DOE Project ID: 0015248
Title: Radiative heating associated with tropical convective cloud systems: Its Importance at Meso and Global Scales
Principal Investigator: Courtney Schumacher
Institution: Texas A&M University

Final report (July 2009 – June 2012)

Executive summary

Heating associated with tropical cloud systems drive the global circulation. The overall research objectives of this project were to i) further quantify and understand the importance of heating in tropical convective cloud systems with innovative observational techniques, and ii) use global models to determine the large-scale circulation response to variability in tropical heating profiles, including anvil and cirrus cloud radiative forcing. The innovative observational techniques used a diversity of radar systems to create a climatology of vertical velocities associated with the full tropical convective cloud spectrum along with a dissection of the of the total heating profile of tropical cloud systems into separate components (i.e., the latent, radiative, and eddy sensible heating). These properties were used to validate storm-scale and global climate models (GCMs) and were further used to force two different types of GCMs (one with and one without interactive physics). While radiative heating was shown to account for about 20% of the total heating and did not have a strong direct response on the global circulation, the indirect response was important via its impact on convection, esp. in how radiative heating impacts the tilt of heating associated with the Madden-Julian Oscillation (MJO), a phenomenon that accounts for most tropical intraseasonal variability. This work shows strong promise in determining the sensitivity of climate models and climate processes to heating variations associated with cloud systems.

Project activities

i) Further quantify and understand the importance of heating in tropical convective cloud systems with innovative observational techniques

The innovative observational techniques centered on the use of radar data to observe relevant properties of the tropical cloud systems. Soundings and satellite measurements were used to expand upon the radar-observed properties. The radars had a diversity of capabilities (scanning and vertically pointing, mm and cm wavelengths, polarimetric and Doppler) to observe the full spectrum of non-precipitating and precipitating clouds associated with tropical convective systems.

Radar observations from Darwin, Australia were a focus of the project because of long-term observations from the permanent ARM site and because of the Tropical Warm Pool-International Cloud Experiment (TWP-ICE), a large DOE-led field campaign that took place in the vicinity of Darwin in early 2006. Satellite observations from the Tropical Rainfall Measuring Mission (TRMM) and International Satellite Cloud Climatology Project (ISCCP) were used to extend the geographical applicability of the work.

Li and Schumacher (2011) quantified thick anvil properties and occurrence across the tropics using the TRMM Precipitation Radar and determined how thick anvil relates to properties of deep convection. For example, the height of the convection matters more than convective intensity in dictating anvil formation. Feng et al. (2011) extended concepts formulated from the Darwin data set to study the top-of-atmosphere radiative budget of raining (i.e., convective and stratiform precipitation) and non-raining (i.e., anvil cloud) portions of deep convective systems over the Southern Great Plains, the latter of which were more important in overall cloud radiative forcing. Li et al. (2012) used radiative heating profile retrievals from Darwin and Manus, Papua New Guinea (another permanent ARM site) and ISCCP cloud regimes to create a tropics-wide climatology of the vertical structure of radiative heating associated with deep convective systems. While the radiative heating accounted for less than a quarter of the total heating, its gradient at upper levels was postulated to have important implications for the large-scale circulation. Feng et al. (2012) is one of the first studies to come out of ARM MJO Investigation Experiment (AMIE) in the Indian Ocean and provides a comprehensive comparison of the vertically pointing and scanning, mm- and cm-wavelength radars deployed during the field campaign.

Schumacher et al. (in preparation) quantified the relative importance of the different components of Q_1 and Q_2 (i.e., radiative heating, latent heating, and eddy vertical transport processes) associated with tropical convection during TWP-ICE. It was shown that heating profiles vary by stratiform rain percent, monsoon regime, surface type, and amount of non-precipitating cloud. Over the mainland (where estimates of heating are best constrained by observations), radiative cooling of about 1 K/day occurs throughout the troposphere, latent heating of 1-2 K/day occurs at low levels and up to 5 K/day at mid levels, and eddy sensible heating of up to 2 K/day occurs at mid and upper levels. The magnitude of the eddy sensible heat component is surprising, but consistent with theoretical considerations. Another study by Schumacher et al. (also in preparation) showed that vertical velocity retrievals from the long-term profiler observations at Darwin can be related to convective height, stratiform intensity, and anvil thickness, the latter of which shows dynamical activity that may be associated with gravity waves. The vertical velocity profiles better quantify the convective-stratiform-anvil transition and provide highly needed model targets.

Li, W., and C. Schumacher, 2011: Tropical thick anvil viewed by the TRMM Precipitation Radar. *J. Climate*, **24**, 1718-1735.

Feng, Z., X. Dong, B. Xi, C. Schumacher, P. Minnis, and M. Khaiyer, 2011: TOA radiation budget of convective core/stratiform rain and anvil clouds from deep convective systems. *J. Geophys. Res.*, **116**, D23202, doi:10.1029/2011JD016451.

Li, W., C. Schumacher, and S. A. McFarlane, 2012: Radiative heating of the ISCCP upper level cloud regimes and its impacts on the large-scale tropical circulation. *J. Geophys. Res.* Conditionally accepted.

Feng, Z., S. A. McFarlane, C. Schumacher, R. A. Houze, and S. Ellis, 2012: Comparison of cloud statistics observed by cloud and precipitation radars during the DYNAMO/AMIE experiment at Addu Atoll. *J. Atmos. Ocean Tech.* Submitted.

Schumacher, C., S. Stevenson, and C. Williams: Profiler observations of vertical velocity in convective, stratiform, and anvil cloud over Darwin, *Mon. Wea. Rev.* In preparation.

Schumacher, C., S. Xie, and S. McFarlane: Eddy vertical transports revisited. *J. Atmos. Sci.* In

preparation.

ii) Use a global model to determine the large-scale circulation response to variability in tropical heating profiles, including anvil and cirrus cloud radiative forcing

Convective-stratiform separations and latent heating profiles produced by the PI have been used to validate both cloud-resolving model and GCM runs during TWP-ICE (Boyle and Klein 2010, Fridland et al. 2012, Lin et al. 2012). The models generally do well during the active monsoon period, but have trouble representing the convective heating during the suppressed and break periods. The PI and her research group have also used tropics-wide heating profiles derived from satellite data (with guidance from ARM observations in the tropical West Pacific) to force GCMs to see the large-scale response to deep convection and upper level cloud (Lappen and Schumacher 2012, Li et al. 2012). Of particular note is a new method we developed to add heating to NCAR's Community Atmosphere Model V4 (CAM4) while maintaining the model's fully interactive physics (this method was also implemented by David Straus's group at COLA). The modeling results unequivocally show that an accurate horizontal *and* vertical distribution of heating are critical in the simulation of the MJO. This more accurate heating came from either satellite-derived latent heating or idealized heating that had a longitudinal tilt more like the observed MJO. Radiative heating of upper level cloud, on the other hand, only slightly modifies an idealized GCM (i.e., one without interactive physics) forced by observed latent heating suggesting that the impact of clouds is more important to large-scale tropical circulation variations because of convective feedbacks rather than direct cloud radiative forcing.

Boyle, J., and S. A. Klein, 2010: Impact of horizontal resolution on climate model forecasts of tropical precipitation and diabatic heating for the TWP-ICE period. *J. Geophys. Res.*, **115**, D23113, doi:10.1029/2010JD014262.

Fridlind, A. M., and coauthors, 2012: A comparison of TWP-ICE observational data with cloud-resolving model results. *J. Geophys. Res.*, 117, D05204, doi:10.1029/2011JD016595.

Lin, Y., and coauthors, 2012: TWP-ICE global atmospheric model intercomparison: Convection responsiveness and resolution impact. *J. Geophys. Res.* In press.

Lappen, C., and C. Schumacher, 2012: Heating in the tropical atmosphere: What level of detail is critical for accurate MJO simulations in GCMs? *Clim. Dyn.*, doi:10.1007/s00382-012-1327-y.

Li, W., C. Schumacher, and S. A. McFarlane, 2012: Radiative heating of the ISCCP upper level cloud regimes and its impacts on the large-scale tropical circulation. *J. Geophys. Res.* Conditionally accepted.

iii) *Mentoring and service*

This grant provided support for the completion of Wei Li's PhD work, partial support for two masters students who were involved in AMIE (Jon Fliegel and Amanda DePasquale), and three-quarters support for Dr. Cara-Lyn Lappen, a research scientist who is spearheading the modeling component of the project. Dr. Li is now a post-doc at Penn State and Jon Fliegel has taken a position with a defense contractor working with military radar applications. Amanda DePasquale will finish her masters in spring 2013.

Beyond the scientific contributions of the PI and her research group, the PI has been an active ASR science team member including playing a significant role in AMIE and GOAmazon2014 planning as a steering committee member for both field campaigns. She served on the ARM ARRA source selection evaluation panel for C-band radars in 2009 and she is currently a member of the ARM radar science steering committee. The PI has also presented her DOE-supported work at a number of universities and national meetings (listed under Presentations related to ASR research).

Papers fully or partially supported by ASR funding

Published or in review

Feng, Z., S. A. McFarlane, C. Schumacher, R. A. Houze, and S. Ellis, 2012: Comparison of cloud statistics observed by cloud and precipitation radars during the DYNAMO/AMIE experiment at Addu Atoll. *J. Atmos. Ocean Tech.* Submitted.

Li, W., C. Schumacher, and S. A. McFarlane, 2012: Radiative heating of the ISCCP upper level cloud regimes and its impacts on the large-scale tropical circulation. *J. Geophys. Res.* Conditionally accepted.

Lin, Y., and coauthors, 2012: TWP-ICE global atmospheric model intercomparison: Convection responsiveness and resolution impact. *J. Geophys. Res.* **117**, DO9111, doi:10.1029/2011JD017018.

Fridlind, A. M., and coauthors, 2012: A comparison of TWP-ICE observational data with cloud-resolving model results. *J. Geophys. Res.*, **117**, D05204, doi:10.1029/2011JD016595.

Lappen, C., and C. Schumacher, 2012: Heating in the tropical atmosphere: What level of detail is critical for accurate MJO simulations in GCMs? *Clim. Dyn.*, doi:10.1007/s00382-012-1327-y.

Feng, Z., X. Dong, B. Xi, C. Schumacher, P. Minnis, and M. Khaiyer, 2011: TOA radiation budget of convective core/stratiform rain and anvil clouds from deep convective systems. *J. Geophys. Res.*, **116**, D23202, doi:10.1029/2011JD016451.

Li, W., and C. Schumacher, 2011: Tropical thick anvil viewed by the TRMM Precipitation Radar. *J. Climate*, **24**, 1718-1735.

In preparation

Schumacher, C., S. Stevenson, and C. Williams: Profiler observations of vertical velocity in convective, stratiform, and anvil cloud over Darwin, Australia, *Mon. Wea. Rev.* In preparation.

Schumacher, C., S. Xie, and S. A. McFarlane: Eddy vertical transports revisited. *J. Atmos. Sci.* In preparation.

Products

Parts of the Darwin C-POL dataset processed by the PI were provided to Guang Zhang, Ann Fridlind, Jim Boyle, Xiouhua Fu, Yanluan Lin, Samson Hagos, and Laura Riihimaki:

- 3-D gridded reflectivity
- convective-stratiform precipitation classifications
- rain rate maps
- latent heating profiles

Similar SMART-R products are being provided to the DOE community as they relate to AMIE science.

Presentations related to ASR research

DOE ASR 3rd Science Team Meeting, Crystal City VA, March 2012
Presentation: Schumacher, C., S. Stevenson, and C. Williams. Profiler observations of vertical velocity in convective, stratiform, and anvil cloud over Darwin
Presentation: Scanning radar observations on Addu Atoll
Poster: Lappen, C., and C. Schumacher. Anomalous heating distributions and the MJO in CAM4
DOE ASR Working Group Meeting, Annapolis MD, September 2011
Presentation: Potential precipitation radar and sounding network observations during GOAmazon and the large-scale implications of Amazonian convection (invited)
University of Kansas, Lawrence KS, September 2011
Seminar: Tropical stratiform rain and climate (invited)
NCAR EOL/MMM, Boulder CO, August 2011
Seminar: The convective-stratiform-anvil transition (invited)
DOE ASR 2nd Science Team Meeting, San Antonio TX, March 2011
Poster: Lappen, C., and C. Schumacher. MJO predicition in GCMs: Is an accurate heating distribution critical?
University of Texas Climate Forum, Austin TX, March 2011
Seminar: Tropical stratiform rain and climate (invited)
RSMAS, Miami FL, February 2011
Seminar: Tropical anvil: Meteorologically important or just a practical joke? (invited)
Michio Yanai Symposium, Seattle WA, January 2011
Presentation: Eddy vertical transports revisited (invited)
SUNY-ALBANY, Albany NY, September 2010
Seminar: Heating in tropical convective cloud systems (invited)
29th Conference on Hurricanes and Tropical Meteorology, Tucson AZ, May 2010
Presentation: Dissecting diabatic heating profiles during TWP-ICE
Poster: Li, W., and C. Schumacher. Tropical thick anvil
Penn State University, State College PA, April 2010
Seminar: Dissecting tropical heating profiles (invited)
DOE ASR 1st Science Team Meeting, Bethesda MD, March 2010
Presentation: Dissecting diabatic heating profiles from TWP-ICE (invited)
DOE ARM Cloud Properties Working Group meeting, Boulder CO, September 2009
Presentation: Anvil radiative heating and the power of look-up tables (invited)
Center for Ocean-Land-Atmosphere Study (COLA), Calverton MD, September 2009
Seminar: Latent heating, radiative heating, and the large-scale circulation (invited)