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NUMERICAL SIMULATIONS OF VERTICALLY PROPAGATING GRAVITY WAVES IN THE STRATOSPHERE ABOVE A HYDROSTATIC LARGE AMPLITUDE SURFACE GRAVITY WAVE ON DECEMBER 12TH, 2002

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1. Introduction

Gravity waves occur frequently throughout the atmosphere, but due to their nature they are hard to find, track, and predict unless we are fortunate enough that a gravity wave forms and moves over our existing data collection sites. Because of this, our understanding of gravity waves still leaves much to be desired. Gravity waves have been shown to redistribute energy and momentum (e.g., Rauber et al. 2001), initiate and propagate along with convection (e.g., Zhang et al. 2003), and be a significant factor leading to clear air turbulence (e.g., Lane et al. 2003). Mesoscale gravity wave generation mechanisms have to shown to be associated with jet streaks (Zhang 2004 and references therein), orography (e.g. Clark et al. 2000), and convection (Lane et al. 2003 and references therein). This paper will be focusing on the environment favorable for stratospheric gravity waves formed above and around moist convection.

On December 12, 2002, a strong upper-level trough dug southward into central Texas and intersected with a strong sub-tropical jet streak over Mexico. The favorable interaction between these two systems allowed for convection to occur along the eastern coast of Texas and the western Gulf of Mexico. As the day progressed the upper-level trough became more negatively tilted, the convection increased in intensity and coverage, and a surface low pressure center formed below the max divergence aloft in the left exit region of the sub-tropical jet. An outflow jet began to form later in the day associated with and downstream of the convection, which had now organized itself into a squall line. However, part of this deep convection had formed north of a warm frontal boundary, above a good duct, and near a jet streak, which is a favorable location for a mesoscale gravity wave to form (Uccellini and Koch 1987). A model based study of the effects this convection has on the downstream environment as it relates to the modeled stratospheric gravity waves above the large amplitude tropospheric gravity wave will be explored in this paper.

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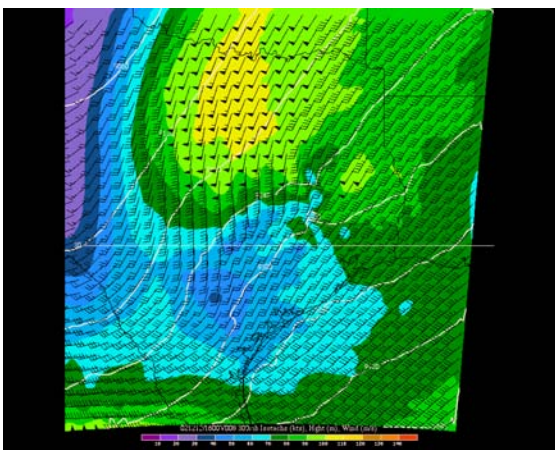
2. Model

The one-way nested stratospheric version of the non-hydrostatic mesoscale atmospheric simulation system (NHMASS) model was used to simulate this mesoscale gravity wave event at horizontal grid spacing of 18 km, 6 km, and 2 km. The 18 km horizontal grid spacing simulation was initialized using NCEP reanalysis at 0000 UTC 12 December 2002. Nested domains of 6 km and 2 km were initialized at 0800 UTC and 1900 UTC 12 December 2002, respectively. All model runs had 90 vertical levels and are similar to Kiefer (2005) setup of the NHMASS model, except for the 2 km horizontal grid spacing simulation, which was run with the convective parameterization scheme turned off. A sensitivity study was also done with a model simulation using no latent heating, to see the importance that latent heating had on development and environment for the large-amplitude gravity waves. The model lid was extended to 30 km in an effort to focus on vertically propagating stratospheric gravity waves. Only the results from the 6 km and 2 km simulations will be shown in this paper.

3. Results and Discussion

The 6 km model simulation begins to form the convective outflow jet at 300 hPa over north central Texas by 1600 UTC 12 December 2002 (Fig. 1a) in which eastern Texas and the Texas/Louisiana border are in the right entrance region of the outflow jet, a favorable region for upper divergence. While this is occurring a residual component of the strong sub-tropical jet is advecting eastward into southern Texas and another momentum maximum is over Louisiana once again putting eastern Texas into a favorable region of upper divergence at 200 hPa (Fig. 1b). Figure 2 shows the 30-minute output of total precipitation associated with the convection and upper divergence at 1600 UTC and while there is some precipitation located across eastern Texas and the western Gulf of Mexico is not very impressive. With this convection a surface low-pressure center of 1008 hPa has formed at it is located off the coast of southern Texas (not shown). By 2000 UTC on December 12, 2002, the convection has formed into a squall line northeast of Houston, Texas (HOU) (Fig. 3a) and the surface low-pressure center has dropped to 1005 hPa (Fig. 3b) with mesoscale gravity waves becoming evident north of the surface low-pressure center. Also, aloft at 200 hPa a mesoscale outflow jet becomes visible north and northeast of the convection (not shown), while the trough at 300 hPa becomes more negatively tilted (Fig. 4). At 2200 UTC the surface low-pressure center is at the Texas/Louisiana border region with more amplified mesoscale gravity waves to its north (Fig. 5). So it is apparent that a large-amplitude surface gravity wave has formed associated with this jet/front system and convection, which compares favorably to observations (not shown), however, the rest of this paper will focus on the modeled stratospheric gravity waves that form above and around the moist convection associated with the lower tropospheric gravity waves.



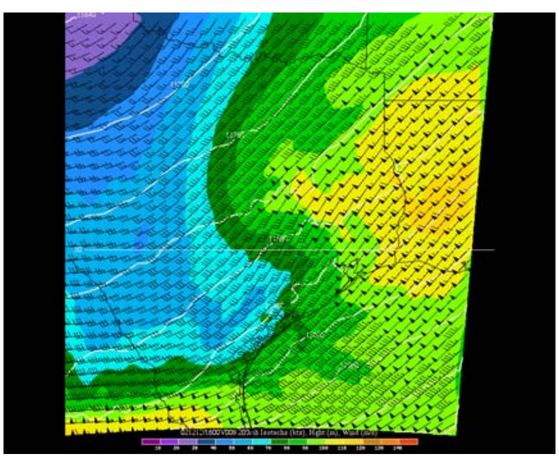


Fig. 1. 6 km NHMASS model 1600 UTC 12 December 2002 isotachs (kts) (colors), geopotential height (m), and wind barbs (m/s) at (a) 300 hPa (b) 200 hPa.

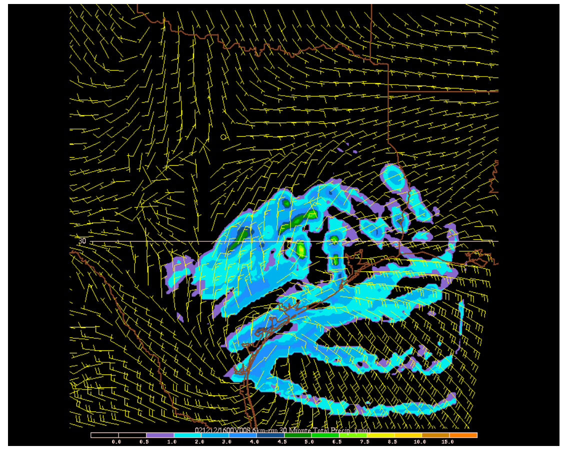
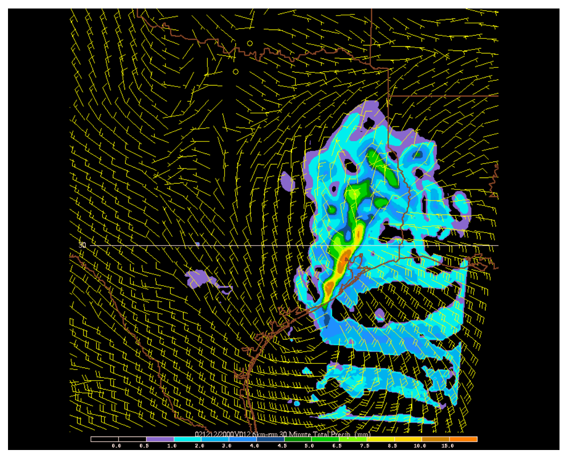


Fig. 2. 6 km NHMASS model 1600 UTC 12 December 2002 total precipitation over the past 30 minutes (mm) and surface winds (kts).



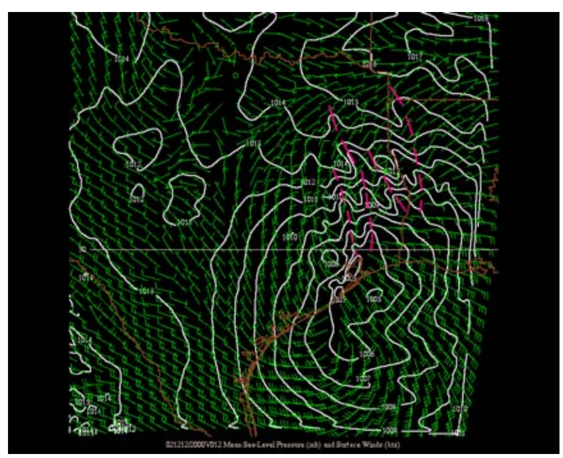


Fig. 3. 6 km NHMASS model 2000 UTC 12 December 2002 (a) total precipitation over the past 30 minutes (mm) and surface winds (kts) and (b) mean sea-level pressure (mb) and surface winds (kts).

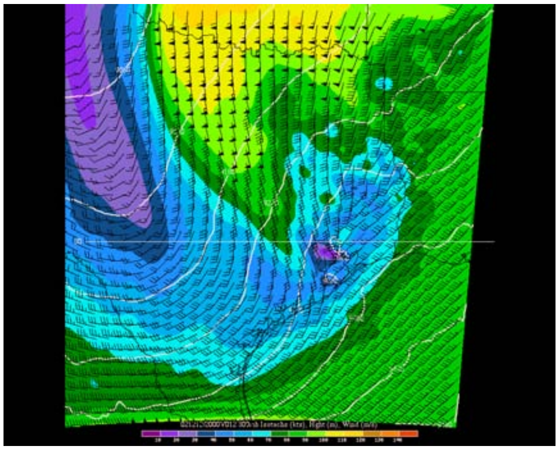


Fig. 4. 6 km NHMASS model 2000 UTC 12 December 2002 isotachs (kts) (colors), geopotential height (m), and wind barbs (m/s) at 300 hPa.

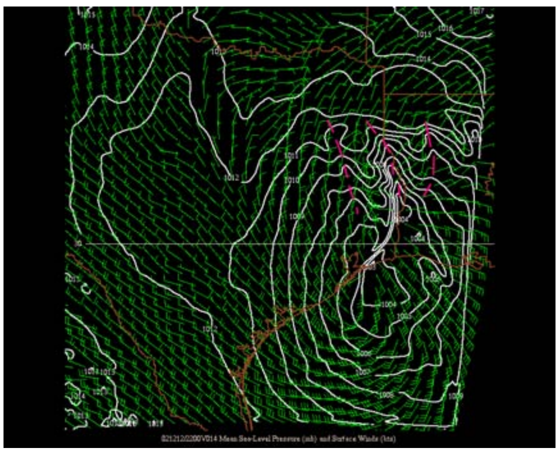


Fig. 5. 6 km NHMASS model 2200 UTC 12 December 2002 mean sea-level pressure (mb) and surface winds (kts).

At 2200 UTC 12 December 2002, the 2 km NHMASS model simulates the convection very similar to the 6 km simulation with the main part of the squall line in eastern Texas (Fig. 6a) and the surface low-pressure center and mesoscale gravity waves along the border of Texas and Louisiana (Fig. 6b). While the convection continues to propagate to the northeast modeled stratospheric gravity waves are beginning to form above and around the moist convection. Between 2200 UTC and 2300 UTC at 100 hPa these modeled stratospheric gravity waves are clearly visible behind the convection forming a wave packet (Figs. 7a and 7b). Figure 8a shows a vertical cross section taken orthogonal to the modeled stratospheric gravity waves with the main jet streak between 200 hPa and 100 hPa and the waves above 100 hPa at 2200 UTC. As the squall line grows stronger and individual convective tops push higher into the stratosphere (not shown), the convection begins to split the momentum of the once continuous jet streak by 2215 UTC (Fig. 8b). At 2230 UTC the split of in the jet streak momentum between 200 hPa and 100 hPa is even more evident (Fig. 8c), and as a result this momentum is being transferred above the blocking, that is the convective tops, and the momentum is causing the stratosphere to become more perturbed. This perturbation is evident by the growth in amplitude of the modeled stratospheric gravity waves between 2215 UTC (Fig. 8b) and 2230 UTC (Fig. 8c). One of the modeled stratospheric gravity waves has a large increase in amplitude by 2245 UTC (Fig. 8d) as one of the convective tops grows above 200 hPa (not shown) and the momentum from the jet streak blocked by this convective top needs to be dissipated into the surrounding environment. Finally, at 2300 UTC the modeled stratospheric gravity waves vertically propagate all the way to 50 hPa (Fig. 8e) as the momentum from the jet streak moves around and above the convective tops.

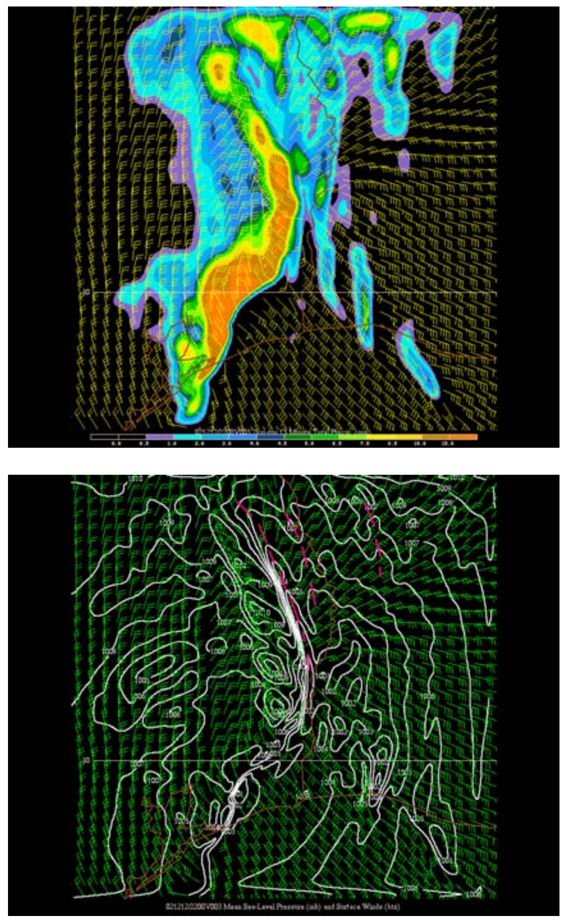


Fig. 6. 2 km NHMASS model 2200 UTC 12 December 2002 (a) total precipitation over the past 15 minutes (mm) and surface winds (kts) and (b) mean sea-level pressure (mb) and surface winds (kts).

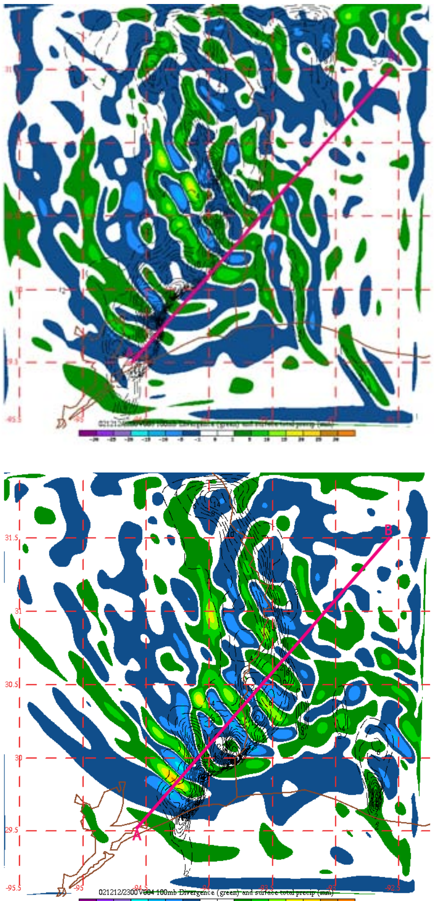
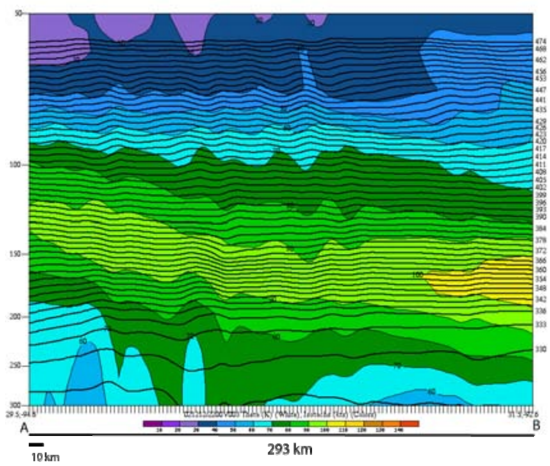
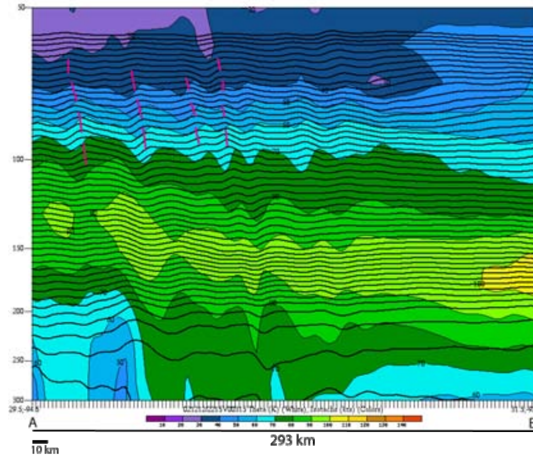
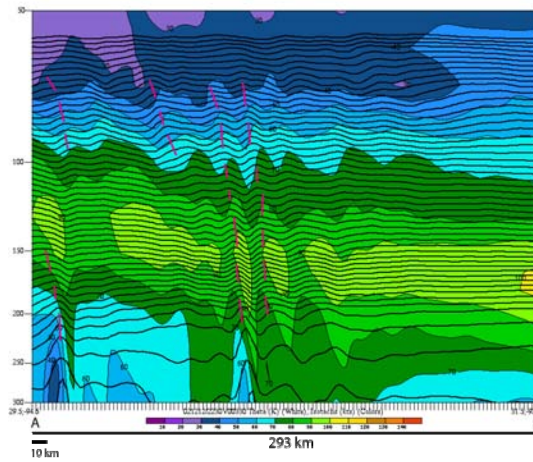
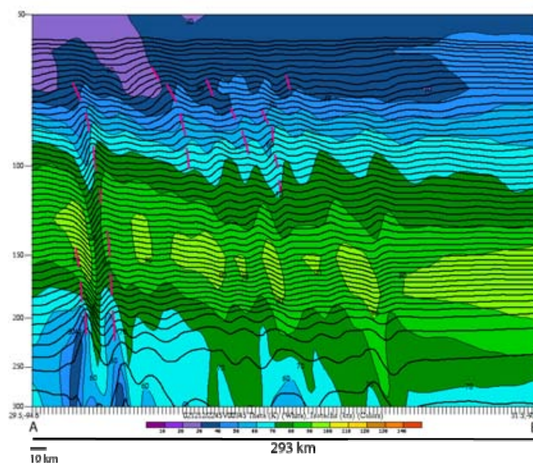


Fig. 7. 2 km NHMASS model 12 December 2002 100 hPa divergence ($1x10^{-4}$ s^{-1}) (green), convergence (blue) ($1x10^{-4}$ s^{-1}), and total surface precipitation (mm) over the past 15 minutes (dashed) at (a) 2200 UTC and (b) 2300 UTC.









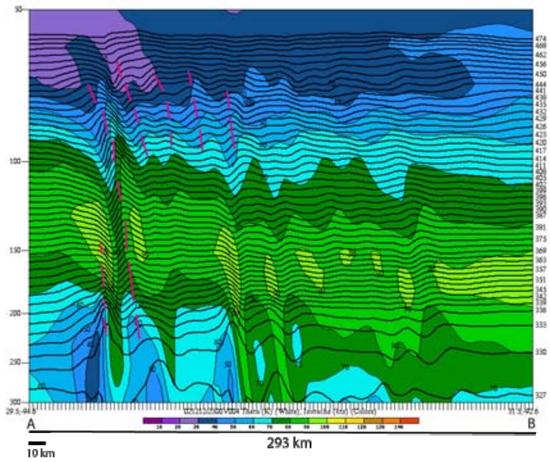
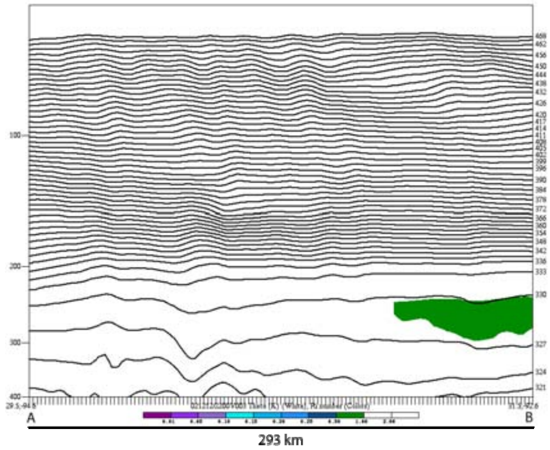


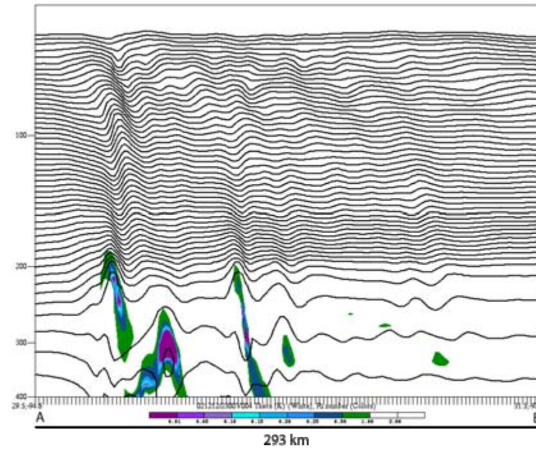
Fig. 8. 2 km NHMASS model 12 December 2002 vertical cross section from 300 hPa to 50 hPa along line A-B (see Figs. 7a and b) of isotachs (kts) (colors) and potential temperature (K) (black lines) at (a) 2200 UTC, (b) 2215 UTC, (c) 2230 UTC, (d) 2245 UTC, and (e) 2300 UTC.

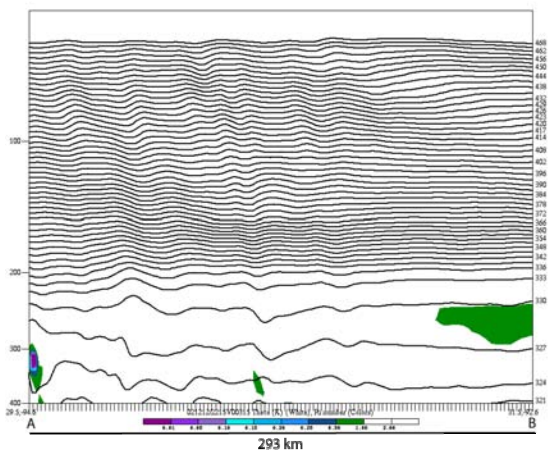
Another way to look at how the modeled stratospheric gravity waves propagate vertically away from the convective tops as the momentum from the jet streak is blocked, is by looking at where the Richardson number is below the critical value of 0.25. Where the Richardson number is below critical will provide a corridor where the blocked momentum can be vertical dispersed. At 2200 UTC along the same cross section when the Richardson number is plotted there is no where along the cross section where the number is below critical, therefore we should expect the modeled stratospheric gravity waves to dissipate quickly if they form at all (Fig. 9a)). However, starting at 2215 UTC there begins to be areas where the Richardson number has gone below its critical value above and around the convective tops (Fig. 9b). By 2245 UTC (Fig. 9c), Richardson numbers below the critical value of 0.25 are right below the largely amplifying modeled stratospheric gravity wave, and this is indicating the momentum from the blocked jet streak is being vertically propagated and tilted into the lower stratosphere. Consequently, at 2300 UTC the low Richardson number values remain below the large modeled stratospheric gravity wave (Fig. 9d) which allows the modeled stratospheric gravity wave to continue to be reinforced with more momentum and allowing the waves to propagate further, rather than being quickly dissipated into the background environment.

Consistent with these modeled stratospheric gravity waves and the convective outflow jet are several sources of observations. Coarse resolution raob data observed at 0000 UTC 13 December 2005 shows the outflow jet over Oklahoma at 300 hPa (Fig 10a), while at 200 hPa the favorable region for upper divergence is along the Texas/Louisiana border region (Fig 10b). So the large amount of momentum seen between 200 hPa and 100 hPa along the vertical cross section of the modeled atmosphere is consistent with the observations. Observations at 150 hPa (Fig 10c) show stronger momentum over the Louisiana area then at 300 hPa, which is similar to the model results as well. Along with the raob observations are several wind profiler sites, which we are fortunate enough that the gravity waves passes over. At the Ledbetter, Texas wind profiler a strong jet streak is observed pass over the area between 1330 UTC and 1800 UTC on December 12, 2002 (Fig 11a). Notice above 13 km (170 hPa) during this time the change in vertical wind shear above the jet core is similar to the model vertical cross sections (Figs 8a-8e). Another interesting feature is the momentum mixing vertically after the jet core passes over Ledbetter, TX (Fig 11a). Some of this momentum mixes vertically up to 16km (95 hPa), while another surge mixes down to 6 km (490 hPa), between 1800 UTC and 2200 UTC 12 December 2002 (Fig 11a). The momentum that mixes downward is similar to Rauber et al. (2001). This pattern can again be seen at Winnfield, Louisiana (Fig 11b), when the main jet core passes over, the momentum once is mixed vertically between 2300 UTC on December 12, 2002, and 0300 UTC on December 13, 2002. The Okolona, Mississippi wind profiler also shows this pattern (not shown) of momentum being vertically mixed/displaced. While these wind profiler observations shown have been taken every hour, study and analysis on six-minute wind profiler data is in process.

Sensitivities studies have been run on this large amplitude gravity wave event as well to see the importance of the latent heating on the process and environment for these waves, in both the troposphere and stratosphere. A no-latent heat model simulation was made to compare to the full physics run. Figure 12 shows the sea-level pressure at 2215 UTC for comparison with figure 6b, and the no-latent heat simulation produces no convection, no strong upper-level divergence, and no latent heating, therefore there are no strong pressure falls at the surface. No tropospheric or stratospheric gravity waves occur in the no-latent heat simulation, and the surface-low pressure center passes through Louisiana six to seven slower than the full physics run, while its magnitude is also 9-mb lower (not shown).







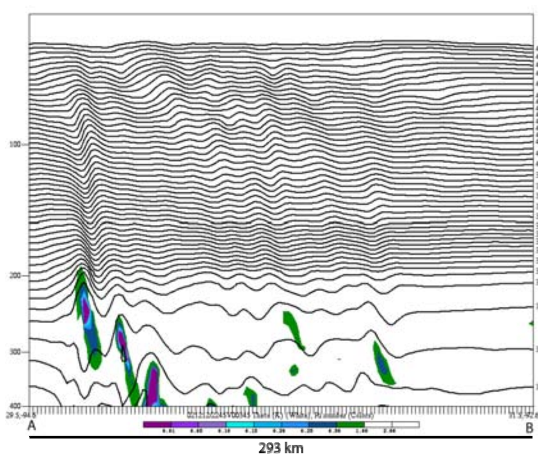
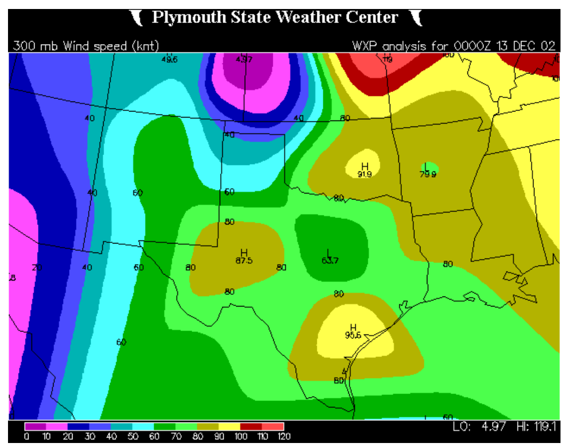
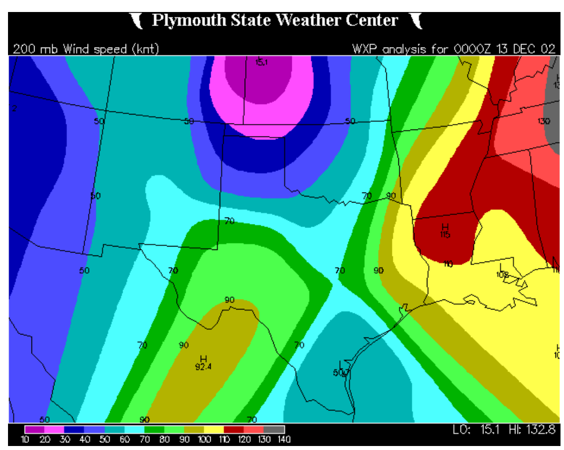


Fig. 9. 2 km NHMASS model 12 December 2002 vertical cross section from 300 hPa to 50 hPa along line A-B (see Figs. 7a and b) of Richardson number (colors) and potential temperature (K) (black lines) at (a) 2200 UTC, (b) 2215 UTC, (c) 2245 UTC, and (d) 2300 UTC.





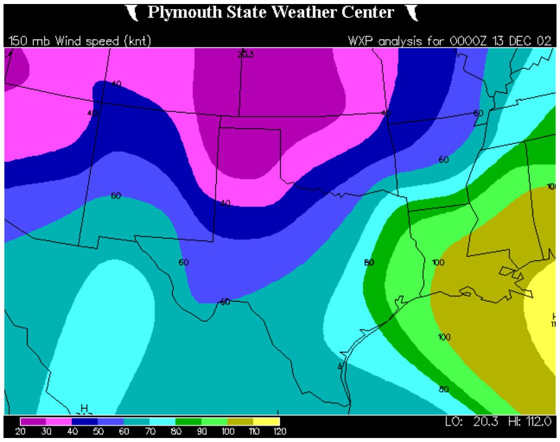


Fig. 10. Wind observation from 0000 UTC 13 December 2002 from <vortex.Plymouth.edu> (a) 300 hPa, (b) 200 hPa, (c) 150 hPa.

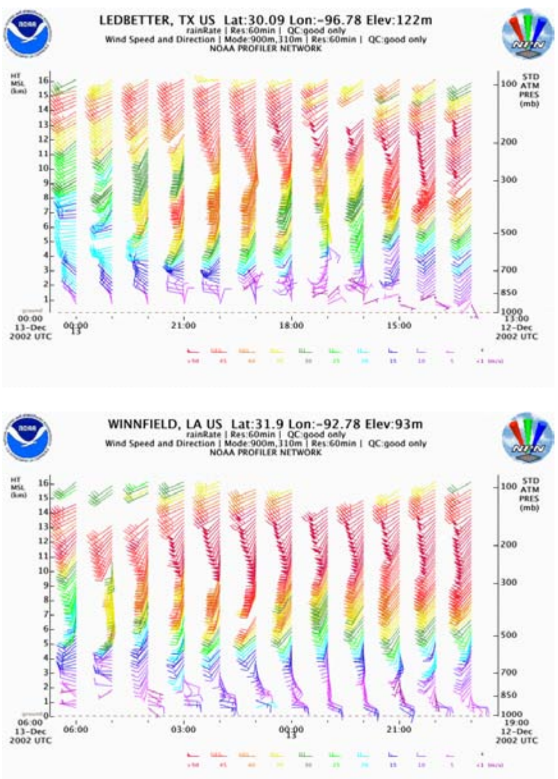


Fig. 11. Wind profilers from 1300 UTC 12 December 2002 to 0000 UTC 13 December 2002 (a) at Ledbetter, Texas, and from 1900 UTC 12 December 2002 to 0600 UTC 13 December 2002 (b) at Winnfield, Louisiana.

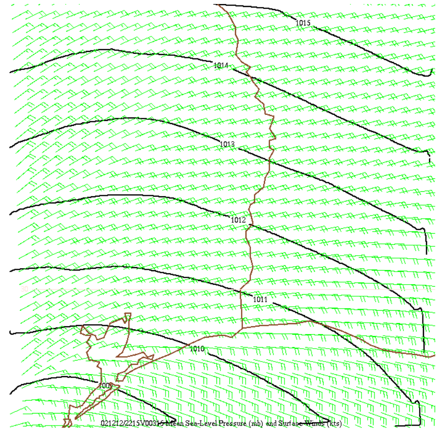


Fig. 12. 2 km NHMASS no latent model 2215 UTC 12 December 2002 surface winds (kts) and mean sea-level pressure (mb).

4. Conclusions

The modeled stratospheric gravity waves in this case allow for the redistribution of momentum aloft around and above the blocking convection. Also, the large amounts of vertical wind shear, seen throughout the troposphere and lower stratosphere in the observed wind profilers, raobs, and the modeled atmosphere, are consistent with the vertical momentum being mixed into the lower stratosphere. Verification of these stratospheric gravity waves is currently being pursued using AMSU data, similar to the study by Wu (2004), and it is our hope to have the data available by the conference.

5. Acknowledgements

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