Numerical Studies Pertaining to Airflow on the West Coast of the US

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LONG TERM GOALS

The long term goal of this project is to improve our understanding and forecasting of coastally trapped disturbances (CTD) that often appear along the west coast of the U.S. in spring and summer. The passage of a CTD is generally associated with a sudden change in the local weather from clear skies to dense stratus clouds. Strong southerly winds may also accompany the leading edge of the CTD in extreme events.

OBJECTIVES

During this last year we have attempted to understand how CTDs can persist as they propagate along the coast without losing their energy to upward propagating gravity waves. Many past researchers, beginning with Gill (1977), have proposed that CTDs are essentially Kelvin waves and that energy is vertically trapped in these disturbances by the marine inversion. Elevated stable layers do not however, prevent vertical energy propagation in internal gravity or Kelvin waves with horizontal wavelengths even 20% the size of the wavelengths associated with observed CTDs. The relative unimportance of the elevated inversion was also indicated by a series of our previous numerical simulations in which roughly similar CTD were produced within a variety of atmospheric structures ranging from a case with two neutrally stratified layers separated by an elevated inversion to a case with uniform stratification from the surface to the top of the numerical domain.

APPROACH

Our investigation has employed a hierarchy of numerical models and analytic theory. A three-dimensional nonhydrostatic model for the simulation of stratified air flow over topography has been used to study the propagation of CTDs along both a smoothed profile of the actual west coast topography and along idealized ridges. Single and two-layer shallow-water models have been used to investigate the horizontal structure of disturbances propagating along both straight and curved side-walls. Analytic theory has been used to describe the small-amplitude response of the fluid in idealized environments. These approaches have been coordinated in an effort to arrive at the simplest physical description of the phenomena that is consistent with the available observations. These investigations have been conducted in collaboration with the following co-investigators at the National Center for Atmospheric Research (NCAR): Drs. Richard Rotunno, Joseph Klemp, William Skamarock and Rajul Pandya.

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WORK COMPLETED

This P.I.'s primary contribution to our collaborative effort during the past year consists of an elucidation of the trapping process that prevents the dissipation of CTDs through vertical energy transport. Additional work with two-layer shallow-water models and the full three-dimensional numerical model was performed by our co-investigators at NCAR and will be described in their separate year-end report.

As mentioned in the preceding section entitled "Objectives," neither linear theory nor our nonlinear numerical simulations suggest that the stability in the marine inversion prevents vertical energy propagation. We had previously hypothesized that nonlinear wave dynamics might generate a low-level disturbance that maintains its amplitude because the energy lost through vertical propagation is replenished by nonlinear wave generation near the leading edge of the CTD. This relatively exotic explanation may be applicable in situations where the leading edge of the CTD has the appearance of a strong density current and is marked by a strong wind shift (e.g., the 15-17 May 1985 event described in Mass and Albright, 1987). Many CTDs, such as the 10-11 June 1994 event (Ralph et al, 1998) are, however, relatively weak and it is less likely that nonlinear process could play an essential role in their dynamics.

Recent work by Samelson (1998) has returned our focus to the investigation of linear trapped modes. Samelson computed linear solutions for disturbances in a continuously stratified fluid propagating along a step of finite height h. These solutions were computed in a manner similar to that employed by Chapman (1982), and employed the reflective upper boundary condition that the pressure was zero at the top of the computational domain. Samelson suggested that this zero-pressure boundary condition might be associated with the presence of a neutral layer that prevents vertical propagation and traps the modes.

We have recomputed Samelson's linear solutions using a different set of nondimensional variables that more clearly reveal that the solution is in fact independent of the location of the upper boundary once that upper boundary is more than 4h above the surface. An example of one such trapped mode is shown in Figs. 1 and 2. Figure 1 shows contours of the x-z structure function for pressure (P), cross-step velocity (u), along-step velocity (v) and vertical velocity (w), where x is the spatial coordinate oriented perpendicular to the step mountain. The vertical axis is scaled in units of the mountain height h; the horizontal axis is scaled in units of the Rossby radius $L_r=Nh/f$, and the location of the step mountain is indicated by shading. At elevations below the height of the step, the structure of this mode is very similar to that of a Kelvin wave. This is confirmed by the horizontal cross-sections plotted in Fig. 2, which show horizontal velocity vectors superimposed on contours of the pressure field. Below the topography, at $z/h=0.5$, the winds are parallel to the edge of the step and in phase with the pressure perturbation, which is precisely the same relationship found in a standard Kelvin wave.
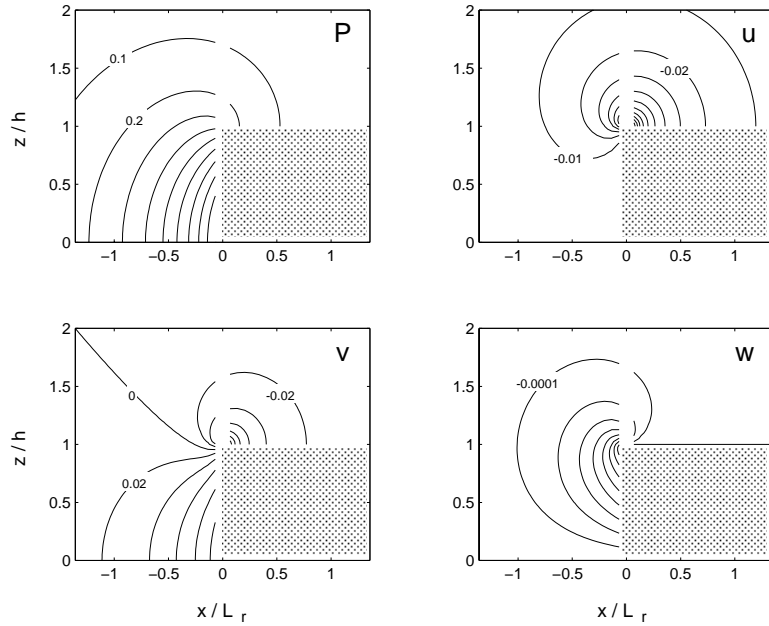
***Fig. 1. x-z structure of pressure (P) cross-step velocity (u), along-step velocity (v)
and vertical velocity (w). The location of the step mountain is indicated by shading.***

Above the topography the disturbance decays rapidly with height, but near the top of the step there is a region of relatively strong perturbation velocities.

If N=.01 s^{-1}, f=10^{-4} s^{-1}, and h= 1 km, the mode shown in Figs. 1 and 2 has an along-coast wavelength of 462 km and a northward phase speed of 5.0 m/s. A series of higher-order, slower moving modes also exist. In particular, the next highest-order mode might be important in explaining the vertical structure of the observations gathered during the 10-11 June 1994 CTD event. Note that in contrast to the wave modes obtained in all elementary problems, the x-z structure of the mode shown in Fig. 1 is not expressible in separable form, i.e., as the product of two functions r(x) and s(z). The determination of these modes is greatly complicated by the fact that they are not separable. The solution procedure of Chapman (1982) and Samelson (1998) cannot be extended to more general topographic profiles, however we have almost completed the coding of a new algorithm to handle the general case. We expect to be able to obtain results for arbitrary mountain slopes in the near future.

RESULTS

The linear solutions obtained above have allowed us to arrive at a fundamental physical understanding of the mechanism that vertically traps the energy in CTDs. Let us make the f-plane approximation by neglecting the variation of the Coriolis parameter with latitude, then all linear atmospheric waves with intrinsic frequencies less than f (hereafter "subinertial") decay with height in any laterally unbounded domain. Classical Kelvin waves, on the other hand, can propagate vertically at both super and subinertial frequencies, but Kelvin waves cannot exist in a laterally unbounded domain. The free linear modes that are present in the step-mountain problem are essentially subinertial Kelvin waves trapped against the side wall in the atmospheric layer below the step. Their energy is trapped vertically by the
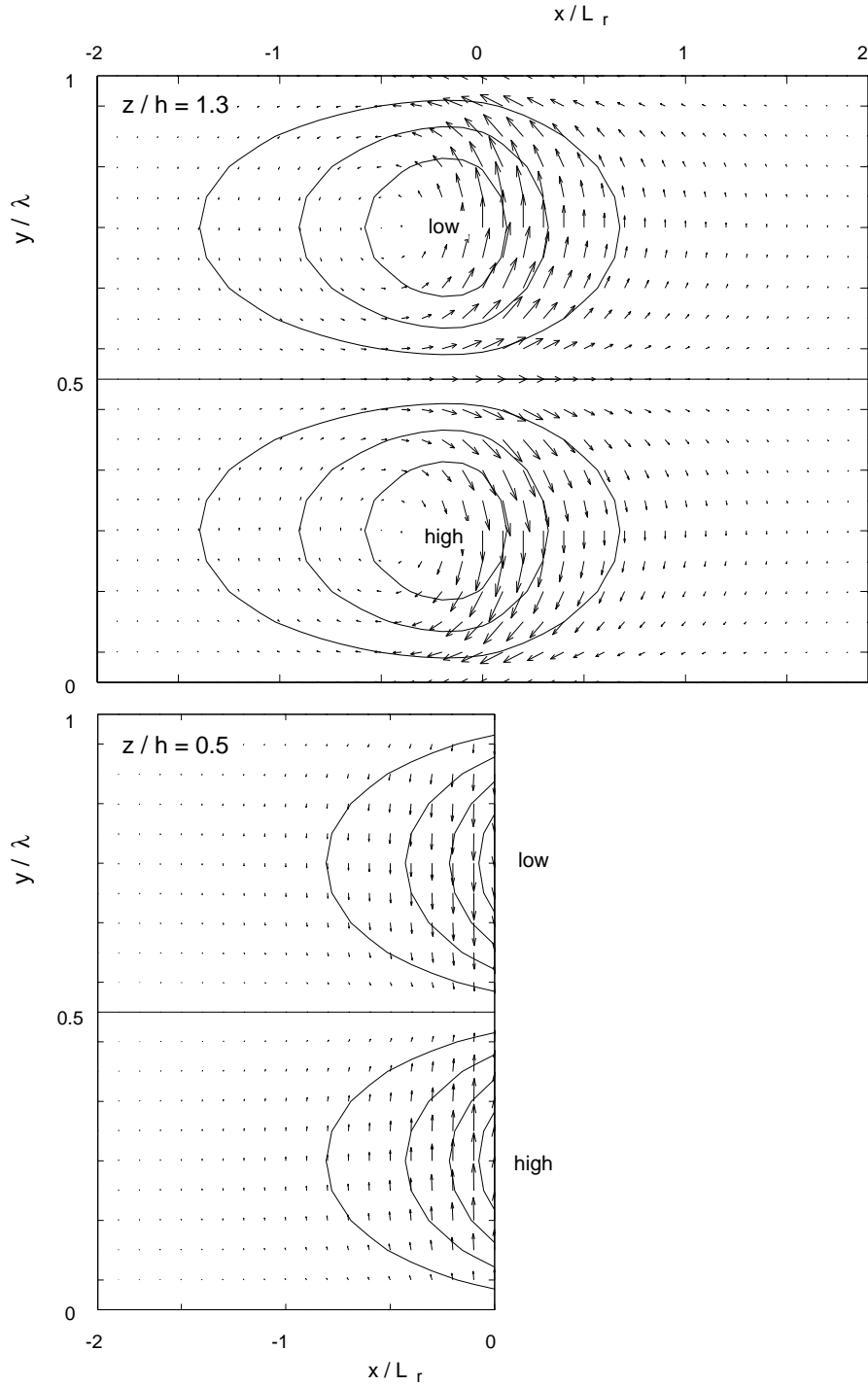
Fig. 2. Contours of pressure and horizontal wind vectors at z/h=1.3 and 0.5. The y-axis is scaled by the along-step wavelength y/λ. The vertical side wall of the step mountain lies along the line x=0.

finite height of the step because no subinertial linear modes can propagate vertically in the laterally unbounded atmosphere above the step. If a marine inversion were present in the step mountain problem, it would change the vertical structure of the free modes shown in Figs. 1 and 2, but it would have no

influence on the trapping of the modes; the modes will remain vertically trapped by the finite height of the topography provided they are subinertial.

Note that the finite height of the topography plays an essential role in trapping these waves. There are no vertically trapped Kelvin waves in a system with an infinitely tall vertical side wall. This physical understanding can be generalized to include the case of non-vertical mountain slopes. Sloping topography would be expected to support some type of subinertial topographic Rossby wave; this wave will decay vertically and horizontally away from the region of sloping terrain, so its energy will be trapped close to the topography. We are close to obtaining quantitative solutions describing these waves.

IMPACT

Disturbances are observed to propagate along the margins of significant topographic features at many locations throughout the world, including the west coast of the United States, the eastern slope of the Rocky Mountains and the southern coast of South Africa. The fundamental issues concerning the propagation and maintenance of these disturbances that we are addressing in this research should ultimately help improve the forecasting of these features at several locations throughout the world.

RELATED PROJECTS

This is a joint project with co-investigators Richard Rotunno and Joseph Klemp at the National Center for Atmospheric Research (NCAR). The funding for our co-investigators has been provided via a separate ONR grant to NCAR also entitled "Numerical Studies Pertaining to Airflow on the West Coast of the U.S."

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