Global Atmospheric Modeling Using the Earth Simulator

One of the most exciting recent developments in the field of environmental modeling is the advent of the Earth Simulator in Japan. Built at a cost of over $350 million, the Earth Simulator is the world's most powerful computer, and a major portion of its computing resources is devoted to climate research. Operations began in March 2002, and already extensive simulations with several atmospheric and oceanic models (see p. 16) have been completed. Global circulation models with unprecedented fine resolution can be run on this supercomputer. In the research activities at the Frontier Research System for Global Change, the Earth Simulator plays a crucial role, and Frontier headquarters are located right beside the Earth Simulator Center in Yokohama.

IPRC scientists are now developing projects with their Japanese colleagues that use the Earth Simulator. In one such collaboration, **Kevin Hamilton**, leader of the Impacts of Global Environmental Change Research Team, and scientists from the Earth Simulator Center are working with the Atmospheric Model for the Earth Simulator (AFES), a global spectral general circulation model. The AFES has been run at extremely high horizontal and vertical resolutions, up to roughly 15-km-grid spacing (horizontal triangular-1279 or T1279) and 96 vertical levels (L96).

Supported by a fellowship from the Japan Society for Promotion of Science, Hamilton worked from mid-May through the end of June 2003 at the Earth Simulator Center (ESC). His visit was hosted by **Wataru Ohfuchi** who leads the AFES group. Ohfuchi and Hamilton started to collaborate on a number of projects that analyze the output from a control integration with the T1279-L96 AFES. Their overall theme is the analysis of explicit ultra-fine resolution results as a guide for parameterizing small-scale effects in modest-resolution climate models. An important example is the parameterization of the pressure drag on the atmosphere as it flows over Earth's topography. The left panel in Figure 8 shows the topography of a region of East Asia as represented in the T1279 AFES model, while the right panel shows the topography degraded to a resolution typical of climate models (approximately T40). The drag on the atmospheric flow over the relatively small-scale topographic irregularities, explicitly resolved in the T1279 model, must be parameterized in the T40 model. Many theoretical studies have addressed the question of how the drag associated with subgrid-scale topography should be parameterized. The T1279 AFES simulation results now allow the explicit evaluation of drag determinations from different parameterizations.

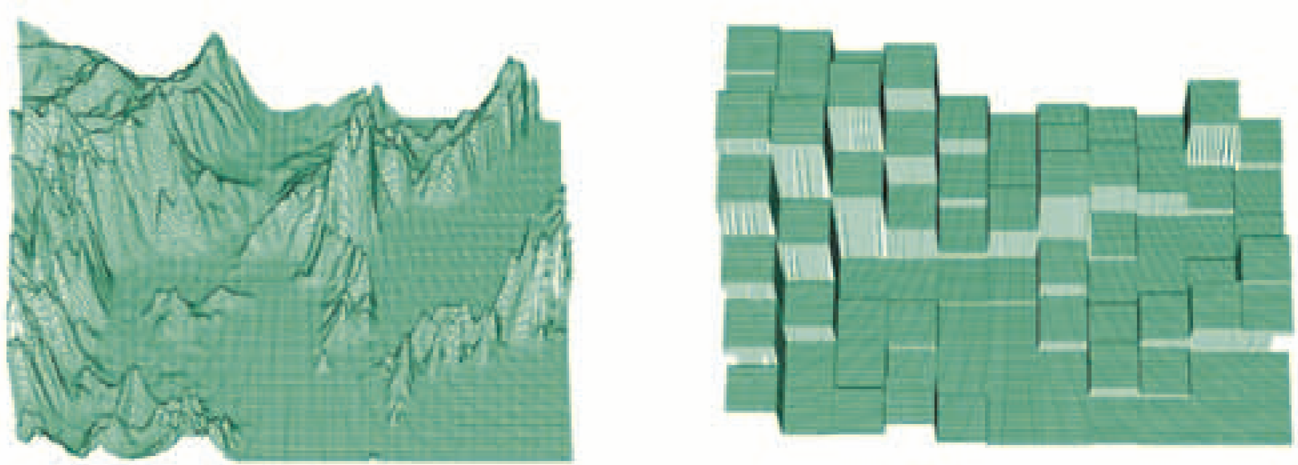


Figure 8. *A northward-looking view of the topography of parts of East Asia: Southeast Asia is in the lower left corner, Korea near the center, and Japan on the right. Left panel: The topography in the T1279 version of the AFES model. Right panel: the mean values for grid squares with dimensions of about 300x300 km, the typical resolution in a present-day model applied to long climate integrations.*

During his visit, Hamilton also began collaborating with Ohfuchi and ESC scientist **Yoshiyuki Takahashi** on a study of the horizontal variance spectra as simulated by high-resolution versions of AFES. The observed atmospheric kinetic energy (i.e., wind variance) spectra on horizontal surfaces show three distinct regimes: a very large-scale one for horizontal wavelengths greater than about 5,000 km, one for intermediate horizontal wavelengths greater than about 500 km but less than 5,000 km (a k^{-3} power-law), and a shallower, mesoscale one for wavelengths shorter than 500 km (something like $k^{-5/3}$). Before the advent of AFES, the only global GCM that had clearly simulated the shallow mesoscale power spectrum realistically was the Geophysical Fluid Dynamics Laboratory SKYHI GCM when run at a resolution roughly comparable to T450 (Koshyk and Hamilton, 2001).

The black curve in Figure 9 shows the horizontal spectrum of zonal wind variance near the midlatitude tropopause as calculated from SKYHI model results. The distinct shallow mesoscale regime is quite apparent. The red curve shows results from the AFES model run at T629 resolution. The fact that AFES is also able to produce a simulation with a realistic mesoscale regime is encouraging and indicates that the AFES running on the Earth Simulator will allow scientists to determine how the mesoscale spectrum is affected by such factors as convective parameterization, vertical resolution, and subgrid-scale hyperdiffusion.

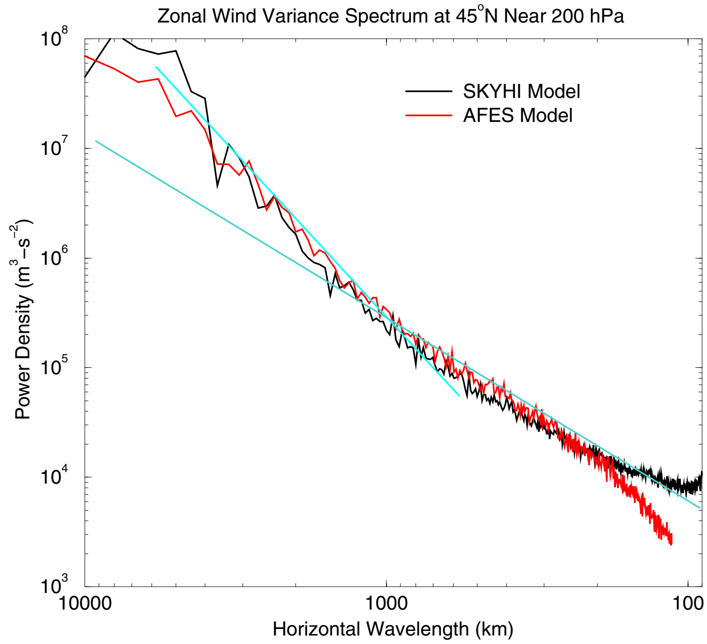
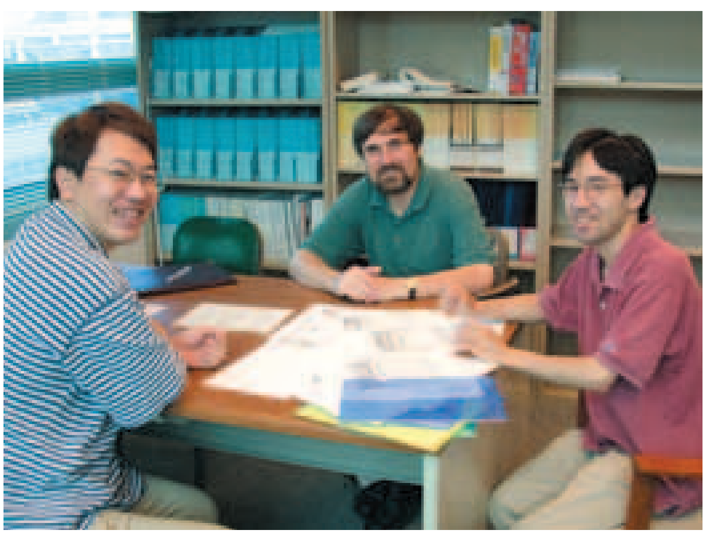


Figure 9. *The zonal wavenumber spectrum of the variance of the zonal wind along the 45°N latitude circle at 200 hPa. Results for simulation with the GFDL SKYHI model (black) and for the AFES (red). The straight lines are drawn for reference and show –3 and –5/3 power-law slopes.*



Wataru Ohfuchi, Kevin Hamilton, and Yoshiyuki Takahashi discussing results from the ultra-high resolution global atmospheric model for the Earth Simulator Center.

Hamilton and his Japanese collaborators are also studying the important issue of scaling the subgrid-scale diffusion coefficient appropriately for different model resolutions. The modest-resolution models applied in typical climate studies are truncated in the k^{-3} power-law range and do not represent the mesoscale range. For such models, the "traditional" diffusion scaling, in which the dissipation time of the smallest resolvable scale is constant, generally works well. With AFES, however, this issue can be addressed with a range of truncations extending into the mesoscale. Preliminary results suggest that, for high-resolution models, the hyperdiffusion time at the truncation point needs to become shorter with the improved resolution.

Ohfuchi and Takahashi visited IPRC for a week in August to work with Kevin Hamilton, who is looking forward to continuing extensive interactions with colleagues at the Earth Simulator Center.

Koshyk, J.N., and K. Hamilton, 2001: The horizontal kinetic energy spectrum and spectral budget simulated by a high-resolution troposphere-stratosphere-mesosphere GCM. *Journal of the Atmospheric Sciences*, **58**, 329-348.

Global Ocean Modeling Using the Earth Simulator

Japan's newest supercomputer, the Earth Simulator, is putting out huge amounts of data from the atmospheric and oceanic models developed for this machine. The IPRC is fortunate to be collaborating with researchers at the Earth Simulator Center on analyzing aspects of these model outputs (see also the article on p. 14). The Asia-Pacific Data-Research Center of the IPRC is serving to IPRC researchers outputs from the OFES, the global ocean circulation model for the Earth Simulator; this model has a resolution of about 11 km in the horizontal and 54 levels in the vertical.

Jim Potemra, a member of the IPRC Regional Ocean Influences Research Team, has begun a partnership with **Yukio Masumoto** at the Frontier Research System for Global Change and with **Hirofumi Sakuma** and **Hideharu Sasaki** at the Earth Simulator Center on analyzing the Indonesian Throughflow from a climatologically forced integration of the OFES.

An accurate description of the flows from the Pacific to the Indian Ocean, and of the transports through the network of straits in the Indonesian seas, is essential for understanding variability in the Indian and Pacific Oceans. Accurate transports through the pathways are also necessary for determining water-mass convergence and its subsequent transformation within the Indonesian seas.

The water masses from the North and South Pacific and the Indian Ocean converge in the Indonesian seas. The mixing of these water masses, modified by surface fluxes, creates Indonesian Sea Water, which is isohaline at 34.5 psu from the near-surface to about 500-m depth. Understanding the formation of this water requires knowledge of its sources (for example, how much North Pacific Water relative to South Pacific Water enters the region) and the different waters' residence time in the region, which determines the degree of their mixing.

Before the arrival of the Earth Simulator, computing resources limited the resolution of numerical models of the western Pacific and eastern Indian Ocean. Assumptions made about the flow were, therefore, based by necessity on coarse-resolution model results and on the sparse observations available. The OFES is changing all this, now allowing researchers to develop a more detailed and better picture of the ocean pathways through the complex bathymetry of the Indonesian seas. What follows are the results obtained by Jim Potemra from an analysis of the OFES output.

Figure 10 shows the mean transport as a function of depth at various inflow and outflow straits. Regarding the inflow, perhaps the most interesting section lies between the Phillipines and Sulawesi. Models have previously treated this as a single section with a year-round westward flow, the strength of which varies with season. The OFES resolves this region so well that Potemra could study this region's flow in 3 sections. The northernmost section always shows westward flow in the surface layer (to about 500-m depth), while the two other sections always show eastward flow. At depth, the flow reverses in each of the three sections. Moreover, water from the Mindanao Current enters the Celebes Sea through the northernmost section, just south of the Philippines, circulates within the sea, and a portion returns to the Pacific north of Sulawesi.

Given these open passages in the OFES model, the flow of South Pacific water can now be traced. It appears to enter the Banda Sea east and west of Halmahera. Two moorings, one in the Maluku Strait to the west of Halmahera, and one to the east in the Halmahera Sea, confirm this flow. These moorings show substantial flow at depth, also evident in the OFES output. The exact pathway of this deeper flow is still unknown.

The OFES runs confirm the three main outflow straits, the Lombok, Ombai and Timor straits, which show enhanced southward flow into the Indian Ocean at the surface as well as a subsurface maximum. A reverse northward flow into the Banda Sea is seen at depth at the Ombai and Timor sections. This reverse flow, which is also observed at some of the outflow straits, provides Indian Ocean water to the Banda Sea.

In the OFES, some flow also exits through the Karimata Strait between Borneo and Malaysia. Interestingly, some of the flow from the Makassar Strait passes into the Java Sea and north into the Karimata Strait. Most numerical models do not have the vertical resolution to include flow in the Karimata. Since there are no observations in this region, this flow in the model cannot be confirmed as yet.

Looking at the annual variations of the Indonesian Throughflow transports, the OFES shows, as other models

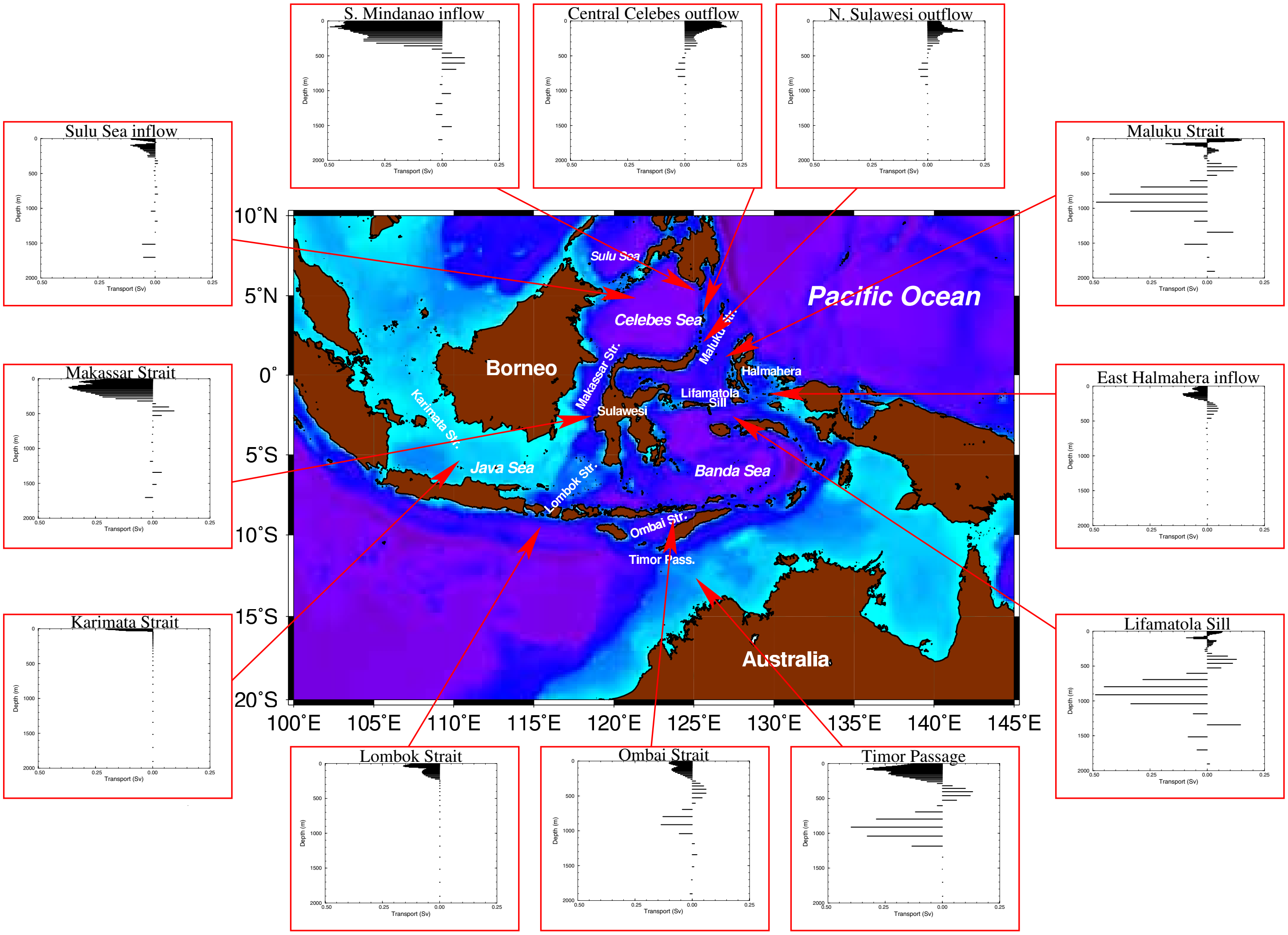


Figure 10. *A map of the main straits in the Indonesian seas together with bathymetry (5,000; 1,000; and 100-m depths are shaded). Depth-integrated transport from the OFES, as a function of depth, is given for selected straits. Negative values indicate southward or westward flow.*

have, extreme values occurring in winter and summer, when the monsoons are strong. Looking at northern summer conditions, the net transport towards the Indian Ocean is greatest during this period. Flow is strong from the Mindanao Current into the Celebes Sea near the south of Mindanao, supplying North Pacific water to the Indonesian seas. The southward flow between Celebes and Halmahera is also greatest during summer; this water comes from the New Guinea Coastal Current and brings South Pacific water into the region. In the OFES, North Pacific Water can now be traced; it flows through the Celebes Sea into the Makassar Strait, which has also peak southward-flow during the northern summer. South Pacific water passes over the Lifamatola Sill into the Banda Sea. Similar to inflow, outflow is maximum through the southern straits from June through August, during the southeast monsoon.

From December to February, the OFES, like other models, shows that inflow and outflow are weak. The exception is a strong southward flow from the Sulu Sea into the Celebes Sea. As flow through the Makassar Strait is weak in January, most of the flow from the Sulu Sea probably exits the Celebes Sea through the southeastern corner of the sea. However, since most models do not have the horizontal resolution to simulate the flow between the Philippines and Borneo, and there are no direct observations of this flow, this flow seen in OFES cannot be confirmed. During January, moreover, flow in the Karimata Strait is southward in OFES. Flow through Karimata is perhaps more important during northern winter months when the southward flow is reduced, and in some cases, reversed. This flow could represent a significant freshwater source to the outflow of the Indonesian Throughflow, since precipitation is high throughout the Java Sea region.

The high horizontal resolution of the OFES not only gives a more complete picture of the flow through the numerous straits in the Indonesian seas, but also allows far more detailed studies within individual straits than before. Figure 11 shows the OFES upper-ocean flow in the Makassar Strait during two seasons. In January, transport is minimum in the Makassar Strait, and outflow through the Lombok Strait is weak. Flow from the Java Sea is evident. In August, transport through the Makassar Strait is at a maximum. Most of the flow exits directly into the Lombok Strait, but some turns to the west and enters the Java Sea. The high-resolution OFES now allows scientists to study the interaction between this flow and the complex topography of individual straits, many of which did not even exist in the coarse-resolution model.

The above are only two examples of how useful the high-resolution OFES results are in examining the flows in the important Indonesian region. The APDRC, as one of the possible OFES data centers, is planning to make such outputs accessible to the public in the future under the IPRC-ESC-FRSGC partnership.

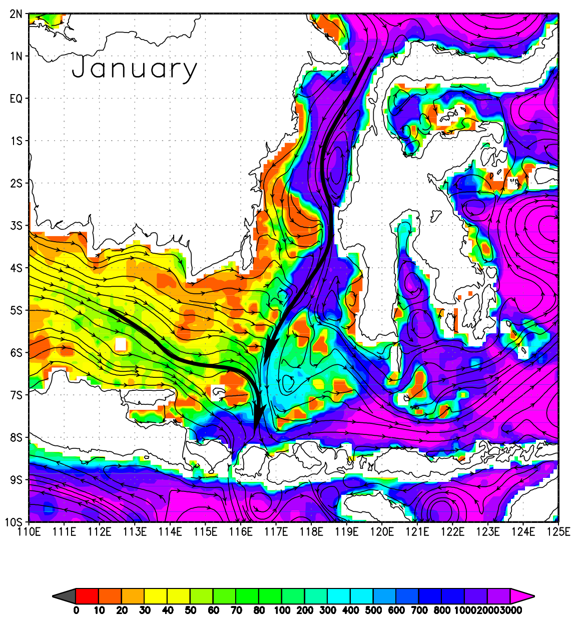


Figure 11. *Upper-ocean flow (surface to 100-m depth mean) for January (left) and August (right) from the OFES. The color shading represents the model's bathymetry in meters (scale at bottom). The thick black lines with arrows highlight the directions of the flows.*