Atmospheric Gravity Waves and their Effects on the Global Circulation

A fundamental difficulty in modeling global atmospheric circulation is the strong interaction among motions on a wide range of space and time scales. Explicit numerical representation of all the spatial scales that determine the global atmospheric circulation is impractical. An example of such difficulties is the effect of small-scale inertia-gravity waves on the circulation. Inertia-gravity waves have relatively high frequency (typically periods between a few minutes to a few hours) and usually represent only a minor component of the tropospheric circulation. The waves propagate vertically, however, and the associated wind and temperature perturbations grow rapidly with height as the mean density drops. Thus the higher one looks in the atmosphere, the more significant inertia-gravity waves become.

Gravity waves act to exchange mean momentum between the surface and the atmosphere and among different layers of the atmosphere and, as such, are crucial in forcing the global-scale circulation in the stratosphere. Since the distribution of many trace constituents in ozone chemistry is strongly affected by the atmospheric circulation, an understanding of gravity-wave effects in the middle atmosphere has become a central issue for practical modeling of stratospheric ozone, and hence for comprehensive climate-chemistry modeling of the global atmosphere. It is likely that waves with horizontal wavelengths as short as about 25 km are significant for mean momentum transport. The development and application of parameterization schemes to adequately account for the effects of gravity waves that cannot be explicitly resolved is now an important task for scientists in global climate-chemistry modeling.

Kevin Hamilton, co-leader of Impacts of Global Environmental Change research at the IPRC, organized an American Geophysical Union Chapman Conference on "Gravity Wave Processes and Parameterization" that addressed key issues in this area. Held in Waikoloa, Hawai'i, January 10–14, 2004, the conference was co-sponsored by the World Climate Research Programme through its SPARC initiative (Stratospheric Processes and their Role in Climate). There were 64 participants from 11 countries, including experts in observations, theory and numerical modeling of gravity waves, and colleagues interested in the practical impact of subgrid-scale gravity-wave parameterization schemes on global model simulations of atmospheric circulation and chemistry.

The meeting highlighted advances in observational knowledge of the atmospheric gravity-wave field. One theme was the influence of global positioning system (GPS) technology on both *in situ* and satellite observations of the gravity-wave field in the atmosphere. GPS technology can now track very accurately the three-dimensional positions of long-lived balloons in the lower stratosphere, allowing unprecedented observations of the three-dimensional wind with frequent time sampling. Since the balloon drifts with the ambient flow, the calculated spectrum of the high-frequency wind and temperature variations at the balloon location is the effective "intrinsic" frequency spectrum, an important function that thus far has had to be derived indirectly. Another recent development is the use of satellite GPS tomography to measure vertical profiles of temperatures in the stratosphere. The measurements can be taken whenever paths between two individual satellites intersect the planetary limb, leading to a widely scattered geographical coverage that supplements the fixed station distribution typical for many other profiling measurements.

The most pressing theoretical issues underlying parameterization of gravity-wave effects relate to wave forcing and wave dissipation. Much work has been based on systems idealized in various ways. Almost all theoretical models have involved at least a simplified geometry such as considering zonally propagating waves in a mean flow that depends only on height and time. Such restrictions mean that in a steady-state, waves transfer mean momentum from regions where they are forced to where they dissipate. The Chapman conference provided one of the first forums for discussion of recent work that has emphasized the new effects introduced with more complicated geometries in which waves refract in such a way that the wave vector at absorption no longer parallels that at forcing. Whether these refraction effects are important in practical terms or whether they can be ignored is unclear. Future research should focus on modeling studies that quantify the real-world importance of this effect.

The question of how a broad spectrum of vertically propagating waves saturates is fundamental to formulating practical parameterization schemes for gravity-wave effects. It is convenient to formulate the parameterizations in terms of the vertical wavenumber spectrum, particularly if the hydrostatic assumption is invoked (in which case the vertical wavenumber is inversely proportional to the intrinsic wave horizontal phase speed). One currently popular parameterization, the Doppler spread parameterization (DSP), considers the statistical effects of nonlinear advection terms on the high wavenumber of the vertical wavenumber spectrum (corresponding to small Doppler-shifted phase speeds in a hydrostatic system); another, the Warner-McIntrye parametrization (WMP), uses an empirically based saturation condition that constrains the growth of the large wavenumber end of the spectrum. The first detailed comparison of the performance of these two parameterizations was presented at the conference. In particular, the gravity-wave drag on the mean flow for various profiles and input spectra at the lower boundary (near the tropopause) was computed using both the DSP and WMP. The two schemes performed very differently: The WMP removed much more of the wave spectrum in the lower atmosphere than the DSP. The momentum flux and flux divergence profiles computed by the two schemes become similar when the saturation fluxes for the WMP are raised by a factor of 25 over their standard values. Why models with empirically based wave-saturation conditions differ from those based on something closer to a self-consistent, first-principles determination of the saturation conditions, needs to be specified.

Advances in understanding and quantifying gravity-wave sources have come from increasingly realistic and fine-resolution explicit numerical simulations using limited-area models. One focus of such studies is the generation of vertically propagating gravity waves associated with intense tropospheric jet streams. For example, one paper described a dry simulation of a growing baroclinic wave in a multiply nested version of a non-hydrostatic regional model. The multiple nesting allowed motions to be considered from the continental scale down to small scales. It was found that there was a very significant flux of gravity waves above the jet exit region, and a measure of the deviation from diagnostic cyclostrophic balance in the jet-level flow indicated the regions of strong gravity wave generation well (Figure 14).

Over the last decade, much work has been performed using 2- and 3-dimensional, cloud-resolving simulations of gravity waves, forced by concentrated regions of convection. The conference provided a chance to review the latest results, including explicit simulations of tropical squall lines, localized diurnal convection forced by local land-sea contrast, and tropical cyclones. The first steps have also been taken in connecting such detailed studies to explicit formulae that can be used to specify the tropopause gravity-wave fluxes in parameterizations.

The conference provided a forum for discussion of the practical issues of implementing parameterization schemes in global circulation models. Since the input spectra are not very well constrained by direct observations, there is still significant scope for tuning the parameters employed in a gravity scheme for a global model. Recent work has expanded from trial-and-error to more systematic objective techniques that constrain the schemes in order to provide the required wave drag for realistic simulations of large-scale circulation. One study using these techniques has inferred that the horizontal phase-speed spectrum of the waves entering the stratosphere must be broader at low latitudes that in midlatitudes.

Though rapid progress has been made on understanding the gravity-wave field and the more immediate engineering aspects of designing and implementing parameterizations in global models, a completely satisfactory parameterization scheme remains a goal for the future. Further progress requires both continued advances in detailed numerical modeling and in constructing a more complete empirical picture of the space and time variability of the atmospheric gravity-wave field.

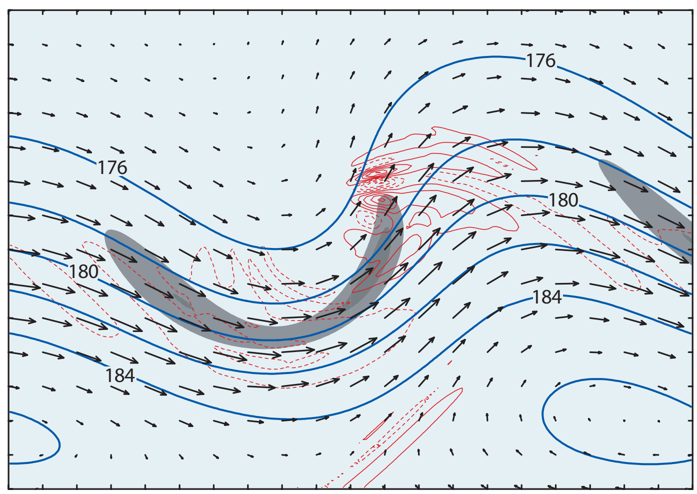


Figure 14. Results from a simulation of an idealized, midlatitude, growing baroclinic wave in a limited-area atmospheric model. Arrows show horizontal winds, the thick blue lines the isobars, and the thin red lines the horizontal divergence, all in the lower stratosphere (13-km altitude). The grey shading shows the region of peak tropospheric jet speeds (at 8-km altitude). The structure of the divergence field reveals the gravity-wave packets emerging from the jet stream. (Courtesy Fuqing Zhang)

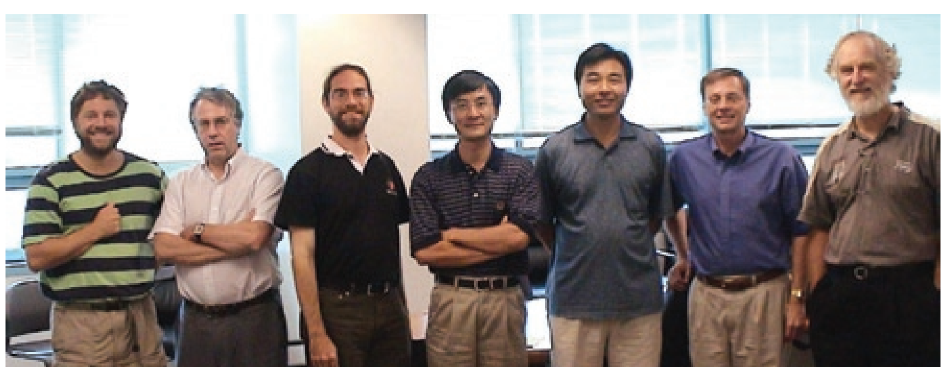
Fourth Annual IPRC Symposium

The Fourth Annual IPRC Symposium was held on May 13 and 14 at the East-West Center in Honolulu. At this event, IPRC scientists present the highlights of their year's research. The annual sharing is a time to pause and reflect upon the progress that has been made in understanding climate phenomena, particularly those affecting the Asia-Pacific region. It is an occasion to solicit comments and suggestions from peers and to detect common research threads. **Kevin Hamilton**, co-leader of the Impacts of Global Environmental Change research team, organized this fourth symposium. As shown in the first pages of this newsletter, a number of talks focused on aspects of the South China Sea climate. Presentations on oceanic research included the development and results of a method for determining accurately global mean sea level, the seasonal variations in water transport through the Indonesian Throughflow, a successful numerical simulation of the Tsuchiya Jets, the development of a slippery sack ocean model, an analysis of the processes causing the Pacific Decadal Oscillation, and the impact of stirring and mixing on the marine ecosystem. Presentations on air-sea interactions included studies of orographically induced air-sea interactions, the impact of ocean mesoscale features on the atmosphere, the formation of the stratus cloud deck in the tropical Southeastern Pacific, and effect of air-sea interaction on intraseasonal variations in the Indian Ocean. Several presentations dealt with tropical cyclone formation, and research into climate change included a study of why the climate sensitivity to increased levels of atmospheric carbon dioxide differs significantly in different climate models.

For the agenda, visit the IPRC website at **iprc.soest.hawaii.edu/meetings/workshops.html**.

Predicting Tropical Cyclones

Tropical cyclone research was on the upswing at the IPRC even before Florida and Japan were struck by an unusual sequence of violent storms this summer. **Yuqing Wang,** IPRC researcher and associate professor of meteorology, organized the "IPRC Workshop on Tropical Cyclones" on August 20, 2004. A small, but representative group of the tropical cyclone research community from Australia, Japan, Taiwan, Korea, and the United Sates discussed large-scale and meso-scale aspects of tropical cyclone formation, structure, and intensity changes, and the relationship between climate change and tropical cyclones. Under the leadership of **Kerry Emanuel**, **Greg Holland**, **John Molinari**, **Michael Montgomery**, **David Raymond**, **Da-Lin Zhang**, and **Yuqing Wang**, progress in these areas was briefly reviewed, and critical issues and future directions were extensively discussed. A list of the most pressing questions for research was drawn up: (1) How does the Madden-Julian Oscillation modulate the genesis of tropical storms and what is the role of vertical wind shear in this process? (2) How do merger, maintenance, and regeneration of convection contribute to the successive development of the "hot



Participants at the Tropical Cyclone Workshop: Michael Montgomery (CSU), Kerry Emanuel (MIT), Sim Aberson (NOAA-HRD), Chun-Chieh Wu (NTU, Taipei), Yuqing Wang (IPRC), John Molinari (SUNYA), and Greg Holland (NCAR).

tower" associated with moist convection in the formation of tropical cyclones? (3) What are the key processes that lead to the formation of a tropical cyclone and affect the cyclone's intensity, and what limits the intensity of tropical cyclones? (4) What improvements can be made in forecasting cyclone intensity, and will models be able to forecast intensity as well as they now forecast cyclone tracks? (5) Do tropical cyclones cool the atmosphere through their impact on the ocean circulation and poleward energy flux? What do paleoclimatic records tell us about such cooling?

A very important concern raised is that present-day climate models lack representations of severe tropical storms and, therefore, cannot directly predict how climate change will affect such storms.

(*Above*) Participants at the Earth Simulator Workshop; (*Left*) Wataru Ohfuchi, group leader of the Earth Simulator Atmosphere and Ocean Simulation Research.

Studies with Japan's Earth Simulator

The IPRC is collaborating with Japanese scientists on analyses of climate simulations run on Japan's Earth Simulator, one of the most powerful supercomputers in the world. Lead scientists at the Earth Simulator Center (ESC) and Frontier Research Center for Global Change (FRCGC) of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) met with IPRC scientists in Honolulu on August 24, 2004, to discuss initial findings from climate simulations with the Earth Simulator and to plan further collaboration.

Global climate models have been limited greatly by lack of computing power and have had to use resolutions somewhere between 200 and 300 km for the atmosphere, allowing only blurred pictures of Earth's climate. These low-resolution models cannot take full advantage of the high-resolution satellite observations, which have been available now for some time. The Earth Simulator, with its over 35 trillion calculations per second, is revolutionizing climate research. Climate models run on this computer now match the resolution of observations from space and are breaking new ground for modelers to exploit available data: Testing these new well-resolved numerical models against satellite observations is critical for gaining confidence in the models' forecasts of regional variations in the ongoing global warming.

At the IPRC–JAMSTEC meeting, the initial results of a high-resolution ocean model (OFES) simulation on the Earth Simulator revealed surprisingly well-organized swift currents at great depths that alternate in narrow bands between eastward and westward flows. These currents persist for years and extend over much of the Pacific Ocean.

Another noteworthy result in simulations with this model on the Earth Simulator concerns slow ocean variations in the upper 500 meters that are associated with movement of huge amounts of heat from one region to another and affect storm tracks and storm intensity. The Earth Simulator results show these movements to be spatially very organized and concentrated across narrow ocean-fronts at the surface. This new knowledge will help climate and fisheries scientists in designing observation systems to monitor changes in these fronts and in their location.

With its highly skilled scientists in atmospheric and oceanic modeling and in analyzing satellite data, the IPRC is well positioned to take advantage of this new frontier created by the Earth Simulator. By weaving information from the Earth Simulator together with satellite observations from space and observations from the new Argo-float ocean measurements, scientists will be able to see what the climate in places like Hawai'i may be like in the next several decades.

Organizers of the PICES/CLIVAR workshop: Kelvin Richards (IPRC), Jim Overland (Pacific Marine Environmental Laboratory), Kimio Hanawa (Tohoku University) and Skip McKinnell (Institute of Ocean Sciences). (Not shown: Dick Beamish, Fisheries and Ocean Canada) and Kuh Kim (Seoul National University).

Scale Interactions in Climate and Marine Ecosystems

The marine ecosystem, like the complex physical climate system, has many interacting scales, from small-scale patchiness to global extent, from shelf to deep-sea populations, and from individuals to communities. To date, most studies of the impact of climate variability on the marine ecosystem have used correlational statistics between a given population and physical climate indices. If we are to understand what controls what, however, we need to go beyond simple correlations and tease out the relationships between the changing physical and biological systems. How do the various scales of climate variability project onto the variability of the population of a given species or the ecosystem as a whole? How does the changing climate impact the scale interactions of the biogeochemical system? What do we need to get right in models used to predict the impact of climate change on the marine ecosystem and fisheries?

A joint PICES and CLIVAR workshop, held in Honolulu in October 2004 as part of the PICES XIII meeting and co-sponsored by the IPRC, focused on these questions. The talks given by experts in Pacific physical oceanography, climate dynamics and variability, marine ecosystems and biogeochemistry, and in fisheries reflect the recent progress in our understanding of factors that affect the physical environment on interannual to decadal timescales and in our ability to model these changes locally and basinwide. Both *in situ* and satellite observations reveal changes in the ecosystem from the regional to the basinwide scale, and in many instances these changes can be linked to changes in the physical environment. Managing fisheries in the face of uncertainties of climate change is particularly challenging, but we understand better now how the timing of environmental changes impacts the growth of populations at various stages of their life cycle.

Much discussion at the workshop dealt with the so-called "regime shift" of the mid-70s, first revealed in biological data and later discovered to coincide with basinwide physical changes, and whether it was truly a regime shift or just a relatively rapid change in a randomly varying system. The prevailing view is that there is no evidence for a regime shift in the physical system, but that one should look in the ecosystem for thresholds that trigger regime shifts in this system.

Nate Mantua's paper "To upscale or downscale" perhaps captured best the essence of the workshop. He notes that statistically comparing large-scale climate indices to local and regional fishery data does not reveal the key processes. Rather "upscaling" locally varying parameters to large-scale climate variability promises to yield a better understanding of the linkages between climate and the marine ecosystem cause and effect. Abstracts of the talks can be found at **www.pices.int/meetings/annual/Pices13.**

IPRC scientists play key role in Western Pacific Geophysics Meeting

The biennial Western Pacific Geophysics Meeting of the American Geophysical Union was held in Honolulu from August 16 to 20, 2004, and brought together over 700 scientists from Asia, Australia, New Zealand, and the United States. IPRC scientists contributed much to the meeting: The Scientific Program Committee included IPRC's **Kevin Hamilton**, and IPRC affiliate members **Bo Qiu** (University of Hawai'i, Department of Oceanography) and **Humio Mitsudera** (Hokkaido University). Moreover, Hamilton convened the Union session "Earth Science on the Earth Simulator," **Shang-Ping Xie** the Ocean Sciences session "Air-Sea Interaction in the Indo-Pacific Oceans," and **Yuqing Wang** the Atmospheric Sciences session "Challenging Issues on Tropical Cyclone Research and Forecasts in the Western Pacific." IPRC scientists authored or coauthored 35 papers and posters presented at the meeting.

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