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Research under this contract addressed a number of aspects of gravity wave propagation and effects in the lower and middle atmosphere. Observational studies utilized data sets collected at several radar installations and *in situ* data obtained during two major rocket campaigns. Theoretical studies examined wave instability and ducting, the relationship between neutral and ion density fluctuations in the presence of chemically active species, and the potential for energy exchange due to resonant wave interactions. Our results showed the motion spectrum in the troposphere, stratosphere, and mesosphere to be highly anisotropic, with an upward flux of horizontal momentum largely opposed to the large-scale mean flow. The motion spectrum was found largely to be consistent with gravity wave theory and saturation. These findings have important implications for the forcing of the mean circulation of the lower and middle atmosphere. Theoretical studies revealed low-frequency motions to favor dynamical instabilities and suggested that resonant wave interactions are not likely to be a major factor for energy transfer in the middle atmosphere due to the rapid vertical transport and dissipation of energy.

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Final Technical Report

This report summarizes work performed under AFOSR Contract F49620-87-C-0024. Research under this contract included both theoretical and observational components in a variety of areas and using a number of experimental facilities. Our research objectives, results, publications, personnel, and professional interactions are described below.

1. Research Objectives

Our research was intended to address the roles, characteristics, and climatologies of gravity waves and turbulence in the atmosphere, primarily through the use of high-resolution radars. Such motions are now recognized to play a fundamental role in determining the large-scale circulation and structure of both the lower and middle atmosphere. Gravity waves are significant because of their ability to transport momentum and energy from source regions, primarily at lower levels, to regions in which waves undergo dissipation. Turbulence is a consequence of wave instability and results in the diffusion of heat and constituents.

Radar studies of wave motions are among the most valuable in understanding the roles and influences of gravity waves in the atmosphere because of the temporal continuity and relatively high spatial and temporal resolution of such data. Frequency and wavenumber spectra of velocity fluctuations are important in anticipating the dominant scales of motion, the influences of Doppler shifting, and the processes responsible for spectral shape and wave saturation. Likewise, estimates of wave energy and momentum fluxes are essential in addressing the influences of gravity waves on their environment. Such studies comprised the majority of our research efforts under this AFOSR contract.

Other data sets are also of value in assessing the nature of wave dissipation, the generation of turbulence, and features of the motion spectrum not resolved by or possible to measure with atmospheric radars. These included primarily in situ rocket probe data which were valuable in addressing the structure of the turbulence spectrum and its association with the wave environment. Finally, our research included a theoretical component intended to provide a physical understanding of various features of the observational data.

2. Research Accomplishments

Our research under AFOSR contract F49620-87-C-0024 has contributed significantly to the understanding of gravity wave and turbulence processes and effects in the atmosphere. Because of delays in the completion of the Poker Flat ST radar, most of our efforts focussed on the use of high-resolution data obtained with other radar systems, including the Poker Flat MST radar in Alaska, the MU radar in Japan, and the EISCAT and SOUSY radars in northern Norway. Other components of our research utilized in situ rocket data obtained in Alaska and Norway to examine the occurrence and characteristics of turbulence within the wave field. Finally, theoretical models of the motion field were used in describing the influences of mean winds and stability variations on the observed spectral shape and the effects of wave dissipation. These advances are described in more detail below.

Radar data obtained with the MU radar used in several multiple-beam configurations during March, October, and November 1986 were used in three studies of the motion field in the troposphere and the lower and middle stratosphere. The fall radar data, together with high-resolution temperature profiles obtained at the radar site throughout the observation periods, were used to assess the consistency of the motion spectrum with the gravity wave dispersion relation and with recent theories of a saturated gravity wave spectrum. The results (Fritts et al., 1988a) showed the wavenumber spectra of velocity and temperature fluctuations to be in almost complete agreement with the spectral amplitudes and shapes expected for gravity waves and to support the view that the high wavenumber portion of the vertical wavenumber spectrum is controlled by wave saturation processes. This is an important issue because it suggests a universal constraint on the shape of the motion spectrum and permits important inferences concerning the effects of wave dissipation (see below).

Data obtained with the MU radar facility during March 1986 were used to examine the anisotropy of and the momentum flux contributed by the motion field in the troposphere and lower stratosphere. Motions were found to be highly anisotropic, with preferred directions of propagation and rapid changes in spectral character and orientation, but with fluctuations that could be accounted for by gravity wave theory (VanZandt et al., 1990).

Momentum fluxes were measured using the same data set and were found to imply flow accelerations or decelerations of ~ 1 - 2 m/s/day above and below the height of the tropospheric jet (Fritts et al., 1990a), in approximate agreement with the expectations of large-scale models. Height-averaged momentum fluxes were found to exhibit considerable temporal variability and to largely oppose the nearly zonal mean flow. This variability, together with a frequency spectrum of zonal momentum flux and velocity variance differences between east and west beams, provided strong evidence that the dominant fluxes were contributed by wave motions with high intrinsic frequencies. This finding at lower levels supports similar findings at greater heights (see the discussion of Poker Flat results below) and also has major implications for the propagation of energy and momentum and the influences of gravity waves on the atmosphere at greater heights. In particular, the importance of high-frequency wave motions in the transport of energy and momentum, together with their rapid and efficient vertical propagation, implies a local and rapid response to wave forcing events such as topography and convection at lower levels.

Data obtained in the mesosphere and lower thermosphere with the Poker Flat MST radar were used for studies of gravity wave influences in this region as well. Summertime zonal mean momentum fluxes of ~ 5 - 10 m^2/s^2, implying eastward accelerations of ~ 100 - 200 m/s/day, and strong meridional flows of ~ 10 - 20 m/s near the mesopause revealed gravity waves to provide a major forcing of the mean atmospheric state in this region (Fritts and Yuan, 1989). Wintertime fluxes and implied accelerations, in contrast, were ~ 10 times smaller (Wang and Fritts, 1990). Also significant, because of the dominance of the momentum flux by high-frequency motions, is the variability of the momentum flux on time scales of a few hours. Hourly averaged fluxes were found to be as large as ~ 6 times the maximum mean values, with variations due, according to recent studies, to local modulation of the high-frequency motions by lower-frequency gravity wave and tidal motions. These observations provide additional evidence that much of the gravity wave forcing of the large-scale flow may occur locally in response to episodic and local gravity wave forcing at lower levels. This would have major implications for modeling of the large-scale atmospheric flow and the likelihood for a realistic response to small-scale, localized sources of gravity waves and wave drag at greater heights.

Studies using the EISCAT and SOUSY radars in northern Norway addressed other aspects of the dynamics of the summer mesopause. Fritts et al. (1990b) used vertical velocity data with very high temporal resolution to examine the structure of the velocity field and the frequency spectrum of such motions under various conditions. Small or downward Eulerian mean velocities were used to infer a significant upward flux of wave energy necessary to induce a large upward Stokes drift. Velocity variances were found to be very large and concentrated in motions near the buoyancy frequency. Finally, frequency spectra were found to vary greatly in time and to provide strong evidence of Doppler shifting effects due to variable background winds. A second study by Hoppe et al. (1990) used primarily EISCAT and SOUSY data to examine the radar echoing characteristics and the likely causes of the dramatic summer mesopause echoes observed by VHF and UHF radars at high latitudes. Several scattering processes were considered, with the existing data providing the most evidence for a signal-to-noise enhancement resulting from electron scavenging by thin aerosol or cloud particle layers.

Studies using in situ measurements of neutral or ion densities and winds were used to examine the relationship of the small-scale turbulence field to the large-scale wave environment (Fritts et al., 1988b; Blix et al., 1990). These revealed, consistent with theoretical and modeling studies, that turbulence occurs preferentially in that portion of the wave field which first becomes dynamically or convectively unstable. This provides support for the simple linear theory of wave saturation and additional evidence of the influences of saturation on the motion spectrum as a whole. The latter study also provided, for the first time, evidence of three spectral ranges, a gravity wave or buoyancy range, an inertial range, and a viscous range, in individual vertical wavenumber spectra. This result is important because it permits a direct measure of the scales separating these spectral ranges and a test of the theories relating spectral amplitudes to the transition scales.

Our final efforts under this AFOSR contract involved theoretical studies of inertio-gravity wave instability (Fritts and Yuan, 1989; Yuan and Fritts, 1989), of gravity wave ducting in a variable environment (Fritts and Yuan, 1990), of chemical and wave influences on the ratio of ion and neutral densities in the mesosphere (Fritts and Thrane, 1990), of nonlinear wave-wave interactions (Fritts and Sun, 1990; Sun and Fritts, 1990), and two surveys of gravity wave and turbulence processes aimed at parameterizing small-scale processes and the differences between the northern and southern hemispheres. Our stability analyses showed dynamical instabilities to only be favored for gravity waves with intrinsic frequencies near the inertial frequency, implying that most higher-frequency motions were likely to undergo an instability of a convective nature. The ducting study revealed a potential for coupling of energy from one ducting level to another, and thus for rapid vertical transports of energy and momentum, due to mode structures that changed rapidly near locations where modal dispersion curves cross. Computation of the ion/neutral density ratio in the mesosphere showed this quantity to vary continuously between adiabatic and chemical equilibrium limits having opposite signs, depending on the intrinsic frequency of motion and the chemical recombination rate. This study provides a significant generalization of earlier work and permits the computation of neutral wave amplitudes from ion density measurements with chemical relaxation effects included. Finally, our wave-wave interaction studies, nearly completed, generalize previous efforts along these lines and attempt to address the potential for energy transfer in a realistic atmosphere. These suggest, consistent with the estimates of gravity wave energy decay time scales provided by Fritts (1989a), that linear (turbulent) instability processes are likely to be more important than systematic wave-wave interactions in removing energy from the wave spectrum in the middle atmosphere.

3. Publications

Fritts, D.C., T. Tsuda, T. Sato, S. Fukao, and S. Kato, 1988a: Observational evidence of a saturated gravity wave spectrum in the troposphere and lower stratosphere, J. Atmos. Sci., 45, 1741-1759.

Fritts, D.C., S.A. Smith, B.B. Balsley, and C.R. Philbrick, 1988b: Evidence of gravity wave saturation and local turbulence production in the summer mesosphere and lower thermosphere during the STATE experiment, J. Geophys. Res., 93, 7015-7025.

Fritts, D.C., and L. Yuan, 1989: A stability analysis of inertio-gravity wave structure in the middle atmosphere, J. Atmos. Sci., 46, 1738-1745.

Yuan, L., and D.C. Fritts, 1989: Influence of a mean shear on the dynamical instability of an inertio-gravity wave, J. Atmos. Sci., J. Atmos. Sci., 46, 2562-2568.

Fritts, D.C., and L. Yuan, 1989: Measurement of momentum fluxes near the summer mesopause at Poker Flat, Alaska, J. Atmos. Sci., 46, 2569-2579.

Fritts, D.C., 1989a: Gravity wave saturation, turbulence, and diffusion in the atmosphere: Observations, theory, and implications, Parameterization of Small-Scale Processes, 'Aha Huliko'a workshop proceedings, P. Muller and D. Henderson, Eds., 219-234.

Fritts, D.C., 1989b: Gravity waves in the middle atmosphere of the southern hemisphere, Dynamics, Transport, and Photochemistry in the Middle Atmosphere of the Southern Hemisphere, A. O'Neill and C.R. Mechoso, Eds., in press.

Fritts, D.C., and L. Yuan, 1989: An analysis of gravity wave ducting in the atmosphere: Eckart's resonances in Thermal and Doppler ducting, J. Geophys. Res., in press.

VanZandt, T.E., S.A. Smith, T. Tsuda, D.C. Fritts, T. Sato, S. Fukao, and S. Kato, 1990: Studies of velocity fluctuations in the lower atmosphere using the MU radar: I. Azimuthal anisotropy, J. Atmos. Sci., 47, 39-50.

Fritts, D.C., T. Tsuda, T.E. VanZandt, S.A. Smith, T. Sato, S. Fukao, and S. Kato, 1990a: Studies of velocity fluctuations in the lower atmosphere using the MU radar: II. Momentum fluxes and energy densities, J. Atmos. Sci., 47, 51-66.

Fritts, D.C., and E.V. Thrane, 1990: Computation of the ion/neutral density ratio in the presence of wave and chemical effects, to be J. Atmos. Terres. Phys., in press.

Wang, D.-Y., and D.C. Fritts, 1990: Mesospheric momentum fluxesobserved by the MST radar at Poker Flat, Alaska, J. Atmos. Sci., in press.

Hoppe, U.-P., D.C. Fritts, I.M. Reid, C.M. Hall, and T.L. Hansen, 1990: Multiple-frequency studies of the high-latitude summer mesosphere: Implications for scattering processes, J. Atmos. Terres. Phys., in press.

Fritts, D.C., U.-P. Hoppe, and B. Inhester, 1990b: A study of the vertical motion field near the high-latitude summer mesopause during MAC/SINE, J. Atmos. Terres. Phys., in press.

Blix, T.A., E.V. Thrane, U.-P. Hoppe, D.C. Fritts, U. von Zahn, F.-J. Luebken, W. Hillert, S.P. Blood, J.D. Mitchell, H.-U. Widdel, G.A. Kokin, and S.V. Pakhomov, 1990: Small-scale structure observed in situ during MAC/EPSILON, submitted to J. Atmos. Terres. Phys.

Fritts, D.C., and S. Sun, 1990: Wave-wave interactions in the atmosphere: A general formulation, in preparation.

Sun, S., and D.C. Fritts, 1990: The effects of inhomogeneity and background fluctuations on resonant wave-wave interactions in the atmosphere, in preparation.

4. Project Personnel

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M.S. Thesis: Numerical Studies of Gravity Wave Ducting and Instability in the Atmosphere, Dec. 1988

Mr. Shaojian Sun, Ph.D. student

Mr. Zhangai Luo, Ph.D. student

5. Project Interactions

Interactions with other personnel took two forms. First listed below are the conference presentations sponsored by this AFOSR contract. Listed second are interactions with personnel at other laboratories.

a. conference presentations

Fritts, D.C., T. Tsuda, T. Sato, S. Fukao, and S. Kato, Observational evidence of a saturated gravity wave spectrum in the troposphere and lower stratosphere from temperature and velocity data obtained at the MU radar, GRATMAP Workshop, Adelaide, May 1987

Tsuda, T., D.C. Fritts, T. Sato, S. Fukao, and S. Kato, An investigation of the frequency spectra, height dependence, and momentum fluxes of atmospheric motions using MU radar data, GRATMAP Workshop, Adelaide, May 1987

Fritts, D.C., The relationship between gravity waves and turbulence in the middle atmosphere, URSI General Assembly, Tel Aviv, August 1987

Fritts, D.C., Observations and implications of local turbulence production in the middle atmosphere, AGU Meeting, San Francisco, December 1987

Yuan, L., and D.C. Fritts, Numerical study of the Kelvin-Helmholtz instability due to a large-scale, low-frequency gravity wave, AGU Meeting, Baltimore, May 1988

Fritts, D.C., An overview of gravity wave studies during MAP/MAC, 26th COSPAR Symposium, Helsinki, July 1988

Fritts, D.C., Wave saturation, turbulence, and diffusion in the atmosphere: Observations, theory, and implications, 'Aha Huliko'a Workshop on Parameterization of Small-Scale Processes, Honolulu, January 1989

Fritts, D.C., Topographic stress in the atmosphere: How much and how variable?, Workshop on Topographic Stress, Kona, January 1989

Fritts, D.C., Gravity wave saturation, effects, and variability in the middle atmosphere, Joint session of 7th AMS Conf. on Atmos. and Oceanic Waves and Stability and 7th AMS Conf. on Meteorol. of the Middle Atmosphere, San Francisco, April 1989

Fritts, D.C., T. Tsuda, T.E. VanZandt, and S.A. Smith, Momentum fluxes in the troposphere and lower stratosphere measured with the MU radar, 7th AMS Conf. on Atmos. and Oceanic Waves and Stability, San Francisco, April 1989

Yuan, L., and D.C. Fritts, Stability analysis of an inertio-gravity wave in the middle atmosphere with and without mean shear, 7th AMS Conf. on Atmos. and Oceanic Waves and Stability, San Francisco, April 1989

VanZandt, T.E., S.A. Smith, T. Tsuda, T. Sato, S. Fukao, S. Kato, and D.C. Fritts, Anisotropy of the velocity fluctuation field in the lower stratosphere, 7th AMS Conf. on Atmos. and Oceanic Waves and Stability, San Francisco, April 1989

Fritts, D.C., Gravity waves in the middle atmosphere of the southern hemisphere, Workshop on Dynamics, Transport, and Photochemistry in the Middle Atmosphere of the Southern Hemisphere, San Francisco, April 1989

Fritts, D.C., Recent advances in the experimental understanding of middle atmosphere gravity waves, IAMAP Meeting, Reading, August 1989

VanZandt, T.E., T. Tsuda, T. Inoue, D.C. Fritts, S. Kato, T. Sato, and S. Fukao, MST radar observations of a saturated gravity wave spectrum, IAMAP Meeting, Reading, August 1989

b. interactions at other laboratories

I have worked in collaboration with Drs. Eivind V. Thrane, Ulf-Peter Hoppe, Tom A. Blix, and Oeyvind Andreassen of the Norwegian Defense Research Establishment, P. O. Box 25, N-2007 Kjeller, Norway under NATO, NDRE, and AFOSR funding on several of the research projects described above. This work was peformed in Norway during October and November 1987 and May - July 1988 and in Alaska during September 1988. In addition, I have acted in a consultant capacity for Dr. E. M. Dewan of the Air Force Geophysics Laboratory on the MAPSTAR project during several visits to AFGL and at CEDAR and AGU meetings in Boulder, CO and San Francisco, CA from 1987 to 1989.

Other advisory responsibilities during the term of this contract include the AMS Committee on the Middle Atmosphere (1986-88), the AMS Committee on Atmospheric and Oceanic Waves and Stability (1985-88), the NSF Aeronomy CEDAR Steering Committee (1986-88), the IUGG Commission on the Meteorology of the Upper Atmosphere (1987-91), and as coordinator of the International MAP Committee on Gravity Waves and Turbulence (1985-89). The CEDAR Steering Committee held approximately twice yearly meetings to guide the NSF CEDAR program, organize research activities, define goals, and coordinate proposal and funding activities. As coordinator of GRATMAP, I was responsible for organizing workshops or sessions of meetings oriented towards this topic. The most significant of these was held in Adelaide, Australia during May 1987 and led to a special edition of Pure and Applied Geophysics.