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.

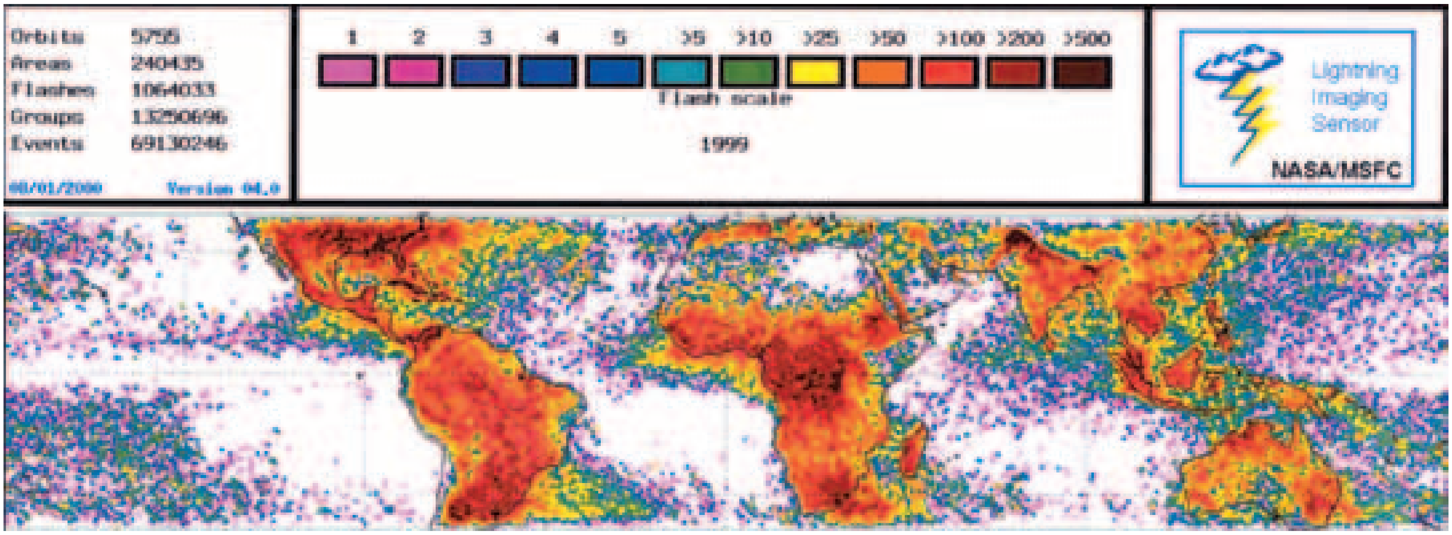

Figure 7. *The number of lighting flashes over land and over the oceans recorded by the TRMM Lightning Imaging Sensor. (Courtesy of the National Aeronautics and Space Administration)*

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

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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 intercomparison 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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