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Case Study Investigations of Large-Amplitude
Inertia-Gravity Wave Environments and Mesoscale Structures

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Name of the Principal Investigator:

Dr. Lance F. Bosart

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1. Background and context

The research effort supported by NASA Grant NAG5-7469, awarded to the University at Albany, State University of New York (UA/SUNY), comprises the following two projects: (i) the observational study of large-amplitude inertia-gravity wave environments over the continental United States; (ii) the definition of opportunities and issues in extratropical cyclone dynamics and related phenomenological studies that may be addressed using high-resolution global datasets produced by the Data Assimilation Office (DAO) at the NASA/Goddard Space Flight Center. The first project was completed by Eric G. Hoffman as part of his doctoral dissertation in the atmospheric science program at UA/SUNY, with Professors Lance F. Bosart (Grant PI) and Daniel Keyser serving as primary and secondary advisers, respectively. Dr. Hoffman was awarded the Ph.D. in spring 2000 and presently is an assistant professor of meteorology in the Natural Science Department of Plymouth State College (Plymouth, NH).

The second project reactivates and extends a research collaboration between Professor Keyser and Drs. Robert M. Atlas and Juan Carlos Jusem of the DAO that was undertaken between 1991 and 1995 on the question of the representation of fronts in global atmospheric models. This renewed collaboration has resulted in an accepted article in the *Bulletin of the American Meteorological Society* on the representation of extratropical baroclinic systems in the Goddard Earth Observing System (GEOS) General Circulation Model (GCM). A supporting objective of the second project was for Professor Keyser to visit the NASA/Goddard Space Flight Center regularly to participate in the synoptic evaluation effort in the DAO; the dates of the visits to the DAO are: 8 July 1999, 30 August 1999, 12 November 1999, 7 December 1999, 9 March 2000, 4 May 2000, 14 June 2000, 14 July 2000, 8 September 2000, 1 December 2000, and 25 May 2001. During these visits, Professor Keyser was engaged in the following activities: (i) advising Mr. Austin Conaty and Dr. Jusem on their research efforts involving extratropical cyclones and fronts; (ii) interacting with various DAO personnel through individual discussions on research topics suitable for investigation using global datasets produced by the DAO; and (iii) becoming familiar with the availability and characteristics of the global datasets produced by the DAO. In connection with these activities, on 27 February 2001, Professor Keyser delivered an invited presentation, entitled "Dynamics of extratropical weather systems," at the DAO-sponsored Global Tropospheric Wind Sounder Workshop (26–28 February 2001, Greenbelt, MD).

2. Summary of results

This section summarizes the outcomes of the respective research projects concerned with: (i) large-amplitude inertia-gravity wave environments, and (ii) extratropical cyclone dynamics and related phenomenological studies.

a. Large-amplitude inertia-gravity wave environments

The goal of this research is to investigate the three-dimensional structure and multiscale evolution of the environments associated with large-amplitude inertia-gravity waves (IGWs) through systematic analysis of composites and individual case studies. Composite soundings are calculated in order to investigate the vertical thermodynamic and wind profiles of IGW environments. The composite soundings show that the vertical thermodynamic structure is characterized by a low-level stable layer that extends from near the surface to between 850 and 700 hPa. A less stable layer extends from the top of the low-level stable layer to a relatively high thermodynamic tropopause located near 250 hPa. The lapse rate in this less stable upper layer is typically near moist neutral. The vertical wind structure is characterized by winds with an easterly component in the low-level stable layer that veer to southwesterly in the lower portion of the upper layer. Winds in the upper layer remain southwesterly and increase in magnitude to jet level near the thermodynamic tropopause. These thermodynamic and wind profiles are consistent with the idealized vertical structure necessary to support IGW wave maintenance identified by Lindzen and Tung.

The composite structure and evolution of the three-dimensional IGW environment is constructed using the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalyses. Results show that IGWs tend to occur: to the north and west of a surface low pressure center; poleward of a frontal boundary; and beneath the inflection point of a short-wavelength trough/ridge couplet. Two jet maxima typically are observed. The first is located in the southwesterly flow on the downstream side of the trough and is moving toward the downstream ridge, whereas the second is located in the northwesterly flow downstream of the ridge in a region of large-scale confluence. The trough/ridge couplet identified in the composite at the time of IGW occurrence evolves as a short-wave trough located ~1000 km upstream of the region of IGW occurrence amplifies and moves toward a quasi-stationary downstream ridge. This evolution results in the rapid contraction (especially in the 12-h period immediately prior to the time of IGW occurrence) of the downstream half wavelength of the trough/ridge couplet. The amplification and contraction of the upper-level flow pattern is accompanied by the amplification and scale contraction of the midtropospheric ascent maximum downstream of the trough, along with large horizontal divergence and large horizontal divergence tendencies in the upper troposphere. Additional signatures of the amplification and contraction of the upper-level flow pattern are the amplification of the pressure ridge (low height) on the dynamic tropopause (DT) and significant steepening of the DT on the downstream side.

A comparison of two case study analyses featuring a large-amplitude wake trough (28 April 1996) and a moderate-amplitude IGW (25 January 2000) shows that the mesoscale structure and environment of these two phenomena is similar. In each case, a region of low pressure and high winds at the surface moves with the back edge of an area of mesoscale precipitation. Wind profiles obtained from Doppler radar velocity azimuth displays and from NOAA 404 MHz profilers show that the region of low pressure and the erosion of the back edge of the precipitation band are associated with a descending rear-inflow jet. This descending rear-inflow jet is associated with midtropospheric downward motion, and adiabatic warming and drying. The adiabatic warming in the low-level stable layer, which is observed in both cases, induces pressure and wind signatures characteristic of a wake trough and an IGW at the surface.

Since IGWs can have a large effect on the surface pressure, wind, and precipitation patterns, it is suggested that forecasters might utilize the results summarized above to recognize and anticipate the typical three-dimensional structure and multiscale evolution of IGW environments. Furthermore, if the characteristic mesoscale features of an IGW or a wake trough are detected, forecasters may be able to issue reliable short-term alerts of IGW-related weather conditions. Finally, the results of this study point to two areas in which future research could shed light on the relationships between IGWs, wake troughs, and the environments in which they form: (i) additional case study evidence needs to be collected and synthesized to firmly establish the connection between the mesoscale structures of IGWs and wake troughs; (ii) idealized modeling studies that incorporate the range of vertical thermodynamic and wind profiles associated with the environments of IGWs and wake troughs need to be conducted in order to elucidate the governing dynamics of these respective phenomena.

b. Extratropical cyclone dynamics and related phenomenological studies

Increasing the horizontal resolution of the GEOS GCM has been a high priority in the DAO during the past several years; reducing the latitude–longitude grid spacing from $2° \times 2.5°$ to $1° \times 1°$ has resulted in substantial improvements in the representation of extratropical baroclinic systems. These systems include cyclones, fronts, jet streams, and the tropopause, the structure and evolution of which are evaluated subjectively from climatological and case-study perspectives. The former evaluation is conducted using climatological fields for the Northern Hemisphere winter season (December through February) derived from the GEOS-1 reanalysis for the 1981–94 period, along with the "Under/Middle/Overworld" conceptualization of the zonally averaged troposphere and stratosphere described by Hoskins, as benchmarks for comparison. Various large-scale circulation features related to the Pacific and Atlantic jet streams are reproduced realistically in the time-mean fields simulated by the GEOS GCM for a single three-month winter season.

The evaluation from a case-study perspective focuses on an extratropical cyclone that developed off the east coast of North America. The evolution of the low-level potential temperature field in this system is suggestive of the Norwegian cyclone model, featuring a meridional extensive cold front, a short warm front, and a narrowing warm sector. Analysis of the DT indicates that the cyclogenesis involves the interaction between a deep tropopause fold and the surface cyclone; three-dimensional visualization of the tropopause fold using Vis5D graphical display software shows this feature to be highly localized, exhibiting a vortical structure. The evolution of the potential temperature field on the DT features a cyclonic wrapup, reminiscent of the LC2 life cycle proposed by Thorncroft et al. The surface cyclone intensifies in the left-exit region of both the time-mean North Atlantic jet stream and an upper-level jet streak depicted in the instantaneous flow field. The cyclonic wrapup in the tropopause potential temperature field may be related to the cyclonically sheared environment of the left-exit region, whereas the evolution of the low-level potential temperature field in accord with the Norwegian cyclone model may be related to the diffluent character of the jet-exit region.

The foregoing evaluations indicate that high-resolution state-of-the-art GCMs are on the verge of resolving mesoscale phenomena and processes explicitly. As such, they offer the unprecedented opportunity to investigate the structure and dynamics of extratropical baroclinic systems from a multiscale perspective over intraseasonal timescales. When run in assimilation mode, GCMs possessing mesoscale resolution will be able to take advantage of the fine structure presently available in satellite data such as scatterometer winds. Specialized observations collected during intensive field programs also may be assimilated into GCMs, yielding unique high-resolution experimental datasets for analysis and diagnosis. Finally, high-resolution GCMs are well-suited to addressing issues related to climate change. As an example, it should be possible to simulate regional weather and climate anomalies with increasing certainty because of the improved resolution of individual weather systems in GCMs applied to various climate-change scenarios.

3. Publications

Hoffman, E. G., L. F. Bosart, and D. Keyser, 1999: Mesoscale structure and evolution of large-amplitude inertia-gravity waves: A case study. Preprints, *Eighth Conference on Mesoscale Processes,* Boulder, CO, Amer. Meteor. Soc., 101–102.

Hoffman, E. G., L. F. Bosart, and D. Keyser, 1999: Large-amplitude inertia-gravity wave environments: Large-scale structure and evolution. Preprints, *Seventeenth Conference on Weather Analysis and Forecasting,* Denver, CO, Amer. Meteor. Soc., 38–39.

Hoffman, E. G., 2000: Large-amplitude inertia-gravity wave environments: Three dimensional structure and multiscale evolution. Ph.D. dissertation, University at Albany, State University of New York, 246 pp.

Conaty, A. L., J. C. Jusem, L. Takacs, D. Keyser, and R. Atlas, 2001: The structure and evolution of extratropical cyclones, fronts, jet streams, and the tropopause in the GEOS general circulation model. *Bull Amer. Meteor. Soc.,* **82,** (in press).