Realistic simulation of tropical atmospheric gravity waves using radar-observed rain rate and echo top height

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Key Points:

• An idealized model forced by radar-derived parameters for simulation of tropical convective gravity waves.
• Relating latent heat to rain rate and echo-top height leads to improved wave simulation compared to observations.
• This approach could improve prediction of tropical gravity waves for forecasting and climate applications.

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Abstract
Gravity waves (GWs) generated by tropical convection are important for the simulation of large-scale atmospheric circulations as e.g. the Quasi-Biennial Oscillation (QBO), and small-scale phenomena as clear-air turbulence. However, the simulation of these waves still poses a challenge due to the inaccurate representation of convection and high computational costs of global, cloud-resolving models. Methods that combine models with observations are needed to gain the necessary knowledge on GW generation, propagation, and dissipation so that we may encode this knowledge into fast parametrized physics for global weather and climate simulation or turbulence forecasting.

Here, we present a new method suitable for rapid simulation of realistic convective GWs. In this work, we associate the profile of latent heating with two parameters: rain rate and cloud-top height. Full-physics cloud-resolving WRF simulations are used to develop a lookup table for converting instantaneous radar precipitation rates and echo top measurements near Darwin, Australia, into a high-resolution, time-dependent latent heating field. The heating field from these simulations is then used to force an idealized dry version of the WRF model. We validate the method by comparing simulated precipitation rates and clouds with scanning radar observations and by comparing the GW field in the idealized simulations to satellite measurements. Our results suggest that including variable cloud top height in the derivation of the latent heating profiles leads to better representation of the GWs especially with respect to wave amplitudes. This improved representation also affects the forcing of GWs on the large-scale circulation.

1 Introduction
Gravity waves emanating from convection in the tropics influence atmospheric circulation on different scales. On the large-scales these are known to drive atmospheric flow patterns as e.g. the Quasi-Biennial Oscillation (QBO) in the zonal winds of the tropical lower stratosphere (e.g. Kawatani et al. 2010 Alexander & Holton, 1997; Lindzen & Holton, 1968; Ray, Alexander, & Holton, 1998; Sassi & Garcia, 1994) while on smaller scales the breaking of these waves can cause clear-air turbulence which is an acknowledged hazard in aviation (Lane, Sharman, Trier, Fovell, & Williams, 2012; Sharman & Trier, 2019). For climate prediction and weather forecasting applications, information on gravity waves from tropical convection are an urgent need (e.g. Beres, Garcia, Boville, & Sassi, 2005; Sharman & Trier, 2019). To address these research needs, we present a new method suitable for rapid simulation of realistic gravity waves emanating from tropical convection, including both developing and more mature storm conditions.

Previous work described model methods for realistic simulations of gravity waves using scanning precipitation radar data (Stephan & Alexander, 2015, hereafter SA15), and the results have been used to study diverse phenomena ranging from stratospheric gravity wave drag effects in climate models to surface pressure waves and wave influences on convective initiation (Stephan, Alexander, Hedlin, de Groot-Hedlin, & Hoffmann, 2016; Stephan, Alexander, & Richter, 2016). The existing method was developed specifically for midlatitude mature continental storm systems during summer conditions.

Applications of the SA15 method have shown that the essential source of gravity waves within precipitating clouds is the localized and time-dependent latent heat that is released, and the nonlinear interactions of that heating with the environment. Linear theoretical studies have shown that the depth and time dependence of the heating strongly influence gravity wave properties in the far field (Beres, Alexander, & Holton, 2004; Beres et al., 2005; Bergman & Salby, 1994; Manzini & Hamilton, 1993). However, the localized, instantaneous latent heating inside convection is highly nonlinear in the sense that the thermodynamic and momentum equations describing the wave generation are coupled through significant momentum and heat flux terms (Song, Chun, & Lane, 2003).
Previous modelling studies had found success in matching the important scales observed in the gravity wave field above convection, but had failed in describing the wave amplitudes (e.g. Alexander, Richter, & Sutherland, 2006; Grimsdell, Alexander, May, & Hoffmann, 2010). In this context, nonlinear effects within the cloud are known to be quite important for determining wave amplitudes (e.g. Alexander et al., 2006; Chun, Choi, & Song, 2008). The depth of the heating is important in two ways: (1) it projects onto the vertical wavenumber spectrum of the waves emitted from convection (Alexander, Holton, & Durran, 1995; Salby & Garcia, 1987); (2) if the top of the heating extends to a layer of significant shear, the interaction in the shear layer produces a separate class of waves, commonly referred to as the obstacle effect (Alexander et al., 2006; Beres et al., 2004; Chun & Baik, 1998; Pfister et al., 1993).

The SA15 method trained an algorithm using output from a non-linear, full-physics cloud resolving model simulations to characterize the profile of latent heating using a single parameter, the near-surface rain rate. Their method found success in realistic representation of the characteristics of observed wave fields surrounding convective rain in mature midlatitude summertime storm conditions over the Continental US. The method gave realistic representation of not only observed spatial extents and horizontal and vertical wave scales, but, uniquely, it also gave realistic representation of wave amplitudes.

Generally, convective latent heating is associated with condensation and freezing of water and consequently the vertical extent of clouds can be directly connected to the depth of latent heating. Therefore in this work, we extend the approach of SA15 and associate the profile of latent heating with two parameters: Rain rate and precipitation echo-top height. We train our algorithm on cloud-resolving model simulations of tropical precipitation in the Darwin, Australia area, where we also have scanning radar observations of rain rates and echo top heights available for validation.

We demonstrate the effect of including the additional echo-top height variable on the gravity wave spectrum generated by tropical convection. We also show dramatic improvements in the representation of amplitudes of gravity waves observed in the stratosphere in a satellite overpass. Finally, we compare the effects of the simulated waves with and without considering the echo-top height variable on the circulation in the lower stratosphere.

In the following we first provide an overview on the data set taken into account in section 2 followed by a validation of the cloud resolving WRF simulations in section 3. In section 4 we present the statistical mean properties of the latent heating profiles and section 5 shows the gravity wave characteristics based on the different lookup tables. Discussions in section 6 followed by summary and conclusions in section 7 conclude the paper.

2 Models and Data

The following study examines convection and gravity waves from 11-13 Jan 2003 with a focus on 12 Jan in the area of Darwin, Australia (12.48°S, 130.98°E). Grimsdell et al. (2010) also studied a particularly strong rain event in this period. Here, our modelling approach follows SA15 by employing two different types of Weather Research Forecasting (WRF) configurations (Skamarock et al., 2008). The first type is a conventional cloud-resolving, full-physics WRF configuration that is used to define the statistical mean properties of latent heating profiles. The goal of this step is the construction of two different reference tables for the vertical profile of latent heating: One as a function of rain-rate following the SA15 approach, and the other as a function of both precipitation-rate and echo-top-height.

The second WRF configuration is a dry, idealized version of the WRF model. The waves in this model are forced by prescribed latent heating that is based on rain-rates
and echo-top-heights derived from scanning precipitation radar measurements. The background wind and stability conditions in these idealized simulations are defined by wind and temperature from reanalysis fields. The idealized model is extended to high-enough altitude that we can sample the wave field with satellite weighting functions for comparisons of observed and simulated waves. The simplicity of this model permits very rapid simulation times for tropical convective GWs.

2.1 Full-Physics WRF Simulations

The cloud-resolving, full-physics WRF simulations in this study consist of three nested domains (see Fig. 1) connected with a one way nesting procedure. Here, the outer domain (D01) spans 3600 km × 3600 km, the middle domain (D02) 1200 km × 1200 km and the inner domain (D03) 408 km × 408 km with horizontal resolutions of 30 km, 6 km, and 2 km, respectively. The horizontal resolution of the inner domain is designed to match the resolution of the idealized model runs for resolution of convectively generated GWs, and it also matches the resolution of scanning radar data in the area. The full-physics model has a vertical grid consisting of 50 terrain-following levels. The vertical spacing increases from the ground up to about 7 km, above which the spacing remains fairly constant at about 700 m. The outer domain is initialized at 12:00 UTC on 11 January 2003 with European Centre for Medium-Range Weather Forecasting (ECMWF) Re-Analysis (ERA-Interim) data which also provides boundary conditions throughout the run. The runs end at 1200 UTC on 13 January, 2019. ERA-Interim data is available at 6h interval on 61 vertical levels with a nominal horizontal resolution of 0.7° (Dee et al., 2011).

For our study we largely use the "Tropical" WRF suite (e.g. Qiao, Song, He, and Li (2019)), but with a different surface layer scheme. The parametrization set includes the WRF Single-Moment 6-class (WSM6) microphysics scheme (Hong & J. Lim, 2006), the Yonsei University planetary boundary layer scheme (Hong, Noh, & Dudhia, 2006), the RRTM (Rapid Radiative Transfer Model) for long- and short-wave radiation (Iacono et al., 2008; Pincus, Barker, & Morcrette, 2003), and the MM5 (revised fifth-generation Pennsylvania State UniversityNational Center for Atmospheric Research Mesoscale Model) surface layer scheme (Jiménez et al., 2012). For the simulation of cumulus clouds the New Tiedke cumulus parametrization scheme (Zhang & Wang, 2017) is used in the outer domain D01. Note no cumulus scheme was used for the inner 6-km (D02) and 2-km (D03) domains.

To get a statistically-robust distribution, an ensemble of four full-physics WRF runs were combined. All four model setups use the same parametrization schemes and initialization data. The runs are referred to as WRF1-4 and differ only in the height of the model top. The model top is 15 hPa (approx 28 km) in WRF1 and WRF2, and increases to 10 hPa (30 km) for WRF3, and to 8.5 hPa (32 km) for WRF4, respectively.

2.2 Idealized WRF Simulations

The idealized WRF model domain covers 700 km in the north-south dimension (9.15°S - 15.45°S) and 1050 km in the east-west dimension latitudes (137.44°E - 127.78°E) (see Fig. 1). Here, the model domain is larger in the east-west direction to allow for sufficient space for the mainly eastward propagating gravity waves in the upper stratosphere (Fig. 2). The resolution is 2 km in both horizontal directions and we specify 110 vertical levels up to the model top at 60 km.

In our study the idealized WRF model is initialized with a temporally and spatially averaged dry sounding of wind and potential temperature of the Modern-Era Retrospective analysis for Research and Applications 2 (MERRA 2) on January 12, 2003 (see Fig. 2). The temporal average is taken over one day and the spatial average is calculated over 10 points spanning a latitude range from 14.5°S to 10°S and over 8 points over a lon-
Figure 1. Maps of the three WRF domains. The entire region is contained in the outer domain with a horizontal resolution of 30 km. The inner black boxes show the area covered by the inner two domains with horizontal resolutions of 6 km and 2 km, respectively. The pink dashed line shows the domain of the idealized WRF simulations with a 2-km horizontal resolution.

The depth and strength of heating are the two most important parameters determining gravity wave propagation and amplitude (e.g. Alexander et al., 1995; Stephan, Alexander, & Richter, 2016). The closest observable parameters from radar data are echo top height and rain rate. The echo top height is estimated from radar measurements by calculating the altitude where the radar reflectivity decreases below 6 dBZ as was also done by Grimsdell et al. (2010). Precipitation rates are derived by using algorithms from Bringi, Huang, Chandrasekar, and Keenan (2001); Bringi, Tang, and Chandrasekar (2004) which take into account reflectivity, differential reflectivity and specific differential phase. An extensive validation including uncertainty estimates of the radar precipitation rates can be found in Grimsdell et al. (2010).
Figure 2. Vertical profiles of the zonal wind speed (u, red in panel a), meridional wind speed (v, blue in panel a) and static stability (N, panel b) used to initialize the idealized WRF simulations.

2.4 AIRS Observations

Located on board of the Aqua satellite (which is part of the A-Train), AIRS orbits Earth with a period of 98.8 min crossing the equator at about 1:30 p.m. local solar time on ascending passes and 1:30 a.m. on descending passes. AIRS is a nadir looking instrument and scans the atmosphere perpendicularly to the satellite’s ground track with a swath width of 1780 km and a horizontal resolution at nadir of 13.5 km. AIRS data products include retrievals of atmospheric temperature, however these standard retrievals include “cloud clearing”, which results in a loss of horizontal resolution and failure to resolve stratospheric gravity waves above deep convective clouds [Hoffmann and Alexander 2010]. Here we instead compare the full resolution AIRS brightness temperatures at 4.3\(\mu\)m to simulated brightness temperatures, computed by filtering the simulated profiles with the AIRS kernel function [Hoffmann and Alexander 2010]. We can then directly compare these model brightness temperatures with the AIRS brightness temperatures. The procedure is the same as was done by SA15.

The region examined in this study is near nadir where the horizontal resolution of the observations is about 14 km (Grimsdell et al., 2010). In the vertical, the AIRS kernel function width permits observation of waves with vertical wavelength longer than 12-13 km. However, it is not only the vertical and horizontal resolution which determines the instrument’s sensitivity to GWs but also the vertical profile of the horizontal wind. Waves traveling upwind into a wind field of monotonic vertical shear are refracted to longer vertical wavelengths which are more visible to AIRS, while waves traveling downwind are less visible due to refraction to shorter vertical wavelengths. Since the horizontal background wind was mainly westward in the lower stratosphere above Darwin we expect an east-west asymmetry in the observed GW field caused by this asymmetry in visibility (Grimsdell et al., 2010, their Fig. 1). Furthermore, the point in time of AIRS observations relative to the time when GWs are convectively excited is important. As waves with different frequencies travel with different speeds, the timing of wave triggering relative to the overpass time of the satellite means the comparison with the model is very sensitive to the timing, shape, and locations of gravity wave sources.
3 Validation of Cloud Resolving WRF Simulations

Figure 3. Composite of echo top height (in km, greyscale) and precipitation rate (in mm/10mins, color) at 12:40 UTC as observed by the C-Pol radar (a) and simulated by WRF using a model top of 28km (b), 30km (c) and 32km(d).

Figure 3 shows instantaneous echo top height (grey scale) and precipitation rates (color contours) at 12:40 UTC for radar observations (a) and for the full-physics WRF simulations over the inner model domain at 2 km × 2 km horizontal resolution (b - d). In this figure only precipitation rates larger than 1 mm (10min)⁻¹ are shown. Similar to the observations, the simulations show organization into a squall-line storm oriented along a northeast to southwest line, which moves to the northwest with time. The observations show a more compact storm structure than the simulations at this time, which may be due in part to the moderate 2-km resolution. 12:40 UTC is approximately an hour before the AIRS/Aqua overpass, so may be close to the time when the gravity waves observed by the satellite were generated. As is typical for cloud-resolving simulations, the peak rain rates occur at different locations and times than in the observations, which is the reason we cannot compare waves in these simulations directly to the single satellite overpass. Instead we seek to realistically simulate a reasonably representative range of convective rain conditions and a statistically representative collection of rain cell properties, that most influence gravity wave properties. For this purpose, our focus is on comparing simulated and observed rain rates and echo top heights.
Figure 4. Timeseries of the total precipitation rate (a), the maximum precipitation rate (b) and maximum echo top heights (c) for convective pixels over the inner model domain. The red lines refer to simulated quantities where the shading highlights the spread of the different WRF simulations and the thick red line the mean of the WRF ensemble. The blue line shows the radar observed quantities. Please note that the simulated total precipitation rate has been normalized per km$^2$.

To evaluate simulated and observed storm development, we next compare the temporal evolution of the precipitation rate and maximum echo top height for convective pixels. Figure 4 illustrates the timeseries of the simulated total precipitation rate (Fig. 4a), maximum precipitation rate (Fig. 4b) and maximum echo top height (Fig. 4c) in the radar and inner domain for the WRF simulations with shading showing the range of ensemble member values. The temporal evolution of precipitation rates produced by the cloud-resolving WRF simulations is similar to the 12 Jan 2003 observations. Both the observed and simulated timeseries show a distinct maximum in precipitation between about 14UTC and 20UTC (Fig. 4a). Note that the total precipitation rate has been normalized per km$^2$ to account for the different areas simulated and observed. In contrast, the maximum precipitation rates show comparable magnitudes and evolution with time (Fig. 4b), but with fewer extremes in the simulations. Also the observed and simulated maximum echo top heights show comparable magnitudes and variability.

To assess the capability of our cloud resolving WRF simulations to reproduce the a statistically similar range of rain and echo tops for convective rain, we compare distributions of these variables to the radar observations.

Fig. 5 a) shows similar distributions for the simulated and observed echo top heights, with values ranging from 2-19 km. For echo top heights ranging between 5 km and about 11 km the two agree well. However, the probability of occurrence of cloud top heights lower than about 5 km is underestimated by the WRF simulations as are the occurrence of the
Figure 5. Probability density function (in histogram style) of the echo top height (a) and precipitation rate (b). Blue lines refer to C-Pol radar observations and red line to WRF simulations, respectively. WRF data used in this comparison is selected to be within the C-Pol range. The shading shows the spread of the different WRF simulations in echo tops and rain rates, respectively.

deepest 19 km tops. Furthermore, the peak of the PDF occurs near 13 km in the observations and 15 km echo top heights in the simulations. Both observed and simulated echo top distributions suggest a double-peaked structure, with one population near 6 km, and a second peak near 14 km.

The PDFs associated with the convective precipitation rates also suggest that the cloud-resolving simulations reproduce the observations in a statistical sense fairly well (Fig. 5 b). For precipitation rates smaller than 20 mm (10min)\(^{-1}\) the PDFs of the observations and simulations even match almost perfectly while the occurrence of moderate precipitation rates between 20 mm (10min)\(^{-1}\) - 40 mm (10min)\(^{-1}\) is slightly overestimated. However, at the highest precipitation rates larger than about 50 mm (10min)\(^{-1}\) WRF simulations underestimate the probability of occurrence compared to the observations and fail to simulate precipitation rates larger than 62 mm (10min)\(^{-1}\) in any of the simulations. Overall, comparing the PDFs of the echo top height and precipitation rates (Fig. 5) we find good agreement between the simulations and observations, but with some missing extreme values in the simulations.

Overall the comparison between CPOL radar measurements and full-physics WRF simulations indicates that our ensemble of simulations is capable of simulating the essential characteristics of the storm development and convective rain cell variability around Darwin, Australia on 12 January 2003. This gives us some confidence that (statistically) the ensemble of cloud-resolving WRF simulations are sufficiently representing the variety of tropical convective gravity wave sources for this case study.

4 Statistical Mean Properties of Latent Heat Profiles

From these simulations, we next compute the statistical mean properties of latent heating profiles for convective rain pixels, again defined as grid points with rain rates exceeding 1 mm/10 min. To derive these profiles we use the results of the innermost model domain of the full-physics WRF simulations with a horizontal resolution of 2 km × 2 km. In particular, following Stephan and Alexander (2015) latent heating is analyzed as the \(h_{\text{diabatic}}\) field and output at the same 10 min rate as precipitation rates.
Figure 6. Histogram of echo top heights and precipitation rates as simulated by the four WRF runs. In (a) the color coding refers to the number of occurrence and in (b) to the latent heating, respectively.

Figure 6a shows a histogram associated with echo top heights and precipitation rates for the complete ensemble of the full-physics WRF simulations. The color coding in this figure is related to the number of points per bin. The bin size for the echo top height is 1 km to match the vertical resolution of the CPOL radar echo top heights. For the precipitation rate the bin size is 1 mm (10 min)$^{-1}$ up to 10 mm (10 min)$^{-1}$ and from there on increases by 1 mm (10 min)$^{-1}$ per decade. We chose this approach to retain a fine resolution even at high precipitation rates where fewer points are present.

The histogram relating precipitation rates and echo top heights shows that large magnitudes of precipitation rates are associated with high echo top heights (Fig. 6a). It also illustrates that lower precipitation rates ($\leq 15$ mm (10 min)$^{-1}$) are not associated with a specific echo top height range. The distribution of echo top heights is characterized by two distinct maxima at about 6 km and 15 km. With a maximum of 62 mm (10 min)$^{-1}$, the precipitation rates found in our study are larger than those associated with mid-latitudinal squall lines (Stephan & Alexander, 2015). In Fig. 6b we relate the maximum in the profile of latent heating rate to echo-top heights and precipitation rates. This analysis suggests that latent heating increases with both rising precipitation rates and echo-top heights.

Fig. 7 presents the statistical mean profiles of latent heating where Fig. 7a shows the profiles associated with precipitation rates only and Fig. 7b - d the profiles related to different ranges of echo top heights. Enhanced values of latent heating (i.e. $> 0.02$ K s$^{-1}$) are concentrated in an altitude range from 3 km to 12.5 km. Above the surface, the profiles are characterized by a distinct cooling layer. Again, our analysis indicates that strongest latent heating ($> 0.1$ K s$^{-1}$) is associated with high precipitation rates ($> 55$ mm (10 min)$^{-1}$) and deep convection (i.e. cloud top heights higher than 13 km, see Fig. 7b). Relating the latent heating profiles with the echo top heights enhances also the latent heating maximum values by about 0.02 K s$^{-1}$ at precipitation rates $< 20$ mm (10 min)$^{-1}$ for deep convection (Fig. 7b).

5 Gravity Wave Characteristics derived from Idealized Model Runs

As already mentioned before, we have modified the idealized WRF model such that the potential temperature field is forced by input heating. To determine this input heating, the statistical mean profiles of latent heating based on the full-physics WRF sim-
Figure 7. Simulated vertical latent heating profiles versus precipitation rate including all echo top heights (a). Panels (b) to (d) show the mean vertical heating profiles associated with echo top heights ranging from 13-19km (b), 7-13km (c) and 2-7km (d), respectively. The vertical latent heating profiles are averages in the inner domain based on a horizontal resolution of 2 km and ten-minute intervals between 11 January 18 UTC to 13 January 12 UTC.

Simulations (Fig. 7) are used as lookup tables. As those latent heating profiles are associated to precipitation rates and echo top heights, we can relate these to observed rain rates and echo top heights in order to derive a three-dimensional, time-dependent input heating for the idealized WRF simulations. In the following we analyse how the addition of the echo top height in the determination of the input heating profile affects the gravity wave propagation characteristics and their amplitudes. For the reminder of this study the latent heating profiles associated with precipitation rates only (Fig. 7 a) are referred to as 1D lookup table while the profiles related to precipitation rates and echo top heights are called 2D lookup table (Fig. 7 b-d).

5.1 Comparison to AIRS observation

Figure 8 shows observed (Fig. 8 a) and simulated (Fig. 8 b to e) brightness temperature perturbations. The brightness temperature perturbations derived from AIRS observations suggest that GW amplitudes range over 4.8 K (between -1.71 K and 3.13 K) with a horizontal wavelength of about 100 km. In principal the idealized WRF simulations initialized with the two different lookup tables largely reproduce the observed GW structures at the same place at a comparable time, however with clear differences.

The maximum perturbations simulated by the setup initialized with the 1D lookup table (Fig. 8 b and d), range only about 2.3 K, less than half of the observed perturbations. In contrast to that, the perturbations simulated with the 2D lookup table setup range over almost 4.0 K (Fig. 8 c and e). At the same time of the observations (16:40 UTC) the perturbations of the two setups reach values up to 1.21 K and 2.76 K, respectively (not shown). Furthermore, Fig. 8 suggests that the heating rate derived from the different lookup tables also affects the temporal evolution of the GW field. While at 16:10 UTC...
Figure 8. Measured and simulated brightness temperature perturbations. Panel (a) shows the brightness temperature perturbations derived from AIRS observations. Panel (b) and (d) illustrate the brightness temperature perturbations based on the dry idealized WRF runs initialized with 1D lookup table and panels (c) and (e) with the 2D lookup table, respectively. The simulated results are valid for 12 January 16:10 UTC (b and c) and 17:00 UTC (d and e) while the measurement was taken at 16:40 UTC.

The GW field based on the 2D lookup table setup exhibits coherent 100-km-scale structures, these structures don’t appear until 17:00 UTC in the 1D lookup table setup. The comparable location of positive and negative brightness temperature anomalies at both presented times suggests that also the horizontal wavelength of the simulated GWs most resembles the observed ones using the 2D lookup table setup. Thus the comparison to AIRS observations clearly shows that including echo top heights in the generation of the lookup table leads to an improved representation of the GW field.

5.2 Momentum flux, phase speed, and propagation direction

Figure 9 shows total horizontal momentum flux (MF) distribution as a function of phase speed and propagation direction at levels in the lower stratosphere. (Note that the colors refer to different scales in panels a and b.) These MF were computed over a time period of four hours starting at 13 UTC. The two spectra show very similar azimuthal dependence. Overall, the GWs simulated by the 2D lookup table setup (Fig. 9 b) transport more horizontal MF than the waves generated by the setup initialized with the 1D
Figure 9. Wave momentum fluxes vs propagation direction and ground-based phase speed derived from idealized simulations initialized with the 1D lookup table (upper row) and 2D lookup table (lower row), respectively. Momentum fluxes are calculated over a period of four hours starting at 12 January 13 UTC and the figures show the mean momentum flux over an altitude range from 19 km to 25 km. The dashed white line overplotted on the momentum fluxes shows the vector stratospheric wind that filters an arc-shaped region of phase speed. Flux units are given per unit phase speed in $10^{-6}$ Pa (ms$^{-1}$)$^{-1}$. Note that the range of the color scale in the two panels differs.

lookup table (Fig. 9 a). Here, the maximum magnitude of the total MFs contained in the GWs excited by the 2D lookup table setup is about double the maximum MF simulated by the 1D lookup table setup. Furthermore, GWs with phase speeds higher than 50 ms$^{-1}$ contain larger total MF in the 2D lookup table setup. This suggests that GWs with different vertical wavelengths are generated in the respective simulations.

As the QBO is affected by the deposition of zonal momentum of GWs and for our case the main wind direction in the lower stratosphere is westward, we next examine the distribution of the zonal MF versus phase speed. For this analysis the zonal MF is integrated over propagation directions with the phase speed projected onto the zonal direction. In Fig. 10, the distribution of the zonal MF shows that eastward propagating GWs contain up to a factor of 2 larger magnitudes of horizontal MF than the westward propagating GWs in both idealized simulation setups. The zonal wind was directed westward in the lower stratosphere above Darwin (Fig. 2 a) which can explain the larger magnitudes of MF transported by eastward propagating GWs at an altitude of 24 km as the westward propagating GWs are filtered by the background wind. The phase speed associated with the maximum MFs is about 10 ms$^{-1}$ for eastward propagating GWs and 20 ms$^{-1}$ to 25 ms$^{-1}$ for westward propagating GWs, respectively.

Two different time periods are shown in Fig. 10: 9-13 UTC representing the developing phase of the squall line, and 13-17 UTC representing the mature phase. The zonal MFs simulated by the 2D lookup table setup are larger than those based on the 1D lookup table setup especially at 13-17 UTC. At this point in time the fluxes of the 1D lookup table setup are only about one-third of the fluxes derived from 2D lookup table setup. Furthermore, the temporal evolution of MF magnitudes is different between the two idealized simulation setups. While the magnitudes of zonal MFs remain rather constant for
Figure 10. Zonal momentum flux versus phase speed based on idealized WRF simulations initialized with the 1D lookup table (upper row) and 2D lookup table (lower row). Momentum fluxes are calculated over a period of four hours starting at 12 January 9 UTC (left column) and 13 UTC (right column). Here, the phase speed resembles the projected phase speed onto the east-west direction. Flux units are given per unit phase speed in $10^{-4}$ Pa (ms$^{-1}$)$^{-1}$.

the 1D lookup table setup, these fluxes increase on average by a factor of about 3 between 9-13 UTC and 13-17 UTC in the simulations initialized with the 2D lookup table setup.

5.3 Zonal forces

Linearly propagating GWs conserve horizontal momentum with altitude. Therefore, a change in zonal MF with altitude indicates the deposition of momentum to the ambient flow by nonlinear processes as e.g. breaking of GWs. In this context Fig. 11a shows the difference between the zonal MFs at altitudes of 19 km and 24 km as a function of projected phase speed. Here, the largest difference in zonal MF is found at 13-17 UTC for the setup initialized with the 2D lookup table where the difference is especially large at lower phase speeds ($c < 25$ ms$^{-1}$) compared to the other realizations. The differences of all other realizations (1D at both times and 2D at 9-13 UTC) of zonal MF with altitude show a similar pattern with comparable magnitudes especially for westward propagating GWs. Interestingly, the difference of zonal MF becomes positive for westward propagating GWs with phase speed magnitudes lower than 25 ms$^{-1}$. Considering the ambient horizontal wind profile (Fig. 2a) shows that westward propagating GWs with that phase speed range are likely to be filtered in this altitude range leading to reduced magnitudes of zonal MF at an altitude of 24 km compared to 19 km.

The force acting on the background flow due to the deposition of zonal MF is presented in Fig. 11b. Following Alexander and Holton (1997) this force has been corrected by the GW energy leaving the simulation domain. However, as this effect is found to be
orders of magnitude smaller than the GW force we won’t discuss it in more detail (not shown). With a maximum eastward force in the plane of GW propagation of up to about 1.5 ms\(^{-1}\)/day and a westward force of up to about 9 ms\(^{-1}\)/day the impact on the ambient flow is significant. However, before comparing these numbers to zonal-mean, time-mean forces driving the QBO, one has to keep in mind that these forces are based on MFs calculated over a time period of only four hours and over a domain width of only 700 km. Therefore, the values given in this analysis would be expected to be larger than GW forcing on the zonal-mean ambient flow. Furthermore, the forcing profiles in Fig. 11 b suggest for all realizations that the impact of the forcing on the ambient flow changes with altitude. Below 21 km the deposition of the zonal momentum flux leads to an eastward force, while above 22 km it is westward. This is likely associated with the change in shear, which is eastward at \(\sim 16-21\) km switching to westward above (Fig. 2a).

As expected from the zonal MF divergence (Fig. 11 a), the excited force on the ambient flow is largest at 13-17 UTC for the idealized WRF setup with heating from the 2D lookup table (see Fig. 11 b). Furthermore, the temporal evolution is more pronounced for the 2D lookup table setup than for the 1D one. While the simulated forces associated with the 1D lookup table setup exhibit no significant temporal evolution, the forces related to the 2D lookup table setup increase by up to a factor of about 5 at an altitude of about 24 km.

6 Discussion

Our previous analysis of the zonal MF shows similar distributions and magnitudes for the simulations 1D 9-13 UTC, 1D 13-17 UTC and 2D 9-13 UTC (Fig. 10). However, the structure changes with time in the simulation initialized with the 2D lookup table and larger values of zonal MF are also found at higher phase speeds \((c > 30\) ms\(^{-1}\)) with a second maximum at about \(c \approx 50\) ms\(^{-1}\). It appears that initially the GWs simulated by the two different setups are comparable however the temporal evolution of GW characteristics and activity diverges with time.

Figure 11. Difference in zonal momentum flux between 24 km and 19 km altitude as a function of phase speed (a) based on idealized WRF simulations initialized with the 1D lookup table (blue colors) and 2D lookup table (red colors). Again, the phase speed resembles the projected phase speed onto the east west direction. Flux units are given per unit phase speed in \(10^{-4}\) Pa (ms\(^{-1}\))\(^{-1}\). Panel b) shows the zonal force per unit mass estimated directly from the convergence of the zonal momentum flux excited on the ambient flow by the simulated GW activity. Force unit is given in ms\(^{-1}\)/day.
Figure 12. Time-series of vertical profiles at the latitude/longitude location of maximum latent heat for the idealized simulations initialized with the 1D lookup table (a) and 2D lookup table (b), respectively.

Generally, the phase speed is inversely proportional to the vertical wavenumber and the vertical wavenumber is proportional to the depth and strength of latent heat. Therefore, we analyze the temporal evolution of the vertical profiles of latent heat (Fig. 12) to study a possible cause for the different temporal evolution in the two different idealized WRF simulations. Here, Fig. 12 shows that the magnitude of latent heating associated with the 2D lookup table is in principal higher than the one related to the 1D lookup table setup. Furthermore, the vertical extent of the latent heating is larger in the 2D lookup table setup by about 2 km between 7 UTC and 10 UTC as well as after 12 UTC. Thus GWs of longer vertical wavelengths and consequently higher phase speeds can be excited which can explain the higher horizontal MFs at higher phase speeds for the simulations initialized with the 2D lookup table. That way this study shows that including the echo top height in the development of the lookup table leads to significant changes of GW characteristics which can in turn also alter their impact on the background atmospheric flow in simulations.

The different realizations of wave amplitudes of the idealized WRF simulations initialized with the 1D and 2D lookup table leads to deviating distribution of the horizontal MF with phase speed. Here, the zonal MFs peak at phase speeds between 0 and about 20 ms\(^{-1}\) in the eastward direction for the 1D lookup table realization and between 0 ms\(^{-1}\) and 25 ms\(^{-1}\) for the 2D lookup table setup, respectively. There are limited observations to which we can compare these results. MFs peak at lower phase speeds, between 0 and about 15 ms\(^{-1}\), in observations shown in Pfister et al. (1993) and Jewtoukoff, Plougonven, and Hertzog (2013). Jewtoukoff et al. (2013) stated that a numerical simulation of a cy-
clonic storm case tend to overestimate the higher phase speeds compared to observations. Recently, Kang, Chun, and Kim (2017) applied a gravity wave parametrization to study climatological gravity waves spanning 32 years, and reported zonal MFs at 15° latitude exhibit a pronounced maxima between about 5-20 ms\(^{-1}\) in the eastward direction and 5 ms\(^{-1}\) - 10 ms\(^{-1}\) in the westward direction, respectively. While our eastward zonal MF distribution compares well to this estimate, the distribution of our westward MF is larger at higher phase speeds. However, these differences might also be due to the nature of the GWs generated by this one regional case study. The zonal MFs related to the 2D lookup table setup at 13-17 UTC show enhanced magnitudes at phase speeds higher than 25 ms\(^{-1}\) which is in concurrence with the results of Kang et al. (2017).

Several numerical studies showed that GW absorption provides a driving force for the QBO (e.g. Kawatani et al. 2010 Alexander & Holton, 1997; Lindzen & Holton, 1968; Piani, Durran, Alexander, & Holton, 2000; Ray et al., 1998; Sassi & Garcia, 1994). Although the GWs taken into account in our study are launched near the edge of the equatorial region, these GWs nevertheless may be indicative of other deep convective sources closer to the equator (Holton et al., 1995). In that spirit already Piani et al. (2000) studied the impact of convectively generated GWs on the mean atmospheric circulation near Darwin, Australia. In their study they used a 3D mesoscale model and found maximum forcing of 1 ms\(^{-1}\)day\(^{-1}\). With a maximum of about 9 ms\(^{-1}\)day\(^{-1}\) the forcing found in our study is significantly larger than in Piani et al. (2000). However, compared to Alexander and Holton (1997) who used a 2D modeling approach, our forcing is in a similar order of magnitude. The difference to the results of Piani et al. (2000) may be related to the strength of the excited convective GWs as their magnitudes of the associated momentum fluxes are one order of magnitude smaller than in our study or in Alexander and Holton (1997). Furthermore, the horizontal wind profiles are different in the studies. While Alexander and Holton (1997) used a horizontal wind profile with a shear layer of similar magnitude at the same altitude region as analysed in our study, the shear layer is located at higher altitudes and of smaller magnitude in Piani et al. (2000).

Observational and numerical modeling studies suggest that the zonal mean forcing necessary to drive the QBO is about 0.3 ms\(^{-1}\)day\(^{-1}\) - 0.4 ms\(^{-1}\)day\(^{-1}\) (e.g. Anstey, Scinocca, & Keller, 2016; Ern et al., 2014; Garcia & Richter, 2019; Holt et al., 2016; Kawatani et al., 2010; Richter, Solomon, & Bacmeister, 2014). The approximate areal coverage of the analysed storm is about 0.8% of the total area equatorward of ±15° latitude. The maximum forcing related to the 2D lookup table setup is of the order of magnitude of 9 ms\(^{-1}\)day\(^{-1}\). Thus, if 5 such tropical storms where present in the entire equatorial region they could account for up to 90% of the forcing required for downward propagation of the shear zones related to the QBO. In former studies, a contribution of convective GW momentum flux divergence up to about 50% was found depending on the phase of the QBO (Alexander & Vincent, 2000; Piani et al., 2000). However, results with global models set up with high resolution vertical grids suggest that GWs with wavelengths smaller than 1000 km contribute substantially to the small-scale momentum flux divergence with magnitudes up to 50% in eastward phase and over 70% for the westward phase of the QBO, respectively (Alexander & Holt, 2019). Furthermore, long-term high-resolution satellite observations suggest that for both QBO phases the 10% strongest GW events account for more than 35% of the total observed momentum fluxes at 20 km altitude (Ern et al., 2014). That way our results indicate lower forcing compared to recent studies. However, we analyzed GWs related to only one strong convective storm where the derived forcing represents an extrapolation of a four-hourly value to a complete day which can lead to an overestimation of the GW induced forcing in our case.

### 7 Summary and Conclusions

In this study we extended the approach of SA15 to a tropical storm system. SA15 had developed a heating algorithm for the realistic simulation of gravity waves (GWs)
specifically excited by midlatitude mature continental storm systems during summer time. Due to the different environmental conditions the lookup tables presented in our study exhibit significant differences to the one of SA15 (see their Fig. 3). Both, the precipitation- and latent heating rates found in our study are larger by a factor of about five and ten, respectively. Due to the deeper convection in the tropics the altitude range covered by enhanced latent heating rates (i.e. \(>0.02 \text{ K s}^{-1}\)) increases by about 5 km. Also the maximum altitude where these values are found increases from 10 km in the midlatitudes to 13 km in the tropics. Although there are marked differences in the mid-latitudinal and tropical lookup tables overall the method proved to be applicable also under tropical conditions.

Furthermore, we developed the lookup table not only as a function of precipitation rate but additionally of cloud top height. In our study we showed that this extension affects the lookup tables (Fig. 7) as the maximum latent heating rates are associated with echo top height larger than 13 km (see Fig. 6). These differences caused a different representation of the convective GW field in the idealized WRF simulations where the 2D lookup table setup resulted in an increase in GW induced brightness temperature amplitudes in the stratosphere by about 1 K (see Fig. 8). Also the temporal evolution of the GW field seems to be affected by expanding the lookup table to the echo top height. Here, the GW field exhibits more coherent structures with higher amplitudes about one hour earlier in the 2D lookup table setup compared to the 1D setup. Overall, we conclude that the extension of the lookup table to the echo top height proved to be valuable by leading to a more realistic representation of the convective GW field especially regarding their amplitudes. Furthermore, the simplicity of the idealized model permits very rapid simulations at low computational cost.

In our study we showed that the method of SA15 can be extended to a tropical storm system above Darwin, Australia. However, further study is required to analyze whether this method is also applicable to other more equatorial locations within the tropics and intertropical convergence zone (ITCZ). Also, an open question is whether there is a difference between the lookup tables related to convection over land mass or oceans. Furthermore, we plan to include the stage of convection (developing or mature convection) in the development of the lookup table as a third variable. For more general applications there remains also the question whether the lookup table has a seasonal dependency.

We have already mentioned before that only limited observations of convectively generated tropical GWs exist to date to which modelling results can be compared. Soon to overcome this shortcoming long-duration flights of superpressure balloons are underway in the Strateole 2 campaign. Equipped with high-resolution instruments, these balloon flights should lead to dramatic new insights into gravity wave generation by convection and wave effects on the mean flow. These data will permit detailed validation of future similar models and further new developments.

Acknowledgments
This work was supported by the National Science Foundation, Atmospheric and Geospace Sciences, CLD and PDM programs, by grant #1829373. MJA was also partly supported by NASA grant #80NSSC17K0169. The MERRA-2 data used in this study have been provided by the Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center. The gravity wave data sets used in this study have been created using AIRS/Aqua L1B Infrared (IR) geolocated and calibrated radiances V005 distributed by the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC). They can be accessed at https://datapub.fz-juelich.de/slcs/airs/gravity_waves or by contacting Lars Hoffmann, Jlich.
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