New Directions in the Radiative Transfer of Cloudy Atmospheres

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Atmospheric radiative transfer plays a central role in understanding global climate change and anthropogenic climate forcing, and in the remote sensing of surface and atmospheric properties. Because of their opacity and highly scattering nature, clouds (covering more than half the planet at any time) pose unique challenges in atmospheric radiative transfer calculations.

Some widely-used assumptions regarding clouds—such as having a flat top and base, horizontal uniformity, and infinite extent—are amenable to simple one-dimensional (1-D) radiative transfer and are therefore attractive from a computational point of view. However, these assumptions are completely unrealistic and yield errors. The ever-increasing need to realistically simulate cloud radiative processes in remote sensing and energy budget applications has contributed to the recent rapid growth of the three-dimensional (3-D) radiative transfer (RT) community [e.g., *Marshak and Davis,* 2005].

This community is no longer limited to a nucleus of 3-D RT theoreticians, code developers, and dedicated practitioners. Rather, the community now encompasses a wide range of Earth scientists interested in improving the algorithms that define geophysical parameters, cloud system resolving models (CSRMs), and large-scale weather and climate models. The raised awareness of the importance of 3-D RT in the geophysical sciences led to the establishment of the 3-D RT Working Group (3DWG) within the International Radiation Commission (IRC) in 2003. This working group links the activities of the Intercomparison of 3-D Radiation Codes project (I3RC, http://i3rc.gsfc.nasa.gov), in cloudy atmospheres, the Radiative Model Intercomparison initiative (RAMI, http://rami-benchmark.jrc.it/) for vegetated surfaces, and 3-D RT in ice and other geophysical fields.

The I3RC, formed in 1997 with the endorsement of the International Radiation Commission and the Global Energy and Water Cycle Experiment (GEWEX) Radiation Panel, concentrates on 3-D RT in cloudy atmospheres [*Cahalan et al.,* 2005]. While the I3RC initially focused on algorithm intercomparison, it has now acquired a broader identity among scientists interested in 3-D RT in clouds. Given this, one objective of this article is to provide an overview of current works in progress and future challenges of atmospheric 3-D RT, and to explain how they relate to other atmospheric science problems, as well as 3-D efforts in other geophysical applications.

All of these issues were addressed to some degree by the almost 50 international speakers and participants (from Canada, France, Germany, Italy, Japan, the Netherlands, Russia, and the United States) in the six sessions of the third I3RC workshop, and in an accompanying poster session.

3-D Model Intercomparisons

The first session of the workshop examined the core activity of I3RC, namely, the intercomparison of 3-D radiation codes, its relationship with other RT code intercomparison activities (e.g., for vegetated surfaces), its past accomplishments, and its future directions. While it was recognized that intercomparisons and efforts to bring together seemingly distinct RT communities should continue, participants expressed some concern that without careful planning to keep the I3RC focused on a set of specific goals and to limit the number and scope of requested experiments the success of future activities may be at risk.

To gauge the interest and needs of the community, a set of new proposed intercomparison experiments was discussed. These experiments aim at helping to understand deficiencies in both passive and active (lidar) cloud remote sensing in the presence of 3-D effects, such as adjacency, mutual shadowing, or enhanced illumination, which can cause erroneous retrievals of microphysical and macroscopic cloud properties.

Presenters Tamás Várnai and Guoyong Wen (University of Maryland Baltimore County (UMBC), Baltimore) explained how the team designing the passive remote sensing experiments combines imagery, measurements, and retrievals from four different instruments aboard the Terra satellite [Moderate-Resolution Imaging Spectroradiometer (MODIS), Multiangle Imaging Spectroradiometer (MISR), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Clouds and the Earth's Radiant Energy System (CERES)] from a Brazil scene consisting of scattered cumulus clouds interspersed with aerosols. The novelty of the experiments is that they allow not only intercomparisons of model outputs, but also comparisons with the satellite observations themselves.

Following a presentation by Jean-Luc Widlowski (Joint Research Center, Ispra, Italy) about the RAMI project, conference participants proposed joint I3RC-RAMI activities and discussed how individual experiences from the two intercomparison projects could be mutually beneficial. This led to a more comprehensive debate on the future of I3RC, beyond its intercomparison activities—notably, how I3RC can provide resources and facilitate scientific cooperation within the 3-D RT community.

Publicly Available RT Codes and Cloud Models

The second session was devoted to publicly available 3-D RT codes and the community Monte Carlo (MC) code developed with I3RC funds and currently distributed via the I3RC Web site. The availability, fundamental technical specifications, and capabilities of the steadily expanding list of public 3-D RT codes were discussed. It was noted that the landscape of freely available 3-D algorithms has vastly improved in the years since the previous I3RC workshops in 1999 and 2000.

Frank Evans (University of Colorado, Boulder) showed comparisons between his Spherical Harmonic Discrete Ordinates Method (SHDOM) algorithm and the community MC code, and identified the main features the latter still needs before becoming an efficient and popular tool for practical 3-D problem-solving. Several participants pointed out that strict adherence to FORTRAN 95 and object-oriented programming techniques may limit wider community participation in future development.

Because of observational limitations, realistic, complete 3-D cloud property descriptions that could be used as input in RT simulations have been a perennial need for 3-D modelers. In recent years, demand has grown conspicuously for cloud fields from CSRMs, large eddy simulation models (LESs), and 3-D probabilistic cloud models. Recent advances in cloud modeling now allow simulations of 3-D cloud fields with some statistical resemblance to reality. It was therefore appropriate that the third session of the workshop provided the opportunity for dynamical and stochastic cloud modelers to present recent progress and to receive feedback on the needs of the 3-D RT community.

Comparisons with 1-D Approaches

While explicit 3-D RT calculations should in principle always be superior to plane-parallel or semi-empirical 3-D approaches, practical considerations (e.g., computational time, integration within other models) often prevent the most accurate methods from being implemented. Therefore, 3-D and 1-D approximations, the focus of two sessions of the workshop, will play an increasingly important role in atmospheric RT applications such as energy budget estimates at scales resolved by CSRMs and LESs as well as cloud property retrievals from space.

Presenters in the fourth session reported on recent progress by current 3D RT approximation theory with these two application areas in mind: (1) estimation of uncertainties in cloud retrievals from passive instruments caused by coarse resolution and development of practical ways for mitigating the errors; and (2) prediction of fluxes and heating rates with 3-D diffusion and perturbation theories as well as using 'effective medium' parameterizations, where the parameters of a standard 1-D RT model are modified to account for unresolved variability.

One of the most common 1-D approximations applied to horizontally variable cloud fields is the Independent Column (or Pixel)

Approximation (ICA or IPA). The fifth session examined the suitability of this approximation for a host of practical problems. The bias between 3-D and ICA calculations cannot be easily generalized for a wide range of cloud fields and external boundary conditions, and standardized cloud scenarios based on fields from either probabilistic or dynamical models are needed. It was suggested that the requirement of radiative flux parameterizations for large-scale models might one day become moot if information on cloud variability at scales of a few kilometers is available; it would then be possible to apply simplified versions of 3-D or ICA algorithms directly.

A related issue for remote sensing involved the distinction between radiance-based (including multi-angle) and flux-based cloud microphysical property retrievals and the need to reconcile the two in the presence of 3-D RT effects.

The sixth session highlighted observational evidence pointing to the omnipresence of 3-D effects in cloudy atmospheres. Passive observations from instruments located on the surface, aircrafts, and satellites were shown to be often inconsistent with 1-D predictions, but to also have the inherent capability to capitalize on the 3-D cloud and vegetation structure for parameter retrievals. The key challenge is then to explore the information content of these observations in order to converge on the true optical and microphysical properties of cloud fields or individual cloud elements.

Despite recent progress on remote sensing diagnostics of 3-D clouds in specific case studies, much work remains before global operational algorithms become credible. One possible solution may be the concept of 'effective state variables' where complex 3-D interactions can be simplified using the 1-D paradigm. Such an approach has been suggested for the remote sensing of vegetation by Bernard Pinty (Joint Research Center). This concept also makes accounting of the combined 3-D effects of clouds overlying relatively complex vegetated surfaces possible, as stressed by Alexander Marshak, (NASA Goddard Space Flight Center, Greenbelt, MD).

With the expectation of continued development of 3-D RT applications, and community involvement in the I3RC open source code, the I3RC and 3DWG participants will likely meet again in 2007. One opportunity is at the July 2007 meeting of the International Union of Geodesy and Geophysics in Perugia, Italy, where there will be a joint symposium on 3-D RT entitled "3-D Radiative Transfer in Complex Geophysical Media Including Clouds, Vegetation, Ice, and Snow."

The third I3RC workshop was held from 11 to 14 October 2005 in Kiel, Germany, and aboard a cruise ship traveling the Kiel-Oslo-Kiel route.

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References

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—LAZAROS OREOPOULOS, UMBC; ALEXANDER MARSHAK, NASA GSFC; ROBERT F. CAHALAN, NASA GSFC; TAMÁS VÁRNAI, UMBC; ANTHONY B. DAVIS, Los Alamos National Laboratory, Los Alamos, N.M.; and ANDREAS MACKE, Leibniz-Institute for Marine Sciences IFM-GEOMAR, University of Kiel

ABOUT AGU

Kivelson Receives 2005 John Adam Fleming Medal

Margaret G. Kivelson was awarded the Fleming Medal at the AGU Fall Meeting Honors Ceremony, which was held on 7 December 2005, in San Francisco, Calif. The medal recognizes original research and technical leadership in geomagnetism, atmospheric electricity, aeronomy, space physics, and related sciences.

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Citation

After a Ph.D. in theoretical physics (with Nobel Prize winner Julian Schwinger) and part-time work at the RAND Corporation during her children's early childhood, Margaret Kivelson entered geophysics in the 1960s. Since then, Margaret has led a remarkable career in the fields of solar-terrestrial physics, heliospheric and planetary science, and, in particular, planetary magnetism. Her achievements include the following.

In the 1970s, being involved in the first definitive in situ measurements of solar-terrestrial coupling showing magnetic reconnection was fundamental, developing the best codification of the Pioneer spacecraft Jovian magnetic field measurements, and laying the foundations of a better understanding of how magnetospheric convection feeds Earth's energetic particle belts.

In the 1980s, picking up the challenge to develop a magnetometer for the Galileo mission to the Jupiter system, developing an understanding of terrestrial ULF [Ultra-low frequency] pulsations, and working on the interaction of small bodies with the solar wind.

In the 1990s, triumphantly leading the Galileo team to a series of astounding discoveries, particularly about the varied magnetic behavior of the Galilean satellites.

In the past 10 years, the scientific harvest of Galileo has been great, and Margaret's part in it has been very large. She has been responsible, through the measurements made by her instrument, for the most surprising and challenging results from the mission. Her discoveries concerning the magnetic fields and the magnetized environments of Jupiter's Galilean moons, Io, Europa, Ganymede, and Callisto, are going to be seminal references in planetary science.

No planetary scientist would have predicted that the major and unexpected differ-

ences in the magnetic fields of each of the moons would be perhaps the most extraordinary of the harvest of results returned by Galileo. Her scientific leadership was required and tested to the full to overturn some of the very strong initial objections. But now our view of the formation of the moons has to change. The discovery of the intrinsic field of Ganymede would have been a discovery alone, enough to etch her name in history. However, the implications of her work in deducing the existence of magnetic induction signals at Europa and implying thereby