Inconsistencies within parcel trajectories that pass beneath the lowest model level

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Introduction

Analysis of modeled parcel trajectories has become commonplace in the study of convective dynamics (Rotunno and Klemp 1985, Wicker and Wilhelmson 1995, Adlerman et al. 1999, Dahl et al. 2012, Naylor et al. 2012, Markowski and Richardson 2013, Dahl et al. 2014, Markowski et al. 2014, Schenkman et al. 2014, Coffer and Parker 2015, Dahl 2015, Davenport and Parker 2015). While advances in computing have precipitated the development of cloud models capable of realistically simulating convection at high spatial and temporal resolution—and thus capable of simulating parcel trajectories with a high degree of realism—the treatment of parcels beneath the lowest model level (henceforth referred to as the 'sub-domain') continues to be an unsolved problem for two main reasons. First, the vertical profile of the horizontal wind beneath the lowest model level cannot be determined by the prognostic equations of the model, and therefore must be parameterized analytically. Second, the profile of non-velocity scalar quantities (such as vertical vorticity and potential temperature, henceforth referred to simply as 'scalar quantities') are similarly unknown beneath the lowest model level, such that a convention to assign these scalar quantities along sub-domain parcel trajectories must be specified.

Objective

The problem of the treatment of the region beneath the lowest model level for parcel analysis is well-known. Indeed, many analyses will simply throw out parcels that traverse the sub-domain (Schenkman et al. 2014). However, merely ignoring such parcels out is not an ideal solution, as many of the most interesting parcels to analyze spend at least some time in the sub-domain near the surface (e.g. parcels that descend within the main downdraft of a supercell and contribute to tornadogenesis [Davies-Jones and Brooks 1993, Dahl et al. 2014, Markowski et al. 2014]). While with our current understanding of the flow near the lower boundary and computational constraints it may not be possible to completely eliminate the sub-domain parcel problem, it is also not immediately obvious how parcel trajectories are sensitive to the treatment of the flow within the sub-domain. This study aims to qualify, and where possible, quantify the trajectory inconsistencies that result from various treatments of variables within the sub-domain of a cloud model.

Method

Using a dry, idealized version of Cloud Model 1 (CM1, Bryan and Fritsch 2002), release 16, the authors simulated a thermally-forced isolated downdraft similar to Parker and Dahl (2015) for 40 minutes with a variety of spatial resolutions and treatments of the vertical wind profile within the sub-domain. These simulations were either low or high resolution and utilize either an extrapolated or constant treatment of the vertical wind profile within the sub-domain.

The low (high) resolution simulations have their lowest model level at 50 (5) meters. The extrapolated treatment of the sub-domain extrapolates the horizontal wind speeds from the lowest two model levels linearly to the ground, while the constant treatment assumes that the wind throughout the sub-domain is the same as the lowest model level. Regardless of the treatment of the kinematic field in the sub-domain, all scalar variables are assumed constant beneath the lowest model level, as is default in CM1. In all the simulations, there is a homogenous neutral-stability base state with a 10 ms^{-1} westerly wind and parcels are introduced at t = 10 minutes in a regularly gridded rectangular volume around the center of the thermal forcing for the downdraft. The parcels are released at a time where the modeled downdraft has achieved a near-steady state, and are integrated forward through the rest of the simulation time.

Result

The results of these simulations show that as soon as parcels descend into the sub-domain, they are immediately assigned scalar values that are inconsistent with the model physics. As an example, two parcels that start from the same initial location are shown in Fig. 1; one is from the high resolution simulation (Fig. 1c) and the other is from the low resolution simulation (Fig. 1a). Given that the only thermal forcing within the dry model is the heat sink that generates the downdraft, it is anticipated that once parcels leave the heat sink their potential temperature should be constant in the absence of strong mixing (since the parcels analyzed here are contained within the downdraft and not along the gust front, it is assumed that mixing does not play a significant role). However, when the parcel from the low resolution simulation enters the sub-domain, it rapidly experiences an erroneous increase in potential temperature. In contrast, the potential temperature of the parcel from the high resolution simulation is conserved for much longer because it never crosses into the sub-domain. In fact, the only time the parcel from the high resolution simulation shows any meaningful change in potential temperature is around x = 8 km, where there is an unusual feature in the potential temperature field that the authors suspect may be numerical error or perhaps the model's representation of a hydraulic jump. This feature requires further investigation to fully understand, and will be the subject of future study. Regardless, the conclusion is clear: Because of the way scalars are assigned to parcels within the sub-domain, the parcel from the low resolution simulation experiences an erroneous warming.

Using two parcels that share an initial location, albeit a different location than the parcels in Fig. 1, Fig. 2 shows that both the parcels from the high (Fig. 2b) and low (Fig. 2a) resolution simulations experience rapid, erroneous increases in potential temperature upon entering the sub-domain. This artifact occurs in the parcel from the high resolution simulation later (closer to the ground) than the parcel from the low resolution simulation because scalars such as potential temperature are considered constant with height in the sub-domain and the high resolution model has a much smaller sub-domain. Thus, a parcel may enter the sub-domain with a certain potential temperature, but while it continues to traverse the sub-domain it will be assigned the potential temperature of the point on the lowest model level directly above it, not the potential temperature it should experience at its actual location. This inconsistency remains until the parcel reenters the model domain and its scalar values can be properly interpolated from the model grid.

In an attempt to mitigate the inconsistency that results from the treatment of scalar assignment to parcels within the sub-domain, the authors implemented a scheme that extrapolates potential temperature from the lowest two levels to the ground. The results of the potential temperature extrapolation are seen in Fig. 1b. While such an extrapolation appears to mitigate some of the inconsistency—Fig. 1b is more similar to Fig. 1c than Fig. 1a is—the trajectory still passes into progressively warmer regions. This suggests that the parcel is still warming inconsistently.

A more serious inconsistency results from the treatment of the sub-domain wind profile. If the sub-domain wind treatment is 'constant,' a sub-domain parcel will experience accelerations based off of the forces that are influencing the point on the lowest model level directly above it. This is a problem because the parcel experiences accelerations governed at a location separate from its own. The 'extrapolated' treatment of the sub-domain wind profile attempts to reconcile this issue by extrapolating the vertical profile of the horizontal wind from the lowest two levels of horizontal wind data to the ground instead of using only the lowest model level. This method has the same issue as the 'constant' treatment in that ultimately parcels that enter the sub-domain are subject to accelerations that do not experience accelerations governed from the physics at their own locations, rather locations on the lowest model levels. Furthermore, since the standard treatment of scalar quantities along sub-domain parcel trajectories is to assign the value of that scalar from the lowest model level to the trajectory (essentially a 'constant' treatment of scalar quantities), if an 'extrapolated' wind profile is used, there is an internal inconsistency between the velocity profile and scalar profile. The inconsistency between the treatment of velocities and scalar quantities in the sub-domain may manifest itself in parcels seeming to disassociate from dynamic and thermodynamic features they were previously associated with before crossing into the sub-domain.

Importantly, while a parcel may return to the model domain after spending time in the sub-domain, it will never recover from the location errors that it has accrued from its tenure within the sub-domain. To understand this, consider a parcel that starts in the model domain, enters the sub-domain and stays there for some time, and then reenters the model domain. This parcel is analogous to a small bug floating on a river. Before the parcel enters the sub-domain, its movement is dictated by the dynamical core of the model, much like how the bug floats along with the flow of the river. The parcel entering the sub-domain is analogous to the bug climbing ashore and moving in a manner specified by some system other than the flow of the river. When the bug reenters the river some time later, the chances it will be part of the exact same portion of flow are very small. In this manner, when the parcel reenters the model domain, while its motions may be dictated once again by the dynamical core of the model, it will not be a part of the same portion of the flow as before.

Figure 3 demonstrates how a parcel can become disassociated from the dynamic flow once it enters the sub-domain. In this example, as soon as the low resolution parcel enters the sub-domain, the distance between it and the high resolution parcel dramatically increases. This suggests that while the low resolution parcel remains part of the physically governed model domain it maintains a comparatively similar trajectory to that of the high resolution parcel, but begins to disassociate from the physical flow. One might expect to find some differences between a parcel trajectory in low resolution and the parcel trajectory initialized at the same location in a higher resolution even within the model domain simply because of the differences in the model discretization (i.e. a high resolution model is expected to capture finer-scale features than a lower resolution model). While the difference in model resolution certainly seems to contribute to at least some of the differences in the location of the two trajectories shown in fig.

3, there is only a relatively small difference in the location of the two trajectories before the low resolution trajectory enters the sub-domain, thus this contribution appears to be minimal.

Summary

This study determines that the errors associated with parcels traversing the sub-domain are a result of the way the wind profile is defined (not dynamically-driven) and the treatment of how scalar quantities are assigned to parcels. In order to minimize the errors that occur with such parcels, it is suggested that they be avoided entirely. This can be accomplished a number of ways. Discarding parcels that spend any time at all in the sub-domain is the safest method. Increasing the vertical resolution of the model may also be a solution, however this may introduce new problems in that surface friction parameterizations may not be optimized for very small sub-domains (such as the 5 meter one used in the high resolution simulation). Ultimately, this is not a permanent solution, because it would be very beneficial to analyze parcels that traverse very close to the surface with mesoscale models in order to understand the effects of friction on vorticity generation and tornadogenesis (Coffer and Parker, 2015).

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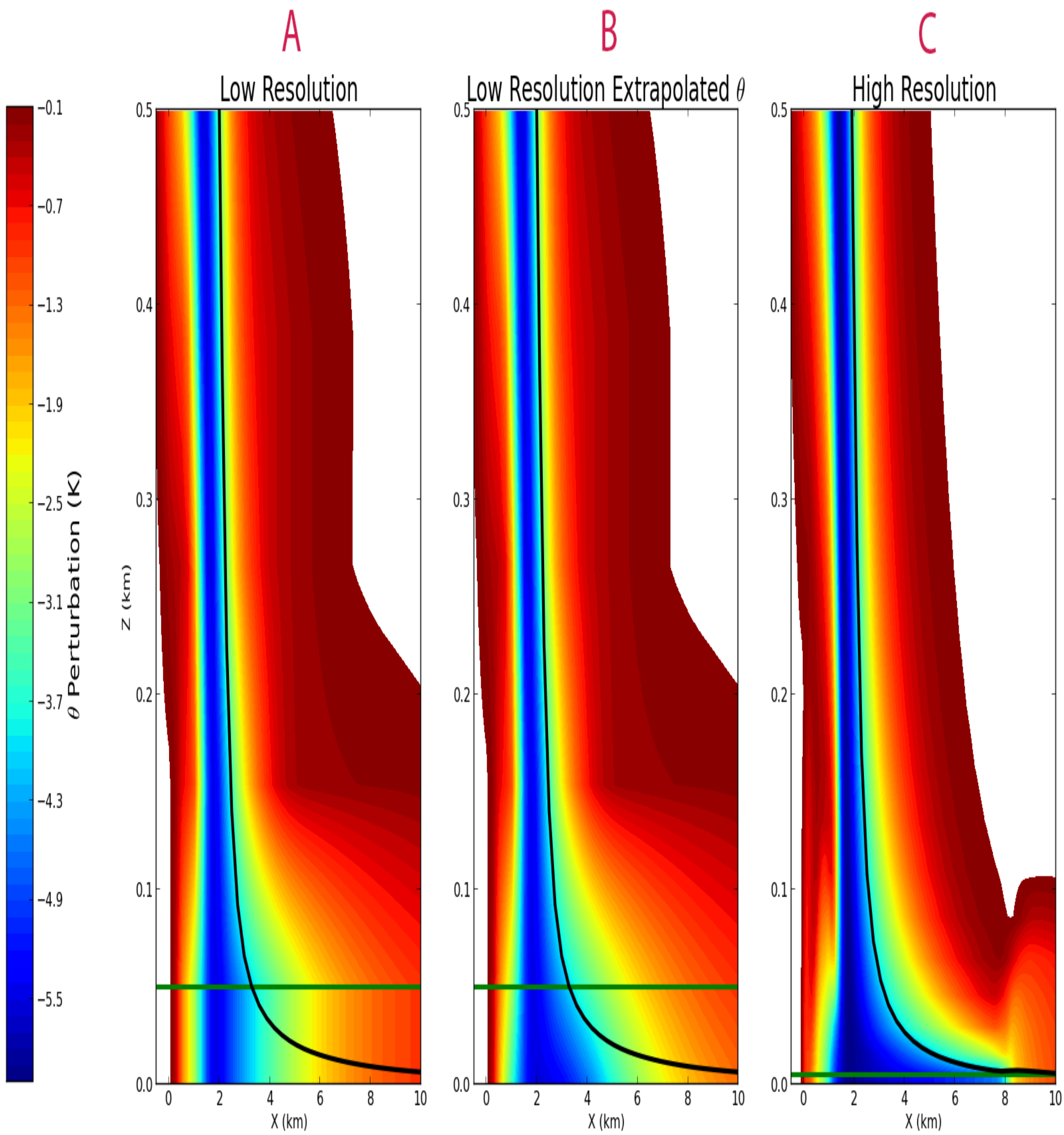

Figure 1: Vertical cross sections of the low resolution (a), low resolution with an extrapolated treatment of potential temperature in the sub-domain (b), and high resolution (c) downdrafts. The lowest model level for each is shown (green line). Each downdraft shown here has achieved a steady state, and trajectories with the same initial positions are overlaid on each. Note that these trajectories are entirely two dimensional (there is no movement in the *Y* direction) and the downdrafts are steady-state, thus the trajectories are accurate in both space and time (i.e. the parcel could be anywhere along its trajectory and the background θ cross section will look as it is shown here). Because scalars (such as θ) are treated as constant below the lowest model level, the parcels that pass beneath the model domain are assigned progressively warmer θ.

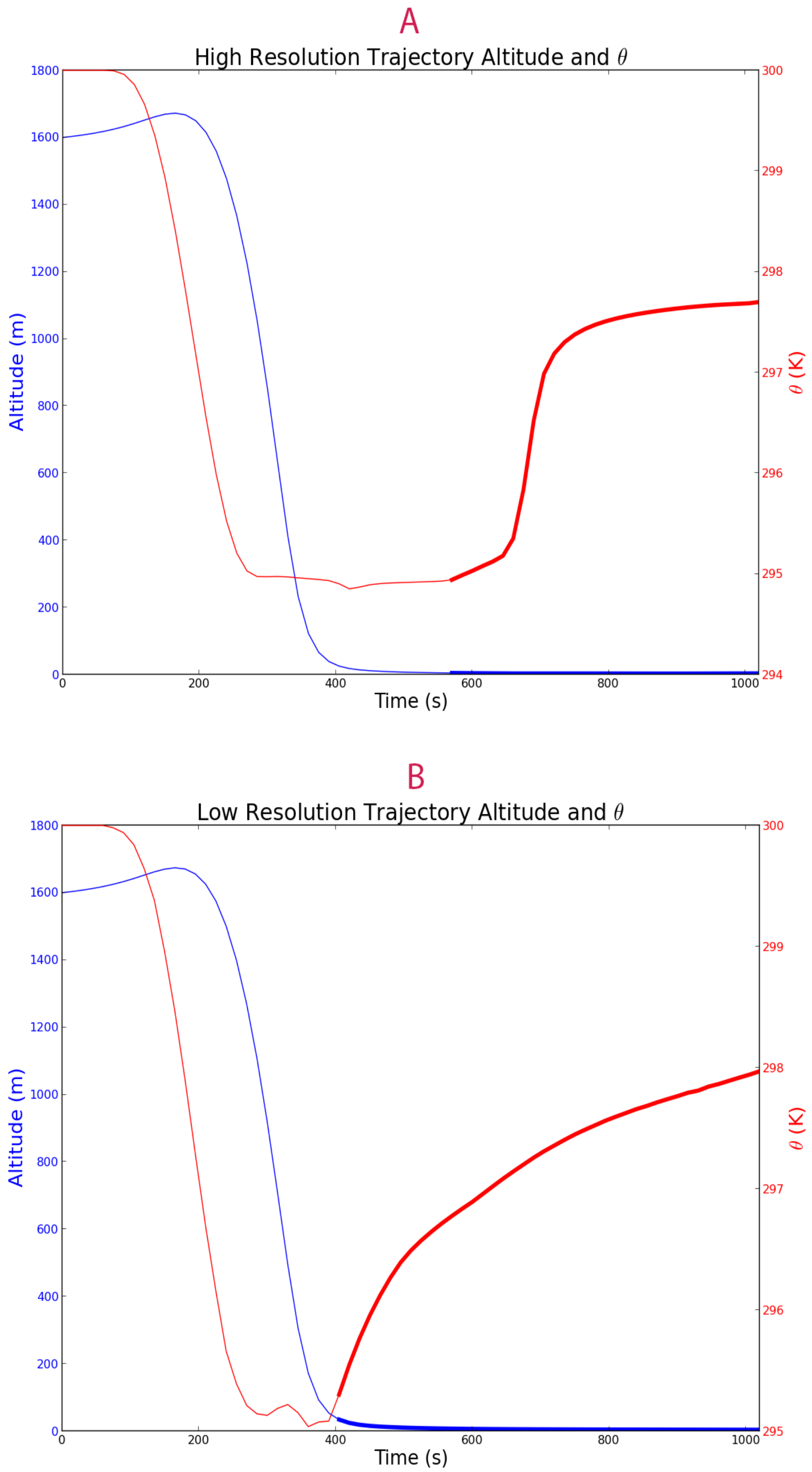

Figure 2: Altitude and potential temperature time series along trajectories that are initialized at the same location for the high (a) and low (b) resolution simulations. Both simulations shown here utilize the 'constant' treatment of the sub-domain wind profile. Bolded lines indicate that the parcel is beneath the lowest scalar model level (50 m for the low resolution; 5 m for the high resolution). Before the parcels go beneath the lowest model level, their θ evolution is qualitatively similar. Once the parcels descend into their respective sub-domains, however, their θ begins to sharply increase.

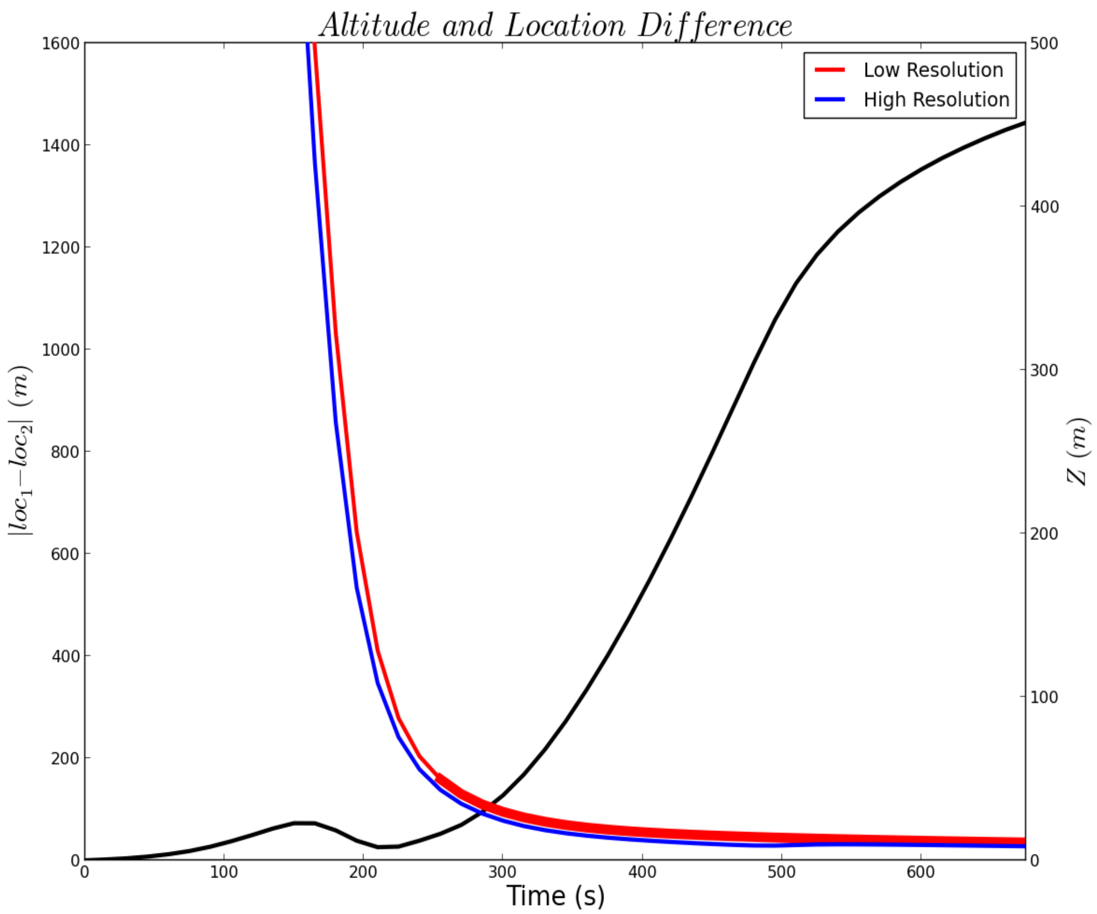

Figure 3: Time series of the altitude (red and blue lines) of two trajectories that have the same initial position, but different model resolutions. The thicker region of the low resolution line indicates that the parcel is beneath its model's lowest level. Additionally shown is the distance between the two parcel locations (black line).