Enabling Multi-Scale Simulations in WRF Through Vertical Grid Nesting

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1. Introduction

As computational power increases, atmospheric models, such as the Weather Research and Forecasting (WRF) model (Skamarock and Klemp 2008), are being used at increasingly fine horizontal resolutions. In WRFv3.2 an option for vertical grid refinement was added called "ndown" which processes WRF model output to provide initial and lateral boundary conditions for a nested domain with a higher vertical resolution (Moustaoui et al. 2009). This vertical grid nesting option is limited to "serial" simulations, where the nested domain is run after the parent domain simulation is complete. A drawback of this method is that lateral boundary conditions are passed infrequently, at the frequency of output from the coarse grid, using linear interpolation between output times.

In this work, a new option allowing for vertical grid refinement over multiple concurrently run domains, has been implemented in WRF v3.5.1. This option uses the vertical interpolation scheme from "ndown" for downscaled variables, but applies it at each time step. Vertical grids can be refined by an integer ratio, or unrelated grid levels can be defined for each domain. Here, we validate our vertical grid nesting routine with idealized cases and two meso-scale simulations, which are standard WRF test cases. Additionally, we demonstrate the use of vertical grid nesting for the real case of a 24 hour forecast in the San Francisco Bay Area.

2. Vertical grid nesting with "ndown"

Version 3.2 of WRF introduced a feature named "ndown", which allows a nested domain to use an increased number of vertical levels compared to the parent domain. One restriction when using "ndown" is that the number of vertical levels in the nested domain must be an integer multiple of the number in the parent domain. Vertical levels in the nested domain are set by inserting $n-1$ vertical levels between vertical levels of the parent domain where n is the integer ratio of the number of vertical levels in the two domains.

In addition, the parent domain must be run independently before running the nested domain. Sequentially running domains is required since initialization and boundary condition updates for the nested domain are based upon model output from the parent domain. As a result, lateral boundaries are updated at the frequency of parent domain model output, with interpolation which is usually at an interval much greater than the parent domain's timestep. The lack of frequent lateral boundary updates is a serious issue for high-resolution simulations where it is desirable to pass turbulent flow features to the nested domain (Michioka and Chow 2008).

The vertical interpolant used in "ndown" is cubic monotonic splines using Hermite polynomials. Interpolation is performed using a vertical coordinate based on log-pressure height, calculated from the pressure at the model top, the model sigma levels, and a reference surface pressure (Moustaoui et al. 2009).

3. Modification of WRF for concurrent vertical grid nesting

We have modified WRF version 3.5.1 to enable concurrent nesting of domains with varying number and placement of vertical levels. Vertical interpolation of variables is accomplished using the same interpolation scheme as "ndown". Vertical interpolation is performed after horizontal interpolation is completed. Include-files, *nest_forcedown_interp_vert.inc* and *nest_interpdown_interp_vert.inc* are created during compile-time and contain calls to subroutines responsible for vertical interpolation of variables that are marked in the registry to be downscaled for initialization of the nest

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or used to force the nest's lateral boundaries during integration.

The code for several WRF physics schemes, particularly the radiation schemes, is written with the expectation that the number of vertical levels will be identical for all concurrently run domains. As a result, several of the commonly used radiation schemes do not function when vertical grid nesting is enabled. The rapid radiative transfer scheme, RRTM (ra_lw_physics=1), has been modified for use with vertical grid nesting. The new version of RRTM, known as RRTMG (ra_lw_physics=4), works without modification with vertical grid nesting. Efforts are underway to modify other radiation schemes, such as CAM.

4. Advantages of vertical grid nesting

Vertical grid nesting allows an increase in the number of vertical levels for domains of interest without adding extraneous vertical levels to the coarse resolution domains. Not only will this decrease the overall time required to run the model but more importantly it provides control over the grid aspect ratio. When running WRF at LES-scales with a Smagorinsky or NBA1 turbulence closure model, a grid aspect ratio $\left(\frac{\Delta x}{\Delta z}\right)$ of approximately 4.0 or smaller at the surface is crucial for rapid development of turbulent features in nested domains (Mirocha et al. 2013). Vertical grid nesting provides control over the aspect ratio for each domain, allowing for nested simulations where each domain has an ideal aspect ratio. The impact of controlling the grid aspect ratio will be investigated in future research.

Vertical grid nesting is also extremely useful for simulations where it would be desirable to lower the model top for a nested domain. The ability to lower the model top for a nested domain has not been added to WRF, however similar results can be achieved through the use of high vertical resolution near the surface then transitioning to very coarse vertical resolution for grid cells near the model top. This approach allows for multi-scale simulations over complex urban terrain, forecasting for wind farms, or other environments where it is desirable to use a high vertical resolution for only a relatively thin layer of the atmosphere.

5. Validation of vertical grid nesting code

Validation of the vertical nesting code implemented in WRF version 3.5.1 was performed by running several test-simulations with and without vertical nesting enabled. We began validation with a simple test-case of uniform flow over a flat plate where we evaluated vertical profiles of velocity. Ideally, the velocity profile of the nested domain should match that of a non-vertically nested simulation using the same number of vertical levels as the nested domain. Next, a simple validation of atmospheric physics was performed by enabling a land surface model, radiation scheme, and surface physics scheme, then initializing with quiescent stable conditions, and evaluating vertical temperature profiles with and without vertical nesting. Our final validation used two standard WRF test cases, a midwestern United States snowstorm from Janurary 2000 and Hurricane Katrina. Results of these two test cases were also compared with and without vertical nesting.

6. Flow over a flat plate

Figure 1 compares vertical profiles of U-velocity for flow over a flat plate. These simulations use periodic lateral boundary conditions and are initialized using an idealized vertical sounding that is dry, with neutral stability and a uniform 10 meter per second U-velocity. Atmospheric physics schemes are disabled, however a surface roughness length of 0.1 meters is specified. This simulation was forced using a pressure gradient in the east-west direction. Both parent and nested domain have size 46x46 points in the horizontal dimensions and horizontal resolution of 600 meters and 200 meters, respectively. The model top was approximately 9600 meters. The number of vertical levels is changed for each of the three simulations with the three setups as follows: 16 levels for both the parent and nest, 46 levels for both the parent and nest, and 16 levels for the parent with 46 levels for the nest. Vertical levels were set with constant spacing in eta. Runtime for this simulation was 7 days. As shown in figure 1, vertical profiles of U-velocity match for all three setups, indicating that the dynamics of the WRF model are producing consistent results with and without vertical nesting.

7. Heating of a flat plate

Figure 2 compares vertical profiles of potential temperature for quiescent conditions over a flat plate with uniform heating. These simulations were performed using periodic lateral boundary conditions and initial conditions prescribed using an idealized input sounding that was dry with a stable, linear temperature profile. In addition to the Noah land surface model and eta similarity surface layer scheme, the RRTM longwave radiation scheme (ra_lw_physics=1) and Dudhia shortwave radiation scheme (ra_sw_physics=1) were enabled. Vertical and horizontal diffusivities were set to 50 m^2s^{-2} to prevent the formation of convective cells in order to make comparisons more straightforward. Both parent and nested domains are size 61x61 points in the horizontal dimensions and have horizontal resolution of 120 and 40 meters, respectively. The number of vertical levels is changed for each of the simulations with the three setups as follows: 16 levels for both the parent and nest, 46 levels for both the parent and nest, and 16 levels for the parent with 46 levels for the nest. Vertical levels were set with constant spacing in eta. The model top was approximately 14400 meters and the runtime was 6 hours.

Vertical profiles of temperature match extremely well for all cases. The agreement confirms that the RRTM radiation scheme is operating correctly with vertical grid nesting and that the temperature field is being passed into the nested domain correctly.

8. WRF test-case, January 2000 snowstorm

A commonly used WRF "test case" is a non-nested meso-scale simulation of a snowstorm over the eastern United States on January 24th 2000. We have introduced a second domain to the test case and run with three different sets of vertical levels. Without vertical nesting, we have run the test case with 30 vertical levels for both domains and with 60 vertical levels for both domains. Using vertical grid nesting, we have run with 30 vertical levels in the parent domain and 60 vertical levels in the nested domain. When using vertical grid nesting, the nested domain's vertical levels are assigned independently from the parent domain's vertical levels. Figures 4 and 5 show slices through the non-vertically nested and vertically nested grids. The parent and nested domains have horizontal resolution of 30km and 10km, respectively.

Comparisons of east-west slices through the domain midpoint of potential temperature (figures 6, 7, and 8) and W-velocity (figures 9, 10, and 11) show similar results for all three simulations. For this simulation it appears that refined vertical resolution does not result in a visually noticable increase in resolved flow features.

9. WRF test-case, Hurricane Katrina

One of WRF's "test cases" with nested domains is a meso-scale simulation of Hurricane Katrina. Three individual simulations were run with different vertical levels: 30 or 60 vertical levels for both domains, and using vertical grid nesting with 30 vertical levels in the parent domain and 60 vertical levels in the nested domain. The parent and nested domains have horizontal resolution of 30km and 10km, respectively.

Results from all three simulations are similar but contain important differences. Vertical contours of wind speed (figures 13, 14, and 15) show some structures within the vertically nested simulation that were under-resolved in the coarse vertical-resolution simulation. For example, the high vertical-resolution results without vertical grid nesting (figure 15) show strong W-velocities below 6 kilometers ASL which are not replicated in the coarse resolution run but are present when vertical grid nesting is used (figure 14). Overall, the wind speed contours contain similar large scale structures for all three simulations. Similarly, horizontal contours of precipitation since the model start time (figures 16, 17, and 18) show near identical large-scale features.

10. Multi-scale simulation of San Francisco peninsula

The San Francisco Bay Area is an ideal location for implementing multi-scale modeling. Local meteorological conditions in the Bay Area are effected by processes on many scales ranging from the Pacific high-pressure zone to small-scale jets forming in gaps between peaks in the coastal mountains. The use of vertical grid nesting provides the ability to increase the vertical resolution in high-resolution domains allowing for the model to resolve features such as "gap flows". A three-domain setup shown in figure 19 was used with domain-1 and domain-2 being 121x91 points in the east-west and north-south dimensions and domain-3 of size 181x181 points. The number of vertical levels for domains one, two, and three were 31, 41, and 61, respectively. Horizontal resolutions for the three domains were 5000, 1000, and 200 meters.

A day with atypically complex conditions, June 17^{th} 2012, was selected in order to demonstrate the advantages of vertical grid nesting. Radiosonde observations from the Oakland International Airport show a strong seabreeze driving on-shore flow near the surface. At approximately 4 kilometers ASL there is a dramatic shift in wind direction from on-shore to off-shore, driven by a strong low-pressure zone off the coast of the Baja Peninsula. Despite the complexity of the conditions, WRF with vertical nesting appropriately reproduces the conditions observed. Additionally, topographic forcings, such as gap flows, can be well represented due to the additonal vertical resolution provided by vertical grid nesting. Figure 20 shows contours of terrain height where several major "gaps" in the coastal mountains are evident, including the Golden Gate at approximately $122°28'W$ $37°49'N$ and the San Bruno gap at $122°26'W$ $37°43'N$. Figure 21 shows wind speed contours at the second model level, which clearly contain several strong gap flows that would be poorly resolved if a more coarse vertical resolution were used.

11. Conclusions

Vertical grid nesting is an important addition to the WRF model and has the potential to improve multi-scale modeling or high-resolution nested LES simulations. Our implementation of vertical grid nesting produces expected results for several common WRF "test cases" and shows promise for use in multi-scale modeling of the San Francisco Bay Area. Additional modification of several radiation schemes is required to make them compatible with vertical grid nesting, however at this time most of the commonly schemes and parameterizations work with vertical grid nesting. Work is currently underway to include vertical grid nesting in a future release of the WRF model.

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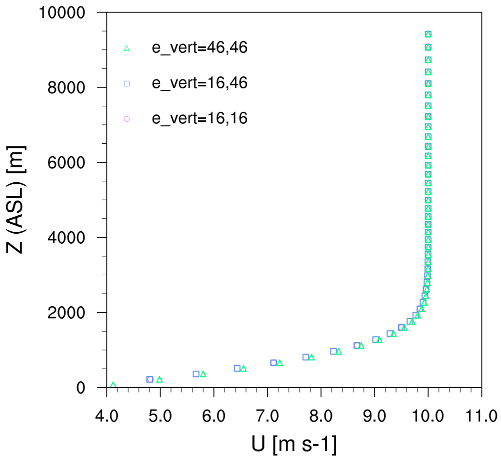

FIG. 1. Comparison of vertical profiles of U-velocity over a flat plate after 7 days.

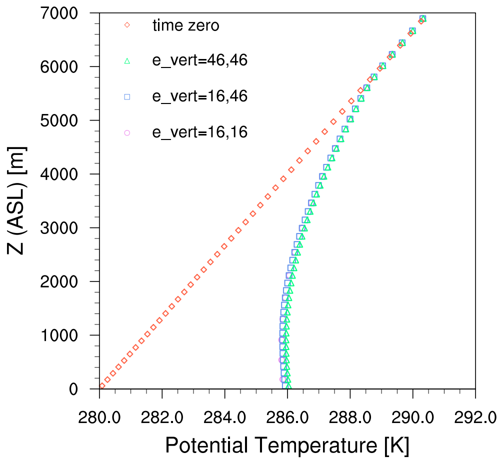

FIG. 2. Comparison of vertical profiles of potential temperature over a heated flat plate after 6 hours.

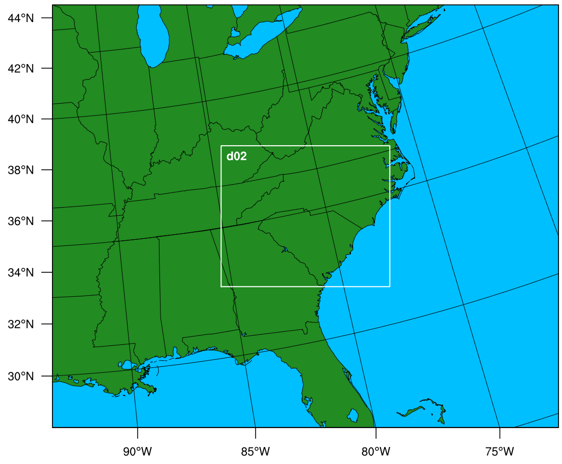

FIG. 3. Domain configuration for the January 2000 snowstorm test-case.

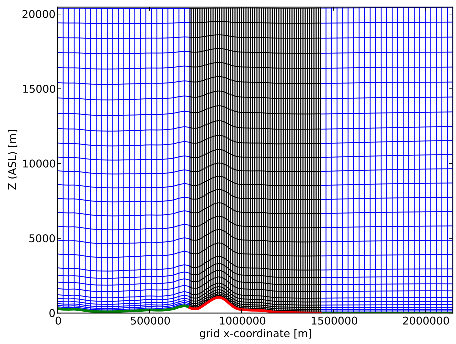

FIG. 4. Cross section through the midpoint of the grids used during January 2000 snowstorm test-case with 30 vertical levels for both parent and nest.

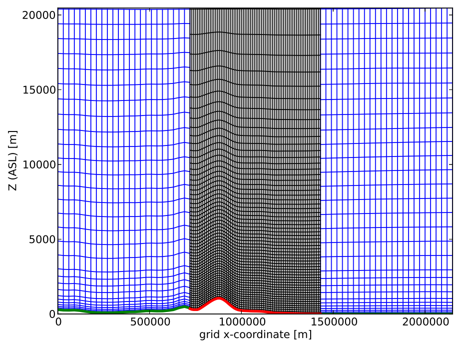

FIG. 5. Cross section through the midpoint of the grids used during January 2000 snowstorm test-case with 30 and 60 vertical levels for parent and nest, respectively.

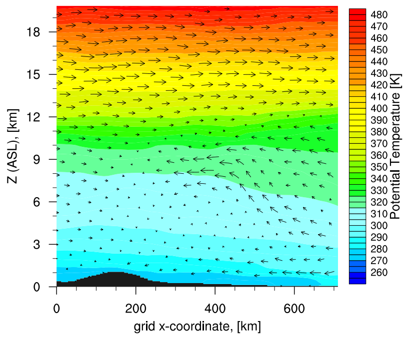

FIG. 6. Potential temperature contours on an east-west slice through the midpoint of the nested domain from the January 2000 snowstorm test-case with 30 vertical levels for both the parent and nested domains.

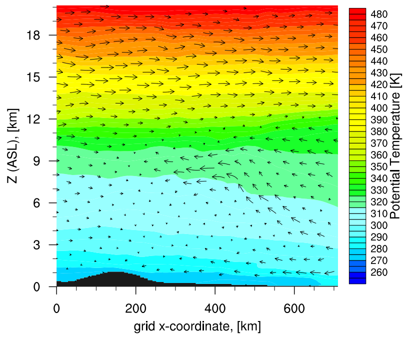

FIG. 7. Potential temperature contours on an east-west slice through the midpoint of the nested domain from the January 2000 snowstorm test-case with 30 vertical levels for the parent domain and 60 vertical levels for the nested domain.

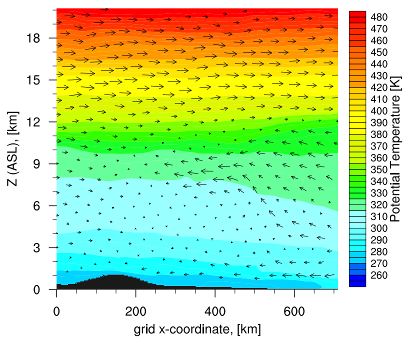

FIG. 8. Potential temperature contours on an east-west slice through the midpoint of the nested domain from the January 2000 snowstorm test-case with 60 vertical levels for both the parent and nested domains.

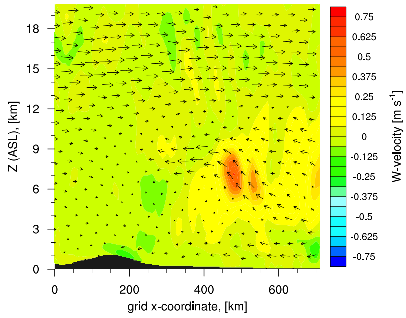

FIG. 9. Contours of W-velocity on and east-west slice through the midpoint of the nested domain from the January 2000 snowstorm test-case with 30 vertical levels for both the parent and nested domains.

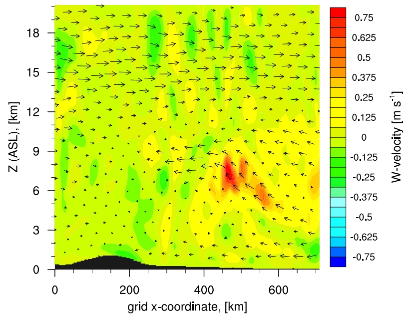

FIG. 10. Contours of W-velocity on and east-west slice through the midpoint of the nested domain from the January 2000 snowstorm test-case with 30 vertical levels for the parent domain and 60 vertical levels for the nested domain.

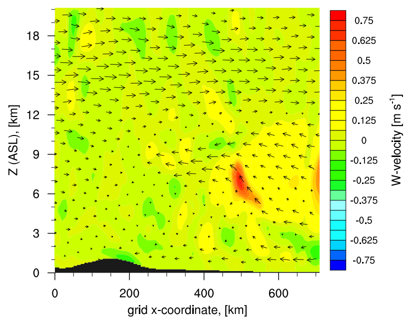

FIG. 11. Contours of W-velocity on and east-west slice through the midpoint of the nested domain from the January 2000 snowstorm test-case with 60 vertical levels for both the parent and nested domains.

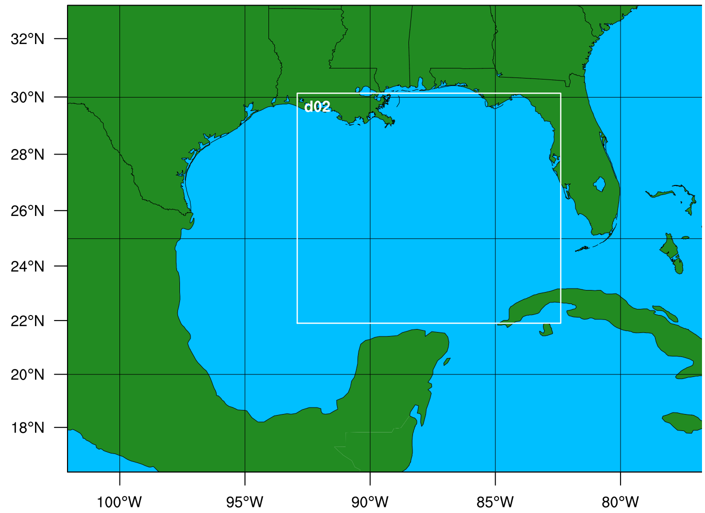

FIG. 12. Domain configuration from the Hurricane Katrina test-case.

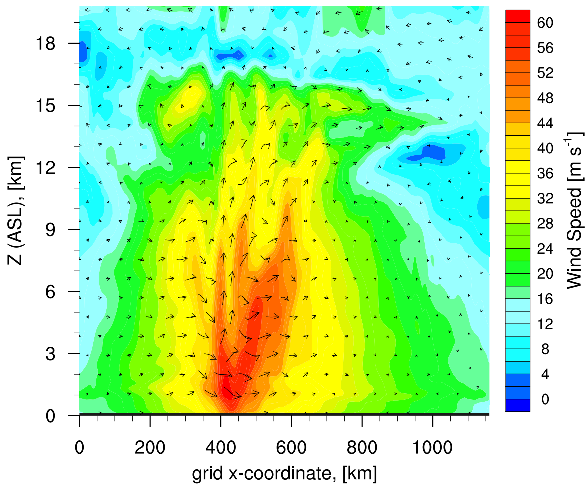

FIG. 14. Contours of wind speed on and east-west slice through the midpoint of the nested domain from the Hurricane Katrina test-case with 30 vertical levels for the parent domain and 60 vertical levels for the nested domain.

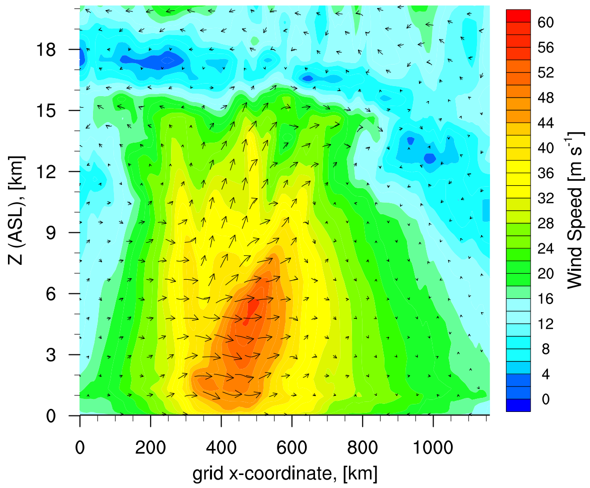

FIG. 13. Contours of wind speed on and east-west slice through the midpoint of the nested domain from the Hurricane Katrina test-case with 30 vertical levels for both the parent and nested domains.

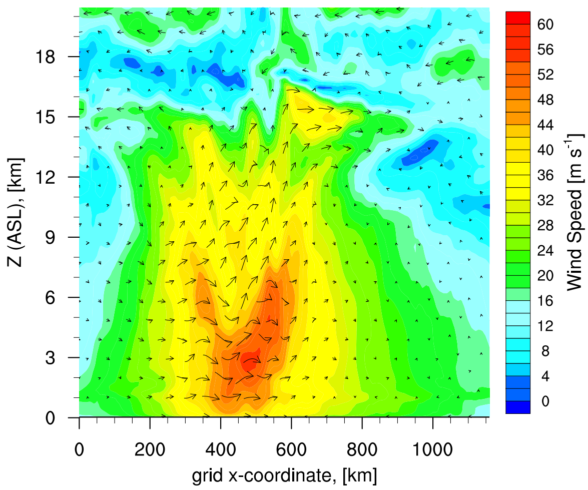

FIG. 15. Contours of wind speed on and east-west slice through the midpoint of the nested domain from the Hurricane Katrina test-case with 60 vertical levels for both the parent and nested domains.

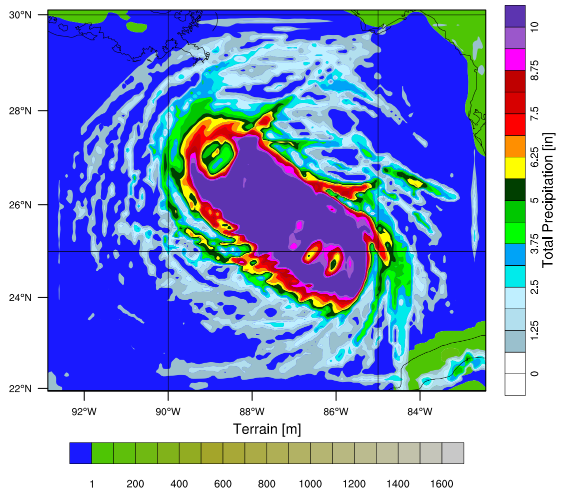

FIG. 16. Contours of precipitation since the model start time on the nested domain with 30 vertical levels for both the parent and nested domains.

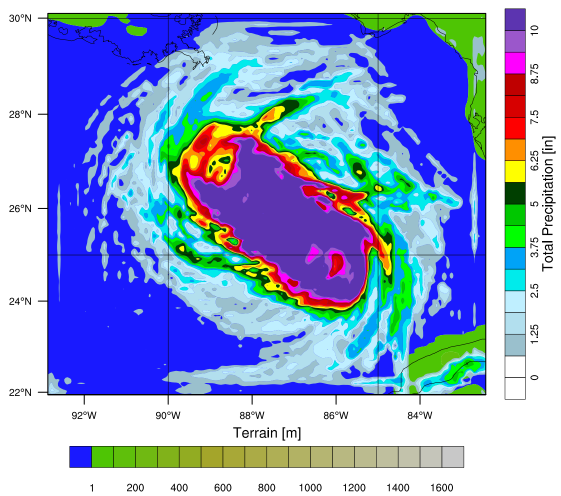

FIG. 17. Contours of precipitation since the model start time on the nested domain with 30 vertical levels for the parent domain and 60 vertical levels for the nested domain.

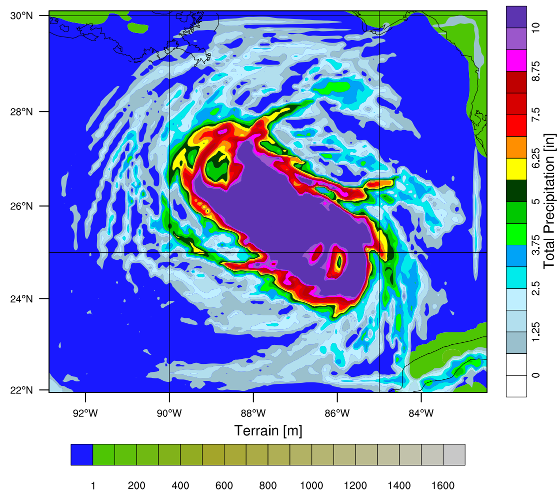

FIG. 18. Contours of precipitation since the model start time on the nested domain with 60 vertical levels for both the parent and nested domains.

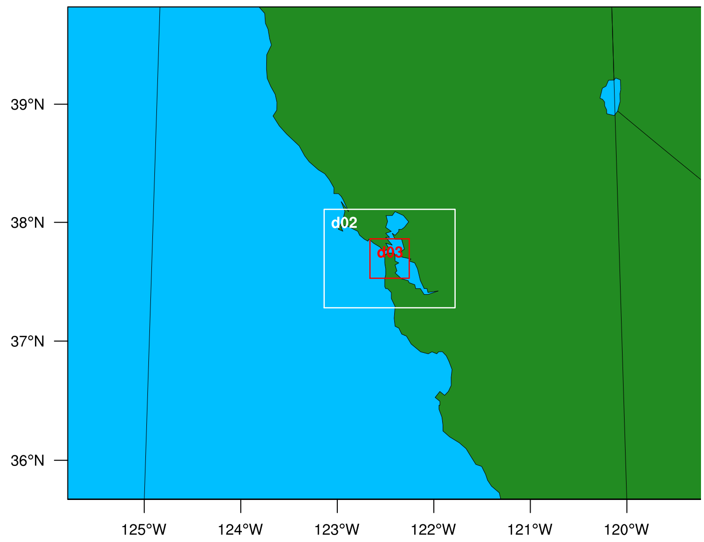

FIG. 19. Domain configuration used for multi-scale simulations over the San Francisco peninsula.

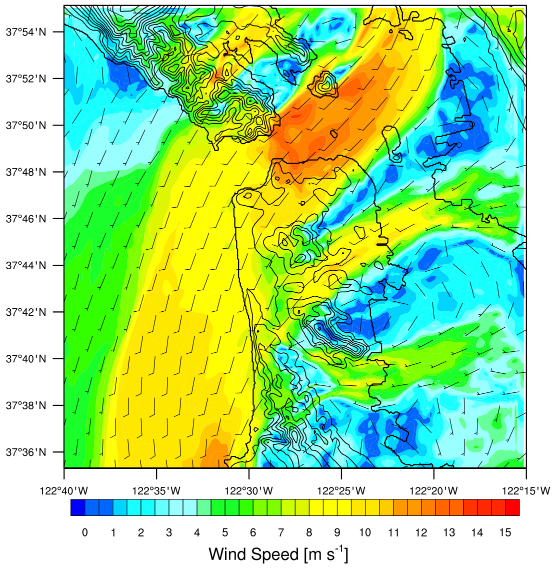

FIG. 21. Contours of wind-speed displaying prominent gap-flows within domain #3 used in the multi-scale simulations over the San Francisco peninsula.

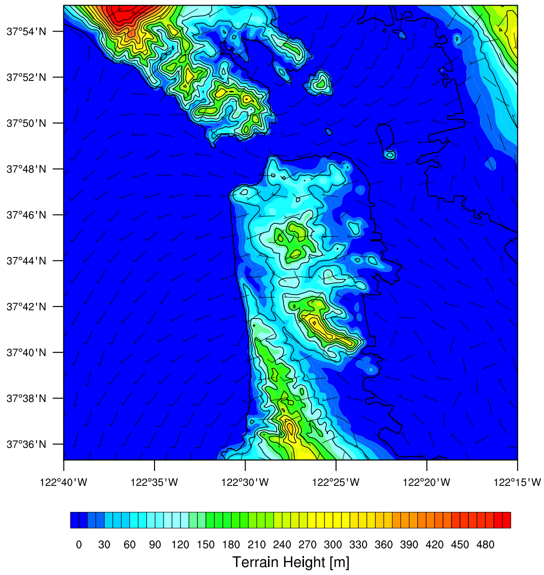

FIG. 20. Contours of terrain height for domain #3 used in the multi-scale simulations over the San Francisco peninsula.

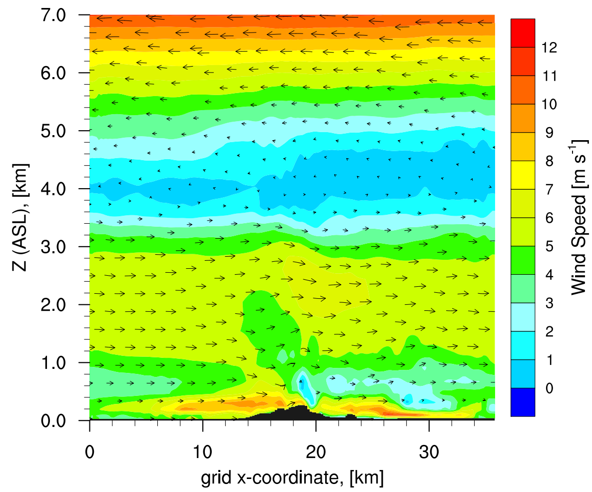

FIG. 22. Contours of wind-speed on an east-west slice through the midpoint of domain #3 used in the multi-scale simulations over the San Francisco peninsula.