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Would "Tornado-Preventing" Walls Work?

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ABSTRACT

Simulations were performed using the Weather Research and Forecasting model in order to evaluate a proposal that called for the construction of three east–west "great walls" in the American Midwest to eliminate the major threat of tornadoes in Tornado Alley. The results of three simulations using the 31 May 2013 tornado outbreak are presented—one with natural terrain, one with 300-m tall walls as proposed, and another with walls much taller than proposed (2500 m). Through comparisons of temperature, moisture, instability, and supercell and tornado composite forecasting parameters, the "tornado-preventing" walls, as proposed, are shown to have very little impact on the atmosphere. When the height of the walls is greatly increased, the location of convective storms shifts eastward, instead of being eliminated. The short-term impacts of the taller walls imply possible desertification and areas with increased probability of non-supercellular tornadoes near the edges of the walls.

1. Introduction

Recently Tao (2014) proposed that the tornado threat in the most tornado-prone area of the United States, commonly known as "Tornado Alley", could be eliminated if east–west walls were built in order to prevent baroclinic zones from forming in this region. The proposal states that, "violent tornadoes in Tornado Alley start from the clash between the northbound warm air flow and the southbound cold air flow". To prevent this "clash of air masses" the construction of "three east–west great walls in the American Midwest, 300 m high and 50 m wide," could "diminish the major tornado threat in the Tornado Alley *forever*" (Tao 2014). A recent review by Schultz et al. (2014) has debunked the notion that tornadoes form due to "clashes of air masses". The present study addresses whether the proposed walls would have any of the desired effects. Since tornadoes have great societal impacts, and since the proposal has received a considerable amount of publicity, it is worth briefly exploring this hypothesis in more detail.

In this study, the full physics, numerical Weather Research and Forecasting model (WRF; Skamarock et al. 2008), was used to test how an observed tornado outbreak might be impacted by such "tornado-preventing" walls. Although these simulations are not tornado-resolving (dx~10m), they are convection-allowing. The premise of the original proposal was to prevent the supercellular storms that produce the vast majority of significant tornadoes. Kain et al. (2008) showed that 4-km grid spacing was sufficient to forecast supercells using the WRF model. In the present controlled experiments, storm ingredients, structures, locations, and areal coverage can be compared. Any differences can be attributed directly to the added man-made geography. Details regarding the methods are described in section 2. Results and interpretation from the simulations are offered in section 3, while a summary of the main conclusions and avenues for future work are presented in section 4.

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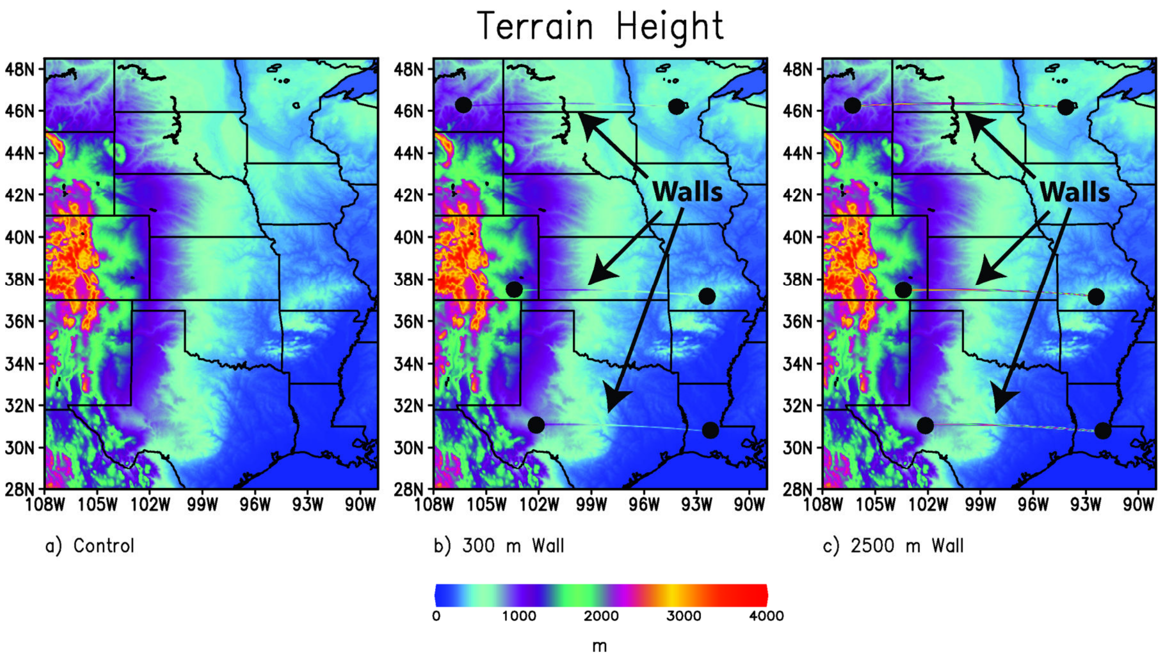

Figure 1: The 1200 UTC 29 May 2013 WRF model terrain height (m) for: a) control simulation with natural geography; b) experiment simulation with 300-m AGL walls in south Texas and Louisiana, near the Oklahoma and Kansas border, and in North Dakota; c) experiment simulation with 2500-m walls.

2. Methods

Using the WRF model (version 3.5.1), a simulation of the 31 May 2013 convective episode in Oklahoma was performed in order to test the hypotheses presented above. This was a high impact convective event which produced a well-documented tornado in central Oklahoma (more detailed information on this tornado and flash flooding event can be found here: http://www.srh.noaa.gov/oun/?n=events-20130531). The simulation starts at 12 UTC on 29 May 2013 and finishes 63 h later at 03 UTC on 1 June. A 63 h simulation was chosen in order to give the tornado-preventing walls sufficient time to affect the advection of warm, moist air northward and cold air southward. Initial conditions for the simulation were provided by the 13 km NOAA Rapid Refresh analysis, which was preferred to forecast predictions (RAP; Benjamin et al. 2004, Brown et al. 2012). RAP analyses were on the hybrid (native) model grid and included hydrometeors. The lateral boundaries were updated every 3 h using the same data source. The domain consists of a singular 4-km grid with 51 vertical levels encompassing most of the continental United States (an area greater than that displayed in Fig. 1). Convection was allowed to evolve freely on the entire domain (i.e., no convective parameterization was used). All simulations used the following schemes: Yonsei University boundary layer (YSU; Hong et al. 2006), revised MM5 surface layer (Jimenez et al. 2012), Rapid Radiative Transfer Model longwave (RRTM; Mlawer 1997), Dudhia shortwave (Dudhia 1994), Noah land-surface model (Chen and Dudhia 2001), and WRF single-moment 6-class microphysics (Hong et al. 2006). These settings were chosen based on computational efficiency. Different cases, initial and lateral boundary conditions, and parameterization schemes were tested. The results were qualitatively similar, thus only one case and configuration is displayed for simplicity.

In order to create the tornado-preventing walls, the model geography file (geo_em.nc) created by the WRF Preprocessing System was modified to add a constant to the surface elevation in the three locations indicated in Tao (2014). These locations are in southern Texas and Louisiana, near the border of Kansas and Oklahoma, and in North Dakota (Fig. 1). Although the proposal called for walls that were 50 m wide, it was easier, and more numerically stable, to make each wall in these simulations one grid-point wide (4 km). The width of the wall should not affect the results, as long as the walls are vertical, because it is the slope of the barrier that is important. Since the slope for a vertical wall is undefined, the blocking is

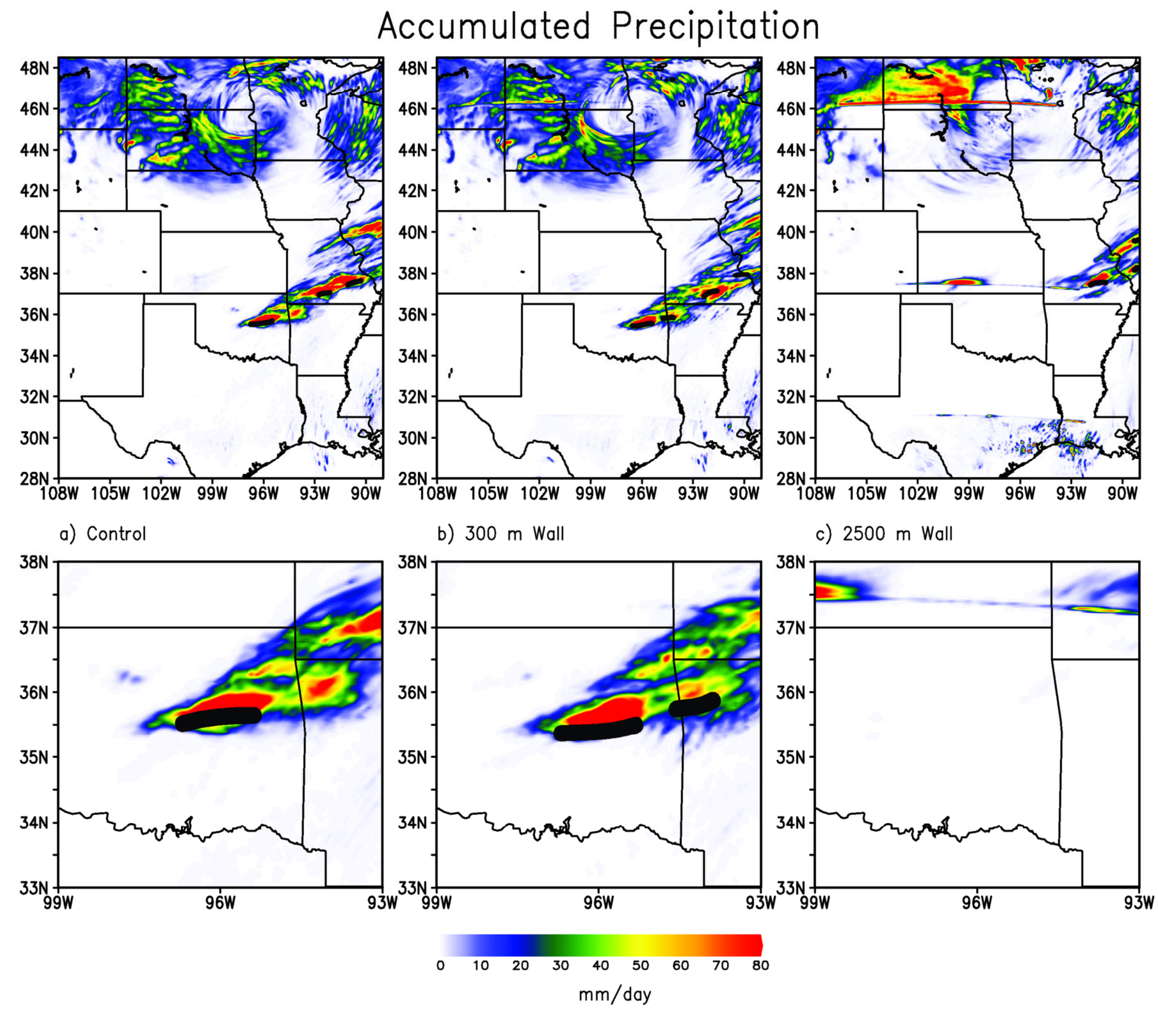

Figure 2: Same as Fig. 1, except displayed is the accumulated total surface precipitation (mm day^{-1}) in the final 12 h of the simulations (1500 UTC 31 May 2013 to 0300 UTC 1 June 2013). Thick, black lines indicate smoothed tracks of 1–6 km updraft helicity >50 m^2 s^{-2} during this time period. The bottom panels provide a closer view of the supercellular convection (or lack thereof) in central Oklahoma.

determined almost solely by the upstream stratification, barrier-normal wind, and barrier height.

To best evaluate the long-term impacts of the proposed walls, additional computationally expensive simulations comparing sophisticated climate models with and without the proposed walls would be necessary. This is beyond the scope of this paper. The outcome of the current simulations suggests that further, long-term simulations are not justified.

3. Results

From basic theory one would anticipate that the walls, as proposed, will have very little influence on the initiation and location of convective storms because they are *too small* and air will simply flow *over* them. This is based on calculations of mountain Froude number (Fr_m) for a 2D barrier:

$$Fr_m = \frac{u_0}{Nh_m}, N \approx \left(\frac{g}{\overline{\theta}} \frac{\partial \overline{\theta}}{\partial z} \right)^{\frac{1}{2}} \qquad (1)$$

where u_0 is the component of the wind perpendicular to the barrier far upstream, N is the Brunt-Väisälä frequency (a measure of static stability), h_m is the height of the barrier, g is gravity, and $\overline{\theta}$ is the environmental potential temperature (Markowski and Richardson 2010). Using the observed soundings from three locations (Corpus Christi and Fort Worth, TX and Norman, OK) on 29–31 May 2013, the

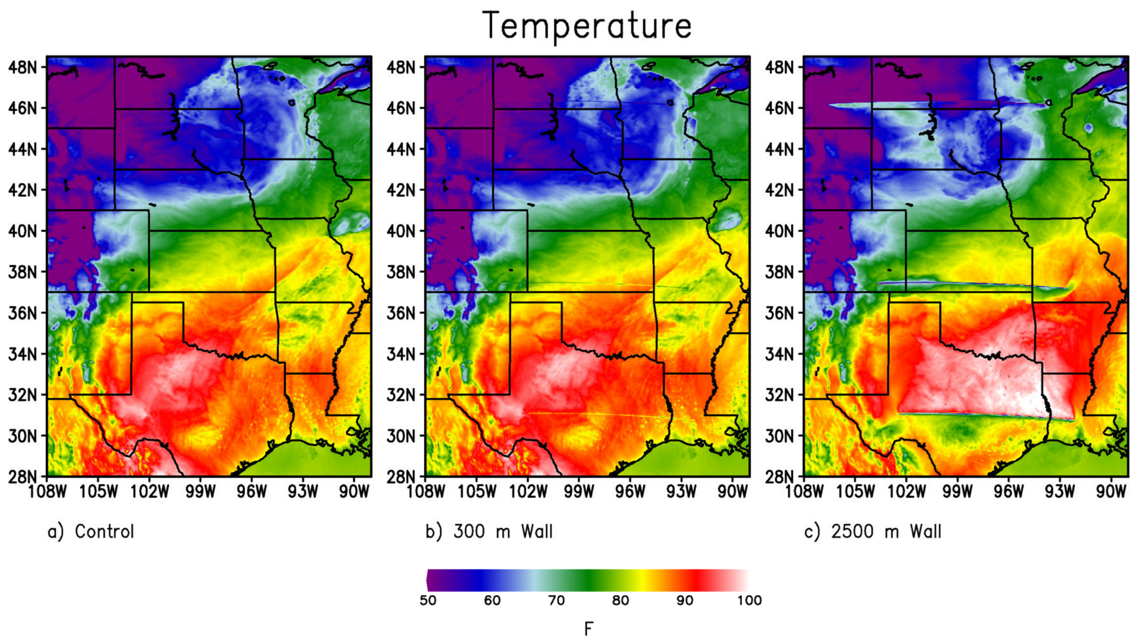

Figure 3: Same as Fig. 1, except displayed is the 2-m temperature (°F) at 2100 UTC 31 May 2013.

Fr_m was calculated using the barrier-normal, 10-m surface wind for u_0 and averaging N over the height of the wall. For a 300-m wall, Fr_m ranges from roughly 2 to 100, depending on the stability (as N decreases, Fr_m increases). A Fr_m >1 implies that the surface air would readily flow over the obstacle. The barrier height at which the Fr_m would become <1 is >1000 m for each sounding, which is similar to the depth of the afternoon planetary boundary layer (PBL). With this in mind, it is hypothesized here that significant modifications to the flow will be evident if much taller walls were implemented. Ignoring the unrealistic cost, constructional feasibility, and unintended ecological impacts of building walls that high, it is intriguing to ask how they might influence the local climate in the central United States. Therefore, three simulations were conducted (Fig. 1): a control simulation with the natural geography and two experimental simulations with a wall height of 300 m (as proposed) and 2500 m (Fr_m well below 1).

a. Modifications from 300-m high walls

In both the control run and the first experiment with 300-m walls, the simulations produced supercellular storms in central Oklahoma. Convection initiation occurred at approximately 21 UTC on 31 May 2013, at the intersection of a dryline and a stationary front. Both simulations produced similar values of accumulated precipitation and tracks of 1–6 km updraft helicity (as defined by Kain et al. 2008) in central Oklahoma (Fig 2a,b). The subtle differences between the control and 300-m simulations are likely caused by weak stagnation during the overnight hours (when stability is largest and the Fr_m is closer to 1). Due to the nonlinear nature of the atmosphere, these small differences slightly alter the initiation and maintenance of precipitation, yielding the minor differences in Fig. 2. The temperature field across the central United States in both simulations is unaffected by the inclusion of the walls (Fig. 3a,b). First and foremost, this shows that the proposed walls do not accomplish their stated purpose. The temperature gradient near the supercellular convection in Oklahoma is actually relatively weak, and is associated with the dryline, due to the enhanced sensible heat fluxes in the drier air mass, not the northward (southward) incursions of warmer (colder) air that the walls purportedly prevent.

As reviewed by Schultz et al. (2014), at least a modest amount of synoptic-scale baroclinicity is required to support supercell formation (supercell formation requires large vertical wind shear, which is linked to baroclinicity through the thermal wind relationship). It is clear that such large scale baroclinicity is not appreciably influenced by 300-m walls (in addition to which,

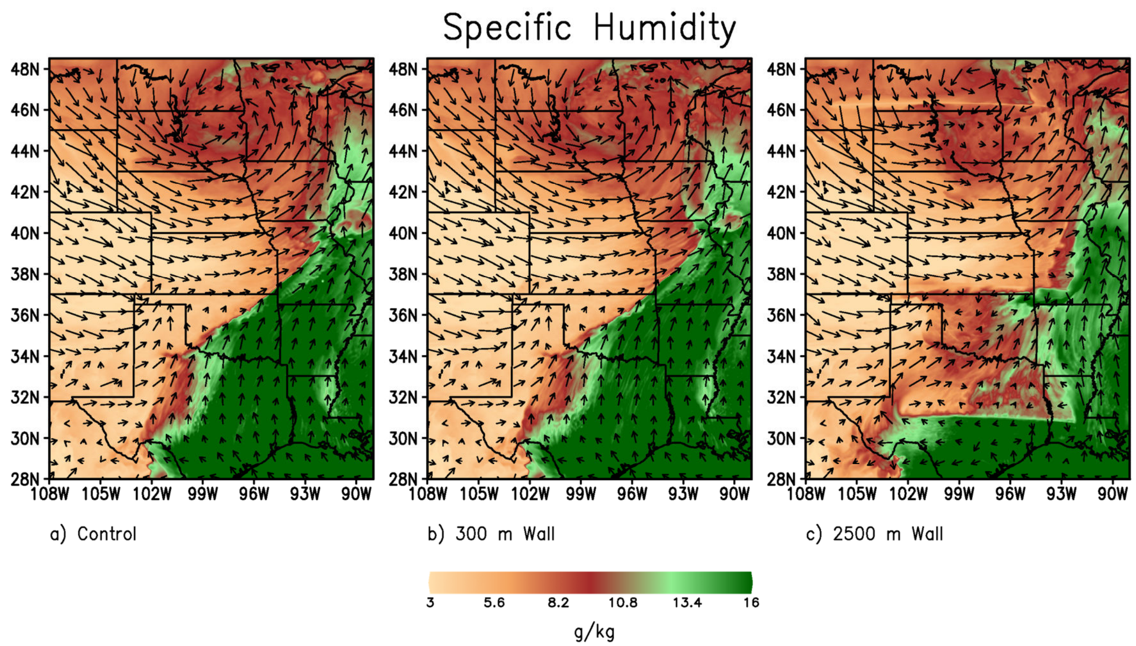

Figure 4: Same as Fig. 1, except displayed is the 2-m specific humidity (g kg^{-1}) and 10-m wind vectors at 2100 UTC 31 May 2013.

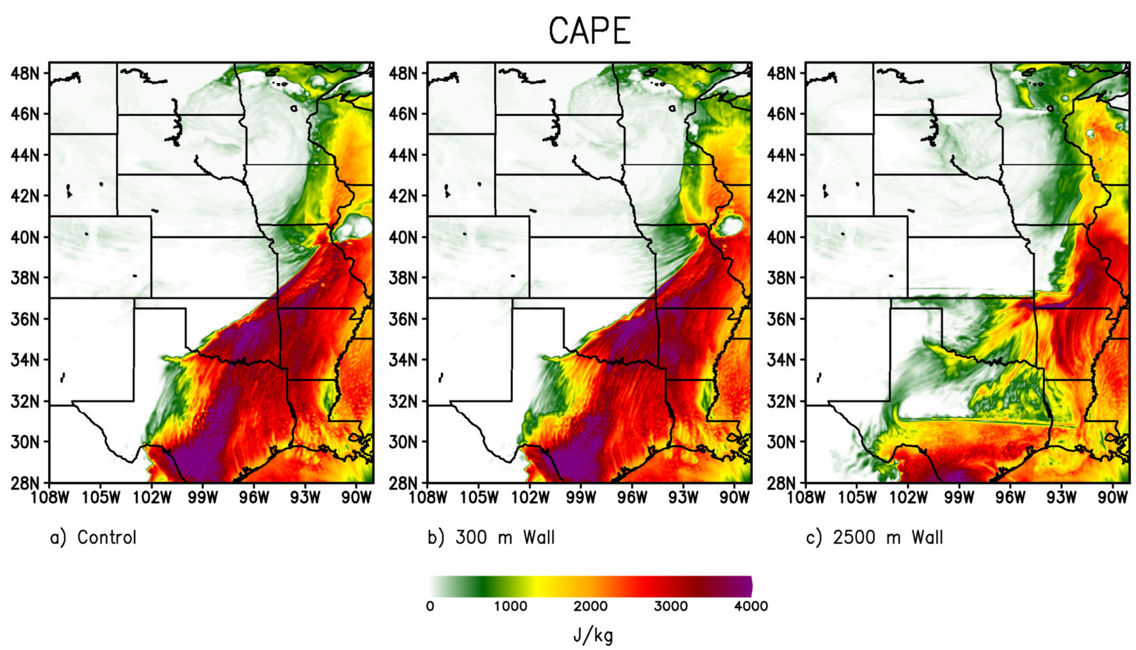

Figure 5: Same as Fig. 1, except displayed is the surface convective available potential energy (CAPE; J kg^{-1}) at 2100 UTC 31 May 2013.

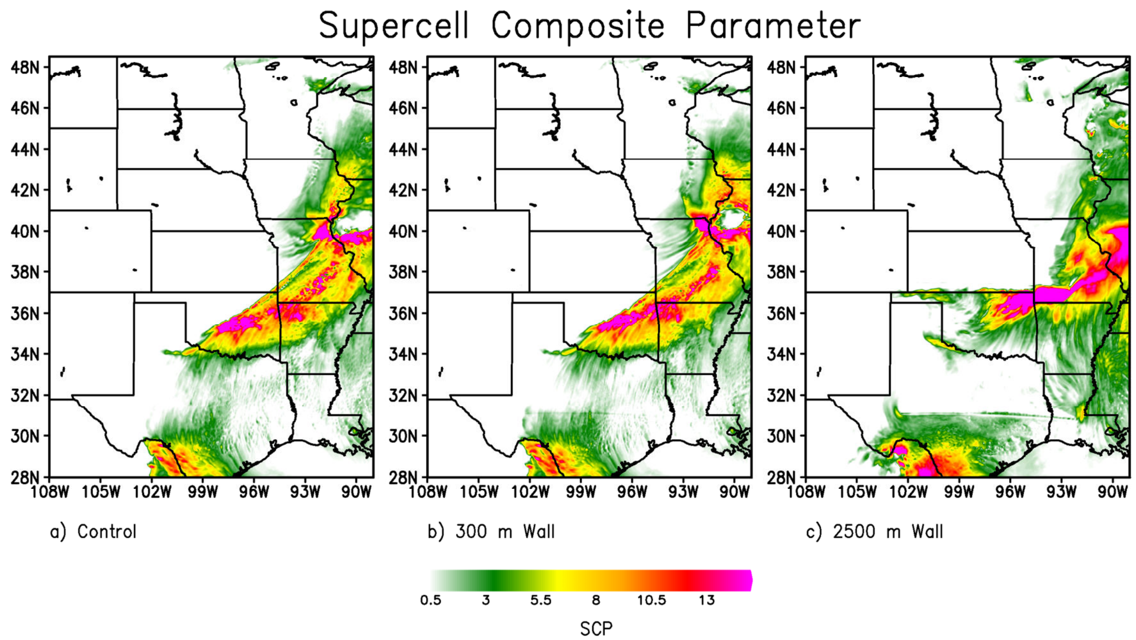

Figure 6: Same as Fig. 1, except displayed is the supercell composite parameter (SCP) at 2100 UTC 31 May 2013.

as detailed by Schultz et al. (2014), this baroclinicity is not directly related to tornado formation itself).

The most important air-mass boundary in this case is the dryline. Here, the top of the subtropical boundary layer, originating from the Gulf of Mexico, intersects the rising terrain in the lee of the Rocky Mountains. This boundary often focuses convection initiation during springtime severe weather outbreaks in the central United States, instead of a warm-cold boundary interaction (Schaefer 1986). The specific-humidity field and dryline location are similar in the control and 300-m experiment, yielding further evidence that the large-scale flow was not altered substantially by the tornado-preventing walls (Fig. 4a,b).

The difference in CAPE between the two simulations is also small (Fig. 5a,b). This is because warm moist air flows up and over the southernmost wall, while the walls do nothing to impede the midlevel, westerly wind aloft with steep lapse rates. The supercell composite parameter (SCP) and significant tornado parameter (STP), statistically skillful measures of the likelihood of supercell thunderstorm and tornado development (Thompson et al. 2004, 2012), were also not affected by the walls. Both simulations have values of SCP (Fig. 6a,b) and STP (not shown) >10 in central Oklahoma. This indicates an environment, in both simulations, that is highly supportive of tornadic supercells, as was observed on this day, regardless of the presence of the tornado-preventing walls.

b. Modifications from 2500-m high walls

Another experiment was performed with a $Fr_m \ll 1$. This simulation had walls that were 2500 m tall in the same locations as before. In this case, convection was significantly displaced to the northeast of the control simulation (Fig 2a,c). Southerly moisture return to the central United States was greatly altered, as flow stagnated on the windward side of the southernmost wall (Fig. 4a,c). In response, strong, dry westerly flow developed, drying out much of Texas and increasing the maximum temperature there (Fig. 3a,c). Due to the stagnation, moisture also pooled and flowed around the eastern end of the Oklahoma/Kansas wall, maintaining the high values of CAPE and SCP in Missouri and Arkansas (Fig 5c, 6c). Thus, although the 2500-m walls lowered the tornado threat in Oklahoma, they instead shifted the tornado threat eastward. Furthermore, due to vortices created by flow past the edges of the walls, pools of high surface vorticity developed in Louisiana, Arkansas and Missouri (Fig. 7c). Considering the additional storm coverage in these locations (Fig. 2c), the tornado-preventing walls could have an opposite effect and lead to

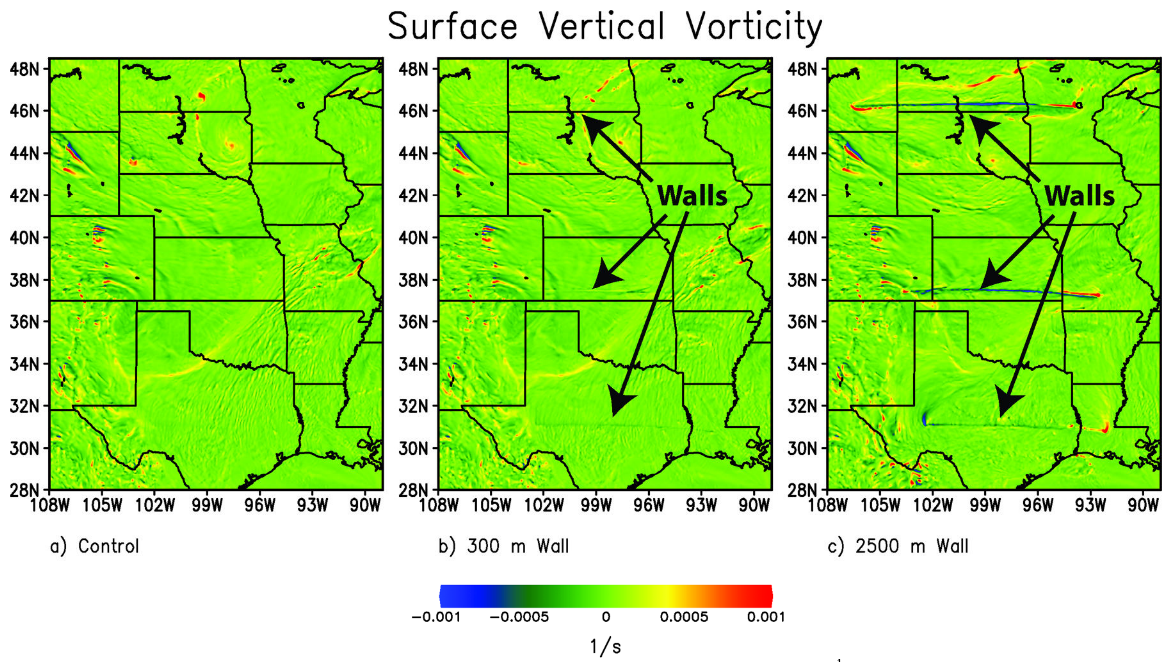

Figure 7: Same as Fig. 1, except displayed is the surface vertical vorticity (s^{-1}) at 2100 UTC 31 May 2013.

an *increase* in tornadoes, although not explicitly revolved in these runs. Non-supercellular tornadoes are known to form when preexisting surface vorticity is stretched by an overlying updraft (Wakimoto and Wilson 1989). A similar phenomenon happens in the Denver convergence-vorticity zone (DCVZ), as air wraps around a southwest–northeast mountain range. A high occurrence of non-supercellular tornadoes is reported in the DCVZ (Wilczak and Glendening 1988).

In just 63 simulated hours, there is also evidence that 2500-m walls (i.e. tall enough to block the low-level flow) would alter the local climate for most of the Texas, including four of the eleven most populated cities in the United States. Desert-like conditions possibly could extend much farther eastward into central Texas (Fig. 3c, 4c). Additionally, elsewhere, large amounts of precipitation might develop in the windward side of each wall due to horizontal mass convergence and induced ascent near the walls (Fig. 2c).

4. Conclusions

The findings are unsurprising given that fluid dynamics theory predicts that weakly stratified atmospheric flows easily should pass over barriers of the height proposed for the tornado-prevention walls, and severe thunderstorms and tornadoes are not the result of clashing air masses anyway. In summary, these simulations show that:

1. The tornado-preventing walls, as proposed (300 m), have *no meaningful impact* on the simulation.
2. Increasing the walls' height to 2500 m causes substantial *displacement*, not elimination, of the convective storms and tornado threat. The local climate impacts could be substantial as well, even in these 63 h simulations. These impacts could include desertification of much of Texas, increased precipitation on the windward side of the walls, and circulations induced by the edges of the walls that could cause an *increase* in non-supercellular tornadoes.

Future work could include seasonal simulations to investigate longer-term storm statistics, but we have no plans to continue this line of work until there is reason to believe the proposed walls would have any effect.

ACKNOWLEDGMENTS

The author would like to thank his advisor, Matthew Parker, fellow MEA716 classmates, especially members of the NCSU Convective Storms Group, and Gary Lackmann for helpful suggestions regarding this work. The wall-building code was developed with help from Gary Lackmann. This manuscript was improved via helpful reviews from Paul Markowski, Michael Baldwin, and Frank Colby. Brice Coffer was partially supported by NSF grant AGS-1156123. RAP analyses were obtained from the Atmospheric Radiation Measurement (ARM) Program sponsored by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, Climate and Environmental Sciences Division.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Paul M. Markowski):

Initial Review:

Recommendation: Accept with minor revisions.

General comment: This is a nice, short contribution to EJSSM that clearly demonstrates the silliness of Tao's proposed tornado-prevention walls. Here are a few suggestions (nothing major):

The author would like to thank the reviewer for numerous suggestions that improved the readability and accuracy of the text.

Substantive comments: Be careful to say "mountain Froude number" instead of "Froude number" (or write it in terms of its math variable). There are a few places where "mountain" has been left out. The two parameters are pretty different. Also, be sure to indicate that, strictly speaking, this is the blocking criterion for a 2D barrier (Tao's walls are 2D, however). One other thing is to specify that your Fr_m calculations are for the blocking of *surface* air (it's obviously easier for air originating at 290 m to climb 10 m to pass over a 300-m tall barrier than it is for air originating at 0 m). In your calculations, can we assume that u_0 is the barrier-normal *surface* wind and *N* is averaged over the lowest 300 m (I'd think this is how you'd want to do it)?

The first paragraph in the results section was reworded based on the above suggestions. The u_0 in the mountain Froude number calculation is indeed the barrier-normal surface wind and N is averaged over the lowest 300 m of the sounding.

All other minor comments and changes were accepted as-is.

[Minor comments omitted...no second review]

REVIEWER B (Michael E. Baldwin):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

General comments: This paper addresses a recent proposal that was made (Tao 2014) that three east–west-oriented walls (300 m tall, 1000 km long) should be constructed order to reduce the threat of violent tornados in the United States. For a recent tornado outbreak event, three numerical simulations are presented to demonstrate the impact of the proposed walls, as well as much taller walls, on the simulated convection and atmospheric conditions. The paper is clearly written and the results have been analyzed using appropriate methods. In my estimation, the "tornado walls" proposal is not one that has been taken seriously by the atmospheric science community. However, since the idea has garnered some attention in the national media, a response that clearly demonstrates that the proposed idea will not work is certainly of interest to the readers of the Electronic Journal of Severe Storms Meteorology (EJSSM). In fact, one might suggest that a key audience for this paper reaches beyond the typical readership of EJSSM and includes the media, interested public, and author of the original paper. I wonder why this paper was submitted to EJSSM and not to International Journal of Modern Physics B as a comment and direct rebuttal to Tao (2014)? This appears to be an indirect way of dealing with the original proposal. I have a few suggestions intended to improve the clarity of the manuscript mainly for that extended audience, and recommend that this paper be accepted pending minor revisions.

Substantive comments: One objection that I would anticipate coming from the author of the original paper would be the fact that the long-term impact of these walls has not been included in the design of these experiments. This would require significant additional simulations, perhaps comparing long-term runs of sophisticated climate models with and without the proposed walls, which is certainly beyond the scope of this paper. While this is addressed at the end of the paper with discussion of future work, I recommend including some discussion of this issue in the Methods section.

Thank you for the many helpful suggestions. Additional text has been added to the end of the methods section: "To best evaluate the long-term impacts of the proposed walls, additional computationally-expensive simulations comparing sophisticated climate models with and without the proposed walls would be necessary. This is beyond the scope of this paper. The outcome of the current simulations suggests that further, long-term simulations are not justified."

Near the beginning of the paper, more discussion and justification should be provided of the criteria used to determine and measure how the walls affect the characteristics of simulated supercells. Expand on the statement: "Although these simulations are not tornado-resolving...they are convection-allowing." For a reader unfamiliar with the recent work in this area, this statement alone will not be enough to clearly justify the experimental design. Is there justification that can be cited to support the foundation for this work, that the convection-allowing approach provides realistic simulations of supercell thunderstorms? The definition of updraft helicity should be provided. How are the simulated supercells identified and tracked? These details are needed to allow reproduction of the results.

Kain et al. (2008) defined updraft helicity and showed that 4-km grid spacing was sufficient to forecast supercells operationally using the WRF model. Even though many important supercellular processes are coarsely resolved at that grid spacing, the formation of a mesocyclone—the defining characteristic of supercellular convection—is still represented reasonably. This reference has been added to the introduction and results section.

It is not clear from the text whether the initial/boundary conditions are from Rapid Refresh analyses or predictions? Is the horizontal extent of the WRF domain indicated by the area covered in the figures? These details should be clarified to allow the results to be reproduced easily.

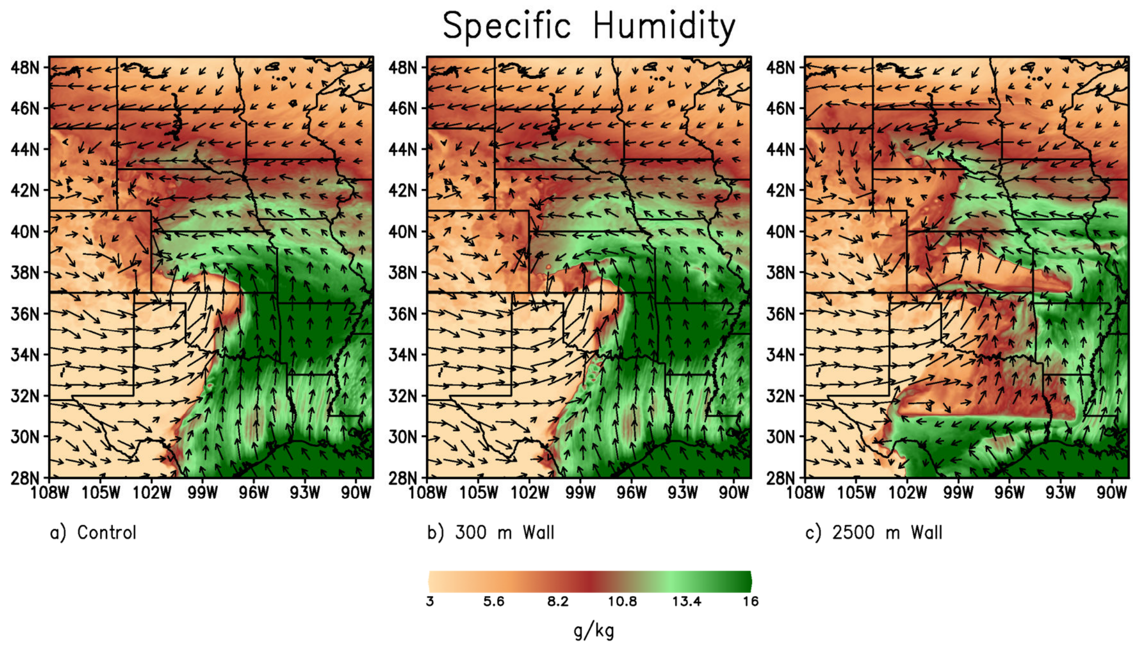
RAP analyses were used herein, thus these are simulations, not forecasts. The horizontal extent of the WRF domain was greater than that displayed in the figures. Clarification has been added to the text.

While many readers will be familiar with the 31 May 2013 event, a brief overview of the atmospheric conditions for the case study would be helpful. For example, is this an example of "clashing airmasses"? In addition, Tao (2014) included discussion of two recent events that could also be considered candidates for example cases (Joplin, MO and Washington County, IL). The conclusions would be strengthened if multiple cases were provided, especially those addressed by Tao (2014).

In lieu of adding more text on the specific case presented herein, I'd prefer to simply provide a link to the extensive review compiled by the National Weather Service Norman Forecast Office.

There is no good example of "clashing airmasses". On the synoptic-scale, there is clearly baroclinicity in the Great Plains, but the temperature gradient in Oklahoma is relatively weak.

Another case was simulated in order to improve the representativeness of the study. This simulation encompasses the Joplin supercell on 22 May 2011, as well as the more organized tornado outbreak on 24 May 2011. The results are very similar. For example, here is the specific humidity field at 00Z on 25 May 2011 (compare to Fig. 4):



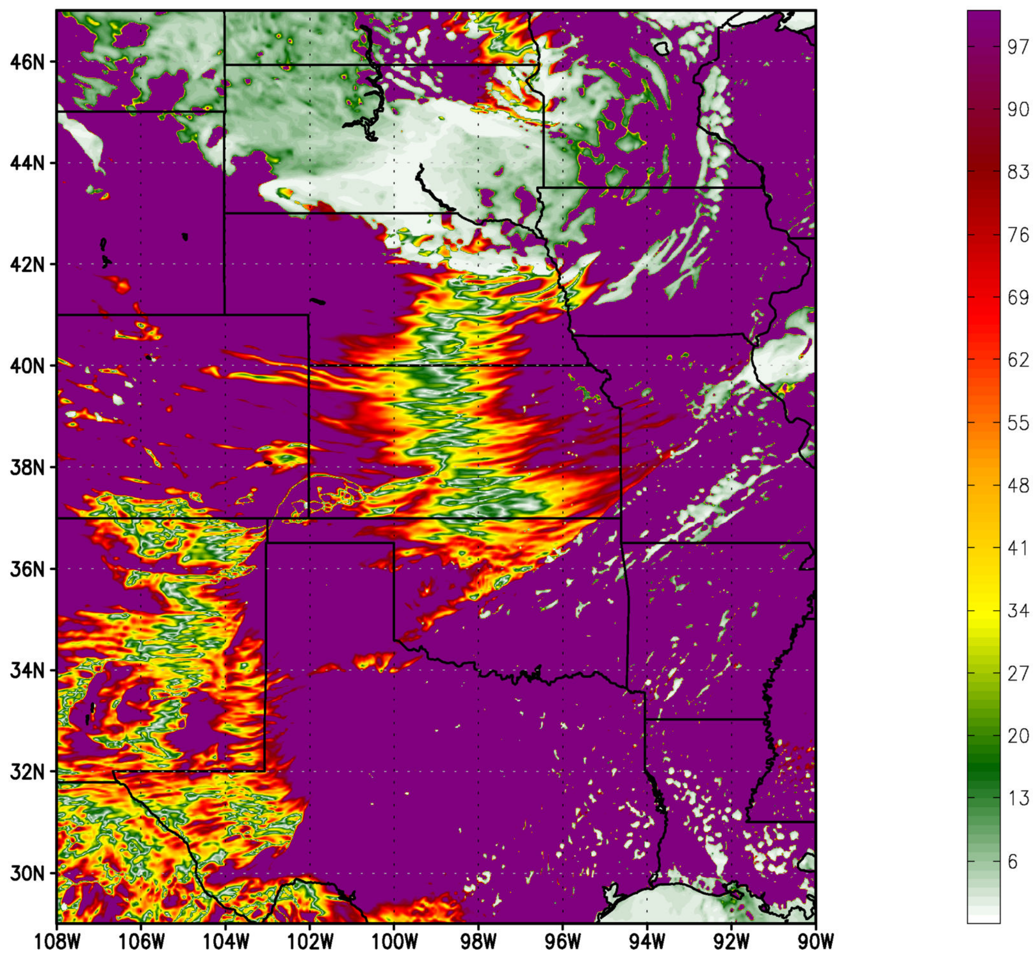
For simplicity, only the 31 May 2013 case is presented, however the following sentence has been added to the methods section: "Different cases, initial and lateral boundary conditions, and parameterization schemes were tested. The results were qualitatively similar, thus only one case and configuration is displayed for simplicity."

The Washington, IL EF4 tornado occurred east of the proposed walls and thus was not considered as a potential case. The reasoning for the discussion of this case in Tao (2014) stems from his belief that walls could be built surrounding small towns to locally prevent tornadoes. This idea is separate from the three-great-walls idea this paper is evaluating.

In section 3, some additional information regarding the Froude number and obstacle blocking of flow would be helpful. I suggest that the author consider the reader who is not familiar with atmospheric dynamics and provide some explanation of why this dimensionless number can be used to indicate whether or not flow is blocked by an obstacle, how is this derived? Additional discussion of the types of flow/vertical stability profiles that would be affected by these walls, and whether or not those situations are typically associated with tornadic/supercell thunderstorms, would also be helpful. In addition, I am not convinced that Corpus Christi, TX, is the best location to analyze the Froude number for this case, could the Froude number for each wall height be analyzed/displayed on a map from the WRF output (at the same time as figures 3–7)?

Along with some suggestions by Reviewer A, additional text has been added to this section clarify the mountain Froude number.

Mountain Froude numbers were also calculated at Fort Worth, TX, and Norman, OK. Both were similar to Corpus Christi. These locations were chosen based on the assumption that the warm, moist air mass is the most relevant low-level air mass for supercell formation. Observed soundings were initially preferred to WRF output because of the high-resolution data in the low levels and ease of calculation. In order to calculate the mountain Froude number from the WRF grid, the model output was reprocessed to include data at every vertical level, instead of standard pressure levels. Displayed below is the mountain Froude number for a 300-m wall at 2100 UTC 31 May 2013:



Most of the area has mountain Froude numbers »1, especially at 2100 UTC near peak heating. These values are much closer to 1 during the overnight hours, as stability increases. This may account for the subtle differences between the control and 300-m simulations. Additionally, where the wind has a greater u-component, the mountain Froude number approaches zero because surface wind no longer has a barrier-normal component. Because these plots are somewhat messy, I have chosen to retain the mountain Froude number calculations from the observed soundings in the manuscript.

Updraft helicity tracks are very difficult to view in Fig. 2. Recommend zooming in on the area of interest. Difference fields for variables may also be helpful, the reader must visually subtract two images and the details of these differences are difficult to obtain in this way, particularly in the 300m wall simulation. There is not much discussion of the differences that do exist in the 300m wall simulation. Given the different updraft helicity tracks and precipitation patterns, one must conclude that there were changes in the details of the simulated supercells, even with the 300-m walls. The 300-m walls (over a short time period) were enough to alter or perturb the simulated supercells, but not prevent them completely. This should be clarified and discussed in the text.

Figure 2 has been revised to now include a zoomed-in area of the supercellular convection (or lack thereof) in Oklahoma, without eliminating other interesting aspects of the figure. Difference fields are not quite useful. Large differences can exist if the maxima are off by even a single grid point. The difficulty of visually obtaining the differences between the control and 300-m simulations is one of the primary takeaways from panels a) and b) in each of the figures. This highlights the minor differences between the two simulations. As briefly discussed above, the subtle differences in the control and 300-m simulations is likely due to the mountain Froude number approaching 1 during the overnight hours, when stability is *largest. Some blocking or stagnation of the flow is likely present in the model solution, although this effect is clearly minor. There are small differences in the temperature, specific humidity, and CAPE fields, and due to the non-linear nature of the atmosphere, these small differences slightly alters the initiation and maintenance of precipitation.*

Additional text has been added to address the above discussion.

In section 3a, some additional explanation of concepts and terms related to baroclinicity would be helpful. This is a key section of the paper, and the text is a bit confusing: some baroclinicity is required, but some other baroclinicity is not. There is an implication here that some type of baroclinicity potentially could be affected by the proposed walls, but that type is not an important factor for supercell formation or tornadogenesis. This needs to be very clearly explained. Perhaps more details, including examples and definitions of the concepts of "large-scale", "mesoscale", and perhaps "storm-generated" baroclinicity would be helpful.

Schultz et al. (2014) has a more detailed explanation on the problems with the "clash of air masses" description of supercell formation. The text has been reworded to hopefully make it clearer that no baroclinicity is required in the immediate vicinity of the supercellular convection, which is what the "clash of air mass" description implies.

[Minor comments omitted...]

Second review:

Recommendation: Accept.

General comment: The revision has satisfactorily addressed the comments and suggestions that were provided by the reviewers. I recommend that it be accepted for publication.

REVIEWER C (Frank Colby):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

Substantive comments: I've read the paper over carefully and on the whole, it is well-written and the project explained in the paper was well-conceived and executed. The author is to be congratulated on his restrained comments about the manuscript by Tao (2014). It's surprising that the idea gained as much traction as it did.

Thank you for the comments and suggestions. All minor changes were accepted as-is.

[Minor comments omitted...no second review]