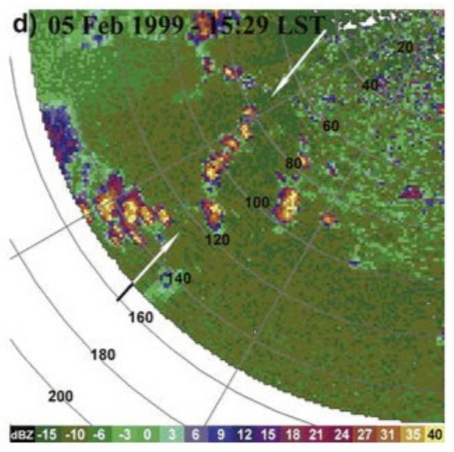
Effects of Cold Pools on Precipitation Development in the GISS GCM

Anthony Del Genio[1] Mao-Sung Yao[2] Jingbo Wu[3] Audrey Wolf[3]
[1]NASA GISS, New York, NY [2]Trinnovim LLC, New York, NY [3]Columbia University, New York, NY

Introduction

It has become obvious in recent years that cumulus parameterizations in GCMs need stronger convective entrainment to simulate several important aspects of precipitation variability such as the Madden-Julian Oscillation (MJO) and the diurnal cycle of precipitation. Doing so, however, often comes at the cost of degrading other aspects of the climate. Cloud-resolving model studies have consistently shown that entrainment weakens as convection deepens. The challenge for cumulus parameterizations is to predict when the shift from strongly to weakly entraining convection should occur and thereby simulate (a) the timing of the light-heavy rain transition, and (b) the shift from bottom-heavy to top heavy latent heating that accompanies it as convection begins to organize. Cold pools formed from cold downdraft outflows are a potentially important mechanism for initiating the transition.

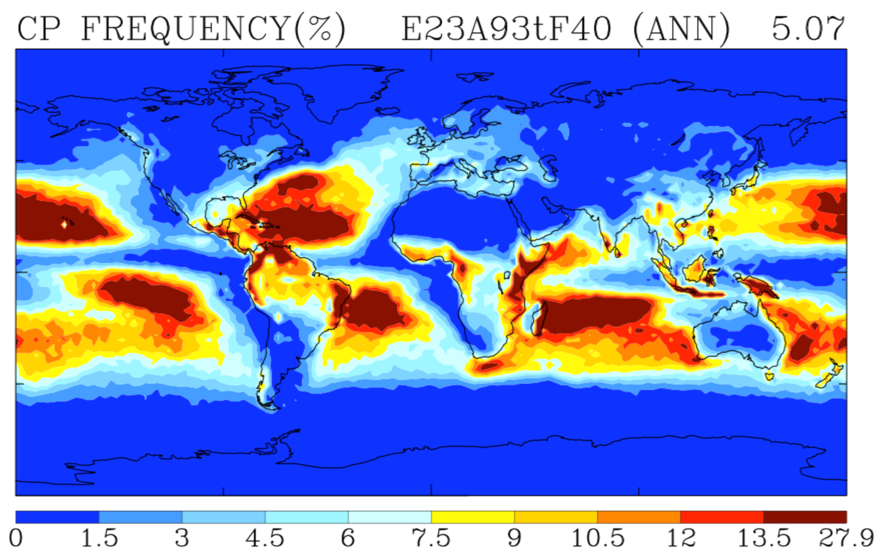


The figure on the left shows S-Pol radar reflectivities over the Amazon during the TRMM-LBA experiment (Lima and Wilson 2008, MWR). Convective storms develop as two cold pool gust fronts collide. In this study, 71% of the storms whose initiation mechanism could be determined formed at either individual gust fronts or collisions of multiple cold pools.

Cold pool parameterization

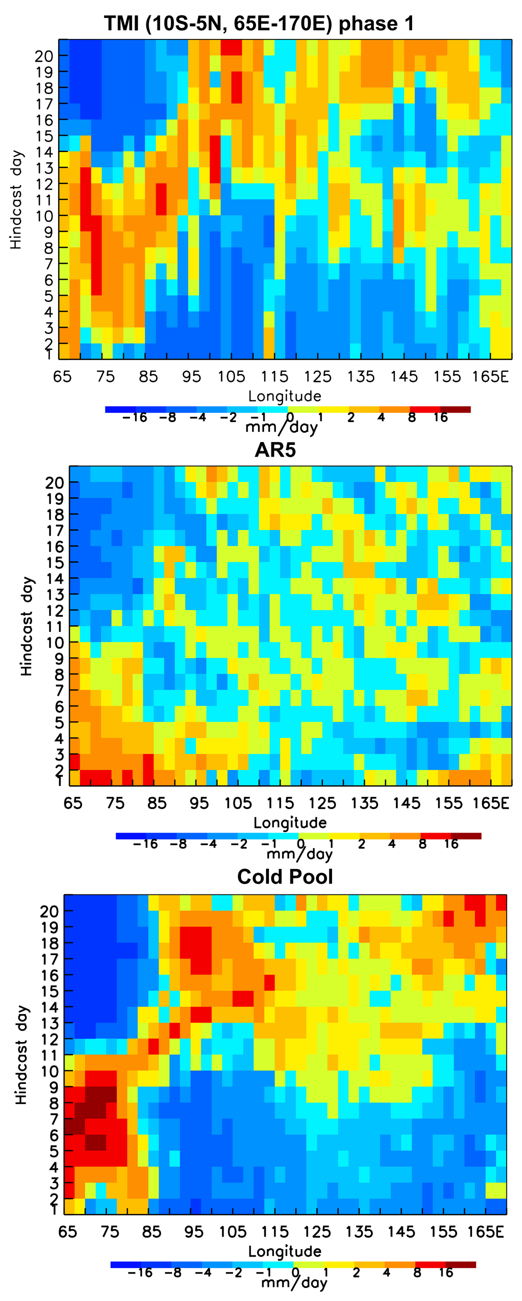
We have developed a simple parameterization of cold pools for the GISS GCM and tested it against hindcasts of a TRMM-observed MJO event during the Year of Tropical Convection (Del Genio et al. 2015, J. Clim.). The parameterization makes the following assumptions:

- Downdrafts form from mixtures of updraft and environmental air close to that which gives maximum negative buoyancy, with a stochastic deviation from that mixing fraction
- A downdraft that reaches the PBL with virtual potential temperature colder than that of the ambient PBL creates a cold pool, defined by 4 prognostic variables (depth, area, temperature depression, humidity depression)
- The cold pool spreads at a rate slower than that of an individual density current to account for cold pool collisions
- The balance between that spread and additions of mass from subsequent downdrafts determines the evolution of cold pool depth
- Cold pool temperature and humidity relax to ambient PBL conditions over a specified relaxation time
- While it exists, cold pool and ambient air remain distinct, and future convective events are initiated with the properties of ambient air lifted over the depth of the cold pool
- These cold pool-generated secondary convective events have weaker entrainment than convection that occurs without cold pools



GCM cold pools occur primarily over the tropical oceans and in the equatorward parts of the extratropical storm tracks, but also over the convecting regions of tropical continents and to a lesser extent over the southern-eastern parts of North America and Asia. There are no global statistics of cold pool occurrence to verify against, but one region that seems notable in its absence of cold pools is the Great Plains of the U.S., where the dynamics that initiates convection often occurs on mesoscales not resolved by the GCM (this version has 2°x2.5° resolution.

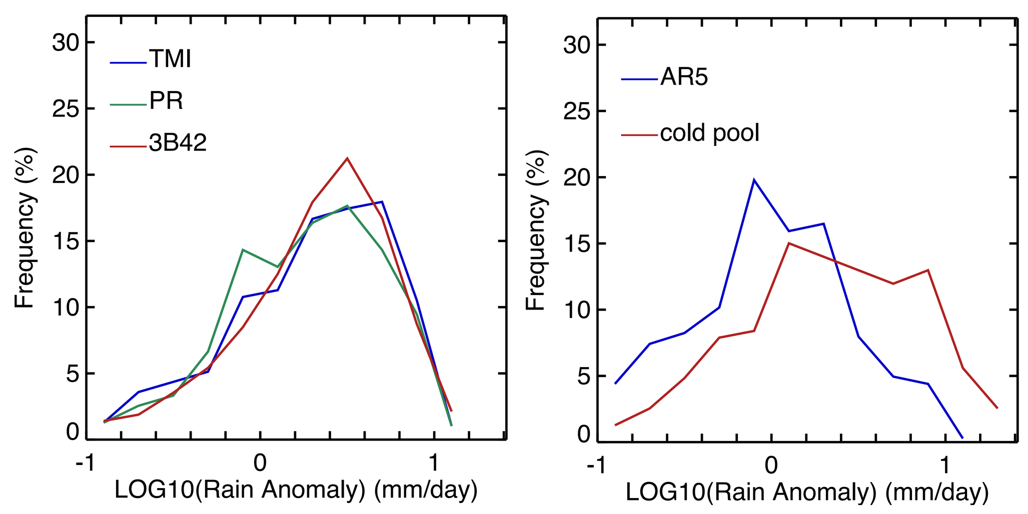
TRMM TMI and GCM Rain Anomalies



We ran the GCM for a series of 6 20-day hindcasts initialized on consecutive days with an ECMWF analysis for YOTC MJO event E during Wheeler-Hendon Phase 1 (Oct. 29 – Nov. 3). The figure on the left shows composite 20-day rain anomaly Hovmöller diagrams for TRMM TMI (upper panel), the GISS AR5 GCM (middle panel), and the GISS GCM with the cold pool parameterization (lower panel). The AR5 GCM produces at best a very weak, diffuse MJO signal. The cold pool model produces a vigorous MJO that propagates at the correct speed and retains significant predictability over the full 20-day hindcast period. The key feature that permits the GCM to simulate the MJO is its ability to maintain the initial contrast between the relatively suppressed region in the central Indian Ocean, where rain anomalies in the TMI data are strongly negative, and the strong positive rain anomalies that develop in the west Indian Ocean after day 1.

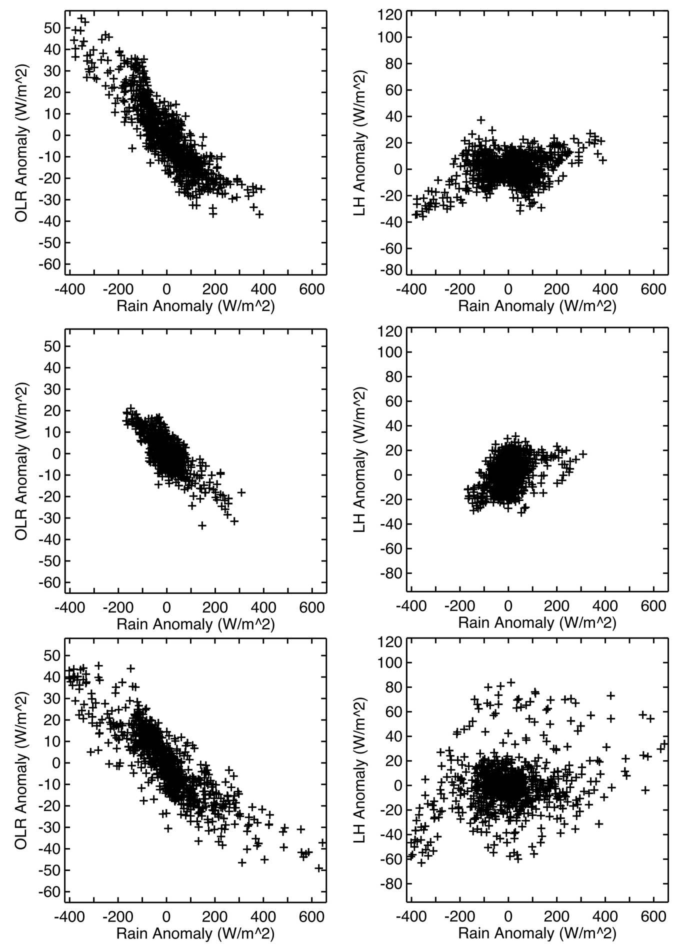
Model version	% of convective events in Plume 1	Convection occurrence relative to AR5	TMI-GCM rain anomaly correlation
AR5	48.5	1	0.22
Stronger entrainment only	49.0	1.23	0.48
Cold pool	19.4	1.39	0.63

Cumulus mass flux in the GCM is divided between strongly (Plume 1) and weakly (Plume 2) entraining plumes. In AR5 both plumes occur unless low-level divergence is present. In the cold pool model, Plume 1 only forms after cold pools generate secondary convection, and it accounts for only 19% of all convective events. However, convection occurs 39% more often than in AR5. This occurs partly because strongly entraining convection is less effective in stabilizing the atmosphere, but also because cold pools, by segregating cold air from warm, humid PBL air perpetuate convection. The correlation between the TMI rain anomaly pattern above and that for the AR5 model is only 0.22, while it is 0.48 with only stronger entrainment included and 0.63 for the cold pool model. (The correlation between TMI and PR is 0.70.) The effect of cold pools is most noticeable late in the hindcast: the anomaly correlation for the second 10 days remains high (0.60), while for the case with only stronger entrainment, it drops to 0.35.



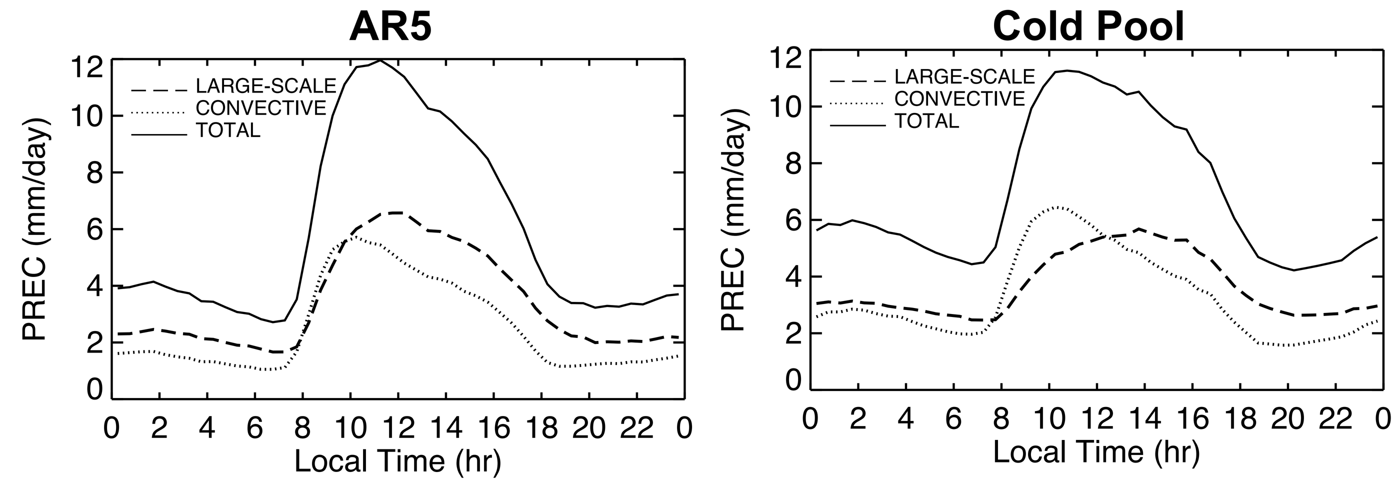
The PDF of MJO rain anomalies is similar for 3 different TRMM products (TMI, PR, 3B42), peaking at ~ 3 mm/day, though some of the details are different for the different datasets. AR5 rain anomalies are systematically weaker than observed, peaking near 1 mm/day. The anomalies for the cold pool model have a broader distribution than observed but clearly peak at higher rain rates than is the case for the AR5 model.

Sources of MJO Column Moist Static Energy



If the gross moist stability is positive, the MJO requires an external source of moist static energy to grow. The two possible sources are cloud radiative heating (OLR) anomalies from the stratiform/anvil regions of organized convection, and surface latent heat fluxes. The figure above shows (left) OLR vs. precipitation anomalies and (right) LH flux vs. precipitation anomalies for YOTC event E from observations (ISCCP for OLR, OAFlux for LH flux, TRMM 3B42 for precipitation), the AR5 GCM, and the cold pool GCM. In addition to the larger and more realistic magnitude of anomalies in the cold pool run relative to the AR5 run, the cold pool model better represents the more in-phase relationship of OLR to precipitation relative to that of LH flux: -dOLR'/dP' = 0.13 (obs), 0.11 (AR5), 0.14 (cold pool), while dLH'/dP' = 0.07 (obs), 0.20 (AR5), 0.05 (cold pool).

Diurnal Cycle of Precipitation in Amazon Basin



We examined the diurnal cycle of precipitation over the Amazon basin in the AR5 and cold pool models. GCMs habitually simulate peak rainfall too early in the day compared to TRMM radar observations. The AR5 GCM is a good example of this problem, with a rain peak just before noon due to a convective component that peaks at 10 LST and a stratiform component that peaks at 12 LST and is actually bigger than the convective component. The cold pool model surprisingly does not shift the timing of the convective component, suggesting that the problem may lie elsewhere, e.g., the mass flux closure. However it does reduce the magnitude of the stratiform component and shift its peak to 14 LST, both of these in somewhat better agreement with TRMM data. (For example, the first two PCs of rain in the analysis of Kikuchi and Wang 2008, J. Clim., peak at 12 LST and 15 LST.)

Conclusions

✧ A simple cold pool parameterization has been implemented in the GISS GCM to differentiate weakly from strongly entraining convection

✧ The cold pool GCM produces realistic 20-day hindcasts of an observed MJO event, with significant rain predictability over 20 days and a pattern correlation with TMI data almost as good as the TMI-PR correlation

✧ Cold pools extend the duration of convection and thus allow the GCM to convect much more frequently

✧ The cold pool model better predicts the magnitude of rain anomalies and the in-phase OLR'-P' vs. out-of phase LH'-P' relation

✧ Cold pools reduce the stratiform rain component and shift its diurnal cycle over the Amazon by several hours