Topographic Effects on Radiation in the WRF Model with the Immersed Boundary Method: Implementation, Validation, and Application to Complex Terrain

ROBERT S. ARTHUR, KATHERINE A. LUNDQUIST, AND JEFFREY D. MIROCHA

Lawrence Livermore National Laboratory, Livermore, California

FOTINI K. CHOW

Department of Civil and Environmental Engineering, University of California, Berkeley, Berkeley, California

(Manuscript received 22 March 2018, in final form 13 July 2018)

ABSTRACT

Topographic effects on radiation, including both topographic shading and slope effects, are included in the Weather Research and Forecasting (WRF) Model, and here they are made compatible with the immersed boundary method (IBM). IBM is an alternative method for representing complex terrain that reduces numerical errors over sloped terrain, thus extending the range of slopes that can be represented in WRF simulations. The implementation of topographic effects on radiation is validated by comparing land surface fluxes, as well as temperature and velocity fields, between idealized WRF simulations both with and without IBM. Following validation, the topographic shading implementation is tested in a semirealistic simulation of flow over Granite Mountain, Utah, where topographic shading is known to affect downslope flow development in the evening. The horizontal grid spacing is 50 m and the vertical grid spacing is approximately 8–27 m near the surface. Such a case would fail to run in WRF with its native terrain-following coordinates because of large local slope values reaching up to 55°. Good agreement is found between modeled surface energy budget components and observations from the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) program at a location on the east slope of Granite Mountain. In addition, the model captures large spatiotemporal inhomogeneities in the surface sensible heat flux that are important for the development of thermally driven flows over complex terrain.

1. Introduction

In mountainous terrain, the diurnal variations of the surface sensible heat flux can lead to thermally driven upvalley or upslope flow during the daytime and downvalley or downslope flow during the nighttime (Zardi and Whiteman 2013). Topographic effects on radiation can strongly influence these flows by creating large spatiotemporal inhomogeneities in the net radiation, and thus in the surface energy budget. These effects include

topographic shading, where direct solar radiation is blocked by surrounding topography, and slope effects (also known as “self shading”), where the local slope angle modifies the incoming solar radiation based on the angle of incidence of the direct solar beam at the surface relative to the local slope.

Previous field work has documented the influence of topographic effects on the surface radiation and energy budgets in mountainous terrain (Whiteman et al. 1989a,b; Matzinger et al. 2003; Katurji et al. 2013). Some studies have extended this work to examine how topographic effects on the surface radiation and energy budgets influence the development of both valley and slope flows. For example, Whiteman et al. (1989b) found that sign reversals in the local surface sensible heat flux corresponded to reversals of both the slope and valley wind systems. Several studies have focused specifically on the development of downslope flows during the evening transition, finding that downslope flow development

Denotes content that is immediately available upon publication as open access.

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/MWR-D-18-0108.s1>.

Corresponding author: Robert S. Arthur, arthur7@llnl.gov

DOI: 10.1175/MWR-D-18-0108.1

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follows the shadow front. On east-facing slopes, the downslope flow transition has been found to follow the shadow front down the slope (Papadopoulos and Helmis 1999; Lehner et al. 2015), while on west-facing slopes, the downslope flow transition may follow the shadow front up the slope (Nadeau et al. 2013).

With this in mind, it is important to capture topographic effects on radiation in atmospheric models over mountainous terrain. Perhaps the first implementation of a topographic shading algorithm in a major mesoscale atmospheric model was done by Colette et al. (2003) in the Advanced Regional Prediction System (ARPS). Since then, other models have included topographic effects on radiation. These include the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5; Zängl 2005) and the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008), which is used in this study. Although topographic shading improves the representation of surface fluxes over sloped terrain, the terrain-following vertical coordinate used by most mesoscale atmospheric models becomes skewed over moderate slopes, which can result in numerical errors (e.g., Janjić 1977; Mahrer 1984; Schär et al. 2002; Klemp et al. 2003; Zängl 2002, 2003; Zängl et al. 2004). The severity of these errors depends on both the steepness of the terrain and the grid aspect ratio (the horizontal grid spacing divided by the vertical grid spacing), as shown in Fig. 1 of Daniels et al. (2016). This limitation restricts the use of models such as WRF in regions of steep and/or complex terrain where topographic effects on radiation are most important.

The immersed boundary method (IBM), which uses a nonconforming grid and represents the topography by imposing boundary conditions along an immersed terrain surface, provides an alternative to terrain-following vertical coordinates. IBM reduces numerical errors related to the terrain slope, thus extending the range of slopes that can be represented on the computational grid. IBM was originally implemented into WRF (referred to here as WRF-IBM), version 2.2, and coupled to a subset of its atmospheric physics parameterizations by Lundquist et al. (2010). Topographic effects on radiation were not included in the standard WRF release until version 3 (see <http://www2.mmm.ucar.edu/wrf/users/wrfv3/updates.html>), so they were not coupled to IBM or tested in the Lundquist et al. (2010) study.

Here, WRF-IBM (based on WRF, version 3.6.1) is modified to include topographic effects on radiation, expanding on the implementation of Lundquist et al. (2010). Changes to the model are validated by confirming agreement in radiation and land surface fluxes, as well as temperature and velocity fields, between WRF-IBM and

standard WRF when the same initialization and forcing conditions are applied. The validation is performed in a domain with an idealized two-dimensional valley that is forced by incoming solar radiation. The maximum valley slope is relatively small (approximately 15°) such that WRF still performs well with terrain-following coordinates. Thus, WRF-IBM and standard WRF results are expected to agree in this case.

Following validation, the WRF-IBM implementation is applied to a semirealistic simulation of Granite Mountain, Utah, where topographic shading is known to affect downslope flow development in the evening (Fernando et al. 2015; Lehner et al. 2015; Jensen et al. 2017). The horizontal grid spacing in this case is 50 m, and at this resolution, local terrain slopes reach roughly 55° . This case does not run in WRF when its native terrain-following coordinates are used, so direct comparison to standard WRF is not possible. To the knowledge of the authors, this is the first application of WRF using physics parameterizations to model flow over steep, nonidealized complex terrain at such high resolution. This application effectively combines the functionality of a traditional computational fluid dynamics model for simulating flow over complex geometries with that of an atmospheric model for including detailed parameterizations for atmospheric physics. The simulation of thermally driven slope flows on Granite Mountain thus demonstrates the applicability of WRF-IBM to investigate atmospheric flows in complex terrain environments.

This work is part of an ongoing effort to enable multiscale simulations over complex terrain within the WRF modeling framework. A major focus of this effort is the use of IBM to overcome the slope limitations associated with WRF's native terrain-following coordinate. Lundquist et al. (2010) first implemented a two-dimensional IBM in WRF with a no-slip boundary condition and coupling to the MM5 (Dudhia) shortwave radiation scheme, the RRTM longwave radiation scheme, the MM5 surface layer module, and the Noah land surface module [for documentation of these schemes, see Skamarock et al. (2008), and references therein].

Additional WRF-IBM development projects have included extending the method to three dimensions and using WRF's Smagorinsky turbulence model (Lundquist et al. 2012), as well as the implementation of a surface momentum flux parameterization based on logarithmic similarity theory (Bao et al. 2016, 2018). Because WRF-IBM uses an alternate vertical grid that requires points underneath the terrain, specialized routines must be developed for the IBM domain to receive lateral boundary conditions from analysis data or to nest an IBM domain within a WRF domain using terrain-following coordinates. The capability to use an independent vertical grid on each domain was implemented by Daniels et al. (2016) and

FIG. 1. Example grid and topographic effects on radiation for (a) standard WRF and (b) WRF-IBM. The incoming solar radiation at point A is increased by slope effects resulting from the nearly perpendicular angle of incidence of the radiation with respect to the topography. The incoming solar radiation to the east of point B on the slope is blocked by the topography and is therefore shaded.

Mirocha and Lundquist (2017), and efforts to nest domains using IBM within those using terrain-following coordinates are detailed in Wiersema et al. (2016, 2018). Studies by other groups have also used the immersed boundary method in WRF. For example, Ma and Liu (2017) demonstrated neutral boundary layer flow over Bolund Hill using WRF at horizontal grid spacings of 1 and 2 m.

A final consideration impacting the integration of WRF and IBM is the need for each WRF physics parameterization to be coupled to IBM separately and subsequently validated. Given that the aforementioned WRF-IBM projects are in various stages of development, the present work is focused on extending the original implementation of WRF-IBM in Lundquist et al. (2010, 2012) to include topographic effects on radiation. The roles of turbulence, regional or synoptic forcing, or other physical processes are therefore not investigated here, and are reserved for future studies.

The computational cost of the present WRF-IBM implementation is roughly a factor of 2 larger than that of standard WRF for comparable cases such as the idealized two-dimensional valley validation case. However, computational cost cannot be compared directly in more complex terrain cases, such as Granite Mountain, because standard WRF does not run. Much of this increase in cost is a result of WRF's pressure-based vertical coordinate system, for which the vertical levels change every time step, thus requiring new interpolation factors for variables at the immersed boundary. In a code with a fixed vertical grid, these factors would only need to be calculated once. Decreasing the computational cost of WRF-IBM is a subject of future work.

2. Implementation

As of version 3, the standard WRF release includes topographic effects on radiation within the MM5

(Dudhia) shortwave radiation module. In this section, the coupling of topographic effects on radiation to IBM is described; all changes to WRF are made within version 3.6.1, but are also applicable to future WRF releases. The MM5 (Dudhia) shortwave radiation scheme parameterizes topographic effects on incoming solar radiation at the surface, accounting for both the local slope angle in relation to the angle of the sun in the sky and the location of surrounding terrain that may intercept the solar radiation (see Fig. 1). During WRF execution, the downward flux of solar radiation (both direct and diffuse components) at the surface is first computed at each horizontal grid location assuming flat terrain (denoted here as SW_0). Following Garnier and Ohmura (1968) and Zängl (2005), this value is then modified based on both the local terrain slope and shadowing due to surrounding terrain with

$$SW_{adj} = \left[D + (1 - D) \frac{\cos(Z_{adj})}{\cos(Z_0)} \right] SW_0, \quad (1)$$

where SW_{adj} is the incoming solar radiation adjusted by topographic effects, Z_{adj} is the solar zenith angle relative to a surface normal vector, Z_0 is the solar zenith angle assuming flat terrain, and D is the fraction of SW_0 that is diffuse.

When the WRF namelist option "slope_rad" is activated, the incoming solar radiation is corrected based on the solar zenith angle relative to the local surface normal vector. The slope correction increases the solar radiation on surfaces whose slopes approach perpendicularity with the incoming solar beam [$\cos(Z_{adj})/\cos(Z_0) > 1$ in Eq. (1)] and decreases it for slopes tilted away from the incoming solar beam [$\cos(Z_{adj})/\cos(Z_0) < 1$ in Eq. (1)]. Note that the slope correction is applied only to the direct portion of the incoming solar radiation, hence the factor $(1 - D)$ in Eq. (1).

When the namelist option “topo_shading” is activated, WRF searches within a radius “slp_dist” (another namelist option) around each grid point to determine if any topography intersects a line drawn between the sun and the given grid point. If so, a topographic shadow is cast on that grid point (the WRF variable “shadowmask” is set to 1) and the direct component of the incoming solar radiation is set to 0. Effectively, D is set to 1 in Eq. (1) such that SW_{adj} includes only diffuse radiation.

In standard WRF, the terrain height is used to define both the elevation of the surface terrain and the lower extent of the computational domain. In WRF-IBM, however, the elevation of the surface terrain is represented by an immersed boundary, while the lower extent of the computational domain is beneath the immersed boundary. Coupling WRF’s algorithm for topographic effects on radiation to IBM therefore involves changing the relevant terrain height variable to that representing the immersed boundary surface (see Fig. 1). The terrain slope and solar zenith angle Z_{adj} must also be calculated using the immersed boundary terrain.

It should be noted that the immersed boundary method (including the implementation discussed here and in other references) is not yet included in the standard WRF release. However, in the process of implementing topographic effects on radiation in WRF-IBM, an error was discovered in the standard WRF implementation that caused the diffuse component of solar radiation to be incorrect when the terrain slope was zero. This error was fixed in the WRF code used here, and in the standard WRF, version 3.7, release (see <http://www2.mmm.ucar.edu/wrf/users/wrfv3.7/updates-3.7.html>).

3. Validation

The validation of land surface coupling in WRF-IBM with topographic effects on radiation follows the approach of Lundquist et al. (2010), who originally validated land surface coupling without including topographic effects. Radiation quantities, surface fluxes, and temperature and velocity fields are compared between WRF-IBM and standard WRF in a domain with an idealized two-dimensional valley. This case was used previously in Lundquist et al. (2010) and Schmidli et al. (2011), and was chosen because it combines the use of atmospheric physics parameterizations with an idealized terrain and atmosphere, making the setup suitable for validation cases. Although the results are not included herein, an additional validation case with a three-dimensional Witch of Agnesi hill was completed to confirm agreement in topographic shadow location between WRF-IBM and standard WRF for a variety of seasons and latitude–longitude locations.

In validating land surface coupling, it is necessary to turn on several atmospheric physics modules (in addition to the aforementioned shortwave radiation module) that were originally implemented in WRF-IBM by Lundquist et al. (2010), including the RRTM longwave module, MM5 surface layer module, and Noah land surface module. These routines required minor modifications to update the coupling to the immersed boundary method from WRF version 2.2 (used in Lundquist et al. 2010) to version 3.6.1 (used here). Validation of their updated implementations is thus included in the present study.

a. Model configuration

The idealized two-dimensional valley is defined by

$$h(x) = \begin{cases} 0, & |x| \leq V_x \\ h_p \left[0.5 - 0.5 \cos \left(\pi \frac{|x| - V_x}{S_x} \right) \right], & V_x < |x| < V_x + S_x \\ h_p, & V_x + S_x \leq |x| \leq V_x + S_x + P_x \\ h_p \left(0.5 - 0.5 \cos \left[\pi \frac{|x| - (V_x + S_x + P_x)}{S_x} \right] \right), & V_x + S_x + P_x < |x| < V_x + 2S_x + P_x \\ 0, & |x| \geq V_x + 2S_x + P_x \end{cases}, \quad (2)$$

where the peak height $h_p = 1.5$ km, the valley floor half-width $V_x = 0.5$ km, the hill half-width $S_x = 9$ km, and the peak width $P_x = 1$ km. The WRF domain size is $(L_x, L_y, L_z) = (60, 0.6, 10)$ km with $(N_x, N_y, N_z) = (301, 3, 60)$ grid points, giving a horizontal grid spacing of $\Delta x = \Delta y = 200$ m. The minimum vertical grid

spacing occurs at the hill peaks ($\Delta z_{\min} = 95.6$ m) and the maximum occurs at the top of the domain ($\Delta z_{\max} = 307.6$ m). In the WRF-IBM model, the bottom of the domain is at $z = -200$ m to allow for at least two grid points below the terrain. Thus, the WRF-IBM domain has a size of $(L_x, L_y, L_z) = (60, 0.6, 10.2)$ km with

$(N_x, N_y, N_z) = (301, 3, 62)$ grid points. The horizontal grid spacing is again $\Delta x = \Delta y = 200$ m. The minimum vertical grid spacing occurs at the bottom of the domain ($\Delta z_{\min} = 101.9$ m) and the maximum occurs at the top of the domain ($\Delta z_{\max} = 307.2$ m). A time step of 1 s is used. Both models are initialized with a quiescent, stably stratified sounding where the potential temperature $\theta(z) = \theta_s + \Gamma z + \Delta\theta[1 - \exp(-\beta z)]$ with $\theta_s = 280$ K, $\Gamma = 3.2$ K km⁻¹, $\Delta\theta = 5$ K, and $\beta = 0.002$ m⁻¹. The sounding is moist with a constant relative humidity of 40%.

The location of the valley is set to 36°N, 0°, and the model is run between 0600 and 1800 UTC 21 March 2007. Certain land surface properties that are used as inputs in WRF's radiation, land surface, and surface layer models are also initialized following Lundquist et al. (2010). These include spatially uniform values of soil type (sandy loam), land use (savannah), and vegetation fraction (0.1). The initial soil temperature is equal to the initial surface atmospheric temperature, and the soil moisture is set to 0.0868 m³ m⁻³ (a 20% saturation rate for sandy loam).

Lateral boundary conditions are periodic for all variables. At the immersed boundary, either Dirichlet or Neumann boundary conditions can be used. Boundary conditions at the immersed topography are set as in Lundquist et al. (2010), where a Dirichlet boundary condition is used for velocity and a Neumann boundary condition is used for potential temperature and moisture.

The bottom boundary condition for each velocity component is no slip (i.e., $u, v, w = 0$). In WRF, the surface stress τ_s is usually set as a lower boundary condition and is defined as $|\tau_s| = \rho u_*^2$, where ρ is the density of air, and the friction velocity u_* is calculated in the surface layer module using Monin–Obukhov Similarity Theory (MOST; Monin and Obukhov 1954). With a no-slip boundary condition, the surface stress τ_s can instead be calculated as

$$\tau_s = -\rho \nu_t \frac{u_1}{z_1 - z_s}, \quad (3)$$

where ν_t is the eddy viscosity and the subscript 1 denotes the first grid point above the immersed boundary surface (z_s). Surface stress parameterizations based on logarithmic similarity theory have been combined with the immersed boundary method and have shown improvement over no-slip boundary conditions for meter-scale grid spacing (e.g., Ma and Liu 2017; Bao et al. 2018), though they have only been applied to flows with neutral stability profiles, which is not the case here. Additionally, Bao et al. (2016) showed that at the coarser resolutions used here, current IBM implementations based

on similarity theory perform similarly to those using a no-slip condition, with reasons varying based on the specifics of the implementation. Thus, a no-slip boundary is used in the present study to simplify validation as a result of the strict enforcement of a Dirichlet condition. A no-slip option was previously added to WRF for use with terrain-following coordinates (Lundquist et al. 2010), and is used here so that direct comparisons between the immersed boundary and terrain-following simulations are possible.

The potential temperature and moisture boundary conditions in WRF-IBM make use of the surface sensible heat flux Q_H and surface moisture flux Q_v calculated by the Noah land surface and MM5 surface layer routines. A Neumann bottom boundary condition based on the surface sensible heat flux Q_H is then applied to the potential temperature θ ,

$$\frac{\partial \theta}{\partial n} \Big|_s = \frac{-Q_H}{\kappa_t c_p \rho}, \quad (4)$$

where n is the direction normal to the immersed boundary surface, κ_t is the eddy diffusivity of heat, c_p is the specific heat capacity of air at constant pressure, and ρ is the air density. A similar bottom boundary condition is applied to the moisture q_v based on the surface moisture flux Q_v ,

$$\frac{\partial q_v}{\partial n} \Big|_s = \frac{-Q_v}{\kappa_t \rho q_v}. \quad (5)$$

The Noah land surface and MM5 surface layer routines use MOST in the calculation of surface fluxes and have been modified to use quantities (i.e., velocity, temperature, and moisture) at a uniform reference height above the immersed boundary. Thus, while the friction velocity u_* is calculated and used to set surface fluxes of heat and moisture, it is not used to set surface momentum fluxes because of the performance issues mentioned above and detailed in Bao et al. (2016).

In the validation cases, a constant eddy viscosity $\nu_t = 90$ m² s⁻¹ is used. The eddy diffusivity is $\kappa_t = \nu_t / \text{Pr}_t$, where the turbulent Prandtl number $\text{Pr}_t = 1/3$, the default condition in WRF. While the use of relatively large, constant eddy viscosity and diffusivity values is not applicable to realistic atmospheric flows, it facilitates validation in the present study. The value of ν_t is chosen to make the comparison of WRF-IBM and standard WRF solutions more straightforward by damping out resolved convective plumes that form at arbitrary locations when smaller values of ν_t are used. Additionally, holding κ_t constant in Eq. (4) helps to ensure that any differences in the temperature boundary condition between

FIG. 2. Comparison of horizontal velocity u profiles between WRF-IBM and standard WRF for the two-dimensional valley test case at 1200 UTC. The color scale shows the potential temperature θ field from the WRF-IBM simulation.

WRF-IBM and standard WRF are due to Q_H , which is of primary interest here. Smaller eddy viscosity values are used following validation (in section 4), when turbulent flow features are of interest and the model grid is sufficiently fine to support resolved turbulence.

b. Model results

Over the course of the day, solar heating of the valley topography leads to thermally driven flow near the surface (Fig. 2). Air flows upslope on both sides of each hill, and a buoyant plume of warm air rises at each peak. Return flow develops within the valley and on the outside of each hill, completing the circulation. Such flow is typical of valley topography with surface heating, and is similar to the flow modeled in Schmidli et al. (2011).

Because surface forcing ultimately drives the flow in the valley test case, the validation of land surface coupling is first focused on comparing the relevant surface flux quantities calculated by the radiation and surface schemes in WRF-IBM and standard WRF. These quantities include incoming longwave and shortwave radiation, as well as surface sensible heat and moisture fluxes. Instantaneous across-valley plots of surface flux quantities (Fig. 3) show overall good agreement between WRF-IBM and standard WRF. Plots are shown at three times (0900, 1200, and 1500 UTC) to demonstrate the evolution of surface fluxes over the course of the day, and to highlight the importance of topographic effects.

Although the incoming longwave radiation values (Fig. 3a) are nearly equal when the simulation is initialized, they diverge over time, leading to a maximum

instantaneous difference of 1.73 W m^{-2} (0.61%) at the end of the simulation (1800 UTC). This divergence is caused by slight differences in atmospheric temperature and moisture structure, which affect the absorption and emission of incoming longwave radiation, between WRF-IBM and standard WRF.

Very good agreement is found for the incoming shortwave radiation (Fig. 3b). The maximum instantaneous difference between WRF-IBM and standard WRF is -1.27 W m^{-2} (-1.20%) at 1745 UTC, when the magnitude of shortwave radiation values is low. At the time of peak shortwave radiation, 1200 UTC, the maximum difference is similar, but the relative difference is reduced to 0.08%. As noted by Lundquist et al. (2010), the differences in radiation quantities between WRF-IBM and standard WRF are quite small relative to differences caused by elevation and/or topographic effects. They are due in part to the differences in the vertical grid, which affects the numerical integration over a vertical column that is used in the radiation schemes.

The surface sensible heat flux Q_H is of primary interest because it controls thermally driven boundary layer flows through the temperature boundary condition in Eq. (4). Instantaneous across-valley plots of the surface sensible heat flux (Fig. 3c) show good agreement between WRF-IBM and standard WRF, with a maximum difference of 2.36 W m^{-2} (1.22%) at 1100 UTC. The maximum difference in the surface moisture flux (Fig. 3d) is $-3.32 \times 10^{-7} \text{ kg m}^{-2} \text{ s}^{-1}$ at 1730 UTC. Because of the relatively low magnitude of the moisture flux at this time, the percent difference is relatively large

FIG. 3. Instantaneous (a) incoming longwave radiation, (b) incoming shortwave radiation, (c) surface sensible heat flux, and (d) surface moisture flux as functions of x at 0900, 1200, and 1500 UTC for the idealized two-dimensional valley test case using WRF-IBM and standard WRF. In (b)–(d) WRF-IBM results are shown both with and without topographic effects on radiation.

(−19.4%). However, at 1100 UTC, when the sensible heat flux difference is at a maximum, the moisture flux difference is more in line with other differences, $2.52 \times 10^{-8} \text{ kg m}^{-2} \text{ s}^{-1}$ (0.49%).

Having achieved good agreement in surface flux quantities between WRF-IBM and standard WRF, the resulting temperature and flow structure are compared using time-averaged differences between WRF-IBM and standard WRF, defined as

$$\Delta\phi = \overline{\phi_{\text{IBM}}} - \overline{\phi_{\text{WRF}}}. \quad (6)$$

The variable ϕ is a placeholder for the potential temperature θ (Fig. 4a), the horizontal velocity u (Fig. 4b), or the vertical velocity w (Fig. 4c), and the overbar represents a time average over the entire simulation (i.e., between 0600 and 1800 UTC). The WRF-IBM solution ϕ_{IBM} is interpolated to the terrain-following grid used in the standard WRF Model to allow for a direct subtraction.

Differences between the WRF-IBM and standard WRF simulations are concentrated at the surface, where land surface forcing and the implementation of boundary conditions affect the flow. The potential temperature field in WRF-IBM is slightly cooler near the surface, with $\Delta\theta_{\text{min}} = -0.072 \text{ K}$ (Fig. 4a). The potential temperature difference approaches 0 K aloft, with a

maximum difference of $\Delta\theta_{\text{max}} = 0.010 \text{ K}$. Since the flow is thermally driven, differences in θ lead to differences in velocity, which are apparent primarily on the valley slopes and at the valley peaks (Figs. 4b,c). The horizontal velocity differences are $\Delta u_{\text{min}} = -0.112$ and $\Delta u_{\text{max}} = 0.118 \text{ m s}^{-1}$, while the vertical velocity differences are $\Delta w_{\text{min}} = -0.091$ and $\Delta w_{\text{max}} = 0.032 \text{ m s}^{-1}$. The largest vertical velocity differences occur at the valley peaks because of an offset in the location of the buoyant plume created by surface heating.

Some of the disagreement between WRF-IBM and standard WRF shown in Fig. 4 is due to the difference in the grids used for each simulation. Because WRF balances the initial atmospheric pressure, temperature, and moisture profiles onto the model grid, grid differences prevent the initial profiles from being identical, and these differences persist throughout the simulations. Despite minor disagreements, the same overall flow structure occurs in both models, as demonstrated in Fig. 2. The temperature and velocity differences between WRF-IBM and standard WRF in this study are also similar in magnitude to those reported by Lundquist et al. (2010) for the same case without topographic effects on radiation included. Their minimum/maximum differences [also calculated using Eq. (6)] were $\Delta\theta_{\text{min}} = -0.023 \text{ K}$, $\Delta\theta_{\text{max}} = 0.099 \text{ K}$, $\Delta u_{\text{min}} = \Delta u_{\text{max}} = \pm 0.254 \text{ m s}^{-1}$, $\Delta w_{\text{min}} = -0.068 \text{ m s}^{-1}$, and $\Delta w_{\text{max}} = 0.133 \text{ m s}^{-1}$. Thus,

FIG. 4. Time-averaged differences in (a) potential temperature $\Delta\theta$, (b) horizontal velocity Δu , and (c) vertical velocity Δw between WRF-IBM and standard WRF for the idealized two-dimensional valley test case. Note that $\Delta\phi = \phi_{\text{IBM}} - \phi_{\text{WRF}}$ as defined in Eq. (6).

WRF-IBM performs well in comparison to standard WRF for the idealized valley case both with and without topographic effects on radiation.

4. Application to realistic complex terrain

Following the successful implementation and validation of topographic effects on radiation in WRF-IBM,

the model is applied to a real complex terrain environment. The chosen site is Granite Mountain, a relatively isolated desert mountain in Utah that experiences thermally driven downslope flows during the evening. These flows were a focus of the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) program and are strongly affected by topographic shading (Fernando et al. 2015; Lehner et al. 2015;

FIG. 5. (a) The full WRF-IBM domain used to study Granite Mountain, including both the outer (d01) and inner (d02) domains. (b) A zoomed-in view of the inner domain (d02), including the location of MATERHORN tower ES5, the location of surface flux measurements shown in Fig. 8. In (b), the box indicates the region shown in Fig. 9. (c) Land-use and (d) soil-type data included in the inner nest of the WRF-IBM domain, based on the USGS classification system. The topography of Granite Mountain is shown by black contour lines between $z = 1400$ and $z = 2000$ m MSL with an interval of 200 m.

Jensen et al. 2017). Because of errors associated with terrain-following vertical coordinates in regions of steep slopes and WRF's choice of numerical schemes, it is not possible to model Granite Mountain at high resolution (less than roughly 100 m) in standard WRF without modifications to account for steep terrain. With the 50-m horizontal grid spacing used here, local slope values can be as large as 55° .

a. Model configuration

Granite Mountain is modeled using the nested ideal WRF setup shown in Fig. 5a. The inner domain (d02) covers the topography of interest, as shown in Fig. 5b. It is a $15 \times 15 \text{ km}^2$ grid with $(N_x, N_y) = (300, 300)$ points, resulting in a horizontal grid spacing of $\Delta x = \Delta y = 50$ m. The outer domain includes only flat terrain located at an elevation of 1300 m MSL and is $45 \times 45 \text{ km}^2$ with

FIG. 6. (a) Potential temperature θ and (b) vapor mixing ratio q_v from a radiosonde launched at the Playa site near Granite Mountain during MATERHORN Spring IOP 4.

$\Delta x = \Delta y = 150$ m (a grid nest ratio of 3) and periodic horizontal boundary conditions. Both the inner and outer domains are 4 km in height with $N_z = 100$ grid points. Exponential grid stretching is employed such that the vertical grid spacing $\Delta z \approx 8 - 27$ m near the immersed boundary surface and $\Delta z \approx 70$ m near the top of the domain. Rayleigh damping is employed within the top 500 m of both domains. The time step is $\Delta t = 0.27$ s on the inner domain and $\Delta t = 0.8$ s on the outer domain. Note that the nested setup is employed to prevent lateral boundary effects from reaching the area of interest in this idealized configuration, however, analysis is focused on the inner domain.

Realistic land surface data around Granite Mountain are used in the model setup. For the inner domain, the topography of Granite Mountain is read from $1/3$ -arc-s (approximately 10 m) data from the U.S. Geological Survey (USGS) National Elevation Dataset. Realistic land-use and soil-type data are also included on the inner domain, as shown in Figs. 5c and 5d. Land-use data are read from a 1-arc-s (approximately 30 m) resolution dataset created for 4DWX (Liu et al. 2008), an operational model used at Dugway Proving Ground, where Granite Mountain is located. Soil-type data are read

from the 30-arc-s (approximately 1 km) resolution State Soil Geographic (STATSGO)/Food and Agriculture Organization (FAO) dataset, which is standard in WRF and is also used in 4DWX. For the outer domain, a constant land use of “shrubland” and a constant soil type of “silt loam” are used.

The model is initialized using a single input sounding that contains potential temperature θ , vapor mixing ratio q_v , and horizontal velocity (u , v) as a function of height and is applied to every x - y point in both domains. The potential temperature and vapor mixing ratio fields are initialized from radiosonde data collected during MATERHORN Spring IOP 4 (Fig. 6). The radiosonde launch site was approximately 15 km west of Granite Mountain [the “Playa” site in Fernando et al. (2015), see Fig. 3 therein], where the conditions are generally representative of the regional conditions surrounding Granite Mountain. To allow for adequate model spinup before sunset, the simulation is initialized at 1320 mountain standard time (MST: UTC $- 7$ h) based on radiosonde data from 1318 MST. Both domains are initialized at the same time. The initial horizontal velocity is set to zero in the model such that the atmosphere is quiescent before thermally driven flows develop.

FIG. 7. Modeled shadow propagation (black contours) and surface sensible heat flux Q_H (color scale) on Granite Mountain during the evening. The topography of Granite Mountain is shown by gray contour lines between $z = 1350$ and $z = 2150$ m MSL with an interval of 100 m. Also shown is the location of MATERHORN east slope tower ESS (green dot), the location of surface flux measurements in Fig. 8.

The model is forced by incoming solar radiation, moderated by slope and topographic shading effects. The model soil moisture is initialized as $0.15 \text{ m}^3 \text{ m}^{-3}$ based on the average seasonal values presented by Jensen et al. (2016). A constant eddy viscosity is used in both domains. The value used on the inner nest is $\nu_t = 0.5 \text{ m}^2 \text{ s}^{-1}$, which was found to be the smallest possible value needed to maintain stability of the model. Because of increased radiative forcing during the daytime, $\nu_t = 1.0 \text{ m}^2 \text{ s}^{-1}$ is necessary for stability during model spinup. However, ν_t is reduced to $0.5 \text{ m}^2 \text{ s}^{-1}$ at 1815 MST as downslope flows develop.

b. Model results

1) SURFACE ENERGY BUDGET

As seen in field observations, model results suggest that on the east side of Granite Mountain, the evening reversal of the surface sensible heat flux Q_H is driven by topographic shading (Fig. 7). As the sun sets to the west of Granite Mountain during the spring, the upper elevations on the east side of the mountain become shaded first, and Q_H becomes negative in these regions (Figs. 7a,b). The shadow front then propagates to the southeast, moving down the mountain with a

corresponding reversal of Q_H (Figs. 7c–f). Owing to the complex terrain of the mountain, the shading is quite heterogeneous, resulting in small-scale patches of shaded terrain that experience negative sensible heat flux. Generally, east-facing slopes become shaded first, and west-facing slopes remain unshaded for a longer period of time. At later times when the east side is fully shaded (Figs. 7e,f), the west side still experiences incoming solar radiation and Q_H remains positive. The magnitude of Q_H is, in fact, slightly higher on west-facing slopes than on the surrounding flat terrain at similar times in the evening because of the angle of incidence of incoming solar radiation relative to the slope (self-shading).

The surface sensible heat flux is dependent on the surface energy budget following Zardi and Whiteman (2013):

$$Q_H = -(R_n + Q_G + Q_L), \quad (7)$$

$$R_n = Q_{Si} + Q_{Li} - Q_{So} - Q_{Lo}, \quad (8)$$

where R_n is the net radiation, Q_G is the ground heat flux, Q_L is the latent heat flux, Q_{Si} is the incoming shortwave radiation, Q_{Li} is the incoming longwave radiation, Q_{So} is the outgoing shortwave radiation, and Q_{Lo} is the outgoing

FIG. 8. Modeled (—) and observed (---) (a) surface radiation and (b) surface energy budget components at ES5. The vertical dotted line indicates local sunset in the model.

longwave radiation. Based on a comparison with MATERHORN field observations at ES5 (the location of which is shown in Fig. 5b) during Spring IOP 4, the model generally captures the surface energy budget components accurately (Fig. 8). Note that the variability in the observed incoming shortwave radiation Q_{Si} is influenced by the presence of clouds, which were observed by Lehner et al. (2015) during the afternoon of 11 May 2013 but are not captured in the model. Starting in the early afternoon, Q_{Si} decreases gradually until a sharp drop at local sunset (denoted by the vertical dotted lines in Fig. 8), when the local topography is shaded. Diffuse shortwave radiation still contributes to Q_{Si} after this time until astronomical sunset, when Q_{Si} goes to zero.

Since the latent heat flux Q_L is small in this desert region (and therefore not shown in Fig. 8), the surface sensible heat flux Q_H is controlled by the net radiation R_n and ground heat flux Q_G . The most notable difference between the modeled and observed surface energy budget components is the partitioning of the available energy at the surface between Q_H and Q_G , causing the modeled Q_H to be smaller and the modeled Q_G to be larger than the observed values after local sunset (Fig. 8b). Based on the general agreement between the modeled and observed R_n , these differences may be a consequence of the land surface model or soil initialization parameters. Errors in heat flux partitioning have been reported previously in WRF with the Noah land surface model (e.g., Gibbs et al. 2011), although the specific cause is unknown.

The model soil moisture, which was initialized at a constant value of $0.15 \text{ m}^3 \text{ m}^{-3}$, likely plays a role in this discrepancy because it affects the soil thermal conductivity and thus the ground heat flux Q_G . Spatial

heterogeneity in soil moisture can lead to large near-surface temperature differences (e.g., Hang et al. 2016) and is likely an important factor in the surface energy budget over complex terrain. Additionally, the parameterization of the soil thermal conductivity as a function of soil moisture can affect the surface energy budget. Massey et al. (2014) suggested changes to the Noah land surface model in WRF for certain soil types, including loam and silt loam, which are prevalent on the east slope of Granite Mountain (see Fig. 5d). Finally, the spinup time for the land surface model also plays a role in the surface energy budget (e.g., Cosgrove et al. 2003; Chen et al. 2007), and is likely longer than the spinup time used here for the atmospheric variables.

Ultimately, because this is only a semirealistic WRF run, detailed agreement between the modeled and observed surface energy budget is not expected. With continued development of WRF-IBM, future simulations using a nested setup with more realistic model initialization and forcing should allow for improvements in this regard. However, the comparisons in Fig. 8 show that the relevant components of the surface energy budget are generally well captured by the present model.

2) DOWNSLOPE FLOW DEVELOPMENT

Downslope flows are known to develop on sloped terrain after the “evening transition” of the surface sensible heat flux Q_H from positive during the day to negative at night. Over complex terrain such as Granite Mountain, topographic effects on radiation are an important factor in this transition, as seen in Fig. 9, where the color scale shows the near-surface potential temperature at 0.5 m AGL, vectors show the horizontal velocity (u, v) at

FIG. 9. Near-surface potential temperature (θ at 0.5 m AGL) and horizontal velocity vectors (u, v at 30 m AGL), as well as the location of the shadow front (black contours). The topography of Granite Mountain is shown by gray contour lines between $z = 1350$ and $z = 2000$ m MSL with an interval of 50 m. Also shown is the location of ES5 (green dot), the location of surface flux measurements in Fig. 8.

30 m AGL, and the black contours show the location of the shadow front. Potentially cool air (small blue regions in Fig. 9a) forms first at higher elevations (upslope of ES5) where the topography is first shaded. This cool air then flows downslope toward ES5, as shown in subsequent figure panels, where the downslope flow follows behind the shadow front until reaching the foot of the mountain an hour later (Fig. 9d).

The application of WRF-IBM to Granite Mountain allows the spatial heterogeneity of downslope flows to be resolved over a broad range of physical scales. Downslope flow develops primarily within the shaded area, while convective and/or upslope flow remains outside of the shaded area where Q_H is still positive. A combination of the topography of the drainage basin and topographic effects on radiation dictates the development of the downslope flow in the region shown in Fig. 9. Because of the path of the sun through the sky in May, the shadow propagates from northwest to southeast, which is generally aligned with the axis of the drainage basin. The area of steep terrain above ES5 is shaded uniformly and the downslope flow develops predominantly from the west-northwest within gullies

that feed the upper drainage basin (Figs. 9a,b). As the shadow moves down the slope, a more organized downslope flow that is fed by the gullies at higher elevations develops. This drainage flow then progresses down the slope, maintaining a strong westerly-northwesterly component (Figs. 9c,d).

The drainage flow can be visualized in three dimensions in the form of downslope-flowing plumes of cold air (Fig. 10). Figure 10 shows isosurfaces of u_α , defined as the component of the horizontal velocity vector (u, v) in the downslope direction $\alpha = -(dh/dx, dh/dy)$. Note that the isosurfaces of u_α are only shown within the shaded region that denotes the topographic shadow. This isolates the regions of u_α associated with downslope drainage flow from those associated with convective flow outside of the shaded region.

The present simulation of thermally driven downslope flow on Granite Mountain is intended as a proof of concept for WRF-IBM with topographic effects on radiation, not as a fully realistic atmospheric simulation. A simplified physical setup is employed to show that WRF-IBM is able to capture the basic surface forcing mechanisms of thermally driven flows over

FIG. 10. A three-dimensional view of the downslope flow on the east side of Granite Mountain at 1855 MST. Blue isosurfaces are shown for the downslope velocity $u_\alpha = (0.5, 1.0, 1.5, 2.0, 2.5) \text{ m s}^{-1}$, and the opacity of the surface is proportional to the magnitude of u_α . A real terrain image from Google Static Maps API is used, and topographic shading is shown by darkening of the terrain. The locations of MATERHORN ES towers 1–5 are shown as green dots. An animated version of this figure is available in the online supplemental material.

complex terrain. For this reason, although the modeled downslope flow is qualitatively representative of what was observed during MATERHORN Spring IOP 4 by [Lehner et al. \(2015\)](#) in that it develops behind the shadow front, direct comparisons of flow speed, direction, and vertical structure are reserved for future work.

There are several additional caveats to consider when interpreting the downslope flow in the present simulation of Granite Mountain. Regional- and synoptic-scale features that may influence thermally driven flows on Granite Mountain ([Fernando et al. 2015](#)) cannot currently be captured in WRF-IBM because of forcing limitations at the lateral boundaries and are therefore not considered at this time. Additionally, the model results are case specific. Seasonal differences in shadow propagation and soil moisture likely influence the location and timing of downslope flow development and should be examined in future studies. Nevertheless, this test case illustrates the capabilities of WRF-IBM to simulate atmospheric flow over realistic complex topography where topographic effects on radiation strongly influence near-surface dynamics.

5. Conclusions

Topographic effects on radiation, including both topographic shading and slope effects, have been successfully implemented into the WRF Model with the immersed boundary method. Validation was performed by comparing surface fluxes, as well as temperature and velocity fields, in a domain with a two-dimensional valley.

The validation simulations highlight the spatial variations in incoming solar radiation and surface sensible heat flux that are present in model runs that include topographic effects on radiation. The spatial variation in surface fluxes leads to changes in the resulting velocity structure that would not be captured without topographic effects.

Following validation, the implementation of topographic effects on radiation in WRF-IBM was applied to a semirealistic simulation of the evening transition to downslope flows on Granite Mountain, Utah. It is not possible to model flow over Granite Mountain at high resolution in standard WRF, or in other atmospheric models with a terrain-following vertical coordinate, due to numerical errors associated with large terrain slopes. This work thus represents an important advancement in the use of WRF to model thermally driven flows over complex terrain surfaces.

The use of IBM allowed WRF to capture the strong spatiotemporal variations in incoming solar radiation and surface sensible heat flux on Granite Mountain, and the surface energy budget components in the WRF-IBM model showed good agreement with observations from the MATERHORN program. Furthermore, downslope flows that are qualitatively consistent with the observations of [Lehner et al. \(2015\)](#) developed in the model in response to surface cooling behind the shadow front. While these results demonstrate that the use of IBM enables WRF to successfully capture the driving force of downslope flows over heterogeneous terrain, certain simplifications in the model setup preclude direct comparison

to observed downslope flows, which is reserved for future work.

With continued development, WRF-IBM with topographic effects on radiation will provide a computational tool to study many boundary layer flow processes over complex terrain. Future work on thermally driven downslope flows in particular will focus on improving agreement between modeled and observed flow characteristics, including vertical structure and development timing relative to local sunset. The coupling of IBM with WRF's turbulence closure models and appropriate surface boundary conditions for mesoscale and large-eddy simulations will improve the representation of unresolved physical processes in the model and should lead to better flow prediction over complex terrain. Although previous implementations of surface stress parameterizations (e.g., Senocak et al. 2004; Chester et al. 2007; Diebold et al. 2013; Ma and Liu 2017; Bao et al. 2018) have been shown to perform well with fine grid spacing (roughly 10 m or less), Bao et al. (2016) showed that these methods do not significantly improve upon the no-slip boundary condition with larger grid spacings of tens of meters and greater, as used in this study. A new method developed in Bao et al. (2016) was shown to improve results at these coarser resolutions in two-dimensional simulations, and is undergoing extension to three-dimensional simulations. Additional development of WRF-IBM to allow for nesting within terrain-following WRF domains (e.g., see Daniels et al. 2016; Wiersema et al. 2016, 2018) will enable the study of thermally driven flow interaction with larger-scale meteorological features, including regional or synoptic winds, cold pools, or mountain wakes, all of which were observed around Granite Mountain during the MATERHORN program.

Acknowledgments. A portion of this work was prepared by LLNL under Contract DE-AC52-07NA27344. Arthur and Chow received support from the Office of Naval Research Award N00014-11-1-0709, Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) program. Lundquist and Mirocha received support from the U.S. DOE Office of Energy Efficiency and Renewable Energy and the LLNL Laboratory Directed Research and Development program as Project 14-ERD-024. Some of the simulations used in this work were performed on the University of California, Berkeley, Savio cluster. We acknowledge S. W. Hoch for sharing MATERHORN ES5 surface flux data with us. We also acknowledge A. D. Anderson-Connolly and D. J. Wiersema for their help in setting up the model, and P. D. Scholl for assisting in data visualization.

REFERENCES

- Bao, J., K. A. Lundquist, and F. K. Chow, 2016: Comparison of three different implementations of the immersed boundary method in WRF (WRF-IBM). *22nd Symp. on Boundary Layers and Turbulence*, Salt Lake City, UT, Amer. Meteor. Soc., 4B.5, <https://ams.confex.com/ams/32AgF22BLT3BG/webprogram/Paper295786.html>.
- , F. K. Chow, and K. A. Lundquist, 2018: Large-eddy simulation over complex terrain using an improved immersed boundary method in the Weather Research and Forecasting Model. *Mon. Wea. Rev.*, **146**, 2781–2797, <https://doi.org/10.1175/MWR-D-18-0067.1>.
- Chen, F., and Coauthors, 2007: Description and evaluation of the characteristics of the NCAR high-resolution land data assimilation system. *J. Appl. Meteor. Climatol.*, **46**, 694–713, <https://doi.org/10.1175/JAM2463.1>.
- Chester, S., C. Meneveau, and M. B. Parlange, 2007: Modeling turbulent flow over fractal trees with renormalized numerical simulation. *J. Comput. Phys.*, **225**, 427–448, <https://doi.org/10.1016/j.jcp.2006.12.009>.
- Colette, A., F. K. Chow, and R. L. Street, 2003: A numerical study of inversion-layer breakup and the effects of topographic shading in idealized valleys. *J. Appl. Meteor.*, **42**, 1255–1272, [https://doi.org/10.1175/1520-0450\(2003\)042<1255:ANSOIB>2.0.CO;2](https://doi.org/10.1175/1520-0450(2003)042<1255:ANSOIB>2.0.CO;2).
- Cosgrove, B. A., and Coauthors, 2003: Land surface model spin-up behavior in the North American Land Data Assimilation System (NLDAS). *J. Geophys. Res.*, **108**, 8845, <https://doi.org/10.1029/2002JD003316>.
- Daniels, M. H., K. A. Lundquist, J. D. Mirocha, D. J. Wiersema, and F. K. Chow, 2016: A new vertical grid nesting capability in the Weather Research and Forecasting (WRF) Model. *Mon. Wea. Rev.*, **144**, 3725–3747, <https://doi.org/10.1175/MWR-D-16-0049.1>.
- Diebold, M., C. Higgins, J. Fang, A. Bechmann, and M. B. Parlange, 2013: Flow over hills: A large-eddy simulation of the Bolund case. *Bound.-Layer Meteor.*, **148**, 177–194, <https://doi.org/10.1007/s10546-013-9807-0>.
- Fernando, H. J. S., and Coauthors, 2015: The MATERHORN: Unraveling the intricacies of mountain weather. *Bull. Amer. Meteor. Soc.*, **96**, 1945–1967, <https://doi.org/10.1175/BAMS-D-13-00131.1>.
- Garnier, B. J., and A. Ohmura, 1968: A method of calculating the direct shortwave radiation income of slopes. *J. Appl. Meteor.*, **7**, 796–800, [https://doi.org/10.1175/1520-0450\(1968\)007<0796:AMOCTD>2.0.CO;2](https://doi.org/10.1175/1520-0450(1968)007<0796:AMOCTD>2.0.CO;2).
- Gibbs, J. A., E. Fedorovich, and A. M. J. Van Eijk, 2011: Evaluating Weather Research and Forecasting (WRF) Model predictions of turbulent flow parameters in a dry convective boundary layer. *J. Appl. Meteor. Climatol.*, **50**, 2429–2444, <https://doi.org/10.1175/2011JAMC2661.1>.
- Hang, C., D. F. Nadeau, D. D. Jensen, S. W. Hoch, and E. R. Pardyjak, 2016: Playa soil moisture and evaporation dynamics during the MATERHORN field program. *Bound.-Layer Meteor.*, **159**, 521–538, <https://doi.org/10.1007/s10546-015-0058-0>.
- Janjić, Z., 1977: Pressure gradient force and advection scheme used for forecasting with steep and small scale topography. *Beitr. Phys. Atmos.*, **50** (1), 186–199.
- Jensen, D. D., D. F. Nadeau, S. W. Hoch, and E. R. Pardyjak, 2016: Observations of near-surface heat-flux and temperature profiles through the early evening transition over contrasting surfaces. *Bound.-Layer Meteor.*, **159**, 567–587, <https://doi.org/10.1007/s10546-015-0067-z>.

- , —, —, and —, 2017: The evolution and sensitivity of katabatic flow dynamics to external influences through the evening transition. *Quart. J. Roy. Meteor. Soc.*, **143**, 423–438, <https://doi.org/10.1002/qj.2932>.
- Katurji, M., P. Zawar-Reza, and S. Zhong, 2013: Surface layer response to topographic solar shading in Antarctica's dry valleys. *J. Geophys. Res. Atmos.*, **118**, 12 332–12 344, <https://doi.org/10.1002/2013JD020530>.
- Klemp, J. B., W. C. Skamarock, and O. Fuhrer, 2003: Numerical consistency of metric terms in terrain-following coordinates. *Mon. Wea. Rev.*, **131**, 1229–1239, [https://doi.org/10.1175/1520-0493\(2003\)131<1229:NCOMTI>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<1229:NCOMTI>2.0.CO;2).
- Lehner, M., C. D. Whiteman, S. W. Hoch, D. D. Jensen, E. R. Pardyjak, L. S. Leo, S. Di Sabatino, and H. J. S. Fernando, 2015: A case study of the nocturnal boundary layer evolution on a slope at the foot of a desert mountain. *J. Appl. Meteor. Climatol.*, **54**, 732–751, <https://doi.org/10.1175/JAMC-D-14-0223.1>.
- Liu, Y., and Coauthors, 2008: The operational mesogamma-scale analysis and forecast system of the U.S. Army Test and Evaluation Command. Part I: Overview of the modeling system, the forecast products, and how the products are used. *J. Appl. Meteor. Climatol.*, **47**, 1077–1092, <https://doi.org/10.1175/2007JAMC1653.1>.
- Lundquist, K. A., F. K. Chow, and J. K. Lundquist, 2010: An immersed boundary method for the Weather Research and Forecasting Model. *Mon. Wea. Rev.*, **138**, 796–817, <https://doi.org/10.1175/2009MWR2990.1>.
- , —, and —, 2012: An immersed boundary method enabling large-eddy simulations of flow over complex terrain in the WRF Model. *Mon. Wea. Rev.*, **140**, 3936–3955, <https://doi.org/10.1175/MWR-D-11-00311.1>.
- Ma, Y., and H. Liu, 2017: Large-eddy simulations of atmospheric flows over complex terrain using the immersed-boundary method in the Weather Research and Forecasting Model. *Bound.-Layer Meteor.*, **165**, 421–445, <https://doi.org/10.1007/s10546-017-0283-9>.
- Mahrer, Y., 1984: An improved numerical approximation of the horizontal gradients in a terrain-following coordinate system. *Mon. Wea. Rev.*, **112**, 918–922, [https://doi.org/10.1175/1520-0493\(1984\)112<0918:AINAOT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1984)112<0918:AINAOT>2.0.CO;2).
- Massey, J. D., W. J. Steenburgh, S. W. Hoch, and J. C. Knievel, 2014: Sensitivity of near-surface temperature forecasts to soil properties over a sparsely vegetated dryland region. *J. Appl. Meteor. Climatol.*, **53**, 1976–1995, <https://doi.org/10.1175/JAMC-D-13-0362.1>.
- Matzinger, N., M. Andretta, E. Van Gorsel, R. Vogt, A. Ohmura, and M. W. Rotach, 2003: Surface radiation budget in an alpine valley. *Quart. J. Roy. Meteor. Soc.*, **129**, 877–895, <https://doi.org/10.1256/qj.02.44>.
- Mirocha, J. D., and K. A. Lundquist, 2017: Assessment of vertical mesh refinement in concurrently nested large-eddy simulations using the Weather Research and Forecasting Model. *Mon. Wea. Rev.*, **145**, 3025–3048, <https://doi.org/10.1175/MWR-D-16-0347.1>.
- Monin, A. S., and A. M. F. Obukhov, 1954: Basic laws of turbulent mixing in the surface layer of the atmosphere. *Tr. Akad. Nauk. SSSR Geophys. Inst.*, **24** (151), 163–187.
- Nadeau, D. F., E. R. Pardyjak, C. W. Higgins, H. Huwald, and M. B. Parlange, 2013: Flow during the evening transition over steep alpine slopes. *Quart. J. Roy. Meteor. Soc.*, **139**, 607–624, <https://doi.org/10.1002/qj.1985>.
- Papadopoulos, K. H., and C. G. Helmis, 1999: Evening and morning transition of katabatic flows. *Bound.-Layer Meteor.*, **92**, 195–227, <https://doi.org/10.1023/A:1002070526425>.
- Schär, C., D. Leuenberger, O. Fuhrer, D. Lüthi, and C. Girard, 2002: A new terrain-following vertical coordinate formulation for atmospheric prediction models. *Mon. Wea. Rev.*, **130**, 2459–2480, [https://doi.org/10.1175/1520-0493\(2002\)130<2459:ANTFVC>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<2459:ANTFVC>2.0.CO;2).
- Schmidli, J., and Coauthors, 2011: Intercomparison of meso-scale model simulations of the daytime valley wind system. *Mon. Wea. Rev.*, **139**, 1389–1409, <https://doi.org/10.1175/2010MWR3523.1>.
- Senocak, I., A. S. Ackerman, D. E. Stevens, and N. N. Mansour, 2004: Topography modeling in atmospheric flows using the immersed boundary method. Tech. Rep., Center for Turbulence Research, NASA Ames/Stanford University, 10 pp., <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050061074.pdf>.
- Skamarock, W. C., and Coauthors, 2008: A description of the Advanced Research WRF version 3. NCAR Tech. Note NCAR/TN-475+STR, 113 pp., <http://dx.doi.org/10.5065/D68S4MVH>.
- Whiteman, C. D., K. J. Allwine, L. J. Fritschen, M. M. Orgill, and J. R. Simpson, 1989a: Deep valley radiation and surface energy budget microclimates. Part I: Radiation. *J. Appl. Meteor.*, **28**, 414–426, [https://doi.org/10.1175/1520-0450\(1989\)028<0414:DVRASE>2.0.CO;2](https://doi.org/10.1175/1520-0450(1989)028<0414:DVRASE>2.0.CO;2).
- , —, —, —, and —, 1989b: Deep valley radiation and surface energy budget microclimates. Part II: Energy budget. *J. Appl. Meteor.*, **28**, 427–437, [https://doi.org/10.1175/1520-0450\(1989\)028<0427:DVRASE>2.0.CO;2](https://doi.org/10.1175/1520-0450(1989)028<0427:DVRASE>2.0.CO;2).
- Wiersema, D. J., K. A. Lundquist, and F. K. Chow, 2016: A framework for WRF to WRF-IBM grid nesting to enable multiscale simulations. *22nd Symp. on Boundary Layers and Turbulence*, Salt Lake City, UT, Amer. Meteor. Soc., 38, <https://ams.confex.com/ams/32AgF22BLT3BG/webprogram/Paper295239.html>.
- , —, and —, 2018: Development of a multi-scale modeling framework for urban simulations in the Weather Research and Forecasting Model. *23rd Symp. on Boundary Layers and Turbulence/21st Conf. on Air–Sea Interaction*, Oklahoma City, OK, Amer. Meteor. Soc., 8A.7, <https://ams.confex.com/ams/23BLT21ASI/meetingapp.cgi/Paper/346364>.
- Zängl, G., 2002: An improved method for computing horizontal diffusion in a sigma-coordinate model and its application to simulations over mountainous topography. *Mon. Wea. Rev.*, **130**, 1423–1432, [https://doi.org/10.1175/1520-0493\(2002\)130<1423:AIMFCH>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<1423:AIMFCH>2.0.CO;2).
- , 2003: A generalized sigma-coordinate system for the MM5. *Mon. Wea. Rev.*, **131**, 2875–2884, [https://doi.org/10.1175/1520-0493\(2003\)131<2875:AGSSFT>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2875:AGSSFT>2.0.CO;2).
- , 2005: Formation of extreme cold-air pools in elevated sinkholes: An idealized numerical process study. *Mon. Wea. Rev.*, **133**, 925–941, <https://doi.org/10.1175/MWR2895.1>.
- , L. Gantner, G. Hartjenstein, and H. Noppel, 2004: Numerical errors above steep topography: A model intercomparison. *Meteor. Z.*, **13**, 69–76, <https://doi.org/10.1127/0941-2948/2004/0013-0069>.
- Zardi, D., and C. D. Whiteman, 2013: Diurnal mountain wind systems. *Mountain Weather Research and Forecasting*, F. K. Chow, S. F. J. De Wekker, and B. Snyder, Eds., Springer, 35–119.