Year 2 Progress Report for:

"Calibration and Analysis of Global Latent Heating Estimates Using Passive and Active Microwave Sensor Data"

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(1) Project Description

Our primary task is to calibrate a method for deriving global latent heating distributions from passive microwave radiometer observations from multiple satellite platforms using an extended time series of high-resolution, spaceborne radar estimates of precipitation/latent heating vertical structure. A method developed by Iguchi et al. (2000) is used to derive precipitation vertical profiles from Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) data. Latent heating is assigned to the high-resolution precipitation profiles by scaling tabulated cloud-resolving model heating profiles by the estimated divergence of precipitation into specified atmospheric layers. This method, and the extensive sampling of precipitation systems in the tropics/subtropics by the PR, leads to a heating profile calibration dataset that is fairly general and relatively unbiased. The dataset is used to calibrate the radiometer algorithm for estimating heating profiles.

The radiometer heating algorithm currently developed for the TRMM Microwave Imager (TMI) will be extended to other satellite microwave radiometers, including the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) and Special Sensor Microwave/ Imager (SSM/I). Radiometer latent heating estimates will be evaluated against independent PR heating estimates as well as rawinsonde network analyses of heating. We will initially apply the latent heating estimation method to the 10+ year record of TMI data and the 5+ year record of AMSR-E data, as well as SSM/I data overlapping these periods. This record will be extended using SSM/I data back to 1992. Experimental multi-satellite latent heating products, including instantaneous and 3-hourly, 0.5^{o} resolution products suitable for water/energy cycle analysis and data assimilation will be derived and evaluated. Errors associated with these products will be estimated and attached to each product.

(2) Accomplishments of the Past Year

First, the "test" heating algorithm (developed during the previous reporting period) for applications to TMI observations was analyzed in depth to determine strengths and weaknesses. Even though the time series of TMI heating showed reasonable agreement with rawinsonde diagnoses of heating from the South China Sea Monsoon Experiment (SCSMEX), there were still troubling biases in long-term mean heating profiles, including persistent and excessive low-level evaporative cooling, and an upper-level heating maximum that occurred at an altitude somewhat below the altitude of peak heating from the SCSMEX data. Therefore, much of the year was spent trying to understand the causes of these biases and exploring heating algorithm modifications that would reduce or eliminate them. For example, it was determined that much of the bias in low-level cooling was due to a bias in the cloud-resolving model simulation used to calibrate the algorithm. Comparisons of model-simulated reflectivities and TRMM PR reflectivities (over ocean, where the algorithm is applied) showed a mean decrease in model-simulated reflectivities between the freezing level and the surface, while PR reflectivities showed very little decrease. This comparison indicated significant mean evaporation of rain in the model simulations below the freezing level, while the PR observations suggested very little evaporation on average. As a consequence, this excess of evaporative cooling in the model caused a similar bias in the heating algorithm estimates.

Since model biases were suspected of causing biases in our heating algorithm's estimates, a series of model simulations were performed to understand some of the weaknesses of the model, and to determine how sensitive the model was to factors such as environmental conditions, model grid resolution, domain size, 2D vs. 3D simulations, and microphysics. It was determined that the 2D simulations at 1 km resolution that we had used to provide algorithm calibration data were not optimal, although certain water budget components such as the transport of condensate from convective to stratiform regions were fairly realistic compared to 3D simulations at the same resolution (our collaborator, Dr. Shoichi Shige, found that 3D simulations had to be run at much higher resolution to reproduce transport correctly). Higher-resolution simulations in 2D (250 m) produced overall better simulations with less lower-tropospheric evaporative cooling; however, variations in prescribed environmental conditions were still a strong factor in determining the convective heating/cooling response.

Aside from the impact of model biases, we also examined the impact of data information content on biases in heating retrievals. Our TMI algorithm is calibrated using spaceborne radar (PR) heating profile estimates, and since the PR data contain more detailed precipitation/heating information than the TMI data, we used PR vs. TMI heating comparisons to determine where TMI was biased due to its lower information content. Over most ocean regions, TMI heating was nearly unbiased relative to PR heating; however, in the tropical Eastern Pacific, the TMI exhibited greater lower-tropospheric heating than the PR in monthly-mean estimates. We initially suspected that this was due to the fact that the TMI data contain less information for separating convective and stratiform rain regions, especially when precipitation systems are relatively shallow, as they are in the Eastern Pacific. However, the overall depth of the Eastern Pacific systems was correctly diagnosed by TMI, and convective/stratiform separation in shallow systems has a relatively weak influence on latent heating vertical structure, as long as the overall depth of the systems is ascertained. Therefore, the substantive error in heating estimates from either PR or TMI may be more a function of the retrieved surface rain rates- reasons for biases in *both* PR and TMI surface rain rates in the tropical Eastern Pacific have been proposed, but this issue has yet to be resolved.

A third area of study was the assignment of cloud-resolving model tables for estimating heating from the PR (the training data for TMI) based upon environmental conditions. As noted above, environmental conditions have a strong impact on simulations of convection using cloud models, but given the myriad combinations of possible surface and atmospheric parameters (primarily SST, temperature and humidity, their tendencies, and winds) describing environmental conditions, a method for identifying the primary modes of environmental variability was needed to reduce the corresponding number of cloud model simulations to something computationally feasible. Reanalyses from the NASA's Goddard Earth Observing System-3 (GEOS-3) model were used to identify separable environmental modes, based upon an EOF analysis of the environmental parameters. The modes were established by classifying environments based upon their EOF projections. In early tests, it was determined that ~20 modes were required to classify the 6-hourly, 1^{o} resolution reanalysis environments. Once a final set of environmental modes is established, cloud simulations based upon these modes will be used to create heating tables specific to those modes. Then, in applications of the PR heating method, reanalysis data will be used to "select" an appropriate heating table consistent with the environment observed during a given PR overpass.

Finally, our collaborative work with scientists at other research and operational centers continues. We have combined our latent heating (Q_1-Q_R) estimates with estimates of Q_R from Tristan L'Ecuyer (CSU) to create estimates of Q_1 that have been directly compared to estimates of Q_1 from rawinsonde analyses. This is important because from rawinsonde analyses, one can only infer time series of Q_1 and not components of Q_1, such as latent heating. We have also submitted our heating estimates to the TRMM Heating Intercomparison Project for evaluation. With Duane Waliser and Xianan Jiang at JPL, we are helping to diagnose the structure and evolution of the Madden-Julian Oscillation (MJO), and meanwhile evaluate model reanalyses of heating for this phenomenon. Preliminary results show, for example, that the ECMWF model overestimates heating in the deep tropics, and this is linked to excessive precipitation produced by the model. Also, the vertical distribution of model heating does not change appreciably over the ~2 week passage of the active phase of the MJO, while TMI estimates show considerable variation, consistent with independent observations of the shallow-to-deep-to-stratiform progression of precipitation/heating structure during the MJO active phase.

(3) Work Plan for Next Year

Work will continue on the study of cloud-resolving model simulations that are the basis of improved lookup tables for the PR-based heating method. Our second year of Science Mission Directorate support for high-performance computing at the NASA Center for Computational Sciences will focus on generating 2D and 3D simulations that span the range of environmental conditions that the PR and TMI sensors are likely to encounter. Based upon these new simulations, lookup tables relating PR observations and heating will be established, and the classification method described in (2), above, will be used to target heating lookup tables to specific environments.

A first "production" heating algorithm for applications to TMI data will be finalized in March 2008. This algorithm will be used to conclude validation studies and produce long-term datasets for our JPL, CSU, and TRMM Heating working group collaborators. It will also serve to produce heating datasets for the NEWS Question #2 studies initiated at the Fall 2007 NEWS meeting. We will shortly thereafter begin processing of the entire

TRMM record of TMI observations over ocean, and transfer the resulting heating estimates to the GMU NEWS Data and Information Center. Within the next year, we expect to deliver a global oceanic latent heating algorithm that can be applied to TMI, SSM/I, and AMSR-E microwave radiance data; extension of this algorithm to "over-land" applications will follow.

(4) NEWS Connections and Interactions

As described above, we will continue to collaborate with NEWS investigator Wei-Kuo Tao to improve the cloud resolving model simulations that support our latent heating algorithm. Dr. Tao is also leading a series of heating algorithm intercomparison workshops for the TRMM project, and we have combined our latent heating estimates with radiative heating estimates from NEWS investigator Tristan L'Ecuyer to derive the total diabatic heating over the SCSMEX region for these intercomparison studies. We have also supplied NEWS investigator Duane Waliser and Xianan Jiang (JPL) with latent heating estimates from our current algorithm for their studies of the structure and evolution of the Madden-Julian Oscillation, which impacts the weather of the tropics as well as the extra-tropics.

Following the Fall 2007 NEWS team meeting, we joined the Question #2 working group which will explore the potential for understanding floods and droughts over the Southern Great Plains using a variety of NEWS energy/water cycle data sets and model-based reanalyses. Seager et al. (2003; 2005) proposed a mechanism relating multi-year anomalies of SST and atmospheric temperature changes in the deep tropics to a zonally-symmetric response of lifting/subsidence at midlatitudes, resulting in flood/drought periods in numerical simulations that compared favorably with climate records. Our contribution to the Question #2 group will be heating and precipitation estimates in the tropics and subtropics for the purpose of contrasting the 2006/2007 drought/flood years in the Southern Great Plains and evaluating model reanalyses for these years.

Regarding integration needs, even though we fully utilize the information from spaceborne radar and radiometer observations to make our latent heating profile estimates, certain products from the other NEWS investigators could serve as useful constraints on these estimates. For example, in a space-time average sense, the flux of water vapor from the ocean surface plus the convergence of vapor in the atmosphere, less any local increase in the atmospheric water vapor (Wentz), should be balanced by the flux of precipitation at the surface (Adler), neglecting the storage of condensed moisture in the atmosphere. Therefore, both the Wentz and Adler studies provide alternative estimates of the vertically-integrated net condensation of moisture in the atmosphere, which results in latent heating. And so these studies, which utilize more time-continuous data to estimate the net condensation, could provide valuable constraints on the vertical integral of our latent heating estimates.

(5) Problems/Concerns

Since our study is a NEWS "Discovery-driven" investigation, more development time has been required for us to establish both confidence in our product as well as error estimates. Therefore, we are in synch with similar investigations such as Tristan

L'Ecuyer's in deriving test products and validating these products, and indeed we have combined latent and radiative heating estimates for intercomparison studies. After much intensive study over the past year, we are now finalizing a first "production algorithm" for latent heating that has undergone at least preliminary evaluation using surface observations. Heating uncertainty estimates can also be produced based upon the uncertainties of the input observations, uncertainties in the PR heating lookup tables, and the Bayesian formulation of the TMI heating algorithm itself. The question therefore may be raised: once the accuracy of our products is quantified, is there a possibility for longer-term latent heating product evaluation and integration, as in the "Product-driven" investigations?

References:

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Shige, S., Y. N. Takayabu, W.-K. Tao, and D. E. Johnson, 2004: Spectral retrieval of latent heating profiles from TRMM PR data. Part I: Development of model-based algorithm. *J. Appl. Meteor.*, **43**, 1095 – 1113.

(6) Project-related Publications

Grecu, M., W. S. Olson, C.-L. Shie, and W.-K. Tao, 2008: Estimation of latent heating rates from a satellite microwave radiometer algorithm, trained using spaceborne radar observations. (in preparation)

Zhou, Y. P., W.-K. Tao, A. Y. Hou, W. S. Olson, C.-L. Shie, K.-M. Lau, M.-D. Chou, X. Lin, and M. Grecu, 2007: Use of high-resolution satellite observations to evaluate cloud and precipitation statistics from cloud-resolving model simulations. Part I: South China Sea Monsoon Experiment. *J. Atmos. Sci.* , **64**, 4309 – 4329.

Olson, W. S., S. Yang, J. E. Stout, and M. Grecu, 2007: The Goddard Profiling Algorithm (GPROF): Description and current applications. *Measuring Precipitation from Space, EURAINSAT and the Future*, V. Levizzani, P. Bauer, and F. J. Turk, Eds. Springer, 772 pp.