Modeling Cold Pools in California's Central Valley

Travis Wilson * and Robert Fovell

Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles

ABSTRACT

Despite our increased understanding in the relevant physical processes, forecasting radiative cold pools and their associated meteorological phenomena (e.g., fog and freezing rain) remains a challenging problem in mesoscale models. The present study is focused on California's Tule fog where the Weather Research and Forecasting (WRF) model's inability to forecast the event is addressed and substantially improved. An intra-model physics ensemble reveals that no current physics is able to properly capture the Tule fog and that model revisions are necessary. It has been found that revisions to the height of the lowest model level in addition to reconsideration of horizontal diffusion and surface-atmospheric coupling are critical for accurately forecasting the onset and duration of these events.

1. Introduction

Whiteman et al. (2001) defined a cold pool as a topographically confined, stagnant layer of air overlaid by warmer air aloft. A dramatic and well known example is the Tule fog of California's heavily populated Central Valley (CV), of which can persist for several days. If a cold pool last longer than one diurnal cycle it is classified as a persistent cold pool, whereas diurnal cold pools form at sunset and decay at sunrise (Whiteman et al. 2001). While the Central Valley is a common example, cold pools are most prevalent in mountain valleys during periods of high atmospheric pressure, light winds and low solar isolation (Daly et al. 2009). Due to their characteristic inversions, cold pools are also conducive to freezing rain that creates a hazard to transportation and safety (Whiteman et al. 2001).

In this paper, an attempt to properly fix the cold pool modeling problem in California's CV will be undertaken. Most recently, Ryerson (2012) noted the Weather Research and Forecasting (WRF) model's inability to produce fog in and around the CV, which was largely traced to a overnight warm bias. In order to fix this, he applied post-processing corrections which added significant overnight skill; however, due to the non-linear evolution of fog, only modest skill increases were seen after sunrise. This paper is not an attempt to amend the cold pool model problem via post processing techniques, but rather, by way of model physics improvements.

Advancements in modeling cold pools need to be made not only for forecasting fog and precipitation type, but also for air quality as it is of great concern to the U.S. Environmental Protection Agency (EPA) Office of Air Quality Planning and Standards (Baker et al. 2011). The meteorological conditions associated with cold pools create stagnant air that cannot mix out vertically due to capping inversions. This increases ozone or PM2.5 (particulate matter with diameter <2.5 um) concentrations that can exceed the National Ambient Air Quality Standard (NAAQS) in many parts of the Western United States including, but not limited to, the Pacific Northwest, the Central Valley of California, and Great Basin (Gillies et al. 2010). Of course, elevated ozone and PM2.5 levels pose a large health risk to many Americans. Despite the impact they impose on air pollution and weather, persistent cold pools have received relatively little research attention (Zhong et al. 2001).

WRF, along with the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5), have failed to reproduce the intensity and persistence of cold pools despite systematic improvements to both model physical parameterizations as well as horizontal and vertical resolution (Baker et al. 2011). Data assimilation and surface nudging have also been explored, both failing to add value to the already poor representation of cold pools (Avery 2011). Of the cold pools that are resolved, they often mix out too early, leading to erroneous surface temperatures, ozone, and PM2.5 concentrations (Avery 2011). It is becoming increasingly clear that a cold pool-aware surface and/or boundary layer schemes are needed in WRF to accurately reproduce these stagnant air quality episodes (Baker et al. 2011; Avery 2011).

The process of cold air pooling can be enhanced by sheltering from valleys and nearby trees that effectively reduce the vertical mixing that would otherwise bring warmer air down to the surface (Gustavsson et al. 1998). In addition to this, Whiteman (2000) has demonstrated that further cooling in valleys is possible simply because of their shape; a cross sectional column of air over a valley is always less than that of flat terrain. That said, Whiteman et al. (2004) showed the cooling effect is counteracted by the the downward longwave radiation originating not only from the atmosphere, but also from the valley walls.

The usual conceptual model of cold pool formation in valleys involves cool air drainage. Just after sunset, winds diminish and a shallow, stable, boundary layer forms due to the strong radiative flux divergence. Negatively buoyant air originating on the side slopes of the valley descends to the stable layer, detaches from the side wall, and flows out over the center of the basin (Clements et al. 2003). Essentially, the air aloft is efficiently cooled by the basin walls before becoming detached; this acts to enhance the cooling *above the surface* due to the sensible heat flux divergence (Whiteman et al. 1996).

Nevertheless, Whiteman et al. (1996) found the sensible heat flux at the surface to be near zero. Neff and King (1989) produced similar results in their research showing that drainage flows along the Colorado River basin overlay a stronger surface based inversion of lighter winds. This suggests that the cooling above the surface can be due to advective effects while the cooling at the bottom occurs *in situ*. It should be noted that cooling aloft by drainage flows indirectly assists the *in situ* cooling at the surface by reducing the downward longwave radiation. Though this effect is suspected to be insignificant, it is currently unclear how important it may be.

Drainage flows do not always become detached from the basin walls and have been well observed flowing in valley locations (Hootman and Blumen 1983; Gudiksen et al. 1992; Bodine et al. 2009). Yet, their role in the production of cold pools remains controversial. In the 1997 Cooperative Atmospheric Surface Exchange Study (CASES-97) at the Walnut River watershed in Kansas, LeMone et al. (2003) attributed cold temperatures at the low elevation sites to cold air drainage and radiative cooling. However, the fast drainage flows observed at higher elevations were extremely weak lower down, causing the authors to suggest that the flows were elevated over a more dense cold pool. Mahrt et al. (2001) examined the CASES-99 observations in south-central Kansas and found that while the drainage flows do exist, their influence on the surface fluxes were undetectable because the shallow flows decoupled the observations (located at 3-10m) from the surface. It is worth noting that of the surface fluxes measured, the sensible heat remained downward-directed; that is, it acted as a heat source throughout the night.

In contrast, earlier research performed by Thompson (1986) suggests that cold pool formation in open and closed valleys is a direct result of sheltering and *not* cold air drainage; the latest research agrees. In the gently sloping terrain of Oklahoma, Hunt et al. (2007) concluded that the cooling observed in cold pools occurred *in situ* which counters the results of LeMone et al. (2003). More recently, Bodine et al. (2009) found that cold pools were suppressed by the katabatic winds in the Lake Thunderbird Micronet, a dense collection of surface stations (28 stations) in the gently sloping terrain of Lake Thunderbird, Oklahoma. In fact, they went as far as stating that, "pooling of cold air as a result of drainage flow can clearly be excluded as a factor causing the CP [cold pool] development at the micronet". Instead, cold pool formation was likely caused by the cooling that occurred *in situ* due to the radiative heat loss and diminishing turbulent heat transfer in sheltered regions.

Sometimes, drainage flows are not even observed, as Clements et al. (2003) has shown. When inspecting the closed 1km Peters Sinks basin in Utah, the winds ceased in the entire basin roughly 2 hours after sunset when they became "too weak to measure accurately". This led to their conclusion that downslope flows in the Peters Sinks basin play only a minor role in the formation of cold pools. These weak flows were somewhat expected as Katurji and Zhong (2012) have shown that weaker drainage flows do correspond to smaller basins with larger slope angles in two-dimensional idealized simulations. Additionally, they found the main cooling process near the basin floor (<200m) to be the longwave radiative flux divergence, while the vertical advection of temperature dominated the cooling process in the upper basin area.

Although the production of cold pools may be slightly controversial, the latest research agrees that temperatures are not further reduced due to cold air drainage. This is important because if they were, drainage flows of only a few meters would be extremely difficult to resolve and would somehow have to be parameterized. However, since this is not case, we believe cold pools in California's Central Valley can be resolved with relatively coarse resolution.

2. Methodology

Using WRF version 3.5, cold pools in California's Central Valley will be modeled with and without several modifications to the default WRF. Different atmospheric initializations were tested and their influence was deemed relatively unimportant; because of this, all atmospheric variables will be initialized from the North American Regional Reanalysis (NARR). In contrast, simulations were sensitive to the soil initialization, so we have consequently chosen to extract these surface fields from a variety of sources including the NARR, North American Mesoscale model (NAM), ERA-Interim, and from offline simulations spun using NCAR's High Resolution Land Data Assimilation System (HRLDAS). Offline forcing for the HRLDAS system was made available via phase 2 of the National

Aeronautics and Space Administration's (NASA's) North American Land Data Assimilation System (NLDAS).

The simulation period of interest is December 4th-16th 2005, a mostly dry and stagnant period conducive for cold pool formation. Minimal precipitation fell from a weak front that made its way though the CV on December 8th and 9th. The model reconstructions will combined a sequence of shorter, overlapping simulations, in which a new run is initialized (as a cold start) every other day. This means the first 24 hours is overlapped by the previous simulation and is subsequently removed. Offline HRLDAS simulations were initialized from the NAM model January 1st, 2004 and integrated until our time of interest, December 2005.

The model setup includes a doubly nested design with a horizontal resolution of 36 and 12km in addition to 51 vertical levels. The area encompassed by the 36km domain can be seen in Fig. 1 with the 12km nest shaded. The standard model physics included Lin microphysics, the Rapid Radiative Transfer Model (RRTM) and Dudhia radiation, Yonsei University (YSU) Planetary Boundary Layer (PBL) scheme, and the Kain-Fritsch cumulus parameterization. This setup will be referred to as the default WRF.

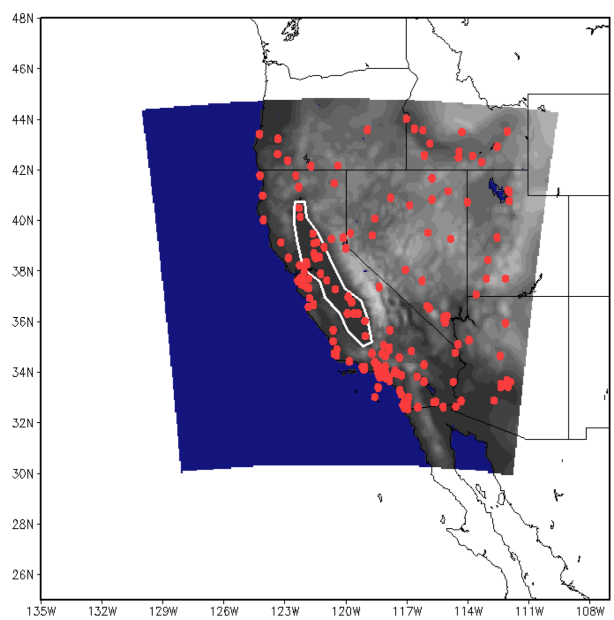

Fig. 1. The 36 (white) and 12km (colored) domains used throughout all simulations. The red dots represent surface ASOS or AWOS stations used to verify the model while the white polygon enclose stations used in the CV subset.

Validations of the weather reconstructions have been performed principally with the Model Evaluation Tools (MET) software, maintained by the Developmental Testbed Center at NCAR. This package was used to compare observations to model reconstructions spatially interpolated to the observation point. Observational data were collected from the Meteorological Assimilation Data Ingest System (MADIS) which consists of surface ASOS and AWOS stations. The exact locations of these data used to verify the model are shown in Fig. 1 (red dots) which will occasionally be referred to as the Full domain statistic. However, since we modeling cold pools in California's CV, results will focus on statistics computed from a subset of stations outline by white polygon called the CV subset.

3. Results

Observed and modeled relative humidity (RH) from December 5th-8th for the CV subset can be seen in Fig. 2 with error bars representing plus or minus one standard deviation. Here, overnight relative humidity values are extremely moist – upwards of 90% – and the variation among observations is quite small. In contrast, the WRF default using atmospheric and soil initializations form the NARR – abbreviated Noah/YSU NARR – is several standard deviations away from reality. Not much better, despite it being our best reconstruction, is the Noah/YSU NARRera; abbreviated this way because the atmosphere is still initialized from the NARR, but using soil information from the ERA-Interim. Furthermore, simulations with soil information from the HRLDAS and NAM – labeled NARRspun and NARRnam, respectively – are very comparable, and actually a bit worse.

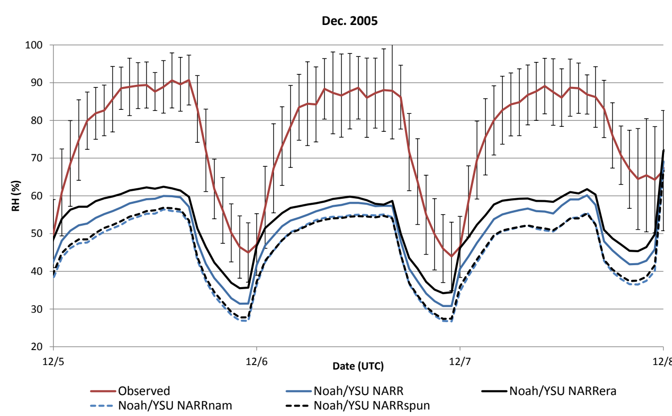

Fig. 2. Observed and modeled relative humidity for the CV subset (Fig. 1) during December 2005. Plus or minus one standard deviation for observed RH is shown.

It should noted that the large errors from the simulations done in this time period are by no means unique, but rather quite typical. If one inspected the entire simulation period, December 4th-16th (shown later), results look very similar. Furthermore, reconstructions from different years yield the same answers. It is important to note that this bias in relative humidity is a result of both warm overnight temperatures and low dew points.

Areas for Improvement

The default WRF is by no means capable of forecasting cold pools as was shown in Fig 2. In fact, it will be shown that the default setup actually prevents them from forming in the first place. Because of this, a number of modification will be performed to properly forecast the diurnal and persistent cold pools in the Central Valley.

1) DIFFUSION

It has been shown that horizontal diffusion operating along sigma coordinates can have an impact on forecasting topographically confined cold pools (Billings et al. 2006; Zängl 2005). However, examining its impact on the CV's Tule fog is important, and to the authors' knowledge, has not been done. A dramatic example of the effects of diffusion is presented in Fig. 3. Here, visible satellite imagery (Fig. 3a) shows the Tule fog encompassing the entire San Joaquin Valley at 10am local time January 5th 2011.

This is compared to the total modeled condensate (g/kg) in the lowest 4 sigma levels for the Noah/YSU NARR (Fig. 3b). One can observe that almost no fog is present in the simulation that has diffusion operating on model levels; however, when diffusion is turn off – abbreviated as Noah/YSU+diffopt0 NARR – the problem is fixed (Fig. 3c). This is because when diffusion operates on model levels, which is the default in the WRF model, warmer and drier air from the surrounding mountain ranges is forced down the slope into the CV. This quickly erodes any fog that may have formed and substantially inhibits any future development. It should be noted that while only a morning snapshot is shown here, this particular Tule fog lasted throughout the day, which is certainly not uncommon for winter months. The simulation without diffusion correctly simulated the fogs persistence.

For this resolution, there is no option currently available in the WRF model that has diffusion operating in physical space. This is a problem due to the fact that high profile weather events such as fog and freezing rain may go completely undetected. It has been suggested and discussed that WRF even add a simple diffusion option that operates on model levels, but becomes inactive as grid points approach sloping terrain. As of now this has not been implemented, but it is agreed that the second best option would be to deactivate horizontal diffusion completely.

Billings et al. (2006) noted that increasing the horizontal resolution could produce results similar to lower resolution runs that had diffusion calculated on *model levels*. Testing this in the Tule fog case revealed that 4km horizontal resolution runs with diffusion on, had results similar to that of 12km with no diffusion. However, increasing the horizontal resolution to account for the limitations of diffusion in the WRF model is not a practical solution, especially because of the increased computation cost. Many parts of the Southern San Joaquin Valley approach or even exceed 100km in width, meaning at 12km horizontal resolution, the 8 grid points resolving the valley are insufficient for diffusion calculated on model levels. If one considers that most valleys in the Western United States are substantially smaller than the CV, increased resolution will always result in unresolved features that could be resolved if diffusion was handled properly. So as previously stated, increased resolution is not the solution, but a way to mask diffusion errors when calculated on sigma levels.

Reverting back to our December 2005 case, particularly the 5th-8th, one can find the average overnight (12Z) relative humidity in the Central Valley is around 87% (Fig. 2). This is compared to our NARR and HRLDAS initialized soils which had a relative humidity of 58 and 54%, respectively (Fig. 2). Now, deactivating diffusion and rerunning simulations results in an 11% increase in overnight relative humidity. Certainly a large improvement, but values still several standard deviations away from the observed mean. While deactivating diffusion can improve forecasts for certain events, like the January 2011 Tule fog, it is not a cure all and additional modifications need to be explored.

TABLE 1. Default and shifted sigma levels used in WRF simulation.

Default	0.993	0.983	0.970	0.954	0.934	0.909
Shifted	0.997	0.986	0.972	0.955	0.935	0.909

2) COUPLING STRENGTH

The coupling strength between the atmosphere and land is controlled by the exchange coefficient, C_h, among other factors. Chen and Zhang (2009) found that the Noah LSM underestimated values of C_h in forested regions while simultaneously overestimating it in more barren landscapes. In order to account for the changes in coupling strength due to vegetation heights, they made modifications to the thermal roughness length that is referred to as IZ0TLND in this paper, or more simply, IZ0. With this option, their results were in better agreement with the long-term AmeriFlux data. Simulations presented in this paper also benefited from this option and will be discussed in depth momentarily.

3) SHIFTED LEVELS

Our last area of improvement focuses on the height of the lowest model level. By default, this level is set to 0.993, which is approximately 27 m above the surface. This is independent of the number of vertical levels specified. When

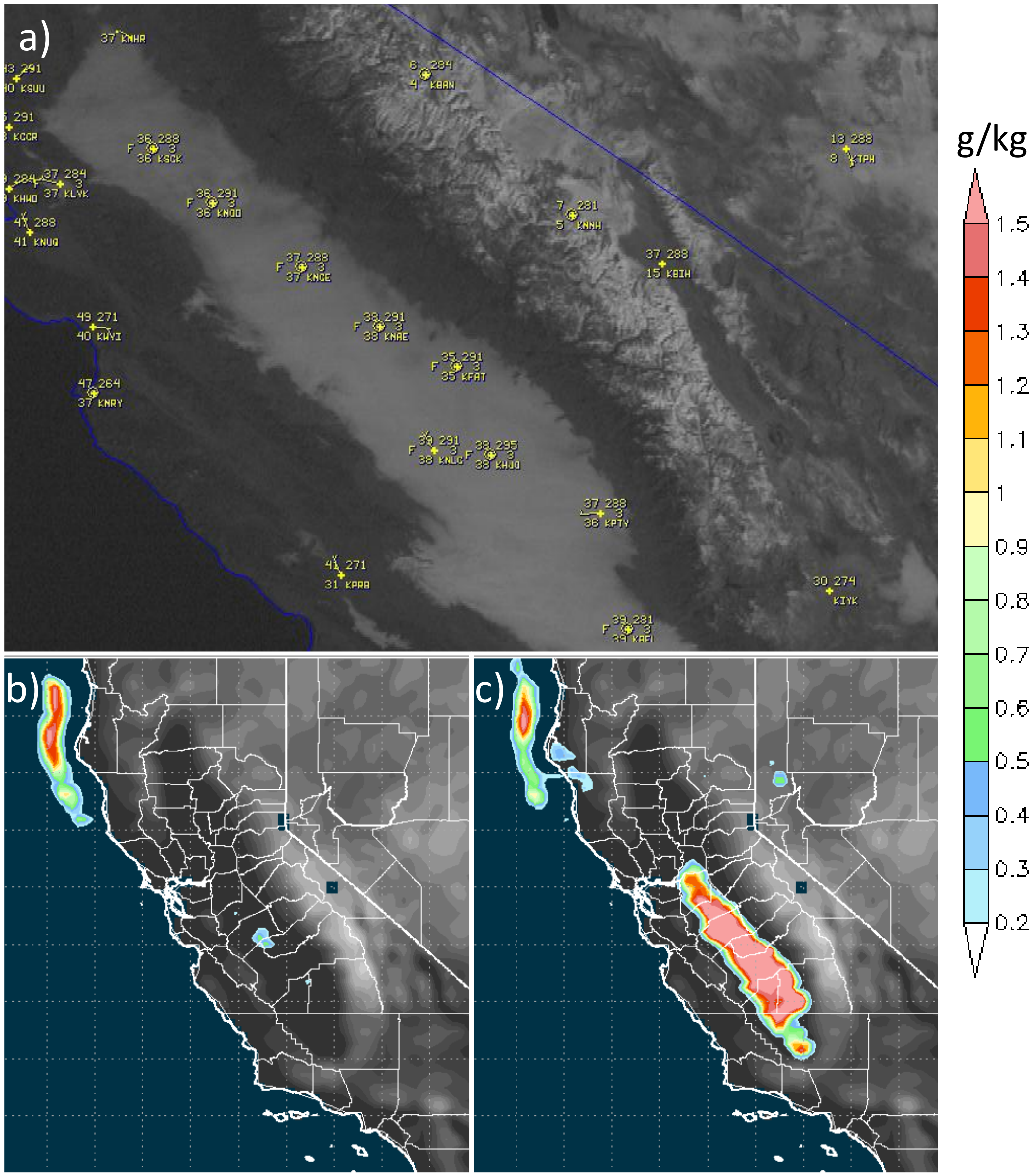

Fig. 3. Visible imagery (a) captured by GOES-11 at 18Z Jan. 5th 2011 centered over the San Joaquin Valley. At bottom, Total condensate (g/kg) on the lowest 4 sigma levels for the Noah/YSU NARR (a) and Noah/YSU+diffopt0 NARR (b) during the same time period.

one sets the lowest sigma value to 0.997, which is approximately 13 m above the surface, a slight shift in the energy balance, among other changes, can be observed which has a positive impact on simulations. Additionally, the next 4 model levels are also shifted downwards so there is no large jump in resolution; the exact values of each level can be seen in Table 1. While resolution is increased at the surface, it is decreased – though slightly – aloft since no additional levels were added. This modification will sometime be referred to as 'levels' in the labels applied to experiments.

Results with improvements

The results with and without our 3 areas of improvement – which may all be referred to as the cold pool configuration – are presented in Fig. 4 from December 6th-8th Here, the observed temperature (at top) and dew point (at bottom) are plotted against the the default simulation (black) for the CV subset. Here, the previously discussed warm bias in temperature and dry bias in dew point can

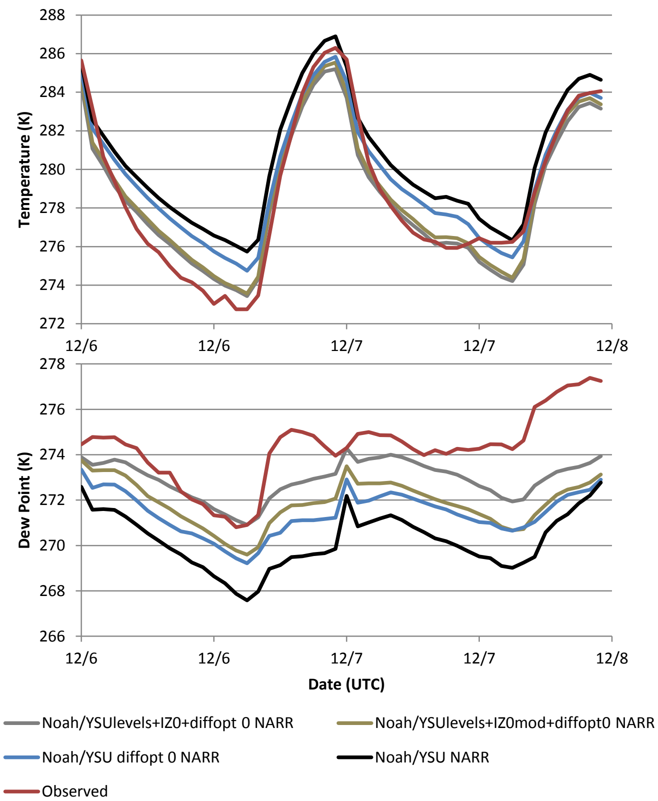

FIG. 4. Observed and simulated temperatures (at top) and dew points (bottom) from December 6-8th for the CV subset.

be observed, a common occurrence throughout our entire simulation period. By turning off diffusion (Noah/YSU diffopt0), an improvement in both temperature and dew point can be seen.

Implementing all improvements (gray line), which is labeled as Noah/YSUlevels IZ0 diffopt0, one can see another incremental decrease in temperature and increase in dew point that is roughly the same magnitude as just turning off diffusion. The overnight minimum temperatures (15Z) appear to be more realistic and have virtually no bias (only 0.1 K) when averaged over the entire simulation period, December 4th-16th. This is a substantial improvement over the default WRF which had an overnight minimum that was, on average, 2.4 K too warm. The dew point is also improved but still has a slight dry bias which is maximized during the day.

Interestingly enough, the increase in evaporation and consequently dew points due to the IZ0TLND option does not arise from the Central Valley, but rather from the surrounding terrain. Figure 5a illustrates this by showing the average latent heat flux difference between a run utilizing IZ0TLND to one that does not from December 6-8th 2005. Then, just by shifting the levels, evaporation further increases (Figure 5b), though by a substantially smaller amount. During this 48 hour period one can see that the amount of evaporation from the run utilizing the IZ0TLND option increases by roughly 5-25 W/m^2 in the surrounding terrain and while only 5 W/m^2 is caused by shifting the levels. The areas with the largest differences arise from the landuse categories that have the largest roughness lengths, landuse 11-15. These are forested regions which are easily seen in Fig. 5. It should be noted that while the simulations presented in Fig. 5 are initialized using NARR soils, results are independent of initialization.

It was hypothesized that the increase in dew points seen throughout the Central Valley from our cold pool configurations were a direct result of the increased evaporation in surrounding terrain. In order to test this, a modified version of the IZ0TLND option, called IZ0mod, was created with the IZ0TLND option activated everywhere except landuse 11-14 (the forested terrain that surrounds the CV). The results from this modified version is presented in Fig. 4 as Noah/YSUlevels IZ0mod diffopt0 NARR. Here, we can see that the dew point from the modified version looks strikingly similar to the member that does not have the IZ0TLND option activated. This means for dew points, the increased evaporation from the surrounding forests acts to increase moisture in the CV. For surface temperature (Fig. 4 top), the modified version of the IZ0TLND options resembles the member utilizing all cold pool configurations. So, the increase in dew points is a non-local effect while the decrease in temperature is local, a result from both shifted levels and IZ0TLND.

TABLE 2. Dew point bias for the CV subset using different WRF configuration during December 6th-8th.

Configuration	Dew point Bias (K)
Default	-4.07
Diffopt0	-2.86
IZ0+Diffopt0	-1.96
Levels+IZ0+Diffopt0	-1.35
Levels+IZ0mod1+Diffopt0	-2.40
Levels+IZ0mod2+Diffopt0	-2.27

Presented in Table 2 is a summary of how each modification changes the dew point in California's CV from December 6th-8th. Starting from the top, one can see that turning off diffusion decreases the dry bias by about 1.2 K. Now, if one were to add IZ0TLND (IZ0 + Diffopt0) it would further mprove the dry bias to -1.96K, a 0.9K change. However, it is when the levels are shifted (Levels + IZ0 + Diffopt0) do things become interesting. This

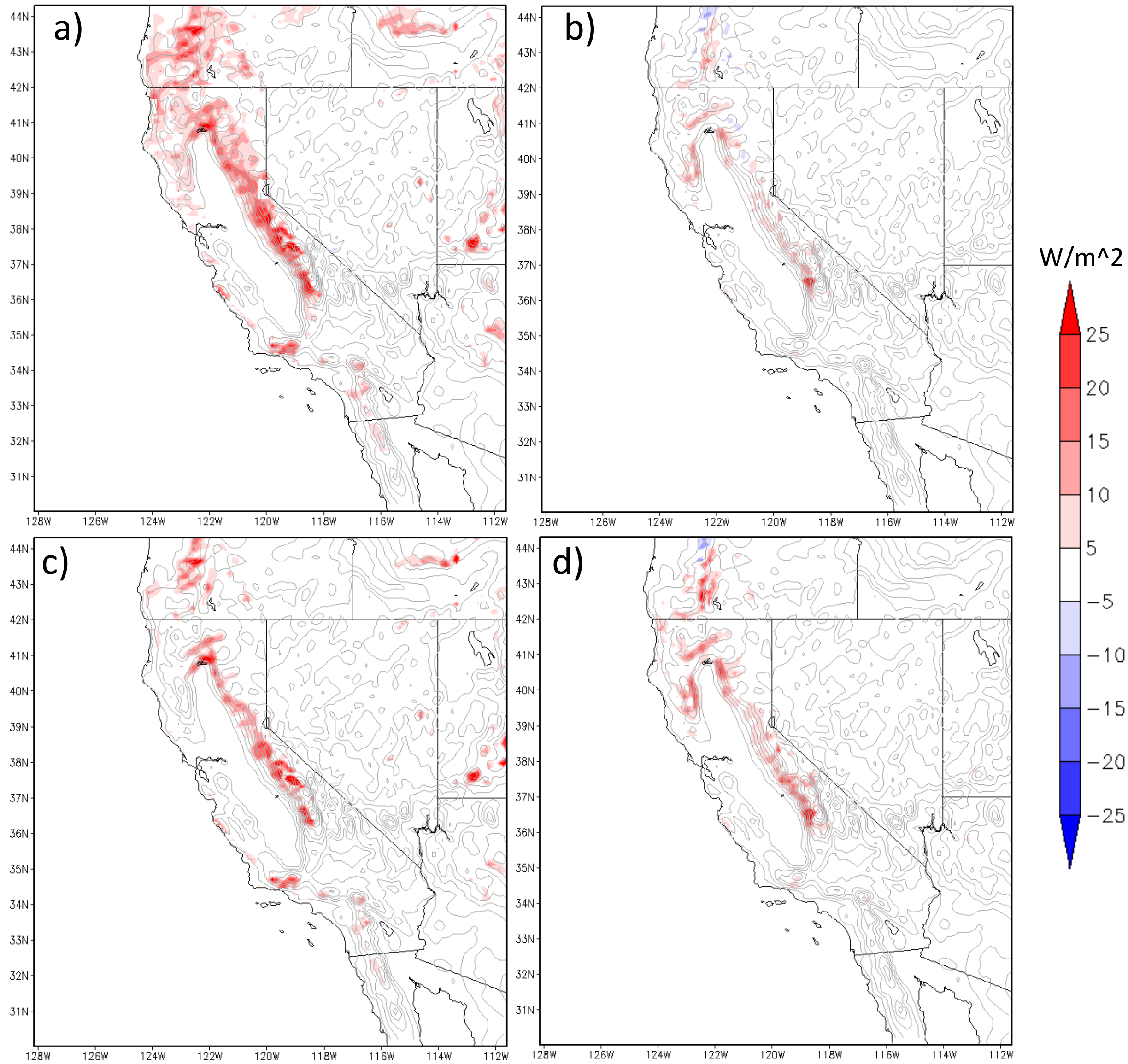

FIG. 5. The average latent heat flux (W/m^2) difference (shaded) from December 6-8th for the Noah/YSU+IZ0+diffopt0 minus Noah/YSU+diffopt0 (a), and Noah/YSUlevels+IZ0+diffopt0 minus Noah/YSU+IZ0+diffopt0 (b). Figures c and d correspond to figures a and b, respectively, but illustrates the difference for only overnight (00Z-12Z) hours. Results presented here use the NARR dataset, although, results are independent of initialization. Terrain is contoured every 300m.

is because you do not see a small improvement, which is suggested by Fig. 5b, but a rather large 0.61K dry bias reduction.

In order to explain why such a small increase in the latent flux caused by shifted levels (Fig. 5b) can bring a large increase to dew points relative to IZ0TLND (Fig.5a), one needs to inspect different hours of the day. Fig. 5c,d are the same images as Fig. 5a,b; however, they show the increased latent heat flux from overnight hours only. When viewed this way, the differences between the IZ0TLND option and shifted levels are much smaller. Because of this, it was hypothesized that not only was evaporation from landuse 14 making a difference, but more specifically, the *nighttime* evaporation had the largest effects.

To test this theory, another modified version (mod2) of IZ0TLND was created that was activated everywhere except landuse 14 at nighttime (00Z-12Z). This means the larger evaporation rates seen during the day in landuse 14

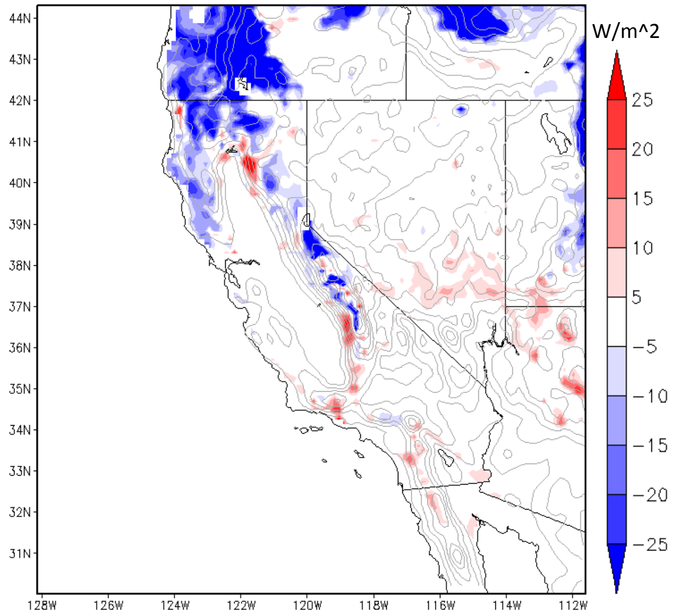

FIG. 6. The average latent heat flux difference between the Noah/YSUlevels + IZ0 + diffopt0 NARR and offline HRLDAS (with IZ0TLND activated) at 12Z from December 4th-16th

would still exist but the nighttime values would reflect that of the default WRF. This version is compared to mod1 (Table 2) which had IZ0TLND implemented everywhere but landuse 14. Here, one can observe that by allowing more evaporation during the daytime but not at night, the dry dew points bias was reduced by a mere 0.13K to -2.27K. If the daytime evaporation made the difference, one would expect to see a dew point bias of -1.35K (Levels + IZ0 + Diffopt0) or of similar magnitude.

The cold pool modifications presented here increase evaporation to mitigate the dry bias, but this may not be consistent with offline simulations. Simply put, is it possible to evaporate more water in the online simulations while the offline model evaporates less. So by reinitializing the model every other day, which is done here, evaporation could be inconsistent and wouldn't be an appropriate fix for modeling cold pools.

To demonstrate the consistency between the online/offline model, Fig. 6 shows the average latent heat flux difference at 12Z from December 4th-16th between an online (Noah/YSUlevel+IZ0+diffopt0 NARR) and offline (HRLDAS with IZ0 activated) simulation. Here, cooler colors represent less evaporation from the online simulation while warmer colors represent more. One can observe that the majority of places surrounding the CV have too little evaporation relative to the offline model. This means that every time the model is reinitialized, places shaded in blue end up losing soil water that should have evaporated into the atmosphere. Of course, the offline model is not necessarily correct, but it is concerning to see such large inconsistencies between online/offline simulations.

The results presented in Fig. 6 are an average at 12Z because the nighttime evaporation was found to be of large importance. However, if one inspects the 24 hour average, not much difference is observed. Figure 6 also shows the NARR relative to the HRLDAS; this was done because the NARR had the largest overnight evaporate rates in landuse 14, owing to its high soil moisture content in this area. This means the ERA, NAM, and spun soil underestimated the evaporate rates even more.

When the IZ0TLND option is activated in the WRF model, technically one should re-spin the soil to account for the changes in the exchange coefficient, however; this has been deemed not necessary and can be explained in the following example. Two simulations were made using the same physics (Noah/YSUlevels IZ0 diffopt0) but with different soil initialization, one spun, and another spun with IZ0TLND activated. Because IZ0TLND was activated offline, the December 6-8th dew point bias shifted by 0.23 K in the full domain while the CV change was only 0.17 K. This difference may be important for some applications, but we find it irrelevant. Because of this small difference, we activated the IZ0TLND option online without re-spinning the soils offline. In addition to this, the other soil datasets (NAM, NARR, ERA) do not provide this option. However, it should be kept in mind that re-spinning the soils is the proper technique, and would change our results by the small magnitude mentioned above.

The different soil initialization used in this study have a dramatic range in moisture values, unfortunately. This is illustrated in Fig. 7 (top), which shows the average soil moisture from December 4-16th for the 21 surface station in the Central Valley by latitude. Here, one can observe that the NAM initialized soils (NARRnam) are actually quite similar to the ones spun offline in the HRLDAS. However, when one compares the average simulated dew points for that same time period (Fig. 7 bottom), the dry bias still persists, especially in the San Joaquin Valley. Of course, the bias would be much worse (Fig. 4) if the cold pool configurations were not utilized.

Even higher moisture content can be seen in the NARR initialized soils. Consequently, the average dew points are also higher, although still too dry. This is the case for all stations except in the northern fringe of the Sacramento Valley where a shallow moist layer had trouble mixing out. For these two stations (KRDD, KRBL), modeled dew points were similar to the rest of the valley, although, observations show that KRDD and KRBL are on average, drier.

Finally, the simulations initialized with ERA-Interim soils, labeled NARRera, provides even more soil moisture

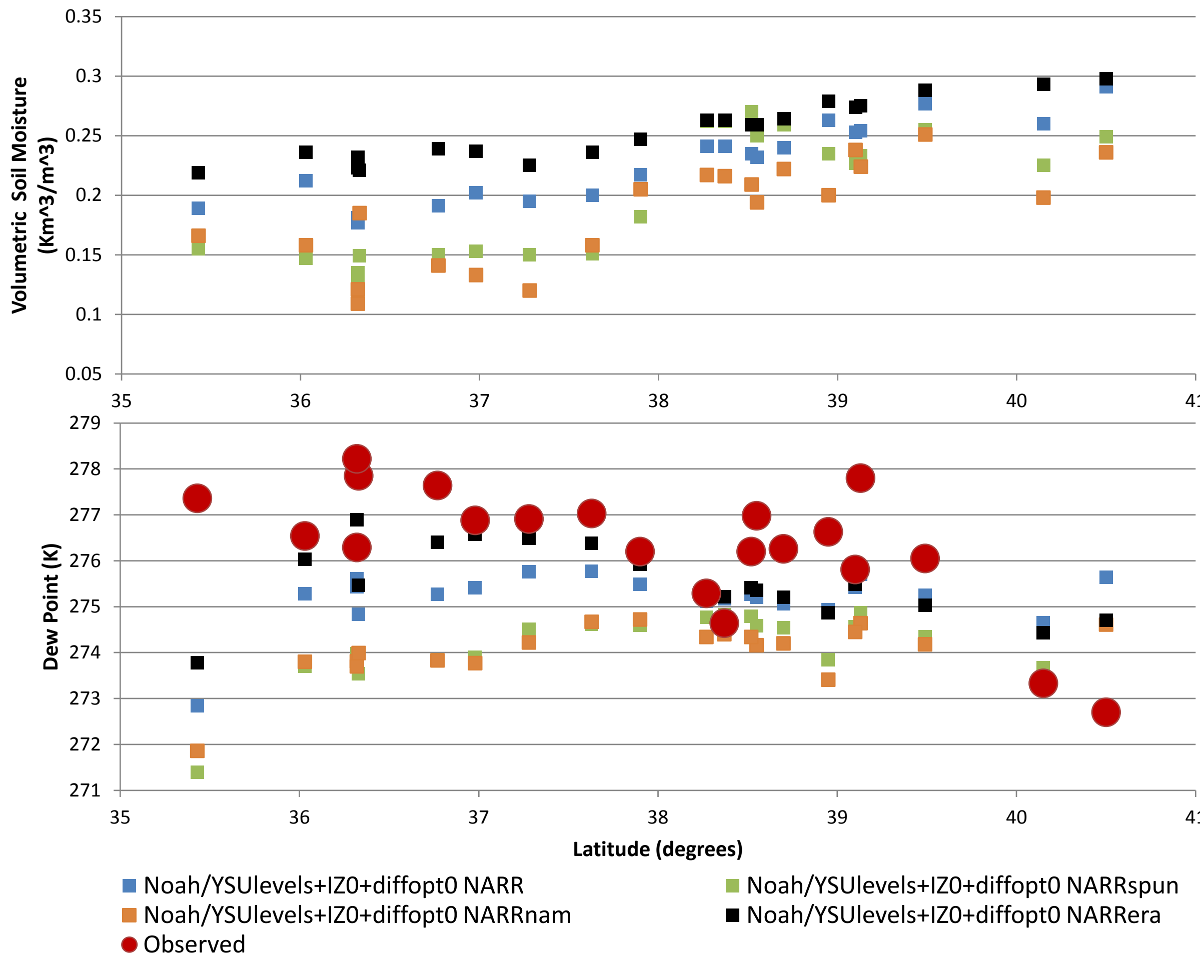

FIG. 7. Average dew point (bottom) and soil moisture (top) from December 4-16th for the 21 surface stations in the Central Valley by latitude.

for the San Joaquin Valley with only slightly more for the Sacramento Valley. This provides a rather large increase in dew points for the area while the Sacramento Valley remains relatively unchanged. With this initialization, the bias between the two valleys is roughly the same magnitude (-1.1K) instead of increasing (in the negative sense) with decreasing latitude, which is most apparent with the NAM and HRLDAS soil initialization.

Because the ERA-Interim soils have the highest water content, it also has the highest latent heat flux in the online simulations. In order to judge whether these larger fluxes are within reason, we can compare modeled fluxes to the Vaira and Tonzi Ranch AmeriFlux sites located south and east of Sacramento. This is shown in Fig. 8 (bottom) for December 4-15th. Notice that both Tonzi and Vaira Ranch are represented by the same model grid point, owing to their close proximity.

Here, one can observe that the two observations do not agree necessarily well for afternoon values, with Vaira Ranch having larger evaporation rates. Nevertheless, the two simulations initialized with ERA-Interim appear to lie between the observations on most days. Additionally, one can observe that shifting the levels and activating IZ0TLND hardly affects the latent heat flux (except late on the 8th) in the CV. This is consistent with Fig. 5.

As mentioned earlier, this option has the most dramatic impact on the forested regions surrounding the CV which is illustrated in Fig. 8 (top). Here, the simulation with shifted levels and IZ0TLND produces larger fluxes throughout the majority of the day. When compared to observations it does appear that these values are too large, though, as both simulations overestimate observed values December 4-8th. Focusing on the later half of the simulation period (9-15th) there appears to be more agreement with observations, although shifted levels and IZ0TLND still slightly over-predict evaporation on most days.

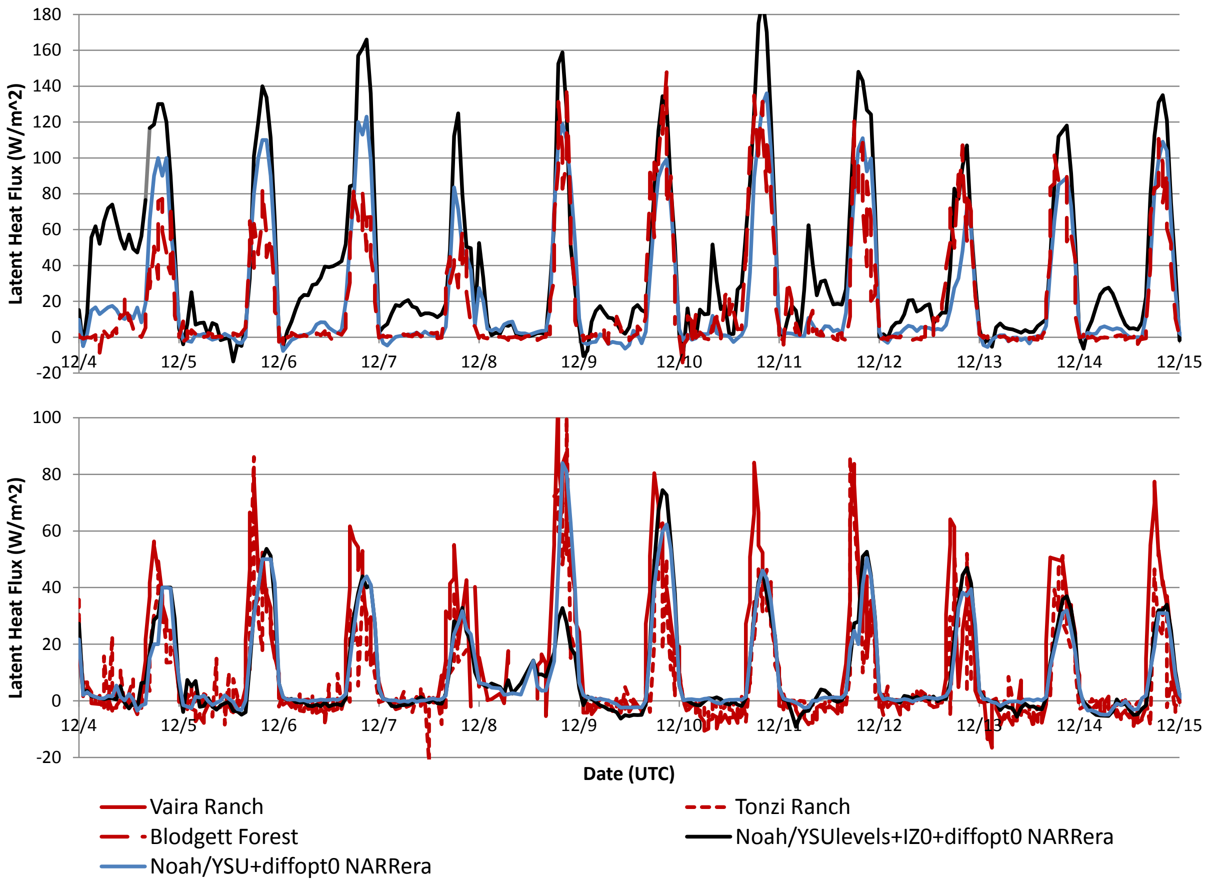

FIG. 8. Observed and modeled latent heat fluxes from december 4th-15th for three Ameriflx sites. Vaira and Tonzi ranch are located on the eastern esge of the CV and are located only 3km apart. The Blodgett Forest site is located further east in the Sierra Nevada mountain range surrounded by evergreen needleleaf forest.

One should also keep in mind that this is the only AmeriFlux site surrounding the CV with publicly available data. Because of this, nothing can be concluded, although, these disagreements should be noted. Additionally, one can observe somewhat large variations just between the Vaira and Tonzi ranch flux sites (Fig. 8 bottom) which shows that there can be large spacial variations and/or difficulties estimating fluxes.

A final look at the observed and modeled relative humidity in the CV is presented in Fig. 9 for December 4th-16th. Here, the default WRF using ERA soils (Noah/YSU NARRera) is compared to simulations using all cold pool configurations (Noah/YSUlevels + IZ0 + diffopt0 NARRera). One can see that on almost all nights, the prevalent dry bias is completely removed. It is important to note that on nights such as the 13th and 14th, where the modeled relatively humidity is quite close to reality, cold pool configurations do not overpredict CV relative humidity values.

4. Conclusion

Results presented here show that the near surface temperatures and dew points are sensitive to the model configuration, which by default gives erroneously dry values of relative humidity. Given the numerous travel corridors in the Central Valley and widespread occurrences of fog, this cannot go overlooked. It was found that diffusion operating along model levels severely degraded simulations by forcing warmer and drier air down into the Central Valley. The other diffusion options found in WRF, diffopt 2, operates in physical space which would fix this problem but unfortunately, cannot run at this resolution.

At the time of this writing other diffusion option are being explored, motivated by this work. A possible solution would be to deactivate the diffusion along sharply sloping points thereby alleviate the problem. In fact, by doing so means that other diffusion options such as diffopt 2, could potentially work at lower resolutions like the one used in this study. As of now, these options are only in the test-

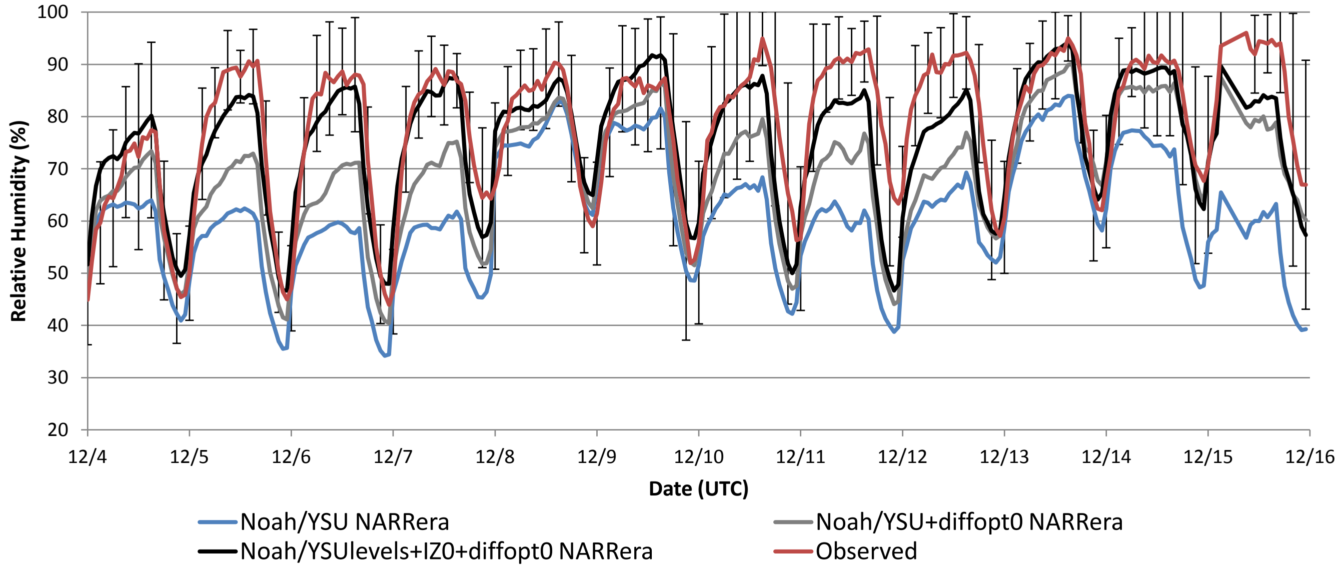

FIG. 9. Observed and modeled relative humidity for the CV subset (Fig. 1) from December 4-16th 2005. Plus or minus one standard deviation for observed RH is shown every third hour.

ing phase so the next best solution would be to deactivate diffusion completely.

Furthermore, it was found that shifting the default vertical levels and activating the IZ0TLND option could further improve the dry relative humidity bias. It was found that small shifts in the surface energy balance due to these options decreased overnight minimum sensible temperatures. Additionally, these options acted to increase the Central Valley dew points because of increased evaporation in the surrounding forests. While both the day and nighttime evaporation increased, only the changes observed in nighttime values were of significance. It can be said that all three cold pool configurations acted to decrease the temperature while also increasing dew points.

Additional research is needed to verify that the larger latent heat flux observed in the forests in the online/offline simulations are in fact, realistic. Due to insufficient flux data around the CV, verification will require running offline simulations in other forested areas and times. With that being said, more consistent evaporation rates between online/offline simulations are needed since the online model almost always underevaporates. The underlying goal of spinning models offline is to be consistent, yet consistency was never achieved here. Understanding the exact reasons why is desirable and ongoing.

California's Central Valley is home to many urbanized areas which are often plagued by diurnal and persistent cold pools conducive for dense fog. Recommendations presented here bring large improvements which can dramatically improve forecasting the non-linear evolution of these events.

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REFERENCES

Avery, L., 2011: Challenges of meteorological and photochemical modeling of utahs wintertime cold pools. Western Meteorological, Emissions, and Air Quality Modeling Workshop, Boulder, CO.

Baker, K. R., H. Simon, and J. T. Kelly, 2011: Challenges to modeling "cold pool" meteorology associated with high pollution episodes. *Environmental Science and Technology*, **45(17)**, 7118–9.

Billings, B. J., V. Grubišić, and R. D. Borys, 2006: Maintenance of a mountain valley cold pool: A numerical study. *Monthly Weather Review*, **134**, 2266–2278.

Bodine, D., P. M. Klein, S. C. Arms, and A. Shapiro, 2009: Variability of surface air temperature over gently sloped terrain. *Journal of Applied Meteorology and Climatology*, **48**, 1117–1141.

Chen, F. and Y. Zhang, 2009: On the coupling strength between the land surface and the atmosphere: From viewpoint of surface exchange coefficients. *Geophys. Res. Lett.*, **36**, L10 404, doi:10.1029/2009GL037 980.

Clements, C. B., C. D. Whiteman, and J. D. Horel, 2003: Cold-air-pool structure and evolution in a mountain basin: Peter sinks, utah. *Journal of Applied Meteorology*, **42**, 752–768.

Daly, C., D. Conklin, and M. Unsworth, 2009: Local atmospheric decoupling in complex topography alters climate change impacts. *International Journal of Climatology*, **30**, 1857–1864.

Gillies, R. R., S. Wang, and M. R. Booth, 2010: Atmospheric scale interaction on wintertime intermountain west low-level inversions. *Weather and Forecasting*, **25**, 1196–1210.

Gudiksen, P. H., J. M. L. Jr., C. W. King, D. Ruffieux, and W. D. Neff, 1992: Measurements and modeling of the effects of ambient meteorology on nocturnal drainage flows. *Journal of Applied Meteorology*, **31**, 1023–1032.

Gustavsson, T., M. Karlsson, J. Bogren, and S. Lindqvist, 1998: Development of temperature patterns during clear nights. *Journal of Applied Meteorology*, **37**, 559–571.

Hootman, B. W. and W. Blumen, 1983: Analysis of nighttime drainage winds in boulder, colorado during 1980. *Monthly Weather Review*, **111**, 1052–1061.

Hunt, E. D., J. B. Basara, and C. R. Morgan, 2007: Significant inversions and rapid in situ cooling at a well-sited oklahoma mesonet station. **46**, 353–367.

Katurji, M. and S. Zhong, 2012: The influence of topography and ambient stability on the characteristics of cold-air pools: a numerical investigation. *Journal of Applied Meteorology and Climatology*, **51**, 1740–1749.

LeMone, M. A., K. Ikeda, R. L. Grossman, and M. W. Rotach, 2003: Horizontal variability of 2-m temperature at night during cases-97. *Journal of the Atmospheric Sciences*, **60**, 2431–2449.

Mahrt, D. Vickers, R. Nakamura, M. R. Soler, J. L. Sun, S. Burns, and D. H. Lenschow, 2001: Shallow drainage flows. *Boundary Layer Meteorology*, **101**, 243260.

Neff, W. D. and C. W. King, 1989: The accumulation and pooling of drainage flows in a large basin. *Journal of Applied Meteorology*, **28**, 518–529.

Ryerson, W. R., 2012: Toward improving short-range fog prediction in data-denied areas using the air force weather agency mesoscale ensemble. Ph.D. thesis, Naval Postgraduate School, Monterey, California.

Thompson, B. W., 1986: Small-scale katabatics and cold hollows. *Weather*, **41**, 146153.

Whiteman, C. D., 2000: *Mountain Meteorology.* Oxford University Press, 355 pp.

Whiteman, C. D., T. Haiden, B. Pospichal, S. Eisenbach, and R. Steinacker, 2004: Minimum temperatures, diurnal temperature ranges, and temperature inversions in limestone sinkholes of different sizes and shapes. *Journal of Applied Meteorology*, **43**, 1224–1236.

Whiteman, C. D., T. B. McKee, and J. C. Doran, 1996: Boundary layer evolution within a canyonland basin. part i: Mass, heat, and moisture budgets from observations. *Journal of Applied Meteorology*, **35**, 2145–2161.

Whiteman, C. D., S. Zhong, W. J. Shaw, J. M. Hubbe, X. Bian, and J. Mittelstadt, 2001: Cold pools in the columbia basin. *Weather and Forecasting*, **16**, 432–447.

Zängl, G., 2005: Formation of extreme cold-air pools in elevated sinkholes: An idealized numerical process study. *Monthly Weather Review*, **133**, 925–941.

Zhong, S. C., D. Whiteman, X. Bian, W. J. Shaw, and J. M. Hubbe, 2001: Meteorological processes affecting the evolution of a wintertime cold air pool in the columbia basin. *Monthly Weather Review*, **129**, 2600–2613.