Final Technical Report for DOE Award DE-FG02-05ER63959

Award Title: ARM-based Development of a New Combined Parameterization for Shallow and Deep Cumulus Convection in Large-Scale Climate Models

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Period of performance: 11/04-10/07 (+ 1 year no-cost extension)

Personnel:

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Research findings

The goals of this work were:

(1) to improve the University of Washington shallow cumulus parameterization, first developed by the PI's group for better simulation of shallow oceanic cumulus convection in the MM5 mesoscale model (Bretherton et al., 2004, *Mon. Wea. Rev.*),

(2) to explore its applicability to deep (precipitating) cumulus convection.

(3) to explore fundamental physical issues related to this cumulus parameterization

The graduate student who was recruited to perform the research left after two years with essentially nothing accomplished, so almost all of the research progress occurred during the third year and the no-cost extension. Nevertheless, several important peer-reviewed publications ultimately emerged from the funded research. Their new scientific findings are described below.

1. *Cloud-resolving simulation of a transition from shallow to deep convection (Kuang and Bretherton 2006)*

The award funded the PI's contribution to the final steps of publishing (with a former postdoc Zhiming Kuang) an analysis of a high-resolution cloud-resolving numerical simulation of an idealized transition from a marine shallow, nonprecipitating cloud field to a deep, precipitating, marine cumulus cloud field. The goal was to shed light on important unresolved aspects of cumulus parameterization, including the thermodynamical properties and vertical velocities of cloud-base updrafts and the statistical distribution of lateral entrainment and detrainment rates. Key findings were:

(1) The properties of cumulus updrafts vary continuously as the cumulus cloud layer deepens, so there is no fundamental justification for separate shallow and deep cumulus parameterizations (as used in many GCMs).

(2) The humidity of the cloud base updrafts is almost identical for all cumuli, and forms the moistest tail of the overall distribution of humidity in the subcloud boundary layer; this has been exploited in several recently-proposed cumulus parameterizations (e.g. Park and Bretherton 2009; Neggers et al. 2010, J. Atmos. Sci.)

(3) The typical cumulus updraft size increases and the corresponding lateral entrainment rate decreases as the cumulus layer deepens and cold pools organize the subcloud boundary layer into mesoscale circulations.

2. *A new bulk model of shallow convection (Bretherton and Park 2008)*

Parameterizations of cumulus convection are part of a hierarchy of models of varying complexity that represent the evolution of layers of cumulus convection, ranging from convective adjustment models to large-eddy simulation models. We proposed a new bulk model of nonprecipitating cumulus convection based on an approach of Albrecht et al. (1989), but refined and simplified to remove some internal inconsistencies in that model. The model was tested against a large-eddy simulation of a shallow cumulus layer from the BOMEX experiment and performs quite well given its simplicity. The model was used to show fundamental features of marine shallow cumulus boundary layers, including their internal and inversion adjustment timescales, sensitivity of vertical structure to changes in sea-surface temperature, and the scaling of typical updraft velocity and buoyancy with parameters governing lateral and penetrative entrainment in the model. For realistic parameter values, the model predicts that cumulus updrafts should have a buoyancy on the order of 10% of the adiabatic value, and a vertical velocity of about 30% of adiabatic, both comparable to observations.

3. *New moist turbulence parameterization and shallow cumulus parameterizations in the CAM climate model (Bretherton and Park 2009, Park and Bretherton 2009)*

These companion papers describe our implementations of the UW moist turbulence (boundary layer) and shallow cumulus parameterizations in the Community Atmosphere Model, part of the world's leading open-source climate model, the CCSM. These are now the standard parameterizations in the latest version of this model, CAM5. The papers show these parameterizations improve the performance of a single-column version of

CAM on benchmark cases and that they improve a basket of overall climate skill metrics by about 15% compared to their predecessors, with particular improvements in the distribution and vertical structure of marine boundary-layer cumulus and stratocumulus clouds. Based on this work, Park was hired as a Scientist I at NCAR where he continues to work on CAM model development.

4. Testing CIN closure using CRM simulations of deep convection over land and ocean (Fletcher and Bretherton 2010)

The grant supported the initial year of research toward this publication, whose goal was to evaluate the fundamental suitability of the mass-flux closure in the UW shallow cumulus scheme if applied to deep convection. The closure is called a CIN closure because it relates the cumulus base mass flux per unit horizontal area to the ratio of the updraft kinetic energy (KE) to the cloudbase convective inhibition (CIN). Previously-evaluated CRM simulations of realistic deep cumulus convection over land (over two weeks at the Oklahoma SGP ARM site) and at Kwajalein Island in the west Pacific ITCZ were analyzed. The cumulus mass flux was indeed found to be well-correlated to the ratio of CIN to KE, but rather than the updraft kinetic energy, it proved necessary to use the total kinetic energy (including horizontal mesoscale motions) to achieve the best results for deep precipitating convection. Nevertheless, the findings support the use of CIN-based closure for deep convection as well as shallow cumulus convection, something which is being now tried at a couple of major modeling centers (GFDL and ECMWF).

Peer-reviewed publications (all acknowledge support from this award)

Kuang, Z., and C. S. Bretherton, 2006: A mass flux scheme view of a high-resolution simulation of transition from shallow to deep cumulus convection. *J. Atmos. Sci*., **63**, 1895-1909.

Bretherton, C. S., and S. Park, 2008: A new bulk shallow cumulus-topped boundary layer model. *J. Atmos. Sci*., **65**, 2174-2193.

Bretherton, C. S., and S. Park, 2009: A new moist turbulence parameterization in the Community Atmosphere Model. *J. Climate*, 22, 3422-3448.

Park, S. and C. S. Bretherton, 2009: The University of Washington shallow convection and moist turbulence schemes and their impact on climate simulations with the Community Atmosphere Model. *J. Climate*, **22**, 3449-3469.

Fletcher, J. K., and C. S. Bretherton, 2010: Evaluating boundary-layer based mass flux closures using cloud-resolving model simulations of deep convection. *J. Atmos. Sci*., **67**, 2212-2225.