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SYNOPTIC/PLANETARY-SCALE INTERACTIONS AND BLOCKING OVER THE NORTH ATLANTIC OCEAN

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I. Introduction

Our current understanding of atmosphere dynamics has been dictated to a large extent by the availability of upper air observations, sufficient to capture many features of synoptic and planetary scale flows yet hindered by data sparse regions of sufficient size to prevent satisfactory, routine sampling of the coupling of these two scales. Although the essential baroclinic and barotropic mechanisms which give rise to synoptic-scale extratropical wave features are rather well understood qualitatively, many nonlinear aspects of this development, including interactions with both mesoscale and planetary-scale phenomena, are less well-understood. This gap in our understanding is important because these interactions are intimately associated with departures from the quasigeostrophic flow model that is often used to describe the life cycle of a synoptic-scale wave. The recent First Global Atmospheric Research Program Global Experiment (FGGE) was designed to provide a better understanding of (and ultimately an increased capability to forecast) global and synoptic-scale dynamics. Accompanying this effort has been an intensified interest in the interrelationship of synoptic and planetary-scale processes, especially in regard to the maintenance of ultralong waves and events leading to blocking (a persistent low index, high amplitude flow configuration of regional or global extent). Recognizing the importance of non-quasigeostrophic processes in cyclone development (e.g., diabatic heating, strong horizontal gradients in static stability and ageostrophic motions), it is natural to question the influence of these features on larger scales of motion. Even when synoptic-scale motions are largely quasigeostrophic, the accompanying eddy transports of heat and momentum representing interactions with planetary-scale motions might not always be described adequately by this theory.

The work completed under this grant represents a continuing investigation of synoptic/planetary-scale interactions over the North Atlantic Ocean in late January, 1979. The focus of attention was a blocking episode that developed over southern Greenland on 21 January (see Tsou and Smith, 1990). However, the diagnosis also extended to antecedent cyclone activity and the role of moist processes during wave development. In all, the project was partitioned into two phases:

1. an extension of diagnoses that were already in progress of the 21 January blocking episode and its antecedent cyclone activity using satellite-enhanced level III-b NASA/Goddard Laboratory for Atmospheres (GLA) analyses; and
2. an analysis of the extent to which the results of Phase I are sensitive to the presence of satellite information.

In the ensuing discussions, referenced papers are restricted to grant publications listed in section III of this report.

II. Summary of results

A. Blocking anticyclone development

Continuing the work begun in the preceding NASA contract, this phase of the project focused on the non-quasigeostrophic forcing and energy transformations that accompanied the 21 January blocking anticyclone development. This work utilized as its primary diagnostic tools the quasigeostrophic and extended height tendency equations (Tsou and Smith, 1990) and several kinetic and potential energy content and transformation quantities (Tsou and Smith, 1990; Smith and Tsou, 1992). Computations in all of the work summarized in this report were done using GLA FGGE Special Observing Period I analyses on a 4° lat by 5° lon grid.

The height tendency diagnoses show that the quasigeostrophic (QG) calculations, which generally yielded height changes that were larger than the extended height tendency model, produced smaller height changes associated with the northward amplification of the ridge from which the block ultimately formed. Further, these smaller values were primarily due to the QG vorticity advection. This suggests that non-quasigeostrophic (NQG) vorticity advection, which usually acted to moderate the wave developments, enhanced the block development. In fact, it is suggested that QG forcing might not have been adequate to produce the observed block development. NQG processes were also significant in the static stability advection (adiabatic) term but were of little consequence in the differential thermal advection.

The energy diagnoses included eddy kinetic energy (KE), release of eddy potential energy (CE), generation of eddy kinetic energy (GK), and exchange between eddy and zonal kinetic energy (CK). In addition, these quantities were partitioned into synoptic-scale, planetary-scale and scale-interaction components. The energetics results indicate the NQG processes strengthened the intensity of the block and the precursor explosive cyclone and that a portion of this increase resulted from enhanced baroclinic conversion of eddy potential to eddy kinetic energy (CE and GK) and reduced barotropic energy conversion from eddy to zonal flow (CK). These transformations were dominated by the synoptic-scale component, in contrast to the authors' previously-reported height tendency results, which yielded significant contributions from both the synoptic and scale-interaction components. Thus, while changes in the mass field depended not only on the synoptic scale but also on the interactions between the synoptic and planetary scales, the corresponding changes in the eddy motion fields responded largely to synoptic-scale processes.

B. Antecedent cyclone development

In view of the importance of antecedent cyclone activity to the block development, studies were undertaken of a marine cyclone that immediately preceded the block development and a continental cyclone that occurred in conjunction with the block development. For both cases attention focused on the 24 hour explosive development period that both cases experienced. The diagnostic tools included the extended height tendency and Zwack-Okossi (Z-O) equations, as reported in the journal papers of Fosdick and Smith (1991), Uhl, et al. (1992), and Lupo, et al. (1992), and an isobaric form of the potential vorticity as reported in the conference preprint paper by Smith and Knabb (1991). Complementary results are also found in the B.S. Honors theses of Hunter (1991) and Stettner (1992). The Z-O equation, which diagnoses near-surface geostrophic vorticity tendencies, is an extension of a similar equation developed in quasigeostrophic form by Dr. Peter Zwack of the University of Quebec in Montreal that saw its first application to real data in this project. It should also be noted that the latent heat release fields were derived by combining parameterized values with satellite-derived precipitation estimates, the latter using an algorithm developed by Dr. Franklin Robertson of Marshall Space Flight Center (Fosdick and Smith, 1991).

The results demonstrate that cyclonic-vorticity advection was the most consistent contributor to the near-surface geostrophic vorticity increases (height decreases) found within and downstream from the cyclone centers. However, warm-air advection and latent heat release also contributed in varying degrees to the vorticity increases. For the more-rapidly deepening marine cyclone, the influences of vorticity and temperature advection dominated the cyclone development, while latent heat release played a significant but smaller role. For the land cyclone, vorticity increases forced by latent heat release were larger than either vorticity or temperature advection. The positive temperature advection contributions were dominated by warm-air advections in the upper troposphere, while latent heat release dominated in the lower-to-middle troposphere for both cyclones. The adiabatic-cooling term contributed negatively to the development of the cyclones and was of the same order as the individual positively contributing processes. Boundary-layer friction and sensible heating also contributed negatively to the development of the cyclone in general, but were at least one order of magnitude smaller than the other terms.

The results also show that the Z-O equation is an effective tool for diagnosing synoptic-scale surface cyclone development. Especially useful is the ability of the Z-O equation to explicitly account for the contribution of all layers of the atmosphere to surface development, thus confirming the importance of upper-air support during surface cyclogenesis. Results indicate that the upper-air support is particularly strong for the cases examined here in the upper troposphere and lower stratosphere, where both cyclonic-vorticity and warm-air advections maximized. Also, results confirm that explosive development is a result of the complementary forcing by both dynamic and thermodynamic processes. When one or more of the development mechanisms becomes sufficiently weak, the sum of these mechanisms is unable to overcome the inhibiting influence of adiabatic cooling and development ceases.

Finally, a comparison of isobaric representations of absolute vorticity (ABS) and potential vorticity (POV) fields relative to the continental cyclone reveals that in many ways the two vorticity fields exhibited similar relationships to the cyclone. As the cyclone developed, it propagated cyclonically around middle and upper tropospheric ABS and POV maxima, both of which were located upstream from the cyclone. This positioning yielded positive advections of both quantities above 500 mb which accompanied increases in ABS and POV at all levels. In contrast, both advections were negative below 700 mb. Thus, any contribution to development had to originate above 500 mb. The primary difference in the two vorticity parameters was in the magnitude of the low level vorticity increases. They were much greater for ABS and were accompanied by a very strong signature in the 900 and 700 mb ABS fields that was lacking in the POV fields, suggesting that the former is a better indicator of low level cyclone development than is the latter.

C. Sensitivity of analyses to satellite data

This work (Lamberty and Smith, 1993) included a statistical diagnosis of the differences between two GLA analysis representations of temperature and wind speed, one containing satellite data influences (SAT analyses) and one without (NOSAT analyses), over the North Atlantic Ocean during 17-21 January 1979, which includes the pre-blocking and block development periods. Results, obtained using area means and standard deviations of the two fields and correlation coefficients and root-mean-square differences between the two fields, indicate that the inclusion of satellite data can have significant impact on ocean-domain analyses. This is especially evident if one examines higher-order fields which represent gradients in the basic variable fields or contain covariances between two different variables (e.g., advections). More specifically, the inclusion of satellite data resulted in a cold (warm) temperature bias at low (high) levels and weaker temperature gradients, stronger winds, weaker vertical wind shears, and a warm air advection bias at most levels. The SAT analyses also exhibited larger standard deviations than the NOSAT for wind speed, relative vorticity, vorticity advection, temperature advection, and 500 mb height tendencies, suggesting that for this case the spatial variability of the circulation features were enhanced by the inclusion of satellite data. Even so, height tendencies forced by vorticity and temperature advection were less sensitive to the addition of satellite data than were the advection quantities themselves, suggesting that apparently the dynamics of the blocking system was less influenced by the presence of satellite data than was the structure of the system.

D. New initiatives

Timely completion of the work described above allowed us to begin two new efforts that will be completed under a new NASA grant that began July 1, 1992.

The first of these is a climatological analysis of blocking anticyclones and antecedent cyclones for the period 1985-88. Included in the statistics are longitudinal and seasonal distributions, lifetimes, the location and intensity of antecedent cyclones, and the presence of jet stream activity between the anticyclone and upstream cyclone. In all, 54 blocking cases have been found with lifetimes of five days or longer extending over a total of 463 days. Of these, 29 occurred during winter and spring over 253 days. The largest number (34) occurred in the Atlantic hemisphere (100W-80E) and all were preceded by a cyclone development 15-30° longitude upstream. At the same time, many cyclone developments occurred without subsequent block formation.

The second is a study of the evolution of a winter anticyclone over North America, initiated as a further test of the Z-O equation and to provide a diagnosis of a prominent continental anticyclone against which our oceanic cases can be compared. Results indicate that the forcing mechanisms responsible for the evolution of this case, although weaker and of opposite sign, are similar to those found to be consistently responsible for extratropical cyclone evolution. Development is largely accounted for by vertically-integrated anticyclonic vorticity and cold-air advection, while decay ensues when these processes weaken and are overwhelmed by adiabatic warming in the descending air.

III. Publications and presentations

A. Refereed publications

1. Tsou, C.-H., and P.J. Smith, 1990: The importance of non-quasigeostrophic forcing during the development of a blocking anticyclone. Tellus, 42A, 328-342.
2. Fosdick, E.K., and P.J. Smith, 1991: Latent heat release in an extratropical cyclone that developed explosively over the southeastern United States. Monthly Weather Review, 119, 193-207.
3. Smith, P.J., and C.-H. Tsou, 1992: Energy transformations associated with the synoptic and planetary scales during the evolution of a blocking anticyclone and an upstream explosively-developing cyclone. Tellus, 44A, 252-260.
4. Uhl, M.A., P.J. Smith, A.R. Lupo, and P. Zwack, 1992: The diagnosis of a pre-blocking explosively-developing extratropical cyclone system. Tellus, 44A, 236-251.
5. Lupo, A.R., P.J. Smith, and P. Zwack, 1992: A diagnosis of the explosive development of two extratropical cyclones. Monthly Weather Review, 120, 1490-1523.

6. Lamberty, G.L., and P.J. Smith, 1993: A study of the influence of satellite data on GLA analyses over the Atlantic Ocean during a period of blocking anticyclone development. Monthly Weather Review, 121, in press.

B. Non-refereed papers

1. Fosdick, E.K., and P.J. Smith: Latent heating associated with a rapidly developing cyclone over the north Atlantic Ocean. Preprint volume of the 12th Conference on Weather Analysis and Forecasting, October 2-6, 1989, Monterey, CA, 282-286.

2. Smith, P.J., A.R. Lupo, and P. Zwack: Diagnosing development, part II: A study of rapid cyclone development using analyzed data fields. Preprint volume of the First International Symposium on Winter Storms, January 14-18, 1991, New Orleans, LA, 220-225.

3. Smith, P.J., and R.D. Knabb: A diagnosis of vorticity fields associated with an explosively-developing winter cyclone over the southeastern United States. Preprint volume of the First International Symposium on Winter Storms, January 14-18, 1991, New Orleans, LA, 340-344.

4. Lupo, A.R., and P.J. Smith: A comparison of synoptic-scale development characteristics for over-water and over-land cases of explosive cyclone development. Preprint volume of the Symposium on Weather Forecasting, January 5-10, 1992, Atlanta, GA, 72-79.

C. Theses

1. **M.S.**

   a. Fosdick, E.K.: The Role of Latent Heating in the Explosive Development of Two Extratropical Cyclones. August 1989.

   b. Uhl, M.A.: Synoptic-scale Forcing of Two Explosively Developing Cyclones. May 1990.

   c. Lupo, A.R.: A Diagnosis of the Explosive Development of Two Extratropical Cyclones. May 1991.

   d. Lamberty, G.L.: A Study of the Influence of Satellite Data on Goddard Laboratory for Atmospheres' Analyses. December 1991.

2. B.S. Honors

   a. Knabb, R.D.: The Role of Vorticity in an Explosively Deepening Extratropical Cyclone. May 1990.

   b. Hunter, M.L.: A Study of an Intense Upper Air Cyclone Development. May 1991.

   c. Stettner, D.R.: Characteristics of Temperature and Vorticity Advection During Extratropical Cyclone Development. May 1992.

D. Presentations[1]

1. Smith, P.J., and C.-H. Tsou: The Importance of Non-Quasigeostrophic Forcing During the Development of a Blocking Anticyclones. Fifth Scientific Assembly of IAMAP, July 31 - August 12, 1989, Reading, UK.

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1. These are in addition to presentations made for which preprint papers were published (see section III.B).

2. Smith, P.J., and M.A. Uhl: A Diagnosis of a Rapidly Developing Winter Cyclone Over the North Atlantic Ocean. Fifth Scientific Assembly of IAMAP, July 31 - August 12, 1989, Reading, UK.

3. Smith, P.J.: Diagnoses of Explosively Developing Extratropical Cyclones. Invited seminar, Department of Physics, University of Quebec at Montreal, December 3, 1990.

4. Smith, P.J.: Diagnosis of a Winter Anticyclone Development. Invited seminar, Department of Atmospheric Sciences, University of Illinois, November 11, 1992.

5. Smith, P.J.: Synoptic/Planetary-scale Interactions and Blocking Over the North Atlantic Ocean, NASA/MSFC Global Scale Atmospheric Processes Research Program Review, June 27, 1989; August 20-21, 1990; May 28-30, 1991; July 7-9, 1992.

IV. Awards

1. R.D. Knabb's undergraduate honors thesis was awarded first place in the 1991 American Meteorological Society Macelwane competition for outstanding original student paper concerned with some phase of the atmospheric sciences.

2. D.R. Stettner's undergraduate honors thesis was awarded third place in the 1993 American Meteorological Society Macelwane competition.