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Newsletter of the International Pacific Research Center

The center for the study of climate in Asia and the Pacific at the University of Hawai'i at Mānoa

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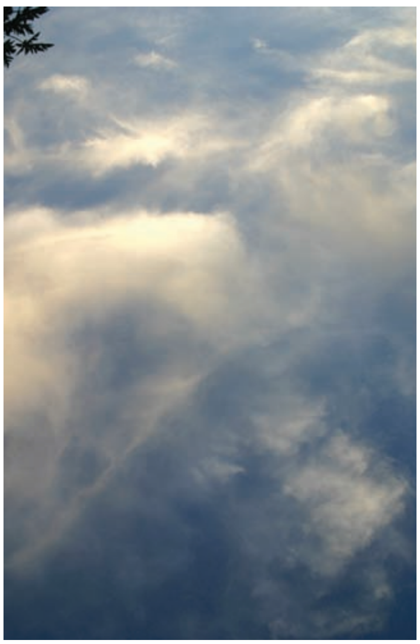

This special *IPRC Climate* issue features IPRC research on fine-resolution global atmospheric general circulation models. (Photo courtesy of Gisela Speidel)

Research

Meetings

University of Hawai'i at Mānoa
School of Ocean and Earth Science and Technology

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.

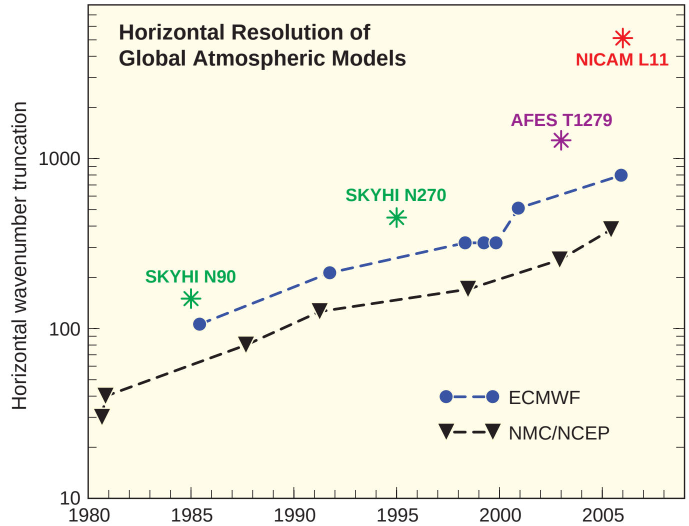

Figure 1. Horizontal resolution of some global atmospheric models plotted against the approximate date that results first became available.

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 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.

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.

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

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

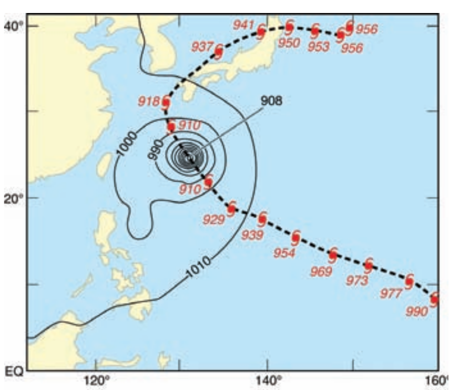

Figure 3. The path of a tropical cyclone simulated in the 1/3^0 SKYHI. Red numbers indicate the minimum sea-level pressure (SLP) in hPa at 12 hour intervals. The contours show the SLP at the time of maximum intensity.

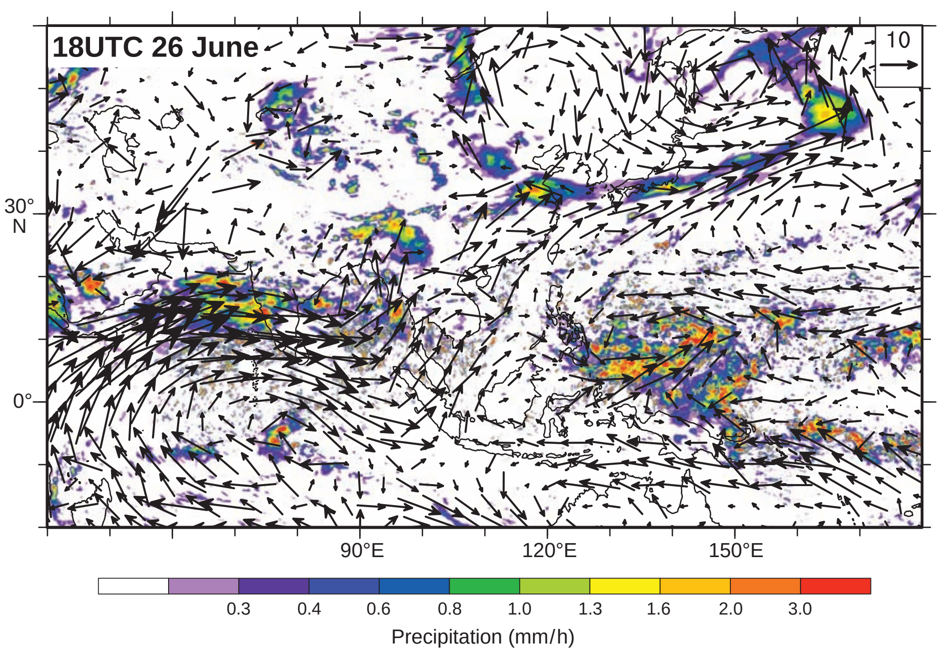

Figure 4. Snapshot of rainfall rate and 925 hPa winds from a control run of the T1279 AFES. From Ohfuchi et al. (2004).

"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.

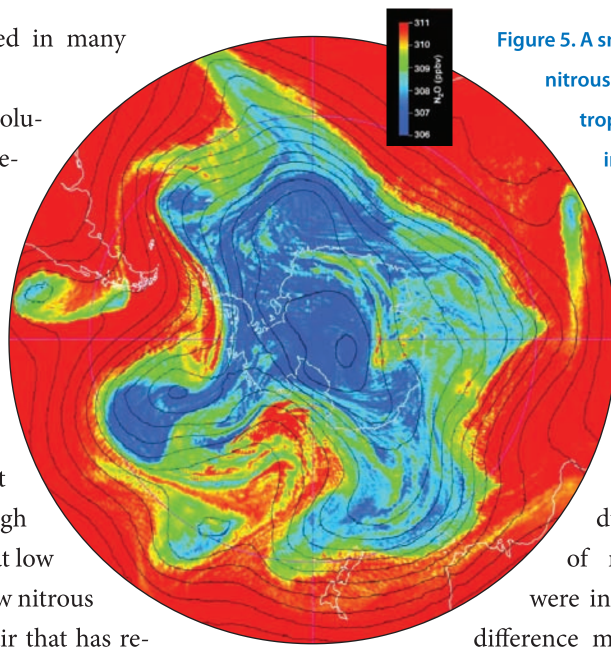

Figure 5. A snapshot of the simulated concentration of nitrous oxide in the 1/3° SKYHI model on an isentropic surface near the tropopause (shading). The contours show the Montgomery streamfunction. From Mahlman (1997).

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

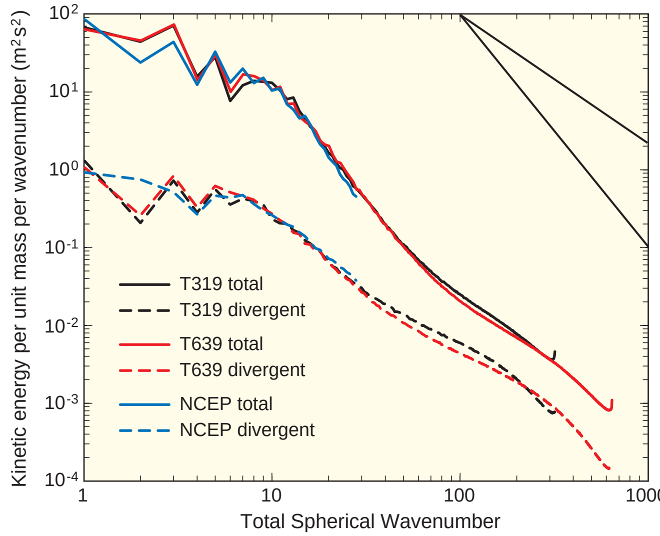

Figure 6. Simulated horizontal kinetic energy spectra at 200 hPa in control runs of the T319 and T639 AFES, compared with observed results derived from NCEP global reanalyses. The dashed curves show results when only the divergent component of the wind field is considered.

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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NICAM Captures the Leading Weather Disturbance of the Tropics

The Madden-Julian Oscillation (MJO) is the most prevalent intraseasonal weather disturbance in the tropics. Most active during December through March, it is characterized by large regions of successive dry and wet spells that move eastward along the equator. The disturbance consists of an envelope of anomalous convection, rainfall, and east-west winds lasting approximately 30 to 60 days. First evident over the western Indian Ocean, and then above the Maritime Continent, the MJO is often still discernable as it moves over the warm western and central tropical Pacific. The signal fades over the cooler eastern Pacific, but may grow again over the tropical Atlantic. Prediction of MJO occurrences could extend weather forecasts by 2 to 3 weeks, but accurate computer simulation of the MJO has eluded forecasters and climate scientists. Now the first global cloud-system resolving model, NICAM, has captured the major features of an actual MJO event and foreshadows greatly improved prediction of these tropical wet and dry spells, and of weather in general.

The NICAM hindcast run was initialized with the actual atmospheric conditions on December 15, 2006, a few days after a wet MJO phase had begun over the western Indian Ocean. The cloud clusters in NICAM evolved over the next 30 days in a way similar to those observed in satellite images, indicating that this the model successfully captured the MJO atmospheric footprint (Figure 1 satellite image and NICAM output of the MJO). These findings were published by **Hiroaki Miura** and his colleagues at JAMSTEC in 2007 in *Science*. A follow-up analysis of the 7-km NICAM resolution simulation has now been performed by IPRC's **Ping Liu** and colleagues at the IPRC, Frontier Research Center for Global Change, and Nagoya University. Their analysis shows how closely the simulated MJO components match those observed, and how small-scale convection interacts with large-scale circulation to sustain the disturbance and to propel it on its eastward path.

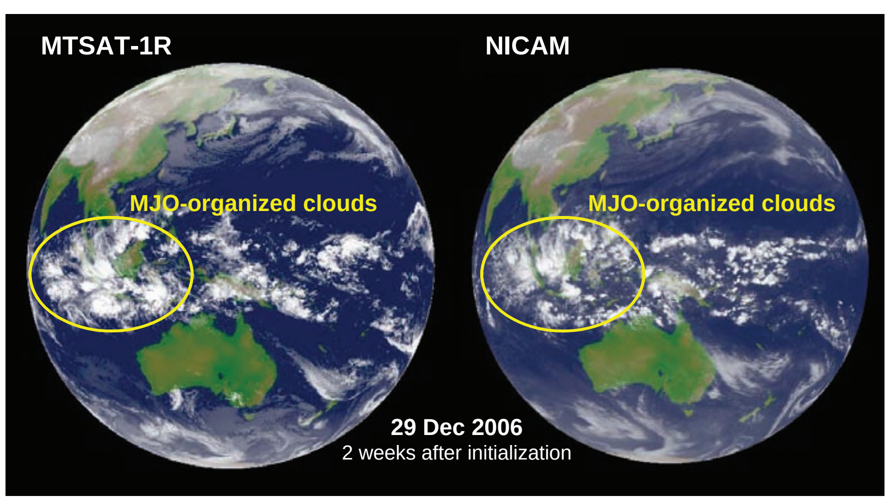

Figure 1. Comparison of the MJO in satellite images and in NICAM on December 29, 2006, 2 weeks after initialization. (courtesy of JAMSTEC)

Liu and his collaborators compared the simulated with the observed MJO using two types of measures: the MJO real-time multivariate (RMM) index as formulated by Wheeler and Hendon in 2004 (composed of the first pair of principal components derived from combined EOF analysis using outgoing long-wave radiation and zonal winds at 200 hPa and 850 hPa levels); and the averaged MJO deviations (i.e., composites of the simple anomalies) from the observed long-term mean in rainfall, winds, and specific humidity for six phases of the MJO.

The evolution of the amplitude of the MJO event is shown in Figure 2. In observations, enhanced covection is detected around December 10; in the model it is noticeable on December 15, the day the simulation began. The simulated amplitude, with its peak on December 28, follows the observed event quite closely for over 3 weeks. The geographical locations for the six successive MJO phases are displayed in the RMM diagram in Figure 3. The blue line shows the observed eastward path of the MJO from December 15 across the Indian Ocean through January 13 into the western Pacific. Gaining in strength, the disturbance moves into the eastern Indian Ocean after the first week. Travelling fairly quickly over the eastern Indian Ocean and on to the Maritime Continent, the signal continues on its journey eastward, weakening significantly, and by the time it reaches the Western Pacific, it is barely discernable. The model MJO follows the observed MJO in path and strength, except that it is stronger in late Phase 3 and early Phase 4, and it still has some strength by the end of the simulation.

A key issue is how the small-scale convection and the large-scale atmospheric circulation interact to create the MJO envelope. The "friction-induced moisture convergence" mechanism, first proposed by IPRC's **Bin Wang** in 1988 in the Journal of the Atmospheric Sciences, hypothesizes that

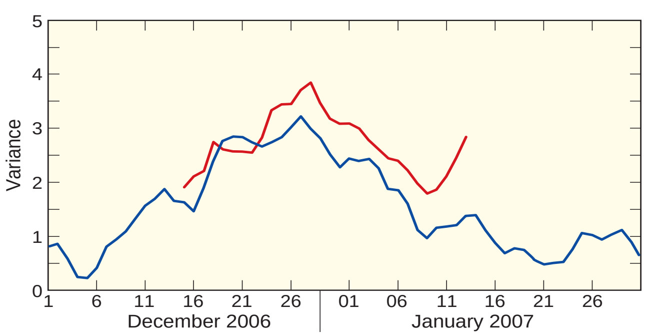

Figure 2. Evolution of the amplitude of the MJO event based on the RMM index: observations (blue) and NICAM simulation (red).

the enhanced convection produces eastward moving Kelvin waves. The sinking and returning flow of the wave warms the region east of the major convection. A low pressure (K-low) area forms in the surface layer where moist air converges mainly due to meridional wind anomalies. The accumulated moist air rises and condenses before reaching 500 hPa, releasing energy that supports the growth of the K-low and draws the major disturbance eastward (see also *IPRC Climate*, vol. 4, no.1).

Both the observations and the NICAM simulation support this mechanism of interaction between the small-scale convection and the large-scale circulation (Figures 4 and 5). Figure 4 shows the developing stage of the MJO when the wet

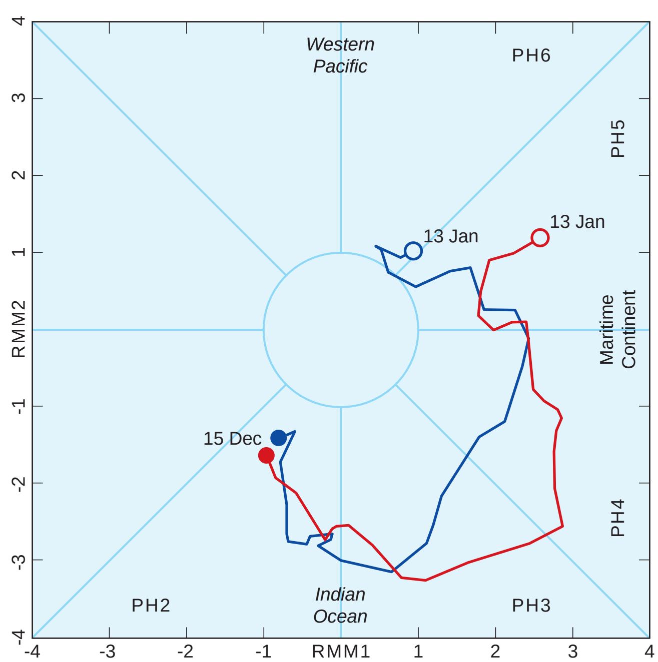

Figure 3: RMM diagram for the MJO event in observations (blue) and the NICAM (red).

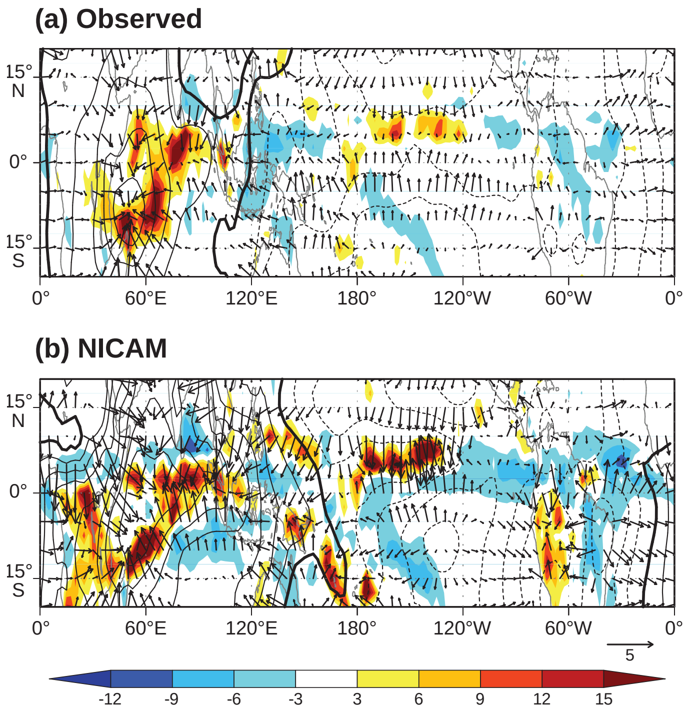

Figure 4. Composited anomalies for Phase 2 of the MJO event in (a) observations and (b) NICAM: velocity potential (contours interval is 1×10^6 m^2/s with thick black as zero) and vectors for divergent wind at 925 hPa. Shading represents precipitation rate (mm/day) from (a) Tropical Rainfall Measuring Mission (TRMM) satellite and (b) NICAM.

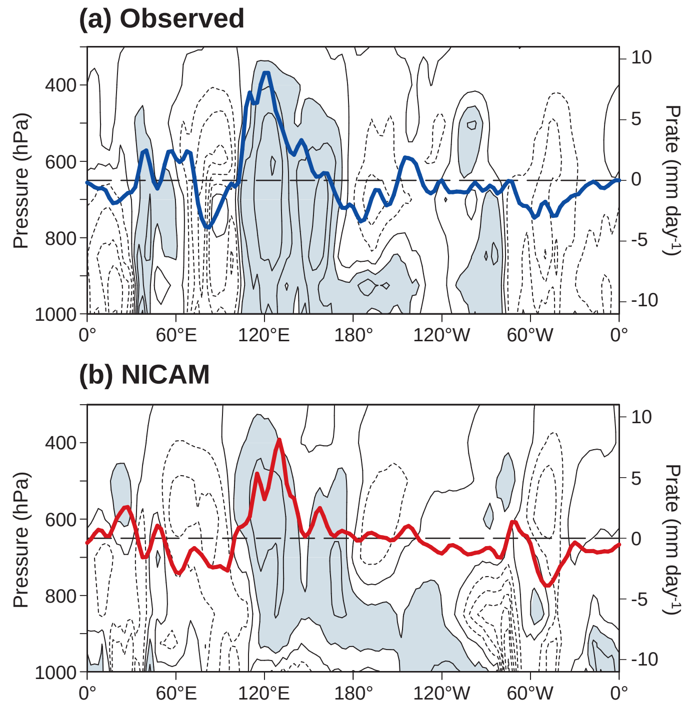

Figure 5. Specific humidity anomalies (contour interval is 0.5 g/kg; shaded areas are equal to or greater than zero). Thick blue and red lines represent precipitation rate anomalies (mm/day) in (a) TRMM and (b) NICAM, respectively. Values are averaged between 15°S and 15°N.

(dark red to yellow) phase is in the western Indian Ocean and the dry phase (blue) is in the western Pacific. During the wet phase, boundary-layer convergence—represented by positive velocity potential in the solid contours—dominates and accumulates moisture. This moisture accumulation precedes the increased rainfall in the Maritime Continent in both model and observation, showing that the accumulated moisture draws the MJO eastward.

Figure 5 reflects conditions in Phase 4 when the rainy phase has moved into the Maritime Continent as shown by the rainfall peak in the thick blue (observed) and red (NICAM) curves. Corresponding to the moisture accumulation at lower levels, specific humidity increases with height towards the west, as illustrated by the shaded areas with humidity of 0.5 g/kg or greater.

The analysis shows that for the first time a computer simulation has captured realistically the progression of the whole MJO envelope from west to east for a period of nearly 30 days after the model was let run freely. This month-long, fairly accurate "prediction" of atmospheric variability augurs well for weather forecasting. The reason for the success, Liu and his co-authors believe, is that the interaction between small-scale convection and large-scale atmospheric circulation is represented explicitly in NICAM rather than by convective parameterizations as in earlier computer models.

Though the NICAM simulation marks a milestone in simulating tropical rainfall variability, significant deficiencies remain. The simulated MJO grows faster over the Indian Ocean, and its peak strength over the Maritime Continent–West Pacific is nearly 30% stronger than observed. A large positive bias also occurs in the outgoing long-wave radiation, a bias that is probably induced by the over-simplified cloud microphysics package. IPRC scientists and their JAMSTEC colleagues will continue to work on improving simulation of the MJO to bring about more accurate weather and climate predictions.

The story is based on the following:

Liu, P., M. Satoh, B. Wang, H. Fudeyasu, T. Nasuno, T. Li, H. Miura, H. Taniguchi, H. Masunaga, X. Fu, and H. Annamalai: An MJO Simulated by the NICAM at 14-km and 7-km Resolutions. *Mon. Wea. Rev., in press.*

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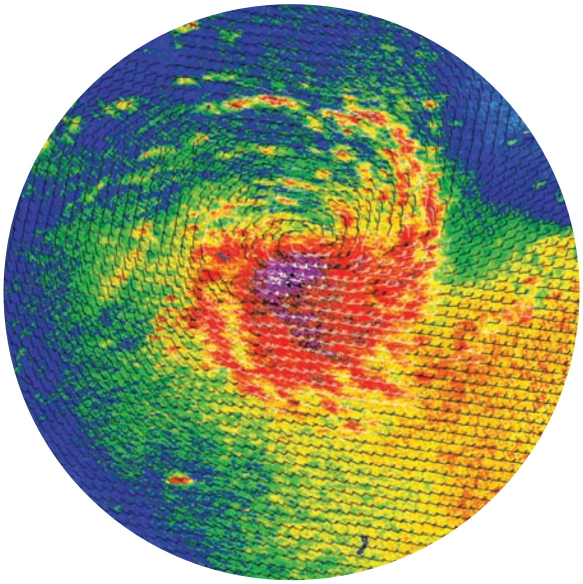
Birth, Growth, & Decay of Tropical Cyclones Simulated by NICAM



Why do some thunderstorm cloud-clusters grow into a powerful, destructive tropical cyclone? Recently NICAM, the first computer model that explicitly represents cloud systems over the whole globe has been developed. Created for the JAMSTEC Earth Simulator, this model has captured, for the first time, the whole lifespan—from before birth to decay—of two tropical cyclones, whose tracks, dates, and atmospheric conditions matched cyclones that actually occurred over the Indian Ocean. This is the conclusion of IPRC's **Hironori Fudeyasu** and **Yuqing Wang** and their Japanese colleagues **M. Satoh**, **T. Nasuno**, **H. Miura**, and **W. Yanase**, after careful analyses of some of the first NICAM output. Figure 1 shows how closely the observed tracks and dates of the storms match those that NICAM generated. This cutting-edge, global cloud-resolving model promises greatly improved weather forecasting and unprecedented opportunities for finding out more about how cyclones form and evolve.

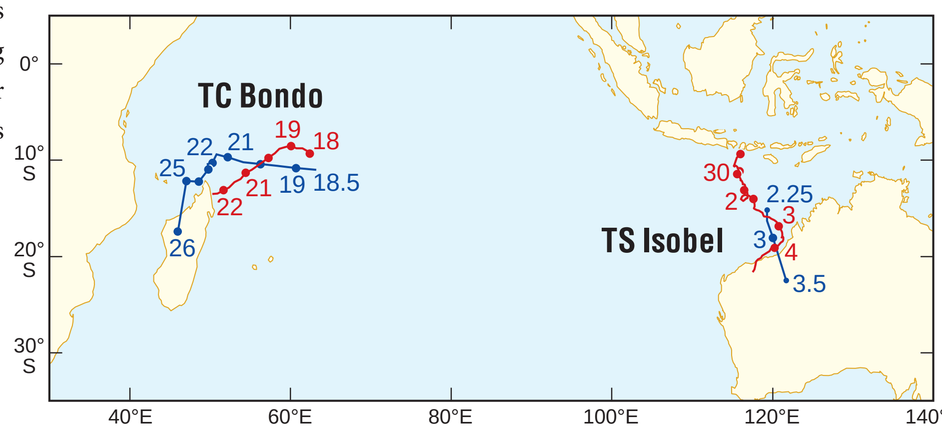


Figure 1. Storm tracks of Bondo and Isobel (blue: Joint Typhoon Warning Center best track data; red: NICAM simulation). Numbers refer to days from end of December 2006 to beginning of January 2007.

The results of the study are all the more exciting because this NICAM experiment was run not with simulation of tropical cyclones in mind, but the Madden–Julian Oscillation (MJO; see previous story). Because the MJO is most active from December through March, NICAM had been started up with observed atmospheric conditions on December 15, 2006 and was run freely through January16, 2007.

The simulation is already answering some fundamental questions about tropical cyclones. Atmospheric scientists, for example, have been debating whether large-scale atmospheric disturbances such as the MJO contribute in any significant way to tropical cyclone formation. The NICAM experiment answers the question clearly, at least for the Indian Ocean: The two storms formed within the MJO depression, first Bondo in the western Indian Ocean, and then not quite two weeks later, Isobel in the eastern Indian Ocean.

The scientists compared the simulated and observed Isobel in great detail. First detected in satellite images over the eastern Indian Ocean at 06 on the Universal Time Clock (UTC) on January 2, 2007, Isobel grew into a storm with a minimum sea-level pressure of 984 hPa and peak winds of 40 knots. It moved southward and made landfall nearly 24 hours later on the northwest coast of Australia, where it dissipated. In NICAM, a storm was detected in the sea-level pressure field over the northeastern Indian Ocean already on December 29. As the storm moved southward, it intensified, reached a minimum sea-level pressure of 965 hPa and peak winds of around 60 knots on January 2, and then dissipated on January 5. Figure 2 shows the match between the observed and the simulated sea-level pressure. Although the simulated storm formed a few days earlier, was stronger, and made landfall one day later on the northwest coast of Australia than the real Isobel did, it is still remarkable how well the model captured the storm after running freely for 2½ weeks.

Further comparisons showed that NICAM also reproduced the large-scale atmospheric conditions over the Maritime Continent in which Isobel was born, namely the movement of the MJO into the region on December 28–29 and the northerly cross-equatorial flow originating from the cold surge over the South China Sea. The cross-equatorial flow, the MJO, and the equatorial westerly wind burst provided the large-scale conditions favorable for the genesis of Isobel in both observations and the NICAM simulation (Figure 3).

Isobel did not develop a typical eyewall, but a large, broken one with little convection in its southeastern section (Figure 3c). The NICAM simulation reproduced this broken eyewall structure and the stronger convection in the western than the eastern section of the eyewall (Figure 3d). It is remarkable that this took place after the model had run freely from the initial atmospheric conditions for 18 days.

The NICAM experiment throws light on another major debate in tropical cyclone formation. The "bottom-up" theory holds that vortical hot towers, horizontally small, but intense, cumulonimbus convection cores with strong updraft and upward heat transport, merge to form a single vortex. The "top-down" theory proposes that the mesoscale vortices that form associated with stratiform precipitation in the mid-troposphere develop downward following the weak subsidence of the stratiform precipitation.

The NICAM results support the bottom-up theory. Following the sequence of events in Figure 4, one can see how the large-scale flows set the stage for the formation of the tropical cyclone vortex. The westerly wind bursts of the MJO meet the easterly

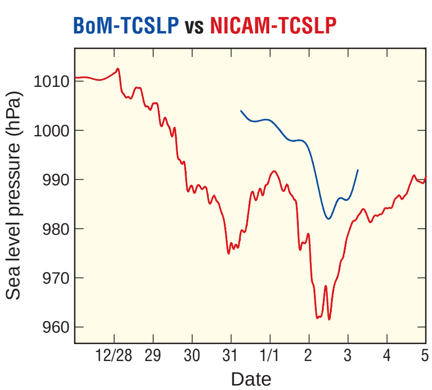


Figure 2. Central sea-level pressure of Isobel from the Australian Bureau of Meteorology best track data (blue) and from NICAM simulation (red) during December 2006 and January 2007.

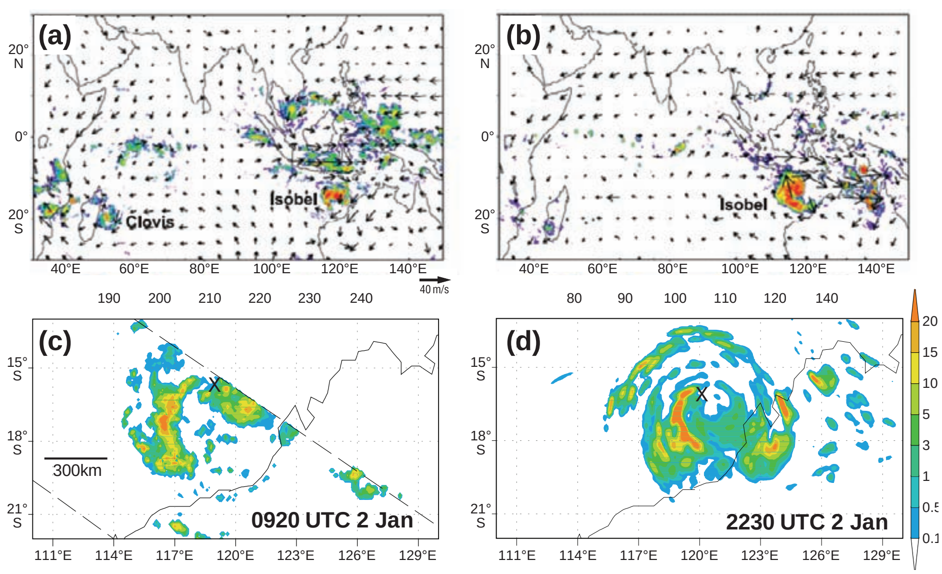
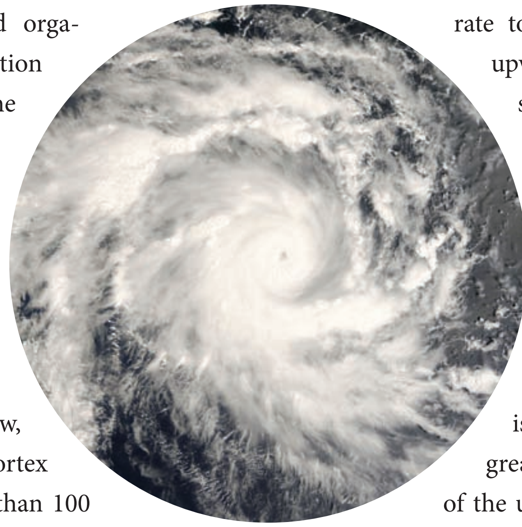


Figure 3. Observed and simulated Isobel on January 2, 2007: (a) Equivalent black body temperature (Tbb in K) from CPC-Infrared Radiation and 850-hPa winds from NCEP analysis and (b) outgoing longwave radiation flux (OLR, W/m²) and 850-hPa winds from NICAM simulation at 0000 UTC and surface rain rate (mm/ hour) derived from (c) TRMM-TMI at 0920 UTC and (d) NICAM simulation at 2230 UTC. In (c) and (d) the X indicates the position of the storm center.



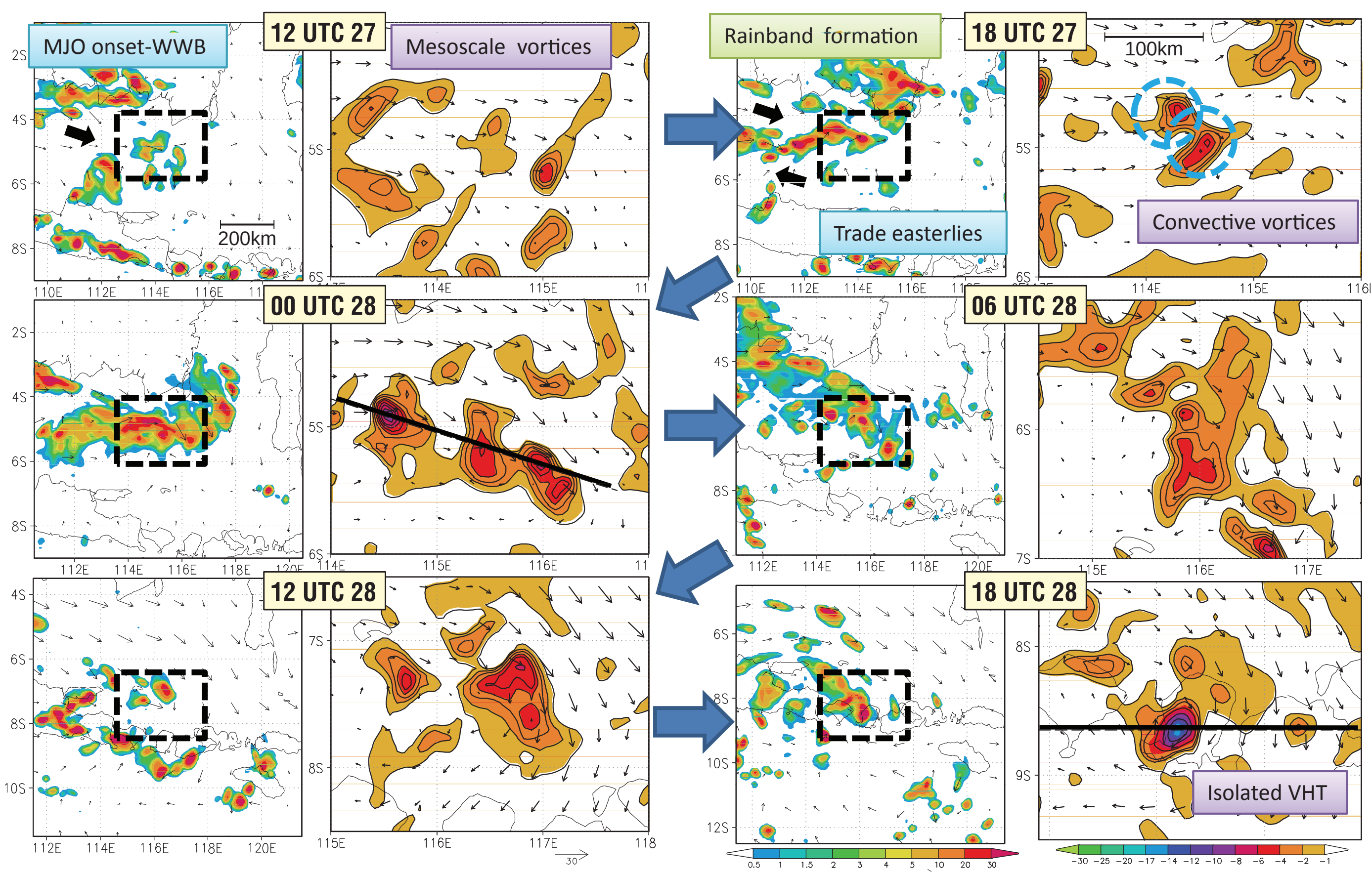
trades, creating cyclonic sheer and organized rainbands with deep convection that reaches into the upper levels of the troposphere (about 15 km high) and a group of cyclonic vortices, ranging from several tens to hundred km in diameter. These mesoscale vortices start to merge and form a single concentric vortex with monopole potential vorticity.

A closer look at Figure 5 shows how, within the rainband and mesoscale vortex region, smaller regions that are less than 100 km in diameter and have high cyclonic potential vorticity, merge to form the single concentric vortex.

The two sets of panels in Figure 5 illustrate the effect of the merging vortical hot towers. At 00 UTC three separate towers are distinguishable with strong upward motion (red-orange shades) that somewhat warm the upper troposphere up to 15 km high (green patches) and are paralleled by strong rainfall. The sea-level pressure, however, shows no storm signal yet. At 18 UTC, a single tower has formed with an intense vortex (blue and purple shades) approximately 100 km wide; there is strong upward motion (red shades), greatly increased convection and warming of the upper troposphere, precipitation, and a distinct signal in the sea-level pressure.

Having found support for the vortical hot tower, bottom-up theory, Fudeyasu and Wang are now planning to use Wang's mesoscale tropical cyclone model (TCM4; Wang 2007) to experimentally isolate the processes by which potential vorticity gets redistributed and merges, a study for which NICAM at present is too cumbersome. They also wish to explore the large-scale environmental conditions and the internal dynamics associated with the organization of the convective and mesoscale cloud features of both Isobel

Figure 4. Time series of the precipitation (left-side of panels) and evolution of cyclonic vortices (right-side of panels) during the genesis process. The cyclonic potential vorticity anomalies embedded in mesoscale convective vortices with horizontal scale around 40 km are the equivalent of the vortical hot towers.



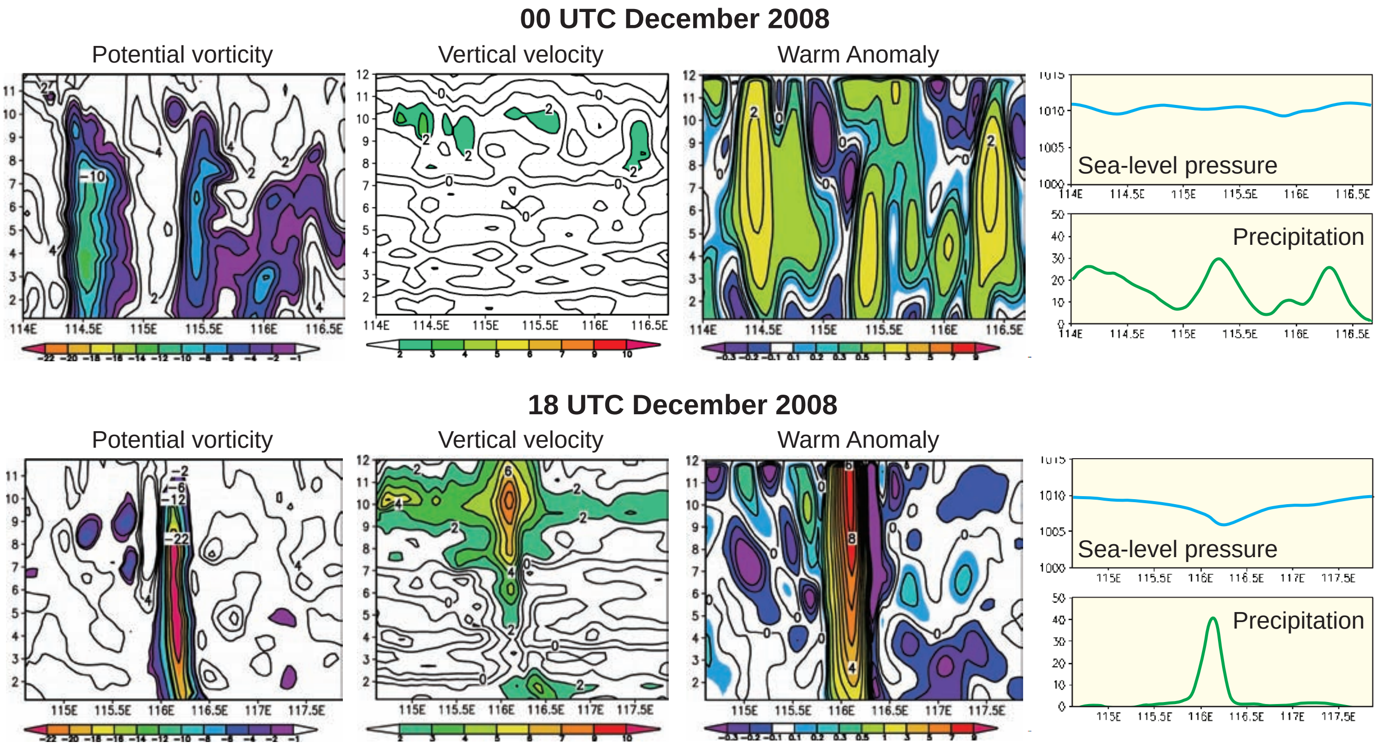


Figure 5. Vertical cross-sections of potential vorticity (PVU), vertical velocity (m/s), warm anomaly (K), sea-level pressure (hPa), precipitation rate (mm/h) at 00 UTC (upper panels) and 18 UTC (lower panels) December28. Location of the cross-sections is marked by dashed lines in Figure 4.

and Bondo, storms that differed greatly in observed size, strength, and lifespan.

In summary, this first major NICAM simulation has furnished a wealth of data on tropical cyclone formation. Moreover by being able to capture atmospheric events up to nearly 3 weeks after it was initialized, NICAM foreshadows accurate weather prediction up to 2 weeks. Fudeyasu and Wang attribute the model's success to the simultaneous realistic simulations of both the large-scale circulation, such as the MJO and the cross-equatorial flow, and the embedded mesoscale convective systems, such as vertical hot towers.

This story is based on the following:

Fudeyasu, H., Y. Wang, M. Satoh, T. Nasuno, H. Miura, and W. Yanase, 2008: Global cloud-system-resolving model NICAM successfully simulated the lifecycles of two real tropical cyclones, *Geophys. Res. Lett.*, **35**, L22808, doi:10.1029/2008GL036003.

Fudeyasu, H., Y. Wang, M. Satoh, T. Nasuno, H. Miura, and W. Yanase, 2009: Multiscale interactions in the lifecycle of a tropical cyclone simulated in a Global Cloud-System-Resolving Model Part I: Large scale aspects. *Mon. Wea. Rev., submitted.*

Fudeyasu, H., Y. Wang, M. Satoh, T. Nasuno, H. Miura, and W. Yanase, 2009: Multiscale interactions in the lifecycle of a tropical cyclone simulated in a Global Cloud-System-Resolving Model Part II: Mesoscale and storm-scale processes. *Mon. Wea. Rev., submitted.*

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(Images of TC Bondo on pages 13 and 15 are courtesy of NASA Earth Observatory)

High-Resolution and Cloud Modeling: Tropical Cyclones

Participants at the *Third International Workshop on High-Resolution and Cloud Modeling.* In the front row with leis are the Organizing Committee members, from left, Teruyuki Nakajima, Masaki Satoh, David Randall, Yuqing Wang, and Kevin Hamilton.

The *Third International Workshop on High-Resolution and Cloud Modeling: Tropical Cyclones and Climate* was held at the University of Hawai'i at Mānoa from December 2 to 4, 2008. The workshop assessed the current status of high-resolution atmospheric models, with a focus on the simulation of tropical cyclones and the connection of tropical cyclones to climate variability and change. Key issues considered were the scale interactions related to tropical cyclone genesis, intensification, structure and intensity changes; the large-scale control and large-scale impact of tropical cyclones; and the dynamical downscaling of the impact of global warming on tropical cyclones. Other topics related to high-resolution modeling and satellite observations of cloud/mesoscale systems and cloud-aerosol interactions were also presented. The full agenda for the meeting can be found at **iprc.soest.hawaii.edu/~kph/DEC_agenda.pdf.**

The meeting attracted 45 researchers from Asia, North America, Europe and Australia, as well as about 20 scientists from the IPRC and the University of Hawai'i Meteorology department.

There was wide IPRC participation. Two IPRC scientists gave invited talks: **Yuqing Wang** presented "Formation and Quasi-periodic Behavior of Outer Spiral Rainbands in a Numerically Simulated Tropical Cyclone," and **Hironori Fudeyasu** presented "Multi-scale Interactions on the Lifecycle of Tropical Cyclones Simulated by Global Cloud-System-Resolving Model NICAM." Five IPRC posters were presented by Yuqing Wang, postdoctoral fellows **Lei Wang** and **Kazuyoshi Kikuchi**, and by long-term visitors to IPRC **Yongqing Wang** and **Qingqing Li**.

IPRC's JAMSTEC partners in analysis of high-resolution atmospheric model simulations contributed extensively. Notably, **Masaki Satoh** of JAMSTEC and the University of Tokyo opened the conference by presenting an overview of the scientific issues. JAMSTEC's **Tomoe Nasuno** and **Kazuyoshi Oouchi** also presented talks.

The meeting was hosted by the IPRC and co-organized with colleagues at JAMSTEC and other institutions. The organizing committee included Yuqing Wang and **Kevin Hamilton** from the IPRC and Masaki Satoh from JAMSTEC, **Teruyuki Nakajima** from the University of Tokyo, and **David Randall** from Colorado State University. This high-resolution atmospheric modeling workshop was preceeded by the successful *First International Workshop on High-Resolution and Cloud Modeling—Fusion of Satellite Observations and High-Resolution Modeling* in 2006 in Kusatsu, Japan, and the *Second International Workshop on High-Resolution and Cloud Modeling—Tropical Convection and the Madden-Julian Oscillation* in 2007 in Reading, UK.

Minisymposium on High-Resolution Atmospheric Modeling

Participants at the *Minisymposium on High-Resolution Atmospheric Modeling,* from left, Masaki Satoh, Yuqing Wang, Hironori Fudeyasu, Kevin Hamilton, Tomoe Nasuno, Kazuyoshi Kikuchi, Yohei Yamada, Wataru Yanase, Kazuyoshi Oouchi.

The IPRC held the *Minisymposium on High-Resolution Atmospheric Modeling* on December 5, 2008. The meeting brought visiting colleagues from JAMSTEC together with IPRC and other UH scientists to review recent progress in analysis of high-resolution models and to consider future collaborations. IPRC's **Kevin Hamilton**, meeting organizer and chair, presented a historical overview of the field of high-resolution global atmospheric modeling, and IPRC's **Yuqing Wang** discussed highlights of recent work with high-resolution versions of the IPRC Regional Atmospheric Model. **Masaki Satoh** (University of Tokyo and JAMSTEC) described the current status and overall plans for development and application of the Nonhydrostatic ICosahedral Atmospheric Model (NICAM). Particularly intriguing was his description of the development of a stretched-coordinate version of NICAM, which will allow very high resolution for selected areas on the globe.

The remaining talks dealt with analyses of NICAM simulations: **Wataru Yanase** (University of Tokyo) discussed tropical cyclone formation; **Kazuyoshi Oouchi** (JAMSTEC) spoke on aspects of summer monsoon circulation; **Yohei Yamada** (University of Tokyo) described preliminary results of global warming experiments; **Ping Liu** (IPRC) described the analysis of the Madden-Julian Oscillation simulation; and **Xiouhua Fu** (IPRC) discused application of high-resolution models to the study of monsoon variability. **Tomoe Nasuno** (JAMSTEC) also particpated in the discussion. **Hironori Fudeyasu** (IPRC) ended the minisymposium with a discussion of plans for future analyses of NICAM data at the IPRC.

First Steps Toward the Next IPCC Assessment Report

In early March, the IPRC hosted the workshop *New Science Directions and Activities Relevant to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* The Media Statement, which was released to over 150 newspapers and news stations worldwide at the end of the meeting by **Thomas Stocker** (IPCC), **Kathy Hibbard** (IGBP), and **Venkatachalam Ramaswamy** (WCRP), follows.

"From March 3 to 6, over 150 leading climate scientists from around the world gathered at the International Pacific Research Center of the University of Hawai'i to discuss the latest developments in Climate Change science. The hosting institute is internationally known for its research in climate variability and climate change and serves as a meeting place for scientists from all over the world. The workshop was jointly sponsored by the Intergovernmental Panel on Climate Change (IPCC), the World Climate Research Programme (WCRP) and the International Geosphere-Biosphere Programme (IGBP).

"The goal of this workshop was to identify the latest developments in Climate Change science and discuss their implications for our understanding of the Earth System and its response to ongoing accelerated emissions of greenhouse gases and pollution particulates (aerosols), and deforestation.

Participants at the workshop *New Science Directions and Activities Relevant to the Fifth Assessment Report.*

The findings of the scientists will be made available for the planning of the *Fifth Assessment Report of the IPCC* which is due in 2013.

"Increasing computational power, and advances in process understanding and observations, now permit global climate models to address regional climate change and extreme events in much greater detail. In an unprecedented effort involving all climate modelling centers around the world, including the participation of developing countries, the World Climate Research Programme (WCRP) is coordinating climate model experiments and their analyses which will be assessed for the next IPCC report. This will result in a better estimate of the uncertainty involved in climate change projections and accelerate the development of climate models.

"In the framework of the International Geosphere-Biosphere Programme (IGBP), these computer models are now evolving into "Earth System" models which are more inclusive of the roles of biology and chemistry, and the role of human activities, in the climate system. These models will be the tools to understand how current and future changes in energy use and environmental management will affect our climate and ecosystems worldwide.

"Among the findings that were discussed by the scientists are interactions between the cycling of carbon and nitrogen in the climate system and new feedback processes involving the atmosphere, oceans, land and ice, details of which are yet to be fully understood and quantified. The fate of the large ice sheets of Greenland and Antarctica in a warmer world and the role of warming oceans in promoting ice-shelf melt, is a continuing concern that has direct implications for uncertainties in the projection of global sea level rise.

"The scientists, gathered from all over the world, who participated in the workshop have extensive experience in performing scientific assessments for policy makers worldwide. In seeking to advance knowledge about the vulnerability of this planet to human-induced climate change, scientific rigor must remain a hallmark of the information that will be used for responsible decisions and wise stewardship."

Climate Processes over the Asia-Pacific Region

The mini-symposium *Climate Processes over the Asia-Pacific Region* was held in conjunction with the visit of **Sir Brian Hoskins** on March 12 (see page 23). Organized and chaired by IPRC's **H. Annamalai**, the symposium featured talks by several IPRC scientists. The presentations included results related to Indian Ocean climate, monsoon dynamics, equatorial oceanography, tropical-extratropical interactions, paleo-monsoon simulations and simulations of clouds and tropical cyclones in high-resolution models. For the complete agenda, visit **iprc.soest.hawaii.edu/meetings/workshops.html.**

Capturing the Impacts of Ocean Mixing on the Circulation

Ocean Mixing Mini-Workshop participants.

By Ryo Furue

Although ocean mixing significantly impacts the large-scale ocean circulation and surface fluxes, it is among the least well understood phenomenon in climate modeling. The processes directly responsible for mixing occur at such small spatial and temporal scales that they must be parameterized by representing small-scale effects on large scales in terms of large-scale variables.

When a team of ocean experts and data assimilation, led by **Detlef Stammer**, from Scripps Oceanographic Institution and the University of Hamburg visited the UH in March, IPRC's **Niklas Schneider** took the opportunity to organize the *Ocean Mixing Mini-Workshop*. The workshop brought together scientists who use a variety of approaches to work on the mixing issue: data assimilation, observations, theories, and large-scale ocean modeling. For the complete agenda visit **iprc.soest.hawaii.edu/meetings/workshops.html.**

Data assimilation has been suggested as a tool for gaining insights into the interaction between mixing and the large-scale circulation and for estimating mixing parameters. The adjoint method of data assimilation minimizes differences between observations and model output ("cost function") by adjusting model parameters (such as mixing parameters) and forcing fields (such as wind stress). The Scripps-University of Hamburg team demonstrated that by adjusting mixing parameters, adjoint data assimilation can indeed reduce the cost function, thereby giving better estimates of mixing parameters. But a similar improvement (i.e., reduction in cost function) can possibly be obtained by adjusting forcing fields. In-depth analyses of the estimated states and parameters will resolve this ambiguity.

Observational studies presented suggest that ENSO modulates the vertical heat transfer at the bottom of the equatorial Pacific mixed layer by a factor of about 10 and that variations in the Kuroshio Extension strength and position modulate the erosion of the Subtropical Mode Water.

Another approach presented to the mixing parameterization issue is the global mapping of vertical diffusivity constructed by combining observations and theories. Such mapping is beginning to show a consistent picture.

A reported modeling study suggests that vertical diffusivity changes the temperature of equatorial subthermocline currents, altering the heat balance of the remote mixed layer where currents upwell. Finally, velocity profiles taken at high-vertical resolution at the western equatorial Pacific reveal a new type of fine-scale disturbances. Theories and numerical simulations suggest that the disturbances are due to the instability of small-scale equatorial waves and that they significantly contribute to horizontal and vertical mixing. A new, simple parameterization to represent the phenomenon has improved representation of the Equatorial Undercurrent in a general circulation model.

The participants were hopeful that combining data assimilation and expanded observations of mixing with an understanding of physical processes and large-scale ocean dynamics will lead to improved modeling of the ocean circulation.

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New UH–JAMSTEC Cooperative Agreement Extends Scientific Partnership

With the negotiation and signing of a new Cooperative Agreement between the University of Hawai'i (UH) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the IPRC research partnership with JAMSTEC, which began in October 1997, will continue through March 31, 2014. Signed by JAMSTEC President **Yasuhiro Kato** and UH President **David McClain**, the new agreement is the first to define the institutional framework for the research conducted under the JAMSTEC–IPRC Initiative.

UH President David McClain, signing the new Cooperative Agreement, with SOEST Dean Brian Taylor (left) and IPRC Interim Director Kevin Hamilton.

JAMSTEC Officials Visit the IPRC

Shiro Imawaki, the new JAMSTEC Executive Director, and **Shiro Matsugaura**, of the JAMSTEC International Affairs Division, visited the IPRC on December 11 and 12, 2009. The visit afforded our JAMSTEC colleagues a chance to hear in detail about research underway at the IPRC, including the exciting work of many of our younger scientists.

Executive Director Shiro Imawaki (left) and Shiro Matsugaura (in white shirt) with IPRC's young Japanese scientists.

Scientific Advisory Committee Reviews New IPRC Science Plan

The IPRC Scientific Advisory Committee met from December 8 to 10, 2008, at the IPRC to learn about recent and ongoing IPRC research and to review and discuss the draft of the new IPRC Science Plan.

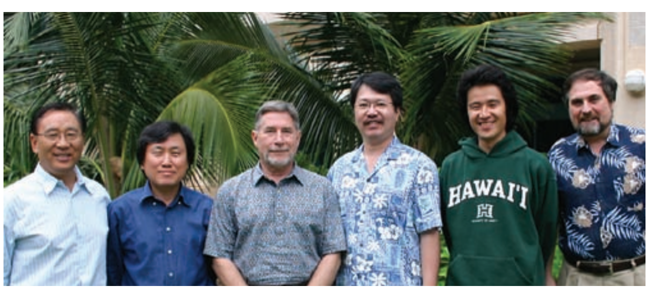
IPRC Scientific Advisory Committee: seated from left, Peter Cornillon (University of Rhode Island), Masahisa Kubota (Tokai University), Toshiyuki Hibiya (University of Tokyo), Masahide Kimoto (University of Tokyo); standing from left, Roberto Mechoso (University of California at Los Angeles), Kevin Hamilton (IPRC Interim Director), Jerry Meehl (US co-chair, National Center for Atmospheric Research), Humio Mitsudera (Japan co-chair, Hokkaido University), and Brian Taylor (Dean, UH School of Ocean and Earth Science and Technology).

Celebrating Research Achievements at JAMSTEC

IPRC scientists participated in two symposia held at the Yokohama Institute for Earth Sciences (YES): the Joint Annual Symposium of the Frontier Research Center for Global Change (FRCGC) and of the Institute of Observational Research for Global Change (IORGC) on March 16, 2009; and the symposium *Past, Present and Future of Climate Variations Research* on March 17. Interim Director **Kevin Hamilton** represented the IPRC at the Joint Symposium, with a presentation of IPRC Research Highlights. The March 17 symposium celebrated the achievements of the FRCGC Climate Variations Research Program (CVRP) and its Director, University of Tokyo Professor **Toshio Yamagata**. In recognition of the important partnership between CVRP and IPRC, two IPRC scientists gave invited talks. **Shang-Ping Xie** presented "Climatic Influences of Indian Ocean Dynamics: The Thermocline Dome and Beyond" and **Tangdong Qu** presented "Tracking the Origin of Thermostad Waters in the Eastern Pacific."

Winter – Spring Visitors to the IPRC

During the 2008–2009 winter and spring IPRC hosted a bumper crop of distinguished international colleagues who made extended visits to collaborate with IPRC scientists. **Hiroyuki Murakami** from Japan's Advanced Earth Science and Technology Organization visited IPRC's **Bin Wang** to analyze tropical cyclones in the high-resolution global simulations produced by the Japanese Meteorological Research Institute. Professor **In-Sik Kang** of Seoul National University also visited Bin Wang to continue their collaboration on seasonal climate prediction. **George Boer** from the Canadian Centre for Climate Modelling and Analysis in Victoria worked with **Kevin Hamilton** on stratospheric influences on tropospheric climate. **Wataru Ohfuchi** from the JAMSTEC Earth Simulator Center visited Hamilton to continue their long-standing collaboration on analysis of high-resolution global atmospheric model simulations.



From left, Bin Wang, In-Sik Kang, George Boer, Wataru Ohfuchi, Hiroyuki Murakami, Kevin Hamilton.

Akio Ishida and **Yoshikazu Sasai**, research scientists at the Frontier Research Center for Global Change, visited the IPRC in February to discuss collaborations between FRCGC and IPRC on studies of the marine ecosystem. Sasai stayed on until late March to work with IPRC's **Kelvin Richards** on the interannual variability of primary production in the Eastern Tropical Pacific. They compared observations of primary production seen in ocean color satellite measurements with results from an ecosystem model embedded in the Ocean General Circulation Model for the Earth Simulator. The model was found to capture much of the observed variation.

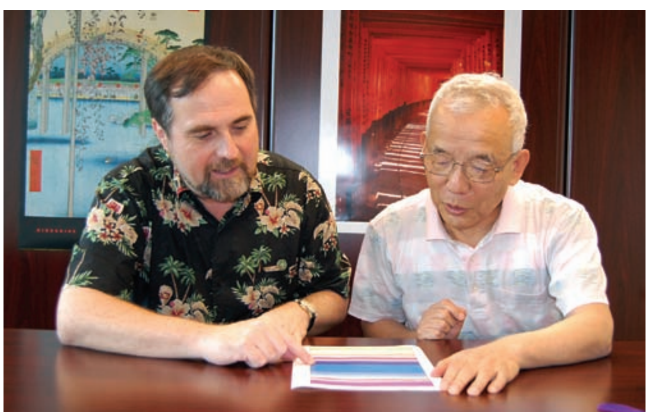
From left, Richards discussing primary production variation in the tropical Pacific Ocean with JAMSTEC colleagues Sasai and Ishida.

Andrey Zatsepin, Head of Experimental Physics of the Ocean Laboratory at the P.P. Shirshov Institute of Oceanology in Moscow, visited **Nikolai Maximenko** in December 2008 to discuss their joint project on the coastal ocean dynamics of the Black Sea. The Black Sea is affected mostly by coastal ocean processes, which are much more complex in an inner sea than in the open ocean. The study will combine satellite and ship observations with laboratory experiments that are conducted in rotating tanks and can simulate the effects of the Coriolis force on the Black Sea.

Andrey Zatsepin (right) discussing rotating water tanks with Nikolai Maximenko.

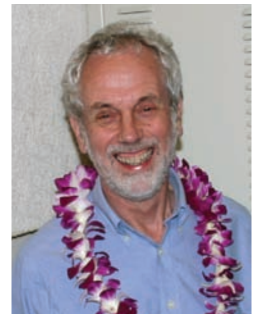
Syukuro "Suki" Manabe visited the IPRC in February. Now a Senior Scientist with the Princeton University Program in Atmospheric and Oceanic Sciences, Manabe has had a distinguished career in both Japan and the US and is widely regarded as the "father of global climate modeling." For many years, he led the climate group at the NOAA Geophysical Fluid Dynamics Laboratory. Then from 1997 to 2001, he was director of the Global Warming Research Program at the JAMSTEC Frontier Research System for Global Change.

IPRC senior and junior scientists took the opportunity to discuss modeling issues with this pioneer in numerical climate modeling. One subject discussed during the visit was finalizing a contribution dealing with Manabe's career for the American Meteorological Society (AMS) Oral Histories Project. This contribution is based on the interview of Manabe conducted in 2005 by *IPRC Climate* editor **Gisela Speidel**. The original version of the interview was published in *IPRC Climate* Vol. 5, no 2. The expanded version will be deposited in the AMS archive. The IPRC is pleased to have been involved in this important project developing primary sources to document the history of atmospheric science!



Suki Manabe (right) in discussion with Kevin Hamilton.

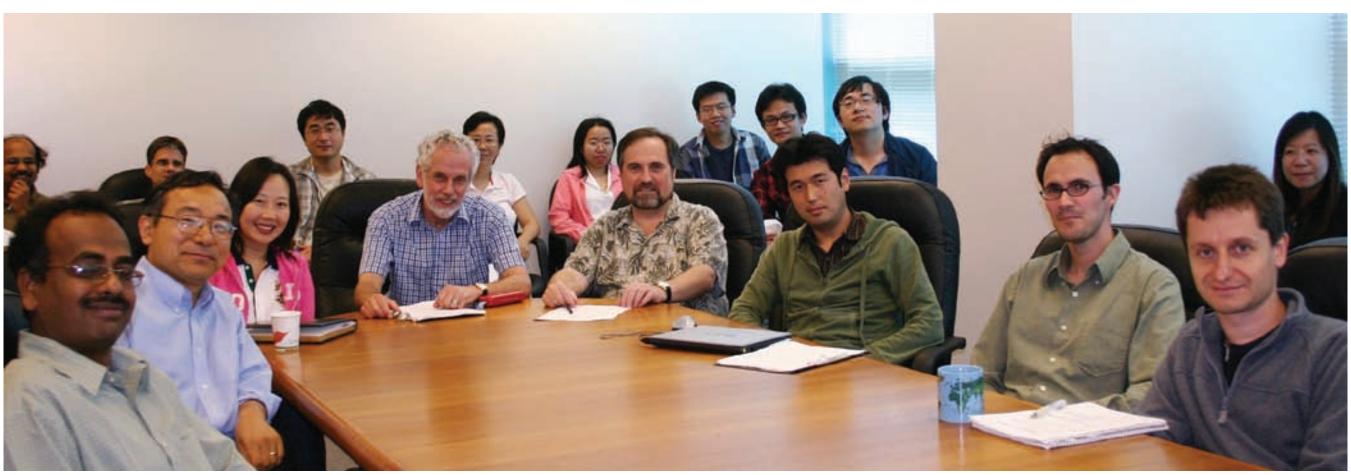
Sir Brian Hoskins, C.B.E., F.R.S, visited the IPRC from March 11 to 13. Hoskins, one of the outsanding dynamical meteorologists of his generation, is Director of the Grantham Institute for Climate Change at Imperial College in London. In his special joint IPRC–Department of Meteorology lecture on March 11, titled "Understanding of Storm Tracks from Idealised World GCM Simulations," he first reviewed observational studies of midlatitude storm tracks, noting particularly the localization and alignment of the North Atlantic storm track. He then presented results of a standard "aqua-planet" global atmospheric general circulation model with specified zonally symmetric sea surface temperatures (SSTs), an experiment that produces a midlatitude track that extends all around the globe and is anchored by the SST gradients. He ended his talk with results from a series of simulations in which more realistic features were successively added: first a flat continent with shape and location similar to North America, then the effects of a topographic barrier representing simplified Rocky Mountains, and lastly, the SST patterns representing the effects of the ocean currents (notably the Gulf Stream). The incremental results showed the impact of North American topography in producing the Atlantic storm track.



Sir Brian Hoskins

The mini-symposium *Climate Processes over the Asia-Pacific Region* was held in conjunction with Hoskins' visit (see Meetings, page 19).

Brian Hoskins during the *Mini-Symposium an Climate Processes over the Asia-Pacific Region.*



Susan Solomon Gives Inaugural Lecture in IPRC Public Lecture Series

The IPRC began an exciting new endeavor on the evening of March 2, 2009, with the inaugural *IPRC Public Lecture in Climate Science* presented by **Susan Solomon**, senior scientist with the National Oceanic and Atmospheric Administration Earth System Research Laboratory in Boulder, Colorado. A leader in the field of atmospheric science, Solomon made some of the first chemical measurements of the ozone hole in Antarctica, establishing manmade chlorofluorocarbon com¬pounds (CFCs) as its cause. These scientific results provided impetus for the negotiation and implementation of the 1987 Montreal Protocol, the international agreement that regulates global CFC emissions. From 2002 to 2008, Dr. Solomon was co-chair of the Physical Science Working Group of the Intergovernmental Panel on Climate Change (IPCC), and her efforts were key in preparing the recent IPCC Fourth Assessment Report on Climate Change. She has won numerous prestigious awards in the US and abroad, among them the US National Medal of Science and the 2004 Blue Planet Prize of the Asahi Foundation in Japan. In 2008 *Time* magazine recognized Solomon as one of the "100 most influential people in the world."

Susan Solomon gives the inaugural lecture of *IPRC Public Lecture Series.*

Solomon's lecture, "A Tale of Environmental Change: Something for Everyone about Climate Change, and Climate Gridlock," attracted an audience of nearly 200 students, faculty, and members of the general public. She began by describing the approach adopted by the IPCC in preparing its assessments of the current state of climate science, and noted the wide participation by the global science community in the process. The IPCC emphasizes the aspects of the science that are most clearly established and takes pains to identify those areas that are potentially very important, but still uncertain. Solomon noted that the final "summary for policymakers" in the IPCC assessments must be approved word-for-word by the representatives of the 113 national governments involved in the IPCC process.

Solomon went on to describe some of the well-established scientific results that should underpin societal response to the global warming issue. Although individual decadal periods may not show rising global-mean surface temperatures, the overall record from the late 19th century to the present shows an unequivocal warming trend. The warming trend is clearest when the data are averaged over the globe—at individual locations the warming trend can be less obvious.

The degree and rapidity of the global-mean warming over the last century appear to be unprecedented, in recent times at least, and coincide with unprecedented rapid increases in the atmospheric concentrations of long-lived greenhouse gases, most notably carbon dioxide. These changes in atmospheric composition are largely due to human activities. Sophisticated models of the climate system account for the observed warming only when human-induced greenhouse gas concentrations are included together with natural processes.

The models can be used to project the response of the Earth system to possible scenarios of future human greenhouse gas emissions. The most plausible scenarios have global-mean temperature rising by about 3°C by the end of the 21st century. The local implications of such a climate change will likely be considerable. For example, rainfall patterns can be expected to shift significantly, and most dry regions in the

Susan Solomon with IPRC Interim Director Kevin Hamilton discussing research with graduate student Jian Ma and postdoctoral fellow Axel Lauer.

midlatitudes can be expected to become drier. By the end of the century, models predict in some areas as much as a 20% reduction in average rainfall. To put this in context, Solomon pointed out that during the famous "Dust Bowl" era, the Great Plains of the US had roughly 10% less rainfall than normal for about 15 years. Control of these climate changes would involve major changes in the world's economy. The development of the broad international consensus required to significantly regulate emissions is complicated by the inequities in wealth and industrial development. Solomon pointed out that currently the wealthiest 1 billion people are responsible for 5 times the per capita emission of the remaining 5.5 billion people. Even within the developed world there are inequities, with the average emission of each American roughly twice that of a person in Europe or Japan.

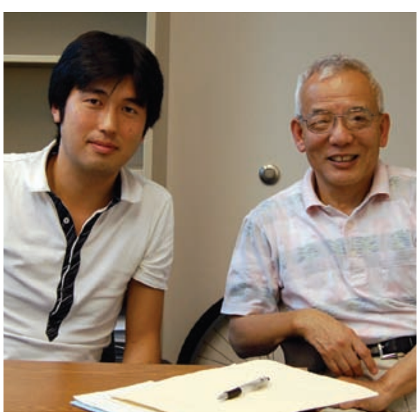
Solomon noted that, just as the water level in a bathtub depends upon the amount of water coming in and draining, the level of carbon dioxide in the atmosphere is controlled by emissions and sinks (notably uptake by the ocean and the terrestrial biosphere). Currently the emission rate exceeds the capacity of the sinks to absorb all the added carbon dioxide; in the analogy, the bathtub is filling even with an open drain. To stabilize carbon dioxide concentrations it will be necessary to reduce very significantly current emission rates.

Comparing the situation with the successful Montreal Protocol on CFC reduction, Solomon said, "The times, the numbers and players at the table, equity issues, sustainable development issues, and poverty alleviation make this issue much more complex. It will be a heroic task in the next generation: stabilize and then reduce emissions while developing countries develop. Never before has there been a greater need for a joint and well-informed societal choice."

Building on this successful start, the IPRC will establish the IPRC Public Lecture in Climate Science as an annual event. We plan to bring a distinguished environmental scientist each year to the IPRC to interact with our scientists and students and to present an evening lecture to the general public. This is a high-profile addition to outreach efforts at the IPRC and the University of Hawai'i to inform the public about the science that underlies critical environmental issues.

IPRC–JAMSTEC Research on Modeling Tropical Cyclones Garners Wide Attention

The publication of tropical cyclone results from the NICAM model (p. 13) made quite a media stir. The study, led by IPRC postdoctoral fellow **Hironori Fudeyasu** and co-authored with IPRC's **Yuqing Wang**, University of Tokyo Prof. **Masaki Satoh** and JAMSTEC's **Tomoe Nasuno**, **Hiroaki Miura**, and **Wataru Yanase**, was published under the title "Global Cloud-System-Resolving Model NICAM Successfully Simulated the Lifecycles of Two Real Tropical Cyclones," in November 2008 in *Geophysical Research Letters*. Chosen as an "AGU Journal Highlight," the paper led to stories appearing in over 20 online news sites (**iprc.soest.hawaii.edu/news/newslinkssaved/08_12_Fudeyasu.html**), including some in India, Malaysia and Korea. This work was also featured in the News section of the *Bulletin of the American Meteorological Society*. An interview with Satoh about this work was published by *Mainichi Newspapers* in Japan (**iprc.soest.hawaii.edu/japanese/news/news.html**).



Hironori Fudeyasu discussing tropical cyclone simulations with IPRC visitor Syukuro Manabe.

Discussing monsoon research using NICAM, from left, Tomoe Nasuno, Yoshiyuki Kajikawa, Kazuyoshi Oouchi, Yoshiki Fukutomi, Kazuyoshi Kikuchi, Masaki Satoh, Hirofumi Tomita.

Monsoon Studies with NICAM

From March 19 to 31, 2009, **Kazuyoshi Kikuchi** and **Yoshiyuki Kajikawa**, who are doing monsoon research at the IPRC, visited JAMSTEC scientists working on the global cloud-system-resolving model NICAM. They discussed with **Masaki Satoh** (Subleader, Global Environment Modeling Research Program), **Hirofumi Tomita** (Research Scientist, Global Environmental Modeling Research Program), **Kazuyoshi Oouchi** (Research Scientist, Global Environment Modeling Research Program), **Tomoe Nasuno** (Research Scientist, Global Environment Modeling Research Program), **Yoshiki Fukutomi** (Research Scientist, Hydrological Cycle Research Program), and other JAMSTEC colleagues possible future collaborations on analyzing the existing NICAM output and designing future NICAM experiments—experiments that would provide new detailed knowledge about monsoon processes and could help in forecasting monsoon rainfall.

IPRC–Hokkaido University Collaboration Continues

The exchange between IPRC and Hokkaido University, begun by Hokkaido Prof. **Youichi Tanimoto**, has continued with the January–March visit of Hokkaido graduate student **Kohei Yoshida**. While at the IPRC, Yoshida worked with **Kevin Hamilton** on observational studies of the structure of the Quasi-biennial Oscillation near the tropical troposphere. Yoshida gave an "IPRC Luncheon Discussion" on results of his work.

Kevin Hamilton with Hokkaido graduate student Kohei Yoshida.

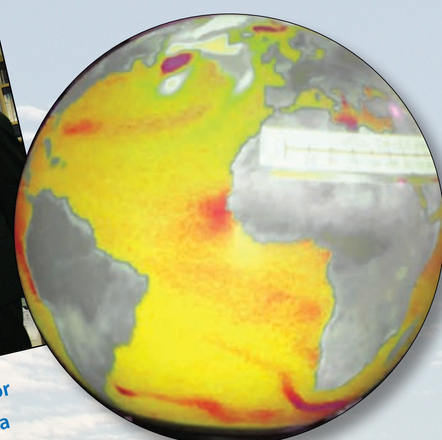
IPRC Acquires Magic Planet

With the support of UH School of Ocean and Earth Science and Technology (SOEST) and a generous gift from former IPRC Executive Associate Director **Lorenz Magaard**, the IPRC has acquired a "Magic Planet." This system allows still images or animations to be projected on a glowing 24-inch diameter sphere. The software for the computer-driven projections permits the planetary rotation to be automatically added to the images and the orientation of the rotation axis to be varied. The Magic Planet is being used for visualizing IPRC's model simulation and diagnostic data sets as well as for educational and outreach activities at IPRC and other units of SOEST.

A valuable feature is that presentation material developed for the IPRC Magic Planet can be adapted easily for display on the 8-foot diameter NOAA Science-on-a-Sphere (SOS) at Honolulu's Bishop Museum and at other institutions around the world. The acquisition of the IPRC Magic Planet projector was spearheaded by **Jim Potemra**, a faculty member at the IPRC and the Hawai'i Institute of Geophysics and Planetology (HIGP).

Magic Planet. *Inset:* Former Executive Associate Director Professor Lorenz Magaard, whose generous donation helped the IPRC acquire a Magic Planet.

At the Bishop Museum's *Mad About Science* festival, Jim Potemra displays for comparison two different global warming scenarios: one on the Magic Planet provided by the IPRC and one on a borrowed system from NOAA (see page 29; photo courtesy of Bishop Museum).



Admiring the new Magic Planet, from left, Interim Director Kevin Hamilton, Jim Potemra, Visiting Researcher Mototaka Nakamura and JAMSTEC Executive Director Shiro Imawaki.

IPRC Scientists Active in Climate Research Community

IPRC Interim Director **Kevin Hamilton** visited Boulder from November 17 to 20, 2008, to participate in the external advisory panel review meetings for the National Center for Atmospheric Research Earth & Sun Systems Laboratory (ESSL) and its constituent Divisions and Institutes. In addition to participating in the main ESSL review, Hamilton chaired the review panel for The Institute for Integrative & Multidisciplinary Earth Studies (TIIMES).

Bin Wang is serving on the special committee for "Assessment of Climate Predictability and Prediction on Intraseasonal to Seasonal Timescales" of the National Academies' Atmospheric Science and Climate Board. The committee is charged with writing a national report on climate predictability and prediction. Wang is also co-chair of the Organizing Committee for the International Monsoon Symposium, which will be held in Jakarta, Indonesia, July 16–17, 2009; and he is a co-organizer of the 6th workshop for the Asian Monsoon Years (AMY 2007–2012).

IPRC's **Nikolai Maximenko**, **Niklas Schneider**, and **Oleg Melnichenko** organized and convened with **Emanuele Di Lorenzo** (Georgia Institute of Technology) the special session *Anisotropic Mesoscale Structure of Basin-Wide Ocean Circulation* at the 2008 Fall AGU Meeting in San Francisco held December 15–19, 2008.

Kevin Hamilton talking with NCAR Senior Scientist John Gille during the ESSL review.

IPRC's Alumnus Receives Okada Prize

Former IPRC scientist **Fumiaki Kobashi** received the Okada Prize at this year's Spring Meeting of the Oceanographic Society of Japan, which was held from April 5 to 9, 2009, in Tokyo. The prize is awarded to a young member of the Society who has made outstanding contributions to the progress of oceanography.

Kobashi was honored with this prize for his "Analytical study on the North Pacific subtropical front," which consists of two parts: the formation mechanism of the subtropical front, which he discovered with **Humio Mitsudera** and **Shang-Ping Xie** while he was at the IPRC, and a description of air-sea interaction over the subtropical front, which he recently analyzed with Xie and other colleagues (see *IPRC Climate*, vol. 8, no. 2). Kobashi is now professor at Tokyo University of Marine Science and Technology.

Fumiaki Kobashi receives the Okada Prize.

IPRC Active in the Community

The IPRC took part in the Bishop Museum's "Mad About Science" annual festival, which this year had climate change as its theme.

Axel Timmermann as the Mythbuster.

At Bishop Museum's Festival, Oliver Timm explains 800,000-year-long temperature and CO_2 record.

IPRC Outreach Specialist Gisela Speidel helps Sophia Hudelist create an Ice Age over the twin peaks Mauna Loa and Mauna Kea that were covered by ice 18,000 years ago. (Photo courtesy of Puja Hudelist)

Axel Timmermann (above) played the Climate Change Expert who answered questions and busted climate myths.

Oliver Timm's 800,000-year record of temperature and CO_2 data from the EPICA ice core in Antarctica, which covered over 25 feet of the exhibit walls (top left), was greeted with amazement and many questions.

Jim Potemra (see page 27) asked visitors to compare future air and sea surface temperature projections displayed on two Magic Planets that showed animations for different increases in atmospheric CO_2 concentrations.

Children enjoyed creating an ice age or a meltdown for the Island of Hawai'i (18,000 years ago Mauna Kea had a glacier) with **Gisela Speidel** (bottom left) by letting more snow fall than melt (or more snow melt than fall), to experience what happens when climate processes are not in balance.

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NEW IPRC STAFF

Ju Chen

Ju Chen joined the IPRC as a postdoctoral fellow in November 2008. He received his PhD in 2006 from the South China Sea Institute of Oceanology (SCSIO), Chinese Academy of Sciences, in Guangzhou. For his dissertation, Chen analyzed the contribution of the upper-layer circulation to the interannual variability of the intermediate and deep water of the South China Sea. He continued studying the circulation and water mass of the South China Sea as an assistant researcher at the SCSIO until coming to the IPRC. At the IPRC, Chen is working with **Tangdong Qu** on a project to understand the source, migration, and destination of 13°C water in the Southern Pacific, with a focus on the year-to-year and decade-to-decade variations in the annual subduction rate and how this rate affects tropical Pacific 13°C water.

Puthiya V. S. Kallikkal

Puthiya Veettil Sooraj Kallikkal joined the IPRC as a postdoctoral fellow in January 2009. He received his PhD in 2005 from Cochin University of Science and Technology, India. For his dissertation, Sooraj used observational and modeling diagnostics to study the onset of the South Asian summer monsoon. After completing his PhD, he worked first as a research associate at the Centre for Atmospheric and Oceanic Science, Indian Institute of Science, analyzing the sea surface temperature cold bias in CCSM simulations of the tropical Indian Ocean, and then as a postdoctoral fellow at the Climate Environment System Research Centre of Seoul National University, Korea. At the IPRC, Sooraj is working with **H. Annamalai** on a project to develop a dynamical seasonal climate prediction system for the Pacific Islands; he is also interested in issues related to the seasonal prediction of the South Asian Monsoon. Sooraj says, "I continue to be fascinated by the rather chaotic nature of weather and the challenges in trying to develop seasonal forecast procedure."

MinHo Kwon

MinHo Kwon joined the IPRC as a postdoctoral fellow in November 2008. He received his PhD in atmospheric sciences from Seoul National University in 2006. For his dissertation, he analyzed the decadal variability of the East Asian summer monsoon. He found that the monsoon circulation changed significantly in the mid-1990s, and he investigated how these changes might be related to global climate variations. After receiving his PhD, he worked for the Research Institute of Basic Sciences at Seoul National University and at the Korea Meteorological Administration on their forecast of seasonal mean climate of East Asia using statistical models. At the IPRC, Kwon is working with **Tim Li** on changes in the characteristics of tropical cyclones under a warmer climate. He says, "I am curious about what controls the number of tropical cyclones in a warmer climate state."

Shayne McGregor

Shayne McGregor joined the IPRC as a postdoctoral fellow in March 2009. He completed his Masters and PhD degrees in the Department of Environment and Geography at Maquarie University, Sydney, Australia. His dissertation focused on investigating the mechanisms that contribute to the interdecadal variability of the El Niño-Southern Oscillation. At the IPRC, McGregor is working with **Axel Timmermann** on identifying changes in tropical Pacific climate during the last millenium. This project also seeks to indentify whether the changes in tropical Pacific climate are driven by processes internal or external to the climate system. McGregor: "I am fascinated and absorbed by tropical Pacific variability and the strength of its global climatic impacts."

Laurie Menviel

Laurie Menviel, who joined the IPRC as a postdoctoral fellow in January 2009, hails from France. She received her Master's degree in Geochemistry from the University of Aix-Marseille in 2002 and her PhD from the Department of Oceanography, University of Hawai'i at Mānoa, in 2008. Her dissertation dealt with the interaction between the carbon cycle and climate on millennial to glacial timescales. At the IPRC, Menviel is working with **Axel Timmermann** to further understand the interaction between climate and the carbon cycle. At present, their main project focuses on describing the response of climate and the marine carbon cycle to past (and eventually future) freshwater releases from Antarctica. Their tool is an Earth system model of intermediate complexity, the LOVECLIM, which consists of the following components: atmospheric circulation, carbon cycle, ocean circulation and sea ice, vegetation cover, and ice-sheet surface and flow.

Jing Xu

Jing Xu joined the IPRC as a postdoctoral fellow in November 2008. She worked for over a decade at the National Meteorological Center of the China Meteorological Administration and comes with abundant experience in research and operational short-range weather forecasting, and in marine and applied meteorology. She received her PhD from Nanjing University of Information Science and Technology (NUIST) in 2008. Her dissertation dealt with forecasting such hazards as debris flows and landslides, particularly landslides triggered by typhoon rain. At the IPRC, Xu is working with **Yuqing Wang** on a project to understand the physical mechanisms that control tropical cyclone intensity and structure changes. She says, "I am curious about what determines the distribution and the extent of heavy rainfall and high winds in a tropical cyclone."

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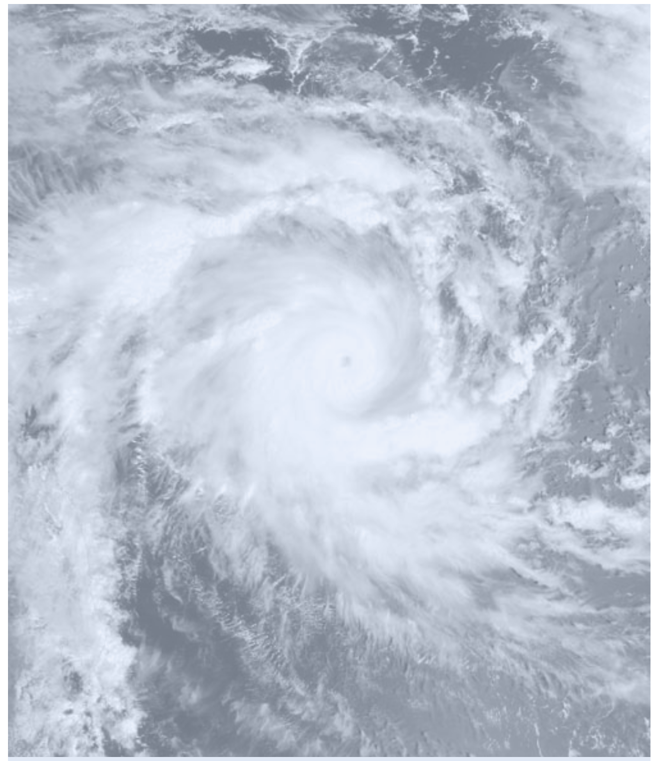

IPRC Bids Sayonara

Three scientists from the IPRC have relocated to the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and are now working in the Climate Variation Predictability and Applicability Research Program of the Research Institute for Global Change: **Mototaka Nakamura** is working as senior scientist on research of extra-tropical air-sea interactions, troposphere-stratosphere interactions, and extreme events. **Hidenori Aiki** is working as scientist on the nonhydrostatic simulation of tidal internal waves in the Indonesian Sea. Former Postdoctoral Fellow **Ingo Richter** has become a JAMSTEC scientist and is studying decadal climate variability and seasonal climate forecasts in southern Africa.

The new Research Institute for Global Change has been created from a merger of the Frontier Research Center for Global Change (FRCGC) and the Institute of Observational Research for Global Change. The Climate Variation Predictability and Applicability Research Program has emerged from the former Climate Variations Research Program of the FRCGC.

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