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Implementation of the Probabilistic CuP Cumulus Parameterization in WRF

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1. Introduction

A universal feature of current atmospheric models is poorly predicted shallow clouds. This has implications for entrainment at the top of the boundary layer and the radiation budget. Because the physics governing shallow cumulus clouds is tightly coupled to boundary layer dynamics, an approach linking the two can potentially improve model results. The Cumulus Potential (CuP) parameterization (Berg and Stull 2004; 2005) is a new parameterization that does this using probability density functions (PDFs) of temperature and mixing ratio within the boundary layer to represent the range of parcels available to trigger convection. The first 3-D application of the CuP parameterization has been to embed it into the Kain-Fritsch cumulus parameterization in the Weather Research and Forecasting (WRF) model (Skamarock et al. 2005). Initial results for selected case studies are promising with improved precipitation characteristics.

2. CuP Description and Implementation

The overall approach of CuP is to probabilistically treat the range of available air parcels within a grid column that would trigger convection. This contrasts with the traditional approach used in cumulus parameterizations where the grid-cell mean conditions are used to deterministically determine if sufficient buoyancy exists for a convective cloud to form. In CuP, the boundary layer characteristics of temperature and moisture at the surface, in the mixed layer, and in the entrainment zone are used to generate a PDF representing the range of parcels within the boundary layer and the probability of each type of parcel. An example is shown in Figure 1. The PDF can then be coupled with a complete cumulus parameterization, replacing the existing trigger function.

In WRF, we have coupled CuP with the Kain-Fritsch parameterization (KF-Eta) (Kain and

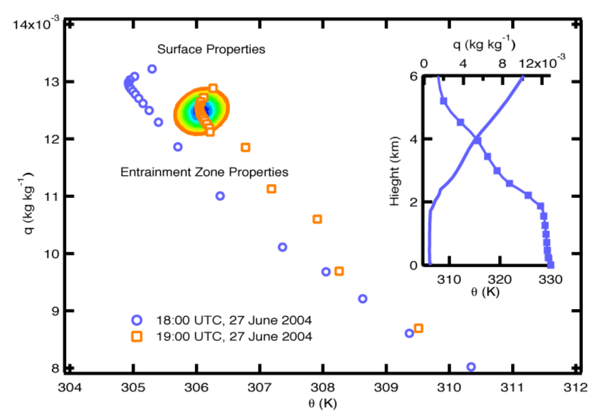

Figure 1 Mixing diagram of water vapor (q) and potential temperature (θ) computed from WRF output at 18 and 19Z on 27 June 2004. Colored contours represent probabilities of a (θ,q) pair based on the PDF computed from the surface, mixed layer, and entrainment zone properties at 19Z (Berg and Stull 2004).

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Fritsch 1990; Kain 2004), making a new cumulus parameterization option called KF-CuP. When atmospheric conditions are stable, the standard KF-Eta methodology is used since the PDF is not physically meaningful in a stable atmosphere. When atmospheric conditions are unstable, the convective trigger temperature and moisture in KF-CuP are determined from values in the PDF bins. KF-CuP determines what type of cloud (none, shallow, or deep) and the resulting meteorological tendencies that would form for each PDF bin with a probability greater than a given threshold. Then, if the net probability of deep convection is greater than a threshold (currently five percent) the most probable deep convective event is used to determine the cumulus tendencies in that model column. If deep convection would not develop and the probability of shallow convection is greater than zero, the resulting cumulus tendencies are formed by averaging the results from all the PDF bins exhibiting shallow cloud behavior using probability weighted averages.

3. Results

A series of three case studies have been simulated for days exhibiting shallow clouds over the Central Research Facility of the Department of Energy's Atmospheric Radiation Measurement Southern Great Plains facility in Oklahoma using 12 km grid spacing. Case 1 is for the dates 25 June 2004 12Z through 28 June 2004 0Z, case 2 for 17 July 2004 12Z through 20 July 2004 12Z, and case 3 for 16 May 2004 0Z through 18 May 2004 12Z. Each of the case studies was repeated using three different explicit moisture parameterizations (Lin, Thompson, and WSM5) to compare interactions between the cloud componenets of WRF. The results are slightly dependent upon the explicit moisture parameterization used, but in general point to increased vertical mixing when using KF-CuP versus KF-Eta. Shallow clouds are triggered in the KF-Cup scheme more often and over a larger area than with KF-Eta. Figure 2 shows the observed cloud fields alongside the type of cloud predicted by simulations using either KF-CuP or KF-Eta. Note the larger area of shallow convection with KF-CuP that better matches the low-level clouds in the satellite images compared to KF-Eta.

Summer-long seasonal simulations were also

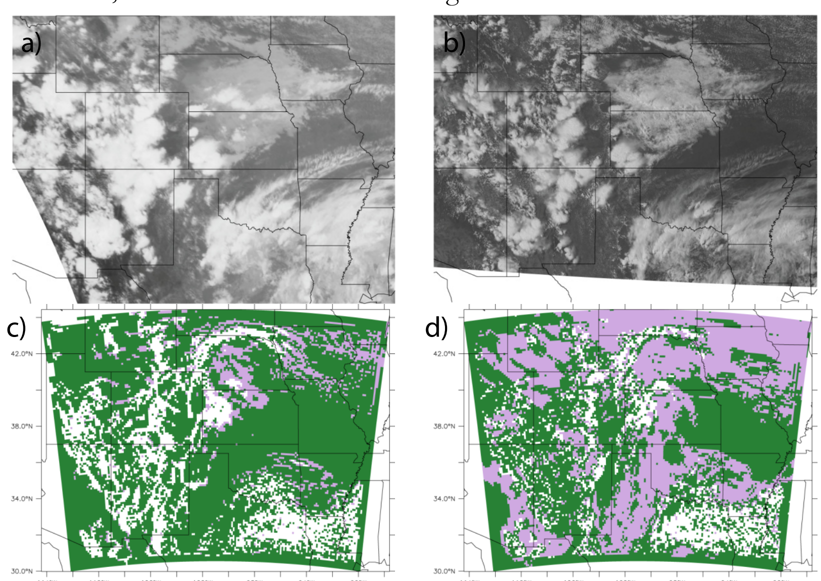

Figure 2 Comparison of KF-Eta and KF-CuP convection type for 26 June 2004 21Z. (a) Infrared satellite image, (b) visible satellite image, (c) convection type using KF-Eta, and (d) convection type using KF-CuP. In (c) and (d), greens indicate no convection, purples indicate shallow convection, and white indicates deep convection.

		Bias			ETS w/ Lin		ETS w/ Thompson		ETS w/ WSM5	
		Lin	Thomp.	WSM5	2.54 mm/6 hr	12.7 mm/6 hr	2.54 mm/6 hr	12.7 mm/6 hr	2.54 mm/6 hr	12.7 mm/6 hr
Case 1	KF-Eta	2.26	1.93	1.99	0.10	0.04	0.10	0.04	0.11	**0.05**
	KF-CuP	**1.73**	**1.31**	**1.56**	**0.12**	**0.05**	**0.14**	**0.05**	**0.14**	0.04
Case 2	KF-Eta	1.83	1.55	1.64	0.15	0.06	0.18	0.08	0.17	0.07
	KF-CuP	**1.50**	**1.19**	**1.28**	**0.21**	**0.08**	**0.20**	**0.11**	**0.23**	**0.12**
Case 3	KF-Eta	1.06	1.01	1.06	0.04	**0.01**	**0.05**	0.00	0.05	0.00
	KF-CuP	**0.82**	**0.80**	**0.81**	0.04	0.00	0.04	0.00	0.05	0.00
Season	KF-Eta	1.35			0.06	**0.03**				
	KF-CuP	**1.22**			**0.07**	0.02				

Table 1 Bias and equitable theat score (ETS) statistics over the Arkansas-Red Basin River Forecast region for three case studies and a summer-long seasonal simulation. ETS is shown at the thresholds of 2.54 and 12.70 mm per 6 hr period with each grid point treated individually over the region. Bold values indicate which parameterization performed better for a given pair. Results using three different explicit phase moisture parameterizations are shown: Lin, Thompson, and WSM5.

done in addition to the case studies. These longer runs were for the dates 1 April 2004 through 22 August 2004. The time series consists of overlapping 36-hour simulation blocks with the first 12 hours of each block neglected as spin-up. The remaining 24 hours is used for analysis. Additionally, the soil moisture and cloud fields are initialized for each block based on the preceding block's values. This allows the soil moisture and temperature to spin-up to an equilibrium within WRF. The first month of the resulting time series is neglected during analysis because of this spin-up process. Due to the cost of these runs, only the Lin explicit moisture parameterization was used for the pair of runs using KF-CuP and KF-Eta.

Statistical comparisons of the precipitation were done by comparing against the gridded precipitation product available from the Arkansas-Red Basin River Forecast Center of the National Weather Service, http://www.srh.noaa.gov/abrfc/precip/daily.php. Results, shown in Table 1, indicate that KF-CuP reduces the excess rain bias in the seasonal run by 10% and in the case studies by about 20%. The equitable threat score (ETS) also improves, particularly at smaller thresholds. The ETS quantifies how well a model predicts a given threshold of precipitation over a region, with a perfect score being 1. The scores shown here appear low because we chose the most stringent criterion for the analysis region, each model column, and then averaged the results.

4. Discussion

The improved precipitation statistics and mixing exhibited in simulations using KF-CuP show the potential of the probabilistic approach to parameterizing shallow cumulus clouds. However, these simulations also reveal a limitation in the traditional approach to separating sub-grid scale and resolved clouds using the loosely coupled convective and explicit moisture parameterizations. In theory, when shallow clouds form in the Kain-Fritsch convective scheme, all the condensed water is transferred to the bulk phase where it is treated by the explicit moisture scheme. This is done with the assumption that shallow clouds do not rain.

However, because the shallow clouds only cover a sub-section of the grid cell, they must be treated using a derived cloud fraction, both for the explicit moisture and radiation parameterizations. In reality, this cloud fraction is not diagnosed accurately and most of the condensate produced by shallow cumuli is immediately evaporated within the explicit moisture parameterization. The net result is that shallow cumuli increase the mixing within the boundary layer but no cloud is seen by the radiation routine. So, entrainment into the boundary layer makes it taller, warmer, and drier. However, the offsetting effect of clouds increasing the albedo and cooling the surface is not present. This leads to a systematic error in the temperature and moisture fields so they statistically worsen, as seen in Table 2. The relative humidity biases are worse for every simulation, and the temperature biases are worse in about half of the simulations.

More work needs to be done to quantify both how the CuP parameterization improves and worsens simulations. Combined with this is the need to address the overall coupling of the boundary layer, cumulus, explicit moisture, and radiation parameterizations. Conceptually it is desirable to treat them each independently, but in reality they are a coupled system that needs to be unified with similar assumptions and proper treatment of the feedbacks between them. Advances in this area should lead to improvements in model simulation accuracy.

		Temperature Bias			Relative Humidity Bias		
		Lin	Thomp.	WSM5	Lin	Thomp.	WSM5
Case 1	KF-Eta	**-0.13**	-0.49	-0.61	**-2.05**	**-1.41**	**-0.73**
	KF-CuP	0.24	**0.04**	**0.02**	-4.00	-3.51	-3.45
Case 2	KF-Eta	**0.08**	**0.10**	**0.14**	**-14.93**	**-15.05**	**-14.48**
	KF-CuP	0.36	0.41	0.39	-15.65	-16.40	-15.79
Case 3	KF-Eta	1.72	**0.98**	**0.98**	**-14.27**	**-14.50**	**-14.29**
	KF-CuP	**1.04**	1.06	1.07	-15.56	-16.31	-15.89
Season	KF-Eta	**0.85**			**-11.10**		
	KF-CuP	1.01			-12.66		

Table 2 Temperature and relative humidity biases for the three cases and summer-long seasonal simulation. Comparisons between the two cumulus and three explicit phase moisture parameterizations are shown. Bold values indicate which simulation is better within each cumulus parameterization pair.

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