Research with Fine-Resolution Global Atmospheric Models

A Personal Perspective

by Kevin Hamilton

Historical Introduction

The dawn of the modern era of global climate modeling may be traced to the work of **Syukuro Manabe**, **Joseph Smagorinsky**, and their colleagues who in 1965 described the first integration of a multi-level comprehensive atmospheric general circulation model (AGCM) that included treatments of the radiation, the dynamics and the hydrological cycle (Manabe et al., 1965). This model had the equivalent of about T30 resolution[1] in the horizontal and had 9 vertical numerical levels representing the atmosphere from the ground to the model top near 30 km. It is somewhat remarkable that in the intervening decades—despite the enormous growth of computational power—for most climate research applications investigators have largely been satisfied with only about 2–3 times the horizontal and vertical resolution used in that original model. Researchers have typically devoted their ever-increasing computer power principally to making longer integrations and incorporating more sophisticated parameterizations into their AGCMs. As a recent example, almost all the models involved in the Intergovernmental Panel on Climate Change (IPCC) intercomparison described in their 2007 Fourth Assessment Report have horizontal resolution corresponding to ~T63 or less, and have less than 30 levels in the vertical.

Although mainstream efforts in climate modeling have been devoted to rather coarse resolution models, for the last two decades there has been modest, but growing, interest in understanding the behavior of very fine-resolution global models, even if they can only be run in "experimental mode" for short periods.

A pioneering effort to apply substantial supercomputer resources to integration of fine-resolution AGCMs was led by **Jerry Mahlman** in the 1980s at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL). By 1985 Mahlman had run simulations with a 1° horizontal resolution version of the GFDL "SKYHI" grid-point AGCM (equivalent of ~T120 horizontal resolution) and 40 levels in the vertical. I was privileged to be involved with this effort at GFDL over the following decade as simulations were performed using SKYHI model versions with 1/3° horizontal resolution (~T360) and with versions having up to 160 vertical levels (Hamilton and Hemler, 1997; Hamilton et. al., 1999).

Assisted by substantial investments in major supercomputer facilities, more research groups have recently become interested in running global AGCMs at very fine resolution. An important advance was reported by our Japan Agency for Marine-Earth Science and Technology (JAMSTEC) colleagues led by **Wataru Ohfuchi** (Ohfuchi et al., 2004), who described brief (~2 weeks) simulations performed with an AGCM with T1279 truncation (corresponding roughly to 10 km grid spacing) and 96 levels in the vertical. These integrations with the Atmospheric GCM for the Earth Simulator (AFES) were made possible by the advent of the JAMSTEC Earth Simulator (ES) and the efforts of ES Center staff to adapt the global model to run efficiently on the ES. The

[1] The equivalence between grid point and spectral resolution is a somewhat complicated issue. Here we adopt the simple convention that the equivalent grid point res¬olution of a spectral model is the circumference of the earth divided by 3 times the truncation wavenumber).

T1279 AFES integrations won the 2002 Gordon Bell Award for the world's peak computational performance. Since then comparably fine resolution AGCM integrations have been performed by US groups as well. Notably the NASA finite-volume AGCM has been integrated with resolutions as fine as 1/8°, and a global version of the GFDL ZAETAC nonhydrostatic grid-point model with ~10-km horizontal resolution has been integrated for a brief period.

The 1/3° SKHYI model, the T1279 AFES model, and other recent experimental models have opened a window into the explicit simulation of the "meso-beta" scale (phenomena with horizontal scales from 20 to 200 km and time scales from 30 minutes to 6 hours) in global models. The next threshold for global models is to explicitly and credibly represent processes within individual clouds. The recent development of the Nonhydrostatic ICosahedral Atmospheric Model (NICAM) by JAMSTEC and University of Tokyo scientists led by **Masaki Satoh** approaches this threshold for the first time (e.g., Tomita et al. 2005; Satoh et al., 2008).

The development of the NICAM model was noteworthy in that somewhat novel approaches were adopted to deal with two issues that become important at fine resolution. The NICAM group invented their own numerical schemes to integrate the fully nonhydrostatic governing equations. They also adopted the icosahedral grid to provide a near-uniform distribution of model grid points over the globe. The finest grid used so far is termed "L11", involving 11 successive bisections of the triangular faces of an icosahedron, which produces a grid-spacing of approximately 3.5 km (~T3800).

The asterisks on Figure 1 plot the horizontal resolution of some of the experimental high-resolution climate models as a function of the date the results first became available. Shown for comparison are the evolution of the horizontal resolutions used in the operational short-term forecast runs at two leading operational centers, the US National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF). As horizontal resolution has improved by roughly a factor of 10 in these operational runs over the last two decades, the vertical resolution (not shown) has improved by roughly a factor of 5.

Mesoscale-Resolving Global Models

What have we learned from the mesoscale-resolving global atmospheric simulations? A common result in many studies is that even the largest scales of the mean circulation

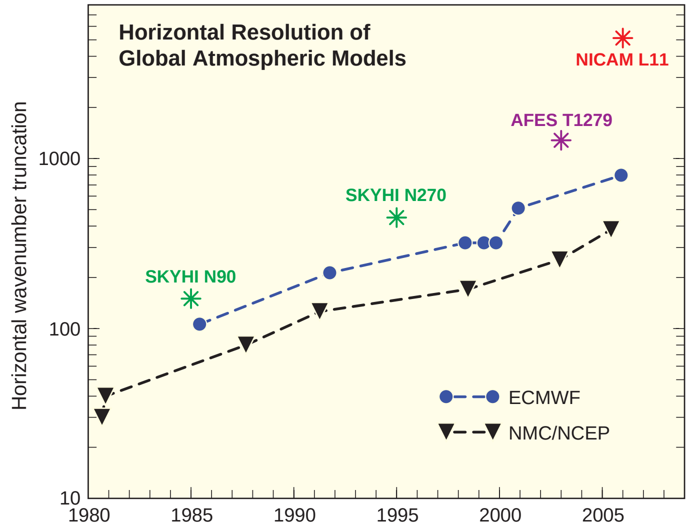

Figure 1. Horizontal resolution of some global atmospheric models plotted against the approximate date that results first became available.

change quite significantly as spectral resolution is increased from ~T21 to ~T42, notably with increased poleward eddy fluxes of eastward momentum, along with increased mid-latitude surface westerlies and corresponding meridional surface pressure gradients. As horizontal resolution is increased still further, these changes in the zonal-mean circulation continue, but become more modest in the troposphere. This behavior has helped convince many investigators that ~T42 resolution may be adequate for studying many aspects of climate. Indeed, as the quote from Byron Boville reproduced here attests, there was for a long time an informal view among many researchers that something like T42 resolution might actually be optimal for producing realistic climate simulations and that results become less realistic when resolution improves further!

In simulating the stratosphere (and higher levels), I have found the situation is quite different and that even the zonal-mean wind and temperature simulations continue to improve substantially as grid and level spacings are reduced to quite fine values (Hamilton et al., 1999). In the tropical stratosphere the dependence of model performance on vertical and horizontal resolution may be dramatic. Coarse resolution models generally produce simulations characterized by weak and very steady prevailing easterly winds in the tropical stratosphere. In the real world, the actual zonal-mean winds in the tropical stratosphere undergo a pronounced quasi-biennial oscillation (QBO) between strong easterlies and strong westerlies. In the last decade, we have learned that models can produce mean-flow oscillations similar to the QBO when

"A well-posed numerical problem should employ sufficiently high resolution… that further increases make no difference in the solution… [but] there have been reports of ***deteriorating*** *solutions with increasing resolution in the folklore of climate modeling…"*

• Byron Boville, Journal of Climate, 1991

run with appropriate convection parameterization and sufficient vertical and horizontal resolution (Takahashi, 1996; Hamilton et al., 1999).

Even if the tropospheric zonal-mean circulation does not change greatly beyond T42, there is still much to be gained by going to, say, T300 or finer resolution. Such models have at least the potential to explicitly simulate mesoscale circulations that are responsible for many of the important weather phenomena we experience. The question of how well such models simulate the statistical properties of the mesoscale variability is one that has occupied me for over a decade and will be addressed below. In terms of subjective appearances, however, my experience is that the simulated "weather" in high-resolution models resembles much more closely that seen in real-world weather maps and satellite imagery. This is particularly apparent in animations of model results. A nice example of a model-generated animation is provided for the T1279 AFES model by our JAMSTEC colleagues at **www.jamstec.go.jp/esc/gallery/movies/afes.flv.** At IPRC we have animated results from an AFES simulation for the "Science-on-a-Sphere" (SOS) projection system; Figure 2 is a photo of this animation running on the SOS system at the Bishop Museum in Honolulu.

High-resolution global models are also useful in helping us to grasp and quantify the connections between large- and small-scale aspects of the circulation. There are many examples of concentrations of observations from aircraft or from special observing networks that allow a local "view" into the mesoscale. Such local measurements can be used to help validate models and, on the other hand, the model results can provide a global context for local-scale phenomena.

Figure 2. Instantaneous rainfall rate in a control run of the T639 AFES displayed on the SOS.

Some Examples of Simulated Mesoscale Circulation Features

Tropical Cyclones

One interesting aspect of climate models is how well they simulate tropical cyclones. Remarkably, some coarse-resolution (~T42) global models can spontaneously generate tropical depressions and cyclones and can even simulate a somewhat realistic climatology of tropical-cyclone occurrence and movement. Of course, mature intense tropical cyclones (hurricanes and typhoons) in the real world are rather small (peak winds typically ~50 km from the center) and can be adequately resolved only by a very fine-scale model. Coarse-resolution models simulate tropical cyclones that are both unrealistically large and unrealistically weak. For example, in multiyear control simulations using T42 global models (Broccoli and Manabe, 1990), the deepest central surface pressure in the simulated tropical cyclones is about 980 hPa. In a control simulation using a global model with T106 resolution reported by Bengtsson et al. (1995), the most intense tropical cyclone appearing had a minimum central pressure of 953 hPa and peak surface winds of ~45 m/s. Sugi et al. (2002) obtained similar results with another T106 model.

Hamilton and Hemler (1997) reported that in a single boreal summer of a control integration with the ~T360 SKYHI model, a realistic number of west Pacific tropical cyclones occurred, with the strongest typhoon having a minimum pressure of 908 hPa and peak winds in the lowest model level of ~70 m/s. These values are comparable to those for the strongest typhoon that might typically be observed in any one summer, but are still weaker than the strongest typhoon ever observed (~870 hPa minimum pressure). The development of the typhoon simulated in the T360 SKYHI is displayed in Figure 3, which shows the location and value of the central pressure each 12 hours, along with the sea-level pressure contours at the time of maximum intensity.

The peak near-surface winds are about 2 grid points (~70 km) from the center, which means that the T360 model can produce simulated mature tropical cyclones with at least roughly realistic size and intensity. Ohfuchi et al. (2004) discussed the evolution of four west Pacific typhoons that developed in a 16-day T1279 AFES simulation. The lowest central pressure simulated in these storms was 921 hPa.

Baiu Front

Another interesting feature in the real atmospheric circulation that has challenged numerical models is the Baiu frontal zone over East Asia, Japan and the far Western Pacific region in late spring and early summer. Having spent the May–June period in central Japan, I can attest that the disturbances of the Baiu front greatly impact the day-to-day weather there! The Baiu front is particularly difficult to model as the frontal zone itself is composed of, and affected by, the interaction among weather phenomena of various scales. As described by Ninomiya and Akiyama (1992), cyclonic disturbances with synoptic and meso scales migrate along the frontal zone. Individual mesoscale cyclones include convective bundles as internal structures that can give rise to locally heavy rainfall. The mesoscale cyclones are often aligned along the stationary Baiu front in the train of a synoptic cyclone.

Attempts to simulate the Baiu frontal zone with moderate resolution AGCMs have been generally disappointing. A breakthrough in this area was achieved by Ohfuchi and his colleagues at the ESC with their T1279 version of AFES. Figure 4 shows a snapshot of low-level wind and rainfall rate over East Asia taken on a day in June from the T1279 AFES simulation. Within the large-scale monsoon flow is a very well defined, strongly convergent, narrow Baiu frontal zone crossing Japan and extending into the ocean off Japan's east coast. At this time, the eastern end of the Baiu front is connected to an eastward-moving synoptic scale cyclone. In the train of the synoptic cyclone, three mesoscale cyclones are embedded in the front, each associated with a rainfall maximum. Capturing such a rich assemblage of weather phenomena in a realistic fashion is a major achievement.

Stratosphere-Troposphere Exchange

It has been known for several decades that the atmospheric flow in midlatitudes can include relatively small-scale intrusions of stratospheric air into the troposphere. The stratospheric air can be identified by its chemical signatures, notably low water vapor and high ozone concentrations relative to typical tropospheric conditions. Such stratospheric intrusions can on occasion even affect air quality at the ground and need to be taken into consideration as part of the natural ozone background when setting pollution regulations. The properties and dynamics of individual stratospheric

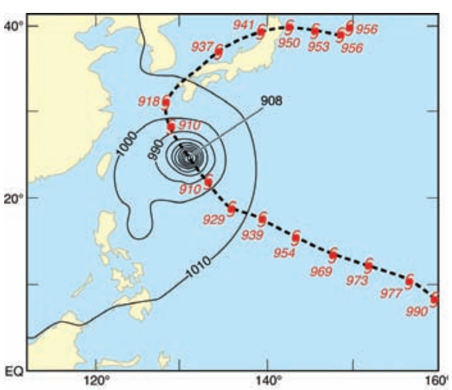

Figure 3. The path of a tropical cyclone simulated in the 1/3^0 SKYHI. Red numbers indicate the minimum sea-level pressure (SLP) in hPa at 12 hour intervals. The contours show the SLP at the time of maximum intensity.

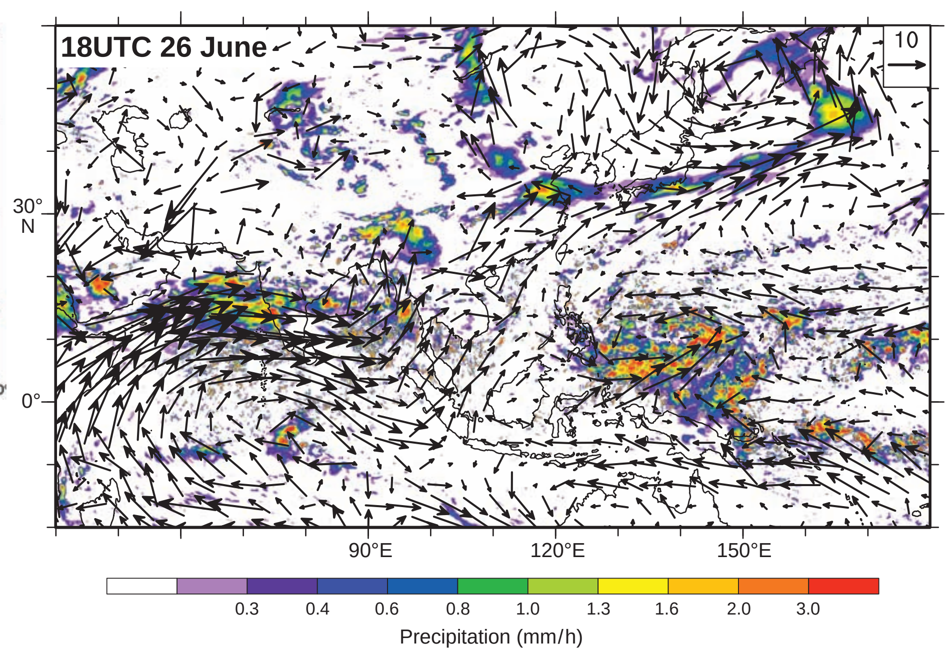

Figure 4. Snapshot of rainfall rate and 925 hPa winds from a control run of the T1279 AFES. From Ohfuchi et al. (2004).

"Finite arithmetical differences have proved remarkably successful in dealing with differential equations… for instance approximate solutions of the equation for the diffusion of heat can be obtained quite simply… In this book it is shown that similar methods can be extended to the very complicated system of differential equations, which expresses the changes in the weather."

• Lewis F. Richardson, Weather Prediction by Numerical Process, 1922

"In many branches of applied mathematics researchers will routinely show that their finite numerical solutions to a particular problem have converged with increasing numerical resolution. In the study of atmospheric and oceanic circulation one rarely has the luxury of such straightforward demonstrations of convergence. The standard practice for attacking difficult problems has been to truncate the model employed at some finite horizontal, vertical and time resolution… it is understood that the model integrations will have deficiencies simply associated with the fact that significant aspects of the real circulation will be unresolved in the finite numerical approximation employed."

• Kevin Hamilton and Wataru Ohfuchi, High Resolution Numerical Modeling of the Atmosphere and Ocean, 2008

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intrusions have been investigated in many limited-area field studies.

With the advent of high resolution AGCMs, the individual regional studies can be put into a global perspective. Figure 5 is from a paper by Mahlman and presents results from the T360 SKYHI model. Specifically shown is a snapshot of the nitrous oxide concentration on a quasi-horizontal surface that resides in the stratosphere at high latitudes and in the troposphere at low latitudes. The blue colors show low nitrous oxide concentrations typical of air that has resided for some time in the stratosphere while the red shading shows higher values typical of the troposphere. The intrusions in midlatitudes are beautifully rendered by the shading of the nitrous oxide field, ranging from what appear to be reversible deformations of the stratospheric vortex to very highly elongated and rolled-up filaments that represent an irreversible mixing of stratospheric air into the troposphere. Such a global snapshot of air properties down to small scales is not possible from observations, but the high resolution AGCM provides the global context for the many limited-area observational studies that have been conducted.

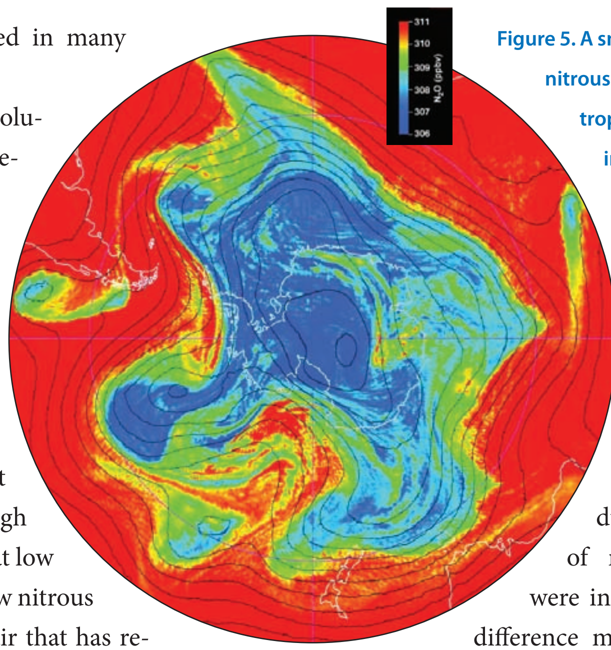

Figure 5. A snapshot of the simulated concentration of nitrous oxide in the 1/3° SKYHI model on an isentropic surface near the tropopause (shading). The contours show the Montgomery streamfunction. From Mahlman (1997).

Convergence of Statistical Properties of the Simulated Climatology

The quote from the pioneering work of **L.F. Richardson** reproduced here shows that the beginnings of numerical atmospheric modeling were inspired by the success of numerical difference methods in producing approximate solutions to much simpler differential equations. The application of numerical methods to the nonlinear governing equations of atmospheric flow has proved to be much more problematic. The quote from my recent article with Ohfuchi notes the unfortunate reality that atmospheric simulation models are truncated at somewhat arbitrary numerical resolution and no genuinely converged solutions are available. One motivation for my work in analyzing fine-resolution models has been the desire to see if the statistical properties of the simulated flow are in fact trending towards realistic states as model resolution is improved, and how model subgrid-scale parameterizations should scale with resolution to insure a reasonable degree of convergence.

One focus has been on characterizing the horizontal kinetic energy spectrum (HKES) of model simulated flows. The HKES partitions the kinetic energy per unit mass among the various horizontal scales, typically characterized by their wavenumber, k. A steep spectrum represents a flow dominated by large horizontal scales, while a shallow spectrum indicates energetic small-scale motions. The observed spectrum can be computed from global analyses for long wavelengths (say > 2000 km), while the spectrum for shorter wavelengths can be deduced from aircraft observations. The reliance on aircraft observations has led to a focus on the upper tropospheric HKES, and the observations indicate that the HKES has a roughly k^{-3} dependence for synoptic scales (i.e., wavelengths of roughly 500–5000 km) and a shallower, roughly $k^{-5/3}$ dependence for the mesoscale (i.e., wavelengths of less than about 500 km).

Figure 6 shows the spectra computed from simulations with the AFES global atmospheric model as described in Hamilton et al. (2008). The results are obtained for versions run with different horizontal truncation. We were able to show that, with an appropriate scaling of the subgrid-scale mixing parameters in the model, a reasonably convergent HKES could be obtained. The simulated HKES in the model is also quite realistic. At large scales this can be seen by comparing with the observational values obtained from global gridded analyses shown in Figure 6. In the mesoscale the model results have been shown to be quite close to those obtained from aircraft observations (not shown; see Hamilton et al., 2008). Our study of the HKES has been continued more recently with analysis of very high resolution NICAM simulations, with very encouraging results.

The Future

The quotes reproduced here from the famous 1960 Tokyo Symposium on Numerical Weather Prediction and from another important meeting held in Japan 46 years later, show how far we have come in our ability to model the detailed behavior of the atmosphere. Simulating just the synoptic-scale features of the atmospheric flow for even a short-term forecast was still a dream in 1960. Now almost a half-century later we are at the threshold of global models that can explicitly simulate processes down to those in individual clouds.

The rapid growth of available computational power is virtually certain to continue. Fueled by the earlier computational improvements, we have seen a 30-fold enhancement in horizontal resolution over the 2 decades separating the debuts of the 1° SKYHI model and the 3.5-km resolution NICAM model. A simple extrapolation suggests that by about 2030 we could be running global models with ~100-m resolution in both the horizontal and vertical directions! Increasing computational power will also allow high-resolution models

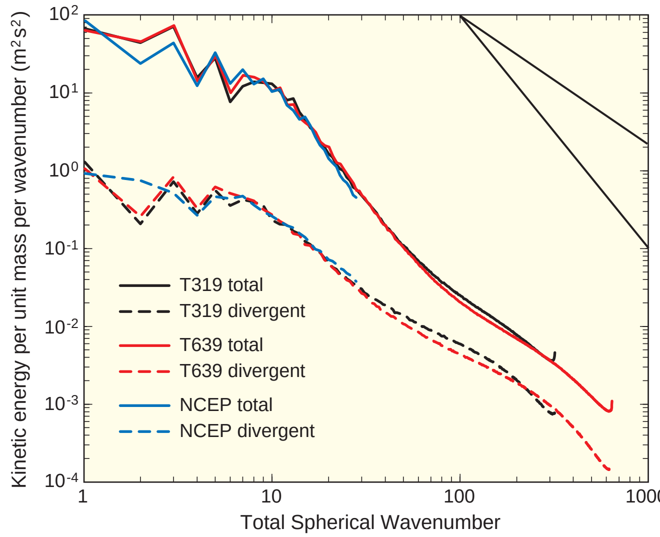

Figure 6. Simulated horizontal kinetic energy spectra at 200 hPa in control runs of the T319 and T639 AFES, compared with observed results derived from NCEP global reanalyses. The dashed curves show results when only the divergent component of the wind field is considered.

to be integrated for longer periods. Already a very impressive project has been conducted by scientists at the Japanese Meteorological Research Institute (using the Earth Simulator) who have run a quite fine-resolution model for multidecadal periods in a climate change study (Mizuta et al., 2005). We can certainly expect that models used to project the response of global climate to the anticipated anthropogenic forcing will be run at ever finer resolution. Understanding the successes and limitations of mesoscale-resolving atmospheric models is thus becoming a central issue for credible climate-change projections.

Recent IPRC Developments and This Special Issue

Since the advent of the Earth Simulator, IPRC scientists have partnered enthusiastically with our JAMSTEC colleagues in analyzing high-resolution global AGCMs. Aspects of high-resolution AFES results have been discussed in earlier issues of *IPRC Climate* ["Studies with Japan's Earth Simulator", vol. 4 (2); "Model Globally, Measure Locally!" in vol. 8 (1)]. Recent

"In computing ... the development of cyclones with baroclinic models we have used grids with a mesh size of 300 to 400 km. We can therefore hardly hope to forecast phenomena with a scale of less than about 1000 km. ...If we look at the distribution of precipitation, e.g. caused by a warm front... we may find a difference of a factor of three in stations some 10-20 km from each other. I think we can hardly hope to be able to forecast those details."

• Bert Bolin — panel discussion at the International Symposium on Numerical Weather Prediction held in Tokyo in 1960.

"NICAM marks a new chapter in the history of attempts to model and understand the atmospheric general circulation. It is currently able to resolve deep-cloud cores and meso-circulation systems with a few km horizontal mesh interval over the globe...with continuing advances in computing power such simulations will be extended to climate timescales, richer ensembles and finer grid meshes....cloud resolving models of climate and weather begin to represent scales commensurate with those being observed by state-of-the-art satellite and ground-based remote sensing."

• Masaki Satoh and Bjorn Stevens, proceedings of the First International Workshop on High-Resolution and Cloud Modeling, 2006, Kusatsu, Japan.

collaborative IPRC–JAMSTEC work on the NICAM simulation of tropical cyclones has attracted favorable attention in the scientific community and in the broader media (page 26, this issue). In December 2008, the IPRC and JAMSTEC co-organized and hosted the *Third International Workshop on High-Resolution and Cloud Modeling* (page 17, this issue). The IPRC also organized and hosted a *Minisymposium on High-Resolution Atmospheric Modeling* featuring IPRC, University Hawai'i and JAMSTEC scientists discussing analysis of NICAM results (page 18, this issue). With all these exciting recent developments here, it seemed an opportune time to devote an issue of the *IPRC Climate* to high resolution global atmospheric modeling. The next two articles will present highlights from IPRC–JAMSTEC collaborations involving analysis of NICAM simulations. One article examines the dynamics of the tropical intraseasonal variability in NICAM, the other describes the simulation of tropical cyclones by NICAM.

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