Final Scientific/Technical Report

CONSTRAINTS ON CLOUD FEEDBACK FROM ANALYSIS OF ARM OBSERVATIONS AND MODELS

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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 innovative analyses of surface remote sensing data from the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains, Tropical Western Pacific, and North Slope of Alaska sites to elucidate some of the physical processes underlying cloud feedbacks on anthropogenic climate change. ARM data strongly influenced parameterization evaluation and development in the GISS (Goddard Institute for Space Studies) General Circulation Model (GCM) over this time. In this report we discuss how ARM funding was utilized for data analyses, model evaluation, and cumulus and stratiform cloud parameterization improvements, highlighting especially the areas of low-cloud feedbacks, cloud phase, and convective entrainment and downdrafts.

Low cloud feedbacks

At the dawn of the ARM era, cloud optical property feedbacks were just being recognized as a serious climate issue. Early GCMs had fixed cloud optical thicknesses or albedos. However, it was argued that liquid water content and thus cloud albedo should increase with temperature, providing a negative cloud feedback. In the first Atmospheric Model Intercomparison Project, a number of GCMs assumed such behavior as a parameterization. Meanwhile, several GCMs were implementing prognostic cloud water budgets, producing different cloud feedbacks depending on specific process representations. Satellite datasets were showing that except at cold temperatures, liquid water path and low cloud optical thickness were negatively correlated with temperature, although there were concerns that this might be an artifact of the satellite sensors' resolution. During this time, early ARM funding contributed to the implementation and evaluation of a prognostic cloud water parameterization in the GISS GCM (Del Genio et al., 1996) and the first evaluation of cloud feedback in that model as part of the FANGIO intercomparison (Cess et al., 1996). The GISS GCM reproduced the satellite behavior, because of liquid water sinks (cloud top entrainment and precipitation) and varying cloud physical thickness, but it was not known whether these were responsible for the observed behavior (Tselioudis et al., 1998). The resulting positive optical thickness feedback increased the climate sensitivity by 0.35°C (Yao and Del Genio, 1999, 2002).

Although cloud radars had not yet been deployed at the SGP, early ARM data permitted a preliminary study of continental midlatitude low cloud optical properties (Del

Genio and Wolf, 2000). The ARM Microwave Radiometer was used to obtain liquid water path (LWP), the Belfort Laser Ceilometer for cloud base height, satellite brightness temperatures and soundings for cloud top height, surface meteorology observations for relative humidity, and surface weather reports of cloud type. From these cloud physical thickness and liquid water content (LWC) were derived, along with indices of boundary layer structure.

The results documented the midlatitudes as a transition region between the satellite-observed low- and high-latitude behavior. Low cloud LWP was invariant with temperature during winter but decreased with temperature in summer. LWC showed no temperature dependence, but clouds physically thinned with temperature, especially during summer and in the warm sector of baroclinic waves. This was due primarily to a rising cloud base with warming as relative humidity decreased and the lifting condensation level increased. The temperature dependence of cloud thickness only occurred in well-mixed or decoupled boundary layers and was in part the result of a shift in the relative frequency of convective and stable boundary layers. Dong et al., (2005) revisited this analysis with accurate radar-derived cloud top heights and a more recent MWR processing and found that LWC decreased with increasing temperature instead, but overall they agreed with the conclusions of Del Genio and Wolf (2000).

Cloud phase

Changes in the relative occurrence of cloud ice and liquid as climate warms exert a negative feedback on climate change, due to their different particle sizes and scattering phase functions and thus in the condensate retained rather than precipitated out. The feedback depends on the temperature range over which the transition (in a statistical sense) from liquid to ice occurs. In principle, both phases can exist from temperatures ~ 0°C down to the homogeneous ice nucleation threshold of ~ -38°C. Which phase exists at a given temperature within this range depends on the cloud-scale dynamics, the resulting degree of supersaturation, the availability of ice nuclei, and the age of the cloud. Some GCMs use single-moment cloud microphysics parameterizations that diagnose cloud phase from grid-scale properties. Others use two-moment schemes that determine phase from parameterized microphysical processes that estimate nucleation rates of liquid and ice and conversions between them. Model comparisons to ARM observations during the Mixed-Phase Arctic Cloud Experiment (M-PACE) IOP at the NSA in 2004 showed significant scatter in the amounts of ice and liquid, and a tendency for the liquid phase to be underpredicted in boundary layer stratocumulus (Klein et al., 2009) but overpredicted in a frontal multi-layer cloud (Morrison et al., 2009).

Parameterizations of cloud phase during the ARM era had been influenced by midlatitude aircraft observations in the frontal regions of baroclinic storms. These data suggested that liquid water was rare at temperatures < -15°C, whereas earlier aircraft data had liquid present down to -40°C. Naud et al., (2010) used the ARM SGP Raman Lidar and the SIRTA lidar in France to compile statistics of cloud phase based on the lidar depolarization ratio. Lidar phase profiles are restricted to optically thinner clouds such as altocumulus that often occur behind fronts, a different sampling than that of the aircraft studies.

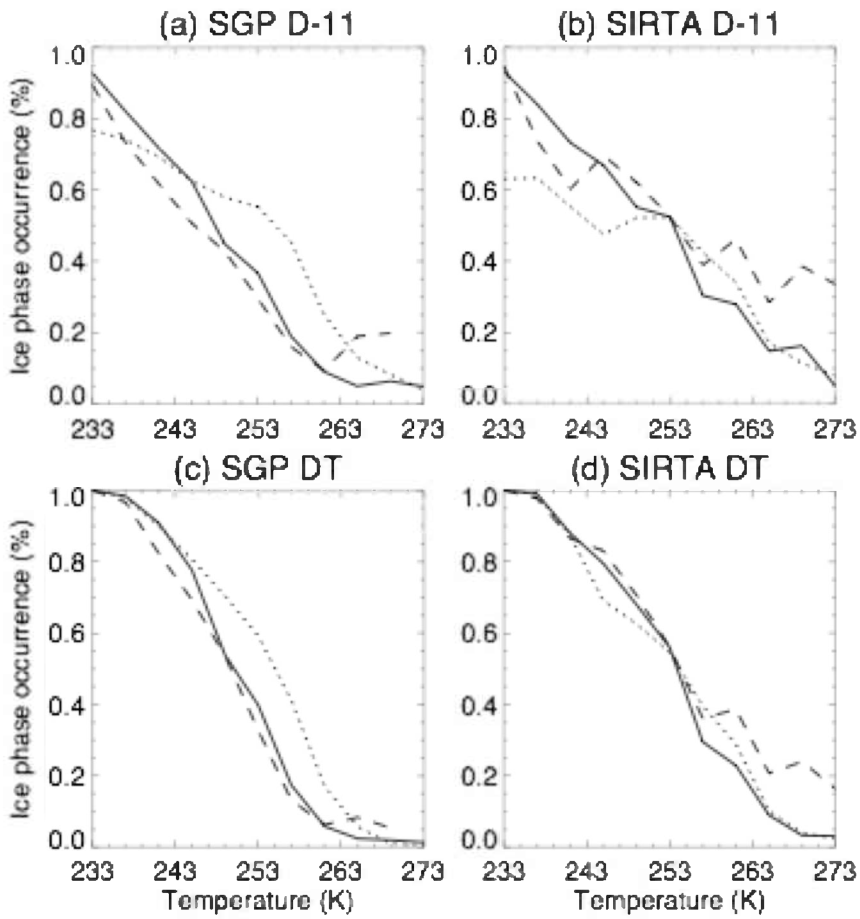

Fig. 1. Lidar-based temperature dependence of the fractional occurrence of the ice phase in optically thin clouds at the SGP (a, c) and SIRTA (b,d) sites (Naud et al., 2010). The upper and lower panels represent two different approaches to specifying the depolarization ratio threshold that separates ice from liquid. The solid curves show the temperature dependence at the median level of the cloud, while the dashed and dotted curves represent the phase at cloud top and cloud base, respectively.

Naud et al. (2010) found that liquid persists in these clouds down to ~ -40°C, depending on the lidar and depolarization threshold used (Fig. 2), much colder than in the aircraft data. Likewise, the temperature at which ice and liquid occur equally is much colder in the lidar data (~ -20°C) than in the aircraft data (-6.5°C). The GISS GCM at that time used a hybrid diagnostic scheme (Del Genio et al., 1996) in which cloud phase at nucleation varies probabilistically with temperature down to -38°C, but with Bergeron-Findeisen glaciation of supercooled cloud liquid by falling snow possible as the cloud ages. The overall resulting dependence of cloud phase on temperature in the GCM appears realistic, but the GCM analysis was not performed separately for thick frontal and thinner post-frontal clouds.

On the North Slope of Alaska and adjacent sea ice, mixed-phase clouds are prevalent, and the amount of ice vs. liquid has first order effects on the surface energy budget. Klein et al. (2009) performed intercomparison studies of SCMs and LES models against aircraft cloud liquid and ice water content data taken during the M-PACE IOP and showed that SCMs tend to systematically overpredict ice. Stramler et al. (2011) analyzed a year of Arctic cloud and radiation surface remote sensing data and found that from an energy flux standpoint, Arctic winter can be separated into two qualitatively different environments: Opaquely cloud skies, in which liquid stratus clouds prevail and the surface energy balance is close to zero, and radiatively clear skies, in which skies are either actually clear or populated by optically thin low ice clouds that do not produce significant downward longwave radiation. Transitions between the two regimes appear to occur primarily when the synoptic situation changes. Xie et al. (2005) and Xu et al. (2005) showed that models also have trouble simulating the correct amount of ice in simulations of winter frontal clouds at the SGP.

Convective downdrafts

The GATE field experiment showed that convective downdrafts are important to the energy and water budgets of convective systems. Downdrafts were neglected in early cumulus parameterizations, though. By the time ARM began, some GCMs had included simple representations of downdrafts, including GISS.

The first GCSS case study to examine midlatitude continental convection was based on the ARM Summer 1997 SCM IOP. CRMs diagnosed updraft and downdraft mass fluxes, and these were compared to those parameterized in 15 SCMs (Xie et al., 2002). The SCM and CRM updraft mass fluxes were in reasonable agreement. Downdraft mass fluxeswere much weaker in the SCMs than in the CRMs, however. Several possible reasons for this were suggested by Xie et al. (2002). First, the cumulus parameterizations only accounted for convective downdrafts, while the CRMs included both convective and mesoscale downdrafts. Second, some parameterizations (including that used by GISS) prescribed a single downdraft with a prescribed fraction of the updraft mass flux and/or did not allow downdrafts below cloud base.

Third, and perhaps most important, is that in most GCMs a stronger downdraft erroneously suppresses future convection. This occurs because in most GCMs, low moist static energy downdraft air immediately mixes with the ambient high moist static energy boundary layer air that gave rise to the convection, prematurely stabilizing the boundary layer. Downdrafts actually form boundary layer cold pools that remain distinct from the ambient air for hours. As the cold pools spread, high moist static energy air at the cold pool leading edge is lifted, triggering the next generation of convection rather than shutting it down. Indeed, several years earlier it had been suggested that GCM downdraft parameterizations were perhaps doing more harm than good because of this behavior.

The Xie et al. (2002) result led to several attempts to strengthen the GISS downdraft. For CMIP3 (Schmidt et al., 2006) the downdraft mass flux was increased by adding entrainment and extending the downdraft below cloud base. For CMIP5 multiple downdrafts were added whenever an equal mixture of cloud and environment air was negatively buoyant. Buoyancy was based only on temperature, rather than on virtual temperature with precipitation loading, because the latter created an excessive downdraft mass flux. Post-CMIP5, as part of an effort to create realistic GCM intraseasonal variability, convective rain re-evaporation was strengthened. This sufficiently moistened the environment that downdraft negative buoyancies were reduced, and it finally became possible to include the precipitation loading effect. Recently, a downdraft cold pool parameterization has been developed, with some effect on convective occurrence frequency.

Convective entrainment and vertical velocities

By 2006, cloud radars were standard at all ARM sites, and the Active Remotely Sensed Cloud Layers (ARSCL) value-added product had become ARM's signature contribution to the evaluation of GCM cloud parameterizations. That year ARM conducted its first full-scale tropical IOP in Darwin, Australia, the Tropical Warm Pool – International Cloud Experiment (TWP-ICE). During TWP-ICE, Darwin experienced changes in weather regime that are characteristic of the Australian winter monsoon season: an active monsoon period of onshore flow and extensive rain; a suppressed monsoon period with drier midlevel conditions and isolated, moderate depth convection; an even drier fully suppressed period of mostly clear skies; and a monsoon break period of building instability and occasional but vigorous deep convection. These regime shifts provided an ideal opportunity to test model convection behavior, and intercomparisons of SCMs in which GISS participated followed.

Before TWP-ICE, convective entrainment had been identified as a glaring shortcoming of cumulus parameterizations. This was based on a GCSS case study of the ARM Summer 1997 IOP that showed that SCMs triggered continental deep convection too early in the day, and a tropical ocean case study that showed that CRM convection depth was much more sensitive to environmental humidity in CRMs than SCMs. This behavior was traced to weak entrainment, a remnant of early cumulus parameterization history in which simulating convection that reached the tropopause was one of the few observational constraints. ARM ARSCL data at Nauru Island site had verified that the depth of cumulus congestus was indeed sensitive to mid-tropospheric humidity (Jensen and Del Genio, 2006).

By the time of TWP-ICE, the GISS GCM was using the Gregory entrainment parameterization, which is based on convective turbulence scalings. The Gregory scheme diagnoses updraft speed w and parameterizes entrainment ε as a function of parcel buoyancy B and updraft speed: $\varepsilon = CB/w^2$. The proportionality constant C indicates the fraction of buoyant turbulent kinetic energy available for use by entrainment. TWP-ICE data documented the more maritime character of active period convection (lower radar reflectivities and less graupel above the melting level, less lightning) relative to the stronger, more continental convection during the break period. Wu et al. (2009) showed that the Weather Research and Forecasting (WRF) model, run at convection-resolving resolution, simulated stronger updraft speeds during the break period than during the active period, consistent with the indirect observational inferences.

Del Genio et al. (2007) implemented the Gregory parameterization in the GISS GCM, with different values of the proportionality constant to represent more- and less-entraining parts of the cumulus spectrum. The parameterization was evaluated by Wu et al. (2009) in SCM tests against the WRF-derived TWP-ICE updraft speeds. The SCM reproduced the difference in convection strength between the active and break periods but overestimated updraft speeds in the upper troposphere. A WRF study of the TWP-ICE break period diurnal cycle tested various proposed parameterizations of entrainment (Del Genio and Wu, 2010). The entrainment rate inferred from the thermodynamic structure in convecting gridboxes decreased over the afternoon as shallow convection gradually gave way to congestus and then predominantly deep convection (Fig. 2, left panel). To see whether these variations were consistent with the Gregory scheme, w, B, and ε were derived from the WRF fields and the implied values of C for different convection depths calculated from these. The results (Fig. 2, right panel) suggest that a single profile of C applies to convection of varying depths except near cloud base, where the deeper events have smaller C than the shallow events. This suggests that the Gregory scheme is in general a good predictor of entrainment but that the SCM shortcomings seen by Wu et al. (2009) may be due to changes in convective parcel properties that the Gregory scheme by itself cannot anticipate, e.g., larger parcel sizes or non-turbulent sources of lifting as convection deepens. If so then the operational GISS GCM approach of allowing weakly and strongly entraining plumes (smaller and larger C) to co-exist at all times needs to be re-considered. Tests with the cold pool parameterization, in which the less-entraining plume exists only after cold pools form, is more in keeping with the WRF inferences and produces some improvement, but entrainment remains an ongoing focus of research.

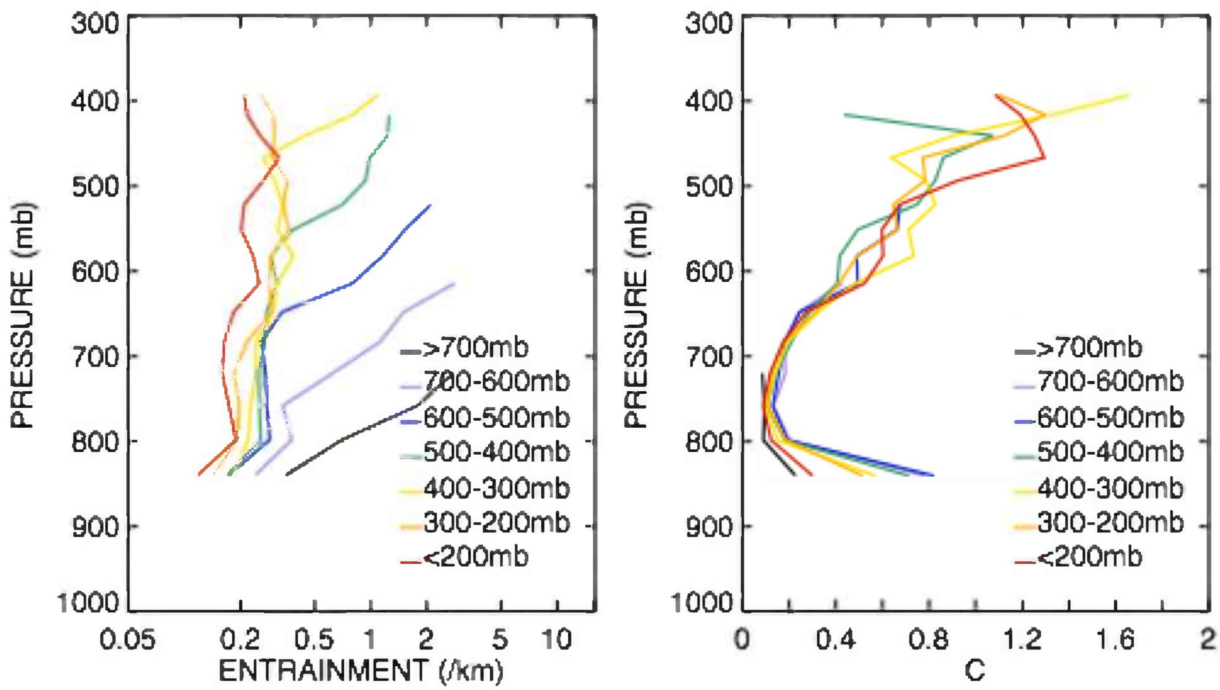

Fig. 2. Left panel: Entrainment rates inferred from the moist static energy profile within convective columns penetrating to different pressure levels as simulated by the WRF model for the TWP-ICE break period (Del Genio and Wu, 2010). Right panel: Parameterization test from the same simulation showing that a single vertical profile of the proportionality constant in the Gregory (2001) entrainment parameterization works generally for all types of convection.

Other studies

Stubenrauch et al. (1997) conducted the first study of subgrid cloud overlap effects on radiation in a GCM, while Naud et al. (2008) used ARM SGP and TWP radar data to observationally constrain overlap in different environmental conditions. Ye et al. (1998) showed that CAPE changes in a warmer climate were smaller than proxies such as wet bulb potential temperature would suggest, and that cold and warm climate changes were not mirror images in their climate response. Bauer et al. (2002) showed that claims of overestimated upper troposphere water vapor feedback in GCMs were an artifact of the sparse eastern Pacific sampling of radisondes used as the basis for objective analyses at that time. Jensen and Del Genio (2003) ahowed that significant cloud ice was present above the level to which rain radars observe, and that the small ice crystals have an important effect on the radiative heating profile. Del Genio et al. (2005) performed the first SCM estimate of cloud feedbacks and showed that subsiding environments dominated by low clouds were the most problematic. Zhang et al. (2005) showed that GCMs uniformly overpredict cloud optical thickness relative to observations. Bauer et al. (2006) developed a midlatitude cyclone detection and tracking procedure and found that composite GCM storms were less frequent and shallower than those in reanalyses. Meno and Del Genio (2007) performed one of the earliest studies of the impact of carbonaceous aerosols on clouds and climate in a GCM. Chen and Del Genio (2009) used ARM Manus and Nauru radar data to show that the ISCCP satellite retrieval tends to misplace clouds in multi-layer situations and predicts more midlevel clouds than are actually observed. Kennedy et al. (2010) used 3 years of SCM simulations driven by the ARM continuous forcing product at the SGP to show that the GISS model overestimates low clouds there and underestimates high clouds, with the errors occurring mostly when there ws a synoptic ridge upstream.

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