

to them from the shared, received stream. Currently, ship-to-shore channels are 96 kilobits per second, and a point-to-multipoint channel from shore to ship is currently 160 kilobits per second for the Pacific satellite and 64 kilobits for the Atlantic satellite.

The hub facility provides bandwidth management, ensuring that the available bandwidth is efficiently shared among all of the ships. For example, when ships transit from one satellite footprint to another, the hub facility manages the reassignment of bandwidth to another satellite. When ships are in port for extended periods, their bandwidths can be reassigned temporarily to other ships.

HiSeasNet can also provide IP services to remote areas not normally covered by commercial Internet service providers. As an example, in October 2005 a service was initi-

ated for the Incorporated Research Institutions for Seismology/International Deployment of Accelerometers Global Seismographic Network station on South Georgia Island and for the resident scientific community of the British Antarctic Service. The global component of the NSF-sponsored Ocean Observatories Initiative comprises both low- and high-bandwidth buoys for collecting observations. The high-bandwidth buoys are large enough to integrate the C-band or Ku-band antennae used in HiSeasNet. For these larger systems, land-based researchers would then have full access to their instruments in the water column and at the seafloor.

The HiSeasNet 'fleet' includes ships operated by Scripps Institution of Oceanography, University of Washington, University of Hawaii, Woods Hole Oceanographic Institution, Lamont-Doherty Earth Observatory, Univer-

sity of Rhode Island, and Harbor Branch Oceanographic Institution. Through the Joint Oceanographic Institutions, Inc., Scripps Institution of Oceanography operates the HiSeasNet hub and manages shipboard installations and maintenance. CommSystems of San Diego (<http://www.comm-systems.com>) is the principal subcontractor for HiSeasNet, providing system integration, installation, and maintenance services for both the hub and the shipboard systems. More information about HiSeasNet is available at <http://www.hiseasnet.net>

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MEETINGS

High Resolution Simulations of Atmospheric and Oceanic Circulation

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The pursuit of fine spatial representation in models of the atmospheric and oceanic circulation has been a theme running through the development of the field of numerical simulation. For example, in studies of the global ocean circulation, a long-standing concern has been the issue of adequately resolving particularly energetic eddies, such as Gulf Stream rings. In global and regional atmospheric models, a key issue has been resolving mesoscale circulations that organize clouds and convection.

With the recent advent of a new generation of high-performance computing systems, such as the Japan Agency for Marine-Earth Science and Technology's (JAMSTEC) Earth Simulator, some notable thresholds in terms of model resolution have been approached or, in some cases, surpassed. For example, the first long integrations with genuine eddy-resolving global ocean models were reported in 2003. On the atmospheric side, decadal integrations with global models with effective horizontal resolution of approximately 20 kilometers have now become possible, and very short integrations of models that explicitly resolve scales approaching those of individual convective elements were first reported in 2005. These developments in global models have been paralleled by rising research activity with increasingly fine resolution regional atmospheric models for climate and short-range forecasting applications.

Producing fine-resolution simulations is a fairly straightforward task, given the availability of suitably powerful computers. However, there are many interesting issues related to the optimal model formulation

and the interpretation of results from high-resolution models that remain to be explored. To assess some of these issues, an international workshop was held recently at the JAMSTEC Yokohama Institute for Earth Sciences, where the Earth Simulator is housed.

Twenty-two speakers were invited from Australia, Canada, Japan, the United Kingdom, and the United States, and more than 60 scientists attended. The speakers presented results from various regional atmospheric, global atmospheric, global ocean, and global coupled models.

New Discoveries

A number of exciting new findings were reported during the workshop. One example was the discovery of a meridionally-banded structure of numerous narrow zonal jets in the deep ocean in a global ocean simulation employing the Ocean General Circulation Model for the Earth Simulator (OFES) run at 0.1-degree horizontal resolution. As reported by Kelvin Richards (University of Hawaii at Manoa), this aspect of the simulation appears to be analogous to the well-known multiple jet structures observed at the cloud-top level in the atmosphere of Jupiter, but occurs at a much reduced horizontal scale consistent with the ocean's small Rossby radius. As also reported by Richards, these new ocean model results motivated his colleagues to examine the limited relevant real-world observations available for model validation. At least some hints of similar behavior can be identified in the real ocean. Given the lack of detailed observations of deep oceanic circulation, high-resolution explicit modeling may

play an important role in discovering some basic features of the circulation.

At least some global atmospheric models with effective horizontal grid spacing of the order of about 20–30 kilometers were shown to be able to simulate a realistic overall horizontal and vertical spectrum of motions down to the smallest resolved scales, i.e., down to those variations with horizontal wavelengths twice the effective grid spacing. Such results were reported by Kevin Hamilton (University of Hawaii at Manoa) for the Atmospheric General Circulation Model for the Earth Simulator (AFES) spectral model run at T639 resolution (roughly equivalent to a 20 km horizontal grid spacing), as well as for the U.S. National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory SKYHI grid-point model run at one-third-degree resolution. The simulated flow fields include representations of prominent mesoscale phenomena such as tropical cyclones and fronts that appear to be realistic in many respects.

A particularly exciting development was the first application of such extremely high resolution global models to climate change problems, as reported by Akira Noda (Japan Meteorological Research Institute, Tsukuba). A global model with 20-kilometer grid spacing was integrated for 10 years with sea surface temperatures (SSTs) taken from a control run of a lower-resolution coupled atmosphere-ocean model, and then for 10 years with SSTs taken from the end of a twenty-first century global warming scenario run with the same coupled model. Since the model is able to simulate a fairly realistic climatology of tropical cyclone numbers, paths, and intensities, this allowed an assessment of the effects of global warming on the tropical cyclones. A significant decrease (~30%) in the global numbers of tropical cyclones occurred in the simulated warmer world. However, the simulations produced an increase in the number of the most intense storms in some regions. The effect of global warming on tropical cyclone climatology is currently a subject of great controversy. The

use of extremely high-resolution global models is a new approach now available to study this issue, one that can supplement existing observational and limited-area model studies.

The first results from a brief (10-day) integration of a global atmospheric model with 3.5-kilometer horizontal resolution were also presented. This study employed the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) that was developed by the University of Tokyo Center for Climate System Research and the JAMSTEC Frontier Research Center for Global Change specifically for such ultrafine-resolution global simulations. The model is run without a convective parameterization, and the main focus in the initial analysis of the results is in seeing how the model flow interacts with and acts to organize tropical convection. A global atmospheric model simulation resolving such fine spatial scales was unimaginable until recently.

Remaining Issues

While the invited presentations emphasized the recent advances in the field, extensive discussions at the workshop highlighted many outstanding questions that remain. Numerical simulation models for either the atmosphere or ocean must rely on a parameterized dissipation of the energy in the smallest explicitly-resolved scales; such parameterizations are often formulated as a sub-grid diffusion. As model explicit-resolution becomes finer, the dissipation parameterization, which is supposed to take into account the effects of unresolved scales, also needs to be modified. It appears that the very basic issues of the appropriate scaling of parameterized subgrid-scale diffusion with model resolution and the role of numerical damping in determining the simulated mesoscale flow are still not completely understood, in either atmospheric or oceanic simulations.

Given the relatively brief integrations needed in short-term weather prediction, very fine resolution operational forecast models have been, and continue to be, developed at major operational weather centers. Interestingly, at least some of these weather forecast models produce simulations with unrealistically suppressed energy levels for the smallest resolved scales of

motion. This energy suppression at small scales was apparent in the results presented at the workshop from experimental forecasts at T2047 spectral resolution (roughly equivalent to a 5-km horizontal grid spacing) conducted at the European Centre for Medium-Range Weather Forecasts (ECMWF).

It may be that there are other considerations (e.g., having realistic topography in the assimilation of surface pressure observations for the initial conditions) that allow such high-resolution models to produce better forecasts in practice. On the other hand, the results presented at this workshop from a number of atmospheric models suggest that simulations with realistic energy levels for the mesoscale motions are possible, and the results for at least some mesoscale features in such simulations look quite promising. Notably, results were presented to show that high-resolution global models can simulate spontaneously the generation and development of such circulation features as tropical cyclones, atmospheric surface fronts associated with extratropical cyclones, and the persistent Meiyu/Baiu frontal zone that plays an important role in the warm-season weather of eastern Asia.

A challenging question remaining for atmospheric simulation is the role of convective parameterization in models that have effective horizontal resolution significantly more than approximately one kilometer but significantly less than about 100 kilometers. Such models are not cloud-resolving in the usual sense and cannot be expected to explicitly resolve the narrow updraft regions in convective clouds. However, these models have such fine resolution that it may not make sense to employ standard convective parameterizations that are developed as representations of the statistical interactions of a large array of convective elements with the resolved-scale flow.

Thus far, coupled ocean-atmosphere global models have not been pushed to the extremes of fine spatial resolution as the ocean-only or atmosphere-only models discussed above. An open question is how the coupled simulation may change if the ocean models can be run with realistic explicitly resolved eddy motions. In the tropics, it is conceivable that an improved explicit resolution of the ocean

dynamics could help eliminate the very prevalent biases in tropical climate produced by the current generation of coupled models. Notably, the near-universal tendency for coupled models to produce simulations with SSTs that are too low along the equator (and an associated split in the Intertropical Convergence Zone) has often been ascribed to deficiencies in the model treatment of clouds, but it is possible that the misrepresentation of ocean dynamics in coarse-resolution models may play a role.

The meeting participants felt that throughout the community, modelers may not have fully utilized the available state-of-the-art high-resolution observations in order to evaluate their models. An example of a data source that has not been fully exploited is the recently developed scatterometer satellite observations that provide fine-resolution representations of the surface wind field. Observers and modelers need to interact closely and formulate research strategies in order to take into account the rapid developments in computational power available to modelers as well as emerging observational techniques.

The Workshop on High Resolution Atmospheric Simulations and Cooperative Output Data Analysis, which was held 21–22 September 2005 at the JAMSTEC Yokohama Institute for Earth Sciences, Yokohama, Japan, was convened by Tetsuya Sato, director-general of the Earth Simulator Center, and sponsored by the Japan Society for the Promotion of Science (JSPS) as part of the JSPS International Meeting Series. Abstracts of presentations are available at the workshop home page, <http://www.es.jamstec.go.jp/esc/research/AtmOcn/hires2005/index.html>. The participants generally agreed that it would be valuable to hold another meeting within a few years focused on high-resolution atmospheric and ocean simulation.

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