Some Lessons Learned from Comparisons of Numerical Simulations and Observations of the JES CIRCULATION

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The Japan/East Sea (JES) is a large, multi-ported, semi-enclosed sea situated between the subtropical and subpolar zones. It exhibits most oceanic phenomena (e.g., wind-driven and buoyancy-driven boundary currents, a subpolar jet and front, and mesoscale eddies) and processes (e.g., intense air-sea interaction, subduction and deep convection, and topographic trapping). JES circulation is driven by wind and thermohaline forcing, tides, and throughflow; however, this circulation is controlled largely by its bottom topography, especially by the large Yamato Rise in the center of the southern half, the large Japan Basin to the north, Ulleung Basin to the west, Yamato Basin to the east, and numerous seamounts. Inflow is primarily through the Korea/Tsushima Strait in the south and the outflow is primarily through the Tsugaru and Soya Straits in the east; however, there is weak inflow seasonally through the shallow Tatar/Mamiya Strait in the north. For these reasons, and due to its small size compared to an ocean basin, the JES is a convenient natural laboratory for numerical modeling and observation of ocean circulation phenomena and processes.

Here, we summarize the implementation of a well-resolved (eddy-admitting) state-of-the-science community ocean model (Princeton Ocean Model [POM]; Mellor, 1998) and evaluate its results against ocean measurements. The model's performance then encourages us to use it to break new ground by exploring the role of synoptic (weather-scale) atmospheric forcing, especially Siberian cold-air outbreaks, in producing wintertime deep convection.

CIRCULATION IN THE JES: OBSERVATIONAL CONTEXT

Upper-layer general circulation in the JES has seven components (Figure 1): (1) the inflowing (from the Korea/Tsushima Strait [KS]) East Korea Warm Current (EKWC) in the southwest; (2) the inflowing Nearshore Branch (NB) in the southeast that reaches Tsugaru Strait; (3) the inflowing Middle Branch (MB) to the northwest of, and parallel to the NB; (4) the eastward Subpolar Jet and Front (SPJF) just north of Yamato Rise; (5) the northward Soya Warm Current (SWC) between Tsugaru and Soya Straits (TS and SS, respectively); (6) the southwestward Liman/Primorski Cool Coastal Current (LCCC) in the northwest; and (7) the southward North Korea Cool Current (NKCC) in the central west. The major circulation feature in this region is the cyclonic subpolar gyre over the Japan Basin that links the LCCC, NKCC, SPJF, and SWC. A typical value for the subpolar gyre volume transport, based on our simulations, is ca. 20 Sv (Mooers and Kang, 1995; Kang, 1997), an order of magnitude greater than the throughflow (ca. 2 to 4 Sv). The modeled subpolar gyre volume transport is, however, dependent on model parameters used. Thus, we attempted to understand our results by performing sensitivity experiments for (1) the model vertical structure, (2) surface wind stress, (3) surface thermal forcing, and (4) inflow condition.

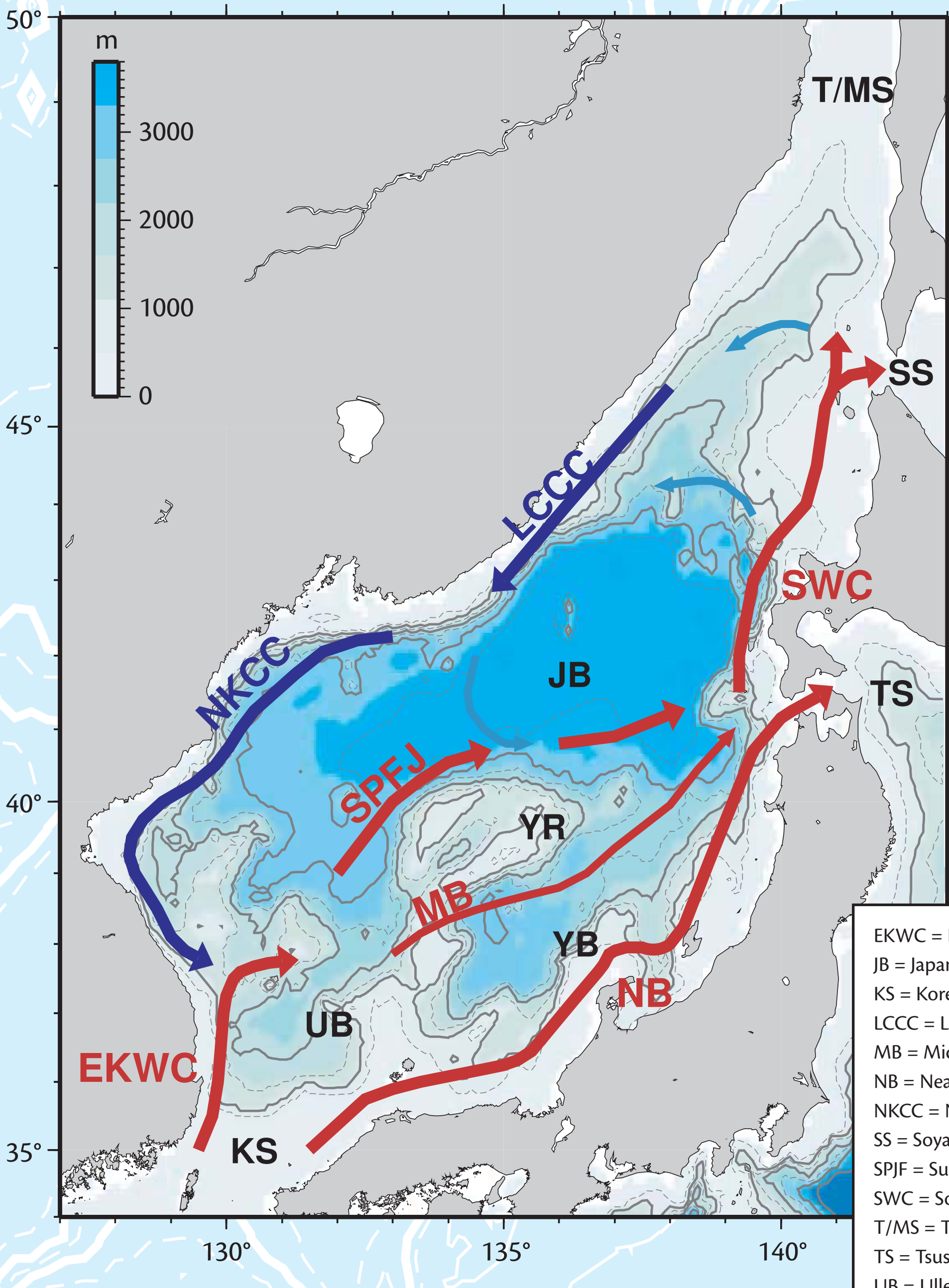

Figure 1. Schematic of upper-layer general circulation in the Japan/East Sea. The Sea's most widely recognized currents and geographical features are highlighted. Red arrows represent relatively warm currents, and blue arrows, cooler currents. Isobaths are indicated with solid lines at 1 km intervals and dashed lines at 500 m intervals.

EKWC = East Korea Warm Current
JB = Japan Basin
KS = Korea/Tsushima Strait
LCCC = Liman Coastal Cool Current
MB = Middle Branch
NB = Nearshore Branch
NKCC = North Korea Cool Current
SS = Soya Strait
SPJF = Subpolar Jet and Front
SWC = Soya Warm Current
T/MS = Tatar/Mamiya Strait
TS = Tsushima Strait
UB = Ulleung Basin
YB = Yamato Basin
YR = Yamato Rise

SIMULATING THE CREAMS I PERIOD: 1993 TO 1997

The JES-POM used for our simulations has a meridional (north-south) grid size of 10 km and a zonal (east-west) grid size that changes from 10 km in the south to 7.5 km in the north. We used 26 sigma (terrain-following) levels in the vertical with finest resolution in the surface and bottom turbulent-boundary layers (Kang, 1997). There are three open ports in the model: Korea Strait for inflow into the JES and Tsugaru and Soya Straits for outflow. Total inflow transport through Korea Strait was prescribed with an annual average of 2.8 Sv by adopting seasonal variations, from a maximum of 3.2 Sv in September to a minimum of 2.4 Sv in January. These figures were taken from the Naval Research Laboratory (NRL) East Asian Seas Model (courtesy of Dr. Dong-Shan Ko).

As input to the JES-POM simulation we used three air-sea exchange data sets obtained from 1993 to 1997 (the period of the Circulation Research of the East Asian Marginal Seas [CREAMS] I cruises) (Kim et al., 1999): (1) six-hour fluxes calculated from six-hour ECMWF (European Center for Medium-Range Weather Forecasting) atmospheric variables (e.g., wind components, air temperature) on a one-degree grid and daily multi-channel sea surface temperature (MCSST) on a 18-km grid (syn model run), (2) monthly fluxes, which are means of six-hour "syn" fluxes (empm model run), and (3) fluxes calculated from monthly averaged ECMWF atmo-

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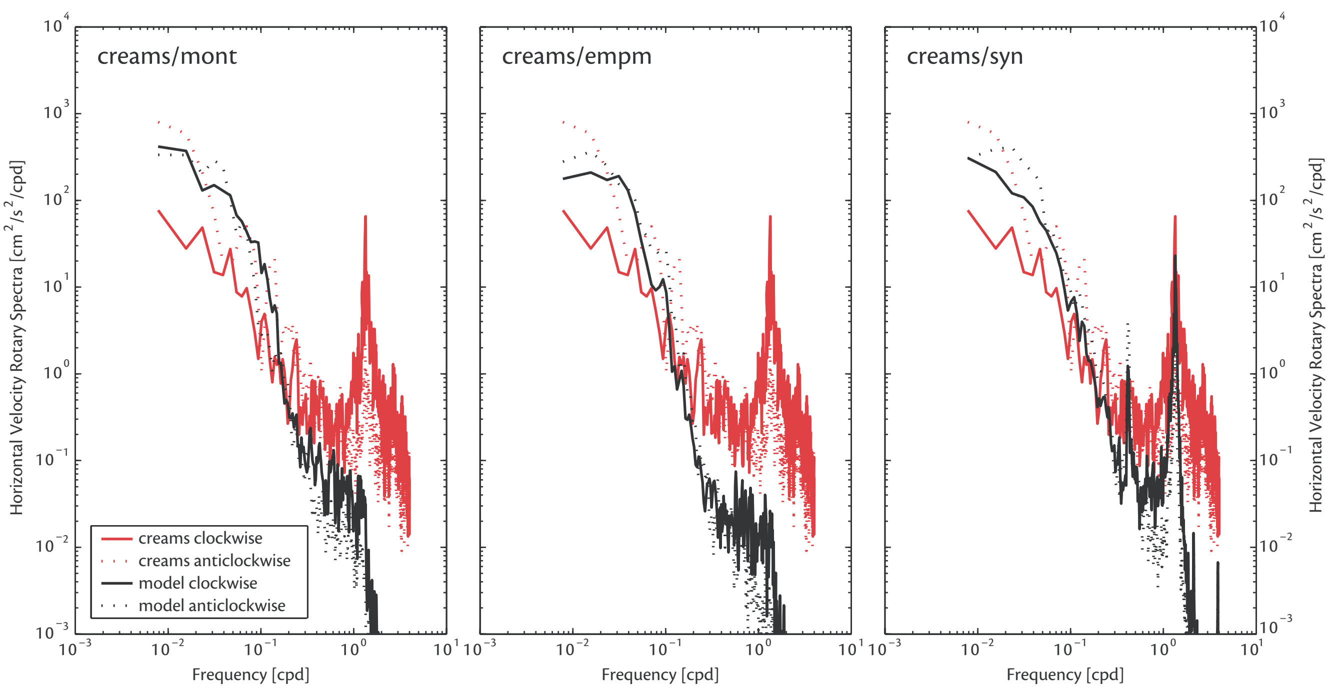

Figure 2. Rotary spectra (diagrams representing clockwise- and counterclockwise-turning current energy as a function of frequency) for observed currents (red lines) and model outputs (black lines) with three different model forcing fields. The "mont" and "empm" fields are monthly averages, and the "syn" field has time resolution good enough to resolve individual storm passages. The important result here is that the model only does a good job for periods of 10 days or less if the forcing fields resolve weather events. The currents were measured from August 1993–July 1996 at 1-km depth in 3.5 km of water at 41.495°N, where the inertial frequency is 1.33 cycles per day.

spheric variables and monthly MCSST (mont model run). Detailed procedures for preparation of these air-sea fluxes can be found in Kang (2001).

Model/Data Comparison: CREAMS I Current Spectra (August 1993 to July 1996)

Japanese colleagues (Takematsu et al., 1999) deployed current-meter arrays with subsurface buoyancy elements for three years at several locations in the Japan Basin, with current meters at depths of 1, 2, and 3 km. The most striking feature of the resultant energy spectra was the appearance of a strong, narrow-band inertial frequency peak at all three depths. The empm and mont model runs, with monthly averaged wind-stress forcing, as anticipated, did not yield such inertial peaks; however, the syn model run, with synoptic wind-stress forcing, produced inertial peaks as energetic as observed at all depths (e.g., at 1 km depth in 3.5 km of water) (Figure 2). Inertial motions have characteristically large vertical shears, which drive vertical mixing. Thus, to the extent that it is important to emulate mixing processes in the ocean interior for accurate mesoscale circulation modeling, it is essential to use synoptic winds in forcing the model. Available numerical weather predictions of synoptic winds (cf. Mooers et al., 2000) are capable of generating inertial motions in numerical ocean simulations comparable to those observed.

Model/Data Comparison: Intermediate Water Routes

Southward subsurface boundary currents along the coasts of Russia and Korea, respectively, are crucial for the southward transport of intermediate waters convected from the surface in the north. The subsurface boundary currents reach Ulleung Basin and Yamato Basin.

Three pathways (Figure 3) for intermediate waters at ca. 800 m have been suggested by others based on hydrographic and Acoustic Doppler Current Profiler

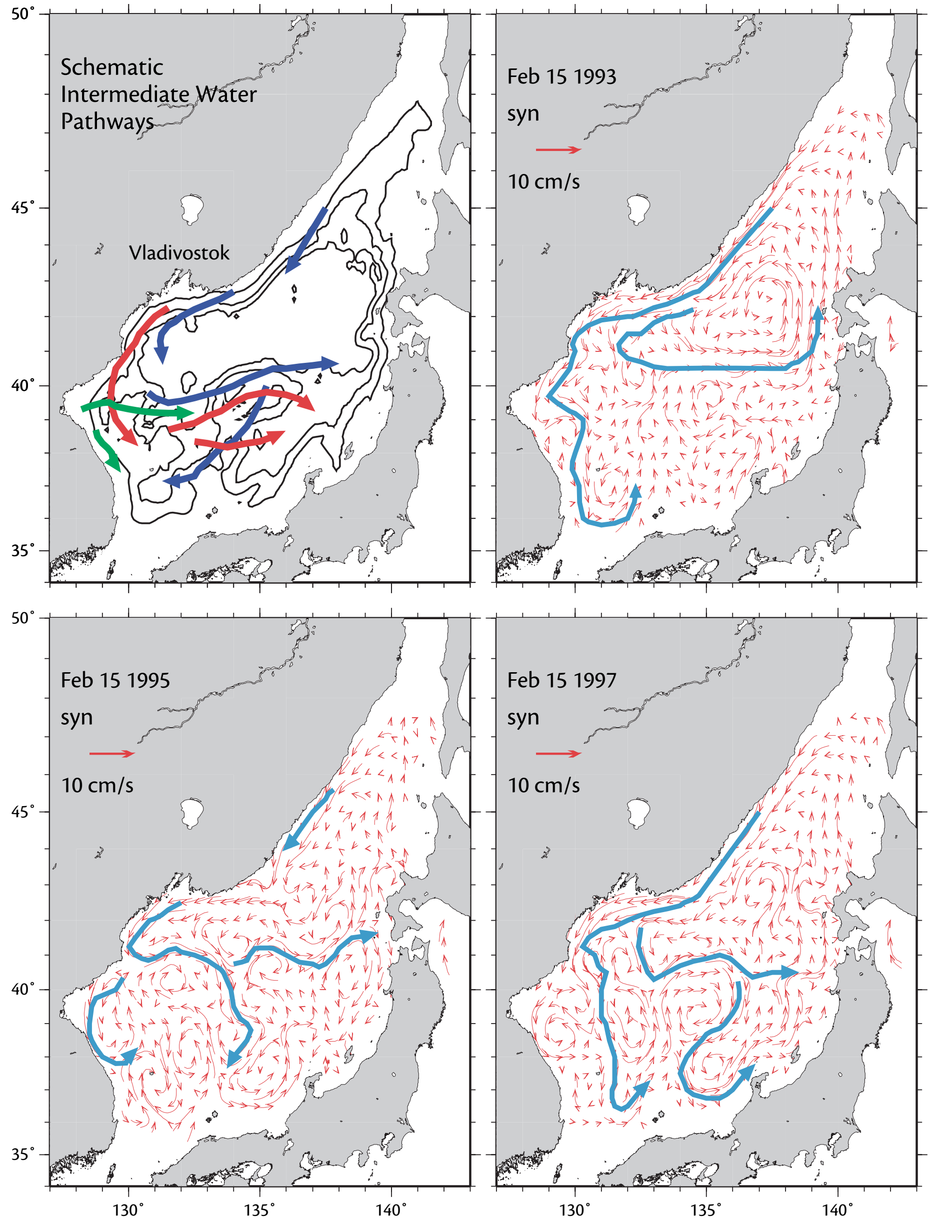

Figure 3. Upper left: Intermediate (about 800-m nominal depth) water circulation in the Japan/East Sea based on observational syntheses by Senjyu and Sudo (1994; red lines), Isobe and Isoda (1997; blue lines), and Senjyu (1999; green lines). The other three panels show modeled (driven by weather-resolving winds) currents at 800-m depth for February 15 of 1993, 1995, and 1997. The model repeatedly reproduces important features such as the southward flow along the western boundary and the eastward flow near 40°N.

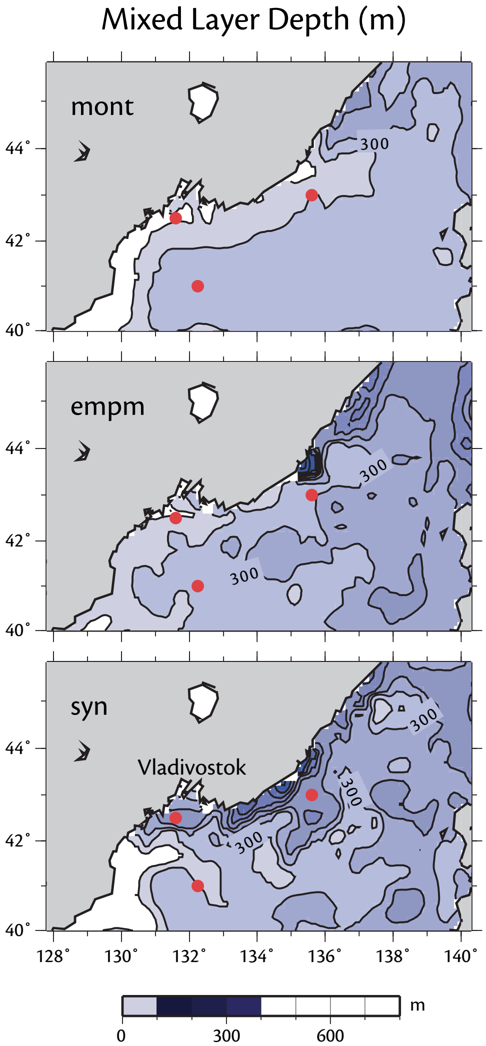

Figure 4. Simulated surface mixed-layer depth in the northwestern Japan/East Sea for March 15, 1997, using different wind forcings (mont = monthly means; empm = monthly means; and syn = weather-resolving). Red dots indicate locations where evidence of ventilation (deep mixing) was observed during February 28–March 15, 2000 by Talley et al. (1999). The weather-resolving forcing appears to simulate the deep mixing most accurately.

(ADCP) observations: (1) a meridional flow along the Korean coast (Senjyu and Sudo, 1994; Senjyu, 1999), (2) a zonal flow along the SPJF (Senjyu and Sudo, 1994; Senjyu, 1999), and (3) a meridional flow over the Yamato Rise (Isobe and Isoda, 1997). We simulated these currents using synoptic forcing in winter. Comparisons to simulated instantaneous flows at 800-m depth for February 15, 1993, 1995, and 1997, as examples during the convection season, indicate flow patterns that are generally consistent with the three suggested pathways; interannual variations are probably due to changes in mesoscale variability.

Model/Data Comparison: Mixed-Layer Depth (MLD) in the Northwestern JES (1997)

We simulated the spatial distribution of MLD in winter using the three atmospheric-forcing data sets for 1997 (syn, empm, mont) (Figure 4). These simulations indicate maximum MLD north of 40°N and west of 138°E, with different magnitudes and areas of local maxima (Kang and Mooers, 2005). Two areas of local maxima are very noticeable, one off Vladivostok and the other along the southern Primorski coast. From winter 2000 observations (Talley et al., 2000; Talley et al., this issue), three stations (Figure 4) show ventilation penetrating well below the summer pycnocline: (1) south of Vladivostok, east of a warm eddy, and north of the SPJF to a depth of 1100 m; (2) the southern portion of Tatar Strait east of the ice edge to a depth of 600 m; and (3) on the continental slope off Peter the Great Bay to a depth of 360 to 1100 m. Two of these stations are located near the area of maximum simulated MLDs. The simulated MLDs are not as great as those observed, but these observations were obtained in 2000 and the simulations used atmospheric-forcing data for 1993 to 1997, so we cannot expect perfect agreement. In addition, these simulations do not include an ice model, which can yield a deeper mixed layer due to brine rejection (Talley et al., 2003).

New Phenomena: Annual Subduction Rate (1997)

There are several areas of simulated local maximum annual subduction rate using 1997 atmospheric-forcing model inputs (Figure 5) (Kang and Mooers, 2005). The primary water-mass formation area off Vladivostock (Area V) is controlled by synoptic atmospheric forcing (syn) associated with Siberian cold-air outbreaks. Area V corresponds to the so-called “flux center” (Kawamura and Wu, 1998), the “subduction region” (Senju and Sudo, 1994, 1996; Yoshikawa et al., 1999), and the “wintertime convection location” (Seung and Yoon, 1995). In addition to Area V, our simulations identified two other areas as possible convection/ventilation sites: Area K (36–39°N, west of 132°E) and Area KB (near Korea Bay) (Kang and Mooers, 2005). Area K has not been previously considered as a potential source region for JES intermediate water, yet it is a ventilation region in the three atmospheric-forcing cases run in all years. This result led us to seek an explanation for the ventilation other than air-sea flux conditions. Because this is known to be an upwelling area, the formation of denser water is possible when this upwelled cool water meets the warm, saline water advected by EKWC. A possible explanation for

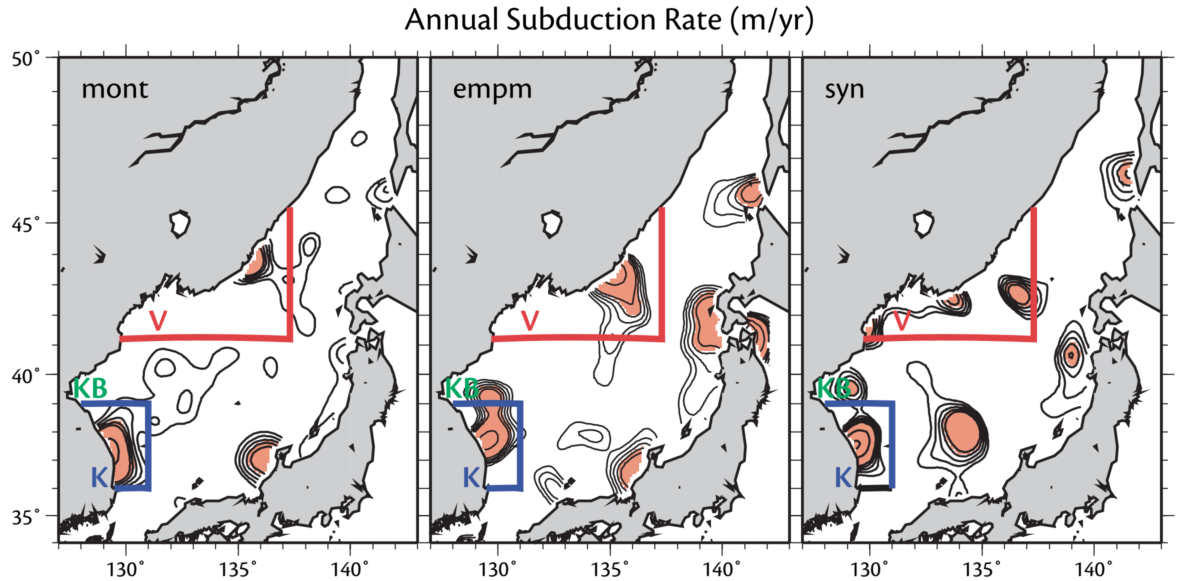

Figure 5. Simulated 1997 annual mean subduction rate (m yr^{-1}) for the monthly mean (mont, empm) and weather-resolving (syn) wind-forcing cases. Red shading indicates subduction greater than 500 m yr^{-1}. Contour intervals are 100 m yr^{-1} for values less than 500 m yr^{-1} and 500 m yr^{-1} for values greater than 500 m yr^{-1}. The labeled boxes represent the Vladivostok area (V), the East Coast Korea area (K), and Korea Bay (KB). The "K" area had not previously been considered a location for active subduction, but these model results suggest that it deserves more consideration.

convection in Area KB is that subduction may be a consequence of a strong EKWC dominated by lateral induction without a steep horizontal MLD gradient (Kang and Mooers, 2005). Also, Area KB has been previously suggested as a possible convection area (Ryabov, 1994) because deep waters may be formed there in frontal zones (i.e., in the confluence of cool, fresh waters with warm, saline waters). Hogan and Hurlburt (this issue) and Lee et al. (this issue) have recently investigated other aspects of subduction along the Subpolar Front.

SIMULATING THE CREAMS II PERIOD: 1999 TO 2001

Building on the experience derived from the simulations for the CREAMS I period, we chose the horizontal resolution to be 0.1 degree, with 21 sigma levels distributed from surface to bottom (viz., seven with increasing separation, eight with constant separation, and five with decreasing separation). We used bottom topography from ETOPO5, smoothed so that $S_h \leq 0.2$ ($S_h \equiv \Delta h/2\bar{h}$), where Δh is the depth difference of two adjacent cells and $\bar{h}$ is the mean depth. We set the lateral friction coefficient (HORCON; Smagorinsky, 1963) equal to 0.2 and used a horizontal Prandtl number (i.e., the ratio of the horizontal eddy viscosity to the horizontal eddy diffusivity) of 1.0. The initial (horizontally uniform) temperature values were determined by averaging the 1/4-degree annual mean temperature profiles (Boyer and Levitus, 1997) from grid points where the water depth is at least 3 km. Below 600 m, we set the temperature and salinity to constant values (T=0.059°C and S=34.069 ppt) to match approximately the observed values (Talley et al., 2001). Surface salinity was relaxed, with a time scale of 30 days, to a monthly climatology constructed from various data sources, including the Japan Oceanographic Data Center (JODC), National Fisheries Research and Development Institute (NFRDI) of Korea, and Far Eastern Regional Hydrometeorological Research Institute (FERHRI) of Russia (Kim, 1996). The transport through Korea Strait was based on 11 monthly mean transport estimates, during the period May 1999 through March 2000, made with an array of bottom-mounted ADCPs from the NRL (Teague et al., 2002); the transport value for April 2000 was estimated by averaging May 1999 and March 2000 values. Then, these monthly values were applied repeatedly in any given year. Based on previous observational studies, the transport on the outflow was partitioned into 60 percent and 40 percent through Tsugaru and Soya Straits, respectively, and assumed to be in phase with the inflow. Temperature and salinity transects across the inflow boundary in the Korea Strait were specified from 1/6-degree monthly transects interpolated from bimonthly data acquired at standard depths by NFRDI (Kim, 1996). The atmospheric forcing consisted of six-hourly wind stress and surface heat flux records (total heat flux and short wave radiation) from NOGAPS (Navy Operational Global Atmospheric Prediction System) on a one-degree grid for 1999 through 2001. The simulated temperature and salinity were relaxed to initial values with depth–dependent weighting (Mooers et al., 2005). From a cold start, we ran JES-POM for four years with 1999 forcing, one year with 2000 forcing, and one year with 2001 forcing. (The spatial mean kinetic energy reached a near-equilibrium state after the third year.) The fourth year of the 1999 run was used for the first year of the 1999–2001 analyses.

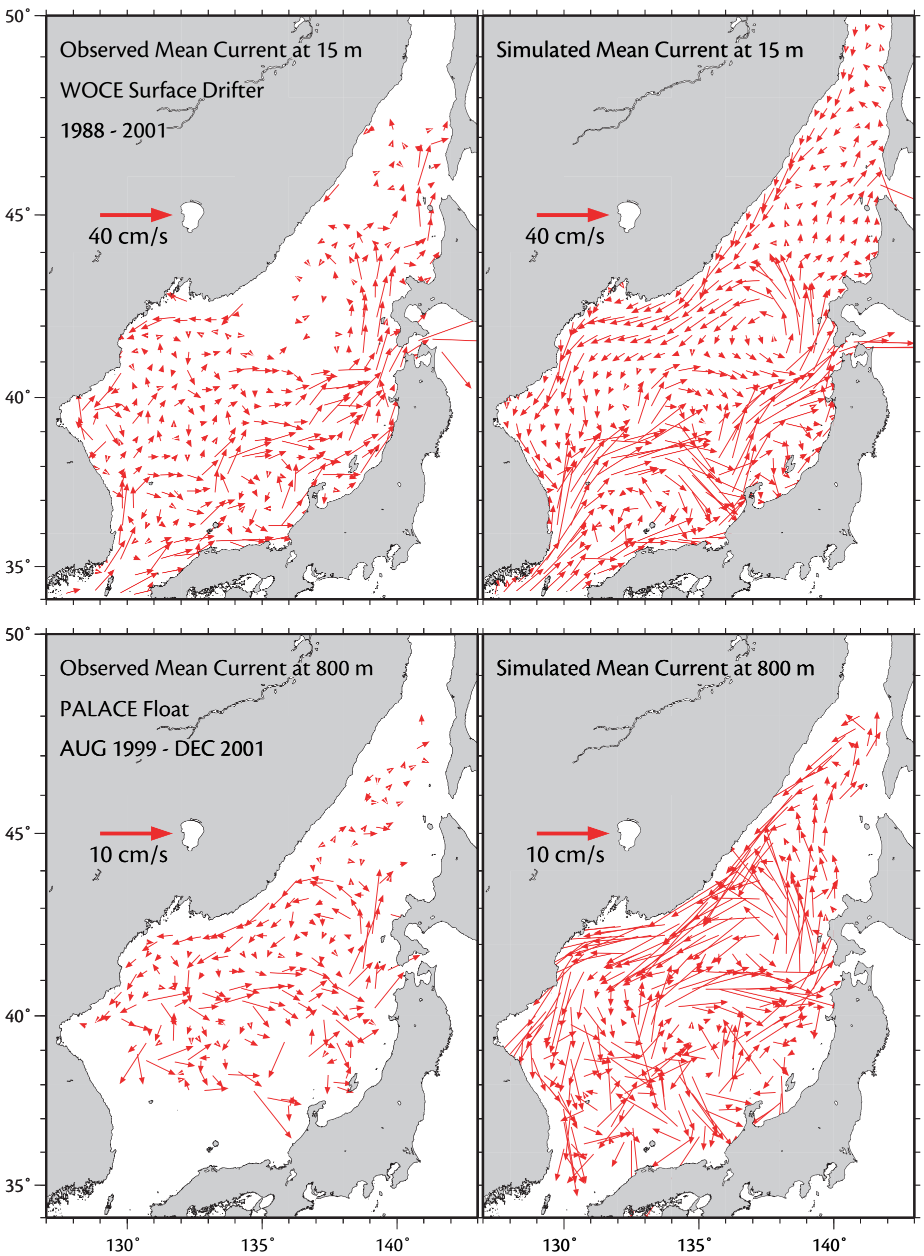

Figure 6. Simulated (right panels) and observed (left panels) mean flow at 15-m (upper row) and 800-m (lower row) depth. The simulated and observed (PALACE float) 800-m currents are for August 1999–December 2001, and the 15-m (drifter) observations span 1988–2001. Note the change in velocity scales between 25 m and 800 m. The model results replicate many of the features in the observations, although modeled speeds are sometimes greater. See also Figure 1 for comparison.

Model/Data Comparison: Mean and Variable Flow

For the CREAMS II period (1999 to 2001), the simulated flows at 15-m depth are compared to the observed flows (Lee and Niiler, 2005) determined from World Ocean Circulation Experiment (WOCE) drifters over a 13-year period (Figure 6). Though the drifters did not cover all of the JES, especially in the northwest, their coverage was sufficient to evaluate the simulations. Comparison of mean flows confirms the presence of the EKWC, NB, MB, NKCC, SPJF, SWC, LCCC, and the cyclonic subpolar gyre over the Japan Basin. The speeds of the mean flows were also comparable, with simulated values a bit greater. The simulated and observed variances (not shown; cf. Mooers et al., 2005) also had similar spatial patterns and magnitudes, with observed values a bit greater.

In turn, the simulated flows at 800 m are compared to the observed flows (Steve Riser, University of Washington, personal communication, 2002) determined from Profiling Autonomous Lagrangian Current Explorer (PALACE) floats (Figure 6). Though the floats did not cover all of the JES either, especially in the south, their coverage was very adequate for evaluating the simulations. Comparison of the mean flows confirms the presence of the vigorous cyclonic subpolar gyre over the Japan Basin. The mean simulated flow also includes penetration of the cool subsurface boundary current to the southern reaches of the JES. Although the mean simulated and observed spatial flow patterns were similar, the mean speeds of the simulated flows were as much as twice those of the observed flows. The simulated and observed variances (not shown; cf. Mooers et al., 2005) had somewhat similar patterns and magnitudes, with simulated values a bit greater.

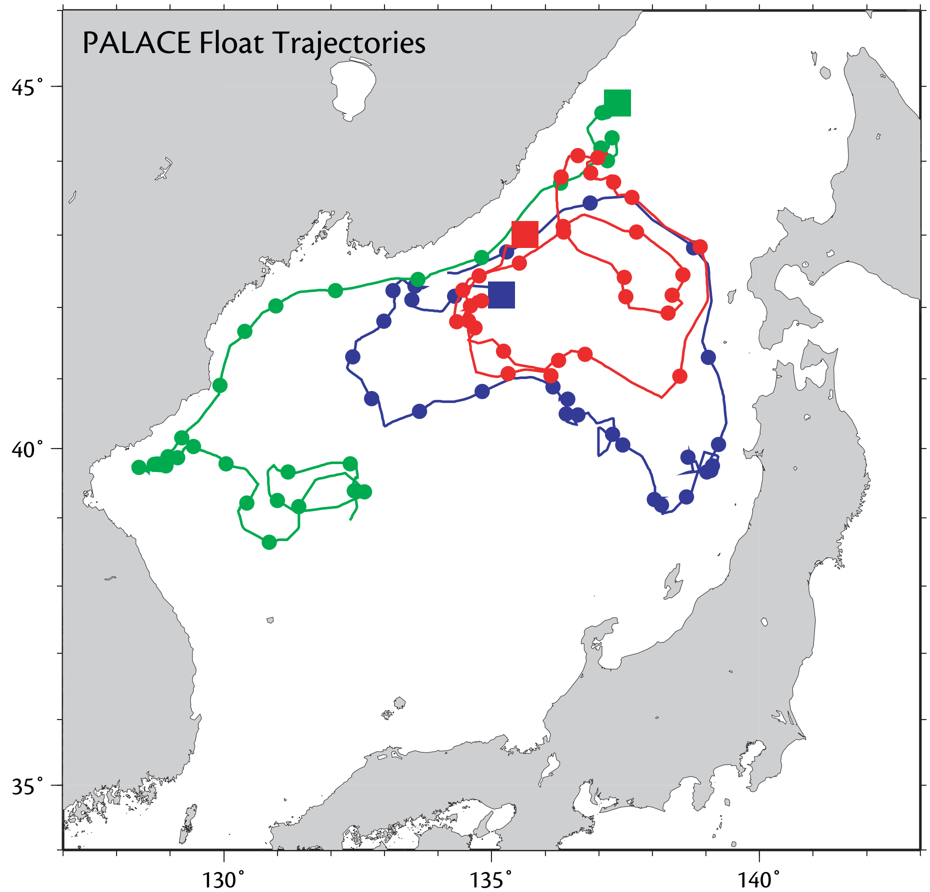

Figure 7. Three representative PALACE float observed trajectories for floats deployed off the Primorski Coast of Russia in the northern Japan/East Sea (August 1999–December 2001). Different colors are used for each of the three trajectories. The start positions are indicated by squares and subsequent positions are indicated every 30 days by circles.

Model/Data Comparison: Simulated Versus Observed Lagrangian Hydrographic Transects (1999–2001)

Three of the PALACE float trajectories that traversed the large Japan Basin cyclone are singled out for closer examination (Figure 7). The first made two and one-third cyclonic loops (one large and one small) over the course of two years. A second made a single, large, almost exactly closed cyclonic loop. The third covered about one-third of a potentially much larger loop before stalling off KB for half a year and then apparently becoming entrained in a large anticyclonic eddy just north of the SPJF. The first float is chosen for comparison of simulated and observed temperature and salinity structures in the upper 400 m by sampling the model output at the same time and position as PALACE float hydrographic profiles (Figure 8). Three seasonal cycles of warming/cooling and freshening/salinification dominate the patterns. The simulations generally underestimate the strength of the seasonal thermocline and halocline. The PALACE floats and the simulations indicated late-winter MLD deepening; however, the degree of agreement varied from year to year and float to float, which might be attributable to discrepancies between predicted and realized atmospheric forcing or model parameter selection. Thus, the PALACE floats exhibit a high potential for use in very discriminating model evaluations.

SUMMARY

Numerical simulations of the mean JES circulation and hydrography, and their variance, have been evaluated to a con-

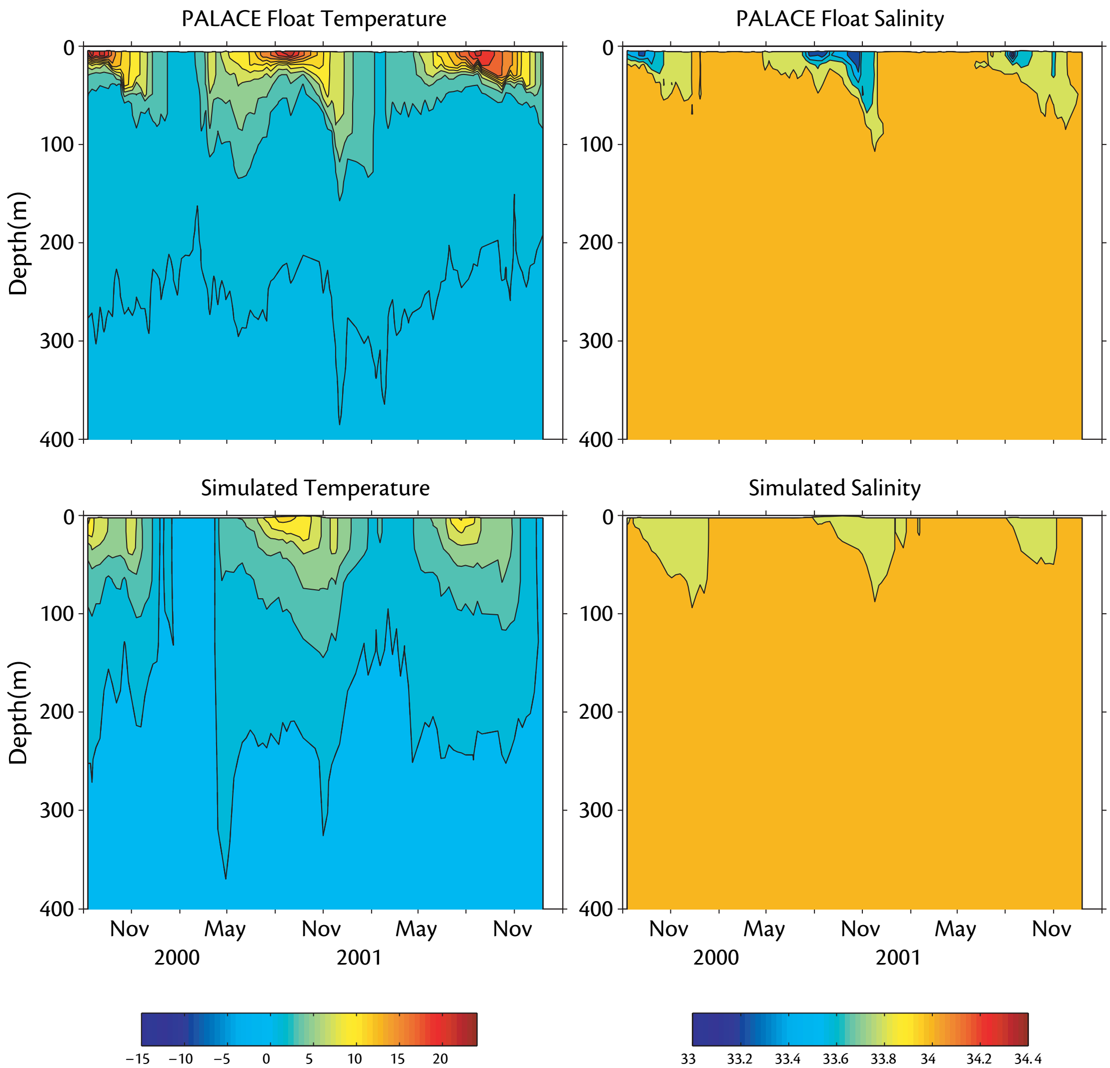

Figure 8. Observed (upper panels) and simulated (lower panels) temperature (left panels) and salinity (right panels) obtained along the red path in Figure 7. Note how the model replicates the general seasonal patterns in both temperature and salinity.

siderable degree using, among other data sets, WOCE near-surface drifters, PALACE mid-depth floats, and Japanese current-meter moorings. An important result has been the demonstration that synoptic wind forcing is extremely important for simulating near-inertial motions, mixed-layer deepening, subduction and intermediate water formation, and deep convection.

With the proven capability of mesoscale-admitting numerical modeling, and with the large number of observations acquired over the past decade or so, there are numerous additional opportunities for instructive model evaluation and process studies. There are also important new opportunities for such studies to take advantage of recently established, operational basin-scale and regional models. These new systems can provide lateral open boundary conditions, and so break the previous unsatisfactorily constraining reliance on very approximate climatologies. However, it is essential for process-model validation and operational-model verification that a sustained monitoring system be implemented for the flow and water-mass properties through each of the four straits. It will be valuable to run models with ca. 1-km horizontal resolution to resolve mesoscale eddies and ca. 50 sigma levels in the vertical to resolve surface and bottom boundary layers for multidisciplinary studies; that combination of horizontal and vertical resolution should also resolve the major fronts of the JES that are so important to subduction processes. An ice model should be coupled to circulation models to treat wintertime convection better. It is now possible to construct an accurate data-assimilative analysis for the JES for at least the past decade if all of the relevant data are made available through programs, such as NEAR-GOOS (North-East Asian Regional Global Ocean Observing System), which is being conducted by Japan, Republic of Korea, the Russian Federation, and China (http://www.gosic.org/goos/NEAR-GOOS_program_overview.htm). New model studies are now able to tackle, for example, the strong cyclonic subpolar gyre, which is evidenced in both observations and simulations over the Japan Basin, but interestingly, this gyre has yet to be studied in its own right. Such studies may be key to future understanding of the dynamics of the JES and developing predictive models.

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