The Importance of Understanding Mesoscale Model Parameterization Schemes for Weather Forecasting

JOHN V. CORTINAS JR.
NOAA/National Severe Storms Laboratory and Cooperative Institute for Mesoscale Meteorological Studies, Norman, Oklahoma

DAVID J. STENSRUD
NOAA/National Severe Storms Laboratory, Norman, Oklahoma
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ABSTRACT

A severe weather outbreak that occurred on 21–23 November 1992 in the southern United States is used to illustrate how an understanding of model parameterization schemes can help in the evaluation and utilization of mesoscale model output. Results from a mesoscale model simulation show that although the model accurately simulated many of the observed mesoscale features, there are several aspects of the model simulation that are not perfect. Through an understanding of the model parameterization schemes, these model imperfections are analyzed and found to have little effect on the overall skill of the model forecast in this case.

Mesoscale model output also is used to provide guidance to evaluate the severe weather threat. By using the model output to produce hourly calculations of convective available potential energy (CAPE) and storm relative environmental helicity (SREH), it is found that regions with positive CAPE, SREH greater than 150 m² s⁻², and model-produced convective rainfall correspond well with areas in which supercell thunderstorms developed. In addition, these parameters are highly variable in both space and time, accentuating the need for continuous monitoring in an operational environment and frequent model output times.

1. Introduction

The success of mesoscale research models, coupled with an exponential increase of computing power and storage over the last decade, has led to the movement of mesoscale models into the operational environment (Warner and Seaman 1990). This trend will culminate in the operational release of a mesoscale version of the step-mountain, eta coordinate (ETA) regional model this year [see Mesinger et al. (1988), Janjić (1990, 1994), and Black (1994) for more details about the ETA model]. This model has a horizontal grid spacing of approximately 29 km and 50 vertical levels, with layer depths that range from 20 m in the planetary boundary layer (PBL) to 2 km at 50 mb. This resolution will give operational forecasters a tremendous opportunity for providing very precise and detailed forecasts. However, unless the model output is interpreted properly, the public may receive a very precise and detailed incorrect forecast! Our experience with mesoscale models suggests that to obtain the maximum benefits from these models, techniques to process and analyze the inordinate amount of model output are needed, in addition to understanding the model's parameterization schemes. It is important to realize that lacking either an understanding of the model or techniques to analyze the model data, the potential utility of these models likely will never be realized.

Knowing how well a model typically performs under certain weather scenarios is an important component of operational forecasting. Although this empirical knowledge will continue to be helpful when evaluating mesoscale model forecasts, an understanding of the basic model physics and, especially, the model parameterization schemes will assume greater importance than in the past. This is due to the strong influence that mesoscale model parameterization schemes can have on model behavior (Fritsch and Chappell 1981; Stensrud and Fritsch 1994b). An awareness of the physical processes that are included in the model and a basic understanding of how these processes are represented are the keys to unlocking model behavior. Are the processes subgrid scale (implicit) or grid scale (explicit)? How does the model decide when this process is active or inactive?

While synoptic-scale models have shown considerable skill in forecasting the development and evolution of extratropical cyclones (Sanders 1987; Junker et al. 1989; Black 1994), consistent inaccuracies in these models, combined with the large grid spacings used

Corresponding author address: Dr. John Cortinas Jr., National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK 73069. E-mail: cortinas@nssl.noaa.edu

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make it difficult to extrapolate their results to smaller scales, where much of the warm season sensible weather occurs. In particular, recent studies have shown that the quantitative precipitation forecast (QPF) is often inadequate in operational synoptic-scale numerical models (Houghton and Rubin 1990; Mesinger et al. 1990; Junker and Hodges 1993). Indeed, QPFs have been, and continue to be, one of the most difficult model forecasts (Charba and Klein 1980; Ramage 1982), since to produce a good QPF of heavier rainfall amounts the model must predict accurately the development and evolution of convection. Therefore, forecasters have had to rely heavily on subjective forecasting methods that use numerical guidance as a component. Funk (1991) describes several such subjective forecasting methods, developed at the Hydro-meteorological Prediction Center (see McPherson 1994), that account for known model deficiencies in order to produce better heavy rain event forecasts than the numerical models.

The QPF problem has led to research that shows QPF deficiencies from the synoptic model simulations can be improved either through enhancements to the numerical scheme and model physics and/or a decrease in the horizontal grid spacing (Mesinger et al. 1990, 1994). Zhang and Fritsch (1986) document that a mesoscale model (horizontal grid spacing of 25 km), using a detailed convective parameterization scheme, simulates many of the mesoscale convective components, including convective line placement, mesohigh placement, and a reasonably accurate distribution of rainfall amounts for the 1977 Johnstown, Pennsylvania, flash flood event. Zhang et al. (1989) show another case in which a mesoscale model simulation performs better than the Environmental Modeling Center’s (EMC; see McPherson 1994) operational models when it simulates the structure and attendant precipitation of an intense squall line over Kansas and Oklahoma. These studies clearly show the potential utility of mesoscale model QPFs.

In addition to providing QPF guidance, it is hoped that mesoscale models can provide improved prediction of severe weather events. Numerous modeling studies have demonstrated the ability of mesoscale models to reproduce mesoscale weather phenomena under certain conditions (Anthes et al. 1982; Perkey and Maddox 1984; Zhang and Fritsch 1986; Zhang et al. 1989; Stensrud and Fritsch 1994b). The ability of a model to simulate these mesoscale features accurately is an important consideration, since observational studies document the importance of the relationships between these features and the development of severe convection (Maddox et al. 1980; Maddox and Grice 1986; Doswell 1987; Rockwood and Maddox 1988). While current synoptic-scale models with adequate numerical procedures and accurate parameterization schemes may be able to indicate areas where severe convection is possible, they cannot resolve these features adequately because of their limited spatial resolution and physical representations. Moreover, Weiss (1987) and Jungbluth and Weiss (1993) show that the EMC’s Nested Grid Model (NGM) underestimates instability in the warm season, an important “ingredient” for severe convection. The focus on mesoscale features in severe storm forecasting (Johns and Doswell 1992) creates an increasing need for an accurate operational mesoscale model, not only with high resolution but also with improved parameterizations (Weygandt and Seaman 1994).

This study uses the severe weather outbreak of November 1992 to demonstrate one approach to interpret mesoscale model output that is based upon a general knowledge of the model parameterization schemes. However, we want to emphasize that we do not advocate that forecasters abandon the use of nowcasting and short-range forecasting techniques discussed by Doswell (1986), McGinley (1986), Funk (1991), and Johns and Doswell (1992), since mesoscale models are not perfect and should not be regarded as “the answer” to all short-range convective forecasting problems. Indeed, we believe that mesoscale model output will present both a tremendous opportunity and a tremendous challenge to operational forecasters.

The purpose of this study is twofold: 1) to illustrate the type of model output operational forecasters can expect from a mesoscale model by examining the simulation of a severe weather outbreak, and 2) to illustrate one way to interrogate the mesoscale model output, with special emphasis on using the model output to assist in the evaluation of the severe weather threat. Section 2 describes the mesoscale model with attention devoted to the model parameterization schemes that play important roles in the evolution of the model fields. Section 3 compares the observations taken during the outbreak with the model simulation, while section 4 describes one approach to interrogating and assessing the model output both to determine the skill of the numerical prediction and to use the model output to help determine the severe weather threat. Section 5 discusses why it is important to include convective parameterization schemes. Section 6 discusses techniques to monitor the model performance, while a discussion and conclusions are presented in section 7.

2. Model description and initialization

For simulations of deep convection, a mesoscale model typically has parameterization schemes for the convection itself, the surface energy budget, the planetary boundary layer, and cloud microphysical processes. There are several different approaches that could be used for including these processes in a mesoscale model, and the particular schemes being used influence how one should interpret the model results. Typically, once you become familiar with one particular scheme, developing an understanding of other schemes is much
simpler, since there tend to be more similarities than differences. Toward this end, we discuss in general terms the physical parameterization schemes used in the mesoscale model simulations reported in this study.

The mesoscale model chosen for use is The Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model version 4 (MM4) (Anthes and Warner 1978; Anthes et al. 1987). This model includes all the necessary model parameterization schemes to simulate deep convection and has demonstrated this ability in a number of case studies (Zhang and Fritsch 1986, 1988; Warner and Seaman 1990). The MM4 is a three-dimensional, hydrostatic, primitive-equation model with a terrain-following vertical coordinate system, where \( \sigma = \frac{(p - p_t)}{(p_t - p)} \), \( p_t \) is the surface pressure, and \( p_t \) is the pressure at the top of the model (\( p_t = 50 \text{ mb} \)). A two-way interactive nested grid (Zhang et al. 1986) is used that allows the model to resolve mesoscale features without having to define the whole model domain at high resolution. Spacings of the coarse and nested grids are specified as 75 and 25 km, respectively, with the coarse grid covering most of the United States and the Gulf of Mexico and the nested grid centered over the southeastern United States for this study. There are 30 vertical levels, with layer depths that vary from roughly 40 m near the surface to 2.3 km at 50 mb.

One of the most important processes to represent accurately in a mesoscale model is deep convection. The Kain-Fritsch (KF) implicit convective parameterization scheme is used for the nested grid (Kain and Fritsch 1990), and the Anthes-Kuo implicit convective parameterization scheme is used for the coarse grid (Anthes et al. 1987). The KF scheme is not used for the coarse-grid calculations, since the scheme is valid only for models with a horizontal grid spacing fine enough to resolve the mesoscale environment. This limits the use of this scheme to model domains with horizontal grid spacings of up to 30 km, as suggested by Kain and Fritsch. The KF scheme parameterizes deep convection by mixing the environmental air with convective updrafts and downdrafts to compute the net effect of convection on the model variables. A simple one-dimensional cloud model that includes entrainment and detrainment is used to determine the amount of mixing that occurs. For simulations of deep convection, it is very important that the parameterization scheme include the effects of moist downdrafts on the environment, since downdrafts produce convective outflows that can further influence convective development.

Another important aspect of the convective parameterization scheme is the decision when to initiate convection. The procedure that determines when convection becomes active is called a “trigger function,” and its formulation has a significant effect on model simulations as shown in the studies of Kain and Fritsch (1992) and Stensrud and Fritsch (1994b). The trigger function used by the KF scheme calculates layer-average properties of parcels for 60-mb deep layers within the lowest 300 mb of the atmosphere. These parcels, beginning with the lowest one, are then given an initial vertical velocity that is related to the model produced vertical motion at the parcel lifting condensation level (LCL) (Fritsch and Chappell 1980). Parcels with initial upward vertical velocities are lifted, mixed, and checked for positive buoyancy. If the parcel arrives at its level of free convection (LFC) while still retaining an upward vertical velocity, then the KF scheme lifts the parcel to its equilibrium level and calculates the cloud depth and the effects of the cloud on the environment through the one-dimensional cloud model.

The Anthes-Kuo parameterization is used within many models that have large grid spacing (>50 km) because of its conceptual simplicity and its small computational cost. This scheme initiates convection based on an affirmative response to the following questions: 1) Is the vertically integrated moisture convergence greater than or equal to a critical value? 2) Is there conditional instability? 3) Does the cloud depth reach a critical value? 4) Is the convective available potential energy (CAPE) positive? If all these criteria are met, then the scheme calculates the convective heating and moistening of the environment using the vertically integrated moisture convergence and normalized vertical profiles, which are based on observations. It is particularly important to note that the Anthes–Kuo scheme does not include the effects of convective downdrafts, and that numerous problems have been found when using the Kuo scheme (Raymond and Emanuel 1993). Since the focus of the present study is upon the nested grid, and very little convection occurs on the coarse grid, our use of the Kuo scheme does not appear to be detrimental to the simulation.

The importance of understanding the model convective parameterization scheme(s) is difficult to overemphasize. For example, while the Anthes–Kuo scheme is able to incorporate some of the effects of convection on the large-scale environment, it is known that grid-scale moisture convergence values are not always highly correlated with convective activity. Fritsch et al. (1976) calculate the mass and moisture budgets for a squall line that develops within a synoptic-scale wave to determine if the synoptic-scale and mesoscale budgets balance one another. Their results show that the rates of consumption of both mass and moisture by the squall line exceeded that which was supplied by the synoptic-scale environment by an order of magnitude. Additionally, Fritsch et al. (1976) also show that CAPE is more positively correlated to the convective heating and moistening of the atmosphere than synoptic-scale moisture convergence. These results indicate that if a numerical model uses a convective parameterization scheme based on examining the values of grid-scale moisture convergence, then the model
likely will underestimate the number of grid points with active convection.

The model calculates grid-scale (resolvable) precipitation by using an explicit bulk microphysics scheme based on studies by Lin et al. (1983), Rutledge and Hobbs (1983), and Hsie et al. (1984). The microphysics scheme first determines if the grid volume is supersaturated. If supersaturation occurs, then cloud droplets or ice crystals form, depending on the temperature of the air. The amount of precipitation that reaches the surface is determined by considering the effects of hydrostatic water loading, accretion, condensation, evaporation, melting, freezing, deposition, and sublimation. Supercooled liquid water is not considered in this scheme. [Readers should refer to Zhao et al. (1991) and Sundqvist et al. (1989) for information about a similar explicit scheme used by EMC's mesoscale ETA model.] Inclusion of resolvable precipitation, such as with trailing anvil precipitation regions within mesoscale convective systems (MCSs), is especially important to the QPF problem, since this precipitation typically accounts for 30%–40% of the total MCS rainfall (Johnson and Hamilton 1988). Zhang et al. (1988) found that using the explicit bulk scheme in conjunction with an implicit convective parameterization scheme is a good approach for simulating mixed convective and stratiform precipitation systems, since the explicit scheme was able to simulate stratiform rain, and the convective parameterization scheme was able to simulate deep convection.

The importance of the PBL evolution to mesoscale weather phenomena requires that subgrid boundary-layer processes be included in all numerical models, including synoptic-scale models. Accurate representations of heat, moisture, and momentum fluxes are important components of any boundary-layer representation. The MM4 planetary boundary-layer scheme is a modified version of the Blackadar (1976, 1979) high-resolution PBL scheme (Zhang and Anthes 1982; Zhang and Fritsch 1986; Pan et al. 1994). The Blackadar scheme contains modules for representing both nocturnal and daytime mixing. The nocturnal module uses an implicit $K$-theory approach, where $K$ is determined by the local Richardson number. The daytime module calculates the exchanges of heat, moisture, and momentum through the mixing of convective elements originating at the lowest model layer with the environmental air throughout the calculated boundary-layer depth. The Blackadar scheme behaves well when the PBL is relatively dry, but our experiences suggest that it tends to underpredict the PBL depth when grid-scale saturation occurs within the model PBL.

The surface energy budget uses the force-restore slab model approach (Blackadar 1976), where the ground temperature evolution is determined from the surface radiation budget, the sensible and latent heat fluxes, and the heat flux into the ground. Deardorff (1978) shows that the force-restore approach is an accurate one to determine ground temperature while it also restrains computational costs. Shortwave and longwave radiation components are altered by "cloud cover," as specified in the cloud parameterization scheme of Benjamin (1983) that calculates low-level (<800 mb), midlevel (800–450 mb), and high-level (≥450 mb) cloud cover based on the maximum relative humidity (RH) in these layers. Cloud fraction (N) in the low and middle levels is defined as $N = 40$ RH – 3.0 and as $N = 2.5$ RH – 1.5 in the highest level. Walcek (1994) shows that a positive correlation exists between the RH in a horizontally averaged 80-km cloud layer and the fractional cloud cover, with a correlation coefficient varying from 0.19 near the surface, to 0.49 at 700 mb, to 0.18 at 175 mb.

Zhang and Anthes (1982) show that the boundary-layer evolution, neglecting cloud effects, is most sensitive to the amount of ground saturation (moisture availability), surface roughness, albedo, and thermal capacity, in order of importance. In the present study, the moisture availability is specified from a climatological land-use dataset at NCAR that includes nine separate land-use categories. Therefore, any variations from this mean climatological state, such as would occur from heavy rainfall events or dry periods, are not represented in the model. Stensrud and Fritsch (1994a) discuss using sensitivity tests to modify the values of moisture availability to reproduce a more representative boundary-layer structure. Unfortunately, this approach is very time consuming and computer resource intensive. In the present study, we use the simplified climatological land-use values since a sensitivity experiment in which values of moisture availability are reduced by one-half indicates that little change occurred in the model simulations. We emphasize, however, that this insensitivity is not always the case and that one must be cautious when using climatology to specify the partitioning of surface fluxes.

An awareness of the data and methodology used for initializing the model also is useful. In order for any model to produce an accurate forecast, it must start with an accurate depiction of the atmosphere. Initialization procedures objectively analyze synoptic-scale rawinsonde and surface observations to the model grid points in order to provide the model initial conditions. Since model grid points often do not match the exact locations of where observations are taken, an accurate initialization may not always look accurate during a comparison of the initial fields with observations. In this study, the initial variable fields over the entire model domain and tendencies at the boundaries are computed using data from the 2.5° × 2.5° EMC global analyses blended with only the standard surface and rawinsonde observations using the objective analysis approach of Benjamin and Seaman (1985). Therefore, while the model initial condition is improved by the use of the rawinsonde and surface data over the continental United States, the initial condition is strongly...
dependent upon the EMC global analyses over water and in other data-sparse regions.

The MM4 is initialized at 1200 UTC 21 November 1992 and a 24-h simulation is produced. This control simulation is compared with the available observations in the following section to demonstrate the model skill during this period.

3. Observations and simulation

On 21–23 November 1992, a significant severe weather outbreak occurred in the southern United States, producing 146 tornadoes, 92 convective wind reports, and 34 reports of 3/4 in. or larger diameter hail (Fig. 1). Twenty-six people were killed, 641 injured, and $291 million worth of property damage occurred with this weather system (NOAA 1993). Riordan et al. (1993) show that this event was forecast well by the National Severe Storms Forecast Center (NSSFC), with only 2 of the 16 tornado watches issued not verifying. Their results show that of the 244 reported severe weather events compiled (defined as one or more severe weather reports from a given county), 195 events occurred during a severe weather warning, while only 49 of them occurred without warning.

In this section, we describe the observed and simulated 24-h sequence of Gulf coast events starting at 1200 UTC 21 November. The analysis represents a synthesis of hourly surface observations, infrared satellite imagery, rawinsonde data, profiler data, and composite radar data to describe the meteorological evolution of the severe weather event.

a. Observations

From 1200 UTC 21 November to 1200 UTC 22 November, an extratropical system develops in Texas and moves through the south-central United States (Fig. 2). At 1200 UTC 21 November, a large upper-level trough covers the western one-third of the United States. The 850- and 500-mb charts (not shown) indicate a negatively tilted, short-wave trough entering the southern plains states, with an associated center of low pressure at the surface in western Texas. A stationary front extends northeastward from the low pressure center to the Great Lakes. Rawinsonde data show that the most unstable stratification is located only along the Gulf Coast, with convective available potential energy (CAPE) values of 564 J kg⁻¹ at Corpus Christi (CRP), 135 J kg⁻¹ at Lake Charles (LCH), 178 J kg⁻¹ at Jackson (JAN), and 310 J kg⁻¹ at Tallahassee (TLH).

During the next 9 h, the cold front moves eastward across Texas and a second low pressure center develops near the Gulf coast in southern Texas between 1500 and 1800 UTC 21 November and moves northeastward. Values of surface convergence along the frontal boundary increase throughout the morning and maximize at 2100 UTC, with values exceeding 1.4 X 10⁻⁴ s⁻¹ indicated. This is used to empirically esti-
mate the upward motion to be approximately 0.1 m s\(^{-1}\) at the top of the PBL. Deep convection initiates ahead of the front between Houston and Victoria, Texas, (VCT) slightly before 1900 UTC and quickly develops into a north–south-oriented squall line that moves eastward.

Radar data and surface observations indicate that severe weather continues to occur as the region of convection moves eastward across Texas, Louisiana, and Mississippi during the next 9 h. At 0600 UTC on 22 November, as the squall line is moving through central Mississippi, forecasters at JAN estimated the CAPE to be over 1500 J kg\(^{-1}\) and the storm-relative environmental helicity\(^1\) (SREH) to range from 200 to 300 m\(^2\) s\(^{-2}\) (Pence 1993, personal communication), suggesting the possibility of continued supercell thunderstorms after sunset, since values of SREH greater than 150 m\(^2\) s\(^{-2}\) frequently are associated with mesocyclogenesis (Davies-Jones et al. 1990). It is emphasized that this SREH value of 150 m\(^2\) s\(^{-2}\) is preliminary and should not be used as a threshold value. Limited operational experience suggests that when SREH is around 100–150 m\(^2\) s\(^{-2}\), supercells are possible (Moller et al. 1994).

**b. Simulation**

Starting with the initial state of the atmosphere at 1200 UTC on 21 November, the model generates many of the observed features by 2100 UTC 21 November (Fig. 3). Two areas of low pressure exist in Texas: one in north-central Texas, and the second area near the Texas coast. The model also generates strong convection near the Texas coast with an associated outflow boundary moving into Louisiana. Strong low-level southerly winds ahead of the cold front are advecting warm, moist air northward toward the frontal system, providing the essential ingredients necessary to sustain the convection.

During the next 9 h, the model moves and deepens the low pressure center such that by 0600 UTC on 22 November, the center of low pressure is located in

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\(^1\) SREH is a quantitative measure of the amount of horizontal vorticity, associated with the storm horizontal inflow, that is converted into vertical vorticity through tilting by the updraft. Davies-Jones et al. (1990) computed the SREH for 28 storms in the south-central United States that produced tornadic supercells and found that ranges of SREH values for weak, strong, and violent tornadoes were 150–299, 300–449, and ≥450 m\(^2\) s\(^{-2}\), respectively.
southwestern Arkansas in good agreement with the observations (compare Figs. 2c and 3c). Several model-simulated outflow boundaries have merged over the past 9 h to form an elongated line of convection that extends from the Gulf of Mexico northward through Louisiana, Mississippi, and Tennessee. Strong low-level southerly flow ahead of the outflow boundary continues to destabilize the atmospheric stratification by advecting warm, moist air from the Gulf of Mexico into southern Louisiana, Mississippi, and Alabama. During the remaining hours of the simulation, the surface low moves northeastward into central Arkansas, with the associated cold front weakening as it moves into western Tennessee, extending southward through western Mississippi and eastern Louisiana (not shown). The line of convection persists and moves slowly eastward into eastern Mississippi.

The qualitative agreement between the model features at these times and the observations is very encouraging. However, a closer comparison of the modeled and observed fields early in the simulation shows several differences that likely would have a strong effect on one’s perception of the trustworthiness of the model simulation if seen in a real-time operational environment. Important differences include: a region of spurious convection that develops within the first few hours of the model simulation near the Texas coast; temperatures and mixing ratios in the warm sector that differ from observed values by up to 7°C and 4 g kg⁻¹, respectively; and winds that differ from observed values.
by up to 90° in direction and 20 m s⁻¹ in speed. Understanding how these discrepancies can occur, and their importance to the overall model simulation, are important components in trying to determine if the model output is providing an accurate simulation of the future atmospheric state.

Although it is possible in a research environment to correct many, if not all, of these discrepancies, we have chosen instead to use this imperfect model simulation to illustrate both the difficulties and opportunities that might be seen with operational mesoscale models in the future. In the following section, we focus upon the inaccuracies in the model simulation and discuss how these might be correctly interpreted in a real-time environment. We admit that these interpretations may be difficult to do in a real-time setting, but we believe the additional effort is justified and can lead to a better understanding of model behavior.

4. Interrogating model output and assessing the severe weather potential

As an example of how one might examine output from a mesoscale model incisively, we interrogate the model output from the real-time perspective of forecasters in Texas, where the severe outbreak begins, and forecasters in Mississippi, where deadly nighttime storms occur.

a. Texas

Forecasters in Texas on the morning of 21 November are faced with the difficult questions of where and when the convection will begin as the front strengthens and moves eastward through Texas. Hourly model convective rainfall totals show that by 1500 UTC 21 November (the time at which output from a real-time mesoscale model run would typically be available) modeled convection is occurring over the western Gulf of Mexico, while infrared satellite imagery shows clear skies over the same area (Fig. 4). This spurious convection is a serious problem, since one may be tempted to disregard the entire simulation because of a low confidence in the model solution. An alternative to disregarding the entire model solution is to examine this error and determine how strongly this spurious convection likely affects the model solution at a later time.

One possible reason for the spurious convection is that the initial data are out of balance with the model physics. This imbalance causes spurious upward vertical motions during the first few hours of the simulation as the model initial conditions are brought into balance with the model physics. During this adjustment process, the convective parameterization scheme may generate small areas of convection. These areas of convection usually dissipate as the model fields reach a balanced state. The amount of time involved in the adjustment process can last up to several hours but varies from simulation to simulation. Zhang and Fritsch (1986) found that the MM4 underwent an adjustment period of three hours while simulating a very dynamic convective environment. In the simulation in this case, the area of spurious convection over the Gulf persists beyond the first few hours, suggesting that most of the spurious convection over the Gulf is not associated directly with the model adjustment process.

Another possible cause of the spurious convection is an inadequate model initial condition. Several studies have found that the effect of inaccurate initial conditions on a model simulation depends on the amount of synoptic forcing present (Zhang and Fritsch 1986; Anthes et al. 1989; Stensrud and Fritsch 1994a). In weakly forced situations, very accurate initial conditions are needed to produce an accurate simulation, whereas in strongly forced situations, small inaccuracies may have a minimal effect on the simulation. For the present study, all available standard data near the region of convection are used to assess the model initialization over the Gulf of Mexico. (Data sources such as satellite-derived quantities and sea surface temperatures from special buoys were not used in the initialization.) An assessment of the model domain yields several data errors over the Gulf that likely affect the simulation: 1) satellite-derived, vertically integrated liquid water values are less than model values (not shown), indicating that the model atmosphere over the Gulf of Mexico is more moist than in reality; 2) a model sounding over the Gulf indicates no convective inhibition (CIN; Fig. 5a); and 3) model temperatures at the lowest model level are cooler than observations in the Gulf, creating a temperature difference between the sea surface temperature and the temperature in the lowest model layer of up to several degrees Celsius (Fig. 5b). Since these errors are restricted to the data void area in the Gulf of Mexico near the Texas coast, it is not surprising that spurious convection develops in this area.

Given the errors in the model initialization, the most important question for forecasters is whether this model error is large enough to influence negatively the remainder of the simulation. Since atmospheric observations over the Gulf are sparse, initialization methods use data from coastal regions to initialize the structure of the marine atmosphere. However, the boundary layer over water can be quite different than that over the nearby land (Betts and Boers 1990). A model sounding from the western Gulf shows an uncharacteristic structure to the boundary layer (Fig. 5a). Instead of a well-mixed marine boundary layer as one would expect, there exists a surface layer characterized by a temperature inversion and nearly saturated conditions. Given a temperature difference between the water and the air at the lowest model level, a strong surface heat flux starts at the beginning of the simulation, quickly warming the air temperature of the
lowest model level. As temperatures warm, there is an increase in the moisture flux, as well. The combination of these processes, in addition to the absence of any significant CIN, appears to generate spurious convection over the western Gulf early in simulation.

As shown by Fritsch and Chappell (1981), modeled deep convection can play a significant role in subsequent convective development through the effects of convective downdrafts. The cold outflows generated by the parameterized convection create pressure perturbations that act as a focusing mechanism for future convective development along their edge (Fritsch and Chappell 1981; Stensrud and Fritsch 1994b). Over land, the KF scheme cools the ground temperature when downdrafts are generated. However, when convective downdrafts occur over the water, the KF scheme is not allowed to adjust the SST; instead, the SST remains constant through-
not be a cause for reduced confidence in this model simulation.

The usefulness of mesoscale model output goes beyond providing a forecast of the basic atmospheric variables. Forecasters can determine if forecasted convection is likely to be severe by using model output to calculate physically based severe convection parameters, such as CAPE and SREH. Of course, CAPE and SREH are not the only factors that determine if convection will be severe, but these parameters, along with areas of modeled convection, can highlight areas of potential concern to the forecaster. For this study, we determine the layer-average thermodynamic properties of parcels in five adjacent layers specified to be 50 mb in depth and starting with the lowest 50 mb above the surface. The layer-averaged parcel with the highest equivalent potential temperature is used in the calculation of CAPE at that grid point. The SREH is calculated from the method described by Davies-Jones et al. (1990), using a climatological mean storm motion estimated by Davies and Johns (1993). This climatological mean storm motion is defined as 30° to the right of the mean wind and 75% of the mean wind speed if the cloud layer mean wind is less than 15 m s⁻¹ or as 20° to the right of the mean wind and 80% of the mean wind speed otherwise. The cloud layer mean wind is estimated using the mean wind from 850 to 300 mb.

At 2100 UTC the simulation highlights an area in eastern Texas and western Louisiana where values of SREH are greater than 50 m² s⁻² and CAPE are greater than 200 J kg⁻¹ (Fig. 6). [These values of SREH and CAPE are chosen to allow for model errors and to provide information about low SREH/high CAPE and low CAPE/high SREH environments, which may produce supercells (Johns et al. 1993).] We use this region, combined with areas where model convective precipitation is occurring, to highlight areas where additional evaluation and monitoring are necessary to determine the possibility of supercell development. Observations of tornadoes and damaging winds at this time agree with the area highlighted by the model. The agreement between the model highlighted areas and the observations of severe weather shows that the information about the timing and placement of severe convection using modeled convection may help to further define an area of potentially severe weather. The use of these model values can give forecast offices notice of potentially severe weather and bring about a heightened awareness of environmental changes conducive to the formation of severe storms on a given day.

Although the accurate simulation of precipitation is the most difficult aspect of any mesoscale model simulation, errors in the basic variables occur as well. Model errors in the lowest-layer temperature forecasts can occur for several reasons. Besides the possible problems with the initialization process, models simulate volume-averaged temperatures instead of point

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FIG. 5. (a) A skew T-logp diagram for a location roughly 275 km southeast of Corpus Christi, Texas, at 1200 UTC 21 November 1992. Temperature and dewpoint temperature are in degrees Celsius. (b) The difference between the model ground temperature and the lowest level model temperature, contoured every 2°C, at the same time as (a).
Fig. 6. Model-calculated (a) SREH and (b) CAPE values at 2100 UTC 21 November 1992. Values of SREH greater than 50 m² s⁻² are contoured every 200 m² s⁻² in regions where the convective available potential energy is greater than 200 J kg⁻¹. (a) Severe weather reports within the past hour. An inverted triangle represents a tornado report, a dot indicates hail reports with a diameter greater than 1.9 cm (0.75 in.), and a cross represents winds in excess of 26 m s⁻¹ (50 knots).
temperatures, terrain fields are smoothed in comparison with the known terrain, and not all model PBL schemes produce superadiabatic layers near the surface, which are observed frequently. Also, clouds are parameterized in mesoscale model because of their importance on longwave and shortwave radiative transfer on the surface energy budget (Slingo 1987), yet these parameterizations are far from perfect.

The parameterization of cloud cover often is adequate to produce qualitative agreement between observed and simulated fields, but it may cause inaccurate temperature forecasts in the lowest model layer by predicting clouds where they are not observed or an incorrect amount of cloud cover within a grid volume.

In this simulation, a comparison of the infrared satellite imagery and predicted cloud cover for the surface energy budget calculation shows that the model over-forecasts the amount of cloud cover over a large area of the model domain during the simulation (Fig. 7). This overestimation results in modeled temperatures in the lowest layer that are cooler than observed during the daytime and warmer than observed at night when advective effects are small.

To determine the magnitude of the effect of cloud cover on the surface-layer temperature forecast, we run the identical simulation, but with the cloud cover artificially set to zero. Results show that the simulation without cloud effects increases daytime temperatures.
and decreases nighttime temperatures by as much as 1°C at Victoria, Texas (VCT), and Ellington Air Force Base, Texas (EFD), near Houston, during the time clouds were significantly overestimated in the original control simulation (Fig. 8). This produces a slightly better agreement between observations and model output. (It is difficult to make an exact comparison between model values and observations since the model values are of the lowest-layer temperature and the observations are those at a specific point.) Discrepancies between observed and modeled values of surface-layer temperatures are not described totally by the effects of clouds but also by the occurrence of convection in the model. Modeled convection that starts at a grid point earlier than observed also begins to cool the surface layer sooner than is observed. This illustrates the importance of having an accurate trigger function in the convection parameterization scheme.

Since surface temperatures are the result of complex boundary-layer processes, it may be difficult to develop a universal correction factor that can be applied to model temperature data. However, by removing the 7-day running mean model bias, mesoscale model high temperature forecasts can be improved dramatically, showing skill equal to the model output statistics (MOS) from the limited-area fine-mesh and nested grid models in certain regions of the country. A basic knowledge of cloud parameterization schemes can provide forecasters with additional information that can help them decide whether the model temperature may be too low or too high for a given situation. The amount of adjustment may be determined best using knowledge of the local meteorology.

b. Mississippi

Forecasters in Mississippi on the morning of 21 November are confronted with many of the same problems as forecasters in Texas when interpreting the model output from this simulation. Will the initial spurious convection affect the rest of the simulation? How accurate is the modeled evolution of convection? Will the convection become severe? Are the simulated temperatures accurate?

![Figure 9](image-url)  
**Fig. 9.** Values of model-calculated and observed CAPE in Joules per kilogram at Jackson, Mississippi, from 1200 UTC 21 November 1992 to 1200 UTC 22 November 1992. Squares indicate CAPE values computed from the thermodynamic sounding data.
Fig. 10. Model-calculated (a) SREH and (b) CAPE values at 0600 UTC 22 November 1992. (a) Values of SREH greater than 50 m$^2$ s$^{-2}$ are contoured every 200 m$^2$ s$^{-2}$ in regions where the convective available potential energy is greater than 200 J kg$^{-1}$. (a) Severe weather reports within the past hour. An inverted triangle represents a tornado report, a dot indicates hail reports with a diameter greater than 1.9 cm (0.75 in.), and a cross for winds in excess of 26 m s$^{-1}$ (50 k). (b) Values of CAPE greater than 200 J kg$^{-1}$ are contoured every 400 J kg$^{-1}$. 
As in Texas, one of the major concerns is the region of spurious convection in the Gulf of Mexico off the Texas coast. However, spurious convection also develops near the coasts of Alabama and the Florida Panhandle within three hours of the simulation (Fig. 4). The effect of this convective activity on the rest of the simulation is minimal, since it dissipates within six hours. Between 1800 and 0000 UTC, Mississippi is free from modeled convective activity, and the boundary-layer warms and moistens owing to diurnal heating and advection from the Gulf. The convective line, which developed in Texas early during the simulation, finally enters Mississippi at 0400 UTC on 22 November. At 0600 UTC on 22 November, the convective line extends nearly north–south from Tennessee, across Mississippi, and into the Gulf of Mexico (Figs. 3c,d).

Whereas forecasters in Texas are concerned with the timing of initial convective development, the big model questions for forecasters in Mississippi are whether the convection will truly persist long enough to enter Mississippi after sunset, and whether the model timing of convection is accurate. For this event, the first question is fairly easy to answer. Model values of CAPE in central Mississippi increase to nearly 1000 J kg$^{-1}$ between the model initial time and 0600 UTC 22 November, primarily due to advection of moisture from the Gulf of Mexico (Fig. 9). This evolution is consistent with what one would expect from a developing cyclone in this location and, thus, would support convection in this region. The second question is more difficult to assess.

Knowing how the trigger function is defined in a mesoscale model provides the information needed to assess the reliability of the model’s timing of convection. As discussed in section 2, the KF scheme determines whether or not to initiate convection by taking 60-mb layer-average parcels and lifting them to their LCL. For convection, this layer-average parcel typically originates in the planetary boundary layer. If the boundary layer has significant variations in potential temperature or mixing ratio throughout its depth, then these variations can influence the layer-average temperature and moisture of the parcel, which can then feed back to the timing of convective development. An east–west cross section of relative humidity through the region of convection shows that the moist layer depth over much of Mississippi is near 90 mb, which suggests that the timing of the model convective activity in Mississippi should be very close to that which is observed (assuming the trigger function is accurate).

Now that it has been determined that convection in Mississippi is likely, one can assess the potential for severe convection. Values of SREH from the simulation at 0600 UTC 22 November show that the regions where the model develops parameterized convection in conjunction with large values of SREH correspond reasonably well with the reported tornadic activity at this time (Fig. 10). These SREH values fluctuate rapidly, with the value at JAN changing as much as 200 m$^2$ s$^{-2}$ in one hour. This trend is also shown at Winnfield, Louisiana, where available profiler data (using observed surface data from El Dorado, Arkansas) and model data show a peak in the SREH near 0100 UTC 22 November (Fig. 11). Determining how well the model predicts the SREH values is difficult without wind profiler data, since rawinsonde data are only available every 12 h. However, observations at 0000 UTC 22 November taken from a rawinsonde site at JAN and output from the simulation both produce a SREH value of 180 m$^2$ s$^{-2}$. This agreement between
observations and model output is encouraging and shows that SREH and CAPE information can be extremely helpful to forecasters trying to locate mesoscale areas where supercells may develop, while also illustrating the importance of having model output available at relatively fine time intervals in order not to miss the important temporal changes in these parameter values.

In addition to interpreting model output for the occurrence of severe weather, forecasters in Mississippi, like Texas forecasters, may want to assess the accuracy of the model surface-layer temperatures. A comparison of infrared satellite data with modeled cloud cover (Fig. 12) suggests that the model produces a reasonable approximation to the amount of nighttime cloud cover over Mississippi. The importance of including cloud effects is shown by a comparison of model temperatures with observations from Keesler Air Force Base in Biloxi, Mississippi (BIX), and from JAN (Fig. 13). During the daytime, the model overestimates cloud cover over Mississippi (Fig. 7), which results in daytime temperatures at BIX and JAN Mississippi that are cooler than observed. At night, however, cloud cover estimates are good, which results in more accurate nighttime temperatures. The results from the simulation with and without cloud effects shows that when clouds are accurately represented, surface temperatures are in better agreement with observations than when the cloud cover is poorly estimated.
In this section, we have shown how various parameterizations are necessary to simulate important atmospheric processes on the mesoscale. In the next section, we investigate further the importance of using a convective parameterization scheme by comparing simulations with and without the scheme. While such a comparison may be of a student-lab character and probably not feasible in an operational setting, it serves to illustrate to the forecaster, who does not have access to such labs, the simulated effect of convection on the mesoscale environment and how the inclusion of convective schemes affects the simulation.

5. Bulk microphysics and cumulus parameterization schemes

The strong feedbacks that can occur from the initiation of modeled convection, particularly when the parameterization scheme includes the effects of convective downdrafts, lead us to examine the usefulness of another model simulation that does not use any convective parameterization scheme. In this simulation, only resolvable-scale precipitation processes are allowed (this simulation is hereafter referred to as the NOCONV simulation). Thus, for precipitation to occur in the NOCONV simulation, grid-scale saturation must be created. A mesoscale simulation with only resolvable-scale precipitation allows one to examine the effects of the parameterized convection on the environment and, in the context of this study, illustrates the importance of including a convective parameterization scheme in any mesoscale simulation. Addi-
25-km grid spacing lacking a convective parameterization scheme suggests that deep convection is likely and that one would expect a convective scheme to be active in the same region at this time. The agreement between precipitation areas in eastern Texas in both simulations suggests that errors associated with the earlier spurious convective activity in the CONV simulation have decreased. If a thought process similar to the one just described had taken place, it is likely that a forecaster would now be confident that by 1800 or 2100 UTC, the mesoscale model is providing useful forecast information. Thunderstorms in eastern Texas along the Gulf Coast are quite likely with initial convective activity expected to begin by 1800 UTC.

Producing a simulation without a convective parameterization scheme shows how modeled convection can effect SREH and CAPE values. The NOCONV simulation indicates SREH values are higher and cover a larger area than the CONV simulation (Fig. 15). Note that in the regions where the convective parameterization scheme is active in the CONV simulation, the values of both CAPE and SREH are reduced in comparison with the NOCONV simulation. This is attributed to the KF scheme mixing both mass and momentum and including the effects of convective downdrafts. The cold outflows associated with the convection in the CONV simulation have stabilized the atmospheric stratification, thereby eliminating or reducing the CAPE, while the convective outflow depicted in the CONV simulation causes the winds in the lowest model layer to become southerly after the passage of the outflow boundary, thus reducing the SREH values.
Fig. 15. Model-calculated SREH values at (a) 0900 UTC 21 November 1992 and (b) 0600 UTC 22 November 1992 for NOCONV simulation. Values of SREH greater than 50 m$^2$ s$^{-2}$ are contoured every 200 m$^2$ s$^{-2}$ in regions where the convective available potential energy is greater than 200 J kg$^{-1}$. Severe weather reports within the past hour are represented by an inverted triangle for a tornado, a dot for hail with a diameter greater than 1.9 cm (0.75 in.), and a cross for winds in excess of 26 m s$^{-1}$ (50 k).
Also, low-level winds east of the surface low have a large easterly component in the NOCONV simulation, which contributes to the large SREH and CAPE values in the warm sector. This comparison between the CONV and NOCONV simulations illustrates the additional utility of a NOCONV simulation. In an area where the CONV simulation produces spurious convection, values of SREH and CAPE will likely be underpredicted.

 Later in the simulation, an examination of the NOCONV simulation at 0600 UTC on 22 November (Fig. 14c) shows that a well-defined region of resolvable-scale precipitation is still present along the frontal boundary. Calculations of SREH at this time from the NOCONV run once again show these values to be higher than the CONV run (Fig. 15). Further examination of these runs shows that there is a significant difference in the placement of the low pressure center and the front from the two simulations. The NOCONV simulation places the surface low pressure center roughly 400 km to the east-northeast of the observed low center, while the CONV simulation places it roughly 250 km to the south of the observed low center. The associated cold front has already reached western Mississippi and Tennessee in the NOCONV, while observations show the front in west-central Arkansas southward through central Louisiana. These differences show that once convection begins, it plays a large role in the development of the synoptic system. Results from model simulations of a squall line event in the central United States, also conducted both with and without a convective parameterization scheme, show that without the convective parameterization scheme a squall-line is never produced (Cram et al. 1992). Thus, any simulation without a convective parameterization scheme should be used only before and during the very early stages of convection.

### 6. Monitoring model performance

With the ever-increasing amounts of data to examine and digest in the modernized NWS Forecast Office, the techniques and tools used to monitor model output and observations become increasingly important to the forecaster. One of the most powerful tools we have found for model assessment is the time series plot of both model and observed data. This method is useful, particularly during the early stages of the simulation.

Any form of model display should provide the capability for observations and model output to be displayed simultaneously. Since the timescales involved with mesoscale phenomena range from 30 minutes to several hours, observations and model data should be output with a frequency of no less than 3 hours. Plummer (1989) describes a display used at EMC to examine model output. This EMC display shows the forecaster a time series plot of hourly single-station surface and 12-h upper-air model output. Although this type of display is able to plot model data in an efficient way, it lacks the capability to plot observational data. We propose another method of display that uses standard station plots of observed and modeled surface data, providing qualitative and quantitative information about the accuracy of the model output. Using such a display, a quick comparison between the observed and the modeled surface data at JAN and VCT (Fig. 16) is facilitated. From this comparison, we see that the model solution agrees qualitatively with the trends in the observed data, while a quantitative discrepancy appears in some of the variables. These discrepancies may be important to the forecaster who is monitoring a situation in which small differences between the model forecast and observations may highlight a model inaccuracy that has a significant influence on the model behavior.

In addition to surface data, data from other sources should always be used whenever possible for model
comparisons. The availability of rawinsonde, wind profiler, and satellite-derived observations makes comparisons of datasets above the surface relatively easy. A comparison of profiler wind data at Winnfield, Louisiana, provides information about the accuracy of the model forecast winds above the surface and information about how well the model forecast the frontal movement (Fig. 17), as well as the evaluation of the SREH (Fig. 11b). Monitoring the model data should help produce a better understanding of how the model performs for a given location. Additionally, changes in model variable fields, in the absence of observations, may heighten forecaster’s awareness of the severe weather potential. This knowledge, coupled with a basic understanding of the model physics, provides the optimal use of numerical guidance.

7. Discussion and conclusions

The grid spacing of mesoscale models allows for the simulation of mesoscale features involved with the formation and evolution of convection. Not only do these models show the ability to provide numerical guidance to forecasters about the timing and placement of convection, but also the likelihood of the convective activity being severe. This offers an improvement over current synoptic-scale models, which offer minimal assistance with locating where and when deep convection will occur. However, even though mesoscale models can simulate a wide variety of convective weather events in the research environment, the true test of the utility of mesoscale models will occur only when they are used and evaluated on a daily basis. This real-time assessment of mesoscale model forecasts is important not only to improving short-term forecasts to the public, but also can assist in the development of improved general circulation models (GCMs). As computer power increases, the grid spacings used in GCMs are becoming smaller. Improvements in mesoscale model skill that can be achieved within the next decade can have a significant positive effect on the next generation of GCMs, since cloud and precipitation processes are one of the largest remaining obstacles to improved climate prediction. This added benefit of real-time mesoscale modeling is yet another reason to understand the model parameterization schemes, since critical subjective and objective evaluations of their performance on the regional scale are very important to improving overall skill.
Results from Cortinas and Stensrud (1994) and this study show that using mesoscale model output to calculate physically based severe storm parameters, such as CAPE and SREH, along with the location of convective precipitation, provides useful guidance for where severe convection may occur. Additionally, the present study shows that SREH and CAPE values can be highly variable in space and time, in agreement with the observational study of Davies-Jones (1993). The use of mesoscale model output can be helpful to forecasters in these dynamic convective situations by helping one to anticipate and monitor sudden changes in the mesoscale environment that may signal an increasing likelihood of severe storms.

The 1992 severe weather outbreak simulation exemplifies how well a mesoscale model can simulate a severe convective outbreak. In addition to valuable information obtained from using a fully configured mesoscale model, there appears to be some value in running simulations from the same model without the convective parameterization scheme, perhaps as an ensemble forecast member. In this configuration, the model only forecasts resolvable-scale precipitation. Producing both of these simulations may help forecasters determine the ability of the model to predict convection (Brooks et al. 1992). If both simulations produce high rainfall rates in the same area initially, then forecasters have an enhanced level of confidence in the forecast of convective precipitation. However, this situation only is likely to occur in strongly forced environments, such as ahead of fronts or when a well-defined synoptic system interacts with topography. In weakly forced environments, such as occur frequently during the summer, it is likely that a model with only resolvable-scale precipitation processes will fail to produce any precipitation. Therefore, the importance of a good convective parameterization scheme is increased (see Stensrud and Fritsch 1994b). In addition, it must be emphasized that deep convection can have a strong influence on the model evolution, such that later in the simulation it is likely that the simulation with parameterized convection will differ substantially from the simulation that only includes resolvable-scale precipitation processes. In this scenario, the simulation that includes a convective parameterization scheme is likely to be correct. Also, these model comparisons provide an understanding of the possible effects of convection on the mesoscale environment and how well the model replicates them. In this way, we not only obtain numerical guidance from the model, but also learn more about the mesoscale environment and its role in the development of severe weather.

Aside from examining the abilities of a mesoscale model, efficient usage of model output depends cru-
cially on the method of display. We agree with Doswell (1992), who discusses the importance of developing a workstation that allows forecasters to interact with model data and observations. Using these displays, forecasters can view data in a form that is based on scientific knowledge of atmospheric processes and not be limited to a predetermined set of plots. Moreover, these displays should allow a variety of both observations and model output to be plotted simultaneously so forecasters can monitor the model solution quickly and efficiently. Since mesoscale environments can change rapidly, especially during convective situations, hourly model output may be needed or important information about the mesoscale evolution may be lost. A comparison of the hourly model calculations of CAPE and SREH with calculations from 12-h rawinsondes shows that model output at 6 or 12 h is inadequate to resolve important changes in the features represented by these parameters. On the basis of this result, we recommend that as much model output as possible be made available to forecasters so that they can evaluate the model simulation using their knowledge of modeling and the atmosphere.

While the focus of this study has been on mesoscale models, it should be mentioned that improvements to model forecasts come not only by increasing the model resolution but also by improved numerics and parameterization schemes (Black 1994; Mesinger 1994). Therefore, as the complexity of these models increases, the importance of understanding their parameterization increases as well.

The introduction of mesoscale models into the suite of National Weather Service operational models begins a new era of numerical guidance, giving forecasters more spatial and temporal detail than ever before. The higher resolution and more accurate physical parameterizations of mesoscale models over synoptic-scale models makes them an attractive addition to the operational model suite. Although these models can improve numerical forecasting guidance for mesoscale phenomena, we feel that to realize these improvements the NWS also must invest resources to teach forecasters about the models and mesoscale phenomena that they simulate. Despite the initial obstacles that will arise with this new generation of models, we are certain that they will have a profound effect on forecasting weather in the future.

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