climatology averaged over 1981-1991. (From Hurlburt et al. 1995a).

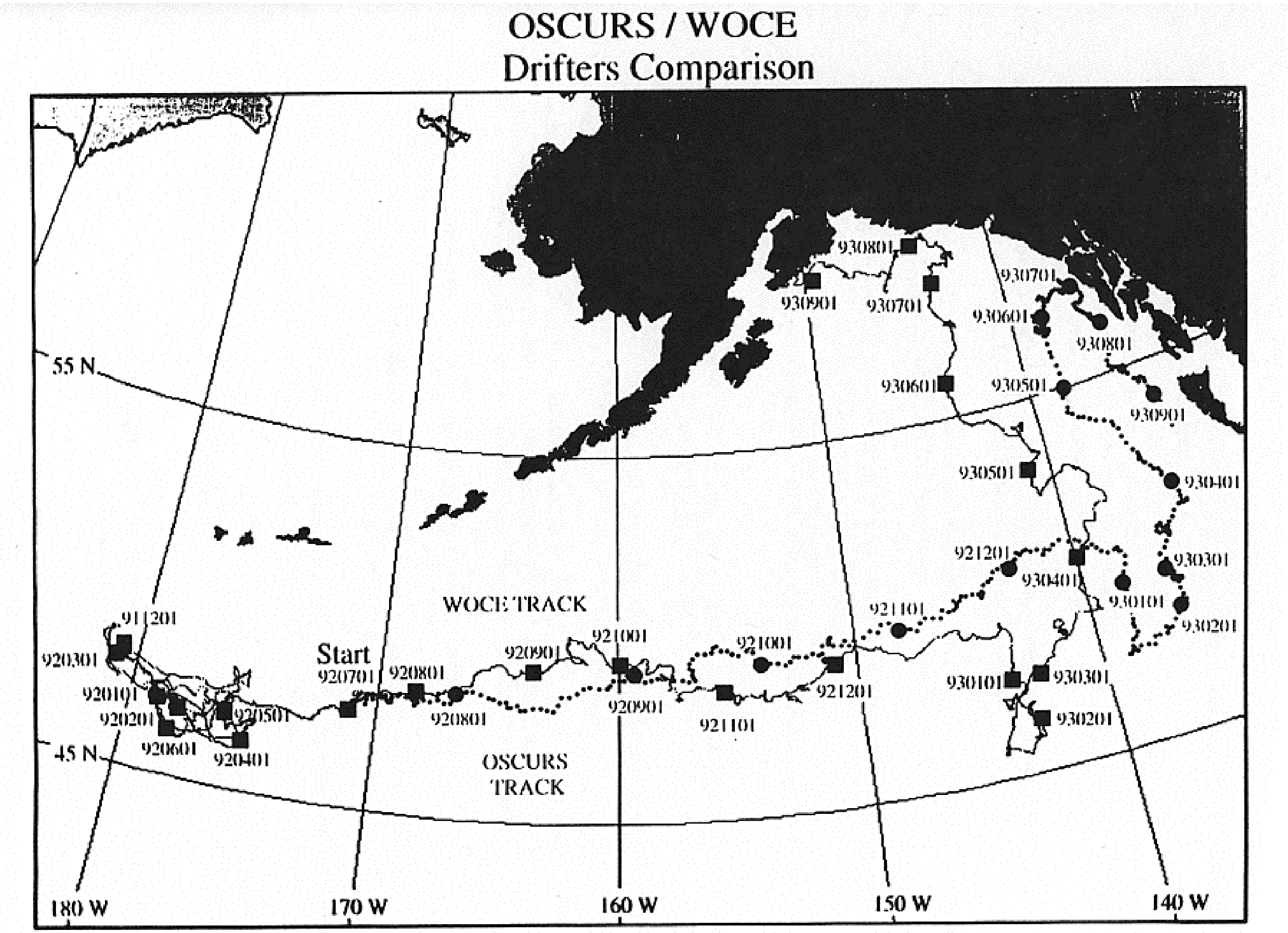

Fig. 31. Comparison of OSCURS model and WOCE drifter paths. The WOCE drifter (drogued with a holey sock at 15 m) was launched Dec 1, 1991 and spent its first six months in eddies off the Alaskan Stream; its path is shown by the solid line and a solid square once a month. Since OSCURS does not include mesoscale eddies, the comparison was initiated only on July 1, 1992; the simulated path is shown by the dotted line, with a solid circle every month. (From LeBlond et al., 1995).

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11.0 APPENDICES

Appendix 1. Terms of Reference

Working Group 7 on
Modelling of the Subarctic North Pacific Circulation

Terms of Reference

Although the subarctic oceans play an important role in the earth's climate system as a region where strong air-sea interactions occur and active ventilation of the oceans takes place, the present state of modelling of the subarctic oceans is not satisfactory even with respect to the physics. This is one of the most important unresolved questions for constructing an accurate climate forecasting system. In view of the importance of modelling of the North Pacific Circulation for the global climate forecast, the Working Group will:

- Review the status of present physical modelling efforts on the subarctic North Pacific circulation and identify the gaps and problem areas,
- Identify the kinds of observations and other information needed to improve circulation models,
- Identify what kinds of knowledge of the related physical processes and of local ocean dynamics (such as in marginal seas) are needed to improve the circulation models, and
- Identify how the incompleteness of the present physical model of the subarctic North Pacific influences other modelling efforts such as the global climate, ecosystems, material transport, etc.

A focus on physical aspects of modelling will be maintained.

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Appendix 3. Working group activities

The working group was created at the PICES meeting in Seattle in October 1993.

Members of the working group were selected by their respective governments in early 1994.

The co-chairmen, LeBlond and Endoh, began electronic communication at that time, circulated ideas and suggestions and solicited input from members of the WG.

It was resolved to hold a meeting in Vancouver in June 1994. Following that meeting, participants, as well as other members of the working group, were sent a rough draft of the report, with requests for contributions at specific points. An interim report was compiled by the co-chairmen and used as a basis for discussions at the PICES meeting in Nemuro.

After a period of reflection, work towards completion of a report was resumed through communication between the co-chairmen in the spring of 1995. A revised draft was circulated in July and comments requested from all Group members towards completion of the report. These comments were incorporated in the draft final report presented at the Qingdao meeting. Final corrections were made to the manuscript in the fall of 1995 following input from the Qingdao meeting.