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A nonlinear, compressible, spectral collocation code has been developed to examine gravity wave breaking and instability processes in two and three spatial dimensions. Initial studies have demonstrated that the preferred mode of instability within a high-frequency gravity wave is a convective instability comprised of counter-rotating vortices aligned transverse to the direction of wave propagation (a horizontal wavenumber normal to that of the gravity wave). Thus, wave instability is inherently three-dimensional, and two-dimensional models are unlikely to adequately describe either the physics of wave breaking or the implications for wave transports and eddy mixing. A parallel effort has emphasized the statistical effects of wave interactions and dissipation processes and developed a new spectral parameterization of gravity wave transports of energy and momentum and their atmospheric effects. This scheme relies on the approximately universal spectral shape of the gravity wave motion field throughout the atmosphere to assess the potential for wave transports and variations with background wind and stability profiles.

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TECHNICAL PROGRESS REPORT - FY93

1. Title: Numerical Modeling and Parameterization of Gravity Wave Effects in the Atmosphere

Grant Number: F49620-92-J-0138

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2. Research Objectives

The goals of this research were to address two sets of problems relating to gravity wave effects in the atmosphere. One approach was intended to apply analytic and pseudo-spectral modeling techniques to studies of wave excitation, instability, dissipation, and interaction processes thought to play important roles in the circulation, structure, and variability of the atmosphere at lower and upper levels. A second effort was intended to apply our current understanding of the spectral character of the atmospheric motion field to the development of a parameterization scheme for the most important wave effects in large-scale models of the atmosphere. Substantial progress has been made in both areas and is discussed further below.

3. Research Progress to Date

A nonlinear, compressible, spectral collocation code has been developed to examine gravity wave breaking and instability processes in two and three spatial dimensions. Initial studies have demonstrated that the preferred mode of instability within a high-frequency gravity wave is a convective instability comprised of counter-rotating vortices aligned transverse to the direction of wave propagation (a horizontal wavenumber normal to that of the gravity wave). Thus, wave instability is inherently three-dimensional, and two-dimensional models are unlikely to adequately describe either the physics of wave breaking or the implications for wave transports and eddy mixing. These studies are described in a series of three papers that have been submitted to *J. Geophys. Res.* Additional numerical studies have addressed the effects of a transverse shear on wave instability and are now being applied to shear instability problems of relevance to mixing and transports in the atmosphere.

A parallel effort has emphasized the statistical effects of wave interactions and dissipation processes and developed a new spectral parameterization of gravity wave transports of energy and momentum and their atmospheric effects. This scheme relies on the approximately universal spectral shape of the gravity wave motion field throughout the atmosphere to assess the potential for wave transports and

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variations with background wind and stability profiles. The scheme is presently working in the NCAR TGCM, is being tested by a number of other modeling groups, and is described in a series of three papers presently in press in *J. Atmos. Sci.*

Finally, we have performed a series of studies of specific gravity wave sources or source processes using both theoretical and data analysis techniques. The latter have shown the dominant sources of small-scale wave motions to be orography, convection, and wind shear. Analytic studies have examined the excitation of gravity waves by geostrophic adjustment of the jet stream and by eclipse forcing. Those papers citing AFOSR support are listed following this report.

4. Future Research Efforts

Our future efforts under AFOSR support will continue to address the physics and consequences of wave propagation and instability, with emphasis on both large- and small-scale effects. At small scales, our simulations will address the transition from laminar to turbulent flow, the intermittency and evolution of turbulence under the influences of stratification, and the induced transports of momentum, heat, and constituents. Such issues are important in understanding the effects of wave instability on the thermal and constituent structures of the lower and middle atmosphere. At larger scales, our efforts will address the constraints imposed by instability processes on wave amplitudes and transports, the spectral evolution of the motion field, the effects of wave-wave and wave-mean flow interactions on wave propagation, and wave influences on the large-scale circulation and thermal structure via their fluxes of energy and momentum.

Specific efforts will include 1) studies of wave breaking for lower-frequency motions which may favor other modes of instability, 2) simulations addressing instability processes, effects, and variability in a multiple-wave environment, 3) studies of the effects of instability and wave-wave interactions on the spectral evolution of gravity waves in the atmosphere, 4) and wave and instability responses to specific sources or propagation environments, such as mountain wave instability and transience and the influences on a gravity wave spectrum of a tidally-varying background wind and thermal field.

These studies will take advantage of new versions of our spectral collocation code that will employ the anelastic approximation in order to permit higher resolution and longer integration times, relative to our previous compressible simulations. Present models using Fourier basis functions in the horizontal and Chebyshev polynomials in the vertical will be applied to studies of shear instability, multiple wave saturation and spectral evolution, and turbulence production and decay. Like gravity wave breaking, shear instabilities are very important to our understanding of transports and mixing in the atmosphere because the conditions leading to instability are quite different than those within a breaking gravity wave. As such, we anticipate that their implications for turbulent transports may also be very different than wave breaking. Yet there have been no studies to date that have addressed the full three-dimensional evolution of such instabilities. High-resolution numerical models are also likely the only means of studying the full nonlinear evolution of a wide spectrum of wave motions and of testing the various theories that have been advanced to try and account for observed spectral features of the atmospheric wave field. Computation of these wave and instability evolutions to late times will also address the morphology of turbulence in stratified flows and address problems of fundamental importance for tracer transports and measurement techniques relying on turbulent backscatter.

Another version of our spectral collocation code using Chebyshev polynomials in the horizontal and vertical will be applied to problems such as mountain wave structure and instability for which inflow and outflow conditions may not be periodic. These flows depend strongly on instability processes and variability, and accurate descriptions of the nonlinear interactions involved are essential to understanding the process as a whole and its implications for the atmosphere at larger scales.

Our parameterization efforts will aim to further refine the gravity wave parameterization scheme developed under current AFOSR support and now being tested and/or implemented in a number of mechanistic and GCM models by various groups. This parameterization scheme was designed with the intent of describing statistically the responses of the gravity wave spectrum to varying environments and its influences on the local mean flow that result from wave saturation and filtering. As such, it responds in an averaged manner to variations in mean winds that is in approximate agreement with the limited observations that are available. The scheme also has the ability to describe the local responses to local gravity wave sources posed at discrete locations and times. However, the scheme does not, at present, have a procedure for distributing these local source effects geographically with increasing height. At greater altitudes, it also is important to include a means of describing the anticipated temporal variations in wave dissipation and induced diffusion in order to account for the tidal modulation of these processes and their influences in turn on the transports of heat and trace constituents. Additional efforts will advance the present scheme, test its responses to various environments in 1-D and 2-D mechanistic models as well as in various GCM's, such as the TGCM at NCAR, which is now using the present version of the parameterization.

PUBLICATIONS CITING CURRENT AFOSR SUPPORT:

Fritts, D. C., and Z. Luo, Gravity wave excitation by geostrophic adjustment of the jet stream, Part 1: Two-dimensional forcing, J. Atmos. Sci., 49, 681-697, 1992.

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VanZandt, T. E., and D. C. Fritts, Spectral estimates of gravity wave energy and momentum fluxes, NATO ASI Workshop on Coupling Processes in the Lower and Middle Atmosphere, Loen,1993.

Fritts, D. C., D.-Y. Wang, and R. C. Blanchard, Gravity wave and tidal structures between 60 and 140 km inferred from space shuttle re-entry data, J. Atmos. Sci., 50, 837-849, 1993.

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Lu, W., and D. C.Fritts, Spectral estimates of gravity wave energy and momentum fluxes, Part III: Gravity wave-tidal interactions, J. Atmos. Sci., in press.

Andreassen, O., C. E. Wasberg, D. C. Fritts, and J. R. Isler, Gravity wave breaking in two and three dimensions, Part I: Model description and comparison of two- dimensional evolutions, submitted to J. Atmos. Sci.

Fritts, D. C., J. R. Isler, and O. Andreassen, Gravity wave breaking in two and three dimensions, Part II: Three dimensionaal evolution and instability structure, submitted to J. Atmos. Sci.

Isler, J. R. D. C. Fritts, and O. Andreassen, Gravity wave breaking in two and three dimensions, Part III: Vortex breakdown and transition to turbulence, submitted to J. Atmos. Sci.