11.A.1 Providing high-resolution surface conditions using a coupled land-surface groundwater model: effects on atmospheric boundary layer simulations over Owens Valley, CA

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1. Introduction

Flow in the atmospheric boundary layer depends significantly on the conditions at the land-surface interface. Surface heating and cooling, as well as topographic features can determine the nature of flow in the boundary layer. The extent to which the air near the land surface is heated or cooled depends on the relative partitioning of energy at the surface into latent and sensible heat fluxes. This is largely determined by the amount of water present in the soil of the land-surface (the soil moisture).

Soil moisture can change significantly over the course of a day due to precipitation events and evapotranspiration, and can vary over longer timescales with changes in vegetation growth or groundwater flow. Soil type and local topography can make soil moisture change over varying length scales as well. This kind of small-scale variability is difficult to capture in soil moisture datasets provided by continental- or global-scale models. In addition, typical land-surface models do not allow for lateral transport of moisture, and hence cannot represent spatial variability due to topography. Finally, field measurements of soil moisture are typically too sparse to provide a complete representation of the soil moisture field in a given region. For these reasons, accurate, high resolution soil moisture data is not often available to initialize mesoscale atmospheric simulations.

The focus of this study is to use a coupled land-surface groundwater model to determine a more accurate representation of the soil moisture distribution in a region of complex topography, Owens Valley in California. Results from this coupled model are then used to initialize soil moisture for high-resolution simulations of atmospheric flow over the region. Results from both the land-surface groundwater model and the atmospheric simulations are compared to observations from the Terrain-Induced Rotor Experiment which took place in Owens Valley in March and April, 2006.

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a. *Motivation*

The amount of water present in soil at the ground surface affects evaporation and transpiration, and can even change the albedo of the soil. These effects lead to changes in the partitioning of energy between sensible and latent heat fluxes at the surface and therefore affect flow in the atmospheric boundary layer. McCumber and Pielke (1981) found that soil moisture was the most important soil characteristic in determining the strength of heat fluxes between the ground and atmosphere. A study by Ookouchi et al. (1984) showed that the intensity of thermally induced circulations over flat terrain with non-homogeneous soil moisture approaches that of sea-breeze circulations when there are large differences in soil water content. Even small amounts of water contained in a patch of soil adjacent to a dry patch induce significant mesoscale flows according to their study. Idealized surface heterogeneity in the form of wet and dry strips investigated by Patton et al. (2005) was shown to significantly change the surface fluxes. The findings of Banta and Gannon (1995) indicate that a wet slope produces weaker katabatic (downslope) flows than a dry slope due to the increased thermal conductivity of moist soil and an increased downward longwave radiation flux from the atmosphere as a result of higher humidity in the air near the surface.

High-resolution surface boundary conditions for mesoscale atmospheric models are often interpolated from coarser grids. In regions of heterogeneous surface conditions this interpolation procedure can lead to misrepresentation of the surface characteristics. For example, even a large valley such as Owens Valley in California, approximately 12 km in width, is not properly resolved at coarse resolutions such as the 32 km grid used in the North American Regional Reanalysis (NARR). Since the valley is surrounded by high mountains, the 32 km NARR grid represents a portion of the valley region as one wide mountain, including snow at the summit. When the snow field is interpolated down to grids fine enough to resolve the valley (e.g. at least 3km horizontal resolution), we find at least part of the valley floor to be (unrealistically) covered in snow. Figure 1 shows an example of this problem. The snow field from 32 km NARR is shown, interpolated to a 350 m grid of Owens Valley for March 29, 2006, a date when

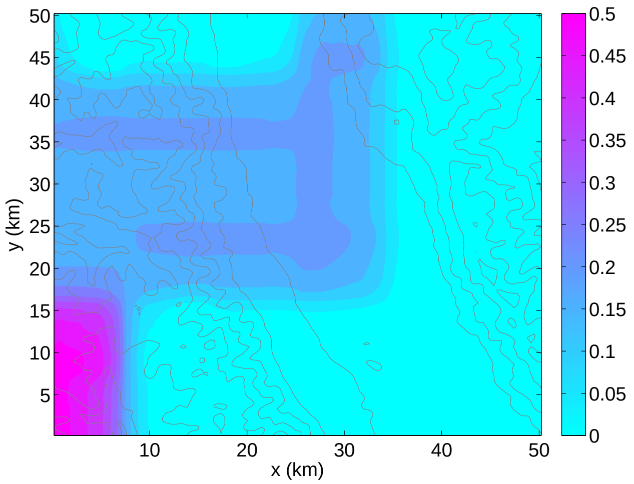


Figure 1: Contours of initial snow depth (m) from NARR interpolated to the 350m grid for Owens Valley, CA. Solid lines show topography contours. (Color contours shown in Fig. 2.)

there was no snow observed on the valley floor. Interpolated surface boundary conditions are especially problematic for surface variables that can change drastically in a short period of time, such as soil moisture, soil temperature, and snow cover.

Current land-surface models coupled to meso-scale codes, such as the ISBA model (Interactions Soil Biosphere Atmosphere), in the Advanced Regional Prediction System (ARPS) used here, are often only two-layer models. Multi-layer models exist (e.g. the unified NOAH land surface model used in WRF Chen et al. 2004; Tewari et al. 2004; Liu et al. 2004), but no current soil model allows for lateral transport of soil moisture. Thus rain accumulated on the steep Sierra slopes will not flow to the valley floor because each grid cell is isolated from its neighbors.

One way to achieve more accurate surface conditions is to run a separate hydrologic model and use the results to initialize the atmospheric model. Previous work in the Riviera Valley in the Swiss Alps showed that soil moisture initialization was a very sensitive parameter for correct prediction of valley wind transitions (Chow et al. 2006b). Running a hydrologic model (WaSiM-ETH) reduced the 3-4 hour delay in the onset of up-valley winds in the Riviera to just 1-2 hours. Improvement of surface initialization can be achieved through the use of hydrologic models; however, many hydrologic models are incapable of simulating lateral flow of water from one cell to the next. Depending on how the model is set up, this can result in a pile-up of water in certain cells, or a net loss of water from the model.

Groundwater models can simulate lateral flow of water in the subsurface. In particular, the watershed model ParFlow (Ashby and Falgout 1996; Jones and Woodward 2001; Kollet and Maxwell 2006) includes fully integrated surface and subsurface lateral flow. Maxwell et al. (2007) coupled ParFlow to ARPS, providing updated high-resolution soil moisture to the ARPS land-surface model at every time step. An off-line spin-up of ParFlow was used to generate a realistic initial soil moisture distribution in the domain. This fully coupled set-up was not necessary for this study because there was no precipitation during the time period chosen for the simulation. In previous work, Maxwell and Miller (2005) coupled a variably saturated groundwater model (ParFlow) to a land-surface model (Common Land Model). Their results showed that including an explicit representation of the water table was important in accurately determining the shallow soil moisture distribution. A slightly different coupling approach was taken by Kollet and Maxwell (2008), though the coupling still takes place through soil moisture, evapotranspiration and infiltration from precipitation.

b. *Objectives*

The coupled land-surface groundwater model of Kollet and Maxwell (2008) is used in the current study and will be referred to henceforth as PF.CLM. PF.CLM takes advantage of the more sophisticated land-surface processes calculated by CLM (such as snow processes). It is a physically-based model that does not require long historical records of precipitation data for calibration to the specific catchment, as many hydrologic models do. The objective of this paper is to describe the spin-up procedure used to determine the initial soil moisture distribution in Owens Valley, then show results of the atmospheric simulations and comparisons to observations from T-REX.

We will focus on a case with observed quiescent conditions where slope flows are important. In a valley, slope flows are observed during the day and at night. Heating of the valley side walls during the day results in bouyant, warmer air moving upslope, perpendicular to the valley axis; conversely, cooling of the valley side walls at night results in heavier, cooler air moving downslope. Similar mechanisms drive flows along the valley axis. Such flows are referred to as upvalley or downvalley (Whiteman 2000; Rampanelli et al. 2004). Thermally driven flow circulations interact with the prevailing synoptic scale winds and thus are best observed under weak synoptic conditions. It should be noted that surface fluxes affect valley flows under strong synoptic forcing as well, though these effects have not been thoroughly investigated.

Thermally driven slope flows are particularly sensitive to surface conditions, since they rely on heating or cooling of the surface. Our investigation will focus on the effects of changing the initial surface conditions in the Advanced Regional Prediction System (ARPS), used here to perform high-resolution simulations of valley flows during T-REX. To see these effects, two simulations are performed, one with a standard initialization procedure, and the other with modified soil moisture initialization from PF.CLM. Results presented here are preliminary, and meant to show the progress of an ongoing investigation into the role of soil moisture in complex terrain boundary layer evolution.

2. Owens Valley

Owens Valley is a rift valley in southeastern California located between the eastern slopes of the Sierra Nevada mountain range and the western slopes of the White and Inyo Mountains. The peaks of the Sierras reach above 4,300 m (14,000 ft) while the valley floor lies at about 1,200 m (4,000 ft), making it one of the deepest valleys in the United States. The valley is approximately 120 km in length ($\sim$75 mi) and runs approximately north-south. Dominant vegetation types on the valley floor include shrubs and grasses (Steinwand et al. 2006). Soils range from coarse sand and gravel to fine sand, clay and silt (Danskin 1998).

a. *T-REX field campaign*

The Terrain-Induced Rotor Experiment (T-REX) took place in March and April, 2006. The main goal of the T-REX field campaign was to investigate the dynamics of atmospheric rotors and lee waves in Owens Valley, with broader goals including complex terrain boundary layer development and stratospheric-tropospheric exchange. Additional scientific objectives include using the extensive T-REX datasets to validate numerical models. Improving the accuracy of mesoscale and microscale modeling is essential for better prediction of aviation hazards, downslope windstorms, as well as transport and dispersion of aerosols. A real case corresponding to Enhanced Observation Period number 2 (EOP2) of T-REX is presented in the later sections of this paper. The focus of the EOPs during T-REX was to observe boundary layer evolution over complex terrain under quiescent conditions, when surface forcing is expected to significantly influence valley flows.

As part of the T-REX field campaign, soil moisture and temperature mesurements were taken at 23 sites around Owens Valley. These are shown in Fig. 2. A more complete description of how these measurements were made can be found in Daniels et al. (2006). The soil moisture measurements collected at these sites will

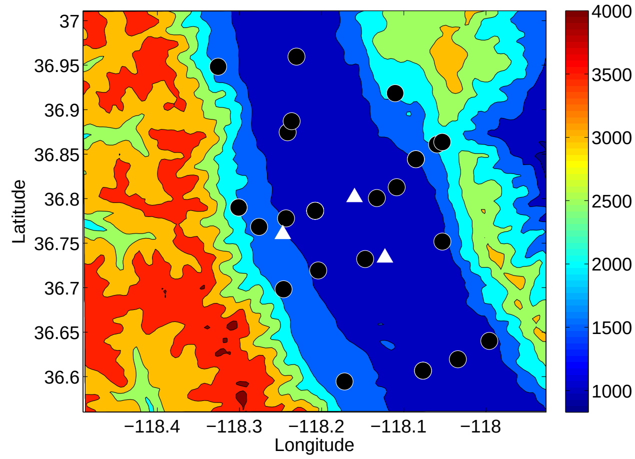


Figure 2: Elevation contours (m) of Owens Valley centered around Independence, CA from the 350 m resolution simulation domain. Circles indicate locations of soil moisture measurement sites and triangles show the three ISFF flux towers. An additional soil sensor was placed north of Independence, near Bishop (not shown).

be used for comparisons to the soil moisture results generated by the off-line spin-up of the coupled land-surface groundwater model, PF.CLM.

3. Coupled model setup

a. *PF.CLM model overview*

PF.CLM will be used to obtain a spun-up soil moisture field to initialize ARPS with a more realistic representation that includes topographic variations in soil moisture. PF.CLM is a groundwater model, ParFlow (PF), coupled to a land-surface model, the Common Land Model (CLM). CLM represents the land surface with a single vegetation canopy layer, up to 5 snow layers, and 10 unevenly spaced soil layers (Kollet and Maxwell 2008; Maxwell and Miller 2005; Dai et al. 2003). The version of ParFlow used for this research incorporates a two-dimensional overland flow simulator into a parallel three-dimensional variably saturated subsurface flow code (Ashby and Falgout 1996; Kollet and Maxwell 2006). The coupling occurs at the surface and in the first 10 layers of soil, where the domains of ParFlow and CLM overlap. All subsurface and surface flows are calculated by ParFlow and soil moisture values are provided to CLM. CLM in turn provides ParFlow with infiltration, evaporation, and root uptake fluxes (Maxwell and Miller 2005).

The coupled PF.CLM model is three-dimensional and can be run efficiently in parallel. To take full advantage of the lateral flow capabilities of PF.CLM, the model should be run in 3D; here in this preliminary work, we use a 2D version of PF.CLM to first obtain a simple representation of Owens Valley soil moisture before moving to three dimensions. The current version of PF.CLM implements uniform forcing and had not yet been extended to distributed meteorological forcing. 2D simulations have allowed us to augment PF.CLM by providing distributed forcing. The Owens Valley region has a varied climatology, such that the weather conditions in one part of the simulation domain are very different from those elsewhere in the domain. Thus, it may rain in the mountains, but remain dry on the valley floor, and it is likely that the temperature on the mountain tops is significantly cooler than that on the valley floor. It is therefore unrealistic to provide uniform meteorological forcing to the PF.CLM domain for Owens Valley. The ability to use distributed forcing, that is, meteorological conditions that vary in both space and time, was added to the PF.CLM framework. This distributed forcing will be extended to accommodate three dimensions and parallel processing in future work.

b. *Grid and subsurface initialization*

A 2D slice of the valley was chosen corresponding to the general location of the main transect of soil moisture measurement sites from T-REX, which is roughly around 36.8 degrees latitude (see Fig. 2) and passes through the town of Independence. This slice was taken directly from the finest ARPS terrain grid (see Table 1). It follows that the PF.CLM Cartesian grid for the 2D slice of Owens Valley has dx = 350 m with nx = 144 points. Vertical discretization is dz = 1 m, with a total of nz = 3250 points. Finer vertical discretization is usually preferred, but dz is limited to 1 m here due to the large number of points required for inclusion of the mountain peaks.

ParFlow maintains a full Cartesian box grid, and relies on the assignment of ”active” and ”inactive” cells to determine which parts of the Cartesian grid are in the simulation domain. For this study, only the cells in the first 500m below the ground surface were part of the ”active” domain.

As a rift valley, Owens Valley is formed by two main parallel faults running lengthwise along the valley axis and separating the alluvial fill of the valley floor from the bedrock of the mountains forming the valley walls. The subsurface of the Owens Valley region is represented in PF.CLM as bedrock below the mountain peaks and soil below the valley floor (see Fig. 3). For these preliminary simulations, constant porosity of 0.1, and hydraulic conductivity of 0.1 were used for the alluvial fill, and 0.0001 for both porosity and hydraulic conductivity of the rock

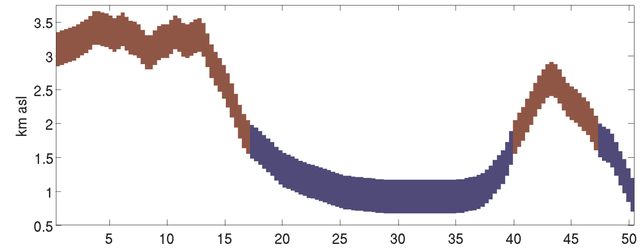


Figure 3: West-East slice of Owens Valley, with the peaks of the Sierra Nevada on the left, the Inyo Mountains on the right. CLM.PF model representation of bedrock in red and soil in blue.

beneath the peaks.

c. *Initial and boundary conditions for PF.CLM*

The initial subsurface pressure head [m] was set to hydrostatic conditions with the water table located 30m below the ground surface. Initial saturation follows directly from the pressure field, with the subsurface fully saturated below 30m. (See Fig. 4.)

CLM requires eight meteorological forcing variables as input: atmospheric pressure, precipitation rate, downward shortwave radiation flux, downward longwave radiation flux, temperature (at 2m above the ground surface), winds (U and V at 10m), and specific humidity (2m). Spatially interpolated meteorological forcing from NARR is provided to CLM at every cell on the ground surface at every time step (3 hrs). This distributed forcing allows meteoroligical conditions to vary over the PF.CLM domain during the year-long spin-up procedure.

d. *Spin-up procedure*

An off-line spin-up procedure is used here to allow the model to reach hydrologic equilibrium. PF.CLM is run for a full water year using meteorological forcing from NARR. The coupled model is run repeatedly for the same water year (2006) of forcing data until the ratio of the change in storage to the total precipitation is less than 1%. The results presented here are preliminary results from the second year of the spin-up, when this condition had not yet been met. Regardless, the soil moisture values in the 2D domain are in the same range as those measured during the T-REX field campaign. Fig. 4 shows how the pressure and saturation fields have evolved from the initial conditions after two years. Subsurface flow is much slower in the regions below the peaks since values of porosity and hyraulic conductivity in those regions are much lower than those assigned to the alluvium of the valley in the model. Changes in sat-

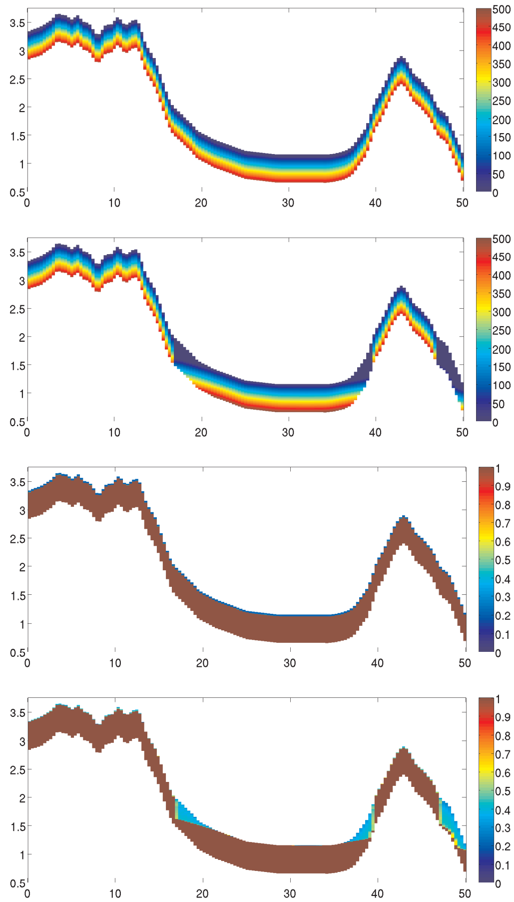


Figure 4: PF.CLM initial pressure head [m] (a), pressure [m] after 2 years of spin-up (b), initial saturation [-] (c), saturation [-] after 2 years of spin-up (d).

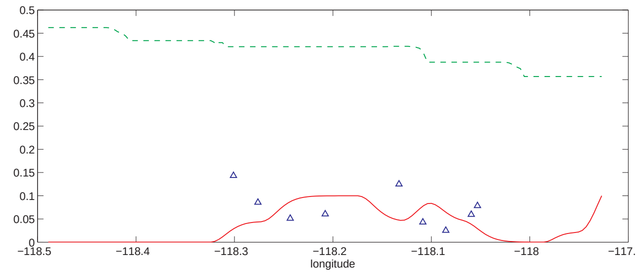


Figure 5: Transect of soil moisture (m^3/m^3) across Owens Valley near latitude 36.8. △ Observations; —— PF.CLM; ---- NARR

uration and pressure are therefore more evident in the valley region and eastern slope of the Inyo mountains.

Volumetric soil moisture is given by saturation multiplied by porosity. Thus, saturation is extracted from the surface cells at the date for which the initialization is needed (in this case, March 29, 2006). The soil moisture from PF.CLM is shown in Fig. 5, along with observed values from the main transect shown in 2, and a slice of interpolated values from NARR at the same location as the PF.CLM slice, for comparison. Soil moisture values from PF.CLM compare quite well with measured values, despite the simplifications in the representation of the subsurface and the limitations of a 2D simulation.

4. Atmospheric model setup

a. *ARPS: model overview*

The Advanced Regional Prediction System (ARPS) has been used to simulate atmospheric boundary layer flow over Owens Valley. ARPS is a comprehensive regional to storm-scale modeling and prediction system (Xue et al. 2000, 2001, 2003). It is a three-dimensional, nonhydrostatic, compressible numerical weather prediction model in generalized terrain-following coordinates and includes a full postprocessing package. Computations were performed using 16 to 64 processors at the Scientific Computing Division of the National Center for Atmospheric Research (NCAR). ARPS is used here in large-eddy simulation (LES) mode with a 1.5 order TKE turbulence closure (Deardorff 1980; Moeng 1984).

b. *Grid nesting and topography*

Four one-way nested grids were used to simulate flow conditions in Owens Valley at horizontal resolutions of 9 km, 3 km, 1 km, and 350 m (see Table 1 and Fig. 2). Topography for all grid resolutions was obtained using the USGS 3 arcsecond topography dataset. The terrain is smoothed at the edges of each subdomain so that the elevations at the boundaries match those of the surrounding coarser grid.

Horizontal grid spacing (Δh) is uniform in both directions. In ARPS, the minimum vertical spacing (Δz_{min}) is at the ground in a terrain-following σ-coordinate system. This minimum spacing, as well as the average vertical spacing (Δz_{avg}) are shown in Table 1. The domain height ($\sim$ 25 km) extends beyond the tropopause. Large (Δt) and small ($\Delta \tau$) time steps must be specified in the mode-splitting scheme used in ARPS (see Table 1). These selections of grid spacing, time steps, and other parameters such as computational mixing coefficients, were made using experience gained through previous simulations over complex terrain (Chow et al. 2006a; Weigel et al. 2006). It is worth noting however, that

Table 1: Simulation parameters for each grid level.

(nx,ny,nz)	Δh	Δz_{min},Δz_{avg}	Δt,$\Delta \tau$
(103,103,53)	9 km	50 m, 500 m	10 s, 10 s
(103,103,53)	3 km	40 m, 500 m	2 s, 4 s
(99,99,63)	1 km	40 m, 400 m	1 s, 1 s
(147,147,63)	350 m	30 m, 350 m	1 s, 0.2 s

use of the positive-definite scalar advection option significantly improved the results of both cases discussed here.

c. *Initial and boundary conditions for ARPS*

Meteorological forcing data from 32 km North American Regional Reanalysis (NARR) provided the initial atmospheric conditions as well as boundary conditions at the edges of the 9km domain. Surface soil moisture and temperature from NARR were used in the simulation referred to here as REF. A snow patch from the 32 km NARR domain covers a portion of the valley floor when the snow field is interpolated down to the finer grids. In order to provide a more realistic representation of the snow cover in the region, a snow level of 2500 m was imposed, below which the snow depth was set to zero based on National Operational Hydrologic Remote Sensing Center data, as well as observations made while in the field during T-REX.

For the simulation referred to here as SM, initial soil moisture conditions on the 9km grid were interpolated from NARR, with no modifications. On the 3km grid, NARR soil moisture was divided by three everywhere in the domain to bring the values closer to the measured valley average. Soil moisture on the two finest grids was based on the PF.CLM spin-up, and is discussed in the following section.

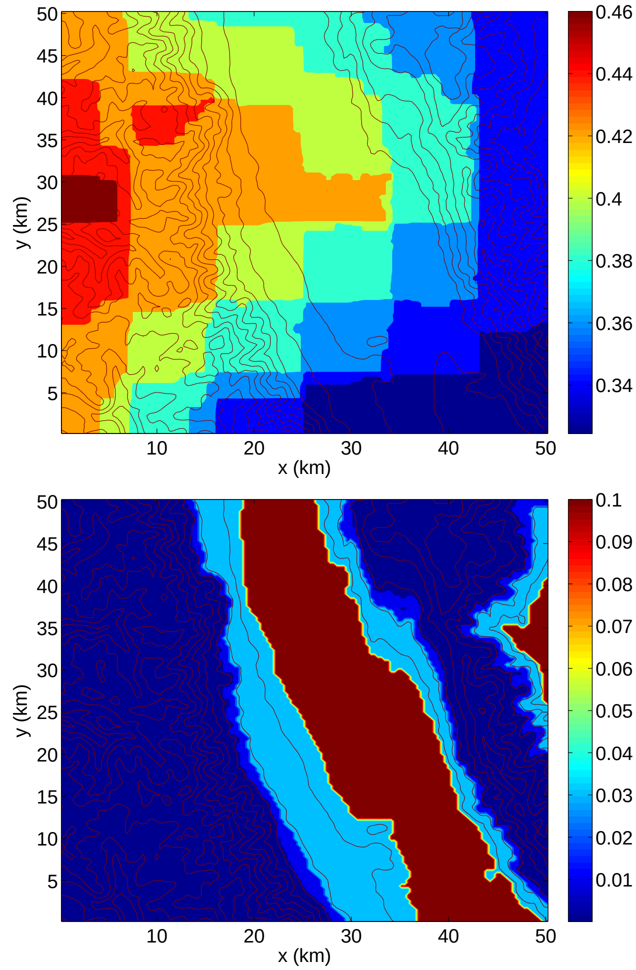


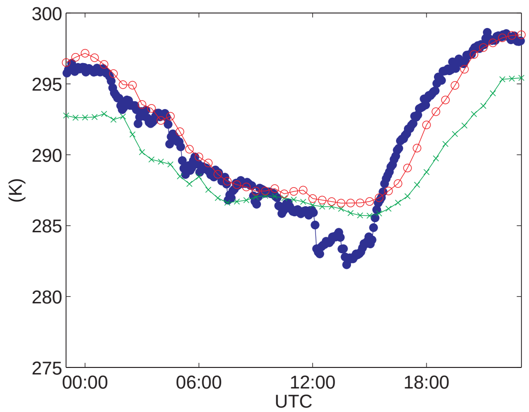
Figure 6: Contours of initial soil moisture (m^3/m^3) on the 350m grid from NARR (top, used in the REF simulation) and PF.CLM (bottom, used in the SM simulation). Solid lines show topography contours.

5. Initialization with PF.CLM

Owens Valley is in an arid region where the soil moisture does not change significantly over a few days if there is no precipitation. No precipitation was observed in the valley during the simulation period discussed here. The length of the atmospheric simulation is 36 hours, including an 11 hour spin-up period. Therefore, initialization of surface conditions, rather than updates at evey time step, is sufficient for the current study.

Since the results of the PF.CLM spin-up are for just a 2D slice of Owens Valley (one line of soil moisture values along the transect), altitude-dependent soil moisture was assigned for the 1km and 350m grids. This altitude-dependent soil moisture field differs significantly from the soil moisture field interpolated from NARR, (see Fig. 6) which was influenced by the unrealistic snow patch shown in Fig. 1. This difference is reflected in the surface heat flux.

The simulations initialized with altitude-dependent soil moisture based on the results from PF.CLM compared well with observations. Fig. 5 shows surface potential temperature for 24 hours during the simulation. Potential temperature at the surface was much better predicted by SM than by REF, though both simulations missed the observed dip in potential temperature overnight. Other surface variables, including winds and specific humidity also compared well with observations; this is reflected in the values of root mean squared errors and bias shown in Table 2. Examples of soundings of potential temperature, wind speed and direction, and specific humidity are shown in Fig. 7. Changing the soil moisture initialization had the greatest effect on the



Surface data time series of potential temperature at ISFF central tower. —•— Observations at 15 m AGL; —○— SM; —×— REF

Table 2: Overall root-mean-square errors (rmse) and mean errors (bias) for potential temperature, wind speed, wind direction, and specific humidity predicted by two ARPS cases compared to surface observations at the ISFF central tower and soundings at Independence Airport.

	Surface		Soundings	
	REF	SM	REF	SM
θ rmse (K)	2.91	1.48	1.42	1.14
θ bias (K)	-1.88	0.40	-0.39	0.10
U rmse (m/s)	3.22	1.55	2.16	2.01
U bias (m/s)	-1.97	-0.37	-0.36	-0.27
ϕ rmse (deg)	53.59	61.22	42.65	37.16
ϕ bias (deg)	1.71	35.80	-0.73	1.72
q rmse (g/kg)	1.11	0.38	0.89	0.65
q bias (g/kg)	0.88	0.03	0.57	0.39

lower 4 km of the atmosphere, which corresponds to the ridge-top height of the Sierra-Nevada mountain range. Errors for sounding comparisions over the entire simulation period are also shown in Table 2. Time-averaged root mean squared errors, and bias for the observation period presented here are lower for SM than for REF, with the exception of wind direction. The bias for wind direction in particular is an order of magnitude lower for the REF case than for the SM case. Further investigation is needed to determine why this is the case.

6. Discussion and future work

The coupled land-surface groundwater model, PF.CLM, was run with distributed forcing in an off-line spin-up procedure to obtain soil moisture fields that are influenced by topography. The agreement of the soil moisture distribution with field observations is significantly improved compared to the NARR interpolated fields. The spin-up procedure will be continued until equilibrium is obtained and the choice of subsurface soil properties will be investigated further in this ongoing work.

In a region of complex topography such as Owens Valley, it is difficult to justify the leap from 2D soil moisture from the slice simulated by PF.CLM to altitude-dependent soil moisture used here over the entire valley region. Even so, the two preliminary simulations presented here show that ARPS is sensitive to soil moisture initialization, and that even the assumption of altitude-dependent soil moisture shows much improvement in comparisons to observations at the surface, and higher up in the boundary layer. One can argue that there are probably some patterns in soil moisture that are aligned with the valley axis, however differences in soil types, (such as volcanic soils, which can have porosities of up to 0.6, compared to 0.1 used here in PF.CLM) and vegetation coverage, as well as small-scale topographical features can all influence the soil moisture field. Given the heterogeneity of the Owens Valley region, it makes sense that a model capable of resolving the land-surface of the ARPS domain, rather than a slice of it, should be used to achieve realistic soil moisture conditions.

To ensure that the influence of lateral flow at the surface and in the subsurface is accounted for, future work will include a parallel distributed forcing capability for 3D PF.CLM. Results from 3D PF.CLM simulations with distributed forcing will be compared to observations and used to initialize ARPS. In addition, results from a spin-up of the HRLDAS (NCAR High-Resolution Land Data Assimilation System) hydrologic model will also be used to initialize ARPS for comparison to the simulations initialized by the fully 3D PF.CLM spin-up results.

7. Acknowledgements

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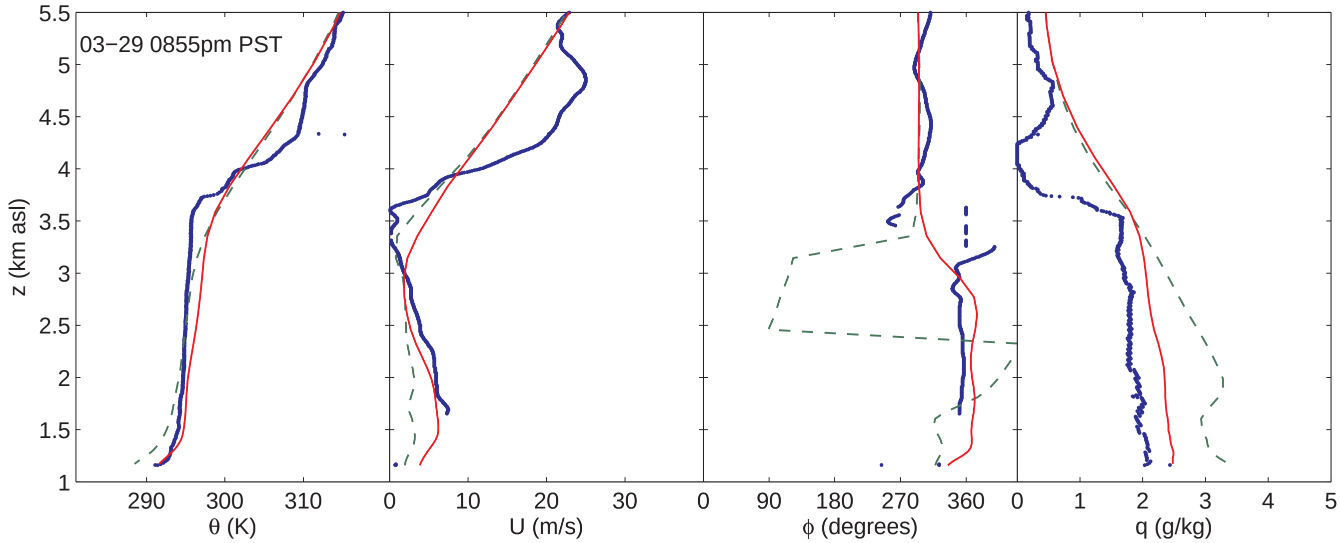

Figure 7: Soundings at Independence Airport of potential temperature, wind speed, wind direction, and specific humidity at 0855pm PST. —— Observations; —— PF.CLM; - - - - NARR

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