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

BY CHRISTOPHER N.K. MOOERS, HEESOOK KANG, INKWEON BANG, AND DERRICK P. SNOWDEN

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 winter-time 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. Iso-baths 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-

Christopher N.K. Mooers (cmooers@rsmas.miami.edu) is Professor, Ocean Prediction Experimental Laboratory, Division of Applied Marine Physics, Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, Miami, FL, USA. Heesook Kang is Postdoctoral Research Associate, Cooperative Institute for Marine and Atmospheric Science, RSMAS, University of Miami, Miami, FL, USA. Inkweon Bang is Research Scientist, RSMAS, University of Miami, Miami, FL, USA. Derrick P. Snowden is Research Scientist and Ph.D. Candidate, RSMAS, Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL, USA.

---

**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...
(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 advedected by EKWC. A possible explanation for
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 $S_h \leq 0.2$ ($S_h = \Delta h/2\bar{h}$), where $\Delta h$ 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 ($T=0.059^\circ C$ 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.

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.

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-
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 meso-scale-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

![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.](image)
ACKNOWLEDGEMENTS

The Office of Naval Research sponsored this research. We are highly appreciative of the cooperation and advice provided by numerous Japanese, Korean, Russian, and American colleagues, but especially Masaki Takematsu, Kuh Kim, Dong-Kyu Lee, Slava Lobanov, Victor Kuzin, Guri Marchuk, Artem Sarkisyan, Yuri Volkov, Ruth Preller, Dong-Shan Ko, Lynne Talley, Steve Riser, and Peter Niiler.

REFERENCES

Boyer, T.P., and S. Levitus. 1997. Objective analysis of temperature and salinity for the world ocean on a 1° degree grid. NOAA Atlas NESDIS 11. US Government Printing Office, Washington, D.C.

Isobe, A., and Y. Isoda. 1997. Circulation in the Japan Basin, the Northern Part of the Japan Sea. *Journal of Oceanography* 53:373–381.

Kang, H.S. 1997. Implementation, Sensitivity Testing, and Evaluation of a Numerical Model for the East/Japan Sea Circulation. Technical Report No. RSMAS-97-008. University of Miami, FL, 174 pp.

Kang, H.S. 2001. *Simulation of Convection/Ventilation and Diagnoses of Water Mass Subduction/Formation/Transformation in the Japan/East Sea (JES): Impact of Atmospheric Forcing with Different Time-Space Scales*. Technical Report No. RSMAS-2001-02. University of Miami, FL, 225 pp.

Kang, H.S., and C.N.K. Mooers. 2005. Diagnoses of simulated water-mass subduction/formation/transformation in the Japan/East Sea (JES). *Deep-Sea Research II* 52:1,505–1,524.

Kawamura, H., and P. Wu. 1998. Formation mechanism of Japan Sea Proper Water in the flux center off Vladivostok. *Journal of Geophysical Research* 103(C10):21,611–21,622.

Kim, C.-H. 1996. A numerical experiment study on the circulation of the Japan Sea (East Sea). Ph.D. Dissertation. Kyushu University, Fukuoka, Japan, 151 pp.

Kim, K., Y.-G. Kim, Y.-K. Cho, M. Takematsu, and Y. Volkov. 1999. Basin-to-basin and year-to-year variation of temperature and salinity characteristics in the East Sea (Sea of Japan). *Journal of Oceanography* 55:103–109.

Lee, D.-K., and P.P. Niiler. 2005. The energetic surface circulation patterns of the Japan/East Sea. *Deep-Sea Research II* 52:1,547–1,563.

Mellor, G.L. 1998. *Users’ Guide for a Three-Dimensional, Primitive Equation, Numerical Ocean Model*. Program in Atmosphere and Ocean Science, Princeton University, Princeton, NJ, 41 pp.

Mooers, C.N.K., and H.S. Kang. 1995. Initial spin-up of a Sea of Japan numerical circulation model. Pp. 350–357 in *Advanced Mathematics: Computations and Applications*, A.S. Alekseev and N.S. Bakhvalov, eds. NCC Publisher, Novosibirsk, Russia.

Mooers, C.N.K., H.S. Kang, and S.S. Chen. 2000. Several aspects of the simulated response of the Japan (East) Sea to synoptic atmospheric forcing due to Siberian cold air outbreaks. *La Mer* 38(4):233–243.

Mooers, C.N.K., I. Bang, and F.J. Sandoval. 2005. Comparisons between observations and numerical simulations of Japan (East) Sea flow and mass fields in 1999 through 2001. *Deep-Sea Research II* 52(11):1,639–1,661.

Ryabov, O. 1994. On a bottom water origin of the Japan Sea. In: *Proceedings of CREAMS 1994 International Symposium*, Kyushu University, Fukuoka, Japan, 91–94.

Senjyu, T. 1999. The Japan Sea Intermediate Water; Its characteristics and circulation. *Journal of Oceanography* 55:111–122.

Senjyu, T., and H. Sudo. 1994. The upper portion of the Japan Sea Proper Water: Its source and circulation as deduced from isopycnal analysis. *Journal of Oceanography* 50:663–690.

Senjyu, T., and H. Sudo. 1996. Interannual variation of the upper portion of the Japan Proper Water and its probable cause. *Journal of Oceanography* 52:27–42.

Seung, Y.-H., and J.-H. Yoon. 1995. Some features of winter convection in the Japan Sea. *Journal of Oceanography* 51:61–73.

Smagorinsky, J. 1963. General circulation experiments with the primitive equations, I. The basic experiment. *Monthly Weather Review* 91:16,053–16,064.

Takematsu, M., Z. Nagano, A. Ostrovskii, K. Kim, and Y. Volkov. 1999. Direct measurements of deep currents in the northern Japan Sea. *Journal of Oceanography* 55:207–216.

Talley, L.D., V.B. Lobanov, P. Tishchenko, P. Ya., V.I. Ponomarev, A.E. Sherbinin, and V.A. Luchin. 2001. Hydrographic observations in the Japan/East Sea in winter 2000, with some results from summer, 1999. In: *Proceedings of CREAMS 2000 International Symposium*, Pacific Oceanological Institute, Vladivostok, Russia, 25–32.

Talley, L.D., V. Lobanov, V Ponomarev, A. Salynuk, P. Tishchenko, I. Zhabin, and S. Riser. 2003. Deep convection and brine rejection in the Japan Sea. *Geophysical Research Letters* 30(4):1159, doi:10.1029/2002GL016451.

Teague, W.J., G.A. Jacobs, H.T. Perkins, J.W. Book, K.-I. Chang, and M.S. Suk. 2002. Low-frequency current observations in the Korea/Tsumiya Strait. *Journal of Physical Oceanography* 32(6):1,621–1,641.

Yoshikawa, Y., T. Awaji, and K. Akitomo. 1999. Formation and circulation processes of Intermediate Water in the Japan Sea. *Journal of Physical Oceanography* 29(8):1,701–1,722.

Oceanography | Vol. 19, No. 3, Sept. 2006 95