# RECOMMENDATIONS FOR DIFFUSION IN IDEALIZED SQUALL LINE SIMULATIONS BY THE WRF MODEL

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## 1. INTRODUCTION

In this paper, we present preliminary results from simulations of idealized squall lines by the WRF Model. We have been comparing the output to previously published results, and to output by other numerical models. Some of our results have been unexpected. For example, we find an obviously unphysical updraft pattern in some simulations. The pattern is unphysical because of a regularly repeating pattern in both the across-line and along-line directions. In addition, the updraft cells within this pattern are sometimes very poorly resolved, with cells that are less than 4 grid lengths in diameter.

Recently, Takemi and Rotunno (2003, hereafter referred to as TR) identified this unphysical pattern using an early version of the WRF Model. They noted that this problem was not expected because the WRF Model has more accurate, higher order advection schemes compared with older models that did not display such an unphysical pattern. They concluded that the older models suppressed the problem through artificial diffusion, which is required when using lower order advection and leapfrog-in-time integration.

It has been assumed that the higher accuracy of the WRF Model numerics, combined with some implicit diffusion in upstream-biased advection schemes, would be sufficient to prevent artificial noise in simulations of convection. However, TR concluded that some additional diffusion was necessary for simulations by the WRF Model. Therefore, they experimented with including artificial diffusion in the WRF Model, and with changes to the model's subgrid turbulence parameterization. Based on their studies, they recommended increasing certain parameters in the turbulence code that act to increase diffusion. They advocated this technique over the use of artificial diffusion, which diffuses all features at all times, whereas the turbulence code is active only in certain conditions where diffusion is needed most, such as when the Richardson number is less than ~0.25.

Our recent work extends the studies by TR. We have been simulating squall lines in a wider range of shear than was considered by TR. We also have been using the newer Eulerian-mass core of the WRF Model, whereas TR used the older Eulerian-height core. In addition, we have made several improvements in the turbulence code, which are now included in WRF 2.0. This paper presents our preliminary findings and our recommendations based on these studies.

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## 2. METHODOLOGY

All simulations use version 2.0.1 of the WRF Model. The model setup and initial conditions are nearly the same as those used by TR. The domain is 600 km long, 80 km wide, and 20 km deep, using 1 km horizontal grid spacing and approximately 500 m vertical grid spacing. The lateral boundary conditions are open in the longer across-line direction, and are periodic in the shorter along-line direction. The horizontally homogeneous initial conditions are based on the analytic sounding of Weisman and Klemp (1982). When low-level shear is included, the shear is confined to the lowest 5 km and is oriented perpendicular to the squall line. We refer to the initial wind profile by the total wind change in this layer ($\Delta U$). Convection is initiated by a line thermal extending the entire along-line width of the domain. Random perturbations are inserted into the line thermal to allow three-dimensional structure.

For subgrid turbulence, we use only the turbulence kinetic energy (TKE) scheme (diff_opt = 2 and km_opt = 2). The TKE scheme now uses a stability-dependent length scale by default. Following the methodology of TR, we keep the parameter $C_e$ set at 0.93 for its unstable limit, and we vary only the parameter $C_k$.

These simulations do not include an upper-level damping term to minimize the effects of gravity waves that reflect off the upper boundary. The damper that is currently available in WRF 2.0, which increases diffusion near the model top, is ineffective for these simulations. Furthermore, the changes that we have made in the turbulence code are incompatible with the damper; thus, the damper cannot be used concurrently with the turbulence code. Future studies will have to revisit this issue when an effective damper, such as a Rayleigh damper, is included in the WRF Model.

## 3. RESULTS FOR VARYING $C_k$

In this paper, we present simulations with three values of wind shear over the lowest 5 km ($\Delta U$): 0, 10, and 20 m s$^{-1}$. The three shears allow for three different squall line structures, from a strongly upshear tilted system with the weakest shear, to an approximately upright system with the strongest shear. Although we refer to the simulations by the amount of shear, the important factor is that three different squall line structures are produced. There are other environments and other model formulations, such as different microphysics schemes, that can produce such squall line structures.

Based on an early version of the WRF Model, TR recommended setting $C_k$ to ~0.20, or approximately twice its standard value of 0.10 (e.g., Moeng and Wyngaard

Table 1. Total rainfall ($\times 10^{12}$ kg) from 1-6 h.

| ΔU (m $s^{-1}$) | $C_k$ = 0.10 | $C_k$ = 0.15 | $C_k$ = 0.20 |
|---|---|---|---|
| 0 | 0.26 | 0.19 | 0.14 |
| 10 | 0.36 | 0.32 | 0.27 |
| 20 | 0.37 | 0.35 | 0.31 |

1988). Based on more recent work, including an improved turbulence code, they now recommend $C_k$ of ~0.15 (Takemi and Rotunno, 2004, personal communication).

Our results from WRF 2.0.1 when $C_k$ = 0.10, 0.15, and 0.20 generally support the range suggested by Takemi and Rotunno (Fig. 1). When $C_k$ = 0.10, the spurious updraft pattern is apparent as regularly repeating, poorly resolved cells (Fig. 1a). When $C_k$ is increased to 0.15, the spurious pattern is mostly eliminated. However, the cells remain poorly resolved (Fig. 1b). For $C_k$ of 0.20, the squall line is practically eliminated; only a few, suspiciously long updrafts exist (Fig. 1c).

These results show that the model-simulated convective system can sometimes be extremely sensitive to the value of $C_k$. For example, the total rainfall for the case is reduced by ~50% as $C_k$ is doubled (Table 1). This extreme sensitivity was not documented by TR, but will be noted in an upcoming corrigendum to their work (Takemi and Rotunno 2004, personal communication).

For simulations with some low-level shear, the results are slightly different. When ΔU = 10 m $s^{-1}$, there is still an arguably spurious updraft pattern with $C_k$ = 0.10 (Fig. 2a). In this case, the pattern is crosshatched in locations, with occasionally long updrafts oriented diagonally across the grid. Also different from the ΔU = 0 m $s^{-1}$ case, with this shear the cells are better resolved. When $C_k$ is increased to 0.15 (Fig. 2b) and to 0.20 (Fig. 2c), the spurious pattern does not occur at t = 4 h. However, at other times, especially before 4 h, there is still evidence of unphysical organization when $C_k$ = 0.15, but not when $C_k$ = 0.20. Strong convective cells exist with all three values of $C_k$. Total rainfall decreases by only 25% for this shear when $C_k$ is doubled.

When ΔU = 20 m $s^{-1}$, there is no obviously spurious pattern when $C_k$ = 0.10 (Fig. 3a). Specifically, there is no regular pattern of repeating updrafts along or across the line. When $C_k$ is increased to 0.15 (Fig. 3b) and to 0.20 (Fig. 3c), the same general character of the convective system is retained; the cells are more continuous along the line, they are located close to the surface gust front, and the system has bowed segments. In this case, total rainfall decreases by only ~16% when $C_k$ is doubled.

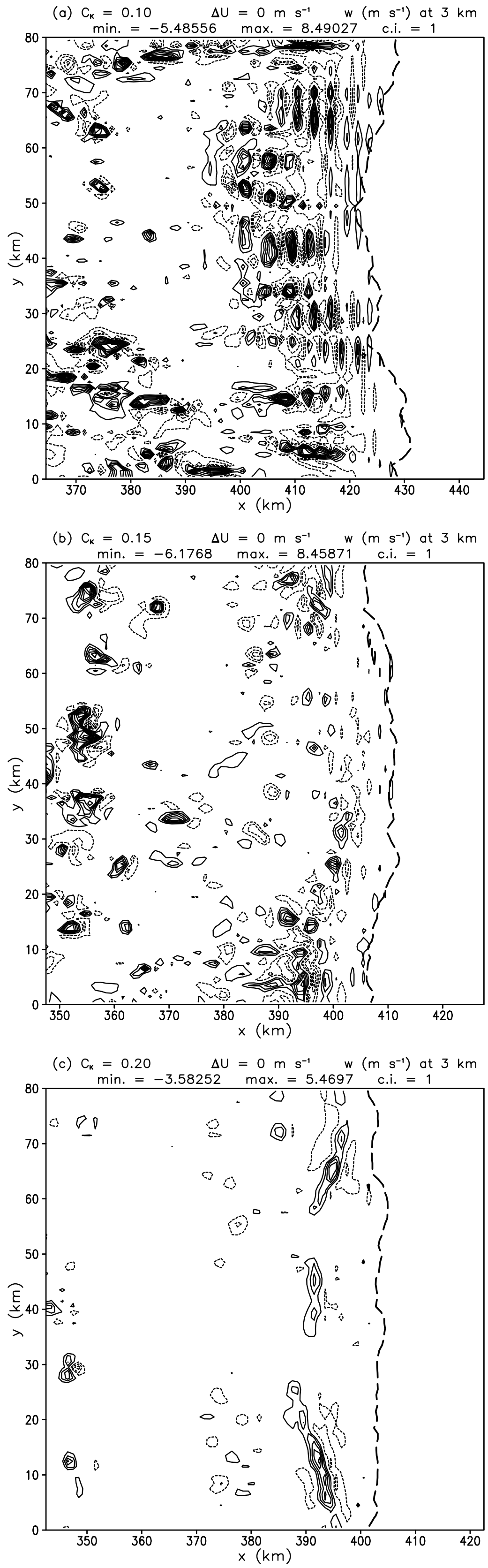


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Fig. 1. Vertical velocity (m $s^{-1}$) at 3 km and 4 h from simulations with ΔU = 0 m $s^{-1}$: (a) $C_k$ = 0.10, (b) $C_k$ = 0.15, and (c) $C_k$ = 0.20. The contour interval is 1 m $s^{-1}$, with negative contours dashed, and the zero contour excluded. The thick, dashed line is the surface gust front.

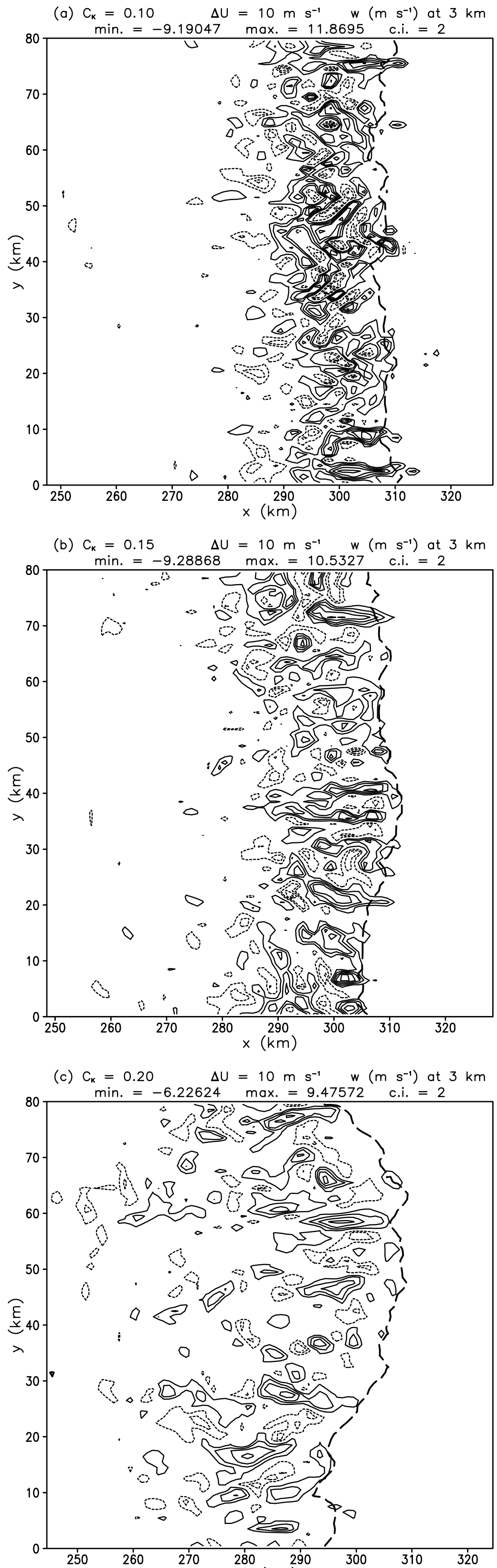


Fig. 2. The same as in Fig. 1, except for ΔU = 10 m $s^{-1}$, and with a 2 m $s^{-1}$ contour interval.

Although not indicated in the figures shown here, we also find that convective systems can evolve more slowly towards their mature state for the larger values of $C_k$. For example, the bowing segments in the ΔU = 20 m $s^{-1}$ simulations appear later when $C_k$ = 0.20.

## 4. CONCLUSIONS

Based on these results, and other simulations that are not shown here, it is our conclusion that convective systems are sensitive to changes in $C_k$ in some environments, but not as a general rule. We have found that upshear-tilted convective systems are most sensitive. This means that users need to be aware of the problem for simulations with weak shear, and in simulations with strong reverse shear, which is often found in tropical squall line environments and in cases with low-level jets. In contrast, we find that simulations of nearly upright and downshear-tilted convective systems are less prone to a spurious updraft pattern. Thus, simulations in strong shear probably do not require additional diffusion, and a lower value of $C_k$ is acceptable.

Fortunately, many qualitative aspects of the simulated convective system are unaffected by the existence of a spurious updraft pattern. For example, the system is clearly upshear-tilted for all values of $C_k$ when ΔU = 0 m $s^{-1}$, and the system is approximately upright for all our simulations when ΔU = 20 m $s^{-1}$. In addition, the trend is for total rainfall to increase with increasing low-level shear in all simulations conducted here (Table 1). However, certain quantitative information is very sensitive to the choice of $C_k$. The convective systems tend to be too strong when the spurious pattern occurs.

There are other techniques that can be used to address the problem of spurious patterns. A recent study with a similar numerical model finds that artificial diffusion and nonoscillatory numerical schemes are promising techniques that allow the user to keep $C_k$ at its standard value of 0.10 (Bryan, 2004, manuscript submitted to *Mon. Wea. Rev.*). These techniques might be considered for the WRF Model in the future.

If an increase in $C_k$ must be used to control spurious structures in the WRF Model, then it is difficult to recommend a single value based on the results presented here. At this time, we do not have a benchmark solution that could be used to decide the best value of $C_k$. Higher resolution simulations are underway, with the hopes of obtaining a benchmark solution. For now, we leave it to the individual model user to decide which solution is best.

*Acknowledgments*

We thank Richard Rotunno and Tetsuya Takemi for their insights on this topic. The Advanced Study Program of NCAR has provided support for this work. NCAR is sponsored by the National Science Foundation.

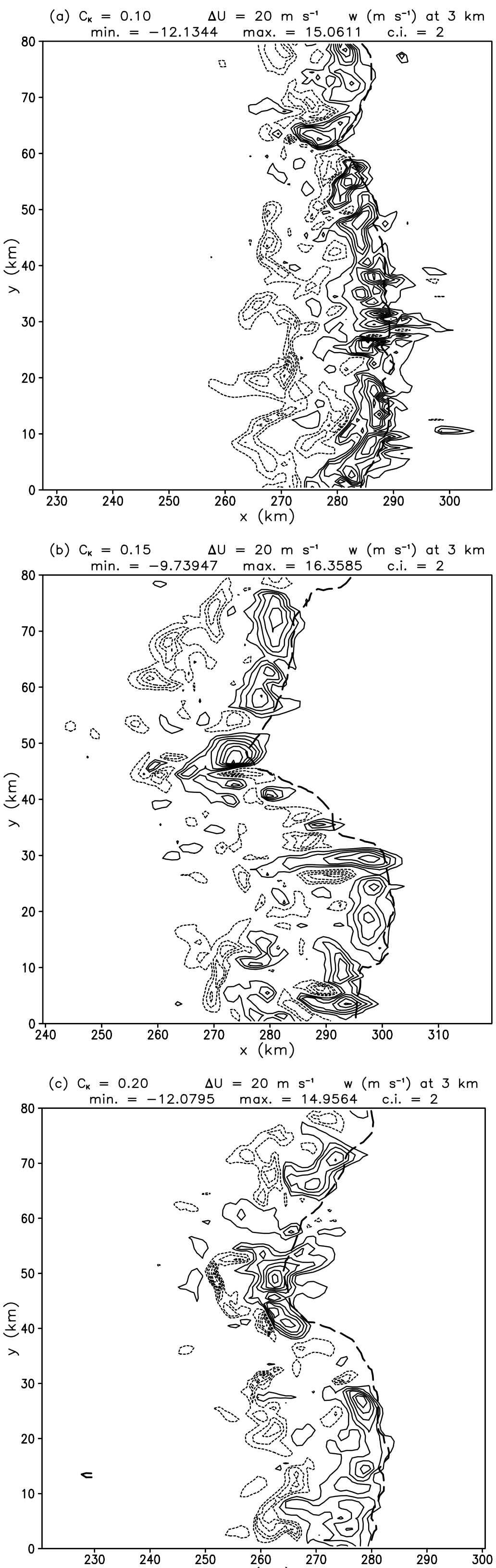


Fig. 3. The same as in Fig. 1, except for $\Delta U = 20$ m $s^{-1}$, and with a 2 m $s^{-1}$ contour interval.

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