The Impact of Positive-Definite Moisture Advection and Low-Level Moisture Flux Bias over Orography

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ABSTRACT

Overprediction of precipitation has been a frequently noted problem near terrain. Higher model resolution helps simulate sharp microphysical gradients more realistically but can increase spuriously generated moisture in some numerical schemes. The positive-definite moisture advection (PDA) scheme in the Weather Research and Forecasting (WRF) model reduces a significant nonphysical moisture source in the model. This study examines the 13–14 December 2001 second Improvement of Microphysical Parameterization through Observational Verification Experiment (IMPROVE-2) case, in which PDA reduces storm-total precipitation over Oregon by 3%–17%, varying with geographical region, model resolution, and the phase of the storm. The influence of PDA is then analyzed for each hydrometeor species in the Thompson microphysics scheme. Without PDA, the cloud liquid water field generates most of the spurious moisture because of the high frequency of sharp gradients near upwind cloud edges. It is shown that PDA substantially improves precipitation verification and that subtle, but significant, changes occur in the distribution of microphysical species aloft. Finally, another potential source of orographic precipitation error is examined: excessive low-level moisture flux upstream of regional orography.

1. Introduction

Mesoscale weather models have become increasingly important tools for short-term precipitation forecasting as more powerful computers and progressively higher resolution provide more realistic simulations of mesoscale features (Stoelinga et al. 2003; Fritsch et al. 1998; Colle and Mass 2000; Mass et al. 2002). However, a number of studies (e.g., Garvert et al. 2005a, 2007; Colle et al. 2000) have found that high-resolution simulations still have deficiencies in their moisture variables, even when the synoptic-scale flow is well forecast. An essential question is whether the source of these problems lies in deficiencies in microphysics, numerics, or some other model aspect, such as the boundary layer parameterization or initialization.

Attempts to address these problems through more sophisticated model microphysics parameterizations have improved model verification but substantial deficiencies still exist. For example, Garvert et al. (2005a,b) documented localized overprediction in the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) on the windward slopes and over a broad region in the lee of the Cascade Range; similar results were obtained using the Canadian global weather forecast Global Environmental Multiscale (GEM) model (Milbrandt et al. 2008), using a triple-moment scheme. Woods et al. (2007) designed and tested a bulk microphysical parameterization (BMP) for MM5 with snow habit prediction, but this more complex approach did not improve the precipitation forecasts beyond the older Thompson scheme (Thompson et al. 2004, 2008), which applied a simple mass–diameter relationship.

Numerical deficiencies are another potential source of error, and both the MM5 and initial versions of WRF lacked positive-definite advection (PDA) schemes. This paper examines the implications of PDA over orography, describes the specific impact of PDA for various microphysics species, and places the considerable research using MM5 and WRF regarding orographic precipitation in context. Finally, another source of model error will be reviewed: model deficiencies in initializing and simulating the moisture fluxes approaching the Northwest terrain.
2. Positive-definite moisture advection

Some moisture quantities, such as cloud liquid water, tend to have sharp gradients. The proximity of these sharp gradients to zero values makes these variables particularly susceptible to the generation of negative quantities in numerical integration schemes that are not positive definite. Such schemes usually set negative values to zero, thereby adding artificial moisture to the model.

Several mesoscale weather models, such as the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) and the Regional Atmospheric Modeling System (RAMS), already possess positive-definite advection—the latter for over 20 yr (Tremback et al. 1987). Even with positive-definite advection, some RAMS simulations have produced precipitation overprediction in both warm and cool seasons. However, this bias declines at high resolution, in contrast to the MM5 and WRF studies, and some of the bias has been attributed to inadequate parameterization of convection (Cotton et al. 2006; Saleeby et al. 2007). The COAMPS model, run in large-eddy simulation mode for a cloud sensitivity study, produced a significant increase in cloud-top height, thickness, and spatial coverage over time for a non-PDA (NOPDA) simulation (leapfrog with second-order differencing), whereas the PDA [hybrid third-order Bott (1989) scheme] cloud field changed little with time (J. M. Schmidt and J. D. Doyle 2008, personal communication). To correct the problem of nonphysical moisture addition in the WRF model, a positive-definite numerical scheme was recently added to the Advanced Research Weather Research and Forecasting model (ARW-WRF), version 2.2 (Skamarock 2006; Skamarock et al. 2008), and its impacts over and near terrain will be explored in this paper.

Two recently published papers documented the effects of the PDA scheme in WRF on hydrometeors and quantitative precipitation forecasts (QPF). Skamarock and Weisman (2009) simulated warm-season convective precipitation and found that 1) PDA remedies the nonconservation of water in the forecasts; 2) PDA reduces, but does not completely remove, the positive precipitation forecast bias; 3) cloud liquid water is the most significant contributor to nonphysical moisture generation in the NOPDA scheme; and 4) the effects of the PDA scheme are significantly reduced as horizontal grid spacing increases. For the 4–5 December 2001 landfalling midlatitude cyclone, Lin and Colle (2009) performed simulations using four different microphysics schemes [Lin, the WRF Single-Moment 6-Class (WSM6), and two Thompson versions], with and without PDA. For the 1.33-km domain over western Oregon, PDA reduced domain-average hydrometeors by 10%–20% aloft, with precipitation decreases of 25%–45% over the Coast Range and 10% over the windward slopes of the Cascades. They attributed the greater reductions over the Coast Range to sharp gradients associated with convective cells triggered by this barrier. For the NOPDA model runs, precipitation exceeded available water sources, whereas water was better conserved with PDA.

There are a number of issues regarding application of PDA in WRF that have not been resolved. What are the effects of PDA over orography for more stable flow regimes and different synoptic configurations? Exactly where is PDA altering the moisture fields and which species are most affected? How does PDA influence the precipitation verification across the domain? Are there other factors that contribute to precipitation overprediction in some areas? These questions will be addressed in this paper, providing a context for understanding the results of previous studies.

3. 13–14 December 2001 IMPROVE-2 case

The Improvement of Microphysical Parameterization through Observational Verification Experiment (IMPROVE) collected a comprehensive observational dataset, capable of evaluating the accuracy of microphysical representations at the core of bulk microphysical schemes. To study the detailed effects of the WRF PDA scheme over terrain, this work examines the 13–14 December 2001 IMPROVE-2 case [intensive observing period 9 (IOP-9)], which has been extensively validated against observations obtained during that field campaign. The 13–14 December IMPROVE-2 case provides one of the best documented examples of the interaction between Pacific frontal systems and orography. The storm was characterized by strong low-level cross-barrier flow, heavy precipitation, the passage of an intense baroclinic zone, and overprediction over the windward slopes of the Cascades and in a broad region in their lee (Garvert et al. 2005a,b). Colle et al. (2005) investigated the microphysical pathways and sensitivities for this storm, finding that excessive snow generation aloft contributed significantly to an area of overprediction in the immediate lee of the crest. With comprehensive data and a large body of literature describing its evolution, this case has become a standard to which others are compared, such as the weaker, more convective 4–5 December 2001 event (Lin and Colle 2009).

4. Method

This study compares PDA (Skamarock 2006) and NOPDA simulations, an approach distinct from studies
of Skamarock and Weisman (2009) and Braun (2006), which assessed the amount of negative precipitation that is removed or clipped. The ARW-WRF, version 2.2, is used for all runs presented here, with 32 vertical model levels and nests of 36-, 12-, 4-, and 1.33-km grid spacing (Fig. 1). Global Forecast Model (GFS) analyses for every 6 h combined with GFS forecasts at 3-h intervals provided input data for all model runs. Analysis nudging of wind, temperature, and water vapor toward the GFS solutions was performed in the free troposphere only for the outer 36- and 12-km domains from 0000 UTC 13 December through 0000 UTC 14 December for all runs. The model setup in this study uses the Medium-Range Forecast (MRF) planetary boundary layer scheme, Community Atmosphere Model (CAM) radiation, and second-order diffusion (horizontal only). Advective transport is fifth order in the horizontal and third order in the vertical, providing some inherent diffusion (Skamarock et al. 2008). All model runs use the Thompson microphysics scheme with updates similar to those found in WRF version 3.0. The Thompson scheme predicts cloud liquid water, cloud ice, rain, snow, graupel, and water vapor, as well as cloud ice number concentration. Thompson uses both ice water content and temperature to generate snow size distributions, which it represents as a sum of exponential and gamma distributions (Thompson et al. 2008).

Several types of model experiments were performed. The first was designed to investigate the aggregate effects when PDA is applied to all microphysical species simultaneously versus none at all. For these simulations, the model was run for 36 h from 0000 UTC 13 December to 1200 UTC 14 December, with hourly output. The second set of experiments evaluated the influence of the PDA scheme for the individual hydrometeor variables in the Thompson scheme.

5. Results

As noted above, positive precipitation biases in MM5 and WRF have been identified over and downwind of the Pacific Northwest terrain, both for the 13–14 December 2001 event and other cases. Figure 2 illustrates cumulative precipitation over the 36-h simulation of the December 2001 event in the 1.33-km domain without and with PDA (Figs. 2a,b, respectively). Both simulations show significant orographic precipitation enhancement over the coastal mountains and the Cascades. The PDA scheme produces a general contraction of precipitation areas for all threshold values and attenuates the large maxima in the accumulated precipitation field associated with the higher topographic features (red; 200+ mm). Figures 2c,d present PDA – NOPDA absolute and percentage precipitation differences, respectively. Large absolute differences are associated with regions with higher precipitation, particularly over the windward slopes of the Cascades. The largest percentage differences of both signs occur to the lee of the Cascade crest. Moderate percentage enhancements by NOPDA compared to PDA occur to the lee of the coastal mountains and over the windward slopes of the Cascades.

Storm-total summary statistics (Fig. 3) quantify the differences between PDA and NOPDA model runs for varying resolutions and regions of interest: coastal waters, coastal mountains, Willamette Valley, windward Cascades slopes, and leeward Cascades slopes. Two trends are discernable: 1) the effects of the PDA scheme become greater at higher resolution for each region of interest and 2) the PDA-related reductions are largest over the windward slopes of the Cascades, where the largest absolute precipitation totals occur. On the 1.33-km grid, PDA-induced precipitation reductions over the windward slopes are 17.2%, whereas over the coastal waters the reductions are only 6.6%.

Figure 4 depicts meridionally averaged precipitation differences and percentage difference fields between PDA and NOPDA model runs beginning at 0000 UTC 13 December and extending through 1200 UTC 14 December. The percentage of spuriously generated precipitation increases rapidly to the lee of the coastal range and remains high until the lee slopes of the Cascades and thus is not solely a function of orographic enhancement. In contrast, the absolute difference field varies closely with precipitation amount, increasing rapidly on the western slopes of the coastal and Cascade ranges.

How can one explain the distribution of PDA impacts across the zonal transect in Fig. 4? First, sharp mesoscale
moisture gradients over the coastal range induce spurious generation of cloud mixing ratio, some of which is converted to precipitation. Because of the narrow extent of the coastal barrier, the spurious precipitation tends to fall over the crest and to its lee. The nonphysical enhancement of precipitation continues downwind over the Willamette Valley because of enhanced water vapor produced by evaporation of the spurious cloud over and east of the coastal mountains. Sharp mesoscale moisture gradients over the windward Cascade slopes lead to increased nonphysical moisture production by NOPDA and the maximum absolute and relative differences between the PDA and NOPDA runs.

For comparison, the 4–5 December event (Lin and Colle 2009) featured a distribution of PDA-related precipitation reductions with larger (25%–45%) decreases over the coastal mountains than over the Cascades (10% decrease); the corresponding reductions for the 13–14 December event were 9.8% and 17.2%, respectively. During the 13–14 December storm, the Cascade windward slopes received nearly twice as much precipitation as the coastal range; in contrast, there were nearly equal amounts during the 4–5 December event. Colle et al. (2008) noted significantly lower moist static stability for the 4–5 December case than for the 13–14 December event. The rapid triggering of convective cells, observed in radar and satellite imagery, as flow impinged upon the coastal range, likely produced very strong moisture gradients for the 4–5 December storm over the coastal mountains and thus enhanced differences between the PDA and NOPDA runs for that event.

Analysis of the impacts of PDA for individual hydrometer variables on the 1.33-km grid initialized 2100 UTC 13 December (Fig. 5) supports the finding of Skamarock and Weisman (2009) that cloud liquid water is associated with the greatest PDA moisture reductions among the simulated hydrometeor species. Indeed, running the model with PDA applied only to the cloud water field, “PDA cloud,” decreases modeled
precipitation over the Coast Range almost as much as the full PDA run and decreases precipitation nearly half as much as the full PDA run over the Cascades. Over the entire 1.33-km domain, PDA cloud reduces precipitation by 8.4%, PDA rain reduces precipitation by 1.7%, PDA snow and PDA graupel each reduce precipitation by 0.5%, and vapor and (cloud) ice PDA have negligible impacts. The origin of these relative contributions will be examined later in the paper. When PDA is applied to all variables, PDA-related precipitation reductions are 17.1%, a greater reduction than the 11.1% total obtained by adding the PDA effects of each individual variable. Nonlinear interactions among the microphysical variables most likely account for this difference and will be considered later.

Although the cloud water contributes the most spurious moisture in the NOPDA simulations, complex microphysical interactions between hydrometeor variables obscure this dominance. Figure 6 illustrates mixing ratios averaged both in time (36 h) and horizontally in the 1.33-km domain for the PDA and NOPDA runs. Figure 6a presents the vertical distributions of the hydrometeors for both runs; PDA reduces hydrometeor values for all fields. Precipitating hydrometeor species (rain, snow, and graupel) accumulated the additional moisture generated by the cloud water field for the NOPDA simulation.

Figures 6b,c show the PDA-NOPDA difference and the percentage difference, respectively. The vapor field accumulates a significant amount of the spurious moisture generated in other fields. Above 1000 m, the difference fields for vapor and snow align quite well with the difference field for cloud water; it may be inferred that vapor and snow receive much of their additional moisture directly from cloud. A secondary maximum in the PDA-NOPDA cloud field difference at low levels (mainly orographic clouds <1000 m) corresponds to a secondary increase in vapor and rain supporting the linkage between these fields, but not snow, because of the high freezing level during the storm. The large percentage change in graupel demonstrates the efficacy with which snowflakes collect excess cloud liquid water.

Zonal cross sections at 44.4°N of storm-averaged hydrometeors for the PDA and NOPDA simulations are shown in Fig. 7. There are widespread reductions in rain, snow, cloud, and graupel mixing ratios and their extent when PDA is applied. Particularly large reductions are evident in the snow hydrometeor field, both in the peak snow region anchored to the Cascade crest and in the lee of the Cascades. PDA also reduces low-level cloud, particularly over the Willamette Valley. For both PDA and NOPDA model runs, the overlap between mixing ratio types is largest over orography and creates the potential for rapid and nonlinear redistribution among the various microphysical species. The reduction in snow mixing ratios aloft results in the PDA run lessening, albeit not completely, the overprediction of snow mixing ratios documented at altitudes between 4.9 and 6 km in Garvert et al. (2005b).

Next, the spatial distributions of the spurious moisture generation are examined. The 24-h forecast of the NOPDA model run initialized at 0000 UTC 13 December 2001 provides inputs for two new model runs, PDA cloud and NOPDA, with output analyzed 1 min into each simulation. Figure 8 presents vertical cross sections based on these two simulations from west of the coastal range to the lee of the Cascades. Figure 8a illustrates the cloud field for the PDA-cloud run, the difference between PDA-cloud and NOPDA-cloud fields, and wind vectors in the $x$–$z$ plane. Large reductions by PDA (negative PDA − NOPDA; dashed) occur predominantly on the upstream side of orographic clouds at low

<table>
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<th>4 km</th>
<th>1.33 km</th>
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<td>-5.1%</td>
<td>-13.6%</td>
<td>-17.2%</td>
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<td>Cascade Leeward</td>
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<td>-8.1%</td>
<td>-10.3%</td>
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<td>-10.6%</td>
<td>-13.4%</td>
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levels, with additional reduction maxima at higher levels on the upstream edges of synoptic clouds. There is little indication that PDA affects the lee side of clouds or regions where the gradients in cloud mixing ratio are small. PDA should have its greatest effect in regions of sharp moisture gradients. Exploring this contention, Figs. 8b,c depict the magnitude of the cloud gradient and cloud advection, respectively. Nearly all of the large PDA − NOPDA differences occur in regions of particularly sharp gradients and advection. Because horizontal winds and gradients are significantly larger than vertical motions and gradients, horizontal advections dominate. Figure 8d combines the principal factors that lead to spurious generation of moisture. The magnitude
Fig. 6. Vertical plots of mixing ratios averaged horizontally and over 36 h of model output for the NOPDA and PDA runs for (a) the distributions of mixing ratio for the NOPDA (solid line) and PDA runs (dashed line) for the various microphysical species, (b) the difference in mixing ratios between the two model runs (PDA-NOPDA), and (c) the percentage change between the two runs as defined in Fig. 2d.
of the gradient is depicted, as in Fig. 8b, but only gradients with positive mixing ratios adjacent to zero cloud mixing ratio values in a neighboring grid cell within the plane of the cross section are shown. Advection of spuriously generated moisture during the 15 model time steps prior to the output time (1 min into the model simulation) resulted in a phase lag between the location of the edge gradient and the location of the PDA – NOPDA differences.

Why is PDA important for the cloud field compared to other hydrometeor variables? Figure 9 illustrates the distribution of “hydrometeor-edge mixing ratios,” defined as the magnitudes of nonzero mixing ratios that are adjacent to zero mixing ratio values in the same hydrometeor category for variables in the Thompson microphysics scheme. The vapor field is not shown because vapor maintains positive values at every grid cell in the domain. The magnitudes of the edge mixing ratios...
for cloud are an order of magnitude larger than those of any other variable. Rain edge values are next largest, followed by snow, graupel, and finally ice. This ordering corresponds precisely to the magnitude of spurious moisture production for each hydrometeor variable in the NOPDA model run. The far larger magnitude of cloud–edge mixing ratio values compared to precipitating hydrometeor-edge mixing ratio values may be explained by larger overall magnitudes and gradients of cloud liquid water compared to other variables. In addition, there are problems with the Thompson scheme, which removes rain, snow, and graupel incompletely, leaving diffuse edges (G. Thompson 2008, personal communication) that lessen the impact of PDA.

PDA-related reductions vary significantly with the phase of the storm. Table 1 presents summary statistics for the 1.33-km domain, using the regions defined in Fig. 3. PDA reduced domain-total precipitation by 24.4% during the prefrontal period [forecast hours (FH) 0–18], 8.5% during the frontal period (FH 19–24), and 17.5% during the postfrontal period (FH 25–36). The frontal period roughly corresponds to the duration of modeled stratiform precipitation, ending with the passage of the cold front aloft over the east end of the domain (approximately hour 24). In contrast, the influence of positive-definite advection was the least when precipitation was heaviest during the frontal period. To help explain this temporal variation, Fig. 10 presents cloud-edge gradients for the NOPDA model run that are subdivided into prefrontal, frontal, and postfrontal time periods. The sharpest cloud edges occur during the prefrontal period, followed by the postfrontal, and
finally the frontal. This order corresponds exactly to the order of the impact of positive-definite advection, with the largest influence during the prefrontal period.

The temporal variations in cloud-edge mixing ratios can be understood by considering the temporal variations in cloud mixing ratio (not shown). During the prefrontal period, cloud mixing ratios average 2–5 g kg\(^{-1}\), with some values, in association with mountain waves, as large as 9 g kg\(^{-1}\). During this period, the low-level cloud never fills in the valleys, allowing enhanced gradients. During the frontal period, cloud mixing ratios are lower (0.5–2.5 g kg\(^{-1}\)), and cloud is widespread at low levels. In contrast, during the postfrontal time period, the modeled clouds appear more convective with higher mixing ratios, exceeding 4 g kg\(^{-1}\) in stronger crest-anchored clouds. Together, increased convection, higher mixing ratios, stronger crest-anchored clouds, and the absence of background synoptic-scale cloud, lead to increased horizontal gradients during the postfrontal period.

Figure 11 presents the domain-integrated cloud and precipitating hydrometeor (rain, snow, and graupel) mixing ratios for the 36-h PDA and NOPDA model runs. Simulated precipitating hydrometeors peak during the frontal period (19–24 h), when the influence of PDA is the least. Increasing precipitation clearly has a large influence on the cloud field, with a rapid decline in cloud mixing ratio during the initiation of heavy precipitation. As precipitation intensity stabilizes and subsequently declines, the cloud field rebuilds. In short, it appears that increasing precipitation reduced the cloud mixing ratio maxima at the same time that synoptic-scale cloud filled the lower elevations. Both of these effects contributed to reduced cloud-edge gradients during the middle portion of the storm, thus weakening the effects of PDA.

6. Verification using surface precipitation measurements

Having established that PDA generally reduces moisture species and precipitation, the question remains...
whether PDA improves the accuracy of the model’s precipitation prediction. Figure 12 presents bias scores of surface precipitation at observation locations within the 1.33- and 4-km domains. Because of assumed precipitation undercatchment at many locations, bias scores $>120$ (purple and red) are considered overprediction, bias scores $<90$ (green and light blue) are considered underprediction, and values in between (dark blue) are considered accurate forecasts. In both the 4- and 1.33-km domains, overprediction (purple and red) predominates for both PDA and NOPDA runs. However, PDA lessens overprediction and some of the improvements are significant. For instance, four overpredicted bias scores (red) in the NOPDA 1.33-km simulation become accurate forecasts (blue) in the PDA simulation. Table 2 quantifies the bias scores by region. “Domain total” values provide a raw average of biases in the five regions of interest, whereas “weighted total” provides an average bias weighted by NOPDA total precipitation in each region of interest. For both the 4- and 1.33-km domains, overprediction (purple and red) predominates for both PDA and NOPDA runs. However, PDA lessens overprediction and some of the improvements are significant. For instance, four overpredicted bias scores (red) in the NOPDA 1.33-km simulation become accurate forecasts (blue) in the PDA simulation. Table 2 quantifies the bias scores by region. “Domain total” values provide a raw average of biases in the five regions of interest, whereas “weighted total” provides an average bias weighted by NOPDA total precipitation in each region of interest. For both the 4- and 1.33-km domains, NOPDA precipitation-weighted bias scores are 140–142; the application of PDA reduces the bias scores to 120–123. Considering that undercatchment is mainly a problem for higher-elevation regions in which snowfall and high winds are significant, these results suggest that although PDA helps significantly, model overprediction still exists, particularly to the lee of mountain barriers.

7. Model moisture flux errors

A potential source of the model overprediction of hydrometeors over the Northwest is excessive moisture fluxes approaching the mountains. Colle et al. (2008) suggested a linkage between MM5 moisture flux biases over Salem, Oregon, and precipitation biases over the 2005/06 and 2006/07 cool seasons over northern Oregon and southwestern Washington. They noted that when the model moisture flux aloft at Salem exceeded the observed by more than one standard deviation, the MM5 consistently overpredicted precipitation. However, when the observed sounding moisture flux exceeded the model by more than one standard deviation, bias scores indicated a scattering of overprediction and underprediction. In the remainder of this section, moisture flux errors for both the December 2001 event and contemporary winter periods are examined.

Figure 13 presents comparisons of WRF (PDA and NOPDA) winds, moisture, and moisture flux values in the lowest 3 km with soundings upstream of the Cascades at Salem for forecast hours 21 (onset of the rainband associated with the cold front aloft), 24 (approximate passage of the cold front aloft), and 28 (immediately following surface frontal passage) for the 13–14 December 2001 event. Table 3 quantifies the biases over the lowest 3 km. Upstream water vapor is overpredicted by 9%–16% at the two earlier times in both runs but is slightly underpredicted (overpredicted) in the PDA (NOPDA) simulation at hour 28. Note that PDA values are similar to those of NOPDA for water vapor, winds, and moisture flux at forecast hours 21 and 24, so PDA did not change upstream forecast moisture for the stable portion of the event. Simulated winds are too strong in the lowest 1.5 km at all hours for both PDA and NOPDA runs. Positive moisture flux biases in the lowest 3 km range from 31% at the onset of the frontal rainband to 11% at forecast hour 24 and decrease to negligible bias (±5%) at the time of surface front passage. At all times, the moisture fluxes in the lowest 1.5 km are too strong. Averaging the three sampled times, moisture fluxes in the lower 3 km exceed

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1 Bias score $= 100 \times \frac{\text{model}}{\text{observed}}$. 
observations by an average of 14.6% and model water vapor exceeds observations by an average of 8.6%.

For a single event, we have shown that the model overpredicts moisture fluxes approaching the barrier, but is the bias systematic? To answer this question, comparisons were made between soundings from Salem (Fig. 14) and Quillayute, Washington (Fig. 15), and the 12-km WRF and MM5 24-h forecast soundings at the same locations from the University of Washington (UW) real-time forecasting effort for the 2007/08 cool season. Figures 14 and 15 and Table 4 provide graphical and quantitative summaries of the biases in moisture flux, water vapor, and wind speed over the lowest 3 km of WRF (PDA) and MM5 (NOPDA) 24-h forecasts and the GFS initializations (F00) and 24-h forecasts (F24).

For Salem (Fig. 14), the moisture flux in WRF is overpredicted in the lowest 3 km by 12.7%, with slightly greater contribution to this error from moisture (4.6% bias) than wind speed (3.6% bias). The moisture flux overprediction at Quillayute is similar to Salem (12.2% for WRF; 12.4% for MM5). At Quillayute (Fig. 15), water vapor biases are consistently positive in the lowest 3 km (5.2% for WRF; 4.6% for MM5), whereas the wind biases are slightly lower (2.7% for WRF; 3.2% for MM5).

To determine the origin of these biases, Figs. 14 and 15 and Table 4 also provide the biases at the two sounding sites for the National Weather Service GFS model, which is used to initialize the UW WRF simulations. In addition, the GFS 24-h forecast biases at the sounding locations are also shown. Both the GFS initializations and forecasts have approximately a 4% water vapor overprediction, a value slightly less than the mesoscale model forecast biases examined previously. The GFS wind biases are small at Quillayute and Salem, with the exception of a modest positive bias for the 24-h forecast at Salem. The moisture flux errors are generally smaller in the GFS initialization than for the WRF and MM5 forecasts; however, the GFS 24-h forecasts share the large moisture flux positive bias of the mesoscale model.

Excessive moisture fluxes approaching regional terrain thus appear to be an additional, and significant, source of error in the prediction of moisture fields in these numerical models. Boundary layer problems have been identified previously in Northwest regional simulations (e.g., Mass et al. 2002; Garvert et al. 2007) and likely contribute to the excessive low-level wind speed. Thus, improvements in precipitation and moisture predictions...
may depend, at least partially, on resolving deficiencies in model boundary layer physics. Further research is required to determine the generality of the incoming moisture flux errors and their impacts on precipitation and other microphysical quantities.

8. Conclusions

WRF model simulations of the 13–14 December 2001 event show that positive-definite moisture advection (PDA) removes significant amounts of nonphysical, model-generated moisture for landfalling Pacific fronts interacting with orography. PDA-related reductions in storm-total precipitation increase with enhanced model

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Table 2. Model bias scores in Fig. 12 calculated from PDA and NOPDA runs at 4- and 1.33-km resolutions and binned according to the regions defined in Fig. 3. “Domain total” precipitation represents an average of each region of interest, whereas the “weighted total” is normalized by precipitation in each subdomain.
resolution, with values averaging 13.4% for the entire 1.33-km domain and 17.2% over the windward Cascade slopes, with lesser reductions over the coastal mountains and to the lee of the Cascades. PDA reduces mixing ratio values in all microphysical fields and at all vertical model levels. However, complex microphysical interactions obscure the relative contribution of each field.

To analyze the microphysical impacts of PDA, it was applied to individual hydrometeor variables. For the entire 1.33-km domain, simulated precipitation reductions were 8.4% for PDA-cloud water, 1.7% for PDA rain, and 0.5% each for PDA snow and PDA graupel, whereas PDA for vapor and (cloud) ice reduced precipitation by negligible amounts. The magnitude of the

Table 3. Vertically averaged (0–3 km) biases in water vapor, wind, and moisture flux for 1.33-km NOPDA and PDA model simulations of the 13–14 Dec event for the profiles illustrated in Fig. 13.

<table>
<thead>
<tr>
<th></th>
<th>2100 UTC 13 Dec</th>
<th>0000 UTC 14 Dec</th>
<th>0400 UTC 14 Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NOPDA</td>
<td>PDA</td>
<td>NOPDA</td>
</tr>
<tr>
<td>Water vapor</td>
<td>9.1%</td>
<td>9.4%</td>
<td>15.6%</td>
</tr>
<tr>
<td>Wind</td>
<td>18.0%</td>
<td>17.9%</td>
<td>-7.0%</td>
</tr>
<tr>
<td>QV flux</td>
<td>31.0%</td>
<td>31.3%</td>
<td>11.2%</td>
</tr>
</tbody>
</table>
spurious moisture production was proportional to the gradients of mixing ratios, with regions of negligible cloud water values adjacent to elevated cloud liquid water amounts contributing most significantly to spuri-

Fig. 14. Salem sounding comparison with WRF (PDA), MM5, GFS (initialization and FH 24), and a Sippican VIZ-B2 rawinsonde launched twice daily at 0000 and 1200 UTC throughout the 2007/08 cool season (2 Oct–12 Apr). Out of 388 potential sounding times, 370 had complete observational profiles and were used in this analysis.

Fig. 15. As in Fig. 14, but for Quillayute and out of 388 potential sounding times, 337 had complete observational profiles and were used in this analysis.

ious moisture. PDA-related percentage precipitation reductions varied temporally as the gradients changed during different phases of the storm: 24.4% during the prefrontal phase of the storm, 8.5% during the frontal phase, and 17.5% during the postfrontal phase. A notable increase in hydrometeor extent and density, as the upper-level cold front approached, attenuated cloud
Table 4. Biases in water vapor, wind, and moisture flux for GFS F00 and F24 and 24-h forecasts for WRF (12 km) and MM5 (12 km) compared to soundings at Salem and Quillayute from 2 Sep 2007 through 14 Apr 2008. Average values over 0–3 km (WRF and MM5) and 0.5–3 km (GFS).

<table>
<thead>
<tr>
<th></th>
<th>Salem</th>
<th>Quillayute</th>
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<tbody>
<tr>
<td></td>
<td>WRF</td>
<td>MMS</td>
</tr>
<tr>
<td>Water vapor</td>
<td>4.6%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Wind</td>
<td>3.6%</td>
<td>5.1%</td>
</tr>
<tr>
<td>QV flux</td>
<td>12.7%</td>
<td>12.1%</td>
</tr>
</tbody>
</table>

mass, contributing to reductions in cloud-edge gradients during the middle stage of the storm. Gradients increased during the third phase with the entrance of postfrontal convection.

Results from the 13–14 December 2001 case may be compared to those of Lin and Colle (2009) for the 4–5 December 2001 event. Lower static stability and resulting convection likely explain the greater precipitation and larger moisture reductions resulting from PDA over the coastal mountains for the 4–5 December case. Convection on the coastal topography created sharp gradients in moisture fields that enhanced precipitation and NOPDA artificial moisture generation.

Although the application of PDA to WRF lessened positive moisture biases at most locations, overprediction still occurred for some moisture variables and locations. Comparison of modeled and observed upstream soundings at Salem during this event found that upstream water vapor fluxes exceeded observations by 31% and 11%, respectively, for soundings taken at 2100 UTC 13 December and 0000 UTC 14 December, encompassing a period of intense rainfall associated with passage of the cold front aloft.

Real-time WRF model runs for the 2007/08 cool season were evaluated against observations at Salem and Quillayute to test the robustness of the upstream sounding biases observed during the 13–14 December event. At both stations, WRF exhibited positive bias in low-level winds (−3%) and moisture (−5%), which combined to produce an upstream moisture flux approximately 12%–13% larger than observed. A portion of this seasonally averaged bias at the upstream sounding sites appears to be derived from the GFS, which overpredicted moisture flux by approximately 4%–6% in the initialization and 9%–12% for the 24-h forecasts at both Salem and Quillayute. Overall, the evidence suggests that biases in moisture fluxes, water vapor, and low-level winds seen in the 13–14 December 2001 WRF simulations may be systematic, pointing to another problem that needs to be addressed to improve the prediction of moisture variables in WRF and other modeling systems.

In summary, this paper documents the removal of a spurious moisture source resulting from a lack of positive-definite advection, which had significantly biased precipitation and hydrometeor forecasts in MM5 and early versions of WRF. Furthermore, positive biases in water vapor, low-level winds, and moisture flux upstream of terrain have been identified as additional potential contributors to the positive biases in mesoscale model moisture variables. Improvements in precipitation and moisture predictions in mesoscale models will thus depend not only on enhancements in model microphysics but also on advances in other elements of the modeling system, such as boundary layer parameterizations and surface physics.

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REFERENCES


