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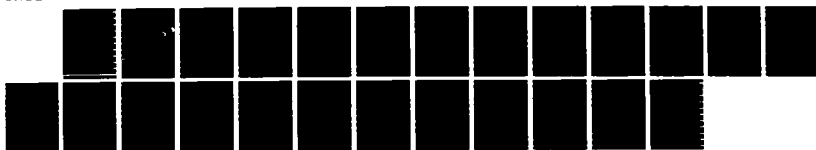
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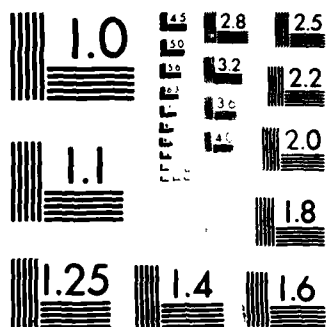
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gravity wave spectrum throughout the atmosphere. Additional theoretical studies addressed the turbulent transport of heat and constituents and the induced mean vertical motions due to vertically propagating gravity waves, contributing to our understanding of apparent differences between observations and modeling results.

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THEORETICAL AND OBSERVATIONAL STUDIES OF GRAVITY WAVE
EXCITATION, PROPAGATION, AND DISSIPATION



FINAL REPORT

May 1986

by

David C. Fritts

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Abstract

Research under this grant focussed on several aspects of gravity wave excitation, propagation, and dissipation that are expected to be important in the atmosphere. Initial studies addressed the excitation of propagating waves by unstable shear layers and found that the nonlinear interaction of evanescent unstable modes is an efficient source of such motions. Other numerical studies examined the consequences of gravity wave propagation and saturation in the middle atmosphere. Important findings include an amplitude limit imposed by wave field instabilities, the self-acceleration of large-amplitude motions which may greatly expand the phase speed distribution of mesospheric wave motions, and the relative insignificance of nonlinearity in limiting wave amplitudes and preventing wave field instability. Observational studies revealed wave field dynamics to be largely consistent with linear instability theory, with turbulence produced at that site in the wave field where the motion is most unstable. Wave amplitudes were seen to be near saturation values and easily described by a simple saturation model of the evolving gravity wave spectrum throughout the atmosphere. Additional theoretical studies addressed the turbulent transport of heat and constituents and the induced mean vertical motions due to vertically propagating gravity waves, contributing to our understanding of apparent differences between observations and modeling results.

1. INTRODUCTION

Research supported under Grant AFOSR 82-0125 has contributed substantially in an area of emerging importance in atmospheric dynamics over the past four years. This area is the study of atmospheric gravity waves, including their excitation, propagation, dissipation, transports of momentum and energy, generation of turbulence, and diffusion of heat and constituents. Also of importance are the very significant effects of such motions on the large-scale circulation and the thermal and constituent structures of the lower and middle atmosphere. While this field has benefitted from contributions by many authors dating back to the pioneering works by Hines (1960, 1963, 1972), Hodges (1967, 1969), and Bretherton (1966, 1969a, b), the purpose of this report is to document the contributions of this research effort. We will, therefore, only refer to other contributions where they indicate the relevance of the present results.

The evolving objectives of this research effort over the term of AFOSR support are described in Section 2. These began as a fairly narrow interest in the excitation of atmospheric gravity waves by unstable shear layers, but rapidly expanded to encompass many aspects of gravity wave propagation, dissipation, and atmospheric effects. Of particular value was the application of a theoretical understanding of gravity wave

processes to the interpretation of observational data. These findings, together with the results of analytic and numerical studies performed under this grant, are reviewed in Section 3. Research under this grant led to a substantial number of publications and presentations. A cumulative listing of these is provided in Section 4. Finally, Section 5 lists other personnel participating in this research effort. References are provided in Section 6.

2. RESEARCH OBJECTIVES

The initial objective of research under this AFOSR grant was to understand the mechanisms that could permit the rapid excitation of atmospheric gravity waves by unstable shear layers. This excitation is thought to be one of the major sources of gravity wave motions in the atmosphere and, as such, must be better understood if we are to anticipate the consequences of such motions on the large-scale circulation and structure of the atmosphere. Because previous linear studies had found the excitation of propagating wave motions to be constrained by very small growth rates, we elected to examine the effects of nonlinearity on this process, specifically the excitation of large-amplitude wave motions via the nonlinear interaction of rapidly growing Kelvin-Helmholtz instabilities.

A second objective of our study was to understand, through numerical modeling, some of the consequences of gravity wave saturation in the middle atmosphere. These included the effects of local convective adjustment of the wave field, the amplitude limits imposed by convective adjustment for single waves and superpositions of waves, the self-acceleration of gravity wave motions due to induced mean flow changes, the excitation of other motions as a consequence of local adjustment, and the relative importance of nonlinear wave-wave interactions and convective adjustment in limiting wave amplitudes. The goal here was to anticipate what wave processes ought to be most significant in determining the gravity wave spectra and characteristics seen in atmospheric observations. A related objective addressed the effects of a localized turbulent diffusion on the dissipation of wave motions and on the transport of heat and constituents.

The remaining objectives of this research effort dealt with atmospheric observations and their interpretation. A primary focus was to understand the very different echoes observed by the Poker Flat MST radar in the mesosphere during summer and winter. The radar velocity and associated temperature data suggested that there may be very different mechanisms at work in the two cases. A related goal was to identify the instabilities responsible for wave field

saturation and the turbulence and wave amplitude limits they produce. Also of interest were the character of the wave spectrum, an identification of the motions primarily responsible for energy and momentum transports, the consequences of local turbulence production and diffusion, and the relative contributions of two-dimensional (2-D) turbulence and gravity waves to the motion spectrum in the middle atmosphere.

3. SUMMARY OF RESEARCH ACHIEVEMENTS

Our initial research objective was met by performing a series of numerical simulations to examine the excitation of radiating gravity waves both via the linear instability of a dynamically unstable shear flow and through the interaction of two rapidly growing Kelvin-Helmholtz (KH) instabilities. The former simulations revealed that radiating waves grow in a manner consistent with linear stability analysis until the motions reach amplitudes sufficient to cause significant modifications of the mean flow. Thereafter the wave motions evolve in a manner that is dependent on the wave structure, with motions that are propagating above and below the source shear continuing to produce significant mean flow changes at large distances from the shear and motions that are evanescent above or below decaying rapidly due to a continuing erosion of

the shear strength. In the presence of nonlinearly interacting KH instabilities, wave motions very similar to the linearly unstable radiating waves were found to be excited very efficiently, to achieve large amplitudes, and to be very transient events due to the nature of the excitation. Because the shear geometry in this study allowed for the presence of radiating unstable modes, however, it was not possible to determine whether the excitation was a resonant interaction or simply a consequence of strong nonlinearity among the KH modes. This work was described in detail by Fritts (1982a).

A subsequent study (Fritts, 1984a) addressed this issue and determined that the latter was the case, with the structure of the radiating modes determined not by linear instability conditions, but by the nonlinearity itself. Also addressed here was the most efficient mechanism for such excitation. That found to be most important was the interaction of two KH modes at similar horizontal wavenumbers to excite a radiating wave at a much smaller wavenumber (larger scale). A second mechanism (vortex pairing) proposed by other authors and observed in unstratified laboratory facilities was found not to be effective in the stratified atmosphere.

The second thrust of our numerical studies was toward understanding gravity wave-mean flow interactions arising in

response to wave transience and dissipation (including saturation). A first study addressed the evolution of a gravity wave packet in a shear flow and the conditions leading to wave instability and breakdown (Fritts, 1982b). It was found that such motions can be strongly influenced by a time-dependent mean flow, either accelerating or retarding the occurrence of instability, and that when such instability occurs for high-frequency motions the likely consequence is the convective instability of the wave field.

Subsequently, a series of papers (Dunkerton and Fritts, 1984; Fritts and Dunkerton, 1984; Fritts, 1985) examined more specific aspects of the saturation of gravity waves in the middle atmosphere. These studies utilized a convective adjustment scheme to achieve a relaxation of the unstable portions of an evolving wave field to simulate the effects of local turbulence generation. The significant findings here included 1) an amplitude limit largely consistent with that expected from linear saturation theory for monochromatic wave motions, 2) a substantial acceleration of the wave phase speed, denoted self-acceleration, due to its residence in a region experiencing significant mean flow accelerations due to wave transience, 3) a saturated amplitude less than the monochromatic limit for a superposition of wave motions, 4) the excitation of additional wave motions at smaller scales

arising as a consequence of the local adjustment of the wave field, 5) and the observation that nonlinearity among the saturating wave motions is not sufficient to prevent the occurrence of convectively unstable regions within the wave field. The last point is particularly important as it suggests that gravity wave saturation is largely a linear process and does not require nonlinearity within the wave field. Point 2) implies that the spectrum of gravity wave phase speeds in the mesosphere may be very different from that in the lower atmosphere, and points 1) and 3) are consistent with recent observations of vertical wavenumber spectra of atmospheric motions. Thus, our modeling studies have given us some important insights into the mechanisms responsible for the observed motion spectra in the middle atmosphere.

In a closely related analytic study, Fritts and Dunkerton (1985) examined the consequences of a localized turbulent diffusion on the transports of heat and constituents and concluded that such an effect could provide for significant wave dissipation while dramatically reducing the effective eddy diffusion acting on the mean thermal and constituent gradients. It is believed that this may account for the very different observed (Hocking, 1985) and required (Strobel et al., 1986) values of eddy diffusion in the mesosphere. A second analytic study completed recently (Cry et al., 1986)

has addressed the Stokes drift due to vertically propagating gravity waves and has shown that such an effect can account for the large and reversed vertical mean motions observed by the Poker Flat radar relative to that needed to balance the meridional circulation.

More recent studies under this AFOSR grant have focussed on the interpretation of middle atmosphere motions observed with the Poker Flat radar (ie., Balsley et al., 1983). Our initial focus was on the large asymmetry between the summer and winter echoes. We now believe that this difference is due to the very large change in the thermal structure of the mesopause region with season, causing winter echoes to be characteristic of gravity waves saturating largely via convective instability, consistent with the temperature data of Theon et al. (1967). Summer echoes, on the other hand, are concentrated near the mesopause. Large-amplitude wave motions are less likely to be unstable below this level, but are driven to saturation amplitudes by the rapid increase in stratification at this height, accounting for the localized echoes and the strong increase in reflectivity relative to the winter condition.

Also examined in detail was data collected during the STATE experiment (Fritts et al., 1986). This study used both radar and rocket velocity and temperature data to define the

temporal and spatial variability of the motion field and address the mechanisms responsible for turbulence production within the wave field. It was found that the motion field was dominated by a large-scale wave motion of long period (~ 7 hr) that strongly controlled the intensity and location of turbulence. This provided strong evidence that the motion field was unstable, with a wave amplitude near that required for dynamical instability (more likely than convective instability for low-frequency motions) and with turbulence occurring at that location in the wave field where linear theory predicted instability. Also significant here was the observation that small-scale motions similar to those found in the numerical study by Fritts (1985) were present in those portions of the large-scale wave field expected to be most unstable and thus most likely sources for other motions.

Finally, three studies addressing the wavenumber and frequency spectra of gravity wave motions have recently been completed. The first by Smith et al. (1985) found the vertical and oblique wavenumber spectra to be consistent with a gravity wave model due to VanZandt (1985), suggesting that gravity waves are a much more significant component of the atmospheric motion spectrum than is 2-D turbulence. A second study (Smith et al., 1986) showed that observed vertical wavenumber spectra can be described by a universal saturation spectrum

with a saturation power consistent with linear instability theory and the wave superposition effects noted by Fritts (1985). This is potentially very significant as it represents a considerable generalization of the previous monochromatic linear saturation theory. The final spectral study by Fritts and VanZandt (1986) addressed the effects of Doppler shifting of gravity wave motions and showed that such effects can account for some of the departures of observed frequency spectra from those predicted in the absence of Doppler shifting effects.

Because of our involvement in both theoretical and observational studies of middle atmosphere gravity waves, we have also been in a position to assess and review developments in the field. This has led to three review papers dealing with research status and direction in this field which hopefully have had a positive impact (Fritts, 1984b; Fritts et al., 1984; Fritts and Rastogi, 1985).

4. PUBLICATIONS AND PRESENTATIONS

During this four-year research effort, AFOSR has contributed full or partial support for 25 presentations at national and international scientific meetings, including seven invited papers, and 28 publications that have appeared, are in press, or have been submitted to scientific journals or conference proceedings. The presentations include:

- "Evidence for seasonally-dependent generation mechanisms," B. B. Balsley, W. L. Ecklund, and D. C. Fritts, URSI Int'l. Symp. on Radio Probing of the High-Latitude Ionosphere and Atmosphere, Fairbanks, Alaska, August, 1982.
- "Evidence of tidal breakdown at the summer mesopause," D. C. Fritts, B. B. Balsley, and W. L. Ecklund, URSI Int'l. Symp. on Radio Probing of the High-Latitude Ionosphere and Atmosphere, Fairbanks, Alaska, August, 1982.
- "VHF echoes from the arctic mesosphere and lower thermosphere, part 1: Observations," B. B. Balsley, W. L. Ecklund, and D. C. Fritts, U.S.-Japan Seminar on Middle Atmosphere Dynamics, Honolulu, Hawaii, November, 1982.
- "VHF echoes from the arctic mesosphere and lower thermosphere, part 2: Interpretations," D. C. Fritts, B. B. Balsley, and W. L. Ecklund, U.S.-Japan Seminar on Middle Atmosphere Dynamics, Honolulu, Hawaii, November, 1982.
- "Gravity wave saturation in the middle atmosphere: A review of theory and observations," D. C. Fritts, 4th AMS Conf. on Dynamics of the Middle Atmosphere, Boston, MA, March, 1983.
- "Radiation of gravity waves by interacting Kelvin-Helmholtz instabilities," D. C. Fritts, 4th AMS Conf. on Atmos. and Oceanic Waves and Stability and 6th AMS Symp. on Turb. and Diffusion, Boston, MA, March, 1983.
- "Estimation of gravity wave motions, momentum fluxes, and induced mean flow accelerations in the winter mesosphere over Poker Flat, Alaska," S. A. Smith and D. C. Fritts, 21st Conf. on Radar Meteor., Edmonton, Alberta, August, 1983.
- "Momentum flux measurements: Techniques and needs," D. C. Fritts, 2nd Workshop on Technical Aspects of MST Radar, Urbana, IL, May, 1984.
- "Estimation of vertical diffusion from observations of atmospheric turbulence layers," D. C. Fritts, 2nd Workshop on Technical Aspects of MST Radar, Urbana, IL, May, 1984.
- "Local effects of gravity wave propagation and saturation," D. C. Fritts, Int'l. MAP Symp., Kyoto, Japan, November, 1984.

- "Vertical Stokes drifts produced by vertically propagating internal gravity waves in a compressible atmosphere," L. Coy, D. C. Fritts, and J. Weinstock, Int'l. MAP Symp., Kyoto, Japan, November, 1984.
- "Gravity wave saturation and local diffusion," D. C. Fritts, MAP Workshop on Gravity Waves and Turbulence (GRATMAP), Kyoto, Japan, December, 1984.
- "Wavefield analysis for the STATE experiment," D. C. Fritts, S. A. Smith, B. B. Balsley, and C. R. Philbrick, MAP Workshop on Gravity Waves and Turbulence (GRATMAP), Kyoto, Japan, December, 1984.
- "Gravity wave spectra observed by Doppler radar: Comparison of a model with mesospheric observations," T. E. VanZandt, S. A. Smith, and D. C. Fritts, MAP Workshop on Gravity Waves and Turbulence (GRATMAP), Kyoto, Japan, December, 1984.
- "Locally enhanced gravity wave saturation as revealed by the STATE experiment," S. A. Smith, D. C. Fritts, C. R. Philbrick, and B. B. Balsley, AGU Meeting, San Francisco, CA, December, 1984.
- "Critical level dynamics in the atmosphere and ocean," D. C. Fritts, 5th AMS Conf. on Atmos. and Oceanic Waves and Stability, New Orleans, LA, March, 1985.
- "Power spectra of mesospheric wind velocity versus wavenumber: Comparison of a gravity wave model with mesospheric observations at Poker Flat, Alaska," T. E. VanZandt, S. A. Smith, and D. C. Fritts, 5th AMS Conf. on Atmos. and Oceanic Waves and Stability, New Orleans, LA, March, 1985.
- "A numerical study of gravity wave saturation including quasi-linear and nonlinear effects," D. C. Fritts, 5th AMS Conf. on the Meteor. of the Strat. and Mesosphere, Boulder, CO, April, 1985.
- "Gravity waves in the middle atmosphere: Recent progress and needed studies," D. C. Fritts, 3rd Workshop on Scientific and Technical Aspects of MST Radar, Aguadilla, PR, October, 1985.
- "Simultaneous rocket and radar observations of an internal gravity wave breaking in the mesosphere," S. A. Smith, D. C. Fritts, B. B. Balsley, and C. R. Philbrick, 3rd

Workshop on Scientific and Technical Aspects of MST Radar, Aguadilla, PR, October, 1985.

"A simple model of the effects of Doppler shifting on internal gravity waves," T. E. VanZandt and D. C. Fritts, 3rd Workshop on Scientific and Technical Aspects of MST Radar, Aguadilla, PR, October, 1985.

"Mesospheric wavenumber spectra from Poker Flat MST radar measurements compared with a gravity wave model," S. A. Smith, D. C. Fritts, and T. E. VanZandt, 3rd Workshop on Scientific and Technical Aspects of MST Radar, Aguadilla, PR, October, 1985.

"Evidence of a saturated gravity wave spectrum throughout the atmosphere," D. C. Fritts, S. A. Smith, and T. E. VanZandt, 3rd Workshop on Scientific and Technical Aspects of MST Radar, Aguadilla, PR, October, 1985.

"Gravity wave effects in the middle atmosphere," D. C. Fritts, Workshop on Upper and Middle Atmosphere Density Modeling Requirements for Spacecraft Design and Operations, Huntsville, AL, November, 1985.

"Observations of gravity wave saturation by MST radars," D. C. Fritts, RASC Workshop on the Development of MST Radar Techniques during MAP and in the Future, Kyoto, Japan, March, 1986.

A cumulative list of publications supported by this AFOSR grant follows:

"The Transient Critical-Level Interaction in a Boussinesq Fluid," D. C. Fritts, J. Geophys. Res., 87, 7997 (1982)

"Shear Excitation of Atmospheric Gravity Waves," D. C. Fritts, J. Atmos. Sci., 39, 1936 (1982)

"Mesospheric Radar Echoes At Poker Flat, Alaska: Evidence for Seasonally-Dependent Generation Mechanisms," B. B. Balsley, W. L. Ecklund, and D. C. Fritts, Radio Sci., 18, 1053 (1983)

"VHF Echoes from the High-Latitude Mesosphere and Lower Thermosphere: Observations and Interpretations," B. B. Balsley, W. L. Ecklund, and D. C. Fritts, J. Atmos. Sci., 40, 2451 (1983)

- "Estimation of Gravity Wave Motions, Momentum Fluxes, and Induced Mean Flow Accelerations in the Winter Mesosphere over Poker Flat, Alaska," S. A. Smith and D. C. Fritts, Proc. 21st Conf. on Radar Meteor., Edmonton, Alberta, 104 (1983)
- "VHF Echoes from the Arctic Mesosphere and Lower Thermosphere, Part 1: Observations," B. B. Balsley, W. L. Ecklund, and D. C. Fritts, Dynamics of the Middle Atmosphere, J. R. Holton and T. Matsuno, Eds., 77 (1984)
- "VHF Echoes from the Arctic Mesosphere and Lower Thermosphere, Part 2: Interpretations," D. C. Fritts, B. B. Balsley, and W. L. Ecklund, Dynamics of the Middle Atmosphere, J. R. Holton and T. Matsuno, Eds., 97 (1984)
- "Shear Excitation of Atmospheric Gravity Waves, Part 2: Nonlinear Radiation from a Free Shear Layer," D. C. Fritts, J. Atmos. Sci., 41, 524 (1984)
- "Transient Gravity Wave Critical Layer Interaction, Part 1: Convective Adjustment and the Mean Zonal Acceleration," T. J. Dunkerton and D. C. Fritts, J. Atmos. Sci., 41, 992 (1984)
- "Research Status and Recommendations from the Alaska Workshop on Gravity Waves and Turbulence in the Middle Atmosphere," D. C. Fritts, M. A. Geller, B. B. Balsley, M. L. Chanin, I. Hirota, J. R. Holton, S. Kato, R. S. Lindzen, M. R. Schoeberl, R. A. Vincent, and R. F. Woodman, AMS Bulletin, 65, 149 (1984)
- "Gravity Wave Saturation in the Middle Atmosphere: A Review of Theory and Observations," D. C. Fritts, Rev. Geophys. Space Phys., 22, 275 (1984)
- "A Quasi-Linear Study of Gravity Wave Saturation and Self-Acceleration," D. C. Fritts and T. J. Dunkerton, J. Atmos. Sci., 41, 3272 (1984)
- "Comparison of Simultaneous Poker Flat MST and Meteorological Rocketsonde Wind Profiles," S. A. Smith and D. C. Fritts, Geophys. Res. Lett., 9, 538 (1984)
- "Momentum Flux Measurements: Techniques and Needs," D. C. Fritts, Handbook for MAP, 14, 216 (1984)
- "Estimation of Vertical Diffusion from Observations of Atmospheric Turbulence Layers," D. C. Fritts, Handbook for MAP, 14, 212 (1984)

- "Fluxes of Heat and Constituents due to Convectively Unstable Gravity Waves," D. C. Fritts and T. J. Dunkerton, J. Atmos. Sci., 42, 549 (1985)
- "A Numerical Study of Gravity Wave Saturation: Nonlinear and Multiple-Wave Effects," D. C. Fritts, J. Atmos. Sci., 42, 2043 (1985)
- "Convective and Dynamical Instabilities due to Gravity Wave Motions in the Lower and Middle Atmosphere: Theory and Observations," D. C. Fritts and P. K. Rastogi, Radio Sci., 20, 1247 (1985)
- "Comparison of Mesospheric Wind Spectra with a Gravity Wave Model," S. A. Smith, D. C. Fritts, and T. E. VanZandt, Radio Sci., 20, 1331 (1985)
- "Local Effects of Gravity Wave Propagation and Saturation," D. C. Fritts, Handbook for MAP, in press.
- "Gravity Waves in the Middle Atmosphere: Recent Progress and Needed Studies," D. C. Fritts, Handbook for MAP, in press.
- "Simultaneous Rocket and MST Radar Observation of an Internal Gravity Wave Breaking in the Mesosphere," S. A. Smith, D. C. Fritts, B. B. Balsley, and C. R. Philbrick, Handbook for MAP, in press.
- "Mesospheric Wavenumber Spectra from Poker Flat MST Radar Measurements Compared with a Gravity Wave Model," S. A. Smith, D. C. Fritts, and T. E. VanZandt, Handbook for MAP, in press.
- "Evidence of a Saturated Gravity Wave Spectrum Throughout the Atmosphere," D. C. Fritts, S. A. Smith, and T. E. VanZandt, Handbook for MAP, in press.
- "The Stokes Drift due to Vertically Propagating Gravity Waves in a Compressible Atmosphere," L. Coy, D. C. Fritts, and J. Weinstock, submitted to J. Atmos. Sci.
- "Evidence of a Saturated Spectrum of Atmospheric Gravity Waves," S. A. Smith, D. C. Fritts, and T. E. VanZandt, submitted to J. Atmos. Sci.
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B. B. Balsley, and C. R. Philbrick, submitted to J. Geophys. Res.

"The Effects of Doppler Shifting on the Frequency Spectra of Atmospheric Gravity Waves," D. C. Fritts and T. E. VanZandt, submitted to J. Geophys. Res.

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Mr. L. Yuan

- student, masters degree candidate
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