THE FOURTH TRMM LATENT HEATING WORKSHOP

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The global hydrological cycle is central to Earth's climate system, with rainfall and the physics of precipitation formation acting as the key links in the cycle. Two-thirds of global rainfall occurs in the Tropics with the associated latent heat (LH) release accounting for three-fourths of the total heat energy available to Earth's atmosphere. In addition, freshwater provided by tropical rainfall and its variability exerts a large impact upon the structure and motion of the upper-ocean layer. The four-dimensional distribution of precipitation in the tropical atmosphere has been observed by the Tropical Rainfall Measuring Mission (TRMM) satellite since its launch in November 1997. TRMM's passive microwave radiometer [TRMM Microwave Imager (TMI)] and precipitation radar (PR) are the primary instruments providing these data.

In the last decade, standard LH products from TRMM measurements have become valuable resources for scientific research and applications. Such products enable new insights on and investigations of the complexities of convective life cycles, the diabatic heating controls and feedbacks of mesosynoptic circulations and their forecasts, the relationship of patterns of tropical LH to the global circulation and climate, and strategies for improving cloud parameterizations in environmental prediction models.

The Fourth TRMM Latent Heating Workshop was convened to exchange scientific information and experience concerning the retrieval, validation, and application of satellite-derived LH products. In addition, the 26 participants met to examine and discuss the results of a comprehensive LH algorithm intercomparison–validation project; define an initial set of standard LH products; discuss validation issues, particularly the use of diagnostic analysis as the primary validation approach; deliberate further scientific requirements and applications issues related to standardized TRMM LH products; and identify future data products and validation procedures that will be required for the upcoming Global Precipitation Measurement (GPM) Mission.

THE FOURTH TRMM LATENT HEATING WORKSHOP

WHAT: Scientists from Japan and the United States shared scientific progress in the development of latent heating products from Tropical Rainfall Measuring Mission satellite measurements, their validation based on use of radiosonde data and Doppler radar measurements, and their applications for weather and climate analysis and forecasting

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WHERE: Seattle, Washington

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This workshop[1] had 25 formal presentations, including one from the Department of Energy's (DOE's) Atmospheric Radiation Measurement (ARM) radiation group. It was organized into separate sessions focusing on 1) preliminary results from the TRMM LH algorithm intercomparison–validation project, 2) LH algorithm designs and planned improvements, 3) new observational and model LH datasets for comparison and validation, 4) issues pertaining to the use of TRMM and other satellite LH data for global-scale modeling and tropical convection studies, and 5) future validation needs.

TRMM LATENT HEATING ALGORITHM INTERCOMPARISON–VALIDATION PROJECT. TRMM is unable to directly measure LH profiles, so they have to be determined indirectly from the application of physically based models to TRMM precipitation measurements. The general approach is to apply models, ranging in complexity from simple profile shapes to cloud-resolving models (CRMs), to TRMM PR and/or passive TMI data.

Five TRMM LH algorithms designed for application with satellite-estimated surface rain rate and precipitation profile inputs have been developed, compared, validated, and applied in the past decade (see Tao et al. 2006). They are the 1) Goddard convective–stratiform heating (CSH) (W.-K. Tao and S. Lang), 2) hydrometeor heating (HH) (E. A. Smith and S. Yang), 3) Goddard profiling heating (GPROF Heating) (W. Olson and C. Kummerow), 4) spectral latent heating (SLH) (S. Shige and Y. Takayabu), and 5) precipitation radar heating (PRH) (S. Satoh and M. Katsumata) algorithms. Each algorithm developer group presented designs, physical bases, and primary assumptions of its algorithm (including assessments of major strengths and weaknesses), and its validation and principal applications. All of the algorithms will undergo further refinement and improvement.

The intercomparison–validation project is considering eight separate datasets—four field experiment cases:[2] South China Sea Monsoon Experiment (SCSMEX; 1 May–30 June 1998), TRMM Large Scale Biosphere–Atmosphere Experiment in Amazonia (TRMM-LBA; 24 January–28 February 1999), TRMM Kwajalein Experiment (KWAJEX; 24 July–14 September 1999), and DOE ARM (1–22 March 2000 and 25 May–15 June 2002); two tropical cyclone cases: Atlantic Hurricane Bonnie (22 August 1998) and Pacific Typhoon Jelewat (2 August 2000); and two large-scale regional cases: a tropical rainforest domain (December 1997–December 2000; 20°S–5°N, 70°–35°W) and a tropical ocean domain (December 1997–December 2000; 20°S–20°N, 160°E–90°W).

The first four cases are being validated with the apparent heating (Q_1) derived from diagnostic budget calculations based on observations from special radiosonde or combined radiosonde–Doppler radar networks. The two tropical cyclones allow for the algorithm-generated instantaneous LH profiles to be compared, but without validation information. In the final two cases, the intercomparisons focused on a hierarchy of space–time-scale variations (including interannual variations) over large-scale regional domains involving tropical rainforest and tropical ocean environments.

Results from the first six cases were presented at the workshop. Initial analyses from the intercomparison indicated that 1) in just intercomparing algorithms, there were certain cases and certain intercomparison procedures that resulted in various algorithms and algorithm combinations exhibiting agreement, at times remarkably close agreement, whereas other intercomparison situations led to substantive disagreement (a second step in the intercomparison–validation process will be required before proceeding with quantitative conclusions); 2) in general, and again in just intercomparing algorithms, heating profiles aloft were in better agreement than those situated at lower levels; 3) there were intermittent instances of agreement between algorithm-generated heating profile structures and diagnostic budget profile structures, but, as with the algorithm intercomparisons, shortcomings in how validation comparisons were made (most of which can be corrected) precluded drawing meaningful preliminary conclusions concerning validation;

[1] The Fourth TRMM Latent Heating Workshop was cohosted by the Department of Atmospheric Sciences at the University of Washington (UWA) and the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC). The First, Second, and Third TRMM Latent Heating Workshops were held, respectively, at the NASA Goddard Space Flight Center in Greenbelt, Maryland, in May 2001, National Center for Atmospheric Research (NCAR) in Boulder, Colorado, in October 2001, and in Nara, Japan, in September 2003.

[2] SCSMEX took place over the South China Sea; TRMM-LBA took place in Rondonia, Brazil; KWAJEX took place around the Kwajalein Atoll, Republic of Marshall Islands; and the DOE ARM Program supports cloud–radiation experiments in Oklahoma at the Southern Great Plains (SGP) Cloud and Radiation Test Bed (CART) site.

4) intermittent sampling by TRMM is the major factor producing validation uncertainties, but this can be partly mitigated at the next step by requiring better time-period matching between TRMM and diagnostic budget data; and 5) for precipitating atmospheres, CRM-simulated radiative heating/cooling (Q_R) profiles were found to be similar to those retrieved by Tristan L'Cuyer (Colorado State University) for SCSMEX based on TRMM measurements input to a radiative transfer model. Finally, it is emphasized that final conclusions will not be drawn until the intercomparison–validation procedures targeted for improvement are implemented.

VALIDATION. Because latent heating cannot be measured directly with current techniques, the validation of satellite LH products can be challenging. However, this quantity can be inferred by measuring the vertical profiles of temperature, humidity, and wind at the stations comprising a closed rawinsonde network through a residual method (called a diagnostic budget). The 1998–99 NASA SCSMEX, TRMM-LBA, and KWAJEX field campaigns provided validation products, consisting of both rainfall and the vertical distribution of latent heating, specifically for TRMM.

Five diagnostic budget talks were presented in the workshop. Richard Johnson (Colorado State University) identified the observational uncertainty in latent heating profiles, estimated from sounding networks, as mainly being derived from network design, instrument errors, random error (e.g., convection), local effects (e.g., topography), analysis technique, and interpretation (e.g., gravity wave dispersion). Courtney Schumacher (Texas A&M University) discussed heating structures found in TRMM field campaigns (SCSMEX, TRMM-LBA, and KWAJEX). The variations in the diabatic heating associated with precipitating convective systems in the Tropics depend on climate regimes, waves, the diurnal cycle, and rain intensity. Ming-Hua Zhang (State University of New York at Stony Brook) compared the heating profiles from several ARM intensive operational periods (frontal stratiform, frontal convective, and summertime convection) with those from KWAJEX (moist versus dry conditions). Heating profiles from sounding networks derived using a constrained variational analysis captured the main physics within different synoptic- and large-scale environmental contexts. Sandra Yuter (North Carolina State University) discussed the lessons learned from KWAJEX for evaluating latent heating estimates, including the advantages and disadvantages of different observing options (e.g., diabatic heating from an upper-air sounding array, and horizontal divergence from a dual or single Doppler). Paul Ciesielski (Colorado State University) showed preliminary analysis of heat and moisture budgets from the enhanced sounding network of the North American Monsoon Experiment (NAME) that was conducted from 1 July to 15 August 2004. NAME datasets (specifically, analyses from soundings, ground-based radar, and an enhanced surface rain gauge network) represent a unique opportunity for TRMM to further develop and validate LH algorithms in a coastal monsoon environment characterized by strong spatial gradients of rainfall and steep mountainous terrain.

These five talks suggested that further improvements are needed, and future research is required for these improvements to be realized. Specific areas of needed research are 1) assessment of the impact of sampling errors for individual field campaigns, 2) analysis of budgets with respect to independent data sources (e.g., surface radar, aircraft), 3) determination of physical consistency of results, and 4) better optimization and testing of sounding arrays and radiosonde instrumentation within future field campaigns.

GLOBAL-SCALE MODELING AND TROPICAL CONVECTION. At low latitudes, LH modulates large-scale zonal and meridional circulations. Latent heating is also a principal energy source in the creation, growth, vertical structure, and propagation of long-lived tropical waves. Moreover, the distinct horizontal and vertical distributions of convective and stratiform LH influence the detailed structure of waves and larger-scale circulations. The relationship of LH to large-scale dynamics pertains to the use of TRMM and other satellite LH data as input to global-scale modeling and tropical convection studies.

Robert Houze (University of Washington) presented the relationship of cloud water budgets to heating profile calculations. He showed that water budget parameters could be used to establish the internal consistency of latent heating, vertical eddy heat fluxes, and radiative heating profiles. David Randall (Colorado State University) presented results from two new state-of-the art modeling systems, a global CRM, and a multiscale modeling framework (MMF). This future modeling capability in the age of TRMM and GPM can simulate cloud/precipitation information on the same scales with high-resolution satellite observations. Mitchell Moncrieff (National Center for

Atmospheric Research) presented a new framework for understanding tropical convection, convective organization, and the effects of these processes on the large scales of motion: a nested tropical channel version of the Weather Research Forecast (WRF) model.

Larissa Back (University of Washington) used TRMM and large-scale model reanalyses to show that within deep convective regimes there is substantial geographic variability in climatological LH and vertical motion profiles. Her research suggests that frictionally driven boundary layer convergence is probably playing a role in causing "bottom heavy" latent heating in the narrow ITCZ eastern Pacific region. Joanna Futyan (Columbia University) combined geostationary infrared (GEO-IR) and TRMM data to investigate the evolution of deep convective systems over Africa and the tropical Atlantic. Results suggest differences in evolution between continental and oceanic systems. Robert Cifelli (Colorado State University) used TRMM data to understand the regional mechanisms that determine the diurnal cycle of convection in the east Pacific. He identified mesoscale convective systems (MCSs) as, collectively, a dominant source of regional variability in the diurnal cycle. Walt Petersen (University of Alabama at Huntsville) emphasized that discrete convective regimes can be identified and that they act over a variety of space–time scales. He suggested combining model statistics with reanalysis or observational products and satellite observations to retrieve integrated heating products.

Yukari Takayabu (Tokyo University) discussed SLH rain retrievals and found that moderately high amounts of convective rain, with similar amounts of stratiform rain, were observed in the KWAJEX region, and that convective rain exhibited a morning maximum in the SCSMEX domain. Jim Mather (DOE Pacific Northwest National Laboratory) used ARM data to examine the vertical distributions of clouds and radiative heating rates in the tropical western Pacific. Measurements of temperature, humidity, and cloud property profiles imply a heating rate structure that complements latent heating. Christopher Bretherton (University of Washington) showed that on global climatological scales the vertical structure of the diabatic heating profile could be simulated by atmospheric general circulation models forced by observed sea surface temperatures.

FURTHER WORK AND RECOMMENDATIONS. During a final discussion session, the following actions were identified as necessary prior to the next TRMM Latent Heating Workshops:

1) A second version of the intercomparison–validation results will be presented and results will be posted on a Web site accessible to all algorithm developers.
2) Final intercomparison–validation results will be made available to the general public (with procedures to be defined at the next TRMM Latent Heating Workshop).
3) Final algorithm intercomparison–validation results will be developed into three to four manuscripts for submission to refereed journals; possible topics include (a) algorithm intercomparison statistics as a function of different time scales (e.g., diurnal, daily, monthly, and seasonal), (b) case-by-case algorithm intercomparison–validation results, (c) detailed algorithm intercomparisons focused on instantaneous hurricane cases, and (d) regime dependence of algorithms for continental and oceanic environments.
4) Profiles of Q_R and eddy heat flux divergence, calculated from CRMs and observed at the ARM site, will be provided to the HH and PRH algorithm developers.
5) Sampling issues concerning the SCSMEX, TRMM-LBA, KWAJEX, and ARM validation cases will be analyzed further with assistance from the diagnostic budget working group.
6) Different spatially and temporally averaged Q_1 products will be examined (1°, 2°, and 5°/diurnal, daily, monthly, seasonal).
7) Different intercomparison–validation metrics will be explored; for example, (a) analyzing composite heating structures according to waves, regimes, and amplitudes/levels of maximum heating, (b) analyzing ratios of LH and integrated LH for different vertical layers, (c) conducting consistency checks with CRMs, and (d) analyzing relationships between LH and the overall mesoscale convective system water budget.
8) Common input parameters for all algorithms will be identified.
9) The relationship between LH and Q_R will be explored.
10) A recommendation to conduct LH validation in regions where large amounts of latent heat are released and have substantial upscale effects on the global circulation will be forwarded to the GPM ground validation group.

Close collaboration among LH algorithm developers is planned. Beta versions of various algorithms (with detailed advice concerning limitations and appropriate applications) will be available in the near future.

The next TRMM Latent Heating Workshop will be held in Maryland on 27 and 28 August 2007. It is expected that results from all eight cases will be compared and validated, and the relationship of LH to radiative heating will be further explored.

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REFERENCES

Tao, W.-K., and Coauthors, 2006: Retrieval of latent heating from TRMM measurements. *Bull. Amer. Meteor. Soc.,* **87,** 1555–1572.