Base-State Substitution: An Idealized Modeling Technique for Approximating Environmental Variability

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ABSTRACT

Base-state substitution (BSS) is a novel modeling technique for approximating environmental heterogeneity in idealized simulations. After a certain amount of model run time, base-state substitution replaces the original horizontally homogeneous background environment with a new horizontally homogeneous environment while maintaining any perturbations that have developed during the preceding simulation. This allows the user to independently modify the kinematic or thermodynamic environments, or replace the entire sounding without altering the structure of the perturbation fields. Such an approach can provide a powerful hypothesis test, for example, in a study of how an isolated convective storm would respond to a different environment within a horizontally homogeneous setting. The BSS modifications can be made gradually or instantaneously, depending on the needs of the user. In this paper both the gradual and instantaneous BSS procedures are demonstrated for simulations of deep moist convection, using first a wholly idealized setup and then a pair of observed near-storm soundings. Examination of domainwide model statistics demonstrates that model stability is maintained following the introduction of the new background environment. Following BSS, domain total mass and energy exhibit the expected instantaneous jumps upward or downward as a result of the imposed changes to the mean thermal and wind profiles, after which they remain steady during the subsequent simulation. The gridded model fields are well behaved and change gradually as the simulated storms respond meteorologically to their new environments. The paper concludes with a discussion of several unique aspects of the BSS approach.

1. Introduction

Numerical simulations of deep, moist convection have often been used to understand the fundamental processes governing its behavior and evolution. While heterogeneity is inherent in many convective storm environments (e.g., Brooks et al. 1996; Weckwerth et al. 1996; Markowski and Richardson 2007), idealized modeling studies have often utilized homogeneous base-state conditions to isolate the key processes at work (see Wilhelmson and Wicker 2001 for a review of such studies). Understandably, accounting for environmental heterogeneity in an idealized setting (i.e., simulations where the goal is to understand fundamental processes, not to replicate real-world events) has largely been avoided because of numerous complicating factors. Thermal gradients imply heterogeneity of fundamental convective ingredients such as convective available potential energy (CAPE) and convective inhibition (CIN), but also lead to three-dimensional mesoscale circulations with localized convergence/divergence. When planetary rotation is included, thermal gradients also imply the presence of a thermal


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wind, which in turn implies heterogeneity of vertical wind shear (e.g., Mahoney et al. 2009). Even without thermal wind balance, lateral boundary conditions are much more challenging to implement properly in idealized models with spatial heterogeneity (e.g., Richardson et al. 2007). These features can prevent a clean separation of cause and effect in experimental results, making it difficult to discern the key mechanisms at work when studying phenomena such as convective storms. Thus, it is sometimes of interest to simplify the effects of heterogeneity in order to isolate the role of environmental parameters in a set of controlled, idealized hypothesis tests.

Recent studies have sought to approximate spatial and temporal heterogeneity in an idealized setting through a variety of means. Atkins et al. (1999) placed a mesoscale boundary containing thermodynamic and kinematic variations in the model’s initial conditions and allowed it to evolve naturally to understand the boundary’s influence on supercell evolution. Other idealized studies have included thermodynamic boundaries in their initial conditions to understand their impact on storm morphology (e.g., Bluestein and Weisman 2000; Jewett and Wilhelmson 2006; Houston and Wilhelmson 2012). Richardson et al. (2007) achieved temporally fixed spatial heterogeneity of vertical wind shear in a prescribed, controlled manner through significant alterations to the model’s boundary conditions. Mahoney et al. (2009) used a channel model with an idealized base state in thermal wind balance and then launched a finer nested grid to study the convection that developed in the environment. Ziegler et al. (2010) utilized a hybrid approach, whereby horizontal heterogeneity in temperature and moisture fields was carefully controlled and constrained by a set of observations, held fixed over time on the model’s outer domain, while a smaller inner domain employed time-varying inflow lateral boundary conditions to move the storm through the prescribed spatial environmental heterogeneity. Other studies have specified tendencies in the base-state environment, gradually nudging thermodynamic and/or kinematic fields toward a desired state (e.g., Kost 2004; Parker 2008; French and Parker 2010; Letkewicz and Parker 2011).

From the perspective of a moving storm, changes to the environment can be either due to temporal variations (an environment changing over time) or spatial variations (the storm moving into a different environment). Experiments with spatially varying environments lose a degree of control because one cannot independently specify the gradients in the environmental variables without also changing the mesoscale circulations that accompany those gradients. Experiments with temporal sponging techniques tend to apply modifications uniformly across the model domain, which may not be truly realistic either. For example, the temporal sponging technique of Parker (2008) cools every grid cell to a reference temperature, which has the disadvantage of artificially cooling warm (undershooting) downdrafts in a stable environment. To address such concerns, a new technique deemed base-state substitution (BSS) has been developed, whereby the model is run for a period of time with a homogeneous base-state environment, then restarted with a new background environment. The method seeks to approximate the temporal tendencies actually experienced by a storm as it encounters a changing environment, without introducing gradients and their associated circulations to the simulation. Additionally, the BSS method allows the user to test how an identical storm would evolve in two different environments. This provides a unique opportunity, for example, to investigate how a mature storm responds to a changing background environment, as opposed to how storms develop in different background environments. Of course, truly identical storms are not likely to be present in different environments. However, there is both pedagogical and experimental value in constructing tests that examine first-order storm response to various environments without allowing for divergence among simulations during the earliest stages of storm development.

The aim of this article is to describe the technique and to document the impacts of BSS on the model, demonstrating its utility in approximating temporal heterogeneity while preserving the ability to isolate key processes and maintain model stability. The next section describes the BSS technique in detail, followed by a discussion of the model configuration and experimental setup in section 3. Section 4 details the results of a series of idealized experiments examining different applications of the BSS to wind and thermodynamic profiles for two environments. Finally, section 5 provides a summary of results with some concluding remarks on the advantages and disadvantages of the BSS method.

2. Technique description

a. Justification

The concept of a wholesale replacement of the background environment in a numerical model may at first sound unconventional. However, this method is firmly rooted in a history of similar approximations used in past model development and in other idealized modeling approaches. To begin, any variable can be thought of as the sum of the background environmental values plus any storm-induced perturbations:

$$\psi(x, y, z, t) = \psi_{\text{env}}(x, y, z, t) + \psi_{\text{storm}}(x, y, z, t). \quad (1)$$
Historically, many cloud models have made the idealization that the environmental values change very gradually in $x$, $y$, and $t$, such that to good approximation:

$$c(x, y, z, t) = c_{\text{env}}(z) + c_{\text{storm}}(x, y, z, t).$$

In essence, the horizontal and temporal changes of the mesoscale environment are treated as negligible. This approximation is somewhat computationally expedient in that a model can then be written in a form that is “filtered.” Temporal tendencies need only be integrated for the storm-induced perturbations, which can then be added back onto the base state to recover the full fields. Since these perturbations are typically much smaller than the total field, and are typically centered on zero, they can be represented in computer memory with higher precision.

Many modern studies of convective dynamics continue to use the approach encapsulated by (2) [i.e., a homogeneous, time-invariant base state, as reviewed by Wilhelmson and Wicker (2001)]. Of course, in nature the background environment likely varies in $x$, $y$, and $t$, and when these variations are substantial they may be important to storm evolution (e.g., Atkins et al. 1999; Bluestein and Weisman 2000; Jewett and Wilhelmson 2006; Richardson et al. 2007; Mahoney et al. 2009, Ziegler et al. 2010; Houston and Wilhelmson 2012). However, there are difficulties associated with the full implementation of $c_{\text{env}}(x, y, z, t)$ from (1) in an idealized model, including the treatment of lateral boundary conditions in the model (e.g., Richardson et al. 2007), the existence of additional mesoscale circulations, and the inability to independently specify thermodynamic and wind variations (when Coriolis accelerations are included). What we seek to do instead through BSS is to create a $c_{\text{env}}$ that is simpler than the fully 4D representation in (1), but captures the possibility that storms move into different environments better than the 1D representation in (2).

The assumed justification for approximating (1) by (2) is that one base-state sounding can represent a storm’s environment with sufficient accuracy. Indeed, most climatologies of convective storms have been constructed this way using “proximity soundings” (e.g., Rasmussen and Blanchard 1998; Evans and Doswell 2001; Thompson et al. 2003; Coniglio et al. 2007; Cohen et al. 2007; Horgan et al. 2007; Kis and Straka 2010; Grams et al. 2012). Philosophically, BSS involves updating a storm simulation to reflect a new storm-relative proximity sounding that embodies any spatial and temporal changes in the environment. The environmental inflow changes sensed by the moving storm can be expressed as

$$\frac{d\psi_{\text{env}}}{dt} = \mathbf{c} \cdot \nabla \psi_{\text{env}} + \frac{\partial \psi_{\text{env}}}{\partial t}. \tag{3}$$

If we think of the horizontal position of an initial near-storm environmental inflow sounding at $t_0$ as being represented by $[x_0, y_0]$ (Fig. 1a), and we think of a storm as moving with a mean vector of $\mathbf{c} = [c_x, c_y]$, we can then determine the appropriate location of a future near-storm environmental inflow sounding at time $t_0 + \Delta t$ to be $[x_0 + c_x \Delta t, y_0 + c_y \Delta t]$, as in Fig. 1b. As suggested by Fig. 1, the differences between the environmental soundings at $t_0$ and $t_0 + \Delta t$ represent some combination of temporal evolution in the fields during the interval and background spatial variations (which are mapped to...
temporal variations via a space-to-time conversion using the storm’s motion across the preexisting gradient). BSS incorporates both spatial and temporal environmental changes together by implementing the new near-storm base-state sounding at \( t_0 + \Delta t \).

Using BSS, the base-state environment is thus a function of time, although it remains homogeneous (i.e., it is not a function of horizontal position). So, instead of (2), BSS assumes the following form:

\[
\psi(x, y, z, t) \approx \psi_{\text{env}}(z, t) + \psi_{\text{storm}}(x, y, z, t).
\]  

(4)

The technique implicitly assumes that small-scale spatial variations in the inflow environment are negligible, which is also the basic principle undergirding all studies that use the homogeneous model formulation given by (2). In other words, the integrated effect of the storm moving across the gradient in \( \psi_{\text{env}} \) over time is assumed to be more substantial than the instantaneous effect of local gradients on the scale of the storm. This is in keeping with the long-held concept of using representative environmental inflow proximity soundings, as reviewed above.

b. Procedure

The procedure to apply BSS is fairly straightforward (Fig. 2): the changes in \( \psi_{\text{env}} \) over time in (4) are implemented in a stepwise fashion. The interval between stepwise updates to the base state is at the discretion of the user (in theory, BSS could be applied every model time step if desired). For the example of an idealized convective storm simulation, the user might initiate a storm in the model within a homogeneous base-state environment and allow it to mature to a quasi–steady state (on the order of 2–3 h). At that point, a model restart file containing the full model fields is written out. Using the information in the restart file, storm-induced perturbations of temperature, moisture, and wind are separated out from the original base state. These perturbations are then placed into a new homogeneous base-state environment, resulting in a new set of full model fields. The model is restarted and the storm (as described by its perturbations of temperature, moisture, and wind) evolves in that new environment, taking into account both spatial and temporal environmental changes [i.e., (4)].

If the base-state thermodynamic profiles are changed during BSS, several adjustments are made before the model is restarted. First, the pressure field in the new base-state environment is adjusted to ensure that it is in hydrostatic balance with the new thermal fields; this adjustment is typically quite small. Second, a saturation check occurs whenever the base-state moisture or temperature has been changed. If a grid point was unsaturated (with respect to water or ice) before BSS, but becomes supersaturated in the new environment, no further changes are made and the model microphysics scheme is allowed to form cloud normally on the first time step immediately after the restart. However, if a grid point was saturated before BSS, but would become subsaturated in the new environment, the grid point’s mixing ratio is adjusted to reset the grid point to a relative humidity of 100%. The rationale for this adjustment is to prevent the model microphysics scheme from producing instantaneous local evaporation that could lead to “holes” within the interior of clouds after the restart.

While saturated grid cells typically have enough cloud mass present that some could be evaporated without creating a cloud-free hole, there is no simple way to guarantee it. As a result of our saturation correction, cloudy grid cells that encounter drier environmental air via BSS will experience gradual evaporation over time via mixing between the cloudy air and the environment, much as in nature. We have rerun our benchmark simulations without the correction, and find only slight differences in simulated storm structures and domainwide statistics, mainly due to minor changes in the phasing of individual updrafts. Although its impact may be small, we advocate the saturation adjustment as being most consistent with the philosophy of preserving the initial storm during BSS and letting it respond to its new environment over time after the model has been restarted.

An important consideration in employing BSS is how quickly the environmental modifications should be made. While an entirely new environment can be introduced in one step (hereafter referred to as instant BSS), such a shift would generally be unrepresentative of real-world conditions, particularly for two very different environments. Alternatively, the environmental modifications

![Fig. 2. Schematic of the procedure followed for base-state substitution. See text for a full description of the procedure.](http://journals.ametsoc.org/mwr/article-pdf/141/9/3062/4280282/mwr-d-12-00200_1.pdf)
can be incorporated more gradually over a number of steps during a simulation (hereafter referred to as gradual BSS). In the gradual case, the BSS procedure is applied multiple times, restarting the model with only fractional environmental changes, at a shorter interval. For example, to test the impact of two different environments observed 1 h apart, the model can be restarted 12 times (once every 5 min), each time changing the base-state environment a proportional amount (i.e., 1/12th of the difference between the first and the second environment, which assumes a linear transition between the environments) until the modifications are complete. This form of BSS more closely approximates the spatial and temporal tendencies actually experienced by an observed storm during the interval between the two soundings.

The choice between instant and gradual BSS hinges upon which approach is better aligned with the purposes of a study. For example, gradual BSS would more realistically represent an observed environment in which the actual near-storm environmental tendencies are known. Instant BSS, while extremely abrupt, can be of use for controlled experiments exploring how an identical storm (as described by its temperature, moisture, and wind perturbation fields) would evolve in two substantially different environments. While the abruptness of this approach is less realistic, it provides the means to understand how an identical storm would respond to a very different environment without allowing for the slowly accumulating differences that occur when a storm gradually encounters a new environment (as it would in gradual BSS). When testing BSS for two environments observed relatively close in time to one another (e.g., approximately 30 min), repeated experimentation has shown that gradual BSS simulations produce a quantitatively similar result to instantaneous BSS, but at a slightly later time (due to the slower onset of the new environment). Longer time lags (e.g., an hour or more) between environments result in greater differences between instantaneous versus gradual BSS simulations because appreciable storm evolution occurs during the period over which gradual BSS is applied.

The main benefit of BSS is that the user can exert a considerable amount of control over changes to the environment. Two features of this method are particularly unique and scientifically useful. First, BSS allows a model user to investigate how a particular mature storm would respond to a completely different background environment, as opposed to triggering storms in different environments. In most prior sensitivity studies, the initial developmental stages of convection diverge among simulations because they are also highly dependent on the background environment. Second, a varying base state can be included without introducing additional divergence or baroclinicity, allowing for the effects of the new thermodynamic and/or wind profile alone to be evaluated. Indeed, BSS permits the user to independently alter the thermodynamic and kinematic environment, such that the roles of each can be isolated, similar to numerous other fully homogeneous parameter space studies (e.g., Weisman and Klemp 1982; McCaul and Weisman 2001; Kirkpatrick et al. 2007; James and Markowski 2010; French and Parker 2010; Letkiewicz and Parker 2011).

c. Limitations

While BSS provides a useful method of approximating heterogeneity in an idealized manner, there are certain limitations that should be considered when applying this method and interpreting the results. First, BSS is not a “true” representation of environmental heterogeneity. As indicated by (3) and (4), BSS assumes that a storm experiences a new environment as it moves at a constant speed through a fixed gradient (akin to a smoothly changing proximity inflow sounding). Because this effect on $\theta_{env}$ is treated as more substantial than the instantaneous effect of local storm-scale gradients in $\psi_{env}$, BSS is likely a more realistic approximation of an isolated storm in a slowly changing environment than a storm crossing an airmass boundary. In the future, additional experiments will compare storm evolution in fully heterogeneous simulations to that in BSS simulations using proximity soundings from the full run. Such tests would further quantify the degree to which the neglect of the instantaneous local $V_h\psi_{env}$ influences the depiction of storm dynamics in horizontally homogeneous models.

BSS also does not conserve the total values of model variables, since the perturbations are maintained but the base state is not. Thus, for example, if an environment is cooled ($\theta_{env}$ decreases) while an outflow’s potential temperature perturbation ($\theta'$) is preserved, the outflow’s total potential temperature ($\theta = \theta_{env} + \theta'$) decreases during BSS. Philosophically, BSS prioritizes the same cold pool strength in a new environment as opposed to the same cold pool potential temperature in a new environment. This nonconservation can be muted by utilizing gradual BSS, where small environmental adjustments (applied at an admittedly arbitrary rate) result in nearly conserved total fields of model variables. However, one consequence of this limitation is that BSS cannot simulate some observed phenomena, such as the stalling of a cold pool in an increasing cool environment (e.g., Parker 2008; Ziegler et al. 2010).

In making the kind of abrupt, and in some cases substantial changes to the background environment that
occur with BSS, one must be assured that they have not lead to spurious or unphysical results in the model. In particular, it is necessary to evaluate whether the model remains numerically stable during this procedure and to ensure that the results depict a physical response to the changing environment. Additionally, it is important to document any signals that can be directly linked to BSS in the model results to account for them when interpreting model output. In short, a thorough evaluation of the technique is needed to ensure that the results of simulations using BSS are indeed linked to physical, meteorological signals rather than some artifact of the technique. In the remainder of this article, we provide a demonstration of BSS applied to the problem of convective storms and show that the technique does not suffer from the aforementioned concerns.

3. Model setup and experiments

This study employed version 1.15 of the Bryan Cloud Model (CM1; Bryan and Fritsch 2002), a three-dimensional nonhydrostatic numerical model designed for idealized simulations. The domain was 300 km × 240 km × 20 km, utilizing a horizontal grid spacing of 500 m, and a vertical grid stretched from 150 m near the model surface to 500 m aloft. The time step was 5 s. For simplicity, Coriolis was turned off and no surface physics were included. Precipitation microphysics were governed by the Thompson et al. (2008) scheme. Unlike the recent studies of Richardson et al. (2007) and Ziegler et al. (2010) that required significant modification to the lateral boundary condition to incorporate environmental heterogeneity, the present simulations used simple open radiative lateral boundary conditions as formulated by Durran and Klemp (1983).

As a result of our personal research interests, BSS was applied to convective storms. To demonstrate the BSS method in a variety of conditions, it was first tested with an idealized environment, and then applied to a set of real-world soundings. For the first set of tests, the model was initialized with the idealized environment described by the canonical Weisman and Klemp (1982) sounding with a constant mixing ratio of 14 g kg$^{-1}$ in the boundary layer (hereafter WK1; Fig. 3a). The corresponding wind profile contains a quarter-circle shear profile up to 2 km AGL and unidirectional shear above that, with a 0–6-km shear vector magnitude of 30 m s$^{-1}$ (Weisman and Klemp 1984, hereafter Quarter; Fig. 4a). After 2 h, this environment was replaced by one modified to contain a low-level stable layer with a lapse rate in the lowest 1 km of −11.5 K km$^{-1}$ (i.e., simulation 1 kmB in Nowotarski et al. 2011, hereafter WK2; Fig. 3b), and/or a unidirectional shear profile with 17.5 m s$^{-1}$ bulk shear in the lowest 2.5 km (i.e., as in Rotunno et al. 1988, hereafter RKW; Fig. 4b). The WK1, Quarter, and RKW environmental profiles have been widely used in a number of idealized modeling studies of convection (e.g., Weisman and Klemp 1984; Rotunno et al. 1988; Weisman et al. 1988; Weisman 1993; Bryan et al. 2003; Weisman and Trapp 2003; Bryan 2005; Mahoney et al. 2009; Morrison and Milbrandt 2011; Letkewicz and Parker 2011) and thus serve as familiar benchmarks to illustrate BSS.

A set of observed soundings from 9 June 2009, launched as part of the Second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) during 2009–10 (Wurman et al. 2012), will also be utilized to further demonstrate the BSS approach and provide an example of a real-world application of BSS. This was a day on which supercell demise was observed by the VORTEX2 teams starting around 0000 UTC 10 June. The 2319 UTC environment is utilized as the initial base state (hereafter S1; Fig. 3c) and the 2354 UTC environment is substituted after restarting the model (hereafter S2; Fig. 3d). Given the rather short time (approximately 35 min) and more subtle changes in environment observed between these two soundings, they provide an effective counterpart to the large environmental change illustrated by the WK soundings, and the corresponding case observations help to provide some grounding for the subsequent storm evolution that occurs in the model.

Since changes to the base-state thermodynamic environment may impact the model in a different manner than kinematic changes, a series of sensitivity experiments were performed to isolate their effects (Table 1). Two control simulations were run (using either the WK1 or S1 environment without subsequent environmental modifications; hereafter WKCNTRL and OBS CNTRL, respectively) to serve as a baseline for the experiments. One set of experiments only modified the base-state wind profile and kept the thermodynamic profile fixed after restarting the model (hereafter WKWIND or OBS WIND), while another kept the wind profile fixed and modified the thermodynamic environment (hereafter WKTHERMO or OBS THERMO). A third set of experiments modified the entire sounding, both the kinematic and thermodynamic profiles, after restarting the model (hereafter WK COMBO or OBSCOMBO). For brevity, only the OBSCOMBO simulation will be discussed.

In each simulation, the storm was initiated with a +1 K (+4 K for the OBS simulations) warm bubble and allowed to mature for 2 h before BSS was applied. Two sets of simulations were run for each environment tested: one set using gradual BSS (approximating realistic environmental modifications) and one set using instant BSS.
To evaluate their different impacts. For the gradual BSS experiments, the model was restarted every 5 min until the substitution was complete. This resulted in 12 restarts for the WK runs (every 5 min for 60 min, an arbitrary benchmark time scale for the given modification) and 7 restarts for the OBS runs (every 5 min for 35 min, based on the time period between the two soundings; Figs. 3c,d).

Fig. 3. Skew $T$–log$p$ diagrams of the thermodynamic environments utilized for the BSS experiments. (a) The canonical Weisman and Klemp (1982) environment (WK1), (b) a modified Weisman and Klemp (1982) environment with a low-level stable layer (WK2), (c) The observed environment at 2319 UTC 9 Jun 2009 (S1), and (d) the 2354 UTC observed environment (S2). Surface-based CAPE and CIN values are indicated in each panel. The WK2 environment in (b) contains 2100 and 0 J kg$^{-1}$ of most-unstable CAPE and CIN, respectively.

(an idealized, extreme case of environmental variability), to evaluate their different impacts. For the gradual BSS experiments, the model was restarted every 5 min until the substitution was complete. This resulted in 12 restarts for the WK runs (every 5 min for 60 min, an arbitrary benchmark time scale for the given modification) and 7 restarts for the OBS runs (every 5 min for 35 min, based on the time period between the two soundings; Figs. 3c,d).
Thus, in the gradual WK simulations, the base state continued to change for 55 min after BSS was first applied, while in the gradual OBS environment, the base state continued to change for 30 min after BSS was first applied. In the instant BSS configuration the model was only restarted once, with the entire environmental change applied over one step. The simulations were then run for an additional 2 h post-BSS in the WK environment (4 h total), and 1 h, 30 min post-BSS in the OBS environment (3 h, 30 min total). This was done to allow all of the simulations to evolve for at least a full hour after BSS was complete.

4. Impacts of base-state substitution

a. BSS in the idealized (WK) environment

One of the most important quality assurances for any new modeling technique is to ensure that model stability is maintained and the simulated fields remain physically meaningful. It is important to demonstrate that the introduction of a completely new base-state environment will not introduce a “shock” to the model such that the model fields become noisy, the simulated storm evolves unphysically, or spurious convection develops. If the trends in the model fields and domainwide statistics are
smooth and meteorologically consistent following an environmental substitution, and spurious convection does not develop, then the technique is inferred to be adequate for the purpose of basic experimentation on the impact of environmental variability upon storms. The discussion below will focus on assessing the model response following BSS, and thus will not attempt to explain in detail the processes governing the storms’ meteorological evolution. How supercell thunderstorms physically respond to environmental changes is the focus of our ongoing research using BSS, and will be the subject of future articles. We first present the results of the WK experiments to provide a familiar benchmark.

1) GRADUAL BSS

As a first-order examination of the impacts of gradual BSS, we show a history of simulated radar reflectivity and potential temperature perturbation at the lowest model level (75 m) for the WKCTRL and gradual WKCOMBO simulations in Fig. 5. The model initially produced a thunderstorm that split into right- and left-moving storms (not shown) as expected from past modeling studies using similar background wind and thermodynamic profiles (see Weisman and Klemp 1984).

By two hours into the WKCTRL simulation (when the new environment was introduced), the right-moving storm had evolved into a well-organized supercell, evident as a hook echo in the simulated radar reflectivity field (Fig. 5a), while the left-moving storm evolved into a multicellular cluster to its north (not shown). The right-moving supercell was quasi-steady in intensity throughout the remainder of the simulation (Figs. 5a–d), and this storm will be the focus of initial comparisons among simulations.

In the gradual WKCOMBO simulation, the initial supercell structure was largely maintained, with only small differences evident after 1 h (Fig. 5). After 1 h the cold pool weakened, and the simulated storm became less well organized (cf. Figs. 5d,h). Given the introduction of a more stable thermodynamic environment as well as a more weakly sheared wind profile, one would expect a decrease in convective intensity (e.g., Ziegler et al. 2010) and an evolution toward multicellular organization (e.g., Weisman and Klemp 1982; Kost 2004; Richardson et al. 2007). The decline in storm organization may have been enhanced by the internally produced weakening of the storm’s cold pool following BSS. Around 30 min after BSS began, regions of positive potential temperature perturbation started to emerge near the rear flank of the supercell and grew larger over time (Figs. 5g,h). This warming appeared to be the result of a few different factors. First of all, preexisting downdrafts within the supercell acted to transport warm air from above the prescribed temperature inversion (Fig. 3b) down to the surface, similar to an observed case described by Goss et al. (2006) where low-level warming occurred in a supercell evolving in an environment not unlike the prescribed post-BSS WK2 environment in the present simulations. This low-level warming is also consistent with convection weakening due to the more stable environment (e.g., Ziegler et al. 2010; Fig. 3b).

Finally, as will be discussed in more detail shortly, the moist low levels of the substituted environment resulted in localized pockets of condensation within the cold pool (owing to the colder environment), which produced a small amount of latent heat release. This latent heat release was generally small (0.08-K gridcell temperature increases on average for each restart), but may have further contributed to the low-level warming. What is important to note, however, is that the cold pool did not completely disappear as a result of this warming, and that the warming occurred gradually over time. Additionally, the simulations run with the OBS soundings (described in section 4b) did not produce this same low-level warming. Thus, we conclude that this behavior is more a reflection of the choice of background environment, rather than an artifact of the BSS method.

In terms of numerical stability, the model did not violate the Courant–Friedrichs–Lewy (CFL) stability criterion or exhibit any major temporal unsteadiness in domain-averaged fields in response to BSS. Furthermore, the meteorological fields remained well behaved and changed gradually in a realistic manner over time, as in other studies that utilized a horizontally heterogeneous base state (Fig. 5; e.g., Richardson et al. 2007; Ziegler et al. 2010). Additionally, there were no unexpected gravity waves or the development of spurious convective cells anywhere within the domain. This indicates that the gradual BSS method does no harm to model stability and produces physical results consistent with an evolving background environment. Maintaining model stability and demonstrating a gradual response of the storm to its new environment is consistent with the overall philosophy of BSS, whereby the storm (i.e., its perturbations of temperature, moisture, and wind) is...
maintained but the background environment is modified. Given the qualitative evidence that the model is relatively unaffected by BSS, we will now turn to the specific, quantitative impacts as assessed via domain-wide statistical output calculated every time step (5 s) after the model restart to identify any unphysical responses to BSS.

The 15-min period following the first few incremental substitutions contained nearly imperceptible changes in the WKWIND, WKTHERMO, and WKCOMBO

FIG. 5. Plan-view plots of simulated radar reflectivity and −1-K potential temperature perturbations less than −1 K shaded for the (a)–(d) WKCNTRL and (e)–(h) gradual WKCOMBO simulations at the lowest model level (75 m). Times indicated in each panel correspond to the length of time post-BSS.
experiments compared to WKCNTRL (Figs. 6–7). Over time, however, the model fields gradually diverged from WKCNTRL, with differences on the order of 5%–10% after 30 min (Fig. 7). Measures of storm intensity (maximum vertical velocity, total upward mass flux) evolved over time in a physical manner, with general decreases in the WKTHERMO and WKCOMBO simulations (due to the more stable thermodynamic environment), and no initial change in the WKWIND experiment (due to changes in storm dynamics taking longer to manifest). Importantly, as the environment continued to be modified, these trends were also smooth, with no dramatic oscillations that would indicate internal modes or boundary reflections as a result of the multiple environmental substitutions.

In contrast to the smooth evolution in storm intensity, several other domainwide statistical fields experienced more abrupt changes immediately following each
environmental substitution. For example, total energy and total mass contained discrete “jumps” after each substitution (Figs. 6c,d and 7c,d), as these fields quantify elements of the background environment that have been changed. Total energy includes both the thermal and kinetic energy of the environment, and one would expect these to change given the altered wind and thermodynamic profiles. Thus, given the increasingly weak shear profile and cooler, more stable substituted environment (Figs. 3b and 4b), a stepwise reduction in energy associated with each BSS application was observed (Figs. 6c and 7c). Similarly, in changing the thermodynamic profile, the mean base-state column density was increased, leading to a change in the total mass in the model (following hydrostatic adjustment; Figs. 6d and 7d). In the WKWIND experiment the base-state density was not changed, and thus the total mass field did not contain any discrete changes. What is important to note is that in the 15-min period following the completion of environmental substitution, both energy and mass fields remained nearly constant in time, indicating that the model was not losing/gaining energy or mass and was thus stable. Furthermore, the subsequent long-term post-BSS changes were quite small (<1% of the WKCNTRL value; Figs. 7c,d), with no unphysical oscillations.

Discrete jumps following each application of BSS were also noted in the total condensate and cloud water mass fields for the WKThermo and WKcombo

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**Fig. 7.** As in Fig. 6, but showing the instantaneous percent change from WKCNTRL (experiment - WKCNTRL) for each field.
simulations, though the initial jumps were masked by the larger long-term modifications in those fields (initial changes were on the order of 2% or less; Figs. 6e,f and 7e,f). These jumps were in response to an increase in relative humidity that occurs coincident with BSS, tied to grid points within the cold pool becoming saturated in the new environment (not shown). In essence, since the base-state environment was becoming cooler and moister in the low levels (Fig. 3b), once the negative temperature perturbations of the cold pool were added on to the new base state, a slight supersaturation was induced at the coldest grid points in the pre-BSS cold pool. As the base state was cooled further and more grid points reached saturation, cloud water mass stair-stepped upward more significantly for each environmental substitution. While the resultant condensation produced a release of latent heat and localized warming in the cold pool, this heating was generally small in magnitude and was not widespread, making the overall effect on storm evolution negligible.

Focusing on the long-term response over the remainder of the model simulation following the completion of gradual BSS, it becomes clear that any abrupt adjustments to BSS occur within the first time step of the new environment being applied, with small, gradual subsequent changes that represent a physical response to the new environment as seen in other studies with environmental heterogeneity (Fig. 6; e.g., Richardson et al. 2007; Ziegler et al. 2010). The maximum vertical velocity and total upward mass flux fields in the WKWIND, WKTHERMO, and WKCOMBO simulations steadily diverged from the WKCNTRL simulation over time (Figs. 6a,b), consistent with the evolution expected for a convective storm responding to a smaller CAPE, weaker wind shear environment (Figs. 4a,b). Thus, BSS is able to produce the expected gradual physical response of a storm in a new environment while maintaining a degree of control over environmental variability and without the complicating effects of horizontal heterogeneity.

There were no long-term adverse effects apparent in total energy and total mass, which (despite their discrete changes during BSS) maintained relatively constant values for the remainder of the simulation, with <1% deviations from WKCNTRL (Figs. 6c,d and 7c,d). The moisture fields also underwent smooth transitions consistent with the given environment. For instance, the total condensate field in the WKWIND simulations dropped slightly below WKCNTRL (Fig. 7e) until approximately 75 min after BSS began, at which point it began an upward trend and increased past the WKCNTRL simulation. We interpret this as representing changes to lifting [i.e., stronger cold pool lifting, as in multicellular convection; e.g., James et al. (2005)] as the convection responded to the new wind profile. In the WKTHERMO and WKCOMBO runs, total condensate continually remained below WKCNTRL (Fig. 7e), consistent the overall weakening of convection owing to the more stable environment, and reflecting the weaker maximum vertical velocity and upward mass flux fields (Figs. 7a,b).

In short, focusing on the long-term response, the response of the simulations to each application of BSS is both smooth and consistent with well-established concepts in the convective storms literature throughout the remainder of the simulation. Importantly, none of the domain-integrated fields (i.e., total upward mass flux, total energy, total mass, etc.) exhibited any unphysical oscillations or runaway behavior after BSS that would indicate that the technique is causing harm to the model.

2) INSTANT BSS

We will now examine the impact of instant BSS using the same WK environments. Given that gradual BSS proved to have little adverse effect on the model, it is of interest to determine whether sharp environmental changes in the model are similarly well behaved. In other words, we seek to determine the impact of the most extreme case where relatively large environmental changes are incorporated into the model within one time step.

In the instant WKCOMBO simulation, the initial supercell structure was maintained through approximately 15 min following BSS (Figs. 8e,f), indicating the basic persistence of the storm’s structure and dynamics across the large instantaneous environmental change. After that, the simulated convective system became increasingly less organized, with little in the way of supercellular organization remaining by 60-min post-substitution (Figs. 8g,h). As in the corresponding gradual BSS WK simulation, the decline in storm organization was likely enhanced by the weakening of the storm’s cold pool; regions of positive potential temperature perturbation emerged near the rear flank of the supercell and grew larger over time (Figs. 8f–h). Overall, weakening of the storm is accelerated compared to gradual BSS because of the instantaneous introduction of the less-favorable environment. Importantly, the meteorological fields remained well behaved and changed gradually in a realistic manner over time (Fig. 8). This indicates that the instant BSS method does no harm to model stability, and produces physical results despite the rather large, abrupt change to the background environment.

As before, it is clear that total energy and mass for the instant WKWIND, WKTHERMO, and WKCOMBO runs diverged from WKCNTRL immediately upon the
environmental substitution (Figs. 9 and 10). Importantly, however, direct measures of storm intensity followed a gradual departure from WKCNTRL after BSS, remaining within 10%–15% of the WKCNTRL value (Figs. 9a,b and 10a,b). This evolution is consistent with the gradual changes observed in the simulated storm morphology (Fig. 8), and shows that storm evolution after instantaneous BSS is not entirely dissimilar from that after gradual BSS.

The magnitude of the discrete jumps in total energy and total mass under instant BSS (Figs. 9c,d) are larger because of the more drastic change in the background environment (this is also true of total condensate and cloud water mass, although the larger long-term trends

Fig. 8. As in Fig. 5, but for the instant BSS simulations.
in these fields mask the instantaneous jump following BSS). Notably, the 15-min period following the jumps in the energy and mass fields contained nearly constant values over time, indicating that despite the rapid adjustment, the model was not losing/gaining energy or mass and was thus stable. Additionally, the subsequent long-term post-BSS changes were quite small (<1% of the WKCNTRL value; Figs. 10c,d), with no unphysical oscillations. The long-term trends in total condensate and cloud water mass reflected the overall intensity of the storm, exhibiting gradual changes over time (Figs. 9e,f and 10e,f). In short, following any minor adjustments that occurred within the BSS step, the response of the simulations to instant BSS was both smooth and consistent with well-established concepts in the convective storms literature throughout the remainder of the simulation. Importantly, it appears that instant BSS causes no more harm to the model than multiple, less substantial modifications (i.e., gradual BSS).

As illustrated by Figs. 5 and 8, as well as Figs. 6–7 and 9–10, there were some differences in overall evolution of both the storm and its associated statistics when comparing the gradual and instant BSS simulations. One might expect that, to a first-order approximation, the two runs would be largely similar, differing only in the timing of evolution. However, given the fact that the environment in the gradual BSS simulations changed much more slowly (over the course of 1 h), appreciable storm evolution occurred within the time span over which the environment was modified. Thus, by the time the

**Fig. 9.** As in Fig. 6, but for the statistics following instant BSS.
background environment in gradual BSS was the same as instant BSS (60 min later as opposed to one time step later), the convection of interest diverged substantially from the control simulation. This precludes a true comparison of model statistics and storm morphology for the different BSS configurations at the point when the background environments are the same. As will be demonstrated in the next section, small time differences (on the order of 30 min) between environments, as well as more similar environments, tend to produce quantitatively similar results for instant versus gradual BSS, while larger time differences (on the order of 1 h or more), tend to produce different results (as in the WK environment experiments). We emphasize that both approaches to BSS (gradual and instant) are stable and well behaved; thus, the choice to use either approach should be determined by the purpose of a user’s study. Instant BSS demonstrates how an identical storm would evolve in substantially different environments, representing an extreme case (e.g., the pedagogical example of a supercell placed in a single-cell environment). Gradual BSS provides a more realistic assessment of how a storm would evolve over time in response to a sequence of environmental observations.

b. BSS in the observed environment

To demonstrate the BSS technique within a more realistic (i.e., not idealized) environmental evolution,
a set of gradual and instant BSS simulations were run with a pair of observed near-storm soundings from 9 June 2009, which were separated by 35 min in time and 30 km in distance (Figs. 3c,d). These soundings sampled the inflow environment of a supercell as it began to dissipate (Fig. 11); thus, a downward trend in simulated storm intensity is expected after BSS is applied. As with the WK environment discussed previously, the same set of THERMO, WIND, and COMBO simulations were run in this environment. Generally speaking, the basic trends as a result of BSS in these experiments were quite similar to those run in the WK environment. Thus, in the interest of brevity, only the OBSCOMBO simulations will be discussed in detail.

Upon initiation, the OBSCNTRL simulation produced left- and right-moving storms, similar to the WK simulations discussed above. However, owing to the much drier environment of the S1 sounding (Fig. 3c), the right-moving storm evolved as a weaker supercell compared to the storm in the WK environment, exhibiting characteristics consistent with a low-precipitation supercell through much of the simulation (Figs. 12a–d). This is qualitatively similar to what was observed on 9 June 2009 (Fig. 11). As with the WK simulations discussed above, gradual BSS in the OBSCOMBO case once again introduced a more stable, weaker sheared environment (S2; Figs. 3d and 4d), which lead to a weakening of the simulated supercell (Figs. 12e–h). The overall weakening of the storm was much less significant than what was observed in the WK simulations, as the differences between the S1 and S2 soundings were more subtle than those between the WK1 and WK2 soundings. Once again the simulated storm evolved gradually over time, and no spurious
convection developed following the application of gradual BSS.

The statistical fields also remained well behaved in response to gradual BSS using the observed soundings (Fig. 13). As seen in the simulated radar reflectivity, the introduction of a more stable, weaker sheared environment lead to a weakening of the simulated convection, evident as a decrease in maximum vertical velocity and upward mass flux over time compared to the OBSCNTRL simulation (Figs. 14a,b). The fields that produced a discrete jump following BSS in the WK environment (total energy, total mass, total condensate, and cloud water mass) also contained sharp changes immediately following each application of BSS in the OBS environment.

**Fig. 12.** As in Fig. 5, but for the OBSCNTRL and gradual OBSCOMBO simulations.
While the signs and magnitudes of the discrete jumps were not identical to those found in the WK experiments, they were nevertheless consistent with the details of the substituted environment (S2). For example, total mass increased after each restart as a consequence of the cooler/more dense environment (Figs. 3c,d), and total energy also increased after the restart due to a higher base-state mixing ratio, which directly adds to total energy (Figs. 14c,d). While kinetic energy was reduced for the OBSCOMBO experiment (not shown) because of the weaker wind shear (Figs. 4c,d), the decrease was not significant enough to overcome the increases in thermodynamic contributions to total energy. The total condensate and cloud mass fields also exhibited discrete jumps following each incremental BSS due to instantaneous condensation forming as a result of an increasingly moist environment near 830 hPa (Figs. 16f and 17f and 3c,d). These fields decreased over time compared to OBSCNTRL as a result of weakening storm intensity (Figs. 13a,b) in the more stable environment. Importantly, as in the WK experiments, subsequent trends in each of these fields following BSS were smooth and meteorologically consistent with the substituted environment. Overall, these metrics demonstrate the model’s response to gradual BSS is consistent among idealized and observed environments.

The instant BSS OBS simulations (Fig. 15) exhibited numerical responses after BSS that were similar to those

(Figs. 13c–f and 14c–f).
The measures of storm intensity gradually deviated from OBSCNTRL over time despite the instantaneous stabilization of the environment (Figs. 16a,b and 17a,b), with discrete changes evident in energy, mass, and condensate fields immediately following BSS (Figs. 16c–f and 17c–f). A head to head comparison of the instant versus gradual BSS OBS simulations is useful given the small lag time between soundings, and it is evident that most fields were quantitatively similar after BSS is complete (i.e., 30 min after BSS began), including upward mass flux, total mass, and total energy (cf. Figs. 13b–d and 16b–d). Larger differences existed for the total condensate and cloud mass fields between gradual and instant OBS BSS simulations after BSS was complete (cf. Figs. 13e,f and 16e,f) due to multiple instances of instantaneous cloud formation.

5. Summary and future work

We have reviewed an idealized technique designed to approximate the spatial and/or temporal variability experienced by a storm while eliminating the higher-order impacts associated with environmental heterogeneity (e.g., mesoscale circulations). Base-state substitution replaces the original horizontally homogeneous environment with a new horizontally homogeneous environment while maintaining storm-induced perturbations (Fig. 2).
accounting for both temporal and spatial heterogeneities in the form of a new environmental inflow sounding [i.e., Fig. 1 and as in (4)]. The technique has the benefit of allowing the user to exert a significant amount of control over the environmental modifications, as well as allowing the user to evaluate the evolution of an identical storm (as described by its wind, temperature, and moisture perturbations) in significantly different environments. In quantifying the effects of BSS on the model, domainwide model statistics demonstrated that modifications following BSS were consistent with the intended environmental changes (i.e., wind profile, thermodynamic profile, or both), whether the base-state soundings were idealized (Figs. 3a,b) or observed.
In the present simulations, storm intensity generally weakened over time as a physical response to introducing a more stable environment with weaker vertical wind shear. This evolution is consistent with other studies that have incorporated horizontally heterogeneous base-state environments (e.g., Richardson et al. 2007; Ziegler et al. 2010).

Following each application of BSS, domainwide total energy exhibited discrete changes that were closely tied to base-state temperature, mixing ratio, and wind profile modifications; decreases in energy were observed after each restart in the WK experiments (e.g., Fig. 6c) due mainly to a reduction in the low-level temperature and mixing ratio (Figs. 3a,b), while increases in energy were observed in the OBS experiments (e.g., Fig. 13c) due to an increase in the low-level mixing ratio (Figs. 3c,d). The total mass of dry air also jumped upward following BSS (e.g., Fig. 9d) as a consequence of the cooler/more dense substituted environments (Fig. 3). The WK2 and S2 environments also contained layers that were nearly saturated (Figs. 3b,d), thus BSS resulted in a sharp increase in total condensate and cloud mass. The point we emphasize is that these changes in domain statistics were due to the intrinsic properties of the newly introduced environments, and do not reflect an unexpected response of the model to BSS. After the initial adjustments, these model statistics depicted smooth, meteorologically consistent trends, indicating that the technique
produces no undue harm to the model, and can thus be used to study physical processes.

We have shown that the BSS technique provides a credible method to test the impact of a varying environment on storm morphology. However, there are unique aspects of the technique that should be considered before it is applied, particularly when substituting the thermodynamic environment. For example, the treatment of convectively generated cold pools is somewhat unique when applying BSS. Cold pool intensity (as measured by its density current speed) is determined by the depth of the cold air as well as the contrast between the temperature in the environment and the temperature in the cold pool. In nature, cold pools may weaken as a result of decreasing storm intensity (fewer hydrometeors produced and less evaporative cooling) or as a result of encountering cooler ambient air, which decreases the temperature difference across the leading edge of the cold pool. This latter effect has been shown to cause a "stalling" phase in the propagation of the density current (e.g., Parker 2008; Ziegler et al. 2010). Because the BSS technique maintains temperature perturbations during each model restart, the introduction of a cooler environment does not directly impact the cold pool intensity (density current speed). Thus, in a BSS experiment, the stalling phase will only occur once storm intensity has weakened in response to the cooler (more stable) environment as an indirect effect of reduced

FIG. 17. As in Fig. 14, but for the instant OBSCOMBO simulation.
evaporative cooling due to fewer hydrometeors. For some studies this may be a drawback, although it is dependent upon the research aims of the user. This unique aspect of BSS would actually be desirable for a study of how the exact same cold pool is influenced by different background environments.

Overall, we view BSS as a potentially powerful technique that may reveal much about how storm processes respond to a changing base-state environment in an idealized setting. This article is intended to serve as a description and evaluation of the technique. At present, we are performing a variety of controlled hypothesis tests using BSS to advance the understanding of convective storms; the results of these studies will be reported on in future manuscripts. Additional research is also needed to compare simulation results using the BSS technique to a wide variety of fully heterogeneous simulations. Ultimately, such comparisons can further quantify the validity of the assumptions inherent to all models with homogeneous environments (including those approximating heterogeneity using BSS).

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