A Multilayer Upper-Boundary Condition for Longwave Radiative Flux to Correct Temperature Biases in a Mesoscale Model

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ABSTRACT

An upper-level cold bias in potential temperature tendencies of 10 K day^{-1}, strongest at the top of the model, is observed in Weather Research and Forecasting (WRF) model forecasts. The bias originates from the Rapid Radiative Transfer Model longwave radiation physics scheme and can be reduced substantially by 1) modifying the treatment within the scheme by adding a multilayer buffer between the model top and top of the atmosphere and 2) constraining stratospheric water vapor to remain within the estimated climatology in the stratosphere. These changes reduce the longwave heating rate bias at the model top to $\pm$0.5 K day^{-1}. Corresponding bias reductions are also seen, particularly near the tropopause.

1. Introduction

Use of mesoscale models has been shown to improve forecasts while providing more detailed structure of the atmosphere, particularly with regard to wind and precipitation over complex terrain (e.g., Mass et al. 2002), hurricane intensity (e.g., Davis et al. 2008), and the location and intensity of convective systems (e.g., Weisman et al. 2008). Nevertheless, significant model biases remain. A recent application using the Weather Research and Forecasting (WRF; Skamarock et al. 2008) model and the Advanced Hurricane Research WRF (AHW; Davis et al. 2008) model in experiments for the 2009 Atlantic hurricane season (hereafter AHW 2009) revealed a bias in temperature, evident by a substantial cooling trend, strongest near the model top. Here, we examine the bias seen in the WRF model by recreating AHW forecasts using the same domain (Fig. 1a) and model configuration, and initialized using Global Forecasting System (GFS) analyses.

A temperature cooling bias is evident when viewing a composite of 6-h forecasts from 0000 UTC 16 August through 0000 UTC 22 August 2009. Figure 1b shows the domain-averaged composite tendencies of potential temperature θ and radiative θ heating rates. The local time tendency of potential temperature $\partial\theta/\partial t$ decreases from ~0 K day^{-1} near the tropopause (~100 hPa) to -10 K day^{-1} at the top model level. Longwave heating $\dot{\theta}_{LW}$ follows a similar pattern, but has larger magnitude in the stratosphere. At these levels, $\partial\theta/\partial t$ is nearly equal to the net radiative heating rate, indicating that $\dot{\theta}_{LW}$ is partially offset by shortwave heating. To verify whether $\dot{\theta}_{LW}$ exhibits a bias, standard tropical (TROP) and midlatitude summer (MLS) clear-sky longwave radiative heating profiles (Ellingson et al. 1991; Clough and Iacono 1995) are shown for comparison. WRF $\dot{\theta}_{LW}$ diverges most strongly from the standard profiles for $p < 100$ hPa, with a value of -15 K day^{-1} at 20 hPa compared to -5 K day^{-1} in the standard profiles. Therefore, the cooling trend in $\partial\theta/\partial t$ is a result of a bias in $\dot{\theta}_{LW}$, as high as -10 K day^{-1} and increasing toward the model top.

Although the bias is most evident near the model top, the rather large magnitudes of -10 K day^{-1} seen here could limit the stability of the model. Impacts of such a cooling trend are especially likely to be seen in applications run over long periods of time, such as regional climate downscaling or data assimilation applications. For example, data assimilation cycling applications use short-term forecasts as a component in estimating the model analysis. The forecasts used in AHW 2009 were initialized using an ensemble Kalman filter (EnKF) consisting of 96 members at 36-km grid spacing with 36 vertical levels (Torn 2010), and analyses were cycled continuously

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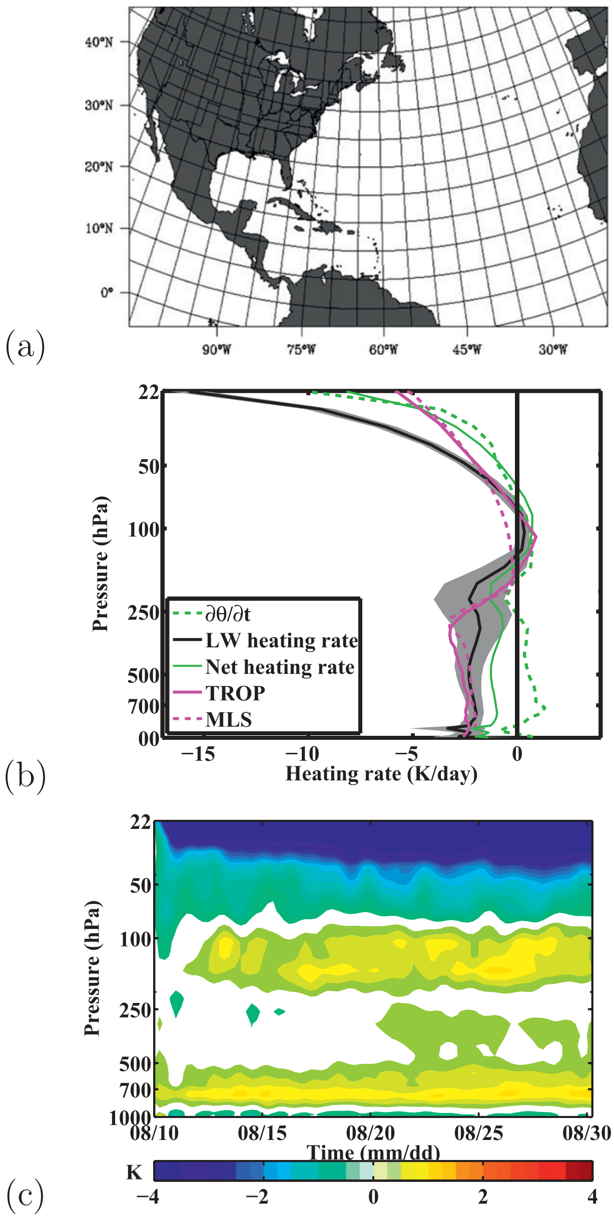

FIG. 1. (a) Numerical test domain and (b) composite potential temperature local time tendency, $\partial\theta/\partial t$ (green, dashed); longwave radiative potential temperature heating rate, $\dot{\theta}_{\mathrm{LW}}$(black); and net radiative potential temperature heating rate (green) compared with standard tropical (magenta) and midlatitude summer (magenta, dashed) longwave radiative potential temperature heating rate profiles from 6-h forecasts initialized with GFS at 0000 UTC 16 Aug–0000 UTC 22 Aug 2009. Profiles are averaged over the entire test domain. Time–height section from the same domain, but from a data assimilation cycling period from 0000 UTC 10 Aug to 0600 UTC 30 Aug 2009 using an EnKF with (c) potential temperature bias (K) with respect to GFS (EnKF-GFS). In (b), the gray shading represents the ± 1 standard deviation limits of $\dot{\theta}_{\mathrm{LW}}$ over the domain.

for 4 months. Most observations were assimilated in lower-atmospheric levels, leaving little opportunity for observations to correct deviations from the background in upper levels. Owing to the long cycling period of the analyses, this provides a good test case for examining the longer-term impacts of the model bias.

A time–height section of the EnKF background θ bias for a 3-week period is shown in Fig. 1c. Biases are computed with respect to GFS (EnKF-GFS) for the period shown, and the data are filtered to exclude time scales of 1 day or less. GFS, a global spectral model operated by the National Centers for Environmental Prediction (NCEP), is run with T382 (~35 km) horizontal resolution, 64 vertical levels, and a model-top pressure of 0.2 hPa. Since the difference in vertical resolution is substantial, and the model top is much higher in altitude, we do not expect similar biases in GFS and AHW 2009. Note that θ diverges most from GFS near the top of the model (Fig. 1c). A slight warming trend is evident with respect to GFS near the tropopause for $100 < p < 250$ hPa, and ~700 hPa. The warming trend ~100 hPa is also evident in Fig. 1b, as most $\dot{\theta}_{\mathrm{LW}}$ values are greater than those expected from MLS, even though a considerable portion of the domain lies within the midlatitudes. The bias produced by the existing boundary condition of ~10 K day^{-1} could potentially limit the stability of the model, especially in very long runs (such as for regional climate simulations) or when cycling a data assimilation scheme for long periods. Here, we investigate the source of the θ bias and devise a method to correct it.

The biases discussed above are present when using WRF with the Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997). Model tops in mesoscale models such as WRF do not generally extend to the top of the atmosphere (TOA), and therefore assumptions must be made to estimate the top of the model radiative boundary conditions. In practice, model tops in mesoscale models range from 10 to 100 hPa. In the WRF version of RRTM (hereafter WRF-RRTM), the upper boundary is treated similarly to general circulation models (GCMs); one level is added between the model top and TOA. In the extra layer, temperature is assumed to be isothermal, and all mixing ratios are assumed to remain constant with height, except O_3, which is reduced by a factor of 0.6 (Iacono et al. 2000). However, model tops in GCMs tend to be closer to the TOA, for example in the NCAR Community Atmospheric Model (CAM), where it is 2.9 hPa (Collins et al. 2006). Standard clear-sky atmospheric profiles show that temperature is nearly isothermal in the lower stratosphere; however, above ~50 hPa it increases with height to the stratopause, located near 1 hPa, by an average of ~40 K (Fig. 2a). In addition to temperature, $\dot{\theta}_{\mathrm{LW}}$ is expected to be most sensitive to carbon dioxide (CO_2) and H_2O, while O_3, although reaching a maximum ~5 hPa (Fig. 2b), is a relatively weak absorber in the longwave bands (e.g., Manabe and Strickler 1964). Since CO_2 is well mixed, and since it is evident from Fig. 2c that H_2O is well mixed in the stratosphere, we hypothesize that assuming a more realistic thermal structure between the model top and TOA can improve the accuracy of radiative flux calculations.

We explore the above hypothesis through single-column experiments using RRTM in section 2. Results from the single-column experiments will then be applied to WRF during the test period described above and discussed in section 3. A summary of the results and changes to thw WRF–RRTM scheme will be given in section 4.

2. Single-column experiments

a. Experimental setup

We use a stand-alone version of RRTM version 3.1 (available online at http://rtweb.aer.com), with standard midlatitude winter (MLW), MLS, subarctic winter (SAW), and TROP atmospheric profiles provided. The standard profiles provided are from the Intercomparison of Radiation Codes Used in Climate Models (ICRCCM; Ellingson et al. 1991), which are based on reference atmospheric profiles by the Air Force Geophysics Laboratory (AFGL; Anderson et al. 1986). Heating rates based upon these standard profiles have been validated for RRTM with line-by-line model calculations (Mlawer et al. 1997) and observations (Clough and Iacono 1995). Control runs use the exact 36 vertical levels from AHW 2009, plus an additional level at the TOA that uses the same assumptions as WRF-RRTM. In the experiment runs, we replace the additional TOA level by a buffer zone, with a variable number of levels, above the pressure at the model top (p_{top}). Experiments are performed using pressure increments of $\Delta p = -8$, -4, and -2 hPa in the buffer zone, inclusive of 1 and 0 hPa. For example, $p_{top} =$ 20 hPa with a pressure increment of $\Delta p = -4$ hPa includes buffer levels of 16, 12, 8, 4, 1, and 0 hPa. These pressure intervals are chosen as a compromise to resolving a realistic temperature profile while not significantly degrading the computational efficiency.

Experiments are designed to account for various atmospheric conditions based on the standard MLW, MLS, SAW, and TROP atmospheres. In the buffer zone, the temperature profile is extended above the model top using the vertically varying mean lapse rate from the standard MLW, MLS, SAW, and TROP profiles (recall Fig. 2a). Below the buffer zone, these initial temperature profiles are linearly interpolated to the given WRF vertical pressure levels in the control case and the experiments. In the control case, volume mixing ratios of CO_2 and O_3 are converted from the average mass mixing ratios in the 2009 AHW experimental domain, while water vapor is converted from mean relative humidity; all other gaseous mixing ratios are set to zero as in WRF-RRTM. In the experiments, all gaseous mixing ratios are interpolated from their respective standard profiles. All cases assume clear-sky conditions.

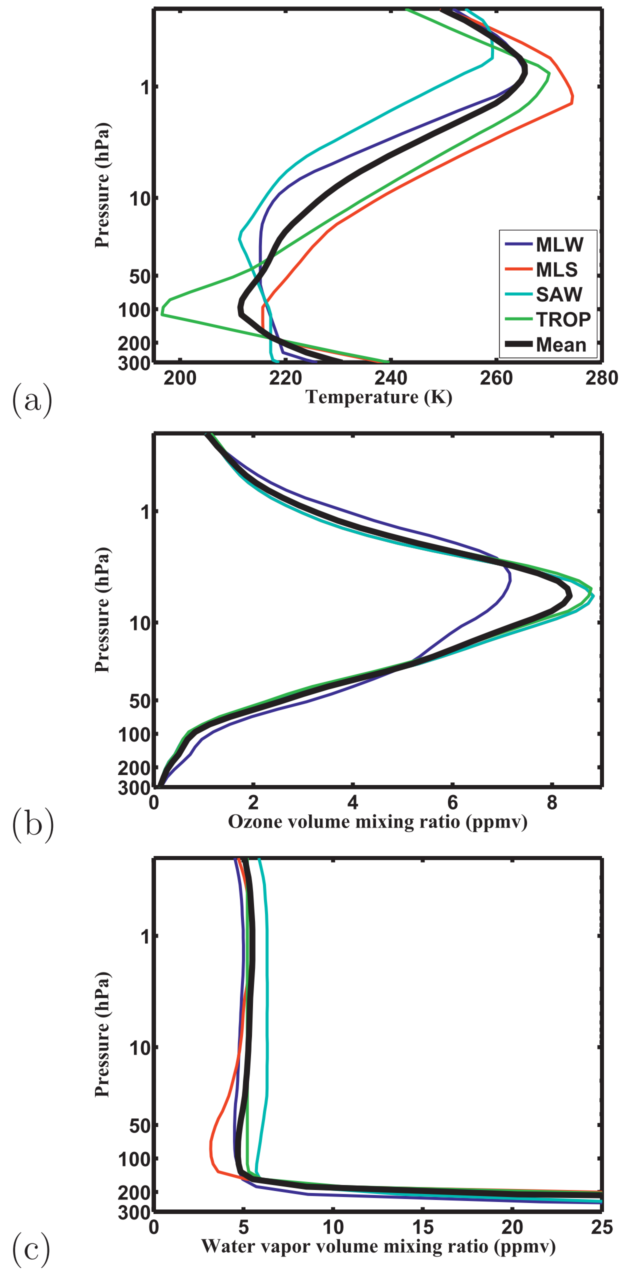

FIG. 2. The standard MLW (blue), MLS (red), SAW (cyan), TROP (green), and mean (boldface black) vertical profiles of (a) temperature (K), (b) ozone (ppmv), and (c) water vapor (ppmv). See text in section 2 for more details regarding these profiles.

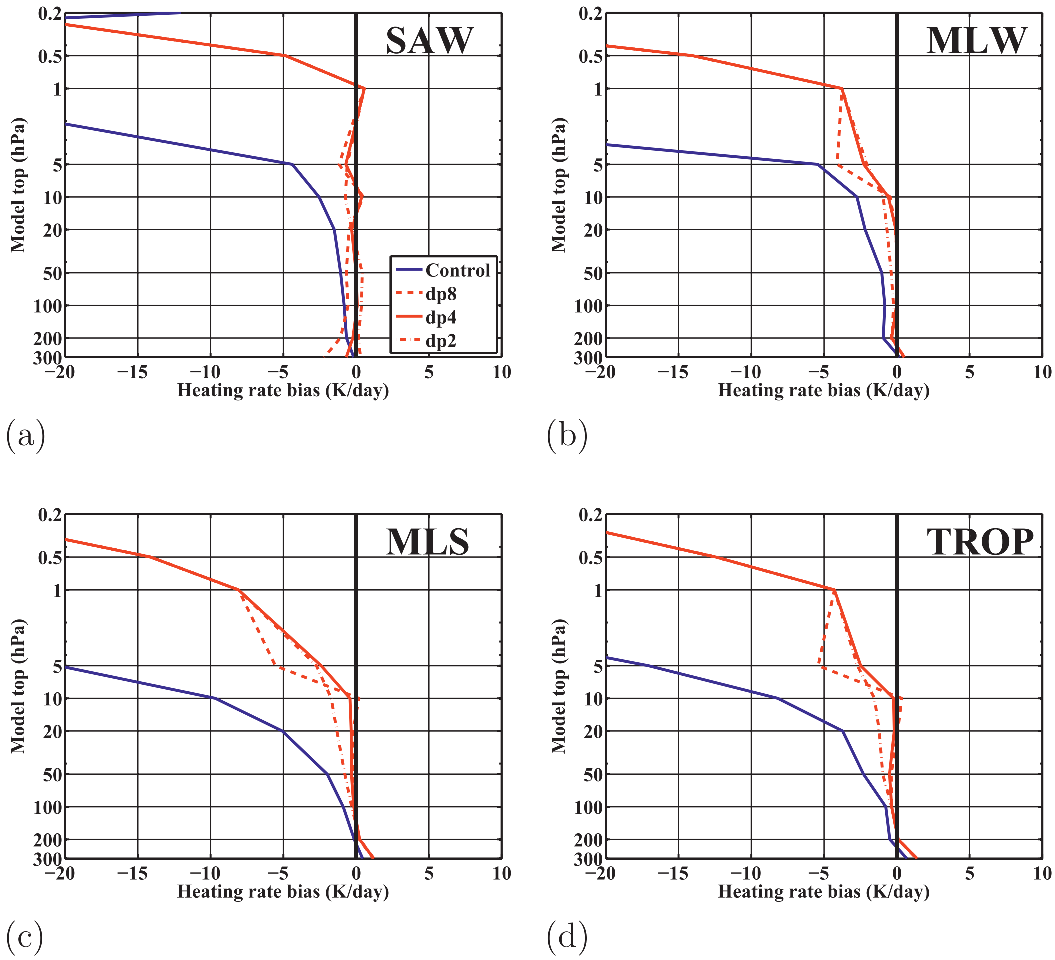

FIG. 3. Longwave radiative heating rates at the top model level minus the respective standard heating rate at the equivalent pressure level ($\dot{\theta}_{\mathrm{LW,model}} - \dot{\theta}_{\mathrm{LW,standard}}$) as a function of model-top pressure based upon standard (a) SAW, (b) MLW, (c) MLS, and (d) TROP atmospheric vertical profiles. The difference in the control experiment is shown in blue. Experiments using pressure intervals of −8, −4, and −2 hPa between the model top and TOA are shown with the dashed, solid, and dashed–dotted red contours, respectively. Note the differences shown are not continuous profiles.

b. Single-column results

Figure 3 shows the differences between the control and experimental $\dot{\theta}_{\mathrm{LW}}$ at the top model level from their respective standard values. To explore a more complete range of solutions, experiments were repeated using p_{top} = 0.2, 0.5, 1, 5, 10, 20, 50, 100, 200, and 300 hPa employing the same WRF η levels in all experiments. In the SAW control, the longwave cooling bias increases with increasing (decreasing) model-top height (pressure), with a bias of -2 K day^{-1} for $p_{\mathrm{top}} = 20$ hPa to values exceeding -20 K day^{-1} with $p_{\mathrm{top}} = 1$ hPa (Fig. 3a). This result is rather surprising, and indicates the closer p_{top} and TOA, the stronger the bias as the vertical resolution is degraded for p_{top} closer to the TOA. The buffer zone reduces the bias to ± 1 K day^{-1} for $1 < p_{\mathrm{top}} < 200$, with the strongest reductions using $\Delta p = -4$ hPa. Similar patterns exist for the MLW, MLS, and TROP cases, where single-column RRTM experiments show a substantial reduction in the $\dot{\theta}_{\mathrm{LW}}$ bias (Figs. 3b–d).

The buffer itself may be problematic for model tops near the stratopause ($p_{\mathrm{top}} < 5$ hPa). Note that although the bias remains large for such p_{top}, it is substantially reduced with a buffer. In the configuration here, as p_{top} decreases, there are fewer levels in a given layer near the stratopause than with a buffer for greater p_{top}. To test whether there is a sensitivity to the number of model levels near the stratopause, we repeat the above for the MLS experiment (recall Fig. 3c), where biases for $p_{\mathrm{top}} <$ 5 hPa were largest. In the experiment here, we define

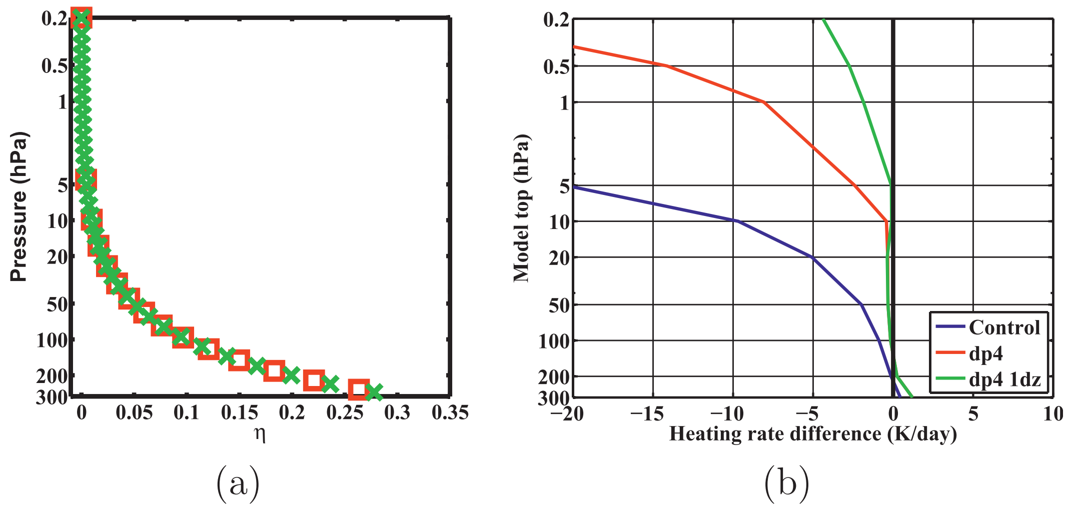

FIG. 4. (a) Distribution of WRF η levels as a function of pressure for the experiment using a pressure interval of -4 hPa (red) and when defining WRF η levels using a constant thickness of ~1.4 km (denoted as 1 dz in the legend, where 1 $dz = 1 \times 1.4$ km) between 20 hPa and the model top (green) for a model top of 0.2 hPa. (b) Longwave radiative heating rates at the top model level minus the MLS standard heating rate at the equivalent pressure level ($\dot{\theta}_{\mathrm{LW,model}} - \dot{\theta}_{\mathrm{LW,standard}}$) as a function of model-top pressure using the vertical levels shown in (a) based on the MLS atmospheric vertical profile. Note the differences shown in (b) are not continuous profiles.

WRF η levels to be of constant geopotential thickness (1.4 km) for $p < 20$ hPa based on the thickness of the AHW configuration near its model top of 20 hPa. This new vertical-level distribution is compared to that of the original experiment in Fig. 4a, and shows the relatively sparse distribution of vertical levels around the stratopause previously. Biases are reduced considerably for $p_{\mathrm{top}} < 5$ hPa by having better vertical resolution near the stratopause (Fig. 4b). From further experiments (not shown), we can attribute the remaining disagreement to differences in the vertical resolution of the troposphere between the standard profile and experiments. The results here show that for $p_{\mathrm{top}} < 5$ hPa, the remaining biases can be reduced by having sufficient vertical resolution near the stratopause, which here is achieved by defining a vertical grid spacing with a constant geopotential thickness of 1.4 km in the buffer.

In addition to temperature, longwave radiative fluxes are also sensitive to concentrations of gaseous absorbers. Currently, the effects of three gaseous absorbers are computed in WRF-RRTM: H_2O, CO_2, and O_3. Sensitivity tests (not shown) indicated that cooling rates respond largely to the change in CO_2 for $p_{\mathrm{top}} < 200$ hPa; for $p_{\mathrm{top}} > 200$ hPa, the largest response shifts to H_2O. There is a small response to changing O_3, except when p_{top} is near the stratopause. Thus, in addition to those for temperature, careful assumptions in CO_2 and H_2O in the buffer zone are important in obtaining accurate $\dot{\theta}_{\mathrm{LW}}$ from RRTM. We next apply the buffer method to a fully three-dimensional case using the AHW model.

3. Application to the WRF model

The new modifications to WRF-RRTM discussed in section 2 are now applied to the same AHW forecasts discussed in section 1. The model domain, configuration, and physics schemes are as in Torn (2010), where longwave radiation is computed with the RRTM (Mlawer et al. 1997) and shortwave radiation with the National Aeronautics and Space Administration (NASA) Goddard shortwave radiation schemes (Chou and Suarez 1994). Note that when applying the modifications to WRF-RRTM, the additional vertical levels are only added to the RRTM radiation scheme itself, and no information about the extra levels is carried outside of it. For $p_{\mathrm{top}} = 20$ hPa, five additional buffer levels are used within RRTM, and the total increase in model run time is ~2.7%. Since the model run time is largely dependent on the number of vertical levels, and the number of vertical levels is determined by Δp (here $\Delta p = -4$ hPa), consideration should be given when choosing Δp for model tops farther removed from the TOA in order to avoid unnecessary increases in run time. We composite a total of thirteen 6-h forecasts, initialized every 12 h using GFS analyses beginning at 0000 UTC 16 August and ending at 0000 UTC 22 August 2009 with boundary conditions derived from GFS forecasts every 3 h. The simulations are performed on a Lambert conformal projection, on a variably located finescale domain within the coarse domain (Fig. 1a) centered on the storms of interest for AHW 2009, using 424 × 325 x and y grid points, respectively, and 12-km horizontal resolution.

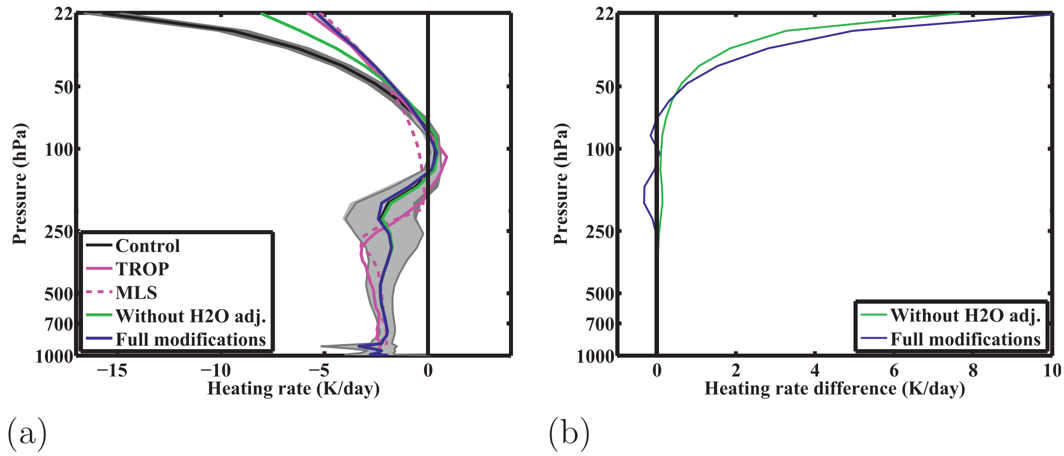

FIG. 5. Composite vertical longwave potential temperature (a) heating rates and (b) differences from the control case ($\dot{\theta}_{\mathrm{LW,experiment}} - \dot{\theta}_{\mathrm{LW,control}}$) of 6-h forecasts initialized with GFS from 0000 UTC 15 Aug to 0000 UTC 22 Aug 2009. The control case (no change in the RRTM longwave radiation scheme) is shown in black, while the TROP and MLS atmospheric profiles are shown by the magenta and dashed magenta contours, respectively. The experiment where only a buffer layer is added with $\Delta p = -4$ hPa is shown in green, while the experiment with the buffer layer and an adjustment to the stratospheric water vapor are shown in blue. All profiles are averaged over the entire test domain (See Fig. 1a). In (a), the light (dark) gray shading represents the ± 1 standard deviation limits of $\dot{\theta}_{\mathrm{LW}}$ for the full modifications (Control) experiments over the domain.

Soon after the experiments began, an erroneous feature was found with regard to water vapor. It was found to arise in the handling of water vapor in the WRF PreProcessing System (WPS) version 3.0.1 when water vapor is not provided from the input data, such as the case with GFS gridded binary (GRIB) data until January 2010, where water vapor extended only to 100 hPa. At levels where $p < 100$ hPa, relative humidity was assumed to decrease proportionally with pressure, with a value of 5% at 50 hPa. This resulted in volume mixing ratios increasing with height to $\sim 2 \times 10^2$ ppmv at p_{top} for $p_{\mathrm{top}} = 20$ hPa. Recall from Fig. 2c that volume mixing ratios should exhibit little variance $\sim$5 ppmv. We hereafter separate our results into those where H_2O is left unchanged (''without H2O adj.'') and where H_2O is fixed to 5 ppmv at all levels where $p < 100$ hPa (''full modifications'').

At p_{top}, TROP and MLS $\dot{\theta}_{\mathrm{LW}}$ are 63.0% (9.9 K day^{-1}) and 66.7% (10.5 K day^{-1}) lower than the control case, respectively (Fig. 5a). Adding the buffer zone reduces the cooling rates by 48.7%, or $\sim$7 K day^{-1} with respect to the control at the top model level, with reductions to levels as far as $\sim$250 hPa (Fig. 5b). The water vapor adjustment reduces cooling rates an additional 2.5 K day^{-1} to cooling rates within ± 0.5 K day^{-1} of the standard cooling rates. Stronger cooling, up to 0.5 K day^{-1}, is seen in the upper troposphere ($\sim$200 hPa) when including the water vapor adjustment. A decrease in the downward flux from less stratospheric water vapor results in enhanced cooling rates, and leads to an increase in upper-tropospheric clouds in areas close to saturation. Thus, the net changes eliminate the stratospheric cooling bias, and additionally correcting the stratospheric water vapor reduces the upper-tropospheric warming trend (recall Figs. 1b and 1c). The spatial distribution of $\dot{\theta}_{\mathrm{LW}}$ at the top model level exhibits a zonal cooling pattern in the control, with increased cooling rates ranging from 8 to 13 K day^{-1} from south to north (Fig. 6a). This latitudinal $\dot{\theta}_{\mathrm{LW}}$ pattern is associated with warmer stratospheric temperatures present during the summer over higher latitudes. The modifications in $\dot{\theta}_{\mathrm{LW}}$ are reflected in $\partial\theta/\partial t$, with θ being 2–4 K warmer on average at forecast hour 6 (Fig. 6b).

4. Summary

WRF (AHW) forecasts initialized with both GFS and EnKF analyses exhibit a negative potential temperature tendency bias of up to 10 K day^{-1}, greatest at the model top. The bias was found to arise when using WRF with the RRTM longwave radiation physics scheme. With the expectation that gaseous longwave absorbers are well mixed at levels where the bias is observed, it was hypothesized that previous assumptions of an isothermal layer between the model top and the top of the atmosphere lead to the flux divergence errors at the upper model boundary resulting in the bias.

Results reveal that the temperature bias can be reduced by 1) creating buffer levels between the model top and the top of the atmosphere by extending a temperature profile above the model top based on the mean,

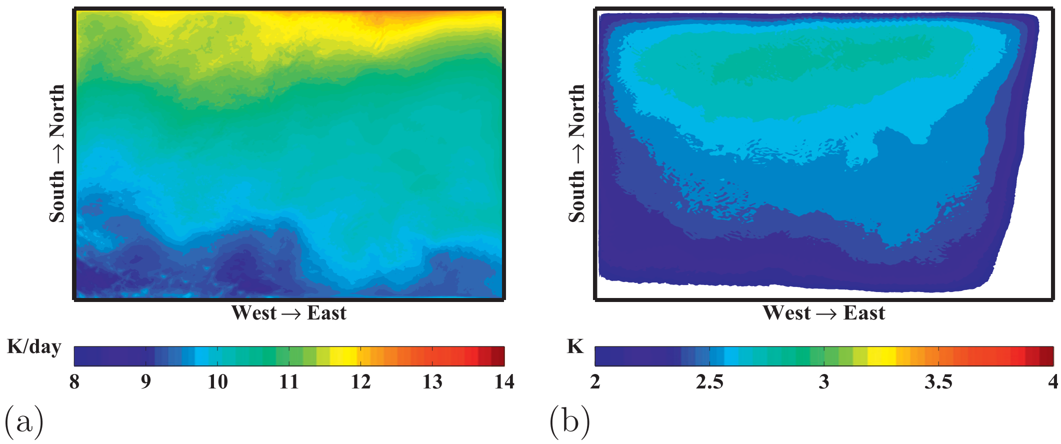

FIG. 6. Composite potential temperature (a) heating rate differences ($\dot{\theta}_{\mathrm{LW,experiment}} - \dot{\theta}_{\mathrm{LW,control}}$) and (b) changes in 6-h forecasts of potential temperature ($\theta_{\mathrm{experiment,forecast}} - \theta_{\mathrm{control,forecast}}$) at the top model level between the control (no change in the RRTM longwave radiation scheme) and experiment (using the modified RRTM longwave radiation scheme). In (b), values below 2 K are shaded in white.

vertically varying standard atmospheric lapse rate and 2) if necessary, setting water vapor mixing ratios for $p <$ 100 hPa to a constant 5 ppmv. The former yields larger downward radiative fluxes at the upper model boundary resulting in a smaller flux divergence, primarily affecting model levels close to the model top. The latter results in less cooling from reduced longwave absorption by water vapor molecules for $p < 100$ hPa and, further, results in greater upper-tropospheric cooling. The combined effects reduce longwave radiative cooling rates for $p_{\mathrm{top}} > 5$ hPa to within ± 0.5 K day^{-1} of the standard rates obtained in the line-by-line clear-sky calculations of Clough and Iacono (1995). Cooling rates are now in more consistent agreement with those found using relatively high vertical resolution and upper boundaries of $\sim$0.1 hPa (Mlawer et al. 1997). Similar treatment of the upper boundary is made using the Rapid Radiative Transfer Model for GCMs (RRTMG) longwave radiation scheme in WRF, and can be corrected using this method. In general, this method is applicable to numerical models using longwave radiation schemes where the model top differs substantially from the top of the atmosphere and requires minimal computational expense.

These results emphasize the importance of carefully specifying radiative fluxes at the upper boundaries of mesoscale models, especially those with model tops significantly below the top of the atmosphere. They further emphasize the sensitivity of longwave heating to stratospheric trace gases, especially water vapor; great care should be placed on the assumptions of these concentrations when data are either unavailable or unreliable. Although the method here substantially reduces the magnitudes of the longwave biases for all model top levels tested, a considerable bias remains for model tops near the stratopause, which can be further reduced by increasing the vertical resolution of the model and buffer levels near the stratopause.

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