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13. ABSTRACT (Maximum 200 words) Our efforts during this research have included the following major emphasis: 1) performance of high resolution studies of KH instability in order to assess the dynamics and impact on optical propagation in support of the ABL program, 2) studies of wave breaking instability and nonlinear wave-wave interactions as other means of limiting wave amplitudes, generating turbulence, and contributing to spectral evolution and optical effects, 3) completion of 2D and 3D studies of vortex dynamics in stratification and shear, and 4) the continuing development of newer, more capable, and more efficient numerical codes for these studies.			
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# FINAL TASK REPORT

**Instructions:** Provide all information identified below for the duration of this project. List "Research Objectives" in bullet format. Provide "Summary of Research" in narrative format.

**Research Title:** Nonlinear Spectral Evolution of Atmospheric Gravity Waves

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**AFOSR Program Manager:** Major Paul Bellaire JR.

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## Research Objectives:

1. define the mechanisms for and spectral energy transfers accompanying gravity wave spectral evolution in the atmosphere (including instability and wave-wave interaction dynamics),
2. examine the competition between wave-wave interactions and wave instability processes in controlling spectral shape when both are operative, and
3. determine the implications of superposed and interacting waves on the occurrence, character, and intensity of wave instability and turbulence generation.

## Funding Summary (\$K): FY98 - 00

In House	Capital Equip. (> \$5,000 each)	Subcontractor	Total
\$248,714			\$248,714

### Summary of Progress:

Our efforts during this research have included the following major emphases:

- 1) performance of high-resolution studies of KH instability in order to assess the dynamics and impact on optical propagation in support of the ABL program,
- 2) studies of wave breaking instability and nonlinear wave-wave interactions as other means of limiting wave amplitudes, generating turbulence, and contributing to spectral evolution and optical effects,
- 3) completion of 2D and 3D studies of vortex dynamics in stratification and shear, and 4) the continuing development of newer, more capable, and more efficient numerical codes for these studies.

The first topic has led to a series of simulations of KH instability for a range of Reynolds numbers and initial flow configurations. These simulations have been the highest resolution KH studies to date and have yielded a wealth of information on the dynamics of KH instability transition and turbulence, turbulence mixing and anisotropy, and implications for optical propagation. These results have also led to a series of publications, including a paper having a cover of Geophysical Research Letters (Werne and Fritts, GRL, 1999), with more recent contributions to radar backscatter assessments (Gibson-Wilde et al., 2000), evaluation of errors in lidar and optical studies of gravity wave effects (Fritts, 2000), and a review paper addressing the nature of wave-driven instabilities and implications for mixing throughout the atmosphere (Fritts and Werne, 2000), among others.

Wave breaking studies focused initially on single waves in order to understand the turbulence transition and dynamics in as simple a configuration as possible. These studies have revealed the character and tendency toward instability for a range of wave amplitudes above and below a "convective" instability amplitude, and have thus confirmed a more pervasive inclination toward instability and turbulence than believed based on simple stability arguments. These studies are also revealing a tendency for turbulence initiation and localization to trigger the excitation of other wave motions and thus a spectral spreading as a natural consequence of the wave breaking process.

We have also completed and published, under this support, two studies of vortex dynamics in 2D and 3D focusing on the effects of stratification and shear. In addition to being relevant to aircraft vortices, these studies are relevant to the evolution of counter-rotating paired vortices such as arise in our KH and wave breaking turbulence simulations.

Finally, our code development activities were considerable, with significant advances in I/O, portability, and functionality. During the final year, we initiated a number of new and higher-resolution studies of shear and wave breaking instability dynamics, with a number of codes being executed on various DoD supercomputer platforms. The highest resolution simulations are now  $\sim 2000^3$  and are the largest being performed on the planet.

## Appendix A: In-house Activities

**Instructions:** Provide all information identified below for the duration of this project. "Personnel" should include each scientist or engineer who contributed to the research during the year. Publication of articles derived from the research should be listed chronologically in bibliography format. Attach reprints. List only invention disclosures derived from this specific research effort. Honors may include recognition both inside and outside the academic and Air Force science & technology (S&T) communities. Extended scientific visits may include collaboration with other research programs, both foreign and US.

### Personnel (all Colorado Research Associates staff):

<u>Name</u>	<u>Degree</u>	<u>Discipline</u>	<u>Involvement</u>
In House Employees time Dave Fritts (PI)	Ph.D.	Physics	1 mo/yr
Joe Werne	Ph.D.	Physics	2 mo/yr
Chris Bizon	Ph.D.	Physics	4 mo/yr

On-site Contractors

Visitors

### Publications Citing this AFOSR Support

- Fritts, D. C., S. Arendt, and O. Andreassen, 1999: The vorticity dynamics of instability and turbulence in a breaking internal gravity wave, *Earth Planets Space*, 51, 457-473.
- Hill, R. J., D. E. Gibson-Wilde, J. A. Werne, and D. C. Fritts, 1999: Turbulence-induced fluctuations in ionization and application to PMSE, *Earth Planets Space*, 51, 499-513.
- Garten, J. F., J. Werne, D. C. Fritts, and S. Arendt, 1999: The effects of ambient stratification on the Crow instability and subsequent vortex reconnection, *Europ. J. Mech.*
- Garten, J. F., J. Werne, D. C. Fritts, and S. Arendt, 2000: Direct numerical simulations of the Crow instability and subsequent vortex reconnection in a stratified fluid, *J. Fluid Mech.*, 426, 1-45.
- Werne, J. A., and D. C. Fritts, 2000: Anisotropy in a stratified shear layer, *Phys. Chem. Earth*, in press.
- Gibson-Wilde, D. E., J. A. Werne, D. C. Fritts, and R. J. Hill, 2000: Direct numerical simulation of VHF radar measurements of turbulence in the mesosphere, *Radio Sci.*, 35, 783-798.

- Fritts, D. C., 2000: Errant inferences of gravity wave momentum and heat fluxes using airglow and lidar instrumentation: Corrections and cautions, *J. Geophys. Res.*, 105, 22,355-22,360.
- Fritts, D. C., J. A. Werne, 2000: Turbulence dynamics due to gravity waves in the lower and middle atmosphere, AGU Monograph, Atmospheric Science Across the Stratopause, AGU Monograph Series 123, 143-159.
- Werne, J. A., and D. C. Fritts, 2000: Structure functions in stratified shear turbulence, 10th DoD HPC User Group Symposium, in press.
- Fritts, D. C., and M. J. Alexander, 2001: A review of gravity wave dynamics and effects in the middle atmosphere, *Reviews of Geophysics*, submitted.
- Chen, C., M. C. Kelley, D. Gibson-Wilde, J. Werne, Walters, R. Beland, R. F. Woodman, and K. Chau, A comparison of balloon data and numerical simulations of the Kelvin-Helmholtz instability, *J. Geophys. Res.*, submitted.
- Chen, C., M. C. Kelley, D. Gibson-Wilde, and J. Werne, Comparison of observed lower atmospheric turbulent structures with a direct numerical simulation, *Annales Geophysicae*, submitted.

#### **Technical Presentations:**

- Fritts, D. C., S. Arendt, and O. Andressen: The vorticity dynamics of instability and turbulence in a breaking internal gravity wave, Dynamics and Structure of the Mesopause Region Symposium, Kyoto, 1998.
- Hill, R. J., D. E. Gibson-Wilde, J. A. Werne, and D. C. Fritts: Turbulence-induced fluctuations in ionization and application to PMSE, Dynamics and Structure of the Mesopause Region Symposium, Kyoto, 1998.
- Fritts, D. C., and S. Vadas, Gravity wave excitation and mean flow forcing by gravity wave body forcing, IAMAS Symposium on Middle Atmosphere Dynamics, Birmingham, UK, July, 1999.
- Werne, J., and D. C. Fritts: Turbulence and mixing in a stratified shear layer: 3D K-H simulations at  $Re = 24,000$ , *Europ. Geophys. Soc.*, The Hague, November, 1999.
- Fritts, D. C.: Turbulence dynamics and effects based on high-resolution numerical simulations, IAP Transition Symposium, November, 1999.
- Fritts, D. C., J. A. Werne: Turbulence dynamics due to gravity waves in the lower and middle atmosphere, AGU Monograph, Atmospheric Science Across the Stratopause, Annapolis, April, 1999.
- Werne, J. A., and D. C. Fritts: Turbulence dynamics and mixing in stably stratified shear flows, NCAR Geophysical Turbulence Program Workshop on Mixing and Reactive Species, Boulder, July, 1999.
- Werne, J. A., and D. C. Fritts: Structure functions in stratified shear turbulence, 10th DoD, HPC User Group Symposium, 2000.

Fritts, D. C., Gravity Wave Instability Dynamics and Mean-Flow Interactions in the Middle and Upper Atmosphere, 10th Int'l. Symp. Equatorial Aero., Antalya, Turkey, May, 2000.

**Invention Disclosures and Patents Granted:**

none

**Invited Lectures, Presentations, Talks, etc.:**

Fritts, D. C., S. Arendt, and O. Andreassen: The vorticity dynamics of instability and turbulence in a breaking internal gravity wave, Dynamics and Structure of the Mesopause Region Symposium, Kyoto, 1998.

Hill, R. J., D. E. Gibson-Wilde, J. A. Werne, and D. C. Fritts: Turbulence-induced fluctuations in ionization and application to PMSE, Dynamics and Structure of the Mesopause Region Symposium, Kyoto, 1998.

Fritts, D. C., J. A. Werne: Turbulence dynamics due to gravity waves in the lower and middle atmosphere, AGU Monograph, Atmospheric Science Across the Stratopause, Annapolis, April, 1999.

Werne, J. A., and D. C. Fritts: Turbulence dynamics and mixing in stably stratified shear flows, NCAR Geophysical Turbulence Program Workshop on Mixing and Reactive Species, Boulder, July, 1999.

Fritts, D. C.: Turbulence dynamics and effects based on high-resolution numerical simulations, IAP Transition Symposium, November, 1999.

Fritts, D. C.: Gravity Wave Instability Dynamics and Mean-Flow Interactions in the Middle and Upper Atmosphere, 10th Int'l. Symp. Equatorial Aeronomy, Antalya, Turkey, May, 2000.

**Professional Activities (editorships, conference and society committees, etc.):**

President, Int'l. Commission on the Middle Atmosphere (ICMA), 1995 - 1999.

Convenor and Session Chairman, Dynamics and Structure of the Mesopause Region Symposium, Kyoto, 1998.

Convenor and Session Chairman, ICMA/IAMAS Symposium on Middle Atmosphere Sciences, Birmingham, UK, July 1999.

**Honors Received (include lifetime honors such as Fellow, honorary doctorates, etc., stating year elected):**

none

**Extended Scientific Visits From and To Other Laboratories:**

A visit to the Institute of Atmospheric Physics (Kuhlungsborn, Germany) for discussions of collaborative measurement campaigns and numerical modeling, 1999.

