the lava's melting temperature at surface pressure. However, for lava at 1870 K to have a basaltic composition (with liquidus melting temperatures ~1400–1550 K at 1 bar), the magma would have to ascend rapidly from nearly 1,000 km deep with little cooling in transit. Though no record of such an eruption exists on Earth, magma may have erupted from nearly such depths on Earth's moon. Alternatively, Io's magmas could be heated near the surface by the electrical induction currents and plasma currents bathing Io. Heating in a tidally deforming dike is inadequate to heat basaltic lavas to the highest temperatures seen on Io, according to our calculations.

**Vapor distillation and "ceramic volcanism."** Lava outside the basalt-peridotite-komatiite system is conceivable due to Io's unique history of intense, high-temperature magmatic processing. The partial vapor pressures of SiO, Mg, Fe, FeO, and other gases of common oxide and silicate systems exceed nanobars at 1500 K and approach microbars at 1900 K [*Stolyarova and Semenov*, 1994]. Vaporization of metals from hot lava can be significant when exposed on flow surfaces and through cracks in solidifying crusts, especially if fluxed by sulfurous volatiles. Vapor pressures and lava evolution due to fractional vaporization were calculated for the system Si-Na-K-Mg-Fe-Ca-Al-Ti-O (L. Schaefer and B. Fegley, Washington University, unpublished data, 2002). Results for an initial Barberton high-MgO komatiite at 1900 K are given in Figure 3. Initial vapors are dominated by Na and K (not shown) and oxygen species. Pressures of other gases, though lower, are orders of magnitude larger than Io's ambient surface pressure. Following rapid loss of alkalis, vapors are dominated by SiO, Fe, FeO, Mg, $O_2$, and O (Figure 3a). If metal and oxide vapors can be lost entirely from Io or cold-trapped at stable sites, compositional evolution of evaporated lava residues would affect igneous phase equilibria and the temperature of subsequent eruptions. Refractory lava residues lack the amounts of $SiO_2$ and FeO in common silicate lavas (Figure 3b) and may have extraordinary liquidus temperatures (Figure 3c).

### *Questions Still to be Answered*

The epic tour of the Jovian system by Galileo has expanded our vision of what is possible in this universe. Io has its own unique and hyperactive behavior that has been produced by and may have affected its global chemical evolution. Unsolved puzzles regard the range of silicate lava compositions and eruption temperatures and the mechanisms by which such large volumes of lava are transported through the crust. How can Io maintain its high magma temperatures without being almost totally molten? Is Io a crusted magma ocean, and if so, how does Io maintain a sufficiently thick and strong lithosphere to support mountains higher than Mount Everest? Is Io a refractory cinder-like body, like a giant meteoritic calcium-aluminum-rich inclusion (with added volatiles)? Why does Io have an extremely volatile, sulfur-rich surface, yet water, carbon dioxide, and many other volatiles are absent? How are we to reconcile Io's peculiar volatility with high-temperature global processing?

Future space missions and astronomical observations could give definitive answers to these questions.

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# MODIS Detects Oil Spills in Lake Maracaibo, Venezuela

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Starting December 2002, the oil industry operating in and around Lake Maracaibo in Venezuela suffered a series of accidents (Figure 1). Fires, the sinking of two barges, rupture of oil pipelines, spills from floating oil storage and transfer stations, and malfunctioning of oil extraction platforms led to extensive oil spills. Local and federal Venezuelan government oil industry experts directly observed the series of spills from aircraft, helicopter, and various surface vessels. The spills were recorded in December by official photography and video of leaking infrastructure, and unofficial recordings continued in January and February 2003 (http://www.comlago.com.ve/fotosvideos.html).

These surveys did not provide sufficient spatial or temporal coverage to assess the magnitude, area covered, or duration of the spills. Clear images of the spill were captured with NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), however. MODIS is effectively a sophisticated digital camera launched aboard the Terra satellite in December 1999, and aboard the Aqua satellite in April 2002 [*Esaias et al.*, 1998; http://modis. gsfc.nasa.gov]. Its medium-resolution bands (250 and 500 m resolution) are available to the public, and have great potential in coastal monitoring. This article demonstrates how MODIS can provide basic and critical assessments of oil spills.


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### *Remote Sensing of Oil Spills: Background*

Techniques for remote sensing of aquatic oil spills includes optical (passive visible and infrared, and laser fluorosensors), microwave, and radar (e.g., Synthetic Aperture Radar) approaches using aircraft or satellites [see reviews by *Fingas and Brown*, 1997, 2000]. Airborne assessments are limited by high cost. Satellites have other limitations. SAR data are expensive, are not available daily, and are limited by sea state [*Liu et al.*, 2000]. The optimal wind speed to effectively detect oil spill slicks by SAR is about 1.5 to 6 m/s. Other features, such as phytoplankton slicks and fresh water slicks, may present interference and cause false detection [*Lin et al.*, 2002]. Traditional satellite optical sensors (e.g., CZCS, SeaWiFS, AVHRR) have not been of much use for oil spill detection due to coarse spatial resolution (~ 1 km per pixel), lack of coverage, cloud cover interference, and lack of algorithms for data processing and interpretation [*Fingas and Brown*, 1997, 2000]. High-resolution optical sensors (e.g., Landsat ETM+, SPOT, IKONOS) do not provide daily observations, and the data with limited spatial coverage are expensive. Here we show that new optical sensor technologies provide an unprecedented capability for oil spill monitoring in marine environments.

### *MODIS Imagery of Oil Spills*

In the past, oil crude has been considered to have a higher surface reflectance than water in the visible region of the electromagnetic spectrum, but no distinctive spectral characteristics that would allow its differentiation from the background under solar illumination [*Fingas and Brown*, 1997; and references therein]. However, recent optical modeling by *Otremba and Piskozub* [2001, 2003] demonstrates that there is a reflectance contrast between an oil film on the sea surface and background turbid water, so that the oil film can be detected under appropriate solar/viewing geometry and wind speeds.

The problems of the oil industry in Venezuela received international news coverage (e.g., *The Miami Herald*, http://www.miami.com/mld/miamiherald/4993381.htm; Reuters News Service, http://www.planetark.org/avantgo/dailynewsstory.cfm?newsid=19401). On becoming aware of what had happened, we decided to examine the real-time MODIS data, collected and archived by an X-band ground station at the University of South Florida at St. Petersburg, to assess whether any pattern that might be related to oil spills over water in Lake Maracaibo could be detected.

We examined the medium-resolution (250- and 500-m) MODIS Level-1 total radiance imagery from 1 December 2002 to 9 March 2003. Of the 68 daily image sets (some gaps exist due to ground X-band antenna malfunction), over half contain cloud cover < 50%. About a dozen images showed patterns within Lake Maracaibo that we suspected could be extensive spill patches. Such patterns were visible even when significant Sun glint contamination was present.

We discounted the possibility that these features could be due to phytoplankton blooms, because such blooms occur mainly along the coast and near large population centers during the rainy season (April-May and October-November), due to runoff. The dark features observed in the MODIS data occurred during the dry season and away from the traditional areas of blooms. Further, there are ample direct observations that the features in the images correspond to oil-contaminated waters. Spectral analysis (see below) also suggests that these features are not due to algal blooms. A complete time series of these images can be found at http://modis.marine.usf.edu/products/maracaibo/.

Here we focus on a few examples for illustrative purposes. Figure 1 shows a 250-m resolution MODIS image illustrating the slicks of oil spilled in Lake Maracaibo. The slicks were detected because of their negative contrast relative to surrounding waters [oil slicks are darker; see *Otremba and Piskozub*, 2001]. Using the software, Environment for Visualizing Images (ENVI, Research Systems, Inc.©), we estimated the number of oil-contaminated pixels at ~2163, corresponding to an area of ~133 km². Some slicks may be masked by clouds, and therefore, the spill may be larger. Because of limitations of the print media, the full MODIS resolution is hard to appreciate in Figure 1. Smaller slicks are visible by displaying and zooming the image on a computer screen. Figure 2 presents more dark water features on 16 and 20 January 2003. Local authorities validated these features to be oil slicks. These covered ~138 km² (2244 pixels) and 136 km² (2216 pixels), respectively. The area covered by the spill was similar over about 5 days (16, 18, and 20 January), but the spatial distribution of the patches changed. Slicks on 16 and 18 January were located in the western part of central Lake Maracaibo. On 20 January, only one large patch (~ 32 km²) was observed in this location, but other patches were found in the eastern part of the lake.

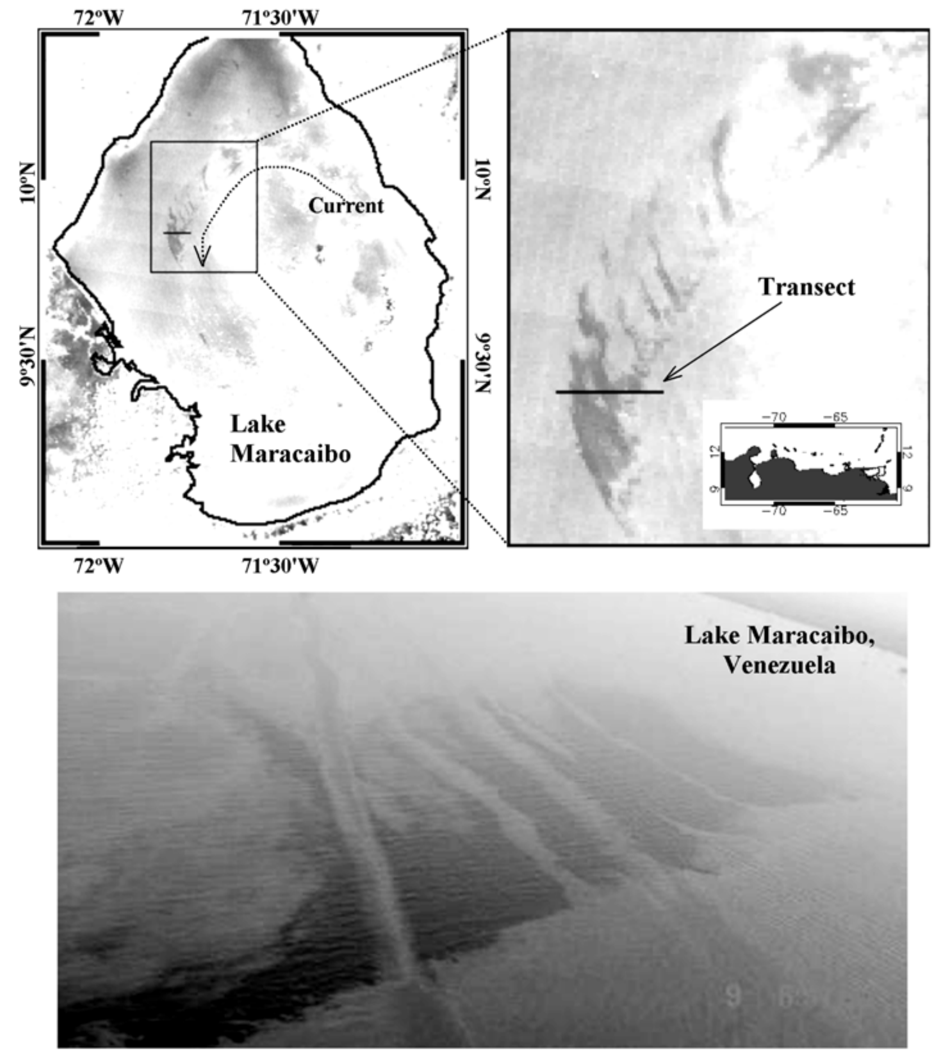


*Fig. 1. Oil spill slicks in Lake Maracaibo, Venezuela. From top left, clockwise: MODIS 250-m (620–670 nm) image taken on 18 January 2003 (white color represents clouds, land, or extreme turbidity near the coast; arrow with broken line indicates current direction, according to observation and numerical model simulations); enlarged image of the region of major oil slicks (even smaller slicks can be viewed at full resolution). Inset shows location of the lake. Bottom: airborne photograph (courtesy of Gobernación del Estado Zulia, Venezuela). Complete time-series of MODIS images are available at http://modis.marine.usf.edu/products/maracaibo/.*

Official reports of oil spills from drilling and storage platforms in eastern Lake Maracaibo surfaced only on 30 and 31 January 2003. The satellite images suggested that the oil spill event started earlier than reported. In an image taken 26 December 2002, we identified slicks similar to those in the 16 and 18 January images.

## *Optical Signature*

Of all the MODIS images examined, including those under direct Sun glint, none has shown positive contrast between oil spill patches and surrounding waters. The negative contrast suggested that the spill dispersed as an oil film floating on the surface, and not as droplets suspended in the water. The latter will always display positive contrast, regardless of wind speed and solar/viewing geometry [*Otremba and Piskozub*, 2003]. To better examine the contrast, the atmospheric radiance had to be removed to obtain the water-leaving radiance or surface reflectance. When first processed using the standard MODIS ocean codes (U. Miami/RSMAS), the large slicks showed positive contrast in water-leaving radiance data (1-km resolution), due to erroneous atmospheric correction. We knew that the standard procedure to remove atmospheric radiance from the data was inadequate for turbid water. We re-processed the data using atmospheric properties derived from within the dark oil patch, and applied those to the surrounding water [as per *Hu et al.*, 2000]. Figure 3 shows the reflectance before and after the atmospheric correction along a transect line drawn across the spill slick (Figure 1). Clearly, the contrast between the patch and surrounding waters was enhanced after proper correction. Any image-enhancing software can be used to contrast-stretch an image to help identify and trace a slick in MODIS data. However, proper atmospheric correction, as used here, provides meaningful geophysical data. Accurate radiances/reflectances offer the potential to derive oil film thickness, if a reliable empirical optical model has been established a priori with in situ measurements. For example, the contrast of the Lake Maracaibo slicks is higher than that found by *Otremba and Piskozub* [2001]. This suggests that the film may be thicker (i.e., have more absorption) than assumed in their simulations (5 μm). Clearly, the degree of turbidity underneath and around the patch also plays a role in deriving accurate results in such empirical approaches.

From the perspective of aquatic optics, and without any prior knowledge of local biogeochemical processes or oil spills, it would be difficult to identify the patterns observed as oil slicks. Phytoplankton blooms can be ruled out because of the reasons mentioned above, and because they would typically have a positive contrast at 555- and 645-nm due to elevated backscattering. The reflectance contrast at multiple wavelengths provides more information than SAR imagery, where phytoplankton bloom can also dampen the signal [*Lin et al.*, 2002]. Yet it is currently not possible to establish an automated feature recognition system that identifies oil spill events. External knowledge about the region, environment, and current events needs to accompany visual examination of the satellite imagery to discriminate between various events.

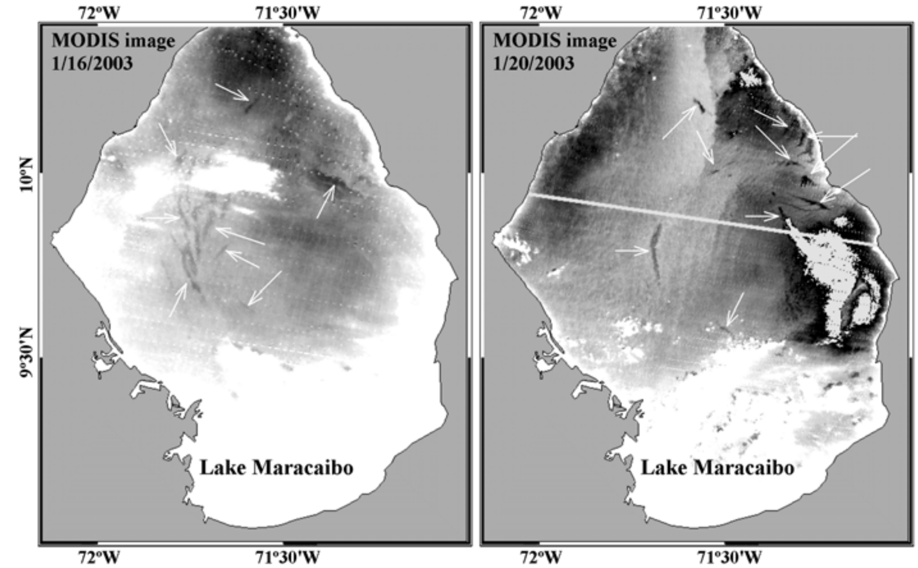


*Fig. 2. MODIS images (841–876 nm) showing oil spill slicks in Lake Maracaibo. Major slicks are marked with arrows. White color represents clouds or extreme turbidity near the coast. Many smaller slicks can be viewed by displaying the image at full resolution.*

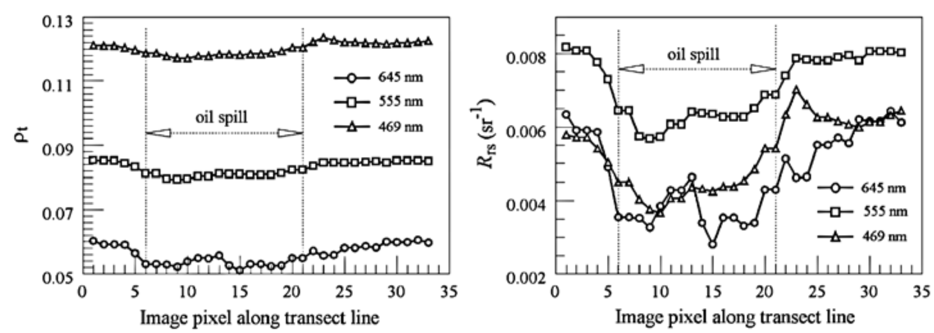


*Fig. 3. At-sensor reflectance (left) and surface remote sensing reflectance (right) for several MODIS bands across the transect line shown in Figure 1. Each pixel is about 250 x 250 m² in size (the 555- and 469-nm data are interpolated from the original 500-m resolution).*

## *Future Directions*

Traditional satellite ocean color sensors typically have ground resolution of about 1 km, making it difficult to detect small features such as oil spill slicks. In contrast, the medium-resolution (250- and 500-m) MODIS channels show great potential for daily monitoring of the coastal environment because of their unprecedented synoptic and repetitive coverage with fine resolution. Our findings show that there is no good reason to continue minimizing the potential of optical satellite sensors to detect oil spill events. We now need to develop strategies to fully integrate these satellite sensors into our incipient Integrated Ocean Observing System (http://www.ocean.us). Our vision is one in which automated sentinels issue alarms for events like oil spills or harmful algal blooms [*SWFDOG*, 2002]. At this stage, intelligent interpretation from a well-trained remote sensing practitioner is required, but we need to develop both stable and accurate radiance products, as well as good empirical algorithms for coastal zones, so that reliable sentinels can be constructed. The medium-resolution MODIS imaging bands were designed for land. Quantitative use of these bands for coastal water monitoring still needs to be investigated. In particular, reliable, operational atmospheric correction and bio-optical inversion codes need to be developed to obtain surface reflectance and the associated water parameters, such as suspended sediment and chlorophyll concentrations.

As of August 2001, 49 MODIS direct broadcast (DB) receiving stations were active worldwide, with 14 of these in the United States (http://rsd.gsfc.nasa.gov/eosdb/). This infrastructure allows repeated coverage of a significant portion of the globe's coastal areas. At the University of South Florida, we are generating online, interpreted, medium-resolution products that are tailored to support coastal resource managers, educators, and the public. We find the EOS platforms to be excellent for developing science-based applications in preparation for the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) and the NPOESS Preparatory mission, to be launched toward the end of the first decade of the new millennium.

## *Acknowledgments*

This work was supported by NASA grants NAG5-10738 and NAG5-11254, and by a contract (#03-751) from the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) between NOAA and the University of New Hampshire. We particularly thank NASA Headquarters (James Dodge) and SeaSpace Corporation for their support and assistance in conducting the assessments described here. IMaRS contribution #0057.

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# Advancing Ideas, Methods in Interdisciplinary Climate Change Research for New Ph.D.s

PAGES 314, 320

The global environmental changes that the Earth is experiencing today impact the smallest of organisms to global biogeochemical cycles. Climate change, one of the most noticeable alterations, is at least partly caused by our influence on worldwide physical, chemical, and biological systems. Climate change also has strong implications for political, economic, and social policy. Because climate change affects such a wide variety of disciplines and people, pursuing research in this field requires an interdisciplinary approach. This need to simultaneously understand climate change and forecast and effectively deal with its impacts on present and future generations presents a great challenge to the global research community.

With this perspective in mind, the Dissertations Initiative for the Advancement of Climate Change Research (DISCCRS) was formed in 2002 to bring together recent Ph.D. recipients across the range of disciplines whose work involves climate change and its impacts.

DISCCRS is a multi-agency and multi-organization initiative sponsored by the American Geophysical Union, the American Meteorological Society, the American Society of Limnology and Oceanography, the Ecological Society of America, and Whitman College; and funded by NASA's Office of Earth Science and the U.S. National Science Foundation's Geosciences Directorate (Climate Dynamics and Education and Human Resources). The goal of DISCCRS is "to catalyze interdisciplinary understanding and peer networking among recent grads" by bringing them together via several different avenues. These various avenues are a Ph.D. Dissertation Registry that is accessible online (over 200 dissertation abstracts were registered during the program's first year; see http://aslo.org/phd.html), an electronic message board that fosters communication among the DISCCRS registrants, and a capstone symposium that brings the registrants together to introduce the concept of interdisciplinary research and its many possibilities.

The first of these symposia was held 10–15 March 2003, in Guanica, Puerto Rico. The week-long event brought together 40 recent graduates from 36 institutions and 11 countries. The participants were selected by a committee from among 72 applicants. Excellence and diversity of research background were the primary selection criteria to ensure that the participants represented a range of expertise.

## *First Symposium Held*

The first part of the symposium was dedicated to sharing each participant's doctoral work. Due to the variety of scientific disciplines represented, many key elements of current climate change research were presented. Topics included:

- **Climate modeling and atmospheric science**. The impact of aerosols, ozone, dust, pollution, and clouds on climate; El Niño-Southern Oscillation (ENSO);
- **Paleoclimate**. Evidence for climate variability from cave stalagmites, Scottish pine, and marine and lake sediments; glacial-interglacial variability of sea ice and the carbon cycle;
- **Modern climate**. Links to biogeochemical cycling, lake ecosystems, carbon sequestration in forests, the hydrological cycle, terrestrial habitat loss, and biodiversity;
- **Tropical climate change**. Relation to variation in coral growth, tropical trees, and ecosystems;
- **High-latitude climate change**. Relation to Arctic sea ice, the carbon cycle in the Arctic tundra and the upper ocean, and glacier dynamics;
- **Social science**. Policy development and conflict resolution in environmental and developmental negotiations.

As can be seen by the list above, correlations were demonstrated between climate and many different natural systems. Implications for the future were woven into both formal presentations and informal discussions. In addition, many of the social and political difficulties of mitigating for and adapting to climate change were highlighted. By showing just how pervasive the impacts of climate change are on our world and how tricky it is to deal with them, these presentations laid the foundation for the rest of the week: the truly interdisciplinary part of the symposium.

For the next 4 days, the participants worked together to develop interdisciplinary strategies for defining the complex processes and interactions of climate change and its impacts. Formal discussions were formed around topics that were chosen by the group. These included the implications of climate change for species interactions, forests, and biogeochemical cycles, as well as ways in which temporal (fast versus slow), spatial (large versus small), and ecological (species versus ecosystem) scales affect our ability to do research and properly understand our results. A large group discussed the politics of climate change and the difficulties inherent in getting people and political entities to acknowledge climate change and pursue its mitigation. Another lengthy discussion focused on mentoring. From these sessions, participants began to learn how to assemble an interdisciplinary team to cover the range of expertise necessary to address the issues of climate change.

To help the group more successfully work in teams, communication consultant Chris Olex led sessions on communication skills and working group dynamics. Another important aspect of being a scientist is sharing your work with the wider public. Ashley Simons of SeaWeb focused on communicating beyond academia, both with the public and the press. The suggestions presented by these two experts apply both to speaking and to writing effectively, skills that new scientists often have not extensively practiced.

## *"Ideal" Climate Change Program*

One of the most important parts of the symposium was a session during which participants were asked to design the "ideal" climate change Ph.D. program. We discussed the positive and negative aspects of our respective Ph.D. programs and tried to identify program components that would be more conducive to creating an environment of "interdisciplinarity" and bestowing general knowledge in climate change. It was commonly agreed that any climate change researcher needs a disciplinary anchor for credibility and for finding job opportunities.

However, many had difficulty finding supervisors and program components that went beyond this disciplinary structure and fostered the pursuit of interdisciplinary research. It was suggested that, rather than creating a specific department or degree in climate change, the ideal program would give students access to a climate change institute on campus from which he or she could take courses and pursue a minor, in addition to the disciplinary major. The institute faculty could serve as co-advisors. In addition to interdisciplinary scientific training, the ideal programs would train students to work effectively as part of an interdisciplinary team.

To pursue professional research, knowledge of funding opportunities and training in proposal development is essential. Representing the U.S. National Science Foundation, Fae Korsmo gave an overview of programs relevant to interdisciplinary research in climate change. Korsmo, symposium organizer Susan Weiler, and two established DISCCRS interdisciplinary mentors, Jerry Mahlman and Ronald Mitchell, provided practical guidelines for writing quality proposals. Jerry, an atmospheric scientist, and Ron, a