Latent Heating Structures Derived from TRMM

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1. What is the Latent Heating?

Latent heating is the heat released or absorbed by the atmosphere as a result of phase changes in water (i.e., gas to liquid, liquid to solid, gas to solid or vice versa) from condensation, evaporation of cloud droplets and raindrops, freezing of raindrops, melting of snow and graupel/hail, and the deposition and sublimation of ice particles. In addition, eddy heat flux convergence/divergence from upward and downward cloud motions can also result in heating or cooling. Latent heating cannot be measured directly with current techniques. But, it can be derived indirectly by measuring the vertical profiles of temperature and the three-dimensional wind fields from extensive rawinsonde networks through a residual method (called a diagnostic budget; see Yanai *et al.* 1973, Johnson 1984; Houze 1997).

2. Why is Latent Heating important?

The global hydrological cycle is central to the Earth's climate system. Rainfall and its associated precipitation processes are a key link in the hydrologic cycle. Fresh water provided by tropical rainfall and its variability can exert a large impact upon the structure and motions of the upper ocean layer. In addition, two-thirds of the global rain falls in the tropics, while the associated latent heat release accounts for three-fourths of the total heat energy for the Earth's atmosphere. The Tropical Rainfall Measuring Mission (TRMM), a joint U.S./Japan project, is a satellite mission intended to provide an adequate measurement of rainfall as well as an estimation of the four-dimensional structure of diabatic heating over the global tropics using an inclined low-altitude orbit and a combination of precipitation radar (PR), visible and infrared radiometer scanner (VIRS) and microwave radiometers. The distributions of rainfall and inferred heating can be used to advance our understanding of the global energy and water cycle. In addition, TRMM data can be used for global circulation and climate models for testing and improving their parameterizations (see Simpson *et al.* 1996).

3. How can Latent Heating be derived?

Cloud-resolving (or cumulus ensemble) models (CRMs) are one of the most important tools used to establish quantitative relationships between diabatic heating and rainfall. This is because latent heating is dominated by phase changes between water vapor and small, cloud-sized particles, which cannot be directly detected. The CRMs, however, explicitly simulate the conversion of cloud condensate into raindrops and various forms of precipitation ice. It is these different forms of precipitation that are most readily detected from space, and which ultimately reach the surface in the form of rain. CRMs have been used to provide cloud data sets associated with various types of clouds and cloud systems from different geographic locations for the TRMM retrieval algorithm database. The data represent instantaneous values and are selected from periods where the cloud and precipitation fields meet predetermined characteristics that are unique or complementary to the database requirements. The output quantities provided include: pressure, temperature, relative humidity, rain rate, hydrometeor (cloud water, ice, rain, snow, and graupel) mixing ratios, vertical velocity, latent heating, apparent drying, vertical eddy heat and moisture flux convergence, radiative heating, and convective-stratiform classification.

Five different latent heating algorithms, the Goddard Convective-Stratiform Heating (CSH), the Goddard Profiling (GPROF) heating, the Hydrometeor Heating (HH), the Spectral Latent Heating (SLH) and the Precipitation Radar Heating (PRH) algorithm have been developed to retrieve latent heating profiles using TRMM rainfall products. The HH algorithm estimates the latent heating profiles of clouds/cloud systems as a function of the vertical derivative of their retrieved hydrometeor profiles (termed a *hydrometeor/heating (HH)* algorithm - Tao *et al*. 1990 and Yang and Smith 1999). The derivation and evaluation of the HH algorithm was based on CRM simulations, and it requires information about the vertical profiles of cloud- and precipitation-sized water and ice particles, all of which can be obtained from the TMI profiler retrievals (Kummerow *et al.* 1996; Smith *et al.* 1992, 1994). The terminal (fall) velocities of the large cloud (precipitating) particles (rain, snow and graupel/hail) are also required for the HH algorithm. Empirical coefficients associated with the condensation of small liquid water droplets and deposition of small ice particle are needed in Tao *et al.* (1990), and these coefficients can be determined using the surface rain rates (Tao *et al.* 1993). Cloud-scale velocity is needed in Yang and Smith (1999), and it is obtained by applying a regression method (to a CRM simulated data base). The second method, the CSH algorithm, only needs information on surface precipitation rates, amount of stratiform rain, and the type and location of observed cloud systems (Tao *et al.,* 1993). A lookup table, however, is used containing stored convective and stratiform latent heating profiles, normalized by total surface rain rates, for various types of cloud systems in different geographic locations. These profiles are mostly obtained from CRM (GCE model) simulations. In the third method, CRM-simulated hydrometeor/latent heating vertical profiles that have radiative characteristics consistent with a given set of multi-spectral, microwave, radiometric observations are composited to create (retrieve) a best estimate of the observed profiles (Olson *et al.* 1999). The SLH algorithm (Shige *et al.* 2004) is also based on GCE model results. It uses PR information (melting layer, precipitation top height, rain rate and type) to select the heating profiles in a look-up table. The PRH algorithm (Satoh and Noda 2001) also uses PR information but without using any heating profiles simulated by CRMs. However, it needs to estimate the cloud drafts and (standard) thermodynamic structures associated with cloud systems. An iteration calculation is applied to match the relationship between rainfall and latent heating.

A quantitative comparison between three of the heating algorithms (CSH, GPROF and HH) was performed (Tao *et al.* 2001). The results indicated that the horizontal distribution or patterns of latent heat release retrieved by these three different methods are quite similar. They can all identify the areas of major convective activity [i.e., a well defined Intertropical Convergence Zone (ITCZ) in the Pacific and a distinct South Pacific Convergence Zong (SPCZ)] in the global tropics. The magnitude of their estimated latent heat release is also in good agreement with each other and with those determined from diagnostic budget studies. The major difference between these three heating retrieval algorithms is in the altitude of the maximum heating level. The CSH algorithm-estimated heating profiles only show one maximum heating level, and the level varies between convective activity from various geographic locations. These features are in good agreement with diagnostic budget studies. A broader heating maximum, often with two embedded peaks, is generally obtained by the GPROF and HH algorithms, and the response of the heating profiles to convective activity is less pronounced. Also, GPROF and HH generally yield heating profiles with a maximum at somewhat lower altitudes than those from the CSH.

4. How can latent heating be validated?

Several field campaigns conducted during 1998 and 1999 were aimed at the validation of TRMM products (i.e., rainfall and the vertical distribution of heating). Since latent heating profiles cannot be directly measured, CRMs are used in TRMM algorithms to provide a link between the latent heating profiles, and PR and TMI observations. Consequently, one of the key components of the TRMM field campaigns is to provide observations of the structure and evolution of mesoscale convective systems (MCSs), and individual convective clouds and their embedded large-scale environment. CRMs require these data sets for initial conditions as well as for the validation of their vertical latent heating structure.

Consistency checks can be also performed by several CRM-generated cloud data base heating algorithms (i.e., the CSH and SLH algorithms). The procedure is to use CRM-simulated parameters [i.e., surface rain rate, stratiform percentage, rain rate at the melting level, and precipitation top height (PTH)] to re-construct (or retrieve) heating profiles and compare them to sounding estimates and/or CRM simulations (Tao *et al.* 2000; Shige *et al.* 2004).

5. Future Work

Since several heating algorithms require CRM-simulated cloud data sets including heating profiles (i.e., the lookup tables for the CSH and SLH algorithms, and rain rates and cloud profiles for GPROF), the number of heating profiles associated with different types of clouds and convective systems from various geographic locations needs to be increased. Data from TRMM field experiments and other major field experiments (i.e., DOE/ARM) can be used to provide initial conditions for CRMs and validate the CRM-simulated latent (diabatic) heating. The heating obtained from numerical model simulations, large-scale model re-analysis (Nigam *et al.* 2000), can be compared with those from retrieval algorithms. This comparison could identify what are the major physical processes that cause the similarities and differences between models. In addition, data from field campaigns can be used to validate and improve CRM microphysics because they are the major processes responsible for latent heat release.

The HH, GPROF, SLH and PRH algorithms can produce instantaneous heating profiles at the satellite footprint. The assumption is that instantaneous heating profiles and cloud structures are related. Shige *et al*. (2004) showed that spatial averaging (at least 50 km) is required to derive meaningful instantaneous heating profiles using the SLH algorithm. The key developers for the TRMM heating algorithms have agreed to examine the possibility of producing a unified heating algorithm using microwave sensors (i.e., TMI/SSM-I) and radar (i.e., PR) products for TRMM. It would require comparing the various heating algorithms using the same rainfall products as in Tao *et al.* (2001).

Two global climate models, from Goddard and the Florida State University, are currently using TRMM data sets to either improve their cumulus parameterization schemes and/or identify problems in their parameterization schemes. The direct use of satellite (and or other ground based) products on heating profiles for atmospheric models requires a physical initialization design. For example, the Florida State University global, spectral model (Krishnamurti *et al.* 1991) has been developing a new cumulus parameterization scheme (NCPS) to use observed and/or satellite-retrieved heating profiles through an empirical approach. Since temperature (heating) and water vapor (moistening/drying) are closely related, a moisture profile is also needed in NCPS. The initial results with the NCPS incorporated into the FSU global spectral model shows improved precipitation and circulation forecasts on day-2 and day-3 (see Rajendran *et al.* 2004). The use of satellite-derived profiles in data assimilation appears very promising but requires much further work. Particularly, there has to be closer cooperation between latent heating algorithm developers and the data assimilation/large-scale modeling communities.

There is another major application using NWP and/or global circulation models with satellite-retrieved heating profiles. As the number of such models subjected to initialization by the different observed/retrieved (i.e., obtained from GPROF, HH, SLH and others) heating profiles increases major improvements in forecasting capabilities via ensemble or superensemble (Krishnamurti *et al.* 2001) techniques can be expected. This is being established as a powerful technique. This aims to reduce overall uncertainties of models, data sets and parameterizations.

6. References

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