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Efforts concentrated on the development of a two-dimensional primitive equation (PE) model of frontogenesis that simultaneously incorporates the frontogenetical mechanisms of confluence and horizontal shear. Applying this model to study the effects of upper level frontogenesis, it appeared to be dominated by tilting effects associated with cross-front variation of vertical motion, in which subsidence is maximized within and to the warm side of the frontal zone. Results suggest that aspects characteristics of three-dimensional baroclinic waves may be abstracted to a significant extent in a two-dimensional framework. They also show that upper-level frontogenesis and tropopause folding can occur in the absence of three-dimensional curvature effects, commonly believed to be necessary for realistic upper-level frontogenesis. An implication of the dominant tilting effects is that they may have to be adequately resolved by numerical weather prediction models, thus requiring better horizontal and vertical resolution. (Keywords)

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Numerical Studies of Frontal Dynamics

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1. Introduction

This report consists of a brief review of research conducted during the three-year project, "Numerical Studies of Frontal Dynamics," performed at the Severe Storms Branch of the Laboratory for Atmospheres, NASA/Goddard Space Flight Center. The intent of this investigation has been to apply two-dimensional dynamical models of frontogenesis to isolate and identify frontal structures, frontogenetical processes, and associated ageostrophic circulations in a context that is more general than highly idealized analytical approaches, yet simpler than realistic situations involving the real atmosphere. An eventual goal of this approach is to contribute to a conceptual framework for qualitatively understanding and subjectively interpreting observational analyses and model predictions of frontal-scale phenomena. A more immediate goal of this research is to provide scientific perspective and background for the continued development and application of novel observing systems and numerical models for the mesoscale by defining and examining the structures and processes that these technologies are intended to resolve.

2. Summary of progress

The research effort has focused on the application of a two-dimensional frontal model to investigate upper-level and surface frontogenesis. The frontal model is original and novel in the respect that it combines the two-dimensional frontogenetical processes of confluence (horizontal contraction in cross-front direction) and horizontal shear (differential temperature advection in along-front direction) into a unified dynamical framework. These frontogenetical processes were treated independently in previous two-dimensional formulations of the frontogenesis problem.

a. Upper-level frontogenesis

Combining the frontogenetical processes of confluence and horizontal shear has led to the realistic simulation of upper-tropospheric frontogenesis bearing an impressive similarity to that documented observationally in baroclinic waves. The generalized dynamical treatment permits the simulation of a configuration of the vertical motion field that is conducive to frontogenesis through tilting effects in the prognostic equations for the vorticity and horizontal potential temperature gradient. Prior to this investigation, it was commonly held that a fully three-dimensional dynamical formulation would be required to simulate upper-level frontogenesis realistically. The results of this investigation are published in the companion papers by Keyser and Pecnick (1985a,b). The results of this investigation also are described in an invited review paper that appeared in the Monthly Weather Review on the structure and dynamics of upper-level frontal zones (Keyser and Shapiro, 1986), the preparation of which has been supported in part by AFOSR.

This line of work was extended collaboratively with Dr. M. A. Shapiro (NOAA/ERL/Wave Propagation Laboratory), resulting in the development and application of an analogy to Petterssen's well-known equation for two-dimensional frontogenesis in horizontal planes. The analogy consists of turning Petterssen's equation on its side to describe frontogenesis in the cross-front vertical plane. This approach brings out the kinematic importance of vertical deformation associated with the ageostrophic vertical circulation in the development of upper-level fronts. Preliminary results of this study, consisting of an application of the proposed analogy to Petterssen's equation to the results of the two-dimensional frontal model described above, were presented by M. J. Pecnick in poster form at the Second AMS Conference on Mesoscale Processes (June 1985). A paper based on this presentation (Keyser et al., 1986) has been published in the Journal of the Atmospheric Sciences.

A practical implication arising from the investigation of upper-level frontogenesis is that tilting effects may have to be adequately resolved by numerical weather prediction models in order to accurately predict the evolution of upper-level short-wave troughs, which are often involved in the triggering of cyclogenesis. Numerical models with coarse vertical resolution may underestimate tilting effects because vertical motions may be weaker than observed and the magnitude of the vertical wind shear may be too small. Sufficient horizontal resolution is required as well in order to adequately resolve horizontal gradients of the vertical motion. An example of a case in which tropopause folding and upper-level frontogenesis accompanied the amplification of a mid-tropospheric short wave is the Presidents' Day storm of 1979 (Uccellini et al., 1984, 1985), which was poorly handled by operational numerical weather prediction models. The link between upper-level frontogenesis and baroclinic wave amplification in advance of low-level cyclogenesis emphasizes the potentially significant role of upper-level frontogenesis in the dynamics of mid-latitude baroclinic waves.

The results of the investigation of upper-level frontogenesis also are important from a theoretical and conceptual point of view. They suggest that the frontogenetical aspects characteristic of three-dimensional baroclinic waves may be abstracted to a significant extent in a two-dimensional framework. Specifically, upper-level frontogenesis and tropopause folding are simulated in the absence of along-front variations in the along-front ageostrophic wind component associated with parcel trajectory curvature. This effect, which is a property of three-dimensional baroclinic wave structure, has been considered by Newton and Trevisan (1984a,b) to be a dominant mechanism in upper-level frontogenesis. Therefore, the findings of this investigation raise the question of the relative importance of the effect of the along-front variation of potential temperature, which can be treated two dimensionally, relative to the effect of curvature in forcing upper-level frontogenesis in three-dimensional baroclinic waves.

b. Surface frontogenesis

The two-dimensional frontal model has been applied to study surface frontogenesis and to contribute to establishing the dynamical differences between cold and warm fronts. Significant findings are that the frontal structures and accompanying vertical circulations are quite sensitive to the sense and magnitude of the along-front thermal advection constituting the horizontal shear forcing. For flow configurations believed to be characteristic respectively of cold and warm fronts, the realistic result emerges that the frontal band of ascending motion tends to be located on the warm-air side of the cold front and on the cold-air side of the warm front. Such a relationship is compatible with observations of cloud patterns relative to the positions of surface fronts.

A direct comparison of the structure of the model cold and warm fronts with their observational counterparts is difficult because of the relative scarcity of observational studies and the omission of diabatic and frictional processes from the model. Nevertheless, the correspondence with idealized three-dimensional baroclinic waves simulated in channel models [e.g., the results of Mudrick (1974) and Hoskins and Heckley (1981)] is encouraging. In particular, differential thermal advection in the along-front direction is frontogenetical in the cold front case and leads to a deep, well-defined frontal zone in the wind and temperature fields. Along-front thermal advection is frontolytical in the warm front case, however, leading to a relatively diffuse frontal zone except at and near the surface. At the surface, the steady-state intensity of the cold front exceeds that of the warm front, consistent with the respective frontogenetical and frontolytical contributions of the horizontal shear effect acting through the along-front thermal advection. These results lead us to believe that the model is capable of abstracting some of the essential dynamical processes found in more realistic three-dimensional situations, despite its simplicity. The outcome of this portion of the research was presented by D. Keyser in oral form at the Second AMS Conference on Mesoscale Processes.

Additional work on surface frontogenesis has consisted primarily of placing the descriptive findings sketched above onto a more quantitative footing. This aspect of the research involves the analysis of the kinematic equations for the evolution of the vorticity and cross-front potential temperature gradient defining the frontal zones and the analysis of the ageostrophic circulation diagnostics described in Keyser and Pecnick (1985b). A specific question that has been pursued is the rather surprising result that the model surface cold and warm fronts undergo a vacillation in intensity. Instead of attaining an approximate steady state, as is to be expected when frontolytical horizontal diffusion balances frontogenetical horizontal deformation, the fronts weaken before reaching a steady state. This issue is of current interest in light of the recent suggestion by Orlanski and Ross (1984) that such weakening of fronts should require the presence of unbalanced dynamical processes linked to inertia-gravity waves. Nevertheless, our findings suggest the importance of horizontal diffusion in frontolysis: the noted frontal weakening occurs as diminishing horizontal deformation is overcompensated by diffusion before a steady state is established. Although the possibility that unbalanced dynamical effects contribute to frontolysis has not been eliminated, horizontal diffusion appears to be playing the dominant frontolytical role. The major findings of the surface frontogenesis study are described in detail in a paper that is scheduled to appear in the Journal of the Atmospheric Sciences (Keyser and Pecnick, 1987).

3. Concluding remarks

In conclusion, the significance of this research effort lies in its potential implications for the conceptual understanding of dynamical mechanisms and processes occurring in both upper-level and surface frontal systems, as well as for mesoscale numerical weather prediction. The ultimate challenge is to extract hypotheses from the idealized two-dimensional work and to generalize the diagnostic methodologies developed in two dimensions to apply to three-dimensional situations involving real frontal systems. Such considerations are discussed further in the review article on upper-level fronts by Keyser and Shapiro (1986) and in the chapter dealing with the observational aspects of atmospheric fronts

(Keyser, 1987) to appear in Mesoscale Meteorology and Forecasting, edited by P. S. Ray. Finally, the great potential offered by regional-scale models incorporating real data for mesoscale research in general and frontal studies in particular is explored in the survey article by Keyser and Uccellini (1987), to appear in the Bulletin of the American Meteorological Society.

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