Final Scientific/Technical Report

EVALUATION AND IMPROVEMENT OF CLOUD AND CONVECTIVE PARAMETERIZATIONS FROM ANALYSES OF ARM OBSERVATIONS AND MODELS

DOE Interagency Agreement DE-SC0001637
Period of Performance: 5/1/2009-4/30/2012

Principal Investigator:
Anthony D. Del Genio
NASA Goddard Institute for Space Studies
2880 Broadway
New York, NY 10025
212-678-5588
anthony.d.delgenio@nasa.gov

Over the performance period the PI and his team performed a broad range of data analysis, model evaluation, and model improvement studies using ARM data. Below we summarize progress and publications resulting from the funded research.

1. Cloud regimes in the TWP and their evolution over the MJO (Chen and Del Genio 2009)

GCMs are sometimes evaluated using "cloud regimes" from ISCCP histograms of cloud top pressure and optical thickness. ISCCP identifies 6 tropical regimes related to deep convective, anvil, congestus, thin cirrus, shallow cumulus, and stratocumulus clouds. ISSCP's passive remote sensing retrieval misses some thin clouds and sometimes places cloud top at the wrong altitude. We aggregated cloud top distributions from ARM ARSCL data at Manus and Nauru and found that ISCCP overestimates middle and low clouds in the anvil and congestus clusters. When ISCCP cloud top heights are adjusted to match ARSCL, the independence of several clusters disappears. Direct clustering of ARSCL profiles produces only 4 independent regimes at Manus and 3 at Nauru.

For the MJO, the congestus and shallow cumulus clusters dominate in the suppressed phase, giving way near the peak to the deep convective and anvil clusters. The thin cirrus regime is insensitive to MJO phase, suggesting a non-convective origin. We conclude that the six ISCCP clusters probably are independent, but represent neither a true distribution of all clouds nor of highest cloud top heights. ARSCL cloud profiles at Manus show that a trimodal distribution of clouds during the suppressed MJO phase gives way to a bimodal distribution of deep and shallow clouds and increasing overall cloud cover as the peak approaches. After the peak high clouds dominate, then give way again to a suppressed phase trimodal profile. Relative humidity profiles are dry before MJO peak and humid at and just after the peak.

The GISS CMIP3 GCM produces only 4 clusters (deep convective, congestus, shallow cumulus, stratocumulus). However, the GCM convection scheme in fact rarely produces congestus, and shallow convection occurs almost equally often in the two suppressed regimes. This indicates that clustering on cloud properties does not accurately reflect the parameterized physical processes operating in the model.

2. ARM M-PACE IOP SCM-CRM intercomparisons (Klein et al. 2009; Morrison et al. 2009)

Results are presented for two case study intercomparisons of CRMs and SCMs from the ARM M-PACE IOP. One captures a deep multi-layer mixed-phase cloud system and the other a single-layer low-level mixed-phase stratocumulus. The models generally overestimate liquid water path (LWP) and underestimate ice water path (IWP) in the deep multi-layer case, while the opposite is true for the stratocumulus case. In general, models with a 2-moment cloud microphysics scheme produce a somewhat more realistic LWP for the deep case, and the CRMs produce greater cloudiness than the SCMs. In the stratocumulus case, a sensitivity study demonstrates that the interaction between liquid and ice-phase microphysics is responsible for the underestimated LWP. In this case too there is evidence that more sophisticated microphysics schemes simulate more realistic LWP and IWP.

3. Simulations of convective updraft strength and depth during TWP-ICE (Wu et al. 2009)

We used the WRF model to simulate cumulus updraft speeds during TWP-ICE. WRF produces stronger updrafts during the break period than the active period, consistent with the more unstable thermodynamic profile, higher radar reflectivities above the freezing level, and greater lightning flash rate observed during the break period. It also simulates shallower congestus convection during the dry monsoon period as observed. The updraft speed profiles are robust to changes in resolution and the microphysics and turbulence parameterizations used.

In the GISS SCM we tested the updraft speed and entrainment rate parameterization of Gregory (2001), in which entrainment is related to buoyancy production by turbulence. We also tested a formula suggested by Neggers et al. (2002), in which entrainment varies inversely as updraft speed. Either scheme can provide reasonable agreement with the WRF updraft speed profile below the 250 mb level, but only when a free parameter varies from one sub-period to another, suggesting that an unaccounted-for dependence of entrainment rate on boundary layer characteristics may need to be invoked.

Unlike the updraft speed profiles, WRF hydrometeor profiles are sensitive to the microphysics scheme used. Darwin C-POL radar hydrometeor type retrievals show more graupel (an indicator of riming of supercooled water in the mixed-phase region) at high altitude in the more vigorously convecting break period than in the active period. The WRF, despite producing more vigorous convection during the break, produces more graupel in the active period using one microphysics scheme and little graupel (but more during the break) with another scheme. This attests to the uncertainty in ice microphysics in CRMs.

4. Evaluation of convective entrainment parameterizations using TWP-ICE simulations (Del Genio and Wu 2010)

GCMs produce warm season continental rainfall that peaks near noon, while observations show that rain peaks in late afternoon or evening. One possible culprit is entrainment rates that are too weak in the models' cumulus parameterizations. We used WRF simulations of the TWP-ICE break period at fine resolution (600 m and 125 m) to explore the daytime transition from shallow to deep convection, since CRMs simulate a realistic diurnal cycle. We inferred entrainment rate from the decrease of moist static energy with height in convective updraft columns and the updraft-environment moist static energy difference. The inferred entrainment rate weakens with time of day and as convection deepens.

This allowed us to test several proposed parameterizations of entrainment rate. The scheme of Gregory (2001), which calculates entrainment as directly proportional to parcel buoyancy and inversely proportional to the square of updraft speed, is consistent with the WRF simulations. A scheme proposed by Neggers et al. (2002) in which entrainment varies inversely with updraft speed is less successful, and the Bechtold et al. (2008) scheme currently in use in the ECMWF IFS, which strengthens entrainment as tropospheric humidity decreases, does not match the WRF behavior. The Gregory scheme was implemented in the CMIP5 version of the GISS Model E GCM.

5. Evaluation of GISS GCM cloud behavior vs. long-term SGP cloud statistics (Kennedy et al. 2010)

We compared 3 years of GOES area-averaged cloud types to ARSCL cloud profiles, and to the CMIP3 version of the GISS SCM, at the SGP. The comparison to GOES indicates that ARSCL cloud statistics are representative of the larger area and thus suitable for SCM evaluation. However, GOES low, middle, and high cloud fractions are biased due to multilayer cloud scenes. The SCM overestimated low clouds, produced reasonable middle cloud fractions, and underestimated high clouds. Stratification of the results by synoptic state using the NARR reanalysis indicates that the SCM produces realistic high clouds when a trough is upstream of the SGP but misses high clouds when a ridge is upstream and vertical motions are weak or downward. The pdf of cloud occurrence is shifted to high relative humidities compared to the observations, in which high clouds often occur at humidities below the stratiform cloud parameterization's threshold for cloud occurrence.

6. Classification of aerosol semi-direct effects on cloud cover (Koch and Del Genio 2010)

This paper synthesizes the results of previous CRM and GCM simulations of the aerosol semi-direct effect. Absorbing aerosols (AAs) such as black carbon or dust absorb solar radiation, perturb the temperature profile, and influence cloud cover. We categorize the effects into several likely regimes. Cloud cover is decreased if AAs are embedded in the cloud layer. AAs below cloud may enhance convection and cloud cover. AAs above cloud top stabilize the underlying layer and enhance stratocumulus clouds but may reduce cumulus clouds. AAs can promote cloud cover in convergent regions as they enhance deep convection and low-level convergence. Most global model studies indicate a regional variation in the cloud response but generally increased cloud cover over oceans and some land regions, with net increased low-level and/or reduced upper-level cloud cover. The result is a net negative semi-direct effect feedback. In some of these climate model studies, the cooling effect of BC due to cloud changes is strong enough to essentially cancel the warming direct effects.

7. ARM depolarization lidar constraints on cloud phase (Naud et al. 2010)

Cloud phase and temperature profiles derived from ground-based lidar depolarization and radiosonde measurements, respectively, are analyzed for two midlatitude locations in winter: the United States ARM Southern Great Plains (SGP) site and the SIRTA site in France. A simple technique that only uses lidar depolarization ratio and temperature profiles is presented and compared with other methods. Because lidars are attenuated in optically thick clouds, the dataset only includes optically thin clouds that occur preferentially 1000-2000 km away from the nearest surface low pressure center in association with the leading or trailing edges of fronts.

At both locations, most of the clouds observed with the lidar are either completely liquid or completely glaciated while approximately 13% are of mixed phase. Most of these mixed phase clouds show an ice layer at cloud top, and clouds with liquid at cloud top are rare. The relationship between ice fraction and temperature only slightly changes between cloud base and top. At both sites liquid is more prevalent at lower temperatures than has been found previously in aircraft flights through frontal clouds. The average temperatures of mixed phase clouds at both locations are consistent with those found using coincident passive satellite remote sensing measurements that sample cloud phase only at cloud top.

8. Preferred states of the winter Arctic atmosphere, surface, and sub-surface (Stramler et al. 2011)

Arctic clouds influence the major surface albedo feedback process (snow/ice melting) in GCMs. We explored the atmospheric and sub-surface factors controlling the surface energy budget (SEB) at the SHEBA Arctic sea ice site using NOAA cloud radar and depolarization lidar and ARM radiometer data.

During winter, the SEB at SHEBA is bimodal, consisting of (a) a dominant clear sky mode (also including occurrences of optically thin cloud) with surface net LW flux of about -40 W/m^2, partly offset by significant heat conduction through the underlying sea ice and snow, and a negative correlation between net LW flux and surface temperature, and (b) a less frequent optically thick cloudy mode with SEB ~ 0 W/m^2, atmospheric inversion temperatures (from which clouds radiate downward) comparable to the surface temperature, positive correlation between net LW and surface temperature, and greatly reduced conduction through the snow, causing the heat flux through the sea ice to warm the snow-ice interface. The atmosphere often maintains itself in these states for 5-10 days at a time, switching rapidly to the other mode when a change in the synoptic situation creates or dissipates clouds. (This aspect of our work was recently highlighted in the Morrison et al. review paper in Nature Geoscience and in Graham Feingold's plenary talk on the predator-prey model at the ASR Science Team Meeting.)

9. Modeling the sensitivity of convection to tropospheric humidity (Del Genio 2012)

This synthesis paper provides a framework for understanding recent progress in cumulus parameterization and a roadmap for the most urgent needs in parameterization development using the "building block" paradigm of Mapes et al. (2006, *Dyn. Atmos. Ocean* **42**, 3-29). The organizing principles of the paper are that (a) tropical biases and climate sensitivity uncertainties in GCMs are at least partly associated with the models' lack of success in simulating the transition from shallow to deep convection and the evolution from full-troposphere heating to a heating-cooling dipole as convection matures, and that (b) inadequate representation of the sensitivity of convection to tropospheric humidity plays a role in both of these shortcomings. The paper discusses the current state of entrainment parameterization (a possible ASR Focus Group topic) and the need for parameterizations of mesoscale organization (of relevance to a possible ASR Convective-Stratiform Transition Focus Group), using among other things, insights from ARM radiosondes and ARSCL cloud products and CRM simulations forced with ARM constrained variational analysis products.

10. Constraints on parameterization of mesoscale organization of convection from TWP-ICE WRF simulations (Del Genio et al. 2012)

GCMs poorly simulate the lifetime of convection and its dipole pattern of upper level heating and low level cooling during the mature phase of the lifecycle. This deficiency highlights the need for GCMs to parameterize mesoscale organization of convection. WRF simulations of TWP-ICE convection in weak wind shear environments of different humidities are used to characterize mesoscale organization processes and provide parameterization guidance. Downdraft cold pools appear to stimulate further deep convection both through their effect on eddy size and vertical velocity. Anomalously humid air surrounds updrafts, reducing the efficacy of entrainment. Recovery of cold pools to ambient conditions proceeds differently over land and ocean. Over ocean increased surface fluxes restore the cold pool to pre-storm conditions. Over land surface fluxes are suppressed in the cold pool region; temperature decreases and humidity increases and both then remain nearly constant while the undisturbed environment cools diurnally. The stratiform rain region area lags convection by 5-6 hr under humid active monsoon conditions but by only 1-2 hr during drier break periods, suggesting that organization is more readily sustained in a humid environment. Stratiform region hydrometeor mixing ratio lags convection by 0-2 hr, suggesting that it is influenced by detrainment. Small stratiform region temperature anomalies suggest that a mesoscale updraft parameterization initialized with properties of buoyant detrained air and evolving to a balance between diabatic heating and adiabatic cooling might be a plausible approach for GCMs.

11. Updraft and downdraft propertics in TWP-ICE simulated convection (Mrowiec et al. 2012)

We analyzed 3 CRM simulations of convection during TWP-ICE, differing in dynamical core and/or microphysics scheme, forced by the ARM constrained variational analysis. The models were constrained by C-POL derived rain rates and utilized a reflectivity-based rain classification algorithm applied to both C-POL data and model fields. Convective updrafts are consistent across the simulations but their hydrometeor loadings differ substantially. Convective downdraft and stratiform updraft and downdraft mass fluxes vary below the melting level, but share similar vertically uniform draft velocities despite differing hydrometeor loadings. Even when downdraft mass flux profiles agree, cold pool properties diverge substantially. Despite these differences, convective updraft and downdraft mass fluxes are linearly correlated with convective area, the ratio of ice in downdrafts to that in updrafts is ~0.5, and the ratio of downdraft to updraft mass flux is ~0.5-0.6, which is related to precipitation efficiency.

12. Insights gained from long-term ARM records at Manus and Nauru (Long et al. 2012)

This paper reviews some of the significant research performed with ARM data from the TWP sites at Manus and Nauru islands over the past decade. These datasets have been used to develop techniques for identifying clear skies in surface radiation data; document cloud effects on surface SW and LW fluxes, their diurnal variation, and their interannual ENSO variability; characterize the SW transmissivity for different cloud types; understand how the vertical structure of clouds changes during the MJO; retrieve cloud microphysical properties and thereby determine the radiative contribution to the total diabatic heating profile for different cloud regimes; differentiate vertical velocity statistics for ocean- and land-forced shallow cumulus; compare the roles of mid-troposphere stability and humidity in limiting the depth of congestus clouds; determine how cirrus properties evolve after ice is detrained from convection; determine the fraction of cirrus that are generated by convection vs. large-scale processes; separate the influence of boundary layer vs. mid-troposphere humidity on convection and precipitation; validate a variety of satellite retrievals, CRMs, and GCMs.

Papers published (in order discussed above):

Chen, Y., and A.D. Del Genio, 2009: Evaluation of tropical cloud regimes in observations and a general circulation model. *Climate Dynam.*, **32**, 355-369.

Klein, S.A., et al., 2009: Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. I: Single layer cloud. *Quart. J. R. Meteorol. Soc.,* **135**, 979-1002.

Morrison, H., et al., 2009: Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. II: Multi-layered cloud. *Quart. J. R. Meteorol. Soc.,* **135**, 1003-1019.

Wu, J., A.D. Del Genio, M.-S. Yao, and A.B. Wolf, 2009: WRF model and GISS SCM simulations of convective updraft properties during the TWP-ICE experiment. *J. Geophys. Res.*, **114**, D04206, doi:10.1029/2008JD010851.

Del Genio, A.D., and J. Wu, 2010: The role of entrainment in the diurnal cycle of continental convection. *J. Climate*, **23**, 2722-2738.

Kennedy, A.D., X. Dong, B. Xi, P. Minnis, A.D. Del Genio, A.B. Wolf, and M.M. Khaiyer, 2010: Evaluation of the NASA GISS Single Column Model simulated clouds using combined surface and satellite observations. *J. Climate*, **23**, 5175-5192.

Koch, D., and A.D. Del Genio, 2010: Black carbon absorption effects on cloud cover: Review and synthesis. *Atmos. Chem. Phys.*, 1**0**, 7685-7696.

Naud, C.M., A. Del Genio, M. Haeffelin, Y. Morille, V. Noel, J.-C. Dupont, D.D. Turner, C. Lo, and J. Comstock, 2010: Thermodynamic phase profiles of optically thin midlatitude clouds and their relation to temperature. *J. Geophys. Res.*, **115**, D11202, doi:10.1029/2009JD012889.

Stramler, K.L., A.D. Del Genio, and W.B. Rossow, 2011: Synoptically driven Arctic winter states. *J. Climate*, **24**, 1747-1762.

Del Genio, A.D., 2012: Representing the sensitivity of convective cloud systems to tropospheric humidity in general circulation models. *Surv. Geophys.*, **33**, 637-656.

Del Genio, A.D., J. Wu, and Y. Chen, 2012: Characteristics of mesoscale organization in WRF simulations of convection during TWP-ICE. *J. Climate*, **25**, 5666-5688.

Mrowiec, A.A., C. Rio, A.M. Fridlind, A.S. Ackerman, A.D. Del Genio, O.M. Pauluis, A.C. Varble, and J. Fan, 2012: Analysis of cloud-resolving simulations of a tropical mesoscale convective system observed during TWP-ICE: Vertical fluxes and draft properties in convective and stratiform regions. *J. Geophys. Res.*, **117**, no. D19, D19201, doi:10.1029/2012JD017759.

Long, C.N., S.A. McFarlane, A. Del Genio, P. Minnis, T.P. Ackerman, J. Mather, J. Comstock, G.G. Mace, M. Jensen and C. Jakob, 2012: ARM research in the equatorial western Pacific - a decade and counting. *Bull. Amer. Meteorol. Soc.*, **94**, 695-708.