D4 N85-32470

1.3A EXCERPTS FROM THE PAPER: RESEARCH STATUS AND RECOMMENDATIONS FROM THE ALASKA WORKSHOP ON GRAVITY WAVES AND TURBULENCE IN THE MIDDLE ATMOSPHERE, FAIRBANKS, ALASKA, 18-22 JULY 1983*

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... 3. THEORETICAL DISCUSSION

Internal gravity waves are disturbances whose intrinsic frequencies $k(c - \bar{u})$ are smaller than the Brunt-Vaisala frequency (N). Their importance arises because:

(1) they are the major components of the total flow and temperature variability fields of the mesosphere (i.e., shears and lapse rates) and hence constitute the likely sources of turbulence;
(2) they are associated with fluxes of momentum that communicate stresses over large distances. For example, gravity waves exert a drag on the flow in the upper mesosphere. However, in order for gravity waves to exert a net drag on the atmosphere, they must be attenuated.

There are two general types of processes that seek to attenuate gravity waves -- dissipation and saturation. Dissipation is any process that is effective independent of the wave amplitude, while saturation occurs when certain wave amplitude conditions are met. Radiative damping is an example of dissipation, while convective overturning, which arises when the wave-breaking condition $|\partial T/\partial z| \sim \Gamma$(or $u' \sim |c - \bar{u}|$) is met, is an example of saturation. The two processes are not mutually exclusive.

Saturation implies that the wave field has reached amplitudes such that either secondary instabilities (LINDZEN, 1981; DUNKERTON, 1982a) or nonlinear interactions, such as the parametric subharmonic instability (LINDZEN and FORBES, 1983), can occur, which limit further wave growth. In the atmosphere, amplitudes sufficient for saturation may result either from exponential growth with height or from the approach of a wave packet to a critical level. The saturation mechanism considered most common is the generation of convective or Kelvin-Helmholtz (KH) shear instabilities. Both instabilities were observed in the laboratory study of gravity-wave propagation by KOOP and MCGEE (1983), but

* Bull. Am. Meteorol. Soc., 65, 149-159.

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convective instabilities were found to dominate when both were possible. The local development of convective and dynamical instabilities may result in the radiation of secondary gravity waves (DUNKERTON and FRITTS, 1983); however, the most important result is the production of turbulence. Turbulence generation initially is confined to regions of dynamical or convective instability within the wave field. Following generation, turbulence may be advected away from the unstable zone, whereas the actively unstable region propagates with the wave.

The most important consequence of saturation on the dynamics of the large-scale circulation is the momentum deposition resulting from the amplitude-limiting mechanism (LINDZEN, 1981). Secondary effects produced by the turbulent layers include heat as well as constituent transport. The study by SCHOEBERL et al. (1983) suggests that the turbulent heat transport drives the mean state towards an adiabatic lapse rate. Using a quasi-linear initial-value model, WALTERSCHEID (1983) found that large-amplitude, gravity-wave saturation produces a rapid reduction in both the intrinsic phase velocity of the wave and the eddy diffusion needed to balance wave growth. There also is some heating due to wave and turbulence dissipation.

This description provides a very simplistic view of the saturation of an isolated monochromatic gravity wave. The detailed evolution of the wave field during saturation, including the production of turbulence and possible wave frequency broadening (WEINSTOCK, 1976; 1982), is not well understood. Advances in this area will have immediate consequences for observational programs. For example, to what extent can waves be partially reflected from neutrally buoyant layers produced by turbulent zones or from large velocity shears due to differential momentum deposition, and could we expect to see evidence of such reflections in the data? Reflection at an internal shock and wave scattering due to localized dissipation were observed in the numerical experiments of DUNKERTON and FRITTS (1983). Finally, there is some evidence that suggests that multiple wave interaction can lead to saturation, although this process has not been studied in detail.

The spatial and temporal variability of gravity waves entering the mesosphere is understood poorly at present. Clearly, the upward flux of waves at the stratopause is a function of the production of waves in the troposphere, their transmission, and zonal and meridional propagation (DUNKERTON, 1982b; SCHOEBERL and STROBEL, 1983). The obvious tropospheric gravity-wave sources are unstable wind shear, topography, and convection. Others may be important as well. Wind shear produces waves with phase velocities characteristic of tropospheric wind speeds, while topography generates gravity waves with a phase velocity distribution centered about zero. Of the three dominant gravity-wave sources, the phase velocity spectrum associated with convection is the least understood. However, it is reasonable to suppose that the phase speed distribution is broad and centered near tropospheric wind speeds. Characteristic scales and amplitudes, as well as the distribution and variability of the sources just mentioned are not well known at present (LINDZEN, 1983). Such information requires additional theoretical work and detailed tropospheric observations of gravity-wave forcing and structure.

The transmission of gravity waves into the mesosphere is controlled by their propagation in, and interaction with, a variable environment. Important effects include refraction, reflection, and critical-level absorption due to variations of $\overline{u}$ and N^2 with height. These variations cause changes in the vertical wavelength and group velocity of the wave and may lead to selective filtering of the gravity-wave spectrum (BOOKER and BRETHERTON, 1967; HINES and REDDY, 1967). For motions with small intrinsic frequencies, nonstationary mean flows and radiative damping also are likely to be important (FRITTS, 1982; SCHOEBERL et al., 1983). Spatial inhomogeneities of gravity-wave sources or transmissivity are likely to produce a vertical smoothing and broadening of the zonally averaged momentum deposition, as well as the excitation of large-scale gravity waves and planetary wa.es. In order to understand the consequences of gravity-wave momentum deposition and turbulence production in the middle atmosphere, however, the morphology of the flux of gravity waves into and through the middle atmosphere must be better known. ...

... 4b. TOPICS

(1) Turbulence

Radar methods provide a powerful tool for studying turbulence in the middle atmosphere (for details, see BALSLEY and GAGE, 1980; ROTTGER, 1980). The backscattered echo power and the Doppler spectral width of the signal returns are related directly to turbulence intensity. The echo power is a direct measure of one spatial Fourier component of the refractive index variation produced by a turbulent region, while the spectral width (used with caution) is a measure of the variance of turbulence velocities.

Turbulence spatial characteristics already have been studied at a number of sites via the backscatter power structure. The presence of vertically thin, horizontally extended turbulent regions that exist for many hours has been noted in both the stratosphere and lower mesosphere (CZECHOWSKY et al., 1979; SATO and WOODMAN, 1982). While some exceptions to this general picture exist (i.e., in the high-latitude summer mesosphere), they probably can be considered typical.

Estimates of vertical diffusion can be made using statistical properties of the thin turbulent regions (WOODMAN et al., 1981). This is of particular importance in the current context, since enhanced diffusivity increases gravity wave damping and the corresponding mean flow accelerations. Estimates of stratospheric diffusion and turbulence dissipation have been obtained from the observed dispersion of rocket vapor trails (ROSENBERG and DEWAN, 1975) and from high-resolution balloon data (CADET, 1977) among other things. Current radar estimates of vertical diffusivity in the lower stratosphere suggest values that may be appreciably larger than those obtained by aircraft techniques (LILLY et al., 1974). Further measurements appear necessary to address this disparity.

The possibility of using radar systems with very good vertical resolution (tens of meters) to study the space-time structure of turbulence within the layers is exciting and should allow us to understand better the underlying generation mechanisms (i.e., dynamical and convective breaking of the waves). In this regard, the use of special rocket and balloon-borne techniques (PHILBRICK et al., 1983; BARAT, 1983) concurrent with radar observations to obtain the high-resolution structure of turbulent regions would appear important for understanding the generation mechanisms of turbulence and would enable a valuable comparison between techniques.

The use of Doppler spectral width to measure turbulence intensity has yet to be exploited fully (SATO and WOODMAN, 1982; HOCKING, 1983). Since the velocity variance is related directly to the eddy dissipation rate, it is clear that a greatly increased observational program using spectral width estimates of eddy dissipation rates would have direct relevance to the development of more accurate general circulation and mechanistic models. Energy dissipation rates also can be used to infer vertical diffusivity and heating, thus spectral width measurements may provide an alternative method of determining vertical diffusivity. Spectral width measurements, however, require a narrow radar beam and a correspondingly large antenna area.

Finally, the general characteristics of the turbulent structure profiles can be expressed in terms of the refractive index structure constant C_n^2 (TATARSKII, 1971). This parameter is useful, for example, in comparing radar, optical, and other turbulence measurements.

(2) Gravity Waves

A significant amount of information on middle-atmosphere gravity waves already has been obtained by existing techniques. Radars can provide a detailed description of the wind field as a function of height and time. They can also produce spectral descriptions of the wind field fluctuations as a function of frequency (BALSLEY and CARTER, 1982). Lidars provide similar information for the temperature fluctuations (CHANIN and HAUCHECORNE, 1981). Data from rocket networks can reveal long-term statistics on the geographical and seasonal variation of the wave field (HIROTA, 1983). Rocket data also provide instantaneous profiles of temperature and wind (THEON et al., 1967) from which gravity wave processes can be inferred.

Two important parameters about which relatively little information has been collected are the horizontal wavelengths (λ_h) and phase velocities (c) of gravity waves. Some information on these parameters has been obtained from studies of airglow emissions and noctilucent clouds (ARMSTRONG, 1982; HERSE et al., 1980; HAURWITZ and FOGLE, 1969). Initial radar estimates of λ_h and c were made by VINCENT and REID (1983) and by FRITTS et al. (1983). VINCENT and REID (1983) also made the first direct measurements of another important quantity, the upward flux of horizontal momentum ($\overline{u'w'}$) in the mesosphere, and VINCENT (1983) used rotary spectra to obtain a lower limit on the fraction of upward-propagating, low-frequency gravity waves in the mesosphere and lower thermosphere. The latter study suggests an upward flux of energy and momentum consistent with the requirement of gravity-wave drag.

Two interpretations have been advanced to account for the low-frequency ($\omega < N$) and low (horizontal) wavenumber spectra observed in the middle atmosphere. One is that the motions are due to a spectrum of internal gravity waves analogous to the "universal" wave spectrum applied to the ocean (VANZANDT, 1982). Such a theory is consistent with both the apparent role of gravity-wave transport, drag, and diffusion in middle-atmosphere dynamics and the observed spectral character of atmospheric fluctuations. A second interpretation, based upon the theory of 2-dimensional turbulence, also appears to be consistent with certain spectral observations (GAGE, 1979; LILLY, 1983), but this theory requires the presence of propagating gravity waves as the primary coupling between the lower and middle atmosphere and is concerned primarily with the spectral distribution of kinetic energy. The actual state of the atmosphere, of course, may involve a combination of gravity waves, 2-dimensional turbulence, and other motions, with further studies needed to delineate their relative importance.

Gravity-wave observations to date have provided good preliminary information on motions, processes, and spectra using a variety of techniques. Often, however, such observations are made without knowledge of the mean velocity and static stability profiles. This is a major shortcoming (particularly the lack of $\overline{u}$) because it causes ambiguities in the determination of the characteristics and/or consequences of the wave motions that might otherwise be inferred.

5. FUTURE RESEARCH NEEDS

(a) Modeling Needs

Because they tend to be computationally efficient and allow individual processes to be studied in isolation, mechanistic models probably will continue to play a major role in the development and testing of parameterizations for gravity wave-mean flow interactions. Both the quasi-geostrophic models and the global primitive equation models will be useful tools. We anticipate, however, that there may be less emphasis on zonally symmetric models in the future, particularly for the study of wave-mean flow interactions in the winter hemisphere. The current primitive state of knowledge of gravity-wave morphology and of the detailed physics of wave-breaking allows for a wide range of assumptions in present models. Ideally, mechanistic models that properly handle wave-mean flow interactions will provide some useful constraints on the possible characteristics of the observed wave climatology. However, there is little prospect that modeling can be in any sense a substitute for observations.

It should be cautioned that measured gravity-wave fluxes and other parameters will not be able to be used directly in middle-atmosphere models. One reason for this is that measured quantities depend on atmospheric conditions in the troposphere, stratosphere, and mesosphere that may be very different from those existing in a model. However, measurements of the global gravity-wave morphology should allow the development of schemes that can represent consistently the proper dependence of the large-scale flow on gravity-wave processes.

(b) Theoretical Needs

Theoretical studies are needed to address a number of problems that are unlikely to be solved using existing observational techniques. The most obvious of these relate to the saturation process itself. In particular, studies are needed that address the detailed mechanisms and consequences of saturation, including wave-scattering and reflection, and multiple-wave saturation, and the effects of the temporal and spatial variability of saturation. The former studies are necessary to understand the evolution of a saturating gravity-wave spectrum; the latter is needed to incorporate correctly the effects of saturation and its variability in mechanistic and general circulation models of the middle atmosphere.

Other areas in which theoretical work is needed are the identification and quantification of the dominant tropospheric sources of gravity waves and the study of wave propagation and filtering through wave-wave and wave-mean flow interactions. Theoretical studies of gravity-wave sources in conjunction with high-resolution observations may help determine the phase speed and horizontal wavelength distributions, as well as their geographical and temporal variability. These distributions are poorly known at present, but they are expected to have a major impact on the occurrence and effects of saturation in the middle atmosphere. Likewise, the propagation of gravity waves through, and their interaction with, a variable environment will influence the character and occurrence of saturation. It also is important to determine to what extent the concept of a universal gravity-wave spectrum can be applied to the atmosphere.

(c) Observational Needs

(1) Gravity wave and turbulence climatology

There is a clear need to extend our studies of the climatology of atmospheric gravity waves and turbulence. Observations of the geographical and temporal distributions of gravity-wave sources, energies, and momentum and heat fluxes, as well as turbulent diffusion, are required. The distributions of momentum fluxes ($\overline{u'w'}$ and $\overline{v'w'}$) and heat fluxes ($\overline{v'T'}$ and $\overline{w'T'}$), in particular, have direct implications for modeling the large-scale circulation and will depend on the dominant sources and the propagation of gravity waves into the middle atmosphere. Measurements of turbulent diffusion and spectral width are needed to address the rate of gravity-wave energy dissipation and the effects of diffusion in the middle atmosphere.

It is also important to address the vertical transport of energy and momentum by the full spectrum of gravity waves under various conditions. To this end, studies of low-frequency motions using rotary spectra and filtering through radiative cooling, and wave-wave and wave-mean flow interactions appear relevant.

Momentum flux, energy, turbulence intensity, and rotary spectrum measurements currently are possible with multiple-beam radar systems; heat fluxes could be determined with combinations of radars and lidars.

(2) Case studies

Case studies of nearly monochromatic wave motions providing the mean and perturbation wind fields and the distributions of vertical wavenumber would permit comparisons with theoretical models and provide evidence of important processes and interactions. Independent measurements of the associated temperature fields would permit a check on the wave parameters inferred from radar measurements. Observations of wave excitation and dissipation (or saturation) are particularly important in this regard. It also would be useful to identify the frequency of occurrence of the various gravity-wave processes and interactions thought to be important in the middle atmosphere.

One example of a useful case study is nearly monochromatic gravity-wave saturation. Saturation is associated with either $|\partial T/\partial z| \sim \Gamma$ or $|u'| \sim |c - \overline{u}|$. Because there are uncertainties in estimating c using data from a single station, however, saturation may be identified most unambiguously in measurements of the temperature structure. Because c is constant and $\overline{u}$ may change with height, $|u'|$ need not remain constant above the saturation level.

(3) Measurement of λ_h and c

Two gravity-wave parameters of particular significance are the horizontal wavelength (λ_h) and the (horizontal) phase velocity (c). They are important because they are essentially constant following the wave motion and they determine the occurrence and distribution of gravity waves in the middle atmosphere. Other relevant wave parameters, such as the intrinsic frequency ($k(c - \overline{u})$) and the vertical wavenumber ($m = 2\pi/\lambda_z$), are not constant, but depend on N^2 and $\overline{u}$. Determination of the phase speed distribution of gravity waves near their source regions in the troposphere and in the middle atmosphere would permit a quantitative assessment of the effects of filtering and wave-wave interactions as the gravity waves propagate vertically. Horizontal wavelength measurements would help establish the degree of homogeneity in the mesospheric response to gravity-wave saturation.

Estimates of λ_h and c can be obtained in certain instances with present radar and lidar systems using multiple-beam techniques. However, such estimates are subject to potentially large errors and may be biased towards relatively small-scale waves ($\lambda_h \lesssim 200$ km) because of small horizontal beam separations. It would be desirable, therefore, to make more direct radar and lidar measurements at a range of spacings from a few tens of a kilometer upwards in order to measure those wavelengths and phase velocities more relavant to middle-atmosphere dynamics. Such spacings are considerably less than those required to address the geographical distribution of gravity-wave saturation and turbulent diffusion.

(4) Measurement of mean winds

In addition to gravity-wave and turbulence measurements, long-term measurements of the mean zonal and meridional wind components in the mesosphere and lower thermosphere are required. At present, the climatology of the mean zonal wind at these levels is not well known, especially in the tropics. The current data base for the mean meridional wind is completely inadequate. The latter is particularly important since gravity-wave drag in the mesosphere is balanced primarily by the Coriolis torque due to the mean meridional motion.

(d) Observational networks

As discussed in several of the previous sections, it would be desirable to establish networks of radar and/or lidar systems for the following reasons:

(1) The horizontal wavelengths and phase velocities of monochromatic atmospheric gravity waves can be measured more reliably by making observations from at least three spatially separated points. Because the wavelengths of longer waves cannot be determined accurately using small spacings, it will be necessary to use a range of spacings.

(2) Studies of the global morphology of gravity waves require that several such facilities be established at geographically distinct locations. Such systems should make extended observations to determine seasonal and interannual variability. The potentially important effects of orography can be examined by establishing sites near extensive mountain ranges and by comparing these results with observations taken in orographically smooth regions.

Other combinations of observing systems also would provide important information on gravity-wave propagation and dissipation processes and morphology. Colocated lidar and radar facilities, for example, would permit much more detailed observations of gravity-wave saturation in the mesosphere. Saturated wave amplitudes then could be compared directly with perturbation lapse rates for both narrow- and broad-spectrum saturation. Meteorological rockets would provide an important complement to both radar (MST or PR) and lidar facilities through the addition of mean wind, temperature, and gravity-wave structure in regions where no balloon or radar wind data are available. Such data would make studies of gravity-wave propagation and the onset of saturation possible.

One final recommendation pertains to establishing such observatories in the tropics. Extended tropical observations, particularly within a few degrees of the equator, will yield (in addition to the low-latitude gravity waves) important new information on long-period equatorial waves. These waves exist only in the tropics and comprise the major mechanism for momentum transport into the middle atmosphere in that region. ...

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