Final Summary Report on NASA Grant NAG-1-1803

Grant Title: Wave Dynamics and Transport in the Stratosphere

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I. Summary of research supported under NAG-1-1803

1. *Gravity waves generated by tropical convection*: Research Assistant Professor Joan Alexander and the PI completed a study in which a two-dimensional cloud-resolving model was used to examine the possible role of gravity waves generated by a simulated tropical squall line in forcing the quasi-biennial oscillation (QBO) of the zonal winds in the equatorial stratosphere. A simulation with constant background stratospheric winds was compared to simulations with background winds characteristic of the westerly and easterly QBO phases, respectively. In all three cases a broad spectrum of both eastward and westward propagating gravity waves was excited. In the constant background wind case the vertical momentum flux was nearly constant with height in the stratosphere, after correction for waves leaving the model domain. In the easterly and westerly shear cases, however, westward and eastward propagating waves, respectively, were strongly damped as they approach their critical levels, owing to the strongly scale dependent vertical diffusion in the model. The profiles of zonal forcing induced by this wave damping were similar to profiles given by critical level absorption, but displaced slightly downward. The magnitude of the zonal forcing was of order 5 m s^{-1} day^{-1}. It was estimated that if 2% of the area of the tropics were occupied by storms of similar magnitude, mesoscale gravity waves could provide nearly 1/4 of the zonal forcing required for the QBO.

In addition to the ACMAP support under this grant, this work was partially supported by the NSF physical meteorology program, which paid a portion of Dr. Alexander's salary, and supported our use of the NCAR Cray YMP supercomputer. This work was reported in Alexander and Holton (1997).

2. *Gravity wave ray tracing studies*: Research Assistant Professor Joan Alexander developed a linear ray tracing model of gravity wave propagation to extend the nonlinear storm model results into the mesosphere and thermosphere. The storm-generated waves were first characterized with a combination of Fourier and wavelet analyses to quantify their wavenumber and frequency characteristics, as well as their amplitudes and wave packet dimensions. These defined the linear model inputs. A saturation condition is included that describes dissipation of the waves at higher levels when they become unstable. The model predicts that the storm-generated waves create large zonal mean flow forces in the mesosphere. The analysis suggested that a single long-lived midlatitude

storm might contribute a large fraction (up to 40%) of the daily total zonal-mean wave-driven forcing in the mesosphere expected from all gravity wave sources. This work is reported in Alexander (1996).
This same model was extended to study global propagation characteristics and effects of gravity waves in the middle atmosphere. In this application, the gravity waves were artificially specified in the troposphere to be globally and seasonally uniform. Despite the absence of any source variability in the model, monthly mean distributions in the gravity wave driven zonal force with the model showed very realistic seasonal, vertical, and geographical variations in comparison to observations. The results demonstrate the importance of variations in the background winds in interpreting observations of gravity waves and their effects on the middle atmosphere. This work is reported in Alexander and Rosenlof (1996) and was partly supported by a grant from the NSF.

3. *Tracer filamentation*: Vertical soundings of stratospheric ozone often exhibit laminated tracer structures characterized by strong vertical tracer gradients. The change in time of these gradients was used to define a tracer lamination rate. It was shown that this quantity is given by the cross product of the horizontal temperature gradient and the horizontal tracer gradient. Climatologies based on UARS ozone data and UKMO temperatures and on an ozone-like pseudo tracer (based on modified potential vorticity) were computed. Three stratospheric regions with high lamination production rates were found: the stratospheric overworld near the edge of the polar vortex, the lowermost stratosphere in the vicinity of isentropes crossing the tropopause, and in the subtropical lower stratosphere. Seasonal variations, and contrasts between the Northern and Southern Hemispheres were explored. This work (which was partially supported by the NASA UARS program) was reported in Appenzeller and Holton (1997).

4. *Mesospheric gravity wave modeling studies*:. Although our emphasis in numerical simulation of gravity waves generated by convection has shifted from simulation of idealized two-dimensional squall lines to the more realistic (and complex) study of wave generation by three-dimensional storms, we realized that owing to several incremental improvements in the two-dimensional cloud model (specifically in boundary conditions) it was possible to extend the top boundary of the model to the region of the mesopause without encountering severe numerical problems (which had not been the case with previous versions of the model). Thus, we have repeated our basic midlatitude two-dimensional squall line simulation but have extended the domain to 2048 km in the horizontal by 90 km in the vertical. Grid resolution is 2 km in the horizontal and 0.5 km in the vertical, and a time-step of only 4 seconds is required to maintain computational stability. Initial zonal wind and temperature profiles corresponding to Northern Hemisphere spring conditions (westerlies in the stratosphere and mesosphere) are compared to a simulation with no shear in the middle atmospheric background winds. The simulation clearly exhibits the dramatic influence that convectively generated waves can have on the dynamics of the mesosphere. High frequency gravity waves quickly propagate nearly vertically into the mesosphere, followed by lower frequency waves, which propagate upward and outward from the storm, forming a fan-like wave pattern that in the mesosphere extends more than 1000 km to the front and rear of the storm. In the simulation with no shear in the background winds of the middle atmosphere, waves

propagating to the rear of the storm dominate in the mesosphere as they did in the lower stratosphere in previous simulations of such midlatitude squall lines. However, when realistic shear in the middle atmosphere is added, corresponding to springtime conditions, the forward propagating waves instead dominate the mesosphere. Wave breaking is vigorous in these forward propagating modes that have been Doppler shifted to high intrinsic frequencies by the shear in the background wind. The breaking not only acts to drive a strong zonal forcing in the mesosphere, but also provides a source for generation of smaller scale secondary waves.

We have used the spectral analysis techniques developed earlier under partial support from ACMAP (Alexander et al., 1995) for a detailed analysis of the mesospheric wave response. The results are similar to estimates from the ray tracing model developed by Alexander (1996), though the latter model tends to somewhat overestimate wave momentum fluxes.

In addition to the ACMAP support under this grant, this work was partially supported by the NSF physical meteorology program, which paid a portion of Dr. Alexander's salary, and supported our use of the NCAR Cray YMP supercomputer. An oral presentation based on this work will be presented as an invited paper at the Rossby 100 Symposium in Stockholm, June 1998, and was published in a special issue of the journal *Tellus* [Holton and Alexander, 1999].

5. *Gravity wave climatology studies*: As a continuation of previous modeling work aimed at developing constraints for parameterizations of the effects of gravity waves in the middle atmosphere, Research Assistant Professor Joan Alexander applied a linear gravity wave propagation model together with observations of the background wind and stability fields to compute climatologies of gravity wave activity for comparison to observations. This work did not lead to the expected constraints for parameterizations because it was found that quantitative comparisons between observations and the model depend sensitively on the strength and intermittency in gravity wave sources, properties which are largely unknown. Instead the results lead to some new interpretations of existing observational studies of the climatology of gravity wave activity. It was found that globally and seasonally uniform gravity wave sources input to the model can reproduce many of the seasonal and geographical trends seen in data from both satellite (UARS Microwave Limb Sounder) and rocket-based platforms. Previous interpretations of the observed climatology have instead often emphasized the importance of seasonal and geographical variations in gravity wave sources for explaining the wave activity variations.

Observations in the lower stratosphere from radiosondes were found to be more sensitive to true variations in gravity wave sources than were the satellite and rocket observations. The results of this model comparison also suggest some new ways to analyze and report observations that can yield useful constraints for gravity wave parameterizations in the future. This work is reported in Alexander (1998), and was also partially supported by the NSF, and through a grant from NASA for UARS research.

6. *Convective forcing of gravity waves*: Professor Alexander in collaboration with Dr. Rajul Pandya, a postdoctoral researcher at NCAR, has completed a theoretical study of gravity wave forcing by convective heat sources in both linear and nonlinear

mesoscale models. The convective heating generated in a nonlinear storm model with full microphysics was used to specify the time- and space-varying heat source in a purely linear, but otherwise very similar, model. A comparison via spectral analysis of the stratospheric wave fields in the two models tests the hypothesis that knowledge of the convective heating can be used in a linear model to infer the spectrum of vertically propagating waves forced by convection. The results suggest it can predict the dominant vertical wavelengths and frequencies of the wave spectrum, but with amplitudes significantly larger than seen in the nonlinear model. The deep convection creates a region of low stability in the upper troposphere that effectively filters much of the short horizontal wavelength energy from the spectrum of gravity waves entering the stratosphere. Dissipation mechanisms active in the nonlinear model also play an important role by both damping the shortest scale waves and redistributing wave energy from shorter to longer horizontal scales. The work has been submitted for publication (Pandya and Alexander, 1999).

7. *Gravity wave observations from UARS*: Dr. Charles McLandress has nearly completed an 18 month visit (partly supported from other sources) to work on data analysis and modeling for interpretation of gravity wave observations from the UARS/MLS in cooperation with Dr. Dong Wu at JPL. The objective of this work is to apply ray tracing, and other model techniques, in order to determine to what extent the horizontal and vertical variation in satellite observed distribution of small-scale temperature variance can be attributed to gravity waves from particular sources (e. g., convective activity over the Amazon or mountain waves generated by flow over the Rockies), rather than reflecting changes in the spectral distribution of waves imposed through filtering by mean winds.
Horizontal temperature variances derived from optically-thick radiance measurements from the Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite are used as a proxy for gravity wave activity in the stratosphere and lower mesosphere. The six-year dataset, which includes both limb-scanning and limb-tracking measurements, provides information for horizontal length scales ranging from 30 to 1000 km. A careful examination of the horizontal and vertical scale-sensitivity of MLS is made and the resulting three-dimensional response functions are used in the interpretation of the results. Seasonal climatologies exhibit regions of large variance at high latitudes in the winter hemisphere and distinct maxima in the subtropics over the continental landmasses in the summer hemisphere. Attention is focused on the summertime maxima since these are unlikely to be a result of filtering effects by background mean winds which exhibit only relatively weak longitudinal variations there. A gravity wave ray-tracing model that employs background mean winds for the same period as the MLS observations and an idealized three-dimensional response function is used as an interpretive tool. The model results reveal that mean wind effects are not responsible for the longitudinal variation of the summertime subtropical maxima. Furthermore the model is also able to simulate the variance patterns for the different viewing geometries of MLS. Finally, a comparison of the MLS results to maps of cloud top temperatures shows a good correspondence in the summer-time subtropics providing evidence that an important source of these waves is deep convection. This work has been submitted for publication (McLandress, et al., 1999).

8. *The annual and interannual variations in temperature and mass flux near the tropical tropopause*: Dr. Elena Yulaeva completed her doctoral dissertation in April 1997. Her work consisted of observational and model studies focused on elucidating the relative contributions of local tropospheric processes (e. g., the Hadley circulation) and remote forcing from the extratropical stratosphere ('downward control') to the temperature and vertical velocity distribution near the 100 hPa level in the tropics. For the observational part of this work Yulaeva used the NCEP/NCAR reanalysis of global weather data for the past 17 years. Evidence from this analysis was that between the 200 and 100 mb pressure levels the vertical circulation changed character dramatically from tropospheric control to stratospheric control. For the modeling study she developed a nonlinear zonally averaged model based on the transformed Eulerian mean equations in which the residual meridional circulation was computed for specified diabatic heating and zonal forcing. Results from the model generally supported the hypothesis that the vertical transport velocity at 100 mb and above is controlled by dynamical processes in the stratosphere. The model also revealed the importance of midlatitude dynamical forcing in influencing the strength of the tropospheric Hadley circulation. A paper based on this work will be submitted for publication.

9. *Three-dimensional cloud model:* Since July of 1996 graduate student Claudio Piani has been studying the stratospheric impact of the generation and propagation of gravity waves in a three-dimensional simulated tropical squall line. As the basis for this modeling effort we are using a new cloud model developed in the MMM Division at NCAR, which has a more accurate advection algorithm than the model that we previously used, can be run in a nested grid mode, and is designed for running on high-end workstations. Unfortunately, we discovered that although the nested grid was satisfactory for tropospheric storm studies, gravity waves in the stratospheric portion of the model domain exhibited unrealistic reflection at the boundaries of the interior fine mesh domain. Hence we were forced to abandon the nested grid approach and are running the model on a single domain with horizontal dimensions of 550 by 550 km and vertical depth of 42 km. The grid elements are 2 km in the horizontal and about 1/2 km in the vertical (with finer resolution near the surface). Mr. Piani initialized the cloud model with December thermodynamic and tropospheric wind soundings from Darwin Australia, a location in the tropics where there are unusually good observations. The initial fields were smoothly matched to the stratospheric wind and temperature fields previously used by Alexander and Holton (1997) in their two-dimensional simulations of tropical squall lines (supported in part by this grant).

Mr. Piani has now completed three simulations: (1) a control case with constant stratospheric winds (nearly zero relative to the storm motion); (2) a case corresponding to the westerly shear phase of the equatorial stratospheric quasi-biennial oscillation; and (3) a case corresponding to the easterly phase of the quasi-biennial oscillation. In all cases the tropospheric convection develops along a bow shaped gust front, but is centered at any instant in 2 or 3 cumulonimbus towers near the center of the domain. An example of the vertical velocity field at the 40 km level resulting from the gravity waves generated by this convection is shown in the attached figure 2. In the control case the waves propagate outward from a source region in a manner analogous to surface waves

generated by a stone thrown into a pond, thus resulting in temperature and wind perturbations that form a circular pattern in the stratosphere. The results shown in figure 2 are very similar to the observations reported in Dewan et al. (1998).
By contrast with the control case, in the westerly and easterly shear cases the wave activity to the east and west of the source, respectively, is filtered by critical level absorption below the 40 km level. Thus only a portion of the "wave circle" remains. Vertical profiles of the wave activity in east-west sections through the storm center show that the three dimensional gravity wave simulation shares many characteristics of the two-dimensional simulations performed earlier. A paper describing this results is being prepared for publication.

II. Publications Supported (wholly or in part) by NAG-1-1803

Alexander, M. J., A model of non-stationary gravity waves in the stratosphere and comparison to observations. In *Gravity wave processes and their parameterization in general circulation models*, ed. K. Hamilton, Springer-Verlag, 153-168,1997.

Alexander, M. J., 1998: Interpretations of observed climatological patterns in stratospheric gravity wave variance. *J. Geophys. Res.*, **103**, 8627-8640.

Alexander, M. J., J. R. Holton and D. R. Durran, 1995: The gravity wave response above deep convection in a squall line simulation. *J. Atmos. Sci.*, **52**, 2212-2226.

Alexander, M. J. and K. H. Rosenlof, 1996: Non-stationary gravity wave forcing of the stratospheric zonal mean wind. *J. Geophys. Res.*, **101**, 23,465-23,474.

Alexander, M. J. and J. R. Holton, 1997: A model study of zonal forcing in the equatorial stratosphere by convectively induced gravity waves. *J. Atmos. Sci.*, **54**, 408-419

Appenzeller, C. and J. R. Holton, 1997: Tracer lamination in the stratosphere —a global climatology. *J. Geophys. Res.*, **102**, 13,555-13,569.

Holton, J. R. and M. J. Alexander, 1998: Gravity waves in the mesosphere generated by tropospheric convection. *Tellus*, **51A**-*B*, 45-58, 1999.

McLandress, C., D. L. Wu and M. J. Alexander, 1999: Seasonal and geographical variation of gravity waves measured by the Microwave Limb Sounder. *J. Geophys. Res. (submitted).*

Pandya, R. E. and M. J. Alexander, 1999: Linear stratospheric gravity waves above convective thermal forcing, *J. Atmos. Sci.*, **56**, 2447-2453.