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PROPAGATION AND SATURATION OF NONLINEAR INERTIA- RAVITY WAVES IN THE ATMOSPHERE

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Inertia-gravity waves play a significant role in the transport of momentum, heat, and constituents in the terrestrial atmosphere. This transport process is sub-grid scale in general circulation models and must be parameterized. A generalized parameterization scheme is developed in which a gravity-wave is subject to localized breaking that creates turbulent mixing and retards amplitude growth. The effect of turbulence localization on turbulent viscosity, diffusivity and mean flow acceleration is described for the convectively unstable case. Possible generalizations to Kelvin-Helmholtz breaking are suggested. Numerical simulations at high resolution illustrate the evolution to small scales characteristic of convective instability. (KR)

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1. INTRODUCTION

Gravity waves are an important feature of the earth's atmosphere, representing one of two classes of oscillation, rotational and gravitational, that are supported by a rotating, stably stratified fluid. Over the last decade, our appreciation of gravity waves has grown tremendously. These waves have been recognized for their role in momentum, heat, and constituent transport in several ways. The drag force exerted by breaking gravity waves in the winter troposphere and mesosphere is responsible for limiting the amplitudes of the major jet streams in these two regions. In tropical latitudes, equatorially trapped gravity and Kelvin waves drive the semiannual and quasi-biennial oscillations. The distribution of temperature and trace constituents such as odd oxygen and water vapor are thought to be affected, at least in part, by the turbulent diffusivity of breaking gravity waves in the upper mesosphere. In the stratosphere, the breakdown of gravity waves is less ubiquitous, but exists in discrete layers, layers constantly changing with time and believed to be associated with upward-propagating inertia-gravity waves. In a statistical sense, it has been argued that the spectral slope associated with gravity waves is saturated throughout the atmospheric column, with amplitudes and cutoff wavenumbers changing with height in such a way that the scales and frequencies increase going upward.

Clearly, the gravity wave component of the fluid motion cannot be ignored in atmospheric modelling and in budget studies of the general circulation. However, the dominance of small-scale motions in the transport process presents a difficulty for numerical models; these motions are sub-grid scale, even in the highest-resolution state-of-the-art GCM's. Parameterization of gravity wave activity is a necessity. The parameterization issue, however, is intimately dependent on the theory of gravity wave transport and saturation. In fact, while observations suggest that such transport and breakdown is occurring in gravity waves, they provide only partial clues as to the precise nonlinear mechanisms taking place; many ambiguities remain. Therefore, observations alone cannot be used to develop parameterization schemes for numerical models. It is at this point that the theory and direct numerical simulation of the gravity wave manifold is essential.

The purpose of the research supported by the Air Force Office of Scientific Research under Contract F49620-86-C-0026 has been to investigate, both theoretically and numerically, the processes governing the propagation, saturation, breakdown, and spectral evolution of nonlinear inertia-gravity waves under conditions typical of the terrestrial atmosphere. Specific objectives of the work are now described.

2. OBJECTIVES OF THE RESEARCH EFFORT

A complete list of the objectives of the research effort is as follows:

a. Role of convective instability in gravity wave saturation

The contemporary theory of convective instability in internal gravity waves began with a paper by Lindzen (1981) who used linear wave theory to deduce expressions for the momentum deposition and effective turbulent diffusivity due to a convectively saturated monochromatic internal gravity wave. The wave amplitude was assumed to be limited so as to maintain neutral stability to convection within the most unstable phase of the wave. This saturation hypothesis was incorporated by Dunkerton (1982) in a time-dependent semi-analytic model of gravity wave, mean-flow interaction.

The scheme of Lindzen (1981), with minor modifications, has already played an important role in the understanding and numerical parameterization of gravity wave saturation. However, the underlying assumptions cannot be considered accurate. First, the convective instability is restricted to a narrow fraction of the wave field; it is unreasonable to expect that such a small region of instability will somehow act to saturate the entire wave field. In fact, observations indicate that gravity waves are supersaturated with respect to convection (at least in instantaneous measurements). Therefore, it is necessary to develop a more realistic parameterization of saturation amplitudes in order to determine momentum deposition.

The Lindzen (1981) scheme also predicts an abrupt onset of turbulent diffusivity and momentum deposition at the lowest altitude of wave breaking. A more realistic parameterization of amplitude growth would therefore be beneficial to numerical models as well.

b. Effect of turbulence localization on gravity wave transport

A second limitation is that the location of turbulent mixing, within the region of overturning, suggests that the effective turbulent mixing of mean potential temperature and constituent fields may be much smaller than anticipated by Lindzen (1981). The reason for this is that mixing, though locally downgradient, is occurring in a region of the wave field whose potential temperature gradient is reversed relative to the stable mean gradient. In effect, the local mixing is countergradient relative to the mean. Consequently, the net mixing of heat and constituents will be much less than one would deduce from the Lindzen (1981) scheme.

This theoretical intuition agrees with other considerations. Laboratory experiments involving convectively unstable gravity waves suggest that very little mixing of the mean density gradient occurs. In the mesosphere, photochemical considerations place an upper limit on the amount of gravity wave mixing, suggesting a large effective turbulent Prandtl number (~ 10).

The anticipated reduction in effective turbulent diffusivity affects not only the diffusion of heat and constituents but also the evaluation of momentum diffusion (effective turbulent viscosity) required to maintain neutral stability of the primary wave. While supersaturation suggests a weaker viscosity, more viscosity is required to compensate for the loss of turbulent diffusivity due to localization of convection. These mechanisms compete with one another, although (as shown below) the net effect of localization is generally to reduce the turbulent diffusivity *and* viscosity.

c. Role of Kelvin-Helmholtz instability in gravity wave breaking

The effect of mean shear and/or rotation causes Kelvin-Helmholtz instability to take precedence over convection as the dominant secondary instability in internal gravity wave motion. For an inertia-gravity wave, the transverse velocity component exhibits its greatest shear in the phase of the wave having a local minimum in total static stability; this phase of the wave therefore can satisfy the necessary condition for Kelvin-Helmholtz instability prior to the overturning of potential temperature surfaces. For a non-rotating gravity wave in mean shear, we obtain a similar result. This type of instability has been observed in the laboratory by Delisi and Dunkerton (1989) in a breaking internal gravity wave.

In general, the existence of secondary instabilities other than local convection could have significant effects on the momentum transport and mixing. However, the location of KH breaking is quite close to that of convection, and might imply results similar to those obtained with convective saturation theory. It will be necessary to examine these instability criteria more closely and develop suitable generalizations to the parameterization scheme for circumstances in which Kelvin-Helmholtz instability is dominant.

d. Effects of parametric subharmonic instability in convectively stable gravity waves

Monochromatic gravity waves are the exception in reality. A spectrum of gravity waves, as observed, admits many nonlinear interactions when individual components attain large amplitude. By interacting with and extracting energy from the primary wave, these interactions can directly affect transport and mixing. Perhaps they can also contribute to the saturation of the wave.

One such interaction, the parametric subharmonic instability, is well-known and has been observed in the laboratory. This interaction arises from the oscillation of isopycnal surfaces, by analogy to the instability of a forced pendulum (McComas and Bretherton, 1977). Unstable growth rates have been examined by Mied (1976), Yeh and Liu (1981), and

Klostermeyer (1982). These growth rates are significant when the primary wave attains an amplitude of the same magnitude as required for convective instability. Perhaps more importantly, the parametric subharmonic instability (like other nonlinear interactions) takes place continuously even when the primary wave stays below the convective instability threshold. We know immediately, then, that the convective saturation theory cannot be generally valid as a gravity wave transport parameterization. However, the nonlinear saturation problem is exceedingly difficult. Simple numerical experiments, reported below, help address this issue and suggest a heuristic modification to the parameterization scheme.

e. High-resolution numerical simulation of inertia-gravity waves

A major, long-term goal of our research effort is to develop and utilize a numerical model of gravity waves in three dimensions. The motivation is two-fold. First, nonlinear processes occurring in two dimensions are sufficiently complicated that we cannot develop general parameterization schemes (or at least understand how accurate they are) apart from direct numerical simulation. Second, the introduction of a third dimension, as in the real world, admits a rotational class of motion that can interact with the gravitational class. It is desirable to understand how the two manifolds interact, and whether one is, say, unstable to motions of the other. Of course, interactions will occur apart from instability; these include mean flow interactions involving gravity waves, equatorial waves, and planetary Rossby waves. Finally, the saturation of inertia-gravity waves with respect to other motions of the gravitational class is itself an inherently three-dimensional process.

3. ACCOMPLISHMENTS OF THE RESEARCH EFFORT

The results briefly summarized below have been published in a series of papers by the author: the material of subsections 3a-c appears in a lengthy review (Dunkerton, 1989) and the PSI experiments of subsection 3d appear in Dunkerton (1987).

a. Parameterization of convective instability

Our desire is to generalize Lindzen's (1981) convective saturation hypothesis and its formulae for momentum deposition and effective turbulent viscosity and diffusivity. To do this, I have altered the underlying assumptions of the hypothesis in two ways:

1) The primary wave is allowed to grow to amplitudes exceeding the convective instability threshold in such a way that the sum of all Fourier harmonics represents a neutral, sawtooth-like wave.

2) The *local* turbulent diffusion is a function of wave phase, a function chosen to maximize at the point of greatest overturning and decay away from this point.

The resulting expression for turbulent eddy viscosity then assumes the form

$$\bar{\nu} = (1 - \beta/a)^{-1} \frac{k\hat{c}^4}{2N^3} \left[\frac{1}{H} - \frac{3\bar{u}_z}{\bar{u} - c} - \frac{2}{a}\frac{\partial a}{\partial z} \right] \tag{1}$$

where a is nondimensional wave amplitude and β is a nondimensional measure of localization. Other parameters are defined in Dunkerton (1989). According to (1), there is competition between the effect of localization (which reduces the effective turbulent diffusivity and therefore requires a higher turbulent viscosity to compensate) and wave growth (arising because the projection of the sawtooth-like wave on the primary wave exceeds unity). In order to use (1) it is necessary to relate the degree of localization to the degree of wave growth; this requires that a functional form of the *local* turbulent diffusion be specified. An example was described by Dunkerton (1989) and compared to the Lindzen (1981) formulae. In our modified scheme, *the mean flow acceleration and turbulent viscosity onset smoothly*. For the example cited by Dunkerton, the turbulent viscosity is reduced, and the effective turbulent diffusivity is reduced even more. Of course, the vertically-integrated acceleration beneath the critical level is invariant.

b. Evaluation of the effective turbulent diffusivity for the mean state

In the above formulation the effective turbulent Prandtl number for the mean state is

$$Pr_{eff}^{-1} = 1 - 2a\beta + a^2(1+\gamma)/2 \tag{2}$$

where γ is a small triple-correlation term (Coy and Fritts, 1988). For further discussion of the derivation of (2) from first principles, see Fritts and Dunkerton (1985). A Lagrangian derivation of the same result has been given by Coy and Fritts (1988).

As already noted, the effective turbulent Prandtl number is much greater than unity, in contrast to the underlying assumption of Lindzen (1981).

c. Criteria for Kelvin-Helmholtz instability in a monochromatic gravity wave

If the criterion for convective instability is $a = 1$, as above, the respective criteria for Kelvin-Helmholtz instability in the presence of rotation or mean shear can be derived and shown to be somewhat less than unity (Dunkerton, 1984; Fritts and Rastogi, 1985; Dunkerton, 1989). For inertia-gravity waves, the relevant amplitude is determined from the expression

$$\sigma^2 - 1 = \frac{.25a^2}{1-a} \tag{3}$$

where $\sigma \equiv \omega/f$. For internal gravity waves in shear, on the other hand,

$$(1-a) \approx \frac{1}{2}\mu^2 \tag{4}$$

where μ is the inverse square-root Richardson number.

A theory of Kelvin-Helmholtz saturation has not been developed and applied to gravity wave parameterization; nevertheless, it would be straightforward to use these instability criteria in connection with the results above to derive the behavior wave amplitude, turbulent viscosity, and so on. Our numerical modelling has the direct simulation of local KH breaking as one of its chief near-term objectives.

d. Numerical experiments involving parametric subharmonic instability

Simple experiments were performed by Dunkerton (1987) to estimate the probable importance of parametric subharmonic instability (PSI) in internal gravity waves. A large-amplitude primary wave was destabilized by the presence of a small-amplitude, resonating partner, leading to the generation of the third member of the triad and (soon thereafter) a cascade of energy to other scales. These experiments demonstrated that the PSI mechanism limits the amount of momentum that can be transported by any single monochromatic gravity wave packet. However, the quasi-linear theory and its associated saturation hypothesis remain viable for the initial evolution of the packet; in the case of short-lived wave events, the quasi-linear theory may be adequate. Further discussion of these results and their implications appears in Dunkerton (1987, 1989).

e. High-resolution two-dimensional simulation of an overturning gravity wave

The most intensive aspect of the research being performed under this project involves the development and implementation of a three-dimensional numerical model with capabilities to simulate inertia-gravity waves on an f-plane and equatorially-trapped waves on a beta-plane. Development of a preliminary two-dimensional version of the code was completed in the second year of this investigation; the third year has been largely devoted to a series of numerical experiments involving forced, large-amplitude gravity waves incident on a critical level. We now briefly describe the methods used in the numerical code and some results for one particular simulation.

The model employs a set of hydrostatic, quasi-Boussinesq equations which on an f-plane assume the form

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\left(\frac{\partial u}{\partial y} - f\right) + w\frac{\partial u}{\partial z} + \frac{\partial \phi}{\partial x} = X \tag{5}$$

$$\frac{\partial v}{\partial t} + u\left(\frac{\partial v}{\partial x} + f\right) + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + \frac{\partial \phi}{\partial y} = Y \tag{6}$$

$$\frac{\partial \phi_z}{\partial t} + u\frac{\partial \phi_z}{\partial x} + v\frac{\partial \phi_z}{\partial y} + w\left(N^2 + \frac{\partial \phi_z}{\partial z}\right) = Q \tag{7}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} - \frac{w}{H} = 0 \tag{8}$$

where u, v, and ϕ are zonal and meridional and geopotential, respectively, and w is the vertical velocity in log- pressure coordinates (z is log-pressure height). These equations are divided into mean and perturbation equations, which are solved separately. (For the simulation reported here, the mean flow is held constant in time.) The dependent variables of the numerical model are u, v, and ϕ_z; equations for these quantities are stepped forward in time using the Adams-Bashforth method. The next step in the calculation is to solve for ϕ and w; this is done with vertical integration across the domain depth, using Simpson's rule. This calculation, and the evaluation of all horizontal derivatives, is done in spectral space. The fast Fourier transform is used to move back and forth between physical and spectral space. In our simulations, forcing is applied at the lower boundary in the form of a vertical velocity perturbation. The Klemp and Durran (1983) condition is invoked at the upper boundary. Nonlinear terms near the lower boundary are artificially weighted by a sine ramp function to prevent the nonlinearity from generating noise at the lower boundary.

For the simulation described here, the mean flow is taken to vary linearly in height (with shear equal to 2 $\mathrm{ms^{-1}km^{-1}}$) such that a critical level ($\bar{u} = c = 0$) exists at the level $z/D = 0.8$, where D is the domain depth (10 km). The horizontal domain is taken to be 200 km wide, and the model is forced by gradually switching on a stationary wavenumber 1 perturbation to a fixed magnitude of 0.1 $\mathrm{ms^{-1}}$ at t = 20000 sec. This forcing generates a nearly monochromatic wavepacket that propagates vertically and grows in amplitude as the critical level is approached. At some time $t = t_{over}$, the primary wave overturns (Fig. 1a), and thereafter, at $t = t_{conv}$, instabilities break out (Fig. 1b). These instabilities involve many higher harmonics, but growth is ultimately most rapid for the highest harmonic resolved by the simulation. In this simulation we have used 32 Fourier harmonics to resolve the zonal direction, and set $f = 0$ (nonrotating case). In order to achieve a perfectly unaliased nonlinear calculation, we are required to truncate the top one-third of the harmonic spectrum at each time step; thus, the highest harmonic visible after truncation is wave 20, as seen in Fig. 1b. The dominance of the highest harmonic is symptomatic of convective instability, as expected from simple theoretical considerations (Dunkerton, 1989). However, it poses a difficulty for numerical simulations which must be overcome with higher resolution and scale- dependent damping. Our current work examines these alternatives, and results will be presented in a forthcoming publication.

Most of our work in the third year has involved model testing and validation. Several

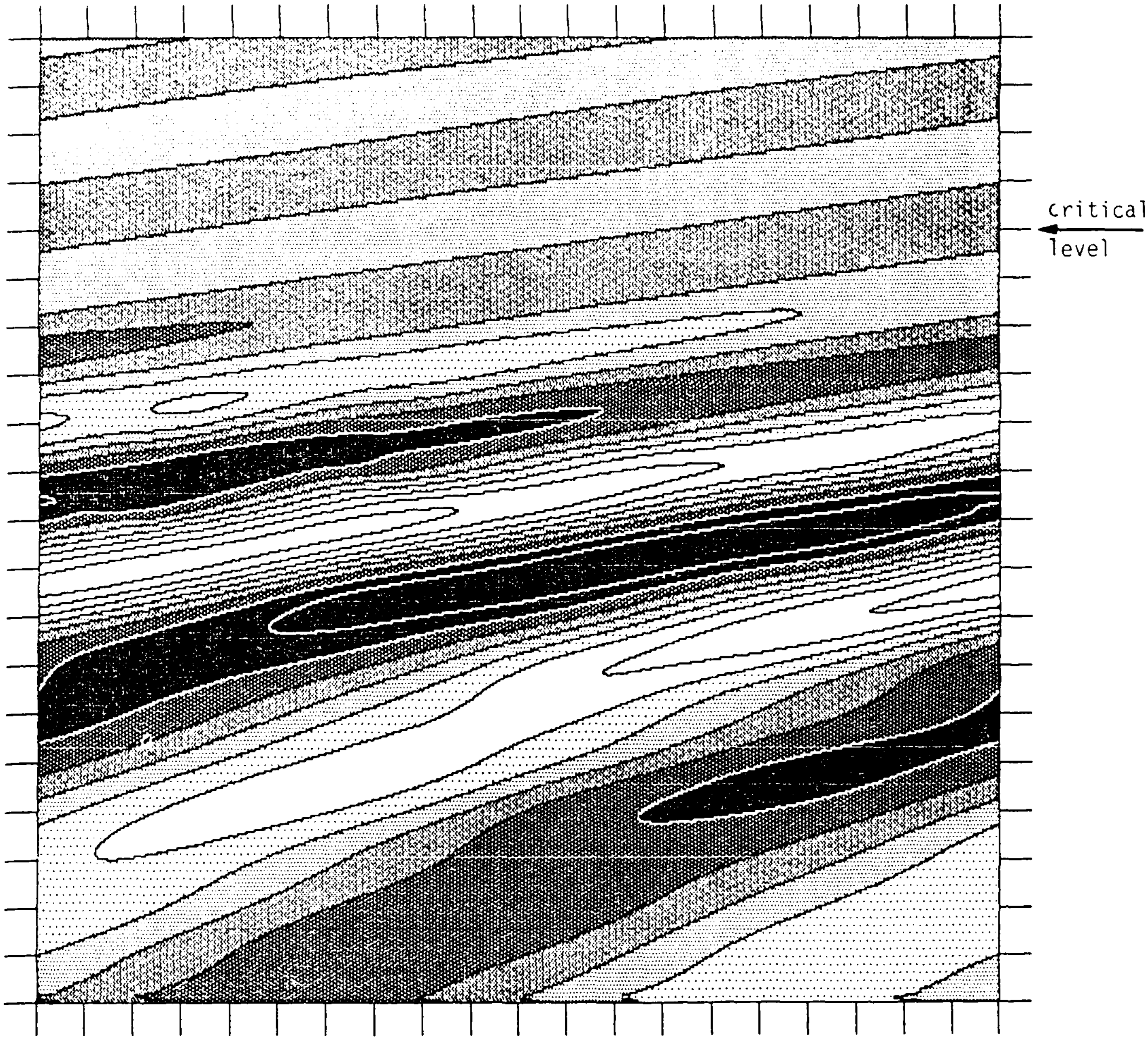

Figure 1a. Perturbation temperature contours at $t=t_{over}$ for numerical simulation discussed in text. Contour interval is 0.05°C where white (black) represents temperature perturbations > 0.1°C (< − 0.1°C). Horizontal (vertical) tic marks represent 10 km (0.5 km).

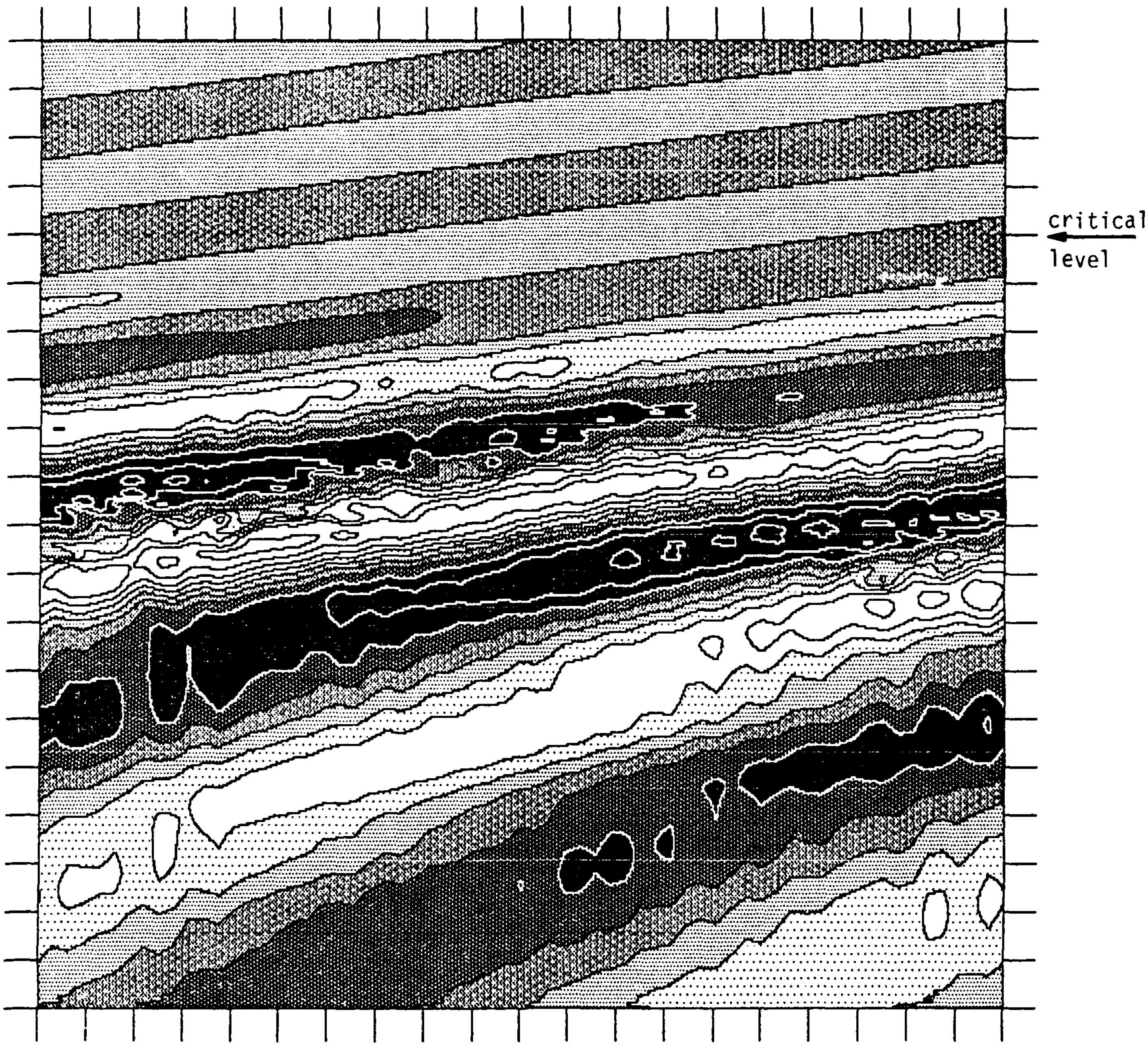

Figure 1b. Perturbation temperature contours at $t=t_{conv}$ for numerical simulation discussed in text. Contour interval is 0.05°C where white (black) represents temperature perturbations > 0.1°C (< - 0.1°C). Horizontal (vertical) tic marks represent 10 km (0.5 km).

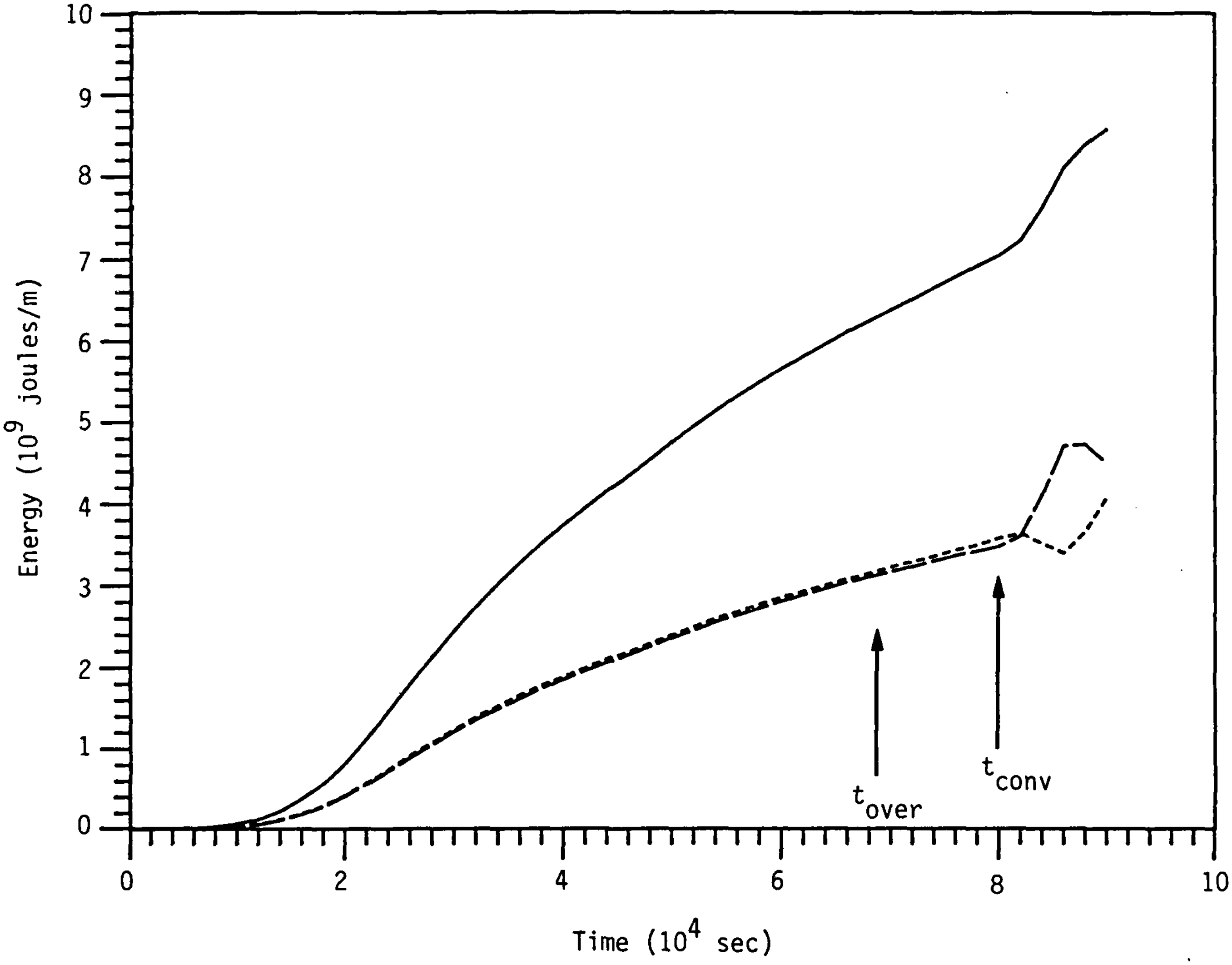

Figure 2. Total (———), kinetic (----), and available potential (—— —— ——) energy versus time for numerical simulation discussed in text. t_{over} and t_{conv} are the times corresponding to Figures 1a and 1b, respectively.

time-stepping methods were tried; the stability of the present scheme is superior to the others that have been tested. Energetic consistency is a particular concern, and we have evaluated the model results in terms of their ability to conserve total kinetic and potential energy (formulated in terms of the Lorenz cycle directly from the model equations above). Fig. 2 shows the energy components (supplied by the pressure work at the lower boundary) which grow at a steady rate, beyond the point of overturning and onset of convection, until late in the calculation. This late-time divergence is symptomatic of numerical instability; model results cannot be believed beyond this point. We think it is significant that the initial process of overturning and convection exhibits realistic energy evolution, suggesting that a genuine simulation of convection has been attained. However, the problem of scale selection remains. We are examining this question presently.

Before proceeding to three-dimensional calculations, we intend to investigate the breakdown of the primary wave in regions of strong mean shear in order to construct an analog of the experimental situation and discovery of secondary KH instability by Delisi and Dunkerton (1989).

4. LIST OF PUBLICATIONS ARISING FROM THIS WORK

Dunkerton, T.J., 1987: Resonant excitation of hemispheric barotropic instability in the winter mesosphere. *J. Atmos. Sci.*, *44*, 2239-2251.

Dunkerton, T.J., 1987: Effect of nonlinear instability on gravity wave momentum transport. *J. Atmos. Sci.*, *44*, 3188-3209.

Dunkerton, T.J., 1989: Theory of internal gravity wave saturation. *Pure and Appl. Geophys.*, in press.

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5. CONCLUSIONS AND RECOMMENDATIONS

There has been considerable progress in the theoretical development of gravity wave parameterizations; these have largely involved some variation of a convective saturation hypothesis. But as seen above, other dynamical mechanisms could also play a part in gravity wave saturation, momentum deposition, and mixing. Some of these mechanisms, like Kelvin-Helmholtz instability, are easily incorporated into the convective saturation hypothesis; others, like parametric subharmonic instability and nonlinear interactions, are sufficiently complex to preclude analytic treatment even in a very simplified way. These complexities point to direct numerical simulation as an avenue of study that will be fruiful in the coming years.

There is, however, an even more basic issue: how well do the existing parameterizations of gravity wave breaking capture the actual processes of local convective and Kelvin-Helmholtz instability? In other words, if one could simulate a monochromatic gravity wave in a numerical model or in the laboratory, would the observed behavior be adequately described by the parameterization? Already there has been mutual stimulation between theory and experiment. In a recent laboratory study by Delisi and Dunkerton (1989), an experiment was devised to study the convective breakdown of a gravity wave incident on a critical layer in a weakly sheared mean flow. As it turned out, secondary instability was achieved, but it appeared to be Kelvin-Helmholtz in character rather than purely convective. These laboratory results, which are robust from experiment to experiment, will be used in the near future to modify the convective saturation theory and incorporate KH breaking.

The real world, however, introduces still greater complexity with a complete spectrum of gravity wave motions; large amplitude waves are present which may interact nonlinearly in ways not addressed by simple saturation theory. Suitable numerical and laboratory experiments are now being devised to address possible saturation mechanisms as nonlinear instability and transitional flow over localized topography.

Emphasis in the coming years, then, should be given to the numerical and laboratory simulation of gravity waves, generalization of theoretical parameterizations, and comparisons between the two. These objectives are included in our current work. In the realm of observational studies there is also much work to be done; particular emphasis should be given to the establishment of radar networks as a means to understand the three-dimensional structure of gravity waves, as well as their spectral evolution and interaction with the rotational class. Single-station observations are, of course, useful in establishing climatological aspects of gravity wave transport that will serve as ground truth in general circulation models incorporating gravity wave parameterizations, but many ambiguities remain concerning the *processes* by which gravity waves are interacting with each other and transporting and depositing momentum in the mean flow. It is the proper understanding of these mechanisms that will ultimately form the foundation of a practically useful theory of gravity wave transport. This theory will, in turn, provide a backbone for gravity wave parameterizations in general circulation models that are intended to enhance our understanding and prediction of atmospheric behavior.

6. PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

Model development is being done by Robert E. Robins of Northwest Research Associates, Inc. His programming expertise has been indispensable to this effort. Some numerics guidance has also been provided on occasion from Dr. James J. Riley of the University of Washington. Theoretical discussions with Drs. Donald P. Delisi, David C. Fritts, and Michael E. McIntyre have been beneficial to this ongoing research.

7. PRESENTATIONS

Dr. Dunkerton presented an invited review talk on gravity waves at the American Meteorological Society meeting held in Seattle, August 1987. He also participated in the MASH/GRATMAP Workshop in Adelaide, Australia in May 1987 and presented a similar talk at that meeting. Aspects of equatorial dynamics were discussed in an invited review talk by Dr. Dunkerton at the recent joint conference of the American Meteorological Society in San Francisco, April 1989.

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