Realistic simulations of atmospheric gravity waves over the continental US using precipitation radar data

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Abstract. Convectively-forced gravity waves can affect the dynamics of the upper troposphere and middle atmosphere on local to global scales. Simulating these waves accurately requires computationally expensive cloud-resolving models and is therefore restricted to case studies. Here, a new modeling approach is introduced that combines the realism of local full-physics simulations with the spatial scope of larger scale models and permits direct validation of the modeled waves with individual cases of observed waves. The modeling approach uses an idealized model framework, but the forcing for the model is derived from observations of precipitation. We first develop an algorithm for converting radar-observed precipitation to three-dimensional, time-varying heating/cooling using full-physics cloud-resolving simulations. Radar-derived heating/cooling fields then force a nonlinear dry idealized model. The focus is on small horizontal and temporal scales typical of intense convection over the continental summer US. It is found that radar products can accurately capture the high spatial and temporal variability in occurrence and strength associated with convective sources of gravity waves. Waves in the idealized model are validated against full-physics simulations and satellite observations. Wave patterns and amplitudes observed in individual satellite overpasses are reproduced in remarkable detail. The relative simplicity of the new model permits longer simulations with much larger and deeper domains suitable for studying the impact of small-scale gravity waves on regional circulation patterns.

1. Introduction

Recent studies have emphasized the stratosphere's role in affecting surface weather and climate. *Charlton et al.* [2004] highlight the sensitivity of medium-range tropospheric forecast skill to the stratospheric initial state. Focusing on the southern hemisphere, *Roff et al.* [2011] suggest that an increased model stratospheric resolution with an improved representation of stratospheric dynamics and thermodynamics improved the quality of extended-range forecasts. *Scaife et al.* [2011] show that stratosphere-troposphere interactions change climatological predictions for the Atlantic storm track with substantial impact on extreme winter rainfall over Europe. As a consequence, models used for operational forecasting, seasonal prediction, and coupled climate simulations are raising their tops to include more stratospheric processes [*Manzini et al.*, 2014].

Dynamical interactions between the troposphere and the middle atmosphere involve waves, both planetary scale and small-scale gravity waves [*Holton*, 1983; *Andrews et al.*, 1987]. While Rossby waves and some large-scale gravity waves are resolved in global models, grid spacings still remain too coarse to capture the physics of small-scale gravity waves. But these waves can have important effects. *Palmer et al.* [1986], for example, showed that adding an orographic gravity wave drag parameterization to the Meteorological Office general circulation and numerical weather prediction models alleviated a systematic westerly bias in the northern hemisphere wintertime flow. *McFarlane* [1987] supported similar findings for the Canadian Climate Centre general circulation model (GCM). Identifying mechanisms that connect different scales and layers of the atmosphere and clarifying the degree to which they need to be represented in weather prediction and climate models remains an important and active area of research (e.g. *Schirber et al.* [2014]).

In addition to flow over orography, convection is known to be an important source of gravity waves, especially in the tropics and summer midlatitudes. Cloud-resolving numerical models now include a multitude of interactive physics packages that can be customized to yield accurate simulations of sub-cloud scale processes. Numerous studies have successfully used such models to relate convective properties to the generated gravity wave spectrum [*Choi and Chun*, 2011; *Lane et al.*, 2001; *Piani et al.*, 2000; *Song et al.*, 2003; *Alexander and Holton*, 1997; *Beres*, 2004]. These results have guided the development of source parameterizations for GCMs that deliver a momentum-flux spectrum that depends on the latent heating properties of the underlying convection and the background wind [*Beres et al.*, 2004, 2005; *Chun and Baik*, 2002; *Kim et al.*, 2013]. While a realistic representation of the general circulation can be achieved with these parameterizations, they make assumptions that can lead to inaccuracies, particularly in local and regional circulations. Common assumptions include that waves propagate, within one time step, and within the same column, to the heights where they deposit their momentum and create drag. It has been pointed out that these assumptions are not consistent with general propagation properties of gravity waves and do not necessarily ensure physically consistent wave-induced forcing [*Song and Chun*, 2008; *Sato et al.*, 2009, 2012].

Here, we present a new modeling approach that combines the realism of local full-physics simulations with the spatial scope of larger scale models. An idealized dry version of the Weather Research and Forecasting (WRF) model is forced with a three-dimensional and time-varying heating/cooling field. Focusing on gravity-wave generating convective storms over the continental US, we introduce an algorithm to derive this heating/cooling field from local precipitation rate measurements. We show that conventional precipitation radar data capture the high spatial and temporal variability of convective cells and are suitable for driving the model. This model can be utilized to study the impact of convectively generated gravity waves on the larger scale circulation in the upper troposphere and the stratosphere.

Section 2 gives an overview of our modeling approach. The algorithm for converting precipitation rates to a three-dimensional heating/cooling field is derived in section 3. In section 4 the idealized model is described and its performance is evaluated. In section 5 the algorithm is applied to radar precipitation fields. In section 6 we present observational validation of the stratospheric gravity waves in deep idealized model simulations by comparison to those observed with the Atmospheric Infrared Sounder (AIRS) instrument on the Aqua satellite. The last section is a summary and discussion.

2. Modeling approach

The Advanced Research WRF (ARW) solver is able to simulate cloud-scale processes for both simplified, idealized frameworks and full-physics runs initialized with assimilated observations. We will refer to these as “idealized” and “full-physics” runs, respectively. Full-physics simulations use reanalysis products to define three-dimensional wind, pressure, temperature and humidity fields as well as time-sensitive land-surface fields (snowcover, soil temperature, soil moisture) for initial and boundary conditions. They are typically run with a combination of physics packages including microphysics, cumulus parameterization, surface physics, planetary boundary layer and atmospheric radiation schemes. Idealized experiments allow for simplified physics and user-defined initial conditions, which reduces their runtime significantly.

In this study we design a dry idealized model that is forced with a prescribed three-dimensional and time-varying heating/cooling field. All physics parameterizations are switched off, which makes the model computationally efficient without jeopardizing the realistic representation of gravity wave propagation and dissipation. The heating field is computed by an algorithm which translates precipitation rates into a vertical heating/cooling profile.

To derive the algorithm we use a full-physics WRF simulation, where moist processes are exclusively governed by a microphysics (MP) scheme. The microphysics latent heating/cooling enters the model through the thermodynamic equation

$$\partial_t(\mu\theta) + (\nabla \cdot \mu\mathbf{v}\theta) = F_\theta. \tag{1}$$

Here, θ denotes the potential temperature, $\mu(x, y)$ is the mass per unit area within a column in the model domain at (x, y), $\mathbf{v}$ is the three-dimensional velocity vector and

$$F_\theta = F_{\theta,MP} + F_{\theta,rad} + F_{\theta,cum} + F_{\theta,pbl} + F_{\theta,mix/dif} \tag{2}$$

represent potential temperature tendencies arising from microphysics, radiation, cumulus parameterization, planetary boundary layer schemes, mixing and diffusion. To ensure correct saturation conditions the microphysics tendency $F_{\theta,MP}$ is evaluated at the end of each time step and stored in a variable called *h_diabatic*. We use this field to find a relationship between ten-minute precipitation rates and characteristics of the vertical heating/cooling profile. Ten minutes is chosen to match nominal radar observation intervals.

The gravity waves in the idealized model will be validated with satellite observations. The AIRS instrument is able to resolve waves with horizontal wavelengths as small as $\sim$30 km. We choose a horizontal grid spacing of 2 km $\times$2km and a history time interval of two minutes for our full-physics and idealized model simulations as this resolution is sufficient for satellite validation and produces results of very similar quality as the 1-km-resolution model used in *Stephan and Alexander* [2014] when validated against radar precipitation fields.

To apply the algorithm to radar measurements we obtain the Storm Total Rainfall Accumulation Product (STP) for individual Next-Generation Radar (NEXRAD) stations. The STP product provides radar-estimated rainfall accumulations within 230 km of the radar in polar coordinates with a resolution of 2 km $\times 1^{\circ}$. Data from several stations are interpolated in space and time to obtain a ten-minute 4 km $\times$4 km mosaic. In this process we average overlapping arrays from different stations to obtain smooth maps. The heating algorithm is therefore developed for a horizontal resolution of 4 km $\times$4 km.

To evaluate the performance of the idealized model we first apply the algorithm to simulated precipitation fields and compare the resulting dynamics in the idealized model to the corresponding full-physics simulations. We find that the idealized model is capable of simulating stratospheric gravity wave spectra that reproduce the propagation and amplitudes of waves in the full-physics models.

Subsequently, the algorithm is used to convert conventional precipitation radar data into heating/cooling fields. For illustration, Fig. 1 is a snapshot of an idealized simulation over a 1152 km $\times$1152 km large domain. The model is forced with a heating/cooling field obtained from radar precipitation rates which are shown as colored contours. The background (shades of gray) is the 95 hPa vertical velocity field showing gravity waves with a wide range of spectral characteristics emanating from individual convective cells. Gravity waves of interest to general circulation parameterizations have horizontal scales ∼10–100s of kilometers and periods of 10 minutes to hours. We find that WRF simulations forced with radar-derived heating can capture most of these waves except at the very highest frequencies.

3. Derivation of the heating algorithm

In this section we introduce the setup of full-physics storm simulations and describe how the algorithm for obtaining vertical heating/cooling profiles from local precipitation rates is derived from a squall line simulation.

3.1. Setup of full-physics storm simulations

Modeling a summer-time squall line on 5 June 2005 over the Great Plains, *Stephan and Alexander* [2014] investigated the impact of the choice of physics parameterizations on gravity wave generation. The shape and magnitude of the simulated stratospheric gravity wave momentum flux spectra did not critically depend on the microphysics scheme. For the full physics storm simulations in this study we use the same combination of physics schemes as the MOR1 simulation of *Stephan and Alexander* [2014], which in a comparison with radar measurements was found to accurately reproduce the storm structure. Three nested domains with horizontal resolutions of 18 km, 6 km and 2 km are connected through a one-way nesting procedure. The Kain-Fritsch [*Kain and Fritsch*, 1990] cumulus scheme is only active on the 18 km domain. On the 6 km and 2 km domains precipitation processes are handled by the Morrison microphysics scheme [*Morrison et al.*, 2009]. The remaining physics choices are the Yonsei University planetary boundary layer scheme [*Hong et al.*, 2006], the Goddard scheme [*Chou and Suarez*, 1999] for short-wave radiation, the Rapid Radiative Transfer Model [*Mlawer et al.*, 1997] for long-wave radiation and the Noah Land Surface Model [*Ek at al.*, 2003].

Figure 2 shows ten-minute precipitation rates over the inner domain at 0200, 0400, 0600 and 0800 UTC. Precipitation radar measurements (left column) are contrasted with model output (right column). The inner domain spans 600 km×600 km and is initialized at 1800 UTC on 4 June 2005. Fig. 2 shows that the period 0100 UTC to 0800 UTC contains fully developed to decaying storm stages and accordingly encompasses a large variety of precipitation strength distributions. Therefore, this seven-hour period provides a range of conditions suitable for deriving an algorithm that may be more universally applicable to continental US severe storm systems.

The outer domain is initialized with ERA-interim (European Centre for Medium-Range Weather Forecasting Re-Analysis) data [*Dee at al.*, 2011], which is available at six-hour intervals at a nominal resolution of 0.7°. The vertical grid, consisting of 95 terrain-following levels, is stretched between the surface and 850 hPa and beyond this point has a constant spacing of about 250 m. A 5-km deep Rayleigh damping layer that was previously shown [*Stephan and Alexander*, 2014] to prevent unphysical wave reflection at the upper boundary is placed below the model top of 40 hPa.

3.2. Heating algorithm

Figure 3 a shows the simulated latent heating/cooling profiles averaged over the convective pixels in the inner domain as a function of ten-minute precipitation rate and height. We only apply the algorithm to grid points that exceed a precipitation threshold of 1.0

mm(10 minutes)$^{-1}$, chosen as the smallest integer value for which the binned peak heating amplitudes exceed 0.004 K/s. This value is typical for heating rates observed in squall lines [*Chong and Hauser*, 1990; *Braun and Houze*, 1996], and was found to provide a useful definition of a convective pixel in *Stephan and Alexander* [2014].

Key characteristics of these profiles and their dependence on the precipitation rate are examined in Fig. 4. Both figures use the same precipitation bins, which are chosen such that each bin contains 400 members. From the contour plot it is evident that there exists a broad elevated heating region with a subjacent shallow cooling layer, which likely represents the cold pool [*Rotunno et al.*, 1988; *Moncrieff*, 1992; *Morrison and Milbrandt*, 2011]. The orange data points in Fig. 4 depict the height where the positive heating peak is reached. We define the top of the heating (light green) as the location where the heating rate falls to 10% of its maximum and the bottom of the heating profile (purple) as the height where the heating rate approaches zero. The green, yellow and blue points at the bottom of Fig. 4 show the top of the cooling region, defined as the height where the profile turns from negative to positive values, the height of the cooling peak, and the bottom of the cooling region, respectively. The straight lines through these six sets of points are linear fits. The corresponding equations are used to convert precipitation rates in units of mm(10 minutes)$^{-1}$ to height in units of kilometers and are listed in Fig. 4. The remaining two linear fits (dark red) pertain to the ordinate on the right-hand side of Fig. 4 and show the heating and cooling amplitude as a function of ten-minute precipitation rate.

In assigning the full vertical heating/cooling profile we assume a quarter-sine shape for each of the four sections, i.e. top of heating to peak of heating, peak of heating to bottom of heating, top of cooling to peak of cooling and peak of cooling to bottom of cooling. When applied to the simulated precipitation field this method accurately reproduces the shape of the heating distribution (Fig. 3 b). The histograms compare the density-weighted vertically integrated heating rates, labeled Q, computed from the algorithm-generated profiles with those from the simulations. Q should be directly related to the net amount of condensation/evaporation in the column. The similarity of the two histograms therefore affirms that our technique yields consistent results.

Since we used numerical data over a period of seven hours it is not obvious that the established relationship between ten-minute precipitation rate and column heating is valid for each individual developmental stage of the storm. Fig. 5 compares the simulated (solid lines) and the algorithm-produced (dashed lines) vertical heating profiles every ten minutes where colors indicate different times. Each profile is the domain average of columns with precipitation rates greater than 1 mm(10 minutes)$^{-1}$. This plot reveals that the algorithm outlined in this section captures the time-evolution of the heating field nearly perfectly, which is important to achieve a realistic representation of wave intermittency in the simulations.

4. Idealized model

In this section we introduce the idealized model and present results from two simulations which are designed to test the model's ability to reproduce several aspects of the storm structure and dynamics of full-physics simulations, in particular the gravity wave momentum flux spectra.

4.1. Implementation

The ARW solver uses a third-order Runge-Kutte (RK3) time integration scheme for each model time step. All forcing terms in Eq. 2 except for the microphysics tendency are computed during the first RK3 sub-step and are held constant throughout the remaining two sub-steps. High-frequency acoustic modes are integrated during small-step loops embedded in the RK3 large-time-step sequence. To avoid the excitation of unwanted acoustic waves it is necessary to incorporate an estimate of the MP tendency. For this purpose, the conventional version of WRF stores the MP latent heating/cooling rate from the previous step in the variable *h_diabatic*. This tendency is included in the acoustic loop of the subsequent time step and then removed from the temperature field at the end of the last acoustic time step. Finally, the MP scheme is called to update $F_{\theta,MP}$ with the correct tendency.

In our modified version of the idealized model the MP scheme is turned off and the latent heating field is instead imported from an auxiliary file. It is read in as the variable *h_diabatic* and takes the place of the MP tendency estimate. Consequently, it is added to the temperature field for the acoustic integration. We modified the source code such that this estimate is no longer removed at the end of the acoustic integration but remains as $F_{\theta,MP}$ forcing the potential temperature field.

As in the full-physics model, vertical levels are specified in terms of a terrain-following hydrostatic-pressure vertical coordinate $\eta = (p_h - p_{ht}) / (p_{hs} - p_{ht})$, where p_h denotes the hydrostatic component of pressure, p_{ht} the pressure at the model top and p_{hs} the pressure at the surface. For the purpose of validating the idealized model we specify the η levels, model top pressure and damping layer properties of the idealized model to be identical to the full-physics simulations. Given that there exists no topography in the idealized simulations, p_{hs} is constant and η-levels coincide with base-state geopotential levels. To attain a smooth time variation we interpolate the heating field from ten-minute to two-minute time intervals before storing it in the auxiliary WRF heating input file.

4.2. Idealized model validation

The algorithm derived in section 3 is based on a full-physics WRF simulation of a squall line event. To validate the idealized model we first apply the algorithm to the precipitation field from this simulation and compare the vertical velocity spectra and gravity momentum flux spectra of the full-physics and the idealized simulation. To test if algorithm and model perform well in other scenarios we repeat the analysis for a mesoscale convective complex (MCC) which occurred on 20 June 2007 over the Great Plains. This storm is chosen because it has multiple characteristics that distinguish it from the squall line event: The MCC is in a mature developmental stage throughout the analyzed time interval and consists of a larger connected area of convection.

The idealized model is initialized with a one-dimensional dry wind and potential temperature sounding. Below 16 km we use the domain-mean 0100 UTC wind and temperature fields of the respective full-physics simulation to compute the sounding. Above 16 km the full-physics model consists of a damping layer and the initialization profiles are extended using MERRA (Modern-era retrospective analysis for research and applications) reanalysis data. Figure 6 shows the resulting profiles of zonal and meridional velocity and potential temperature for the squall line case (left) and the mesoscale convective complex (right). The idealized simulations are compared with their full-physics counterparts over the time period 0100 UTC to 0800 UTC. The idealized simulations are initiated at 0000 UTC to allow for one hour of spin-up time.

4.2.1. Squall line case

The left two panels of Fig. 7 show the gravity wave momentum flux spectra at 95 hPa for the full-physics and the idealized squall line simulations as a function of phase speed (radial coordinate) and propagation angle. These spectra are obtained from seven hours of data and represent averages over an area of 576 km ×576 km. For further details on the computation of the spectra see *Stephan and Alexander* [2014]. The idealized model successfully replicates the general shape of the original spectrum and the total flux is within 12% of the full-physics simulation. The roughly circular regions of low values that appear in the northeast quadrants of the momentum flux spectra are caused by wind filtering between the top of the heating region and 95 hPa. This occurs when a wave approaches a level where the phase speed equals the wind speed. As is evident from Fig. 6 there exists strong shear at these levels in both the zonal and meridional direction.

The shape of the generated momentum flux spectrum in the idealized model is sensitive to the choice of diffusion settings. In the full-physics model vertical diffusion is governed by the planetary boundary scheme, which - like all other physics schemes - is deactivated in the idealized model. Therefore, it is necessary to select a new set of diffusion settings for the idealized model. Initial tests showed that using 2nd-order explicit diffusion in the idealized model leads to imprecise wind filtering, resulting in an unreasonably large minimum in the northeast quadrant. If no explicit diffusion scheme is turned on, vertical velocity amplitudes grow too large compared to the full-physics model. The momentum flux (Fig. 7) and velocity spectra of the idealized model agree best with the full-physics model when only 6th-order hyperdiffusion [*Knievel et al.*, 2007] is enabled. Figure 8 displays the power spectral density as a function of zonal wavenumber for the zonal, meridional and vertical velocity components at 95 hPa and 0500 UTC. Each line represents a latitudinal average at a single time step. The dashed curves of the idealized model show remarkable agreement with the solid curves of the full-physics model. The spectra of both models start to decay around $4{\cdot}10^{-4}\mathrm{m}^{-1}$, which corresponds to a horizontal wavelength of about 16 km or 8 times the grid scale and is consistent with the WRF model's effective resolution of about $7\Delta x$ [*Skamarock*, 2004].

4.2.2. Mesoscale convective complex

The area of the inner model domain for the MCC simulation is four times larger than for the squall line case and spans 1200 km ×1200 km. The full-physics MCC simulation uses identical physics and diffusion settings as the squall line simulation. Fig. 9 shows the simulated (right column) and radar (left column) precipitation field at a 4 km ×4 km horizontal resolution over the inner model domain. Comparing to Fig. 2 the MCC exhibits a more three-dimensional structure in contrast to the two-dimensional squall line. It has a larger spatial extent and is in a mature developmental stage throughout the 0100 UTC to 0800 UTC time interval.

The two spectra on the right of Fig. 7 show the gravity wave momentum flux spectra at 95 hPa produced by the full-physics and the idealized MCC simulations. Both spectra feature a large peak of gravity wave momentum flux in the westward direction and a smaller second peak in the southeastward direction. Compared to the squall line spectra the hole created by wind filtering is slightly smaller and more north-south symmetric. The shape of the spectrum is again accurately reproduced by the idealized model and the magnitude of the flux is 20% larger than in the full-physics simulation. Although this storm differs considerably from the squall line case, the heating algorithm is apparently still applicable, so that in many respects the quality of the results remains unaffected.

5. Simulations based on radar data

In section 3 we introduced the algorithm for converting ten-minute precipitation rates into a three-dimensional heating/cooling field. This method was used on the simulated precipitation fields of two full-physics WRF simulations in section 4 to test the dynamics of the idealized model. In this section we apply the same algorithm to the ten-minute radar precipitation fields (e. g. left columns of Fig. 2 and Fig. 9).

Fig. 10 shows the gravity wave momentum flux spectra at 95 hPa for the idealized simulations based on radar precipitation. For both the squall line and the MCC case the resulting spectra compare well to the respective full-physics WRF simulations (Fig. 7). For the squall line case the integrated momentum flux of the spectrum based on radar precipitation is 23% larger than in the full-physics WRF simulation which is consistent with a 22% larger domain-mean and time-mean precipitation in the observations. For the MCC the full-physics and radar-based domain-mean precipitation amounts averaged over the seven-hour time interval differ by only 1%. The 68% larger flux in the radar-based simulation might be associated with more intense rain cells, see Fig. 9.

6. Comparison with satellite measurements

Up to this point we have examined gravity waves only in model simulations. In this section we present a direct comparison of simulated stratospheric gravity waves to satellite observations for the squall line and the MCC case. The Aqua satellite is part of the

National Aeronautics and Space Administrations (NASAs) Earth Observing System A-Train, a constellation of six satellites in a sun-synchronous orbit at an altitude of 705 km. The orbit has an inclination of 98.2° with an orbital period of 98.8 minutes and equatorial crossing times at 1:30 p.m. local time on ascending passes and 1:30 a.m. on descending passes. The Atmospheric Infrared Sounder (AIRS) is one of six instruments on board Aqua providing high spatial resolution temperature-sensitive infrared radiances. One AIRS scan consists of 90 individual footprints that cover an across-track distance of 1650 km. The footprint diameter is 13.5 km in the nadir and the along track distance between two scans is 18 km.

The two panels on the left hand side of Fig. 11 show AIRS brightness temperature anomalies, computed from 4.3 micron radiances as described in *Hoffmann and Alexander* [2010]. These are descending orbit swaths with an equatorial crossing time of 1:30 am local time on 5 June 2005 (squall line case) and 20 June 2007 (mesoscale convective complex). In obtaining these images the brightness temperatures of 42 AIRS channels (2322.6 to 2366.9 cm^{-1}) from the 4.3 μm CO2 ν_3 fundamental band were averaged. A fourth-order polynomial fit along the across-track direction has been subtracted to eliminate scan angle dependent brightening effects and other background terms. This procedure completely removes any wave components oriented parallel to the along-track direction. The corresponding mean kernel function computed for midlatitude atmospheric conditions is shown in Fig. 12. It has a broad maximum around 30 to 40 km altitude and a FWHM of 25 km.

The two panels on the right hand side of Fig. 11 are computed from idealized model simulations. The size of the idealized model domain is 2000 km ×2000 km. Vertical levels with a constant spacing of 500 m extend from the surface to the bottom of the damping layer, which starts at a height of 50 km. The idealized model runs are initialized at 0000 UTC using the one-dimensional wind and temperature profiles shown in Fig. 6. Our WRF simulations described in sections 3 to 5 focused on the time period 0100 UTC to 0800 UTC. The Aqua satellite passes the central United States around 0755 UTC and therefore observes waves that are generated toward the end of this time interval. The model is driven with the radar-based heating field as in section 5. The heating is only switched on over the regions that correspond to the 600 km $\times$600 km and 1200 km $\times$1200 km model domains of the previous squall line and MCC simulations. These domains are denoted by the red squares in the WRF panels of Fig. 11.

The model images in Fig. 11 show the simulated perturbation temperature field at 0755 UTC after applying the kernel function shown in Fig. 12 and reducing the horizontal resolution to match AIRS. We only use data up to 49 km, the last model level below the damping layer, and consequently only 87.5% of the kernel function are included in our calculation. This may cause the model amplitudes to be slightly underestimated. For both the squall line and the MCC case we find that the idealized model accurately reproduces the wave pattern. While the model amplitudes are too small for the squall line case, the perturbation temperature range shows an almost perfect match for the MCC case. Fig. 13 shows the national radar mosaic at 0130 UTC, 0430 UTC and 0730 UTC for 5 June 2005 (squall line, top row) and 20 June 2007 (MCC, bottom row). For the MCC the heating area (red square Fig. 11) is large enough to capture the entire area of high reflectivities associated with this storm. Furthermore, from the radar mosaic we expect the MCC, which is located over Oklahoma at 0730 UTC, to be the main source of gravity waves. In our squall line simulation, however, we focused on the southern end of a line of storms that extended up to Wisconsin. In this case the heating region, which is located over parts of Texas and Oklahoma, did not include the full line of storms. The national radar mosaic for the squall line case shows a strong isolated cell over Missouri at 0730 UTC. Both the positive and negative peak temperature perturbations in the AIRS picture are situated close to the location of this cell. It is therefore likely that the strongest waves in the AIRS squall line case were forced by a cell that was not included in our idealized simulation.

The results presented in this section show that the idealized WRF model forced with a heating field based on radar precipitation rates is able to accurately reproduce the pattern and the amplitudes of observed waves when the whole source region is included.

7. Conclusion and discussion

We introduced an idealized dry version of the WRF model that is forced with a three-dimensional and time-varying heating/cooling field for wave studies. In conjunction with the model we developed a heating algorithm to convert local radar precipitation rates into vertical heating/cooling profiles. Focusing on intense convection over the continental summer US this new modeling approach was evaluated by simulating a squall line and a mesoscale convective complex. We found that radar precipitation data capture the high spatial and temporal variability in occurrence and strength sufficient to define convective sources of gravity waves.

In comparing simulated stratospheric waves to satellite data it was found that both the wave pattern and amplitudes compare well to observations by the AIRS instrument. *Grimsdell et al.* [2010] have presented a similar case study where a dry idealized model was forced with a heating field estimated from scanning-radar measurements. In a comparison to AIRS data they found that their model produced waves that had much smaller amplitude than observed and that good agreement was only achieved when the heating field was multiplied by a factor of 3.8. Our idealized WRF model produces a remarkably high level of realism without further tuning. This advantage can likely be attributed to the method of converting precipitation rates to vertical heating/cooling profiles. In *Grimsdell et al.* [2010] the derivation of the heating field is based purely on thermodynamical arguments. A half sine profile, which is considered representative for convective rainfall [*Shige et al.*, 2004], was chosen for the shape of the vertical heating distribution. The amplitude of the profiles was determined by the column-integrated heating which in turn was calculated from the observed precipitation. This method did not account for advection, ice-phase processes or evaporation. Our heating algorithm is based on the heating profiles generated by a full-physics WRF model and therefore inherently includes these effects. We can quantify the effects of these processes in our algorithm for comparison to the *Grimsdell et al.* [2010] result. We first examine advection effects.

From the vertical density profile $\rho(z)$ and the vertical distribution of heating/cooling $H(z)$, as given by our algorithm, we can obtain the condensation/evaporation rate $P(z)$ between level z and $z + \delta z$:

$$P(z) = \frac{H(z)C_p\rho(z)\delta z}{\rho_w L_v} \tag{3}$$

Here, C_p denotes the specific heat capacity of air, ρ_w the density of water and L_v the latent heat of condensation/evaporation. The column inetgrated condensation rate is therefore:

$$P_c = \Sigma_{z=0}^{z=Ztop} P(z), \tag{4}$$

where $Ztop$ denotes the top of the heating profile. The blue line in Fig. 14 shows the ratio of P_c and the surface precipitation P_s, $Rconv = P_c/P_s$ as a function of P_s. Advection causes the surface precipitation rate to be underestimated by a factor of 1.5 for small rain rates and by a factor of up to 2.6 for large rain rates. *Shige et al.* [2004] found the same range of values for this quantity.

We next examine effects of ice and evaporation, which primarily affect the shape of the profiles. For a given surface precipitation rate P_s, the quantity R_{G10} is the ratio of the maximum column heating rate in the profile determined by our algorithm and by the method used in *Grimsdell et al.* [2010]. R_{G10} is plotted versus P_s as the red line in Fig. 14. The result shows the maximum heating rate in the profiles given by our algorithm is about three times greater than the maximum resulting from a half-sine shape. These larger heating rates at high elevations in the algorithm profiles are offset by negative contributions in the lower troposphere due to evaporation. Ice phase processes also play a role as they further increase the amount of heat released at high altitudes. Without affecting the surface rain rate, they increase the peak of the heating and weigh the heating profile toward higher altitudes. Accounting for advection, evaporation and ice-phase processes is therefore necessary to represent gravity-wave generation by convection.

Acknowledgments. This work was supported by grant number AGS–1318932 from the National Science Foundation programs in Physical and Dynamic Meteorology and Climate and Large-scale Dynamics. Data used in this study are Next-Generation Radar Level-III products available from the National Oceanic and Atmospheric Administration Satellite and Information Service and Atmospheric Infrared Sounder Level 1B radiance sets available from the Goddard Earth Sciences Data and Information Services Center.

The Weather Research and Forecasting model is a community model supported by the National Center for Atmospheric Research Mesoscale and Microscale Meteorology Division.

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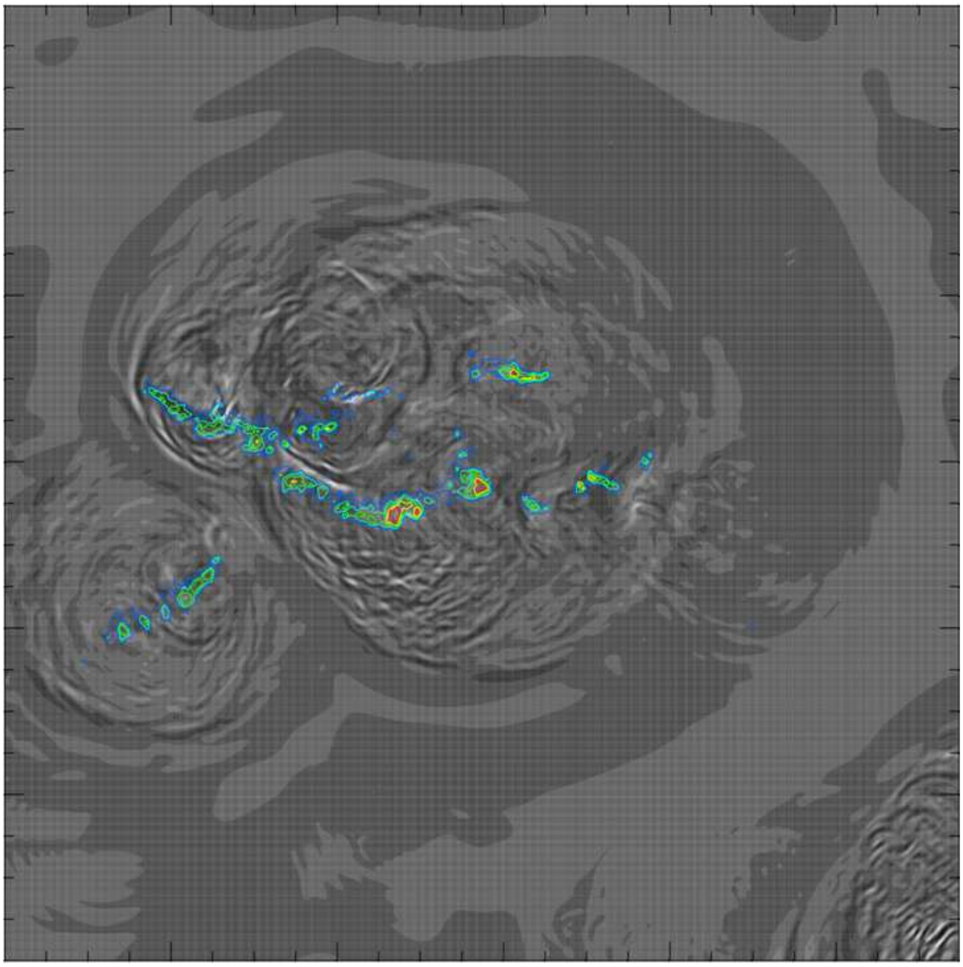

Figure 1. Idealized model simulation of a mesoscale convective complex at 0300 UTC on 20 June 2007 over the Great Plains. The model is forced with a time-varying heating/cooling field derived from radar precipitation rates. Colored contours display ten-minute radar precipitation rates greater than 3 mm (10 minutes)$^{-1}$ in 3 mm (10 minutes)$^{-1}$ increments, based on a resolution of 4 km $\times$4 km. Shades of gray show the vertical velocity field at 95 hPa at a horizontal resolution of 2 km $\times$2 km. Values range from -4.0 m/s to +4.8 m/s. The domain spans 1152 km $\times$1152 km. More details on the simulation are given in sections 4 and 5.

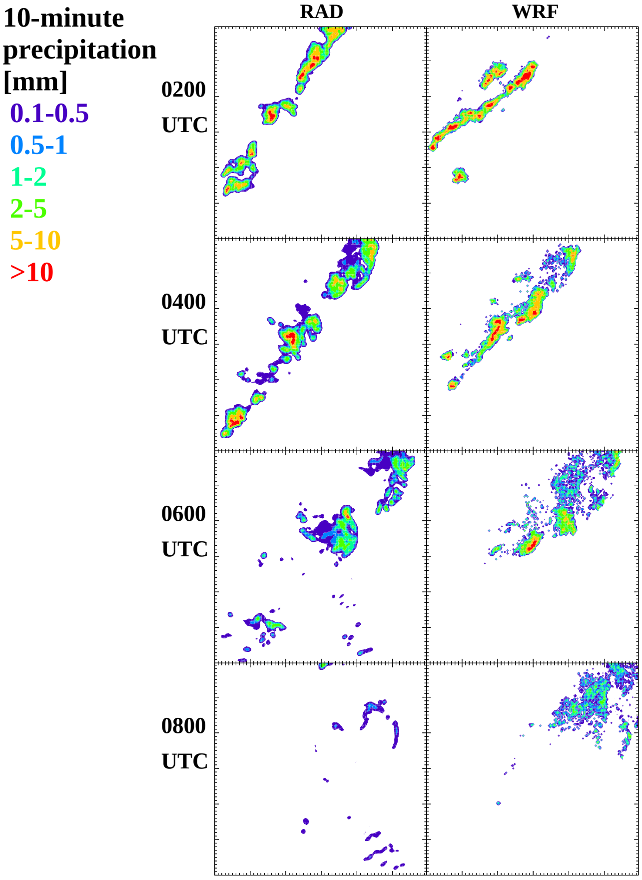

Figure 2. Maps of measured (RAD) and simulated (WRF) precipitation for the squall line case. Each panel shows the ten-minute accumulated precipitation over the area of the innermost model domain spanning 600 km ×600 km. Rows are labeled with the hour in UTC. The left column contains radar measurements and the right column displays simulated values. All plots are based on a horizontal resolution of 4 km.

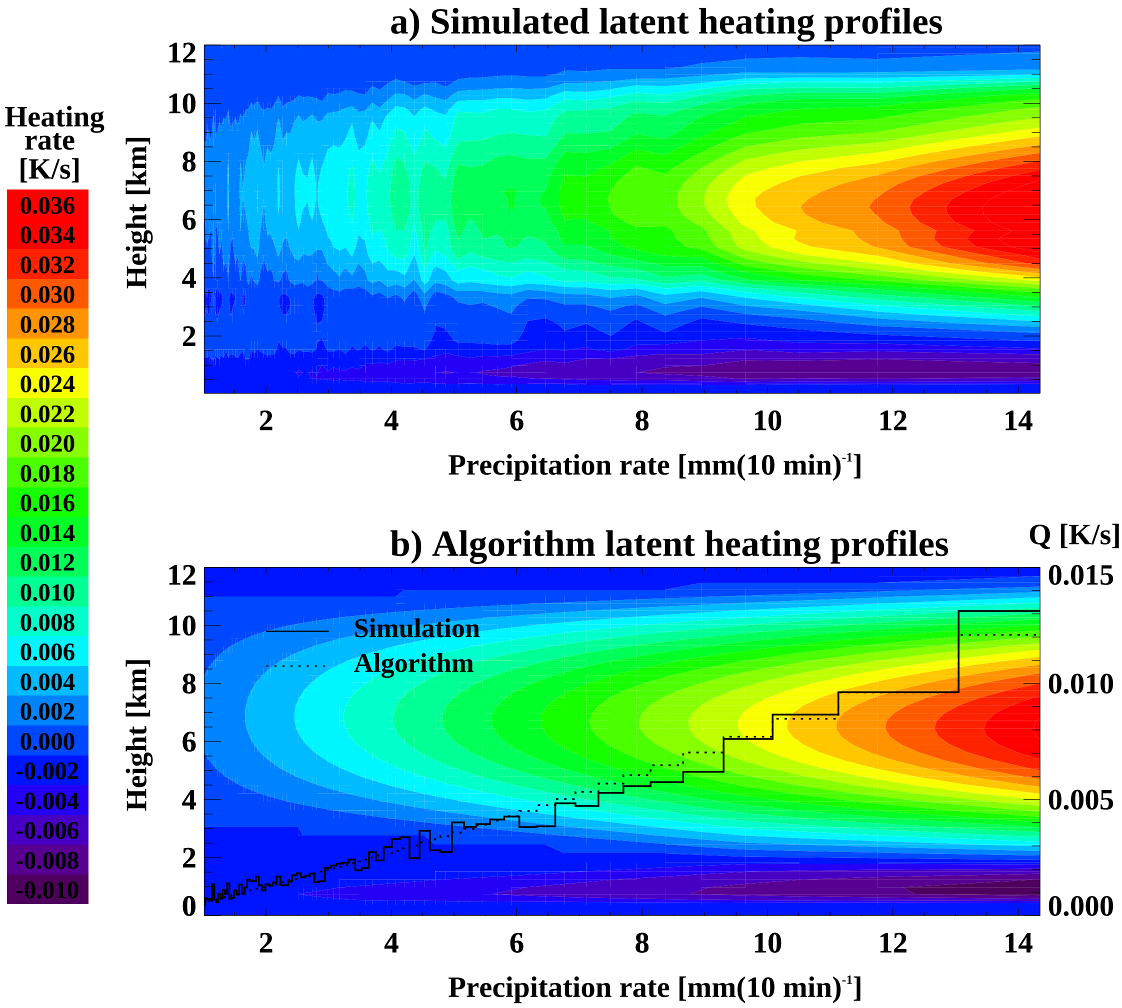

Figure 3. Simulated (a) and algorithm-derived (b) latent heating/cooling profiles versus precipitation rate. These are averages of convective pixels in the 600 km ×600 km domain based on a horizontal resolution of 4 km ×4 km and ten-minute time intervals between 0100 UTC and 0800 UTC. The histograms in panel b pertain to the ordinate on the right hand side and show the density-weighted vertically integrated heating rates, labeled Q. Dashed lines are for the algorithm-generated profiles and solid lines for the simulated profiles.

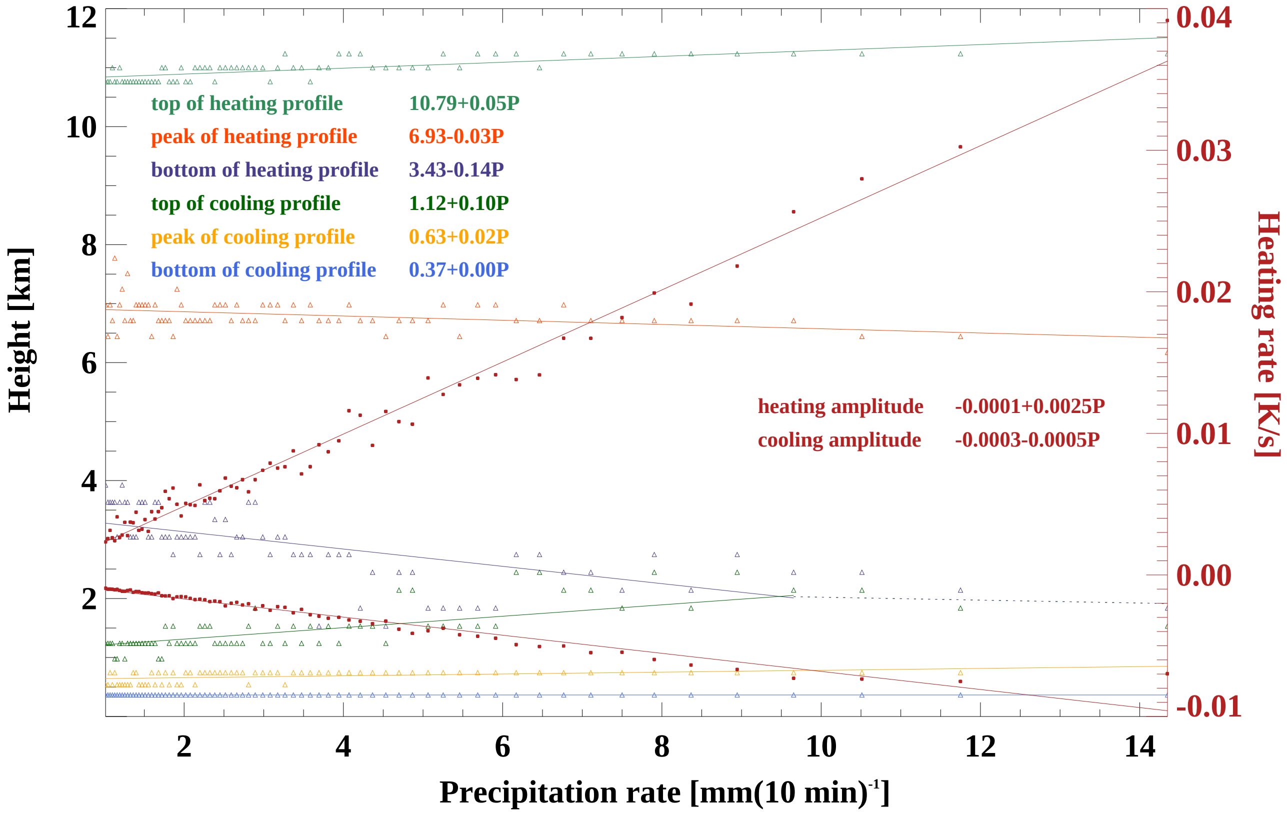

Figure 4. Linear relationships describing key characteristics of the algorithm for vertical heating profiles and their dependence on ten-minute precipitation rate. Individual data points are derived from convective rain pixels in the squall line simulation and lines are linear fits. Light green: top of the heating, Orange: height of maximum heating rate, Purple: bottom of the heating profile, Dark green: top of the cooling region, Yellow: height of maximum cooling, Blue: bottom of cooling profile. The dark red data points pertain to the ordinate on the right-hand side and show the heating and cooling layer amplitudes. These linear fits are used to convert ten-minute precipitation rates to vertical heating profiles. All values are based on a resolution of 4 km ×4 km and the time interval 0100 UTC to 0800 UTC.

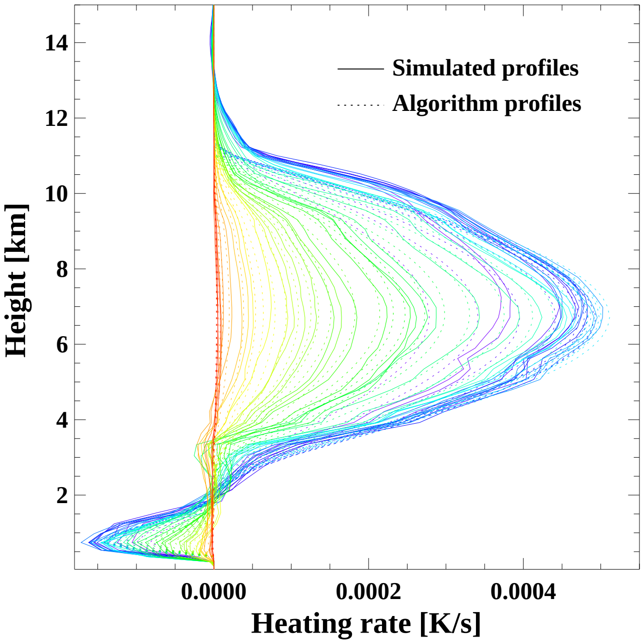

Figure 5. Simulated (solid lines) and the algorithm-produced (dashed lines) vertical heating profiles every ten minutes between 0100 UTC and 0800 UTC. Blue to red colors indicate increasing times. Each profile is a domain average of convective columns as defined in the text.

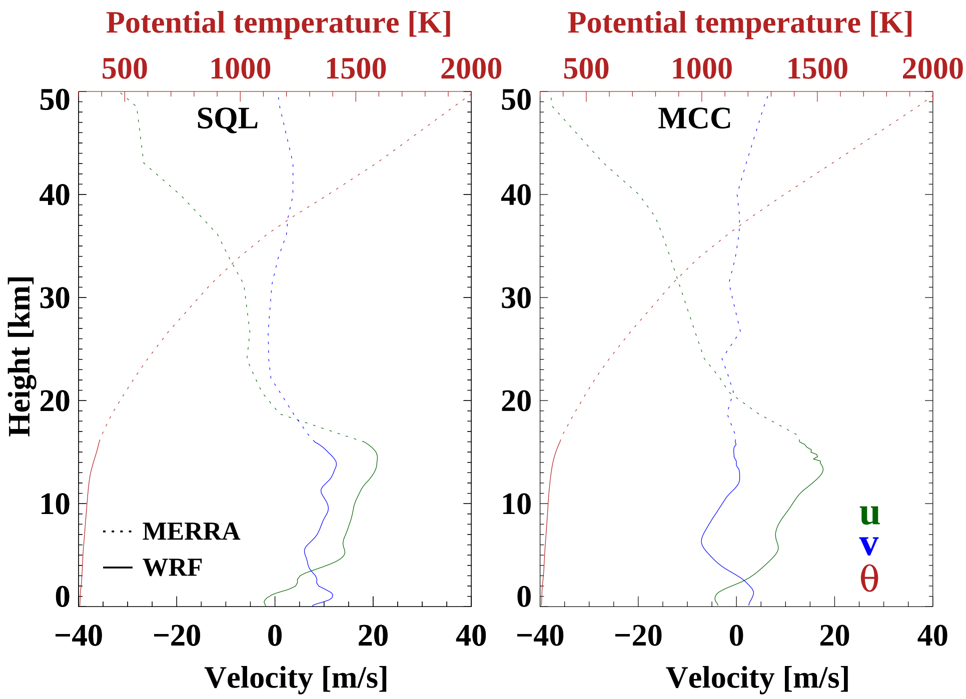

Figure 6. Zonal wind (green), meridional wind (blue) and potential temperature (red) soundings used to initialize the idealized model for the squall line (SQL) and the mesoscale convective complex (MCC) simulation. The solid portions of the graphs are calculated from the domain-mean 0100 UTC wind and temperature fields of the respective full-physics simulations. Above 16 km the profiles are extended using MERRA data (dashed lines).

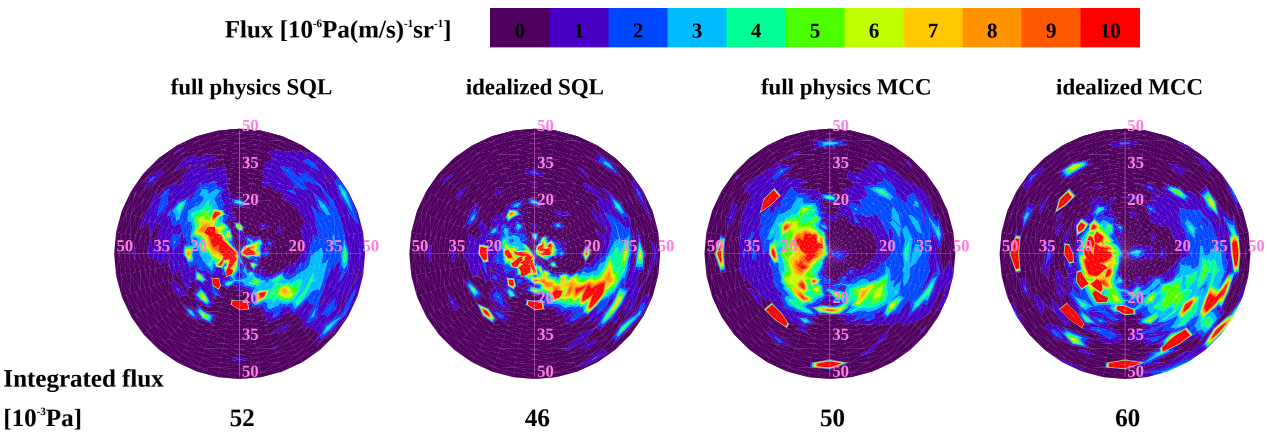

Figure 7. Gravity wave momentum flux spectra at 95 hPa for the squall line (SQL) and mesoscale convective complex (MCC) simulations. The idealized model is driven by a heating/cooling field derived from the precipitation field of the corresponding full-physics simulation. The radial coordinate with a resolution of 2 m/s is phase speed and the angular coordinate with a resolution of 10° denotes propagation direction. Northward is at the top and eastward right in each plot. The numbers below the plot denote the total flux integrated over all phase speeds and propagation angles.

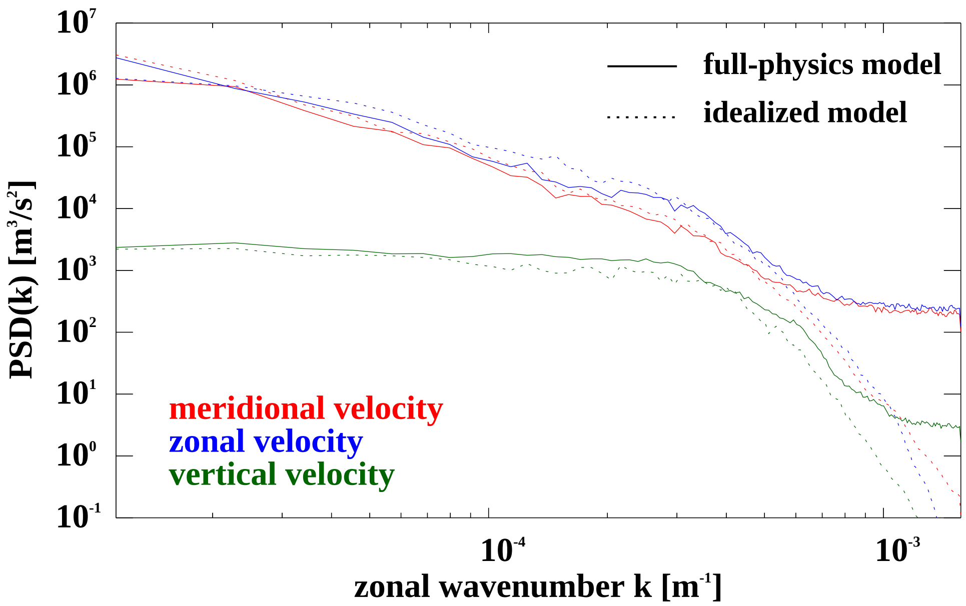

Figure 8. Power spectral density as a function of horizontal wavenumber for the zonal (blue), meridional (red) and vertical (green) velocity components at 95 hPa and 0500 UTC for the squall line case. Dashed curves are for the idealized model and solid curves for the full-physics model. The spectra of both models start to decay around $4{\cdot}10^{-4}\text{m}^{-1}$, which corresponds to a horizontal wavelength of about 16 km or 8 times the grid scale and is consistent with the WRF model's effective resolution of about $7\Delta x$ [*Skamarock*, 2004].

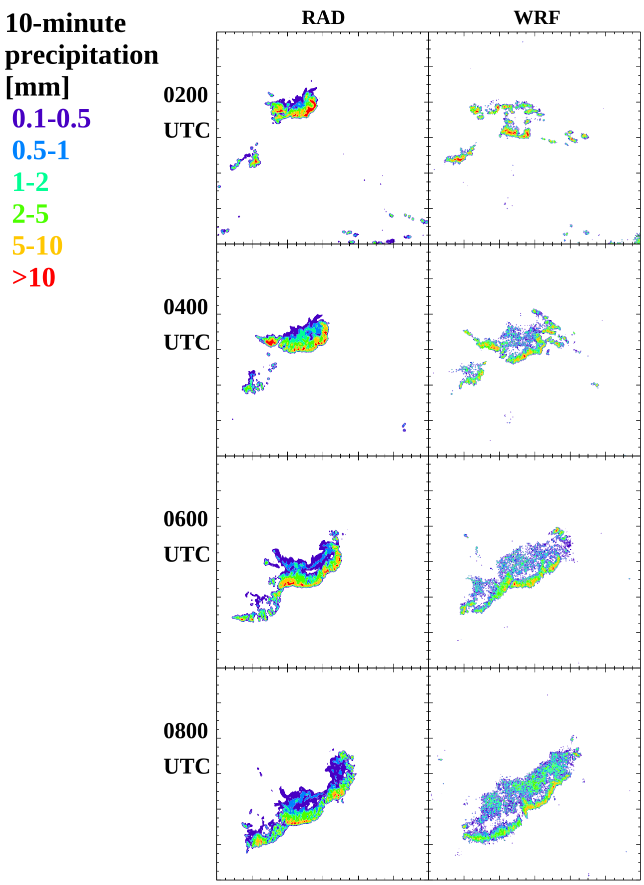

Figure 9. Maps of measured (RAD) and simulated (WRF) precipitation for the mesoscale convective complex. Each panel shows the ten-minute accumulated precipitation over the area of the innermost model domain spanning 1200 km $\times$1200 km. Rows are labeled with the hour in UTC. The left column contains radar measurements and the right column displays simulated values. All plots are based on a horizontal resolution of 4 km.

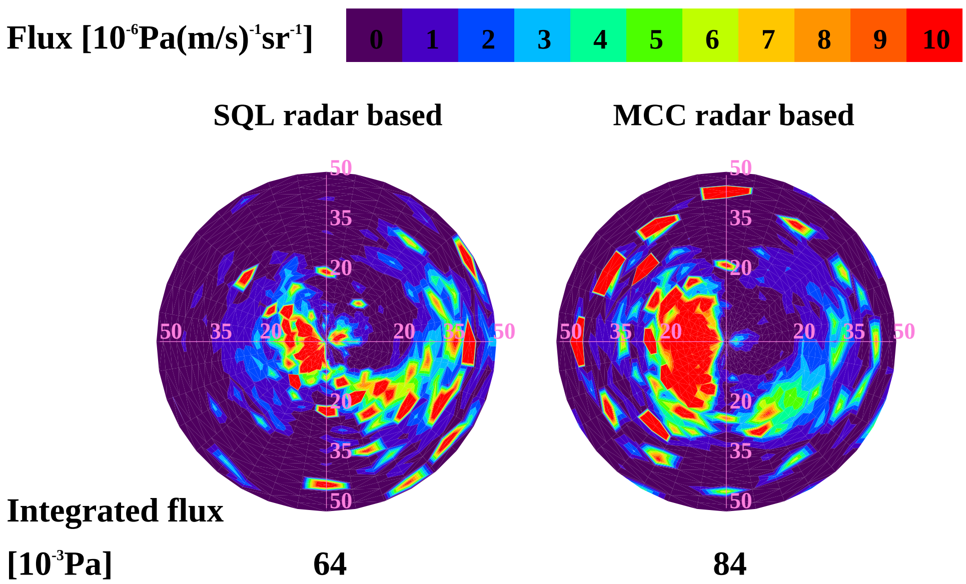

Figure 10. Gravity wave momentum flux spectra at 95 hPa for the idealized squall line (SQL) and mesoscale convective complex (MCC) simulations based on radar data. For these simulations the heating/cooling field is directly derived from ten-minute radar precipitation fields. As in Fig. 7 the radial coordinate with a resolution of 2 m/s is phase speed and the angular coordinate with a resolution of 10° denotes propagation direction. Northward is at the top and eastward right in each plot. The numbers below the plot denote the total flux integrated over all phase speeds and propagation angles.

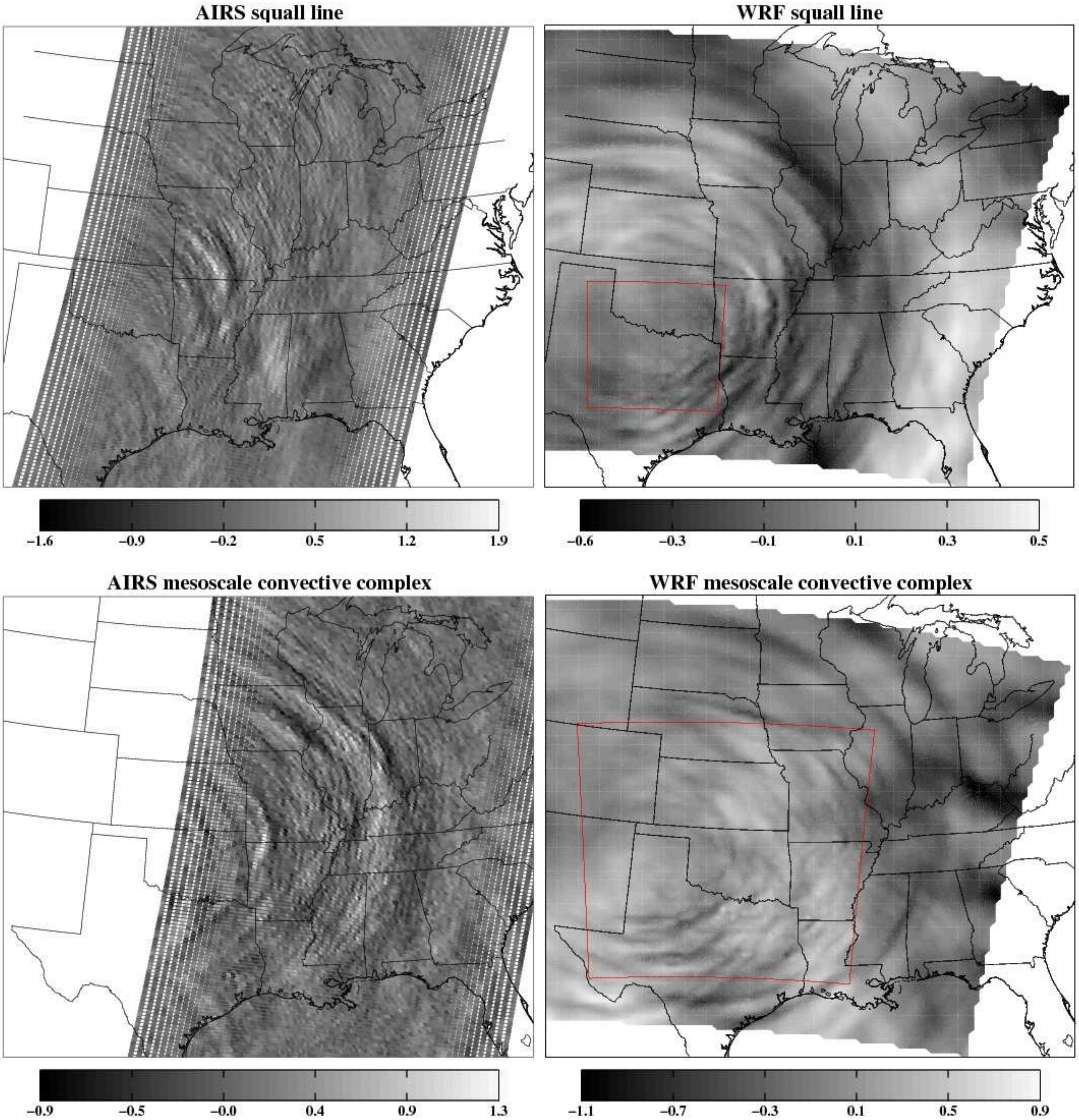

Figure 11. The panels on the left show AIRS brightness temperature anomalies, computed from 4.3 micron radiances as described in Hoffmann and Alexander (2010). These are descending orbit swaths with an equatorial crossing time of 1:30 am local time on 5 June 2005 (squall line case) and 20 June 2007 (mesoscale convective complex). A fourth-order polynomial fit along the across-track direction has been subtracted. The images on the right are computed from simulated perturbation temperature profiles using the kernel function shown in Fig. 12. The model is driven with a radar-precipitation-derived heating field that is only switched on in the area of the red squares. The model images have been degraded to match the AIRS resolution. Shading denotes temperature anomalies in Kelvin.

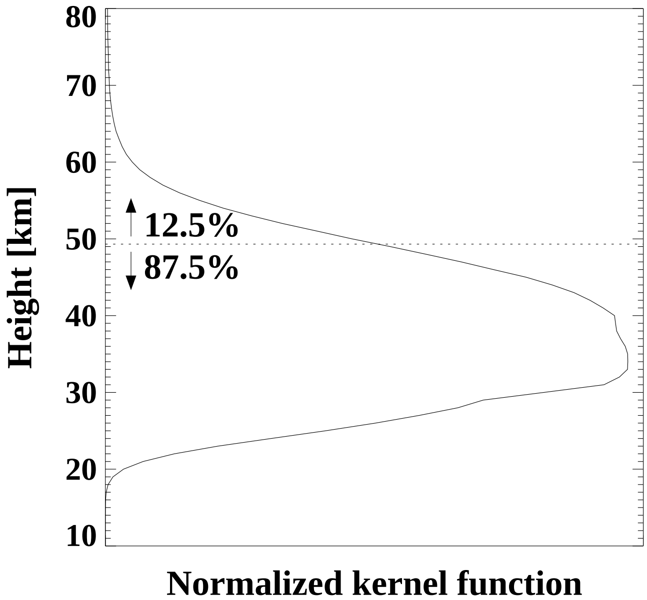

Figure 12. Normalized mean kernel function for 42 AIRS channels (2322.6-2366.9 cm^{-1}) in the 4.3 μm CO_2 band [*Hoffmann and Alexander*, 2010]. The dashed line indicates the height of the last model level situated below the damping layer. The contribution of levels below 49 km (i.e. levels that are included in our calculation) to the kernel function is 87.5%.

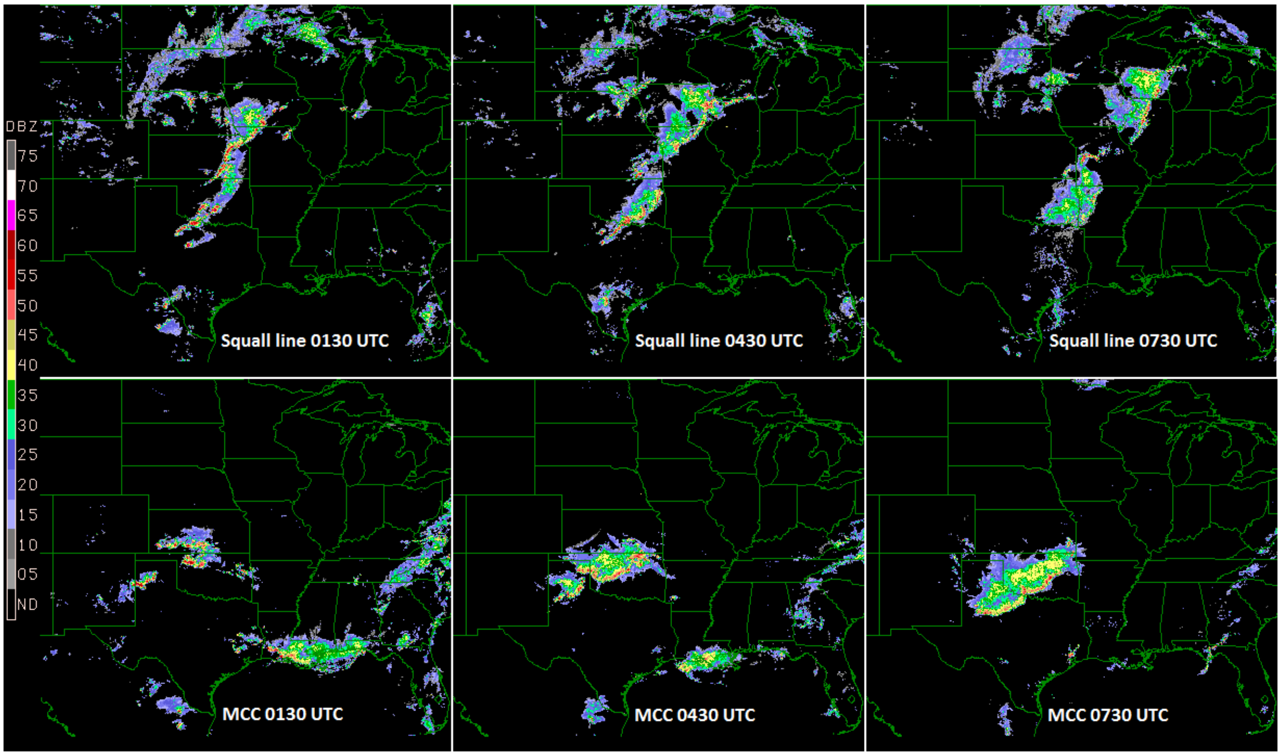

Figure 13. National Operational Weather radar 2km US mosaic showing reflectivities at 0130 UTC (left), 0430 UTC (middle) and 0730 UTC (right) for the squall line case, 5 June 2005 (upper row) and the MCC case, 20 June 2007 (bottom) row.

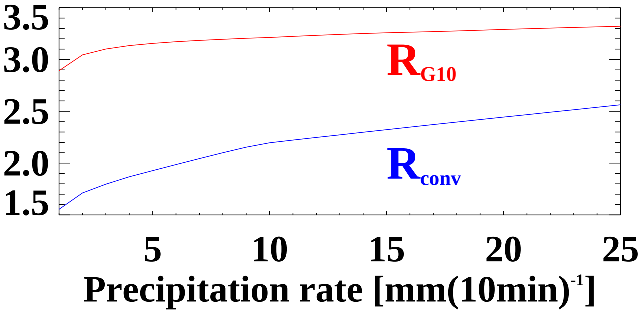

Figure 14. The quantity $Rconv = P_c/P_s$ (blue line) is defined as the ratio of the vertically integrated column condensation/evaporation rate and the surface precipitation rate. *Rconv* is larger than one because hydrometeors are transported out of the column. The quantity R_{G10} (red line) is the ratio of the maximum column heating rate in the profile derived by our algorithm and the method used in *Grimsdell et al.* [2010]. Our algorithm is based on a full-physics model and accounts for ice-phase processes and evaporation while the Grimsdell method neglected these processes. The top of the heating is assumed to be identical in both.