J4.2 MODIFICATIONS OF TWO CONVECTIVE SCHEMES USED IN THE NCEP ETA MODEL

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1. INTRODUCTION

Among the challenges facing numerical weather prediction (NWP) and global models are nonlinear interactions between various physical processes parameterized within the modeling systems. The complexity of these interactions and their rate are often accelerated in the presence of active convection, which is so dominant during the warm season and is almost always present along the Gulf Coast throughout the year. Because of the small-scale nature of convection, their effects must be parameterized in current operational forecast models. Progress in improving the representation of convective cloud processes has been slow, causing many investigators to try a myriad of approaches to resolve the problem. Some have decided to focus future development on explicitly resolving these processes in higher resolution models with grid sizes of several km or less. This, however, is not a viable option for the current suite of NCEP operational models, given the limited computational resources that are available and given the constraints for providing rapid and continuous dissemination of forecast model products.

This paper has been extended to describe two topics. First, modifications and tests made to the Betts-Miller-Janjic (Janjic, 1994; BMJ) and the Kain-Fritsch (Kain and Fritsch, 1993; KF) convective parameterizations will be described. This was the original subject of the conference abstract. Some of the results from this study were then used to broaden the suite of physics options used in running different Eta model configurations for NCEP's Short-Range Ensemble Forecasting (SREF) system (Du *et al*., 2004). The second part of this paper will describe in more detail the expanded suite of physics options used in the SREF diversity and product upgrade scheduled for operational implementation in Fall 2003 or Winter 2004. Interested readers can review the Project Charter describing this implementation into NCEP Central Operations at http://wwwt.emc.ncep.noaa.gov/mmb/SREF-Docs/SREF-Charter-Fall03.doc. This upgrade was motivated by requests from several NCEP Service Centers for greater forecast spread and diversity.

2. GENERAL BEHAVIOR OF THE BMJ SCHEME

The BMJ convective parameterization, which is currently used in the operational Eta model, has been identified as being primarily responsible for overly active shallow convection (Baldwin *et al*., 2002), early triggering of deep convection over too large an area, and a low bias in higher forecast precipitation accumulations. Baldwin and Wandishin (2002) found that the spectral properties of the 3-h accumulated precipitation from Eta forecasts were smoother than those found in the WRF model and against observations. Equitable threat and bias scores of quantitative precipitation forecasts (QPF) from the Eta model generally show a pronounced low bias in forecast daily precipitation amounts greater than roughly 1.0 inch, with progressively lower bias at higher amounts (monthly scores can be viewed at http://wwwt.emc.ncep.noaa.gov/mmb/ylin/pcpverif/scores/). This bias is attributed in part to the convective scheme, particularly during the warm season.

Much of the smoothness of the Eta precipitation fields is based on the smooth manner that convection is triggered in the model. Figure 1 shows smooth textures associated with 18-h forecasts of instantaneous precipitation rate and the 3-h accumulated convective precipitation valid at 06Z on 12 May 2002 from the BMJ scheme. The operational version of the BMJ determines the cloud top based on the highest equilibrium level of

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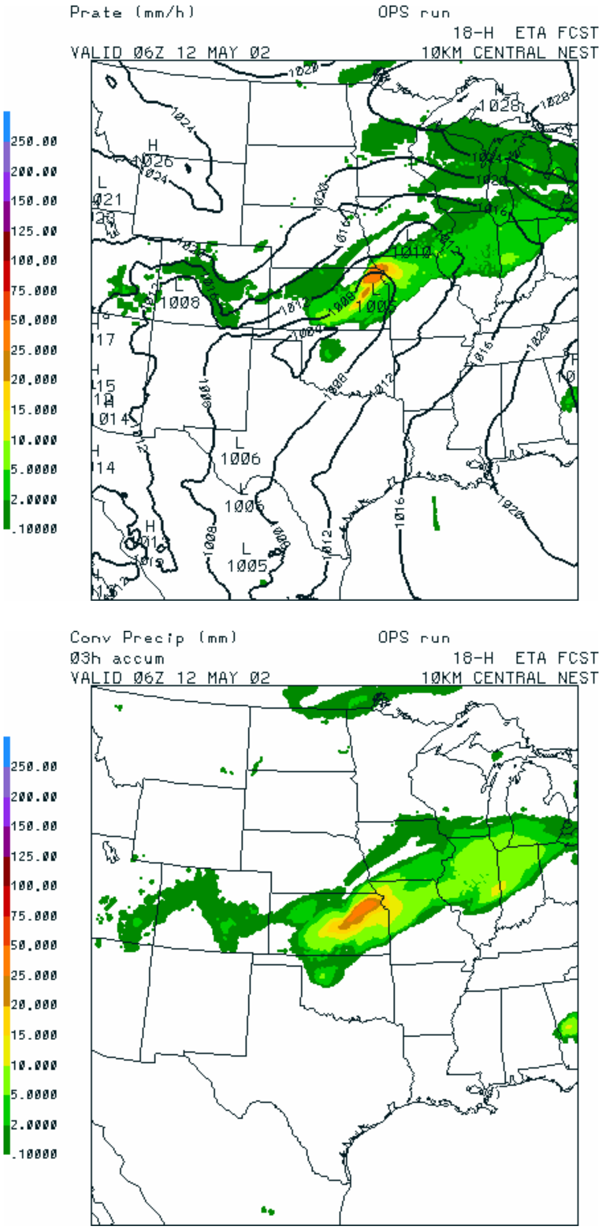

Figure 1. 18-h forecasts from the 10-km Eta central nest of (top) instantaneous precipitation rates (mm h^{-1}) and sea-level pressure (contours in hPa), and (bottom) 3-h accumulations of convective precipitation.

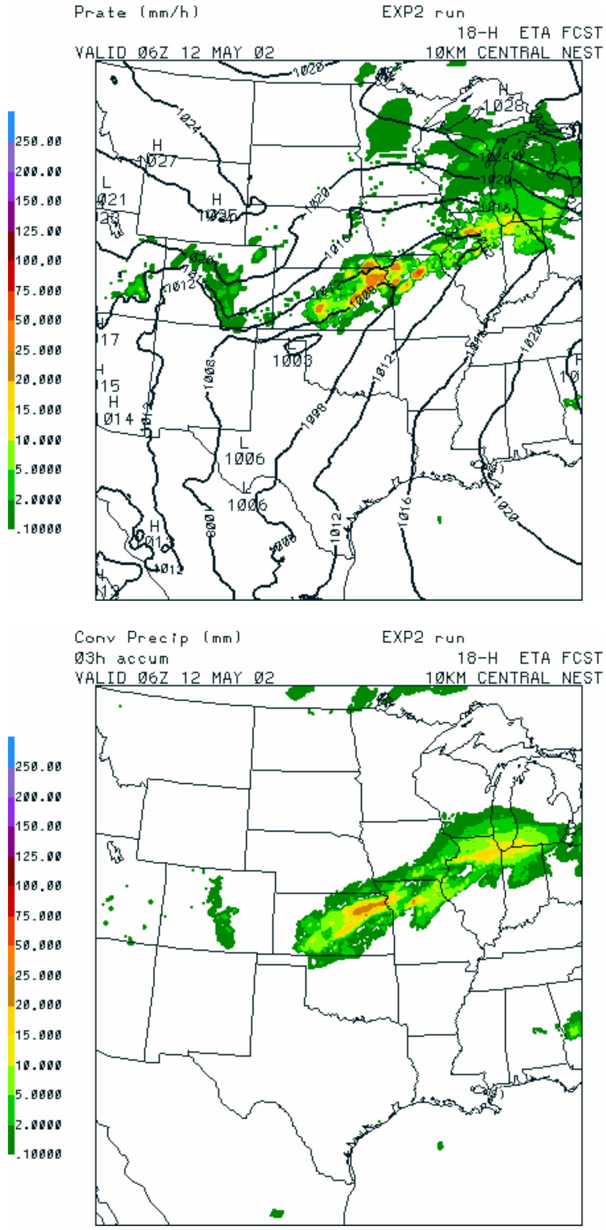

Figure 2. Same as Fig. 1, except that an explicit trigger was added to the BMJ scheme (see text).

the parcel, ignoring stable layers at lower levels of the sounding. The triggering of convection is then determined based on column-integrated enthalpy and entropy considerations. The BMJ scheme will therefore tend to trigger convection in the presence of weak, shallow stable layers, whereas other schemes that take into account the properties of the parcel during their ascent may not. Figure 2 shows a dramatic increase in the horizontal structure of the precipitation fields when the BMJ scheme is modified to trigger deep convection only when the LFC is within 50 mb of cloud base. The inclusion of such explicit triggering of convection will be discussed further in the next section. It should also be noted that the cloud efficiency parameter devised by Janjic (1994) acts to scale back the rate of precipitation production, as well as heating and drying tendencies from convection, as the column becomes stabilized by convection in order to serve as a smooth transition towards grid-scale processes (a more exact description of this process is described in Janjic, 1994). As a result, this cloud efficiency formulation also yields smoother precipitation fields.

3. MODIFICATIONS TO THE BMJ SCHEME

Modifications to the BMJ convective scheme were made to add *more purposeful structure* to the precipitation forecasts by making the QPF more focused in time and space. Forecast precipitation fields were compared against hourly Stage II/IV combined gauge-radar analyses, in which the goal was to improve the timing associated with convective triggering, and to improve the quantitative precipitation forecasts against the 6-h precipitation amounts (there is greater confidence in the 6-h precipitation amounts). The hourly and six-hourly precipitation products, as well as description of how they are produced, are available at http://wwwt.emc.ncep.noaa.gov/mmb/ylin/pcpanl/. A series of 10-km High Resolution Window Eta runs were made over the Central US using initial conditions from 12Z on 11 May 2002, followed by a series of runs over the Eastern US using initial conditions from 18Z on 24 April 2002. Animations of (1) hourly and 6-h rainfall forecasts compared with the Stage IV precipitation amounts (all units in mm), (2) forecast convective cloud-top pressures (in hPa), and (3) total condensate suspended in the column (units of mm, same as precipitable water) can be viewed at http://wwwt.emc.ncep.noaa.gov/mmb/bf/tloops/c10km.2002051112/index.html and at http://wwwt.emc.ncep.noaa.gov/mmb/bf/tloops/e10km.2002042418/index.html for the May 11 and April 24 cases, respectively. These animations are available for most of the other convective schemes described in Sec. 6 (see Table 1).

Based on a series of sensitivity experiments, the following modifications to the BMJ scheme resulted in improved convective initiation and QPF. Hereafter, this version of the convective parameterization will be referred to as BMJ_SAT.

- For explicit triggering of convection, limiting the amount of lifting of air parcels from their source level to their condensation level to no more than 25 hPa, and further lifting to their level of free convection to no more than 50 hPa.

- Candidate parcels are searched over the lower half of the atmosphere, whereas this is limited to the lowest 1/5 of the atmosphere in the BMJ.

- Updated lookup tables and refined calculations of equivalent potential temperature use the algorithm of Bolton (1980).

- Including the effects of ice in calculating the cloud updraft parcel characteristics, as well as in the enthalpy conservation and the entropy evaluation steps. The isobaric freezing of cloud water to ice is included in the parcel calculations following Saunders (1957). The greatest impacts from these changes are higher estimated cloud-top heights due to the increased diabatic heating effects, and drier moisture profiles aloft due to the lower saturation mixing ratios with respect to ice.

- The BMJ scheme, which adjusts towards reference profiles of temperature and moisture, will be delayed in triggering deep convection when moister profiles are assumed. *In this regard, the reference moisture profiles behave as implicit triggers of convection.* In the absence of grid-scale ascent, the reference moisture profiles were modified to be near water saturation at temperatures warmer than -15 C, decreasing linearly with temperature to ice saturation below -40 C. Drier reference moisture profiles are assumed In the presence of grid-scale ascent following eq. (10) in Betts (1986), which prevents supersaturated conditions from forming in the convective column and reduces the occurrence of spuriously large and rapid rates of grid-scale precipitation.

- Since convective triggering will be substantially delayed with respect to the original BMJ scheme, a greater potential exists for grid-scale instabilities to form. The cloud efficiency functionality in Janjic (1994) is therefore removed in order to make the convection respond rapidly when triggered.

4. MODIFICATIONS TO THE KF SCHEME

Many tests were also made modifying the KF scheme. There is a tendency for this scheme to produce larger precipitation amounts than are observed. Based on the experience of forecasters at the Storm Prediction Center (SPC) and from

SPC's multi-year Spring Program, the common view is that the KF scheme performs better than the BMJ in forecasting the initiation of convection, as well as in providing better pre-convective forecast soundings so important in SPC's operations. The same procedure was used as described in the previous section for identifying possible improvements in the performance of the KF scheme for both convective initiation and QPF. The following modifications were found to lead to improved forecasts, based primarily on the 10-km Eta High Resolution Window runs.

- All of the rain and snow calculated in the updrafts are detrained onto the grid, in which all subsequent cloud and precipitation processes are calculated by the grid-scale microphysics. All of the surface precipitation is calculated from the grid microphysics; no convective precipitation reaches the ground. The greatest benefit of this change is a drastic reduction in the high QPF bias. The overall QPF more closely resembles the BMJ in that precipitation fields are smoother in time and space. This change unfortunately hurts convective initiation, at least in terms of the onset of convective rainfall, where the triggering of convection occurs later than observed. There is also a tendency for smaller, weaker convective storms not to be captured with this configuration of the scheme. With gracious assistance from Jack Kain, a version of code was made that allows different fractions of rain and snow to be detrained back onto the grid. Some skill was seen in having a smaller fraction of rain in the updrafts detrained back onto the grid (i.e., not falling to the surface as rain) than ice, but more sensitivity experiments are needed. This parameter clearly exerts a strong influence on convective initiation and QPF.

- Hydrometeor fields calculated from the model, which include cloud water, cloud ice, rain, and precipitation ice (primarily snow, but can be snow/graupel/sleet), are input into the scheme and are modified by convective processes.

- Modifying shallow convection so that hydrometeors, except for rain, remain in the column. In the case of rain, it is converted back to cloud water in order to prevent small amounts of rain to reach the surface. In the version of KF provided to NCEP back in 2002, all condensate was converted back to water vapor for shallow convection. This was found on occasions to lead to a high QPF bias in areas where grid scale precipitation aloft was falling into lower layers of shallow convection, such as in areas of overrunning precipitation in the cold air north of surface fronts.

- Turning off convective downdrafts resulted in slightly improved forecasts. This change, however, may depend on the cases that were selected.

- An optimal relationship for describing the updraft radius as a function of cloud-base vertical motion was obtained as a result of many trial-and-error runs. The updraft radius is important because it affects the assumed entrainment rates. Tests were also done specifying the updraft radius as a function of vertical motion averaged over varying depths of the lower troposphere and over different time periods. It is clear based on comments in the KF code that Kain and colleagues have extensively tested the parametric relationship. Like the detrainment parameter, entrainment can have a large influence on the behavior of the scheme. It was found that the layer-averaged vertical motion relationships resulted in spuriously noisy triggering of convection due to gravity waves (or other sources of vertical motion and convergence) in the model. Relating the updraft radius to cloud-base vertical motion is approximately proportional to boundary-layer convergence, which may account for the perceived improved skill of using this formulation in the vicinity of synoptic fronts, gust fronts, sea breeze fronts, and other types of convergence zones.

5. RESULTS

The BMJ_SAT, which is the modified BMJ scheme described in Sec. 3 with saturated reference profiles, was tested this summer in a real-time parallel run of the 32-km Eta model along with the Global Forecast System's (GFS) solar radiation parameterization (Lin *et al*., 2004), as well as modifications to the Eta Data Assimilation System (EDAS) that include the assimilation of GOES-12 radiances and changes in the assimilation of precipitation. A description of this parallel, as well as links to the verification statistics, can be viewed at http://wwwt.emc.ncep.noaa.gov/mmb/mmbpll/paralog/paralog.etay.newsolarrad.html. The changes to the convection and radiation, in combination, resulted in a much lower bias than the control run, which is the operational code run at a horizontal resolution of 32 km. Interestingly, there was only a slight reduction in the equitable threat scores (ETS) in the parallel, with most of the degradation occurring in the lighter rain amounts (less than 0.5 in day^{-1}). These results, however, are unacceptable, given that the Eta model already has a low bias in summertime precipitation. Unfortunately, a lack of time and computational resources precluded separate testing of the GFS radiation and the BMJ_SAT convection packages.

As intended, there was much more spatial and temporal structure to the convection in the parallel than in the control. The larger low bias in the parallel's precipitation appeared to be associated with convection being shut off too rapidly in areas where heavy precipitation was observed. Several examples of this can be seen in the performance of the EtaY parallel during the period of 13-20 August 2003 in EMC's daily precipitation verification page at http://wwwt.emc.ncep.noaa.gov/mmb/ylin/pcpverif/daily/. There was an also much less deep cloud associated with BMJ_SAT, so on August 20 the reference moisture profiles of the convective scheme were changed back to the drier profiles used in operations. As expected this change increased the triggering of deep convection. This revised (EtaY) parallel ran from 20 August until 9 September 2003 when the new convection was removed.

Parallel runs of the modified BMJ_SAT scheme with the drier, operational moisture profiles, together with the GFS radiation, were continued in offline testing without EDAS cycling from 21 August through 2 September 2003 at 12-km and 32-km resolutions. Comparisons of 3-h precipitation accumulations from the operational version of the Eta against the parallel EtaY can be viewed at http://wwwt.emc.ncep.noaa.gov/mmb/bf/12-32km_runs/. Six-hour precipitation accumulations from the operational Eta, the 12-km EtaY parallel, and from the Stage IV gauge-radar analyses can also be seen at http://wwwt.emc.ncep.noaa.gov/mmb/bf/12km_runs/ (unfortunately some of the operational runs have been overwritten by later runs). These web pages indicated that the inferior performance of the parallel might have been, in part, a result of feedback effects between changes in radiation and convection. Subsequent parallel tests of the new GFS radiation in the Eta have revealed a cool bias in the presence of clouds (Lin *et al*., 2004), which would act to hinder the initiation of deep convection in cloudy areas more than was observed. The stringent constraints for explicit triggering convection in BMJ_SAT (see Sec. 3) may have also adversely impacted performance, together with the moister profiles and implicit triggering alluded to above.

An interesting situation occurred on 00Z 30 August 2003, in that the 12-36 h Eta forecasts of 24-h precipitation failed to capture a heavy rain event that occurred from NE Kansas into NW Missouri. The Eta predicted too much heavy rain along a cold front over northern Texas and western Oklahoma by 36 h, with very little precipitation developing north of the front. At the same time, the event was more accurately predicted in the GFS, in which there was more precipitation over eastern Kansas forming in association with a developing wave north of the surface cold front. This wave continued to develop in the GFS, resulting in substantial amounts of precipitation north of a warm front that extended from Missouri east to Ohio between 36 h and 60 h. During this time the Eta failed to capture this synoptic evolution, including the heavy precipitation north of the front. Most of the precipitation in the GFS was grid-scale in nature in the vicinity of the developing wave and along the warm front, whereas almost all of the precipitation in the Eta was produced from the BMJ convection. A 12-km run using the BMJ_SAT scheme with the saturated moisture profiles (see Sec. 3) produced an excellent forecast, reproducing many of the larger-scale features and synoptic evolution as in the GFS forecast, including the dominance of grid-scale precipitation processes in the areas of the developing wave and north of the warm front. Another 12-km run of the Eta using the modified version of KF with full detrainment (see Sec. 4) also produced a better forecast, though the 36-60 h band of heavy rain did not extend as far eastward as observed. This case is described in more detail in the power point presentation at http://wwwt.emc.ncep.noaa.gov/mmb/bf/presentations/EMC_Sack_Lunch_9-16-03.ppt.

6. PHYSICS DIVERSITY IN THE NCEP SREF UPGRADE

As mentioned earlier, there was a desire to increase the spread and diversity between various model runs of the NCEP SREFs. The current operational SREF is running five Eta model runs using the BMJ convective scheme, five Eta runs using the KF convective scheme, and five runs of the Regional Spectral Model (RSM) at a horizontal resolution of 48 km. During this past summer, each of these runs were made at a horizontal resolution of 32 km in the same configuration as the operational SREF, and their results were compared against a modified system with greater physics diversity. The experiment showed improved forecast spread using physics diversity (Du *et al*., 2004). After extensive discussions, it was decided to add more physics diversity to the Eta model and the RSM members, together with diversity in initial conditions using symmetric breeding cycles. This section will briefly describe aspects of the expanded physics diversity in the Eta model runs of the SREF upgrade.

In order to promote greater physics diversity in the Eta model runs, changes were also made in the grid-scale microphysics to compliment the use of different convective schemes. The final configurations of the Eta model runs are summarized in Table 1. Along with the operational BMJ convection (labeled BMJ in the table), the modified BMJ_SAT scheme (Sec. 3) has been included in the SREF system because of its superior performance in the 00Z 30 August 2003 forecast described in the previous section, as well as the diversity it exhibits with respect to the operational BMJ. Together with the KF convective scheme, the full detrainment of precipitation back onto the grid (labeled KFD in the table) is included in the physics suite. All of the other changes described in Sec. 4, which can be thought of as a modified KFD (MKFD), have only recently been developed and are not included in the SREF upgrade because they have not undergone sufficient testing.

The fifth item in Table 1 refers to the Relaxed Arakawa-Schubert (RAS) convective scheme (Moorthi and Suarez, 1992; 1999). We have relatively little experience with this scheme in the Eta model compared to the RSM and the GFS model. The RAS exhibits encouraging skill when simulating strong convective events and more organized synoptic systems. Compared to the other convective schemes, the Eta-RAS seems to produce a dearth of shallow convection, along with widespread areas of light precipitation falling from the transient triggering of deep convection. In fairness, this model behavior may be a result or

Convection	**Microphysics**	**Breeding**
BMJ	Ops	n1, p1
BMJ_SAT	Exp	n1, p1
KF	Ops	n1, p1
KFD	Exp	n1, p1
RAS	Ops	n1, p1
Shallow	Exp	none

Table 1. Configuration of different Eta model runs in the SREF upgrade.

byproduct of the scheme being run with a suite of physics parameterizations used in the RSM and GFS that are quite different from those used in the Eta. More tuning of the RAS is probably needed for it to achieve better performance in the Eta modeling system. In the central 10-km Eta runs of 11 May 2002, the RAS was the only scheme to trigger transient convection over central Texas and Oklahoma during the first 12 h in the vicinity of a dry line where no precipitation was observed. There are also times when it appears not to trigger when other schemes are active, resulting in spuriously high grid-scale precipitation.

The BMJ, KF, and RAS convective schemes are run using the operational grid-scale microphysics (Rogers *et al*., 2001; Ferrier *et al*., 2002), labeled as “Ops” in Table 1. The BMJ_SAT and KFD are run using an experimental version of the same grid-scale microphysics, labeled “Exp” in the Table, will be described later in this section. All five of the model configurations are run with diversity in initial conditions through negatively (n1) and positively (p1) perturbed breeding pairs.

The last Eta model run in the SREF upgrade, identified as “Shallow” in Table 1 was designed specifically for SPC. It is a shallow convective scheme that is the most conservative in triggering convection later than any of the other schemes, does not calculate convective precipitation (all precipitation is handled by the grid-scale microphysics like in KFD), and therefore does not adversely impact pre-convective forecast soundings as much as the other model runs. However, because this version of the Eta model is expected to produce inferior QPF, primarily through lagged initiation of convective systems and a propensity for spuriously high grid-scale precipitation maxima ("bombs"), it is run without breeding. The horizontal extent of convection is more limited than BMJ and KF with lower convective cloud-top heights. Because there is no limit to the vertical extent of convection, deep convection is still simulated in this scheme, though it rarely extends much above the 300-mb level except in areas with strong forcing and grid-scale ascent, such as near fronts. Detailed offline tests were made of this convective scheme, together with the operational BMJ scheme, using a substantially modified version of the sounding diagnostic software developed by Mike Baldwin. The software was modified to take as input observed soundings, from which the final, convectively modified profiles were also plotted with the observed sounding. A series of 80 observed soundings were used to test (1) the operational BMJ convective scheme, (2) a modified version of the convective scheme used in the Nonhydrostatic Mesoscale Model (NMM; Janjic *et al*., 2001), and (3) the shallow convective scheme. The results of this comparison for all 80 soundings, as well as a description of the various soundings used in the comparison, can be viewed as an html animation at http://wwwt.emc.ncep.noaa.gov/mmb/bf/conv_soundings/animate.html. The shallow convective scheme is referred to as "FSC" for the Ferrier Shallow Convection scheme on this web site, and in other web sites linked within this paper. A more detailed description of the convective scheme is available as a power point presentation at http://wwwt.emc.ncep.noaa.gov/mmb/bf/presentations/SPC_4-24-03.ppt and will only be briefly summarized below.

- Stabilizes the environment using the Betts-Miller (1986, 1993) approach, transporting heat and moisture upward with separate enthalpy conservation of temperature and moisture.

- Candidate parcels are searched from the top of the boundary layer, and triggering is based on instability associated with lifting a parcel up to the next model level (very conservative).

- Cloud-top entrainment effects are considered in calculating parcel instability (Betts and Miller, 1993).

As mentioned in Sec. 3, detailed output of the precipitation, cloud-top, and total condensate fields for nearly all of the convective schemes listed in Table 1 (except for BMJ_SAT, in which there was no time to incorporate the results onto this web site) are available at http://wwwt.emc.ncep.noaa.gov/mmb/bf/tloops/c10km.2002051112/ for the 11-13 May 2002 case and http://wwwt.emc.ncep.noaa.gov/mmb/bf/tloops/e10km.2002042418/ for the 24-26 April 2002 case. In the April case, most of the convective schemes tended to over predict precipitation amounts over Florida. In addition, the convective schemes were challenged with trying to capture the gradual weakening of convection along an, eastward propagating cold front, which is in contrast to the intense convection that developed in association with a strong spring storm in the May case.

The experimental version of the grid-scale microphysics ("Exp" in Table 1) is intended to add a reasonable amount of variability not currently available in the deterministic Eta model forecasts. The impact of this microphysics variation upon the forecasts is expected to be much smaller than the use of different convective parameterizations. The experimental microphysics differs from the operational version in the following ways.

- The temperature at which all liquid water glaciates to ice has been reduced from -10 C to -40 C, coinciding with the homogeneous freezing of cloud droplets to ice crystals.

- The threshold relative humidity (RH_{grd}) for the onset of condensation, which is a function of the horizontal grid resolution, is increased slightly to coincide with a value of RH_{grd}=100% (rather than 98%) for grid resolutions smaller than 5 km. This change is expected to have a very minor impact.

- The temperature at which ice is first nucleated is decreased from -5 C to -15 C. This change was made mostly in response to forecaster comments from N. Carolina and from Gary Lackmann at NC State, in which they identified cases last winter when the Eta predicted winter precipitation when none was verified. Based on recent findings from Manikin *et al*. (2004), this change could adversely affect forecasts precipitation type using the fraction of frozen precipitation output from the model.

- Vapor deposition onto small cloud ice crystals is turned off, based on findings from Canadian studies of a tendency for models to under predict supercooled liquid water contents and over predict ice water contents (Tremblay *et al*., 2003; Vaillancourt *et al*., 2003).

- The rates of cloud water collection by precipitation (rain & snow) are reduced by 0.5 in stable grid columns, and reduced by 0.25 in grid columns with convection. The continuous collection kernels assume horizontally homogeneous conditions, which is reasonable in cloud-resolving resolutions of O(1-2 km) but not necessarily at coarser resolutions, particularly where there is substantial subgrid-scale variability in areas of active convection.

In the interest of time and disk space, many of the concepts described in this paper can be viewed as power point presentations online at http://wwwt.emc.ncep.noaa.gov/mmb/bf/presentations/SPC_4-24-03.ppt and at http://wwwt.emc.ncep.noaa.gov/mmb/bf/presentations/EMC_Sack_Lunch_9-16-03.ppt.

7. FINAL REMARKS

None of the modifications to the BMJ and KF convective schemes that were described herein are currently being considered for immediate implementation in the operational Eta model. Recent changes to the BMJ scheme made by Janjic in the NMM, which led to an improved forecast of hurricane Isabel during landfall, will be investigated in the next few months. Given that no convective scheme has been shown to have demonstrably superior skill in the areas of convective initiation and QPF, the approach of model diversity and physics diversity within short-range ensemble systems continues to be a reasonable approach for pursuit. *Reasonable spread can be achieved from a convective scheme through parameter tuning and modifications to the scheme itself, and that the magnitude of this spread is comparable to that obtained from using different convective schemes.* The SREF upgrade takes into account this variability, together with other significant sources of spread from perturbed initial conditions and the use of different modeling systems. The viability of this approach is currently being verified against extensive precipitation, upper-air, and surface observations.

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