iprc climate

Research

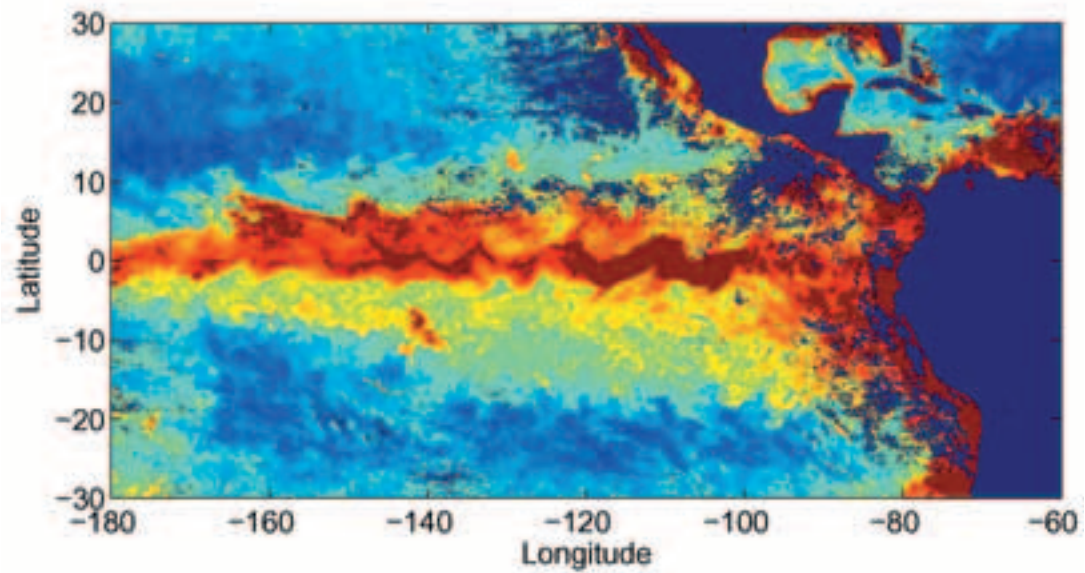## Features

Earth Simulator News

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Figure 1. *The distribution of chlorophyll in the eastern Pacific derived from a composite of data taken by SeaWiFS over the period 18–25 June 2003. Dark blue denotes cloud and land. The picture is dominated by the high production occurring in the Cold Tongue, caused by the upwelling of nutrient rich water. The imprint of Tropical Instability Waves is clearly visible, although there is structure down to the resolution of the instrument (4km).*
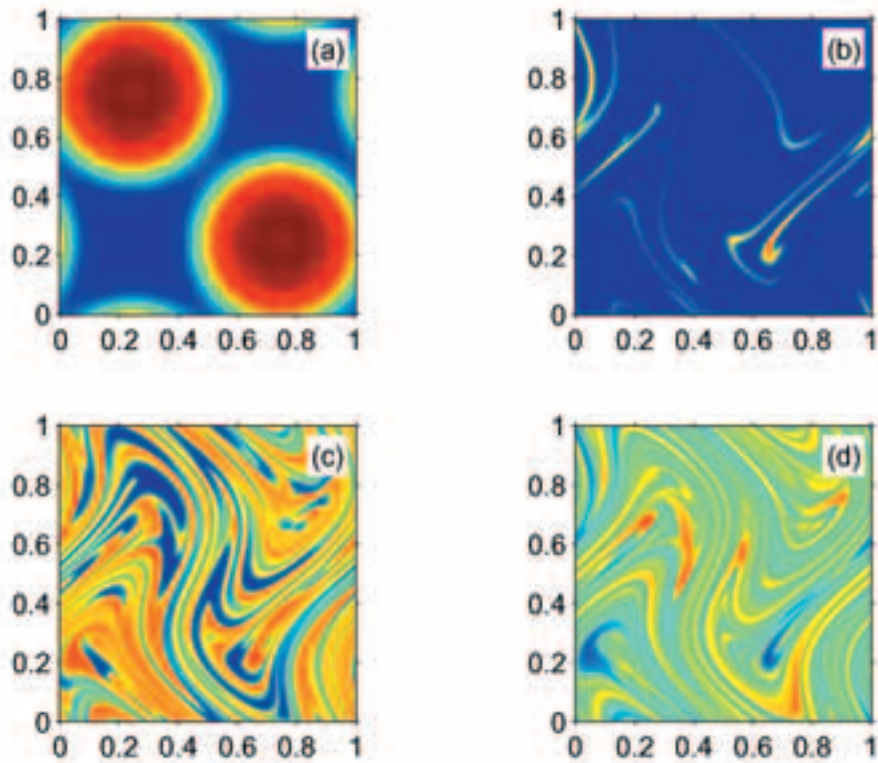

Figure 2. *Snapshots of the horizontal distribution of the phytoplankton concentration for different configurations of a simple ecosystem model. The size of the domain is arbitrary, but can be considered to be 100m–1km for oceanic relevant parameters. (a) With no stirring the system is dominated by reaction waves that spread the regions of high concentration (red) across the domain. (b–c) Stirring produces thin filaments of high concentration. The evolution of the system is dependent on the fraction of the domain that is initially susceptible to excitation, A_i. With A_i =10% (b) filaments are produced but the system does not become globally excited. Increasing A_i =25% (c) produces a global excitation. (d) In contrast to a reactive tracer, the filamentary structure produced by stirring an inert tracer has a smaller amplitude.*

2

Stirring and Mixing of Marine Ecosystems

T he ocean's plankton community sustains fish stocks and plays a key role in the Earth's carbon cycle. It also provides important feedbacks to the physical system of the upper ocean through light absorption and subsequent heating. Determining how the marine ecosystem will change in a changing climate is therefore imperative (see article by Hood, p. 12).

Observations of phytoplankton from space reveal a time-varying spatial structure on a vast range of scales (Figure 1). We can marvel at the richness of the structure, but it is not obvious how important the finer structure is. How does the spatial structure affect the functioning of the ecosystem as a whole? Does the heterogeneity of the system impact on the overall rates of production or the community structure, i.e. the species composition? Does the structure affect the way the biological system responds to changes to the environment? These are important questions.

Given the right conditions, which include sufficient light and nutrients, a massive growth of the marine algae occurs in a matter of a few days, referred to as the "spring bloom." The marine system is similar to a number of chemical and biological systems that exhibit excitable behavior in that a moderate size perturbation of the system can lead to explosive growth of one or more of the system's constituents. Much studied diverse examples include the Belousov-Zabotinskii chemical reaction, slime mould, and the beating heart. The production of phytoplankton, as part of the marine ecosystem, is another example.

A major difference between the marine ecosystem and the other previously mentioned excitable systems is that it exists in a fluid environment. The fluid flow affects the ecosystem in a number of ways including the movement of nutrients into the euphotic zone and the vertical mixing of species and nutrients. **Kelvin Richards**, professor of oceanography and co-leader of the IPRC research team on Regional Ocean Influences, is focusing on an often-ignored aspect—lateral stirring and mixing. Large-scale (order 10–100 km) eddying motions stir the distribution of individual species down to a length-scale where mixing and reaction with other species and nutrients can take place. In the surface mixed layer of the ocean, where the mixing is caused by the three dimensional turbulence created by wind and buoyancy forcing, this mixing, or diffusive, length-scale will be typically a few tens of meters.

Snapshots from four different runs of a simple ecosystem model are shown in Figure 2. The combination of reaction, diffusion, and stirring produces effects that each activity cannot produce by itself. With reaction and diffusion alone, the system can support waves of reaction that travel at a speed related to the reaction rate and the diffusion coefficient. The importance of these waves is shown in Figure 2a. Emanating from a small patch where the system is excited (i.e. both phytoplankton and zooplankton have high values), reaction waves sweep through the whole community so that in a relatively short time the entire domain is excited, called a "global excitation." Stirring produces thin filaments (Figures 2b–d). The width of individual filaments, w_f, is controlled by the strain rate, diffusion coefficient, and reaction rate. The amplitude of the filaments can be enhanced if the reaction rate is fast enough (compare Figures 2c and d).

There are a number of timescales in the problem, but the timescale that determines whether or not the system becomes globally excited is the mix-down time, T_m, which is the time it takes for the stirring to reduce the length scale of a patch initially of size L_p down to the width of a filament, w_f. If T_m is too short compared to the reaction time, any inhomogeneities in the system will be mixed away before significant reaction takes place, and the system does not become excited. For longer mix-down times, the stirring and mixing produces global excitation. There is a twist in the tale. If the mix-down time is too long (if the diffusion coefficient is very small, for instance) reactions will have taken place before any significant mixing takes place. The result is again a weak response of the system.

The ecosystem and flow field used here have been chosen to be particularly simple in order to elucidate the more fundamental aspects of the problem. The results, however, will provide insight into the workings of more complex systems as they are considered.

These findings demonstrate the important role stirring and mixing has in the way a marine ecosystem behaves. Ignoring such effects may lead to erroneous results when "fitting" an ecosystem model to observations. At present these effects are not included in ecosystem models embedded in ocean general circulation models. The challenge and next step are to find ways of doing so.
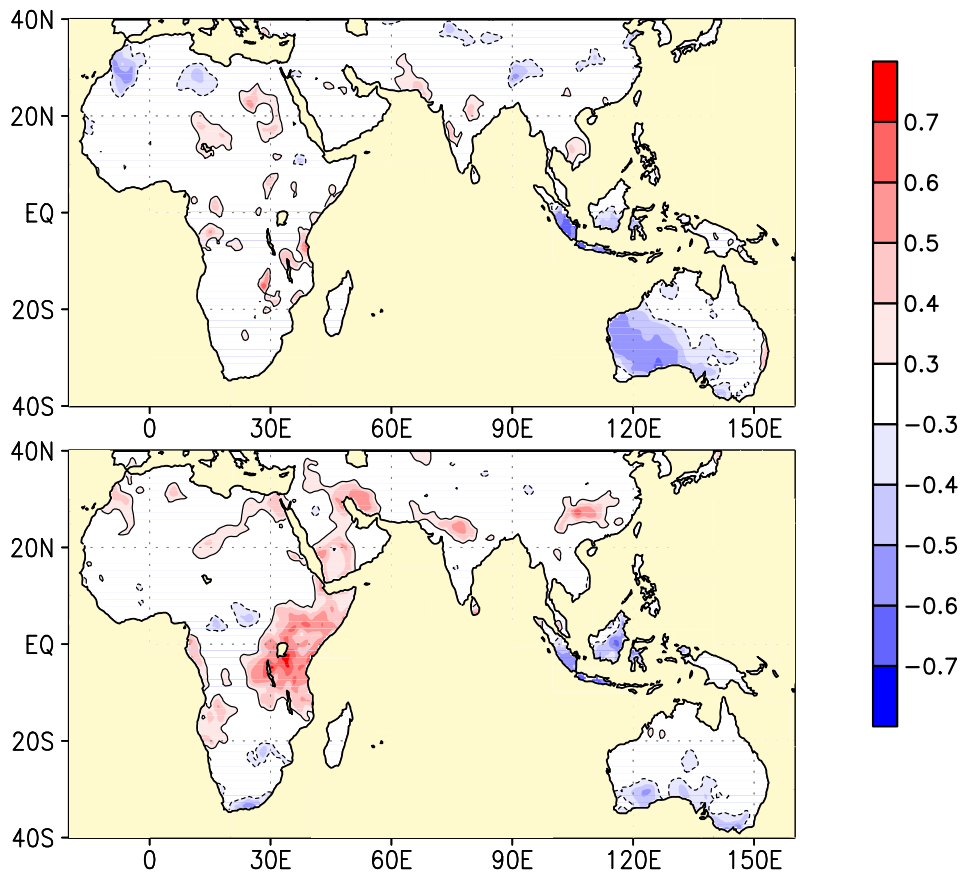
Figure 3. Correlation between the Dipole Mode Index (DMI) and rainfall over land from June through August (top panel) and from September through November (bottom panel). The DMI is defined as the monthly SST anomaly difference between the western (60ºE–80ºE, 10ºS–10ºN) and the eastern (90ºE–110ºE, 10ºS to the Equator) Indian Ocean, where the monthly SST anomaly for each region is the deviation of each month's SST from the average monthly mean for each region from 1958 to 1997.

Figure 4. Correlation between the Dipole Mode Index and land temperature anomalies from June through October.

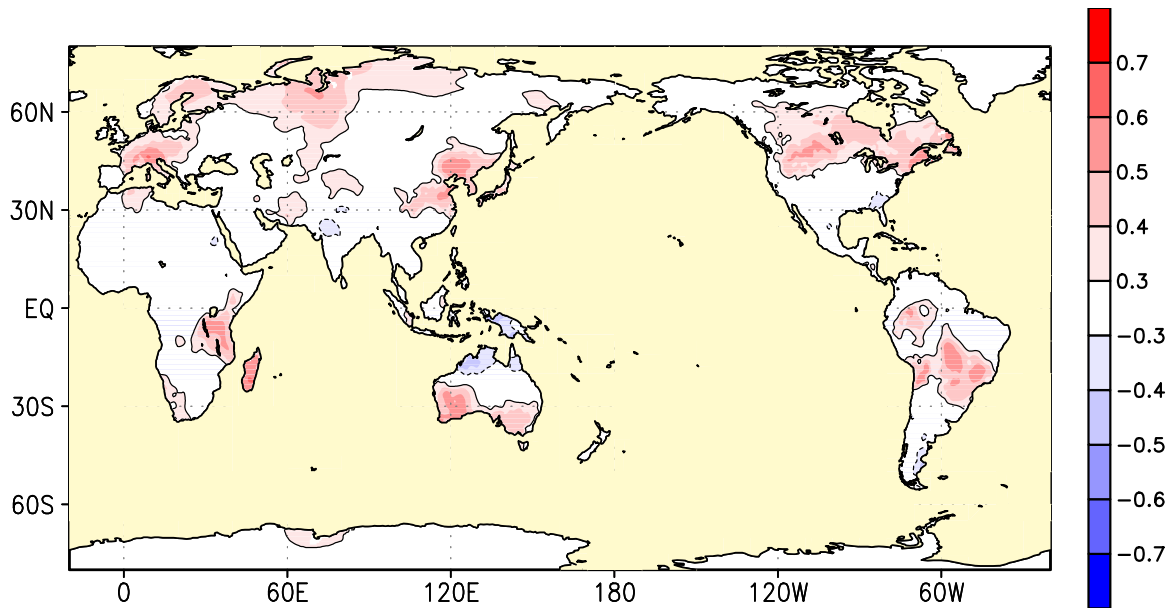# Indian Ocean Temperature Patterns Affect Climate

Until recently, climate researchers viewed sea surface temperature (SST) variations in the Indian Ocean merely as a thermodynamic response to atmospheric flux changes remotely forced by the El Niño-Southern Oscillation (ENSO). The consensus was that the Indian Ocean does not affect climate, and that its SST variations from one year to the next are not useful for seasonal prediction of such things as monsoon rainfall.

New research, however, is challenging this long-held view. On subseasonal as well as interannual timescales, structures in SST variability have been recorded that imply this ocean does influence climate. For example, modeling studies by **Xiouhua Fu** and colleagues at the IPRC have revealed that the ocean-atmosphere coupling in the Bay of Bengal is significant in predicting the wet and dry spells during the summer monsoon.

Interannual variations in Indian Ocean SST are also becoming important for climate prediction. **N.H. Saji**, a researcher with the Indo-Pacific Ocean Climate Team at the IPRC, and **Toshio Yamagata**, Frontier Program Director for the IPRC, along with researchers from the Indian Institute of Science, have noted large variations in the east-west SST gradient along the equatorial Indian Ocean. They termed the occurrence of a steep SST gradient "Indian Ocean Dipole" or IOD event. Analyzing observations, they found that positive IOD events are brought about by anomalous cooling of the eastern Indian Ocean, closely followed by anomalous warming of the western Indian Ocean. The opposite sequence, namely, negative IOD events with cooling in the western Indian Ocean and warming in the eastern, also occurs.

Modeling studies suggest that the evolution of this pattern is coupled to surface winds. When the surface wind is unusually easterly, the thermocline becomes shallower in the eastern, and deeper in the western Indian Ocean. The air-sea interaction results in a positive feedback loop between the induced SST anomaly and the easterly surface winds. Thus, once an IOD event is triggered, the anomalies may maintain themselves or even amplify (see also p. 7).

A strong SST dipole in the Indian Ocean typically persists for two to three seasons, from boreal spring to early winter. In a further study, Saji and Yagamata speculated that because these events occur in the warm pool region, where the atmosphere is highly sensitive to SST, they might affect local and distant climates. Analyzing observational data, they found that, indeed, positive IOD events are closely associated with floods over East Africa, northwest India and Sri Lanka, and with droughts over western Indonesia and southwestern Australia, while the opposite conditions are observed during the negative phase of IOD events (Figure 3).

Saji and Yamagata looked also at how IOD events impact distant climates. Figure 4 shows the association between land temperatures and IOD events, the effects of ENSO on Indian Ocean SST and on land temperatures being controlled for by means of a multiple regression analysis. The closest association between the IOD and land temperatures is over Brazil, where the partial correlation coefficient is +0.7. Correlation coefficients of +0.5 or greater are seen over parts of East Africa, southern Europe, northeast Asia and North America. Their analysis suggests that positive IOD events are associated with unusually warm temperatures and negative events with unusually cool temperatures in the extratropics. Since these results are similar to the composite world map of temperature anomalies observed during the absence of El Niño events (not shown), the correlations in Figure 4 appear to reflect a real link between IOD events and the observed temperatures.

Modeling studies are investigating these associations further. For instance the impacts of IOD events on India and Australia have been simulated using an atmospheric general circulation model (GCM), forced by prescribed SST (Ashok et al., 2001; 2003). The other local and remote impacts still remain to be dynamically verified.

These findings hold promise for predicting seasonal climate in the region based on Indian Ocean SST variations. The feasibility of such prediction depends on two conditions: (1) The dynamical simulation of the atmospheric response to IOD events given prescribed SST forcing. (2) Early prediction of the onset of IOD-related SST anomalies. Several coupled GCM studies have successfully simulated IOD-like variability, and one simulation (Wajsowicz, 2003) hinted at predicting IOD events at least 3 months in advance. Together these studies are throwing light on the air-sea interactions generating IOD events and their climate effects.
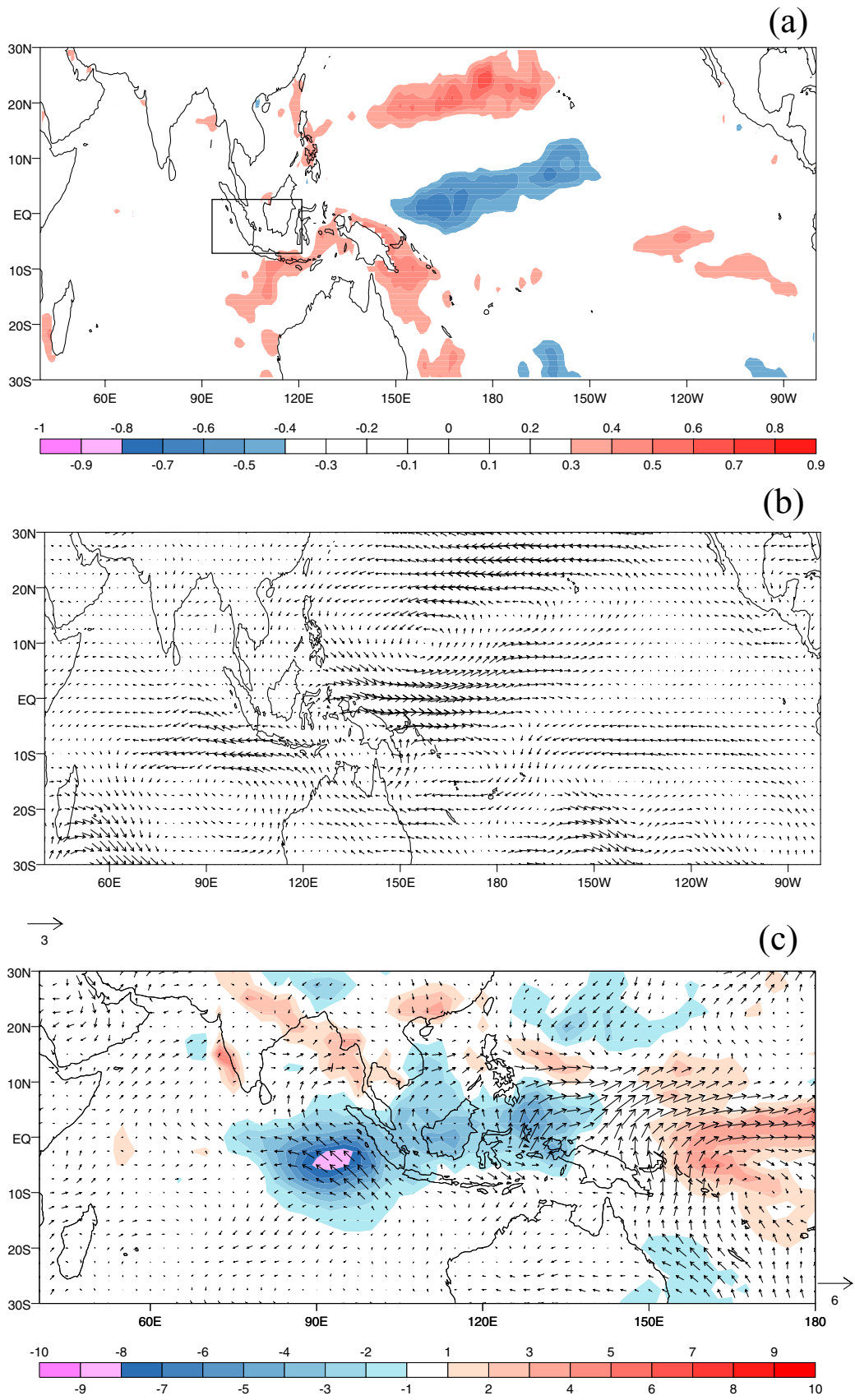
Figure 5. *Simultaneous correlation between spring anomalous precipitation over and near Sumatra (shown in box, 90ºE-120ºE, 10ºS to the equator) and (a) SST, (b) surface winds. (c) Composite anomalous precipitation and surface winds during July-August of years with a strong zonal mode.*

Indian Ocean Climate and El Niño: A Two-Way Affair?

The cold upwelling that occasionally occurs off the eastern coast of Sumatra changes the climate of the region. Such unusual cooling, termed by some the "Indian Ocean Zonal Mode," may or may not be accompanied by a large contrast in sea surface temperature (SST) between the western and the eastern Indian Ocean, the "Indian Ocean Dipole" described on p. 5. Is the upwelling off Sumatra due to local winds, due to westerly wind bursts in the Pacific associated with El Niño events, or due to equatorial waves in the Indian Ocean? And do conditions in the Indian Ocean feedback to the Pacific?

H. Annamalai, who is with the Asian Australian Monsoon Research Team at the IPRC, has been conducting research to answer these questions. He spearheaded a project with **R. Murtugudde**, and IPRC researchers, **Jim Potemra**, **Shang-Ping Xie**, **Ping Liu**, and **Bin Wang** to search for the precursors of the unusual ocean cooling (1 standard deviation cooler than the mean temperature) off the Sumatra coast. Using atmosphere and ocean model-assimilated products together with rainfall data and model estimates of the Indonesian Throughflow transport, they looked at how the El Niño, the Throughflow, and the monsoon affect the upwelling.

The diagnostics conducted by the team showed that in the Indian Ocean there is a natural air-sea coupled mode with weak cooling off Sumatra. During a window from spring to early summer, this natural cooling can intensify, should El Niño-like conditions prevail in the central Pacific. This is because precipitation during spring over and near Sumatra is low in response to the SST anomalies occurring in the Pacific (Figure 5a).

The following sequence appears to happen: Warm SST anomalies in the central Pacific move the descending branch of the Walker circulation westward, inducing subsidence and suppressing rainfall over the equatorial Indian Ocean. This negative heating anomaly results in a Rossby wave that forces an anticyclone in the lower atmosphere of the southeastern Indian Ocean. This anticyclone is accompanied by alongshore winds causing upwelling off Java and Sumatra (Figure 5b). These stronger easterly winds force changes in the ocean currents and raise the thermocline, bringing cool water to the surface and reducing rainfall. These changes, in turn, strengthen the easterly winds, which then lead to the zonal mode.

Sensitivity experiments with an atmospheric general circulation model (GCM) support the hypothesis that the sea surface temperature in the equatorial western and central Pacific affects spring rainfall over the equatorial Indian Ocean. The cooling of the ocean surface off eastern Sumatra interacts with monsoon heating to the north, yielding increased rainfall along the monsoon trough in July and August (Figure 5c). The north-south heat gradient in the atmosphere favors a local north-south circulation that strengthens alongshore winds off Sumatra. The summer monsoon, therefore, may too have a role in the stronger upwelling.

Recently, Annamalai and a group of colleagues analyzed the circulation changes in the Indian and Pacific Oceans associated with the 1976–77 climate shift. From 1950 to 1976, El Niño events were accompanied by a basin-wide warm tropical Indian Ocean; from 1976 to 1999, El Niño events were usually accompanied by a strong Indian Ocean Zonal Mode. This shift was associated with a westward shift of a low-level anticyclone over the South China Sea and with considerably stronger westerly winds that occur during developing El Niño events.

Solutions obtained from both a simple atmospheric model and a comprehensive atmospheric GCM suggest that prior to the shift, the basin-wide warming of the Indian Ocean generates an atmospheric Kelvin wave associated with an easterly flow over the equatorial western and central Pacific. This easterly flow weakens the westerly winds associated with a developing El Niño. The strong east-west SST contrast that has occurred after the shift, however, does not generate a significant Kelvin wave, and the El Niño-induced westerlies are little affected and remain strong.

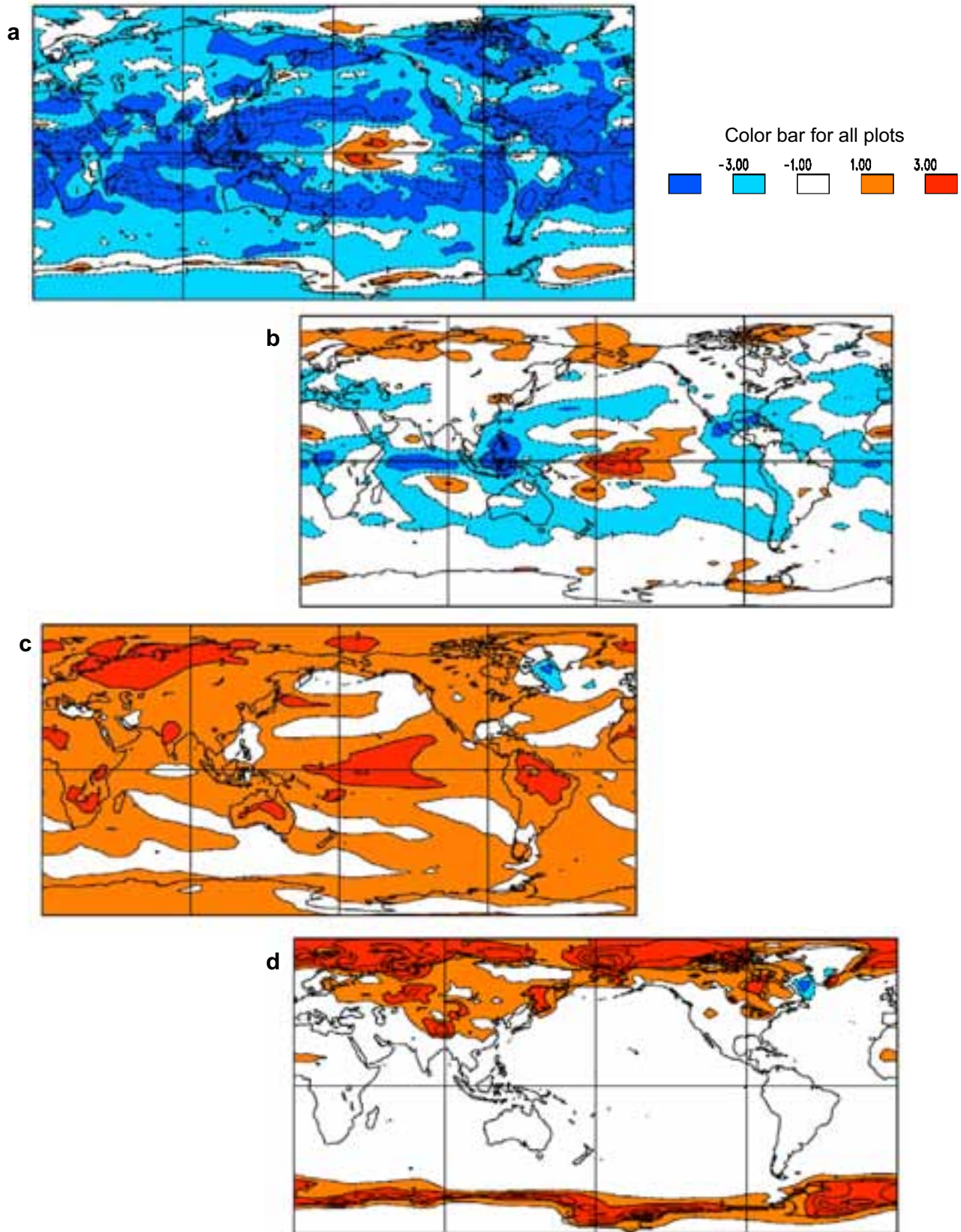**Figure 6.** *Diagnosis of the geographical distribution of local radiative climate feedback, λ, in the NCAR climate System Model. The shading key is labelled in W⁻² K⁻¹. Results diagnosed from a control run and a warmed earth experiment with an increased solar constant: (a) total feedback, (b) feedback from cloud processes, (c) feedback from changes in the clear sky atmosphere, and (d) feedback from surface albedo changes.*

Local Feedbacks and Global Climate Sensitivity

How much the global surface temperature will rise with increasing atmospheric CO_2 concentrations is still uncertain. The Intergovernmental Panel on Climate Change (IPCC 2001) has reviewed the predictions in response to a CO_2 doubling in 20 state-of-the-art coupled atmosphere-ocean climate models and found increases ranging from 2.0 to 5.1°C. The reasons for the large differences among the model simulations of global warming are not well understood. Conventional wisdom would suggest that the differences reflect the various ways in which the models parameterize convective and cloud processes, but a detailed understanding of how these parameterized processes affect climate sensitivity is lacking. The models may also differ significantly in their resolved atmospheric dynamics, water vapor transport schemes, and ocean dynamics.

As a first step to understanding these differences, **Kevin Hamilton**, leader of the IPRC Impacts of Global Environmental Change Team, is collaborating with **George Boer** of the Canadian Center for Climate Modelling and Analysis (CCCMA) on diagnosing local and global climate feedbacks in different climate models. They have begun with analyzing simulations obtained with the NCAR Climate System Model (CSM) under control conditions and under increased solar constant conditions (*IPRC Climate*, vol. 2, no. 2).

Hamilton and Boer define local feedback in terms of the changes in the radiative fluxes with the increased solar constant. For any column $dh'/dt = A' + R' = A' + R* + F$. Here h is the total heat stored in the atmosphere-ocean column, A is the convergence of the dynamical heat flux in the atmosphere and ocean, R is the net radiative flux (downward minus upward) at the top of the atmosphere, and the prime denotes the change in these quantities in a perturbed experiment relative to the control. The change in radiative fluxes can then be written in terms of the climate forcing, F, and the response, $R*$. The climate feedback parameter is defined as $R*$ divided by the surface temperature change in the warm experiment: $\lambda = -R*/T'$. The global climate sensitivity is s, where $s = <T'>/<F> = -<T'>/<\lambda T'>$, and $< >$ denotes a global average.

Global sensitivity, therefore, depends on the reciprocal of the global integral of an appropriately weighted local feedback parameter: Regions of positive feedback parameter increase the overall climate sensitivity, and regions of negative feedback decrease climate sensitivity. It turns out that the feedbacks in the NCAR model vary greatly with region, supporting the idea that the differences among models in the predicted increase in global surface temperature could be at least partly connected to differences in local feedbacks.

Figure 6 shows the feedback parameters for various components of the atmosphere as determined from a comparison of simulations with the NCAR CSM under control conditions and under a solar constant increase of 2.5%. Panel (a) shows the total feedback in adjusting to the warming. The most striking geographical variation in sensitivity is in the tropical Pacific, where the only major region of net positive feedback occurs in the central Pacific. Panel (b) shows the contribution to the feedback that can be attributed to cloud changes, while panel (c) shows the contribution that can be attributed to changes in the cloud free atmosphere, and panel (d) shows the contribution from changes in surface albedo. Not shown is the remaining contribution to the total feedback, namely, the infrared surface feedback, which is strongly negative everywhere.

Most of the geographical variation in the tropics seems to arise from the cloud feedbacks. The cloud response may be connected with a modest maximum in the surface warming that occurs near 160ºW. Interestingly, the structure of the feedback parameter in the tropical Pacific has similarities to that diagnosed in a global warming simulation performed by George Boer with the CCCMA global model (*IPRC Climate*, vol 3., no. 1), supporting the idea that local climate feedbacks are important in determining overall climate sensitivity.

Mysteries of Lightning

Tsutomu **Takahashi**, 2003 winner of the Fujiwara Medal of the Meteorological Society of Japan, is an expert on lightning, clouds, and rain. A professor at Obirin University, Japan, Takahashi visited the IPRC during May and June 2003 to collaborate with **Shang-Ping Xie**, co-leader of the IPRC Indo-Pacific Ocean Climate Team, on studies of tropical rain and its structure using *in situ* and satellite observations as well as modeling experiments. Takahashi is intrigued by recent results from the Lightning Imaging Sensor of the Tropical Rainfall Measuring Mission (TRMM) satellite: On the annual average, there are 100 times more lightning flashes over land and along coastal regions than over the open ocean, while precipitation shows little difference (Figure 7). Why is this?

Having researched lightning clouds for nearly 40 years, Takahashi is well-suited to address this question. "I was pushed into studying lightning by my professor," he recalls. "In the 1960s, when I did my dissertation at Hokkaido University, there were nearly as many theories about the charge-separation process in thunderstorms as there were researchers." Brook's group at the New Mexico Institute of Mining and Technology was then at the forefront of this research. They proposed that a large electrical charge is created during collision between graupel and ice crystals in the cloud, a process called "riming electrification." In the laboratory, they noted that ice crystals had a positive and graupel a negative charge—ice crystals are the light and pristine particles in clouds and graupel the heavier ice particles formed when ice crystals capture supercooled drops.

Takahashi decided to study riming electrification in natural clouds on top of Mt. Teine in Japan. "I found just the opposite: Ice crystals have a negative and graupel a positive charge. My professor couldn't believe the results and came up on skis to check the findings of his student!"

Why is there this difference in electric charges? Takahashi explored the mystery in the laboratory by systematically changing temperature and cloud water. He discovered that the charges of the particles depended upon temperature: Below -10ºC ice crystals are positively charged and graupel negatively; at or above this temperature, the reverse tends to be the case. In other words, the two particles reverse charge-signs with temperature.

The next question then for Takahashi was whether this charge reversal actually happens in natural clouds. He developed a unique videosonde system to study the life of particles and their electric charges in thunderstorm clouds. This sonde sucks in precipitation particles, an induction ring then measures their electric charge, and a video camera captures their image. With this tool, Takahashi could now look at the size and shape of the particles, and found that at –10ºC the graupel charge changes sign. The sonde also succeeded in measuring the basic tripole electric structure of lightning storms. The top, coldest layer, has a relatively high concentration of ice crystals and is positively charged; the middle, warmer layer, has both negatively charged graupel and ice crystals; the bottom, warmest layer, consists mainly of positively charged graupel together with frozen drops and raindrops.

Back in the laboratory, Takahashi studied the physical reason for the sign change at –10ºC. As graupel warms above –10ºC, it forms a liquid coating. This allows ice crystals to "steal" negatively charged hydroxyl radicals (OH) from the surface of the graupel, making the ice crystals negative and the graupel positive. At temperatures lower than –10º, the graupel surface becomes solid. When ice crystals bump into the solid graupel, branches break off the ice crystal and free hydrogen ions are formed that move from the warmer graupel side to the colder ice crystal side, giving the ice crystals now a positive charge and leaving the graupel negatively charged. These different riming processes also explain why around –10ºC there is an unusually large negative charge in the tripole charge distribution: Around this temperature the negatively charged ice crystals, which have stolen the negative charge from the graupel in the lower level and have been drafted upward, meet the negatively charged graupel falling from above.

To explore and confirm his findings, Takahashi developed a numerical thunderstorm model, the first of its kind. With this model he was able to simulate lightning and the importance of the tripole charge structure. The model also showed that a certain threshold concentration of ice crystals and graupel was necessary for lightning.
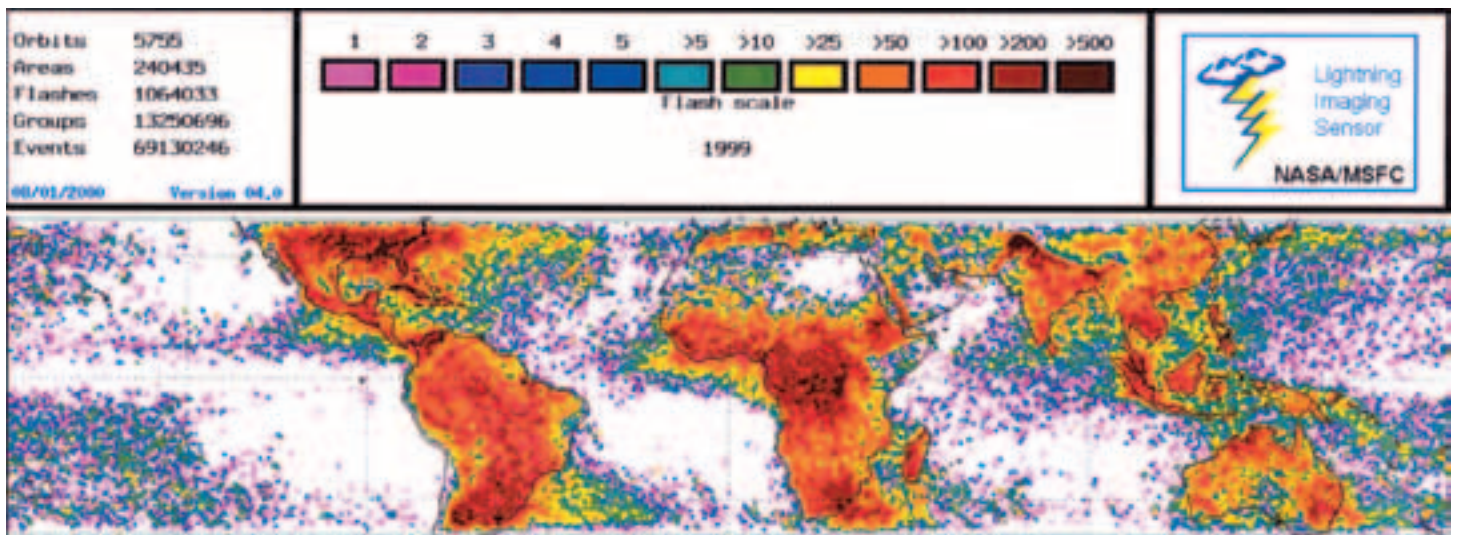
Figure 7. *The number of lighting flashes over land and over the oceans recorded by the TRMM Lightning Imaging Sensor. (Courtesy of the National Aeronautics and Space Administration)*

This research brought Takahashi to a further phase in his work. Why do the monsoon clouds over land regions produce so much more lightning than the monsoon clouds over the open ocean? In an ambitious project over the last 15 years, he launched 208 videosondes in 15 different sites, stretching from Pinliang in northeastern China to Ponape in the South Seas. When he looked at the concentration of raindrops, frozen drops, graupel, and ice crystals in every 500 meters of clouds, he noticed that the concentrations of these particles differed greatly from one station to the next. Moreover, he discovered that these different cloud compositions yield four different rain processes: warm rain, which has no ice particles at all and has rain drops of only about 2 mm in diameter; the frozen drop process, which has raindrops as large as 9 mm and results in intense and heavy, but short-lived rain; cool rain, in which particles grow mostly on ice crystals and graupel, forming drops about 3 mm and producing lighter rain; and mixed rain, in which the upper layer consists of graupel and the lower layer of frozen drops producing long-lasting, torrential rain.

Analyzing the distribution of these four processes for the 15 stations, Takahashi concluded, "Each region has its own recipe for making rain." A pattern, however, did emerge: Over the open ocean, rain tends to form with frozen drops. In a broad band along the coast of Asia, reaching from northern Japan to the maritime continent and northern Australia, rain tends to form through a combination of frozen drops and graupel, that is, mixed rain; in northern interior Asia (Pinliang), rain tends to form mainly with graupel.

These findings, together with the earlier finding that lightning needs high concentrations of graupel and ice crystals, provide an answer to the question posed by the TRMM measurements, Why is there more lightning over land than over the open ocean? The clouds over land consist usually of graupel and ice crystals concentrations large enough to produce the necessary charge for lightning; such clouds occur infrequently over the open ocean, where clouds and rain tend to form with frozen drops.

Takahashi recently developed a 3-dimensional numerical cloud model with explicit cloud microphysics. With this model he is now simulating the four rain processes and looking at how these processes affect cloud organization. Early findings show that frozen-drop clouds appear to be rather isolated clouds, while mixed graupel and frozen-drop clouds occur in a well-organized cloud system.

Clouds play a very important role in climate. With global warming, the global atmospheric circulation pattern may change. "For instance," Takahashi explains, "the descending branch of the Hadley Cell may move further north, and the warm maritime air mass might expand northward. Since the isolated frozen-drop clouds that form in this warm air mass produce sporadic and less rain than organized mixed clouds, severe water shortages in higher latitudes may occur."

The Need for Interdisciplinary Research in Ocean Science

Raleigh R. Hood
University of Maryland Center for Environmental Science, Cambridge MD
This article was contributed by Dr. Hood , who was a visitor at the IPRC from January to July 2003. He collaborated with IPRC Director, Jay McCreary, and with University of Hawaii Oceanography Department faculty on ecosystem, biochemical, and physical ocean modeling.

Perhaps the greatest research challenge we, the earth science research community, face today is developing the ability to predict how the ocean-atmosphere system will respond to increasing global CO_2 concentrations. It is almost certain that the ocean-land-atmosphere system will change drastically over the next century due to the effects of rising CO_2 levels and global warming, and these changes will likely have many negative consequences for life on earth. Yet, at present our ability to predict what the effects will be is limited because we do not fully understand the interactions between ocean and atmospheric circulation and ocean biogeochemical cycles. It is imperative that we develop the means to predict the future so that we can motivate the public and government agencies to take appropriate action. The fate of life on earth may depend on whether or not we can solve this problem in the next decade.

It is sobering to think about the significance of our own work as oceanographers in this context. Our research is often reductionist and discipline-specific, and the need for increased emphasis on interdisciplinary research is very clear. Yet, there are still many prejudices and barriers to doing interdisciplinary research in oceanography. Perhaps the biggest obstacle is training, i.e., virtually all of the major oceanography programs are still departmentalized along the traditional disciplines of biological, chemical, geological, and physical oceanography. The extensive use of discipline-specific scientific jargon exacerbates this problem, leading to the development of "disciplinary languages" that make it difficult to collaborate with colleagues in other fields. There is also pressure among academic scientists toward disciplinary reductionism, and an unspoken (and I would argue misplaced) belief that the most significant research questions in oceanography reside within, rather than at the interface of, these disciplines.

To do more cross-discipline research, we may need to change the culture and maybe even the structure of our academic institutions and our funding agencies. One obvious solution is through funding that requires interdisciplinary research. A good example of one such program is the U.S. Joint Global Ocean Flux Study (JGOFS) Synthesis and Modeling Project. The goal of this program has been to synthesize the observations from the U.S. JGOFS process studies into a set of coupled physical-biogeochemical models, with the ultimate goal of advancing the state-of-the-art in global carbon cycle modeling, a major tool for determining the carbon budget with rising CO2 levels and for predicting the land-ocean-atmosphere response. A fundamentally interdisciplinary endeavor, the project has attracted biologists, chemists, geophysicists, and physical oceanographers, and a mixture of observationalists and modelers, and it has fostered numerous interdisciplinary collaborations that have been very fruitful.

You may have guessed by now that my own research focuses on interdisciplinary problems. It was the impending start 10 years ago of the U.S. JGOFS Arabian Sea Process Study that initiated my collaboration with physical oceanographer and now IPRC Director, Jay McCreary. A biological oceanographer and modeler, I was a postdoctoral fellow at the Rosenstiel School of Marine and Atmospheric Science (University of Miami), working with open-ocean ecosystem models. At the time, there was considerable interest in developing coupled physical-biogeochemical models for the Arabian Sea to help guide future fieldwork in one of the most complex current systems of the world oceans. I began working with Jay on the problem of incorporating a simple biogeochemical model, a "NPZD" model—which focuses on the evolution of dissolved inorganic nutrients, phytoplankton, and zooplankton—into his 2.5-layer physical model of the Indian Ocean. This collaboration gave us significant insights into the relationship between ocean forcing processes and the ecosystem's response. Our paper (McCreary et al., 1996) provided the first basin-scale, coupled biological-physical model for the entire Arabian Sea region, and demonstrated clear links between phytoplankton bloom dynamics and physical processes that

are driven by the seasonal monsoon cycle, i.e., mixed-layer entrainment, detrainment, and upwelling (both coastal and offshore).

Jay McCreary and I have been working together on modeling the Arabian Sea ever since, with the NSF U.S. JGOFS Synthesis and Model Project providing support for our interdisciplinary modeling efforts over the last four years. Our second paper (McCreary et al., 2001) demonstrated that high-resolution surface wind forcing and a diurnal cycle are necessary to properly represent biogeochemical cycles and bloom dynamics in the Arabian Sea (and by analogy, many other places in the ocean). Our most recent efforts are summarized in a third paper (Hood et al., 2003), which focused on validating our physical and biological model results in "four dimensions" (x, y, and z space, and time) with the broad suite of physical, chemical, and biological data collected during the Arabian Sea Process Study. The major result that emerged from this effort was demonstrating that inaccuracies in surface wind forcing and the absence of mesoscale eddies and filaments in the model during the monsoons were responsible for most of the discrepancies between the biogeochemical model results and the observations. An important implication emerging from this work is that a simple NPZD-type biological model works remarkably well *as long as* the physical processes are properly represented. It appears that the proximate challenge we face in the Arabian Sea in our modeling efforts is the need to properly represent biogeochemically relevant physical processes in our physical model.

Looking back upon this work, it now becomes clear that many of our "discoveries" emerged because the biogeochemical model exposed problems in the physical model. Our biogeochemical model was particularly good at revealing whether or not the physical model was properly capturing vertical and horizontal variability in mixed-layer depth, which controls light and nutrient fluxes. Both of these are crucial determinants of phytoplankton growth and therefore of carbon uptake and export to the deep ocean. Coupled physical-biogeochemical models, thus, are important tools not only for predicting how the oceans will respond to increased CO_2 levels, but also for improving ocean models.

These conclusions are being reinforced by findings emerging from a related SMP-funded project with which I have been involved in the Arabian Sea. The project aims to devise the means to make quantitative comparisons between different biogeochemical models of different levels of biological and chemical complexity (Friedrichs et al., 2003). Such model inter-comparison work is a challenge. To overcome many of the problems inherent in such comparisons, we have developed, among other things, the means to force a large suite of models under identical forcing conditions and to force these models using the output from different physical models. This method allows determination of how different physical forcing sets influence biogeochemical solutions. An interesting and surprising finding coming from these studies is that in reproducing observations with these models, the complexity of the biological models does not seem to be as important as the physical forcing sets used. It is the physical forcing sets that provide the ultimate constraints on how different biological models perform. The message here is that in coupled biological-physical models, differences in the physical models appear to have a far greater effect on biogeochemical model performance than differences in the biogeochemical models themselves.

In conclusion, a key result emerging from our studies in the Arabian Sea is that most of the model and data discrepancies we have found are traceable to deficiencies in the representation of the system's physical state. Our biogeochemical models seem to be capturing the fundamental processes, but they are very sensitive to how physical models represent physical reality. Especially sensitive are vertical exchange processes, such as mixing and entrainment (see p. 3), diapycnal exchange, upwelling, and eddy perturbations. Thus, progress in realistic biochemical modeling, so important for understanding the carbon cycle, lies to a significant degree in more accurate representation of the physical state. This conclusion, I believe, applies not only to the Arabian Sea, but also to coupled biogeochemical modeling efforts in general.

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McCreary, J.P., K.E. Kohler, R.R. Hood, and D.B. Olson, 1996: A four-component ecosystem model of biological activity in the Arabian Sea. *Prog. Oceanogr.*, **37**, 117–165.

McCreary, J.P., K.E. Kohler, R.R. Hood, S. Smith, J. Kindle, A. Fischer, and R.A. Weller, 2001: Influences of diurnal and intraseasonal forcing on mixed-layer and biological variability in the central Arabian Sea. *J. Geophys. Res.*, **106**, 7139–7155. IPRC-72.

Global Atmospheric Modeling Using the Earth Simulator

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

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

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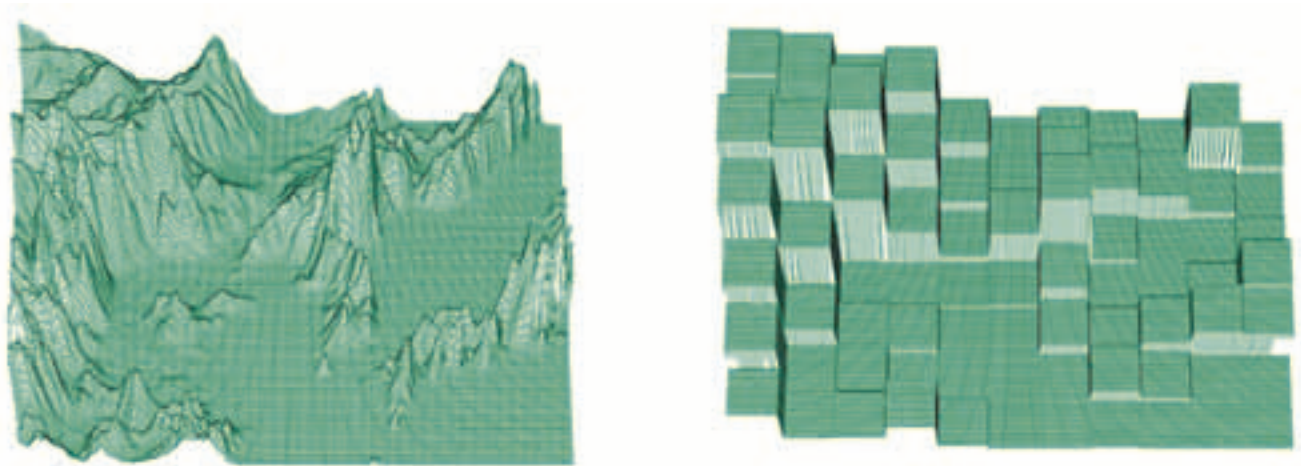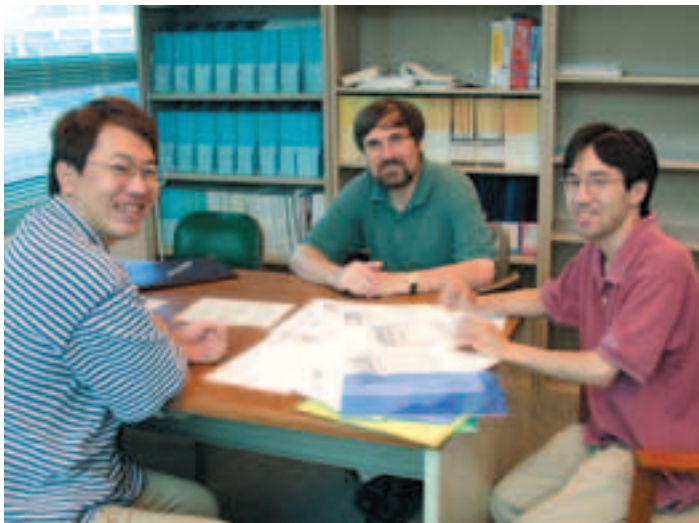

Figure 8. A northward-looking view of the topography of parts of East Asia: Southeast Asia is in the lower left corner, Korea near the center, and Japan on the right. Left panel: The topography in the T1279 version of the AFES model. Right panel: the mean values for grid squares with dimensions of about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

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

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

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

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

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

Wataru Ohfuchi, Kevin Hamilton, and Yoshiyuki Takahashi discussing results from the ultra-high resolution global atmospheric model for the Earth Simulator Center.
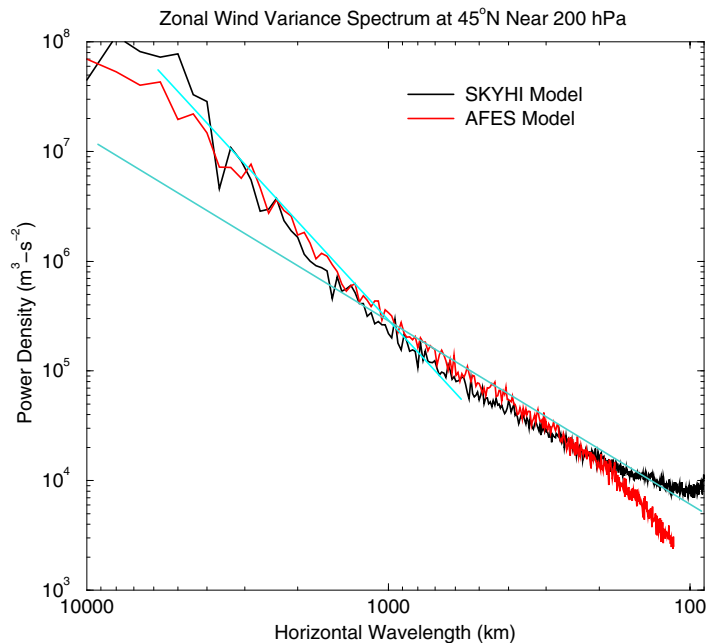
Koshyk, J.N., and K. Hamilton, 2001: The horizontal kinetic energy spectrum and spectral budget simulated by a high-resolution troposphere-stratosphere-mesosphere GCM. *Journal of the Atmospheric Sciences*, **58**, 329-348.

Global Ocean Modeling Using the Earth Simulator

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

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

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

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

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

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

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

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

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

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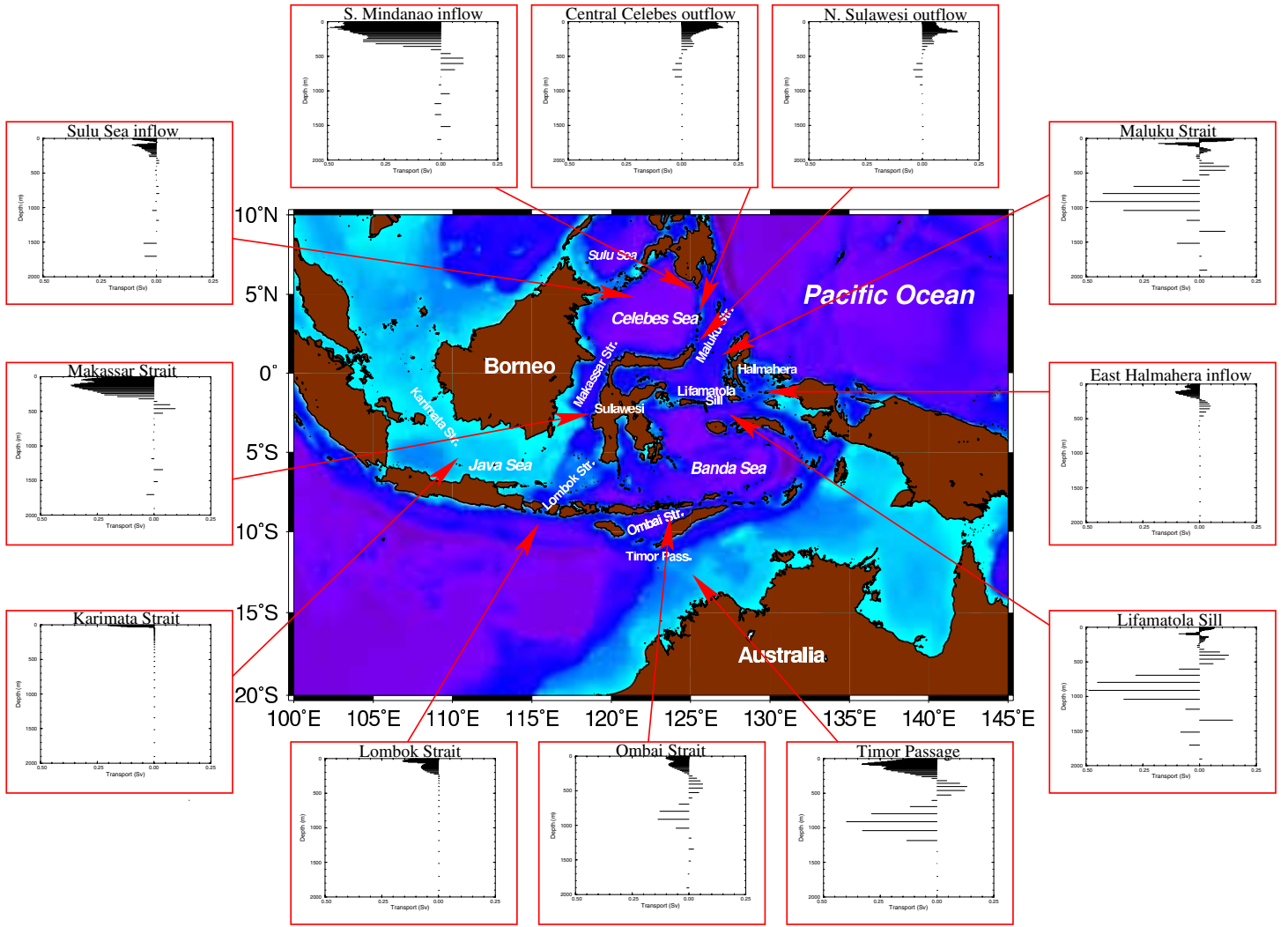
Figure 10. *A map of the main straits in the Indonesian seas together with bathymetry (5,000; 1,000; and 100-m depths are shaded). Depth-integrated transport from the OFES, as a function of depth, is given for selected straits. Negative values indicate southward or westward flow.*

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

the southern straits from June through August, during the southeast monsoon.

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

the southward flow is reduced, and in some cases, reversed. This flow could represent a significant freshwater source to the outflow of the Indonesian Throughflow, since precipitation is high throughout the Java Sea region.

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

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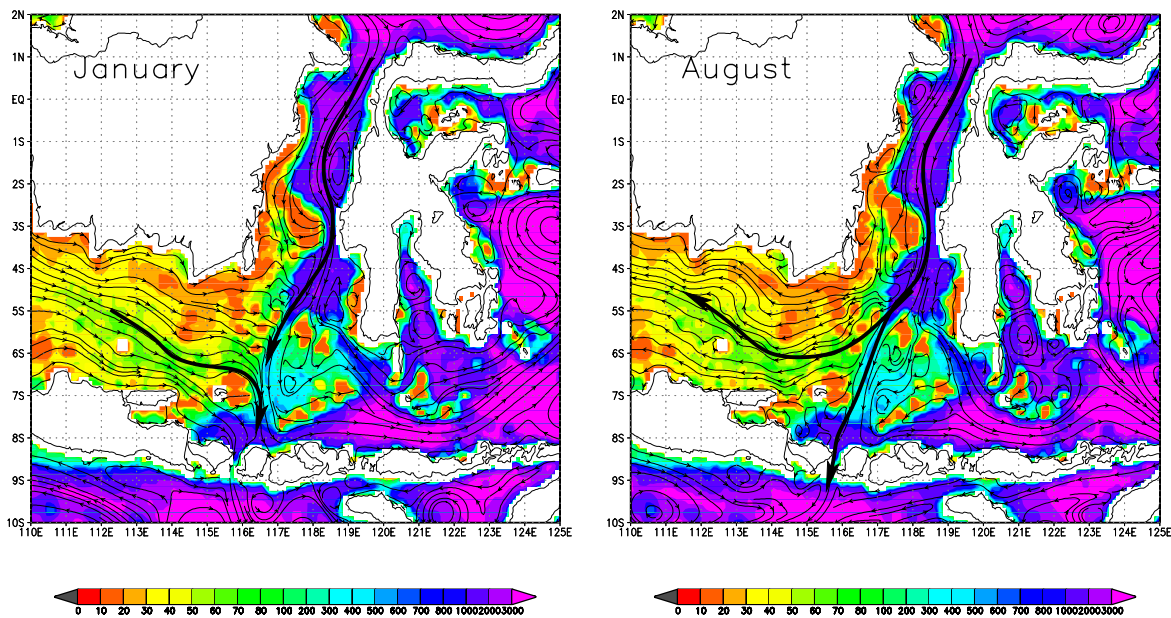

Figure 11. Upper-ocean flow (surface to 100-m depth mean) for January (left) and August (right) from the OFES. The color shading represents the model's bathymetry in meters (scale at bottom). The thick black lines with arrows highlight the directions of the flows.

18

Progress in Predicting Climate

How accurately can scientists forecast seasonal climate anomalies, such as dry or wet summers? What can be done to improve the predictive skill of climate models? These were the questions addressed by the two climate meetings hosted by the International Pacific Research Center at the East-West Center in Honolulu from November 3 to 7, 2003. The "Climate System Observational and Prediction Experiment (COPE) Workshop on Seasonal Prediction" and the "CLIVAR Working Group on Seasonal-to-Interannual Prediction" brought together experts from each part of the climate system: the atmosphere, ocean, land surface, and cryosphere.

"The main objective of the World Climate Research Programme (WCRP) is to answer the question whether climate is predictable," said Dr. Shukla, Director of the Center for Land-Ocean-Atmosphere Studies. "We really haven't answered that question yet. The only way that you can see whether climate is predictable is to predict it. This is why the Joint Scientific Committee of the WCRP decided on conducting the 'Climate System Observational and Prediction Experiment'."

The first task of COPE is to determine to what extent climate is predictable two weeks to a year in advance and what factors currently limit such predictions.

"No climate model yet exists that includes all the elements that scientists know influence climate," says Benjamin Kirtman, professor at George Mason University and chairman of the seasonal prediction project of COPE. The aim of the COPE working group is to make a road map for developing prediction models that include all aspects of the climate system. This is a very difficult process, according to Kirtman, since the coupled system behaves quite differently from what might be expected when each system is studied separately.

Another stumbling block is the paucity of quality climate observations needed to validate and initialize the models. For example, according to Randal Koster of the Goddard Space Flight Center, soil wetness, the climate memory of land, is important to a depth of 30 feet or deeper, but satellites can measure wetness just below the surface. Even straightforward rain gauge stations are far apart in many regions of the world.

Similarly, changes in the cryosphere must affect the atmosphere, ocean salinity, and circulation. Yet, according to Jens H. Christensen of the Danish Meteorological Institute, estimates of the cryospheric variables, such as the polar ice sheet mass, sea ice, and snow-depth, are still poor. Satellite altimetry measurements cannot directly measure the depth of snow or ice sheets, though some good correlations are now being obtained between satellite and submarine measurements of ice depth.

Kirtman felt strongly about the usefulness of COPE: "The experiment must be directly related to predicting events that are relevant to society, and we must be able to say what is predictable and what is not, given today's level of understanding. We'll go back and look at large climate anomalies over the last 30 years and see if we can predict them."

Andreas Villwock, International CLIVAR Project Office, hopes there will be considerable progress towards reliable seasonal predictions within the next 10 years. "This is only possible," he says, "with an international team of scientists who bring to the task knowledge of the various elements of the climate system."

The COPE Workshop was co-sponsored by the World Climate Research Programme, its subcomponent, the Climate Variability and Predictability Program, the Center for Land-Ocean-Atmosphere Studies, and the International Pacific Research Center.

*Participants of the COPE Workshop on Seasonal Climate Prediction.*

IPRC News

Toshio Yamagata Receives Sverdrup Gold Medal

Toshio Yamagata, Director of the Climate Variations Research Program at the Frontier Research System for Global Change and Frontier Program Director for IPRC, has been honored by the American Meteorology Society (AMS) "for his outstanding accomplishments in the study of ocean and climate dynamics, especially with respect to El Niño and air-sea interaction over the Indian Ocean." Yamagata received the AMS's 2004 Sverdrup Gold Medal at the Annual Awards Banquet held as a major event of the 84th Annual Meeting of the Society on Wednesday evening, January 14, 2004 in Seattle, Washington. Yamagata was also elected as a fellow of the AMS for his outstanding contributions to the atmospheric and related oceanic sciences.

Scientific Advisory Committee Meeting
October 23-25, 2003
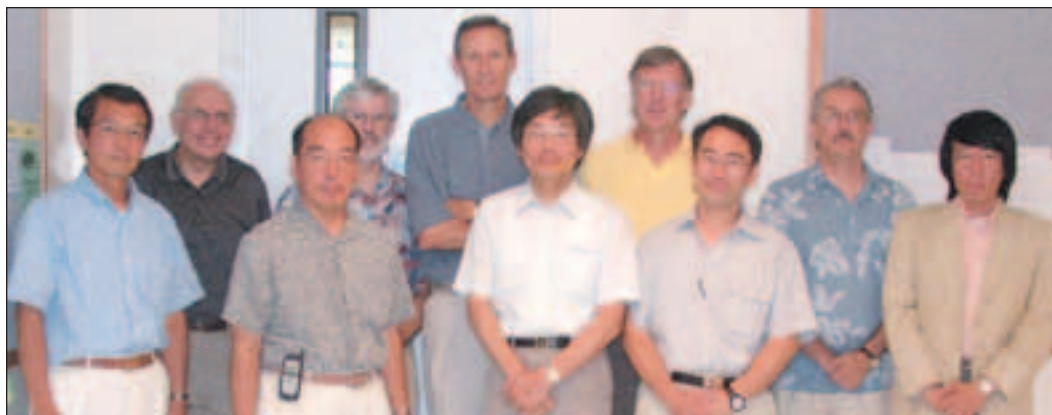
From left to right, back row: Roberto Mechoso (M), Julian McCreary, Jerry Meehl (M), Breck Owens (M), Antonio Busalacchi (Co-Chair); **front row:** *Hitoshi Hotta, Saichiro Yoshimura, Akio Kitoh (M), Ichiro Asanuma, and Atsushi Kubokawa (M). (M identifies committee members.)*

Team Leader Changes at IPRC

Niklas Schneider, Associate Professor of Oceanography, has become co-leader of the Indo-Pacific Ocean Climate Research Team, freeing Director **Jay McCreary** to spend more time on the expanding IPRC. **Kelvin Richards**, Professor of Oceanography, has become co-leader of the Regional Ocean Influences Research Team, replacing **Humio Mitsudera**, who left in spring 2003 for a professorship at Hokkaido University. The IPRC is grateful to **Peter Hacker** for his work as the interim co-leader of this team.

ICMA Elects President

Kevin Hamilton was reelected for a second four-year term as President of the International Commission for the Middle Atmosphere (ICMA), the organization in the IUGG structure that fosters international cooperation in the study of meteorology and atmospheric chemistry from the tropopause to the lower thermosphere. During Hamilton's second term, ICMA will have major roles in the scientific assemblies of the International Association of Geomagnetism and Aeronomy (2005, Toulouse, France) and the International Association of Meteorology and Atmospheric Sciences (2005, Beijing, China) and in the next IUGG General Assembly (2007, Perugia, Italy).

The Third IPRC Annual Symposium

The Third Annual IPRC Symposium was held May 22–23, 2003, in the Marine Science Building of the University of Hawai'i at Mānoa, Honolulu. During this annual event, the IPRC scientists presented their research highlights in a formal setting. It was a time to pause and reflect upon the research progress made by the institution as a whole and to identify areas for future research. This annual sharing is an opportunity to solicit comments and suggestions, and helps to reveal common research threads, which may prompt further collaboration among the scientists from the different IPRC research teams.

Niklas Schneider, co-leader of the Indo-Pacific Climate Research Team organized this third symposium. The topics of the 33 talks given at the symposium included studies of the Asian summer monsoon and prediction, Indian Ocean dynamics, Pacific Ocean variability and dynamics, its western-boundary currents, air-sea interactions that shape climate, climate sensitivity to large perturbations, and developments in the data-serving capabilities of the Asia-Pacific Data-Research Center. The agenda is posted at http://iprc.soest.hawaii.edu/meetings/workshops.html.

Little Islands, Big Wake

The article "Little Islands, Big Wake," which appeared recently on NASA's Earth Observatory (http://earthobservatory.nasa.gov/Study/Wake/), features the astounding effects of the Hawaiian Islands on the Pacific Ocean and atmosphere, an effect discovered by **Shang-Ping Xie**, IPRC co-leader of the Indo-Pacific Climate Team, and his colleagues. The team originally published their findings on the far-reaching effects of the small islands in the June 15, 2001, *Science* issue. The Earth Observatory article is based on an interview that **Laurie Schmidt** conducted with Xie and one of his co-authors, **Timothy Liu** from the Jet Propulsion Laborator. The article has also appeared in *Supporting Earth Observing Science 2003*, a publication of the NASA Distributed Active Archive Center Alliance.

IPRC Bids Sayonara

Weijun Zhu, postdoctoral fellow with the Impacts of Global Environmental Change Team, returned in August to China to become dean at the School of Graduate Study of Nanjing Institute of Meteorology (NIM), and associate professor in the Department of Atmospheric Sciences at NIM. He is teaching general atmospheric circulation to graduate and undergraduate students. His current research focuses on the influence of mid- to high-latitude general atmospheric circulation on the decadal variability of precipitation over East China.

Omer Sen, postdoctoral fellow with the Asian-Australian Monsoon System Team and implementer of the land-surface scheme into the IPRC Regional Climate Model, returned in August to his native Turkey, where he is awaiting a government position.

New IPRC Staff

Ryo Furue, who joined the IPRC in October 2003 as a postdoctoral fellow, came to oceanography in a roundabout way. Wanting to design car engines for a company such as Honda or Nissan, he entered the Department of Machine Engineering after completing his two years of general education at the University of Tokyo. But a course in fluid mechanics completely changed his future—he became fascinated with how a set of simple equations can account for infinitely varied phenomena.

Thus, after completing his courses in machine engineering in 1990, Furue switched fields and entered U. of Tokyo's School of Geophysics as a student of physical oceanography, which to him is a branch of fluid mechanics. Furue recalls: "People were puzzled about my switch; they just didn't see any connection between machines and the ocean. But to me the connection is clear—physics. People take up meteorology and oceanography because they are interested in such phenomena as hurricanes or ocean waves, and they study math and physics to understand those phenomena. For me it was the opposite: I got intrigued by fluid dynamics and its relationship to mathematics. I'm interested in physics not as a tool to understand phenomena, but in physics itself and how it is represented in oceanographic phenomena."

For his master's degree thesis, Furue applied the method of vertical modal expansion to the thermohaline circulation; for his Ph.D. thesis, he chose diapycnal mixing in the ocean, writing a 3-D spectral model for turbulence simulations. Three years before completing his Ph.D. in 1998, this youthful physicist, turned oceanographer, was appointed assistant professor at the Center for Climate System Research, U. of Tokyo.

The thermohaline circulation kept its charm and after finishing his dissertation, Furue studied the equatorial deep jets that appear in numerical solutions of purely thermal circulation. Recently he turned to researching the global circulation associated with North Atlantic Deep Water, in particular, the manner in which the global deep overturning circulation is affected by windstress over the Southern Ocean and by diapycnal diffusivity in the Indian and Pacific Oceans.

It still seems strange to Furue to call himself an oceanographer. "Oceanographers are people who go to sea to make measurements. I'm more of a 'computer oceanographer.'" At the IPRC, Furue will work with **Zuojun Yu** and the Indo-Pacific Ocean Climate Team. Using the U. of Tokyo's oceanic general circulation model, he will apply his expertise in numerical modeling and ocean dynamics to understand the equatorial subsurface currents, which are so important in ocean circulation.

Markus Stowasser joined the IPRC as a postdoctoral fellow in October 2003. Already as a child, he was fascinated by the weather and built a weather station in his backyard and did weather observations. So there was no question when he entered the University of Karlsruhe in Germany that he would study meteorology. After he received his "Diplom", the equivalent of a master's degree, in meteorology, he worked at the Forschungszentrum für Technik und Umwelt in Karlsruhe as a research assistant, while continuing his studies at the University of Karlsruhe, from where he received his Ph.D. in 2002. His dissertation research focused on stratospheric ozone depletion mechanisms for which he analyzed data from a balloon-borne Fourier Transform Infrared spectrometer that was specially tailored to operate on a stratospheric balloon gondola. This instrument allows precise limb emission sounding of chemical constituents related to the stratospheric ozone problem. Comparing the data to calculations with two 3-D Chemical Transport Models (CTMs) of the middle atmosphere, he found that state-of-the-art CTMs still have problems in simulating the diurnal cycle and the partitioning of several minor species of the nitrogen family. The accurate description of these species, however, is extremely important for the correct prediction of ozone-loss rates.

At the IPRC, Stowasser is working with **Kevin Hamilton**, leader of the Impacts of Global Environmental Change Team, on understanding why current coupled ocean-atmosphere climate models have such widely varying global climate sensitivities. He wants to understand why models differ and

what determines their sensitivity. He will also be looking at the geographical patterns of surface temperature sensitivity, and he will try to diagnose the role that ocean and atmospheric dynamics play in determining these patterns.

He plans to work also with **Yuqing Wang** on the effects of global warming on the intensity, number, and tracks of tropical cyclones. For this they will be applying the IPRC Regional Climate Model (*IPRC Climate*, Vol. 1, Fall; Vol. 2, no. 2).

Chi-Yung Francis Tam joined the IPRC as a postdoctoral fellow in November 2003, after completing the Ph.D. program in atmospheric and oceanic sciences at Princeton University. His dissertation is about the impact of the El Niño–Southern Oscillation (ENSO) on atmospheric intraseasonal variability and synoptic-scale disturbances. His results indicate that in the tropics, the extent of the eastward propagation of the Madden-Julian Oscillation (MJO) is greatly affected by ENSO. This is mainly due to the different SST conditions in the central-eastern Pacific during different phases of the ENSO cycle. In particular, further eastward penetration of the MJO-related convection anomalies is associated with warmer SST in the central-eastern Pacific and less penetration, with colder SST in the region. ENSO also influences the intraseasonal circulation in the North Pacific and North America. This latter influence is seen in both the amplitudes and patterns of typical circulation anomalies in the region. The influence on the circulation anomalies in the North Pacific and North America is partly due to changes in the extratropical mean state of the atmosphere during ENSO, and partly due to the impact of ENSO on the characteristics of the MJO-associated intraseasonal convective anomalies in the western Pacific.

At the IPRC, Tam is working with **Tim Li** and **Bin Wang**, co-leaders of the Asian-Australian Monsoon System Team. He plans to study the role of summertime, synoptic-scale activity on the formation of tropical cyclones by using high-resolution observational products such as data from the QuickSCAT satellite and products from the Navy Operational Global Atmospheric Prediction System (NOGAPS). The tropical cyclone research topic is related to the part of his dissertation about synoptic-scale disturbances in the tropics. "In my student days in Hong Kong," Tam recalls, "I was always excited by the phenomenon of tropical storms…because schools were closed when there was a typhoon approaching. I still find the phenomenon very exciting—of course for a rather different reason now."

Hiroshi Yoshinari joined the IPRC in late November 2003 as a postdoctoral fellow to work on a project funded by NOAA and the Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT). Yoshinari's fascination with physical oceanography came while he was a science major at the University of Ryukyus, Okinawa. "They had a great oceanography laboratory there," Yoshinari recalls. "The ocean is so much harder to research than the atmosphere where you can use radiosondes, airplanes, and satellites to take measurements; making measurements in the ocean is much harder." Accordingly, he sees *in situ* data as very important for oceanographic research and has been already on 7 ship cruises. One was in 1996, to obtain Mixed Water data in the Kuroshio-Oyashio region for his master's degree research on the formation, modification, and transport of North Pacific Intermediate Water. On his cruise in 1998, which took him to Hawaii, he collected data for his dissertation on the meridional transport of North Pacific Intermediate Water across 37°N. During these trips, he learned methods of collecting physical, chemical, and biological oceanographic data from ships and mooring systems and their analysis.

Upon obtaining his Ph.D. from Hokkaido University in 2001, Yoshinari worked at the Japan Science and Technology Corporation in Kawaguchi, Japan, on a project that studied the effects of winds on the interannual transport variations of the Kuroshio south of Japan. "For six months I tried to drive this OCGM (the GFDL-MOM2.2) without success; every day I checked and corrected the source code. Finally the goddess smiled on me, and the model ran smoothly, and some of the results are now in press." His next project was a study conducted by MEXT for which he was to collect all available hydrographic data for the Arctic oceans, a rather frustrating task: "I wrote so many emails—to Russia, to Scandinavia—but there is no data."

At the IPRC, Yoshinari is working in the Asia-Pacific Data-Research Center. Having developed in his previous research a way to use geostrophic velocity as a reference in statistically adjusting the velocity measured by Lowered Acoustic Doppler Current Profilers, he now aims to create a correction system for the velocity measurements made by Argo floats. The measurements of velocity taken by these floats as they sink and rise on their journey in the ocean's depths are quite noisy. Measures derived from satellite sea surface height data and wind data will serve as benchmarks for Yoshinari's calibration system.

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