CORRELATION OF CYCLONE CENTRAL PRESSURE TENDENCY AND UPPER-LEVEL PROCESSES

Robert P. Harnack and Johnnie Woo

Department of Environmental Sciences
Cook College – New Jersey Agricultural Experiment Station
Rutgers – The State University of New Jersey
New Brunswick, New Jersey

Abstract

This study attempts to advance our understanding of the important upper-air processes for cyclogenesis by quantifying the relationship between upper-level variables and central pressure tendency, with the focus on sample statistics for land-based cyclones. Simple and multiple correlation coefficients were calculated between upper-level variables and both 3-hour and 6-hour central pressure tendencies. There were 295 eastern U.S. cyclones (November-April 1991-1994) in the sample, 53 percent of which had rising pressure tendency. Statistically significant correlations (largest values less than .45) were found for the overall sample and for the stratification of the sample based on cyclone strength. The strength of the correlations was about the same in the overall and weak samples, but was generally higher for stronger cyclones. The upper-level variables having the highest correlations with central pressure change varied considerably with pre-existing cyclone strength. However, the single variable that showed the highest correlation was temperature advection at 200 or 300 mb, regardless of cyclone strength. The most important two variable combined influence, for the overall cyclone sample, was upper-level temperature advection and mid-level geostrophic vorticity advection (multiple correlation of .35).

1. Introduction

The ability to forecast cyclone pressure tendency is a matter of interest to weather forecasters. Changes in the central pressure of cyclones often indicate changes in the intensity of associated weather, including precipitation, wind, and day-to-day temperature variations. The mixture of contributions by dynamic and physical processes for cyclogenesis is still unclear. The motivation for this study is to diagnose which upper-level processes are most important in causing changes in central pressure over a short time interval (3-6 hours). The results could show to what extent conventional synoptic reasoning and findings from previous case studies are valid in aggregate for a large sample of cyclones. It can also be noted that large-sample studies for land events are rare, since most studies focus on individual land "bomb" cyclone events or oceanic cyclone events. In addition, the strength of the relationships between cyclone deepening and the processes involved need to be quantified.

A theoretical formulation such as the Zwack-Okossi equation (Zwack and Okossi 1986) suggests which processes cause surface pressure change. The Zwack-Okossi equation relates near-surface geostrophic vorticity tendency to horizontal absolute vorticity advection, horizontal temperature advection, diabatic effects, adiabatic effects, divergence, vertical absolute vorticity advection, and frictional effects.

In this study, the focus will be on changes in surface pressure for a sample of mid-latitude cyclones given the state of the atmosphere aloft, directly over the cyclone center. Boundary layer, orographic, frictional, and diabatic effects such as sensible, latent, and radiational heating are not explicitly considered here.

Previous studies on cyclogenesis are either continental or oceanic and for either individual or multiple cases. The multiple cases involve an aggregate sample of cyclones used to calculate statistical relationships and to draw general conclusions. Findings relating to the dynamics or mechanisms responsible for cyclogenesis and/or subsequent intensification are presented. Far more research has been conducted for individual and oceanic cyclones, with strongly intensifying or "bomb" cyclones receiving the greatest attention. Such situations are characterized by 12-hour measured central pressure falls of at least 12 mb, or an average decrease in pressure of 1 mb per hour.

Many case studies have been done to assess processes that cause cyclones to intensify. Studies from the 1940s up to the present have produced a fairly wide variety of findings. Some of the processes or variables suggested as important contributors to cyclone intensification include: potential vorticity anomalies at the tropopause (Davis and Emanuel 1991; Reed et al. 1992; Zehnder and Keyser 1991), positive geostrophic vorticity and vorticity advection (Gyakum et al. 1992; Sanders 1986), thermal effects such as diabatic heating and positive thermal advection, (Krishnamurti 1968; Lupo et al. 1992; Panofsky 1944), upper-level diffluence (Sanders 1993), surface convergence (Bjerknes 1940; Byers 1940; Wash et al. 1992), and frontogenic forcing (Ruscher and Condo 1996; Hines and Mechoso 1991). Lupo et al. (1992) found that positive horizontal temperature advection and latent heat processes due to precipitation, might have positive or negative effects on cyclone intensity, depending on the maturity stage of the cyclone. Businger (1995) found that baroclinic instability, which is dependent on the existence of a meridional temperature gradient, influences atmospheric stability through surface heat fluxes and vorticity advection aloft. He concluded that the larger the gradient and higher the moisture levels, the greater chance for development.

Of particular relevance to the current study are those previous studies using a sample of cyclone events. Rolfson and Smith (1996) conducted a study on twelve cyclone cases occurring over the continental United States during the cool season months (late fall to early spring) in the period 1990-1994. Their study is the only one found involving a sample of land cyclones during the cool season. Their findings indicated that positive cyclonic vorticity advection, which is generally a maximum in the upper troposphere, was the primary contributor to maintaining or increasing cyclone intensity, as was latent heat release, regardless of the stage of development. Rolfson and Smith also found that horizontal temperature advection was significant only during the more intense stages. During the weakening stages and in early development stages, they noted that temperature advection opposed development as warm-air advection aloft was usually compensated by cold air advection in the lower half of the troposphere. They stated that cyclone development cannot occur until lower-tropospheric cold air advection decreases in magnitude, and is coupled with positive integrated cyclonic vorticity advection, latent heat release, and a secondary warm air advection maximum in the lower troposphere.

During the First Global Atmospheric Research Project (GARP) Experiment, a sample of 23 cyclone cases from the North Atlantic and the western North Pacific was gathered by Elsberry and Kirchoffer (1988) to study the upper tropospheric and lower stratospheric processes using operational maps and analyses. They concluded that the most important mechanisms to consider in forecasting cyclone development were the position of the relative vorticity maximum at 300 mb upstream of the cyclones, the location of a potential vorticity lobe, and the location of a jet maximum near the storm. In a study of explosive cyclogenesis over the West-Central North Atlantic Ocean in the period from 1981-1984, Sanders (1986) gathered 500 mb absolute vorticity maxima data, storm tracks, and central values of surface low pressure centers, for 48 cyclones. He performed a regression analysis on the sample data and found that explosive marine cyclones depend heavily on upper-level forcing mechanisms to produce low-level responses. Sanders also noted that positive upper-level vorticity advection over a surface cyclone correlated well with surface pressure falls.

Gyakum et al. (1992) conducted a large-scale study for weakly- and strongly- developing cyclones over the North Pacific and North Atlantic Basins for nine cold seasons (Oct 1 - March 31) beginning in 1975. He found that low-level vorticity growth is an important conditioning process for cyclone development. In the case of two similar pre-existing surface disturbances, the system with initial low-level vorticity growth within a six-hour period tends to intensify more strongly in the development stage than a surface low that develops in an area without significant low-level vorticity.

In a related study conducted during ERICA by Sanders (1993), for the period December 1988 to February 1989, the deepening of surface cyclones was related to the diffluence of upper-level height contours at 700 mb. The author found that storms tended to fill if these contours converged. In contrast, Sanders theorized that diffluent upper-air troughs might enhance cyclone development because diffluence enhances upper-level mass divergence. The author calculated some statistics relating the initial wave formation to the flow field aloft. Values were also computed for comparisons of development to the flow field on both the synoptic and large scales. Sanders' results indicated that initial wave formation occurred in 20% of the cases with confluence aloft, and deepening was rare. In 73% of the cases, deepening was found under diffluent conditions ahead of upper troughs. On the synoptic scale, no high correlation was found between the pattern of upper-level height contours directly over the cyclone center and surface development. 69% of the time (65 of 94 cases), development occurred with initial diffluence aloft. However, Sanders is quick to point out that most lows in general, did deepen, even under confluent flow. Nondeepening cyclones were also found under diffluent flow.

Wash et al. (1992) gathered sea level pressure analyses during GARP. Cyclones were then separated into three separate groups: explosive cases (central pressure falls of at least 12 mb/12 hours), very weak (deepening rates of less than 5 mb/12 hours), and non-explosive (pressure falls between 5 and 12 mb/12 hours). The authors found that low-level vorticity advection (1000-850 mb), upper-level divergence (300 mb), and kinematic vertical velocity (700 mb) were the most important in distinguishing between explosive and non-explosive cyclogenesis. They also mentioned factors that may have played a role, including dry static stability, low-level relative vorticity (1000-850 mb), and the strength of low-level baroclinicity (1000-500 mb).

Land cyclones have not been a major focus of study. A few significant land cyclones have been scrutinized, but in general weaker cyclones have been neglected. This study will attempt to further advance our understanding of the important processes by quantifying the statistical relationship between upper-level variables and surface pressure tendency, with the focus on sample statistics for land-based cyclones.

2. Methodology

a. Data collection

The domain chosen for defining eligible cyclone events extends from 100 degrees west longitude eastward to the Atlantic coast and from the Gulf coast states northward into southeastern Canada (Fig. 1). This region is well suited for the study because of the good radiosonde observation (RAOB) data availability. Also, major orographic effects are avoided.

The data for the cyclones in the study is from 3-hourly sea-level pressure analyses as obtained on microfilm from the NOAA/National Climatic Data Center (NCDC).

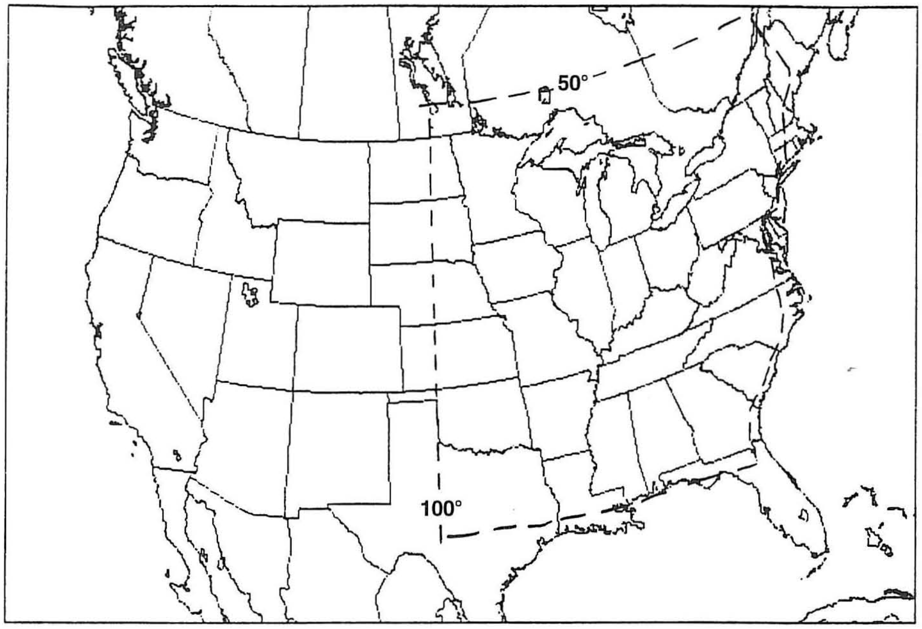

Fig. 1. Spatial domain for study area.

Each reel consists of two months of surface weather maps. Nine reels of data were analyzed for the months of November, December, January, February, March, and April for the winters of '91-'92 through '93-'94. This data set yielded 295 cases, which is a large enough sample to minimize any errors introduced into the statistical analysis due to random observational, analysis, or data extraction deficiencies.

A cyclone case for the present study is required to have the following characteristics:

1) It appears as a NOAA/National Weather Service/National Meteorological Center (now the National Centers for Environmental Prediction) analyzed low-pressure area that falls in the analysis domain as defined above.

2) The low-pressure center has been in existence for at least three hours prior to and three hours after RAOB time (i.e., 21 UTC to 03 UTC or 09 UTC to 15 UTC). Pressure minima that are not present in the domain during the entire 6-hour interval centered at RAOB time are ignored.

The same time intervals are used to measure central pressure changes. The 3-hour central pressure change is defined as the pressure change at the cyclone center from RAOB time to three hours *after* (e.g., 00 UTC to 03 UTC). The six-hour pressure change measures the change in central pressure from 3 hours *before* RAOB time to 3 hours *after* RAOB time. The time at which the storm is present in the analysis domain is recorded, along with the central pressure tendencies at 3-hour intervals for the duration of the storm, the number of closed isobars (from a 4 mb interval pressure analysis) at each observation time, and the position of the storm center in degrees latitude and longitude.

The data sample is stratified based on cyclone strength. The number of closed isobars is used to characterize the strength of each cyclone. Strong (4 or more closed isobars), moderate (2-3), or weak (0-1) are the three designated strength categories. There are a total of 150 (51%) weak cyclones, 101 (34%) moderate cyclones, and 44 (15%) strong cyclones in the sample. The upper-air data for the cyclone cases is extracted from NOAA North American Radiosonde Data Base CD-ROMs (Schwartz and Govett 1992). The files contain raw upper-air data from the radiosonde network for each of the cyclone cases at the specified radiosonde observation (RAOB) date and time.

b. Data analysis

1) Calculation of upper-air variables

To quantify the relationships between upper-air variables and surface pressure change, the numerical values of the variables are evaluated at the cyclone center. The variables that are of particular interest are the temperature advection, vorticity advection, and divergence at various levels of the atmosphere because they have often been cited as useful indicators for cyclone development. Conventional synoptic theory also indicates that processes that relate to rising/sinking motion in the atmosphere contribute to changes in pressure. The Upper-Air Diagnostics program, originally developed by Foster (1988), is the chosen tool for computing the values of upper-air variables for each of the cyclone cases. An enhanced version of the program (Enhanced UA) was developed for this study, which contains a larger group of analyzed and derived upper-air variables.

There is a wide range of variables analyzed, including temperature, wind, moisture, and heights at the mandatory levels; also temperature advection, vorticity advection, moisture advection, and divergence, all of which theoretically contribute to or are associated with changes in surface pressure. See Table 1 for a complete listing of variables. Moisture indicators and moisture calculations above 300 mb are omitted because they tend to be inaccurate or unavailable.

Given the latitude and longitude of the cyclone center, the Enhanced-UA program quantifies the upper-air indicators associated with the storm at a particular time and location by using the Barnes Two-Pass method. In the first pass, the program takes all available sounding data within a 2,286 km radius of the specified center point and uses an inverse distance-weighted interpolation scheme to assign values to each of the grid points. The entire grid is 19 x 15 points, with grid points being about 190 km apart. The program uses this information to assign a "first-guess" value to the center point. In the second pass, the program uses a weighted difference between observed values and the assigned grid point value to calculate a "correction" value. It adjusts the center point value based on this correction.

TABLE 1. Description of variables calculated for each case, including level (in mb) and type.

Temperature (C):	850,700,500,400,300,250,200,150 mb
Dewpoint (C):	850,700,500,400,300 mb
Height (dam):	850,700,500,400,300,250,200,150 mb
Mixing Ratio (g kg^{-1}):	850,700,500,400,300 mb
Wind Speed (kt):	850,700,500,400,300,250,200,150 mb
Theta-E (K):	850,700,500,400,300 mb
Divergence (10^{-5} s^{-1}):	850,700,500,400,300,250,200,150 mb
Vorticity (10^{-4} s^{-1}):	850,700,500,400,300,250,200,150 mb
Temperature Advection (C 12 hr^{-1}):	850,700,500,400,300,250,200,150 mb
Theta-E Advection (C 12 hr^{-1}):	850,700,500,400,300 mb
Moisture Convergence (g kg^{-1} hr^{-1} x 10):	850,700,500,400 mb
Moisture Advection (g kg^{-1} hr^{-1} x 10):	850,700,500,400 mb
Geostrophic Absolute Vorticity (10^{-4} s^{-1}):	850,700,500,400,300,250,200,150 mb
Mean Temperature (K):	700-300, 850-500 mb
Geostrophic Vorticity Advection (10^{-4} s^{-2}):	850, 700, 500, 300 mb
Divergence of Q-vectors (10^{-17} s^{-3} mb^{-1}):	700, 500 mb

TABLE 2. Simple correlation values (3-hour sea-level pressure change) significant at the 5% level using a standard F-test. Results are divided into four cyclone samples: a. ALL, b. WEAK, c. MODERATE, and d. STRONG.

a. ALL (295 cases)	
300-150 mb temperature advection	-0.28 to -0.19
500 mb geost. vorticity advection	-0.19
700 mb div. of Q-vectors	0.16
700 mb moisture convergence	-0.16
300 mb geos. vorticity advection	-0.15
850 mb heights	0.15
400 mb wind speed	-0.15
250 mb divergence	-0.13
700 mb geost. vorticity advection	-0.13
300 mb vorticity	0.13
b. WEAK (150 cases)	
200 mb temperature advection	-0.23
700 mb div. of Q-vectors	0.22
850 mb theta-e advection	-0.19
500 mb geost. vorticity advection	-0.18
850 mb temperature advection	-0.18
150 mb temperature advection	-0.18
c. MODERATE (101 cases)	
300 mb temperature advection	-0.32
400 mb wind speed	-0.32
700-200 mb vorticity	0.22 to 0.32
500 mb wind speed	-0.26
200 mb temperature	0.26
400 mb mixing ratio	-0.24
700 mb moisture convergence	-0.23
700 mb theta-e advection	-0.23
700 mb temperature advection	-0.22
300 mb wind speed	-0.22
d. STRONG (44 cases)	
200 mb temperature advection	-0.45
250 mb temperature advection	-0.44
850-500 mb geost. vorticity advection	-0.35 to -0.40
700 mb moisture convergence	-0.32

TABLE 3. Simple correlation values (6-hour sea-level pressure change) significant at the 5% level using a standard F-test. Results are divided into four cyclone samples: a. ALL, b. WEAK, c. MODERATE, and d. STRONG.

a. ALL (295 cases)	
300-150 mb temperature advection	-0.29 to -0.21
250 mb divergence	-0.21
850 mb height	0.20
200 mb divergence	-0.20
300 mb geost. vorticity advection	-0.18
500 mb geost. vorticity advection	-0.18
300 mb divergence	-0.16
700 mb heights	0.16
500 mb temperature advection	0.14
250 mb wind speed	-0.13
b. WEAK (150 cases)	
500 mb geost. vorticity advection	-0.26
150, 250 mb temperature advection	-0.20
500 mb temperature advection	0.19
400 mb divergence	-0.19
200 mb temperature advection	-0.18
400 mb moisture convergence	0.18
500 mb theta-e advection	0.17
850 mb heights	0.17
700 mb temperature advection	0.13
c. MODERATE (101 cases)	
700-200 mb vorticity	0.31 to 0.44
400 mb goes. potential vorticity	0.38
300 mb temperature advection	-0.38
400 mb mixing ratio	-0.34
200 mb temperature	0.32
400 mb wind speed	-0.30
400 mb dewpoint	-0.29
250 mb temperature advection	-0.28
250 mb wind speed	-0.27
250 mb divergence	-0.26
d. STRONG (44 cases)	
250, 200 mb temperature advection	-0.40 to -0.42
300, 700, 850 mb goest. vorticity advection	-0.32 to -0.36
850 mb vorticity	-0.30

TABLE 4. Magnitude of multiple correlation coefficients significant at the 5% level for 2 and 3 variables using 3-hour sea-level pressure change. Results are divided into four cyclone samples: a. ALL, b. WEAK, c. MODERATE, and d. STRONG.

a. ALL (295 cases)	
200 mb temp. adv. and 500 mb geost. vort. adv.	0.35
200 mb temp. adv. and 300 mb temp. adv.	0.34
200 mb temp. adv. and 700 mb theta-e advection	0.33
200 mb temp. adv. and 300 mb vort. adv.	0.31
200 mb temp. adv. and 700 mb. Div. of Q-vectors	0.31
200 and 300 mb temp. adv, 700 mb theta-e adv.	0.38
500 mb geost. vort. adv., 700 mb theta-e adv., and 200 mb temp. adv.	0.38
500 mb geost. vort. adv., 200 and 300 mb temp. adv.	0.37
700 mb div. of Q-vectors, 200 mb temp. adv., & 500 mb geost. vort. adv.	0.37
300 mb vorticity, 500 mb geost. Vort. adv., 200 mb temp. adv.	0.37
b. WEAK (150 cases)	
200 mb temp. adv and 700 mb divergence of Q-vectors	0.32
200 and 850 mb temp. adv.	0.3
700 mb div. of Q-vectors and 850 mb temp. adv.	0.25
200 and 850 mb temp. adv., and 700 mb div. of Q-vectors	0.35
c. MODERATE (101 cases)	
850 mb wind speed and geost. abs. vort.	0.11
850 mb geost. abs. vort. and 700 mb vort.	0.1
850 mb geost. abs. vort. and 400 mb wind speed	0.1
850 mb wind speed and 700 mb vort.	0.05
400 mb and 850 mb wind speed	0.04
700 mb vort., 850 mb wind speed and geost. abs. vort.	0.11
400 and 850 mb wind speed, and 850 mb geost. abs. vort.	0.11
400 mb wind speed, 700 mb vorticity, and 850 mb geost. abs. vort.	0.1
850 and 400 mb wind speed, and 700 mb vort.	0.05
d. STRONG (44 cases)	
850 mb. geost. vort. adv. and 250 mb temp. adv.	0.55
250 mb temp. adv. and 1000-850 mb thickness	0.51
300 mb temp. and 250 mb temp. adv.	0.49
700 mb moist. adv. and 250 mb temp. adv.	0.47
250 mb temp. adv. and 300 mb vort.	0.46
850 mb geost. vort. adv., 300 mb temp., and 250 mb temp. adv.	0.6
250 mb temp. adv, 1000-850 mb thickness, and 850 mb geo. vort. adv.	0.6
700 mb moist. adv., 850 mb geost. vort. adv., and 250 mb temp. adv.	0.6
300 mb vort., 250 mb temp. adv., and 850 mb geost. vort. adv.	0.59
1000-850 mb thickness, 700 mb moist. adv., and 250 mb temp. adv.	0.57

2) Correlation analyses

The primary objective of this study is to quantify the strength of the relationships between upper-level variables and surface pressure tendency to diagnose which processes or indicators are related to pressure change. Simple and multiple correlation coefficients are used. Statistical significance of the obtained correlation coefficients was determined using the basic F-test as described in Panofsky and Brier (1958). The objective is to determine some meaningful associations that can be readily applied in the educational and operational environment.

3. Results

Of the 295 cases in the dependent sample, 155 cases exhibited rising pressure (53%), 74 showed no change in pressure (25%), and 66 demonstrated pressure falls (22%) in the 3 hours following RAOB time. A little more than half of the sample consists of cyclones that were filling, so the distribution of pressure tendency is biased toward rising pressure.

a. Simple correlation coefficients for the overall sample

Tables 2 and 3 show the statistically significant correlation coefficients (using 5 and 1 percent significance levels) between upper-level variables and three- or six-hour surface pressure tendency for the overall (295 cases) sample. Since there is no major difference in the strengths of the correlations between the variables and 3-hour and 6-hour pressure tendency, the discussion will focus on the 3-hour pressure tendency correlations. Upper-level positive temperature advection (150, 200, 250, 300 mb) shows the highest correlations (-0.19, -0.28, -0.23, and -0.23, respectively) with 3-hour pressure tendency. The negative correlations imply that warm advection in the upper atmosphere is associated with falling surface pressure. The height at 850 mb is positively correlated (0.15) with pressure change. 700 mb divergence of Q-vectors is also positively correlated (0.16) to pressure tendency in a weak manner, so divergence of Q-vectors is indicative of rising pressure and convergence of Q-vectors with falling pressure. Note that from quasi-geostrophic theory, convergence (divergence) of Q-vectors is associated with rising (sinking) tropospheric motion. Geostrophic vorticity advection at the 500 and 300 mb levels is also found to have a significant negative correlation (-0.19 and -0.15) with pressure change. The relationship between vorticity advection and pressure change agrees with conventional synoptic reasoning because one would expect a negative correlation (i.e., positive vorticity advection associated with falling pressure). Moisture convergence at 700 mb and 400 mb wind speed are negatively correlated with pressure tendency (-0.16 and –0.15). 250 mb divergence exhibited a negative correlation (-0.13) which means that divergence at 250 mb has a slight tendency to be associated with falling pressure.

b. Simple correlations for cyclone strength sub-samples

The data are stratified based on the number of closed isobars to determine if different variables are correlated with pressure fall based on an indication of cyclone strength. Such stratification also shows if the size of the correlation coefficients changes with cyclone strength (see Tables 2 and 3). The overall sample is divided into three categories: weak cyclones (0-1 closed isobars), moderate (2-3 closed isobars), and strong (≥ 4 closed isobars). In weak cyclones, temperature advection at 150, 200, and 850 mb is among the variables most correlated to pressure fall (-0.18, -0.23, and –0.18, respectively). However, vorticity at 850 and 300 mb is the

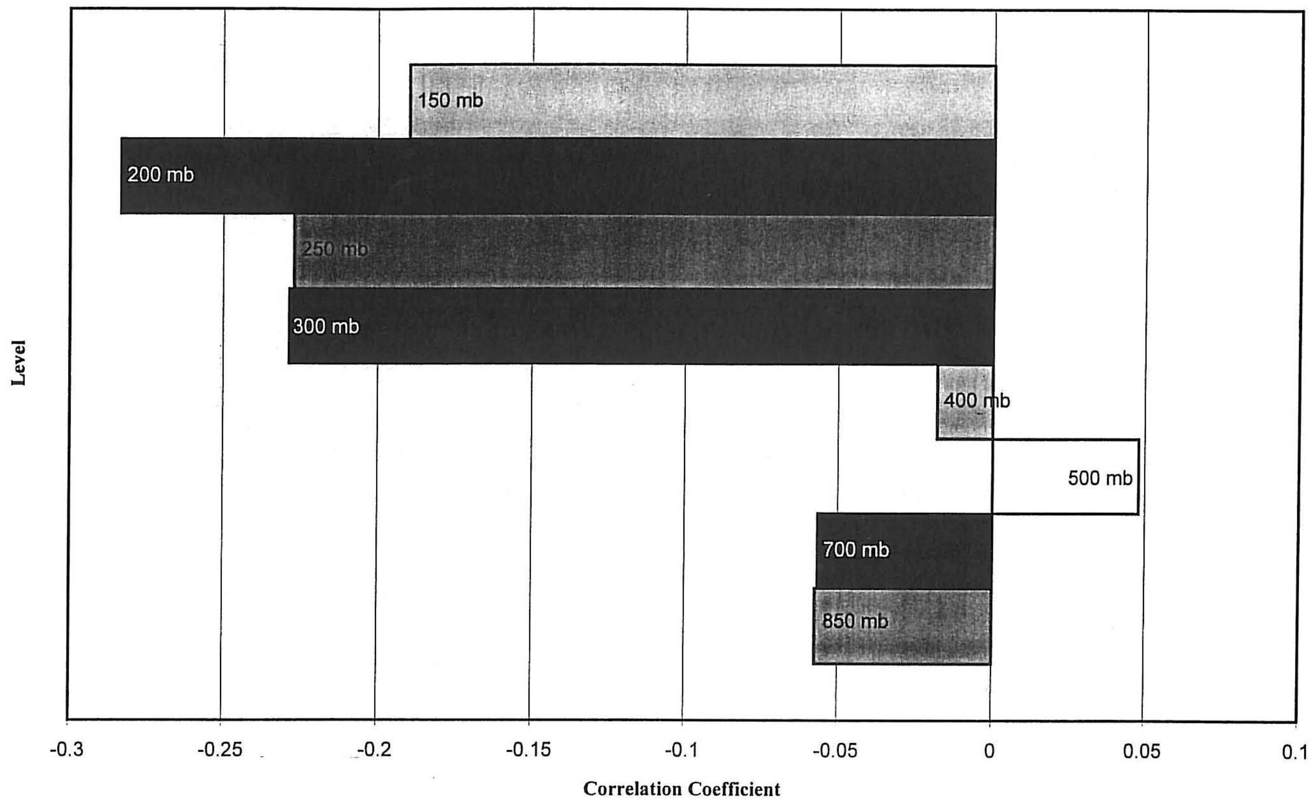

Fig. 2. Correlation coefficients by level for horizontal temperature advection vs. 3-hour sea-level pressure change.

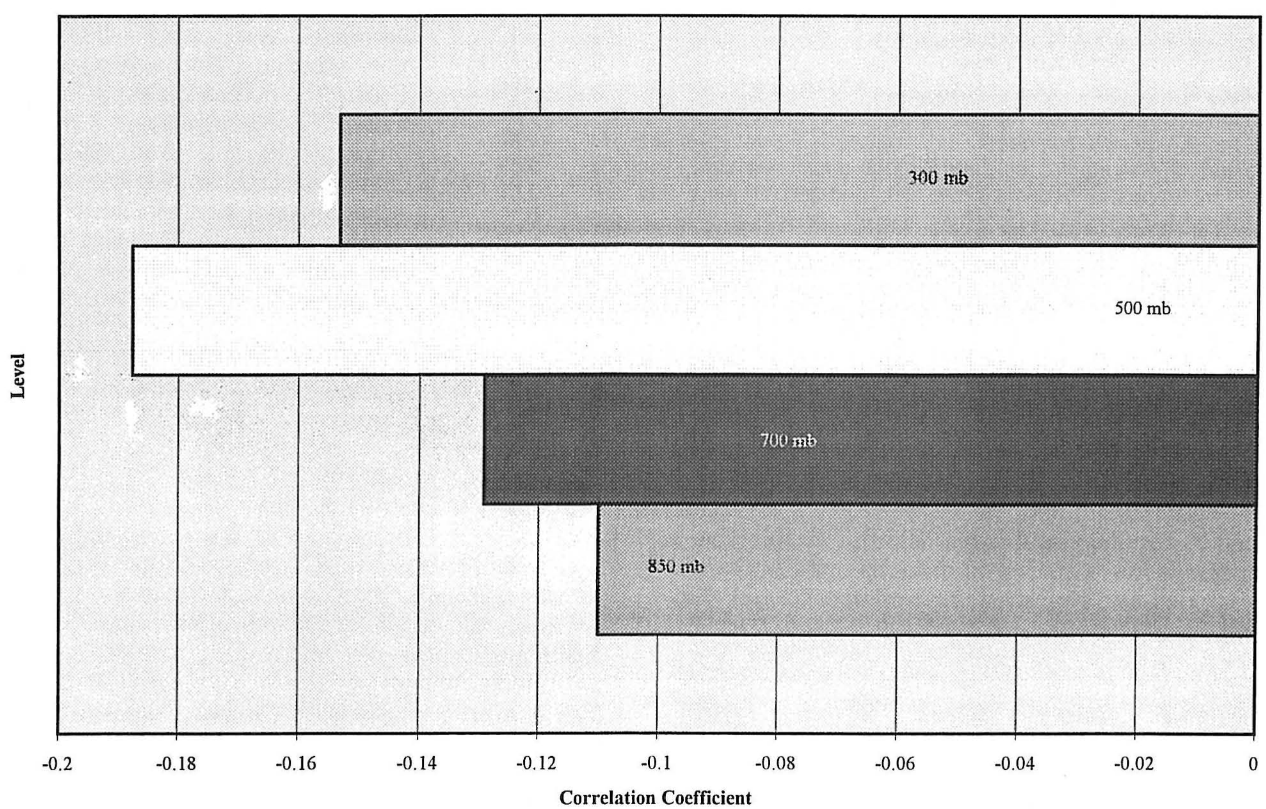

Fig. 3. Correlation coefficients by level for horizontal vorticity advection vs. 3-hour sea-level pressure change.

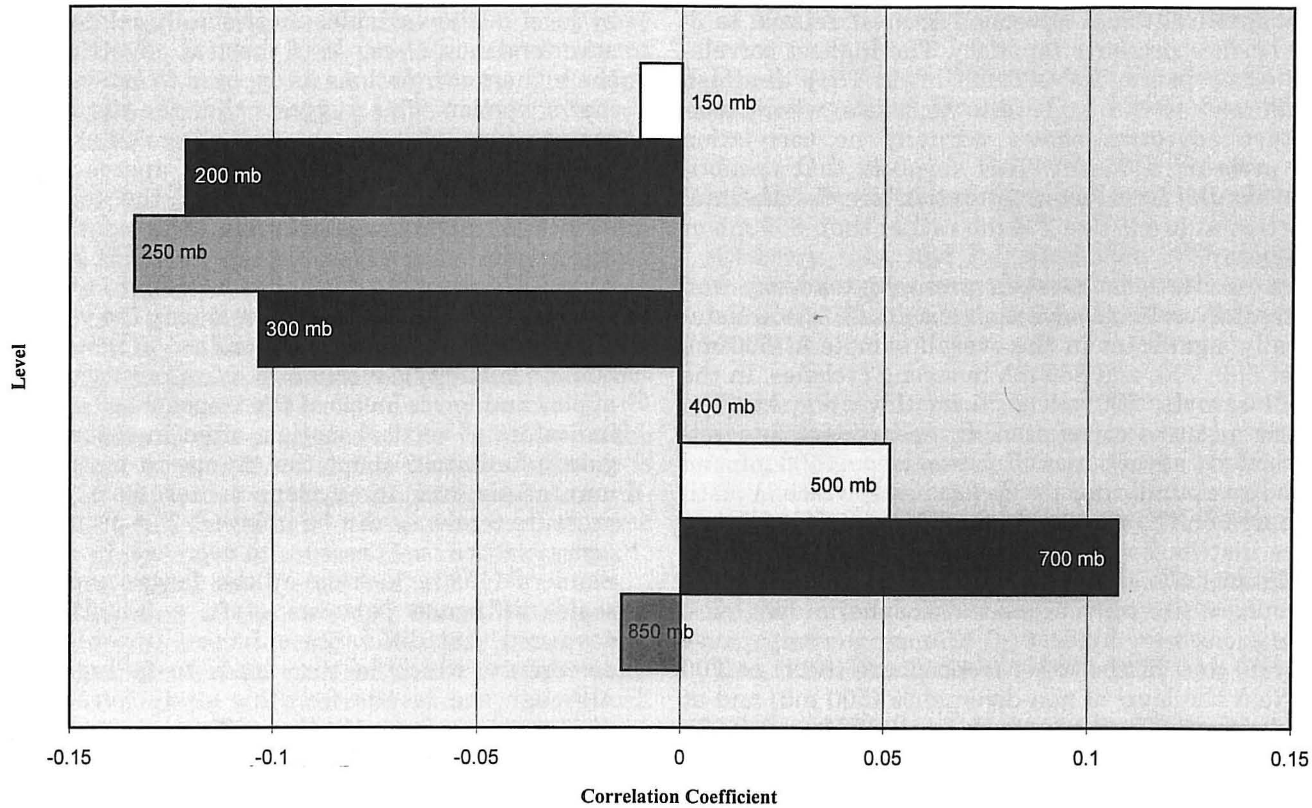

Fig. 4. Correlation coefficients by level for horizontal wind divergence vs. 3-hour sea-level pressure change.

most prominent variable and is positively correlated in moderate cyclones (.21 to .31). Low-level moisture, as indicated by the modest negative correlations between pressure tendency and both moisture convergence and theta-e advection (-0.23 for both), is also significant. In strong cyclones, the pressure tendency is most correlated with vorticity advection (500–850 mb), temperature advection (200, 250 mb) and low-level moisture convergence. This sample best fits conventional synoptic theory as to which factors are most important for causing pressure change.

Further examination of the values from these tables leads to the following additional observations:

1) Correlation values increase slightly as cyclone strength increases.

2) Upper-tropospheric/lower-stratospheric thermal advection is the most important single influence on pressure tendency. Low-level temperature advection at 850 mb shows some correlation in weak cyclones (-0.18) but not in the overall sample or any of the other sub-samples as one might expect.

3) There is a negative correlation between pressure tendency and lower- to mid-level vorticity advection for all cyclone stratifications, as one might expect. Vorticity advection at low- to mid- levels is largest for strong cyclones, especially at 700 mb (-0.40).

c. Multiple correlation coefficients

Multiple correlation coefficients between two or three variables and 3-hour surface pressure tendency were also calculated (Table 4) to provide insight into some relationships between a small group of upper-air variables and pressure tendency.

For the overall cyclone sample, 200 mb thermal advection, 700 mb theta-e advection, and 500 mb vorticity advection in combination showed the highest correlation (0.38) to pressure tendency. This suggests that in general, *upper-level* thermal advection, coupled with *mid-level* vorticity advection, and *low-level* temperature and moisture contribute the most in combination to pressure change. *Weak* cyclone pressure change shows some correlation with 850 mb and 200 mb thermal advection, and 700 mb divergence of q-vectors (0.35). Very small correlations (0.05 to 0.11) were found using the *moderate* cyclone subsample involving 400 mb and 850 mb wind speed, 700 mb vorticity, and 850 mb geostrophic absolute vorticity. Positive values of geostrophic absolute vorticity also favor falling pressure.

In the *strong* cyclone subsample, the two most prominent indicators were 250 mb thermal advection and 850 mb geostrophic vorticity advection, showing moderate correlation (0.55) with pressure tendency.

The strengths of the correlations between thermal advection, geostrophic vorticity advection, and divergence on the one hand, and pressure tendency on the other (for the entire sample) exhibit a vertical profile somewhat like that described by theory. When the correlation coefficients are plotted by level for each of these variables (Figs. 2-4), the difference in strength of the correlations reveals the levels at which these variables are most important. As indicated earlier, upper-tropospheric thermal advection is most related to 3-hour surface pressure tendency. The highest correlations occur in the 150-300 mb layer. They diminish considerably at the mid- to lower-levels, where temperature advection shows virtually no correlation with pressure tendency. This suggests that synopticians should focus more attention on the thermal advection at levels like 200 mb rather than 850 mb or elsewhere.

The correlations between pressure tendency and geostrophic vorticity advection are small, but are statistically significant in the overall sample at 500 mb and at 500, 700, and 850 mb in strong cyclones. In the overall sample, 500 mb vorticity advection has the highest negative correlation. In operational forecasting, vorticity advection is often assessed at 500 mb and is used as an indicator for cyclogenesis, which is justified based on the results obtained here.

The distribution of the magnitude and sign of the correlations of divergence for the different levels of the atmosphere fits conventional atmospheric dynamics. Correlations were highest (-0.13) near the tropopause (250 mb) and in the lower-troposphere (0.11) at 700 mb. Near the level of non-divergence (500 mb) and at 850 mb, correlations were very small (0.05 and -0.02). The sign of the correlation between divergence at upper-levels and pressure tendency is correct in that there is an inverse relationship between the two as one might expect.

4. Conclusions

Simple and multiple correlation coefficients were calculated to assess the relationship between upper-level variables and both 3-hour and 6-hour pressure tendencies. There were 295 cyclones (November-April 1991-1994) in the sample. Small to modest simple correlations were found for the overall sample and for the stratifications of the sample based on cyclone strength. The strengths of the correlations were about the same in the overall and weak samples, but were generally higher for stronger cyclones. The variable that showed the highest correlations was temperature advection at 200 and 300 mb, regardless of cyclone strength. Correlations indicated that the most important influences for the overall cyclone sample were primarily upper-level temperature advection and mid-level geostrophic vorticity advection. The same is true for strong cyclones and to a lesser extent, weak cyclones. These conclusions are most similar to the Rolfson and Smith (1996) study on a sample of weakly to strongly *developing* cyclones over land and the Gyakum et al. (1992) study of *explosive* cyclogenesis. Sanders (1986) also found that positive upper-level vorticity advection had a high negative correlation with pressure falls. Wash et. al. (1992) indicated that some of the most significant indicators for determining the magnitude of the pressure fall included low-level vorticity advection and upper-level divergence. In the present study, low-level vorticity advection has significant correlation in the strong cyclone subsample only. The simple and multiple correlations did show that there is distinction by level of the variables most closely related to pressure tendency. *Upper-level* thermal advection showed the highest correlations as opposed to *lower-level* thermal advection. This suggests that the use of 850 mb temperature advection by forecasters to assess pressure tendency may not be a good approach, though perhaps taking the LaPlacian of the temperature advection might have correlated better. Examining upper-level temperature advection would seem to be better. Geostrophic vorticity advection at 500 mb showed the highest correlation among the various levels, which agrees with the standard practice of using 500 mb vorticity advection to assess cyclogenesis. The upper- and lower-levels of the troposphere are used as indicators of vertical motion, often in concert, and to gain information about the change in mass in a column of air over the cyclone center, from which the pressure tendency can be inferred. Net positive divergence aloft causes pressure to decrease. In a study by Sanders (1993), looking at the large- and synoptic scale diffluence patterns aloft, a hypothesis was advanced that diffluence enhances upper-level mass divergence, which in turn leads to falling pressure. Although the results from his study were not overwhelmingly in favor of using diffluence as an indicator for pressure tendency, upper-level divergence does show some correlation to pressure change as indicated in this paper.

This study is most similar to Rolfson and Smith (1996) in terms of timing and focus. Cool season land-based cyclones of various intensities, not strictly "bombs", were used. The results of that study produced some similarities with the results of the present study. Like their study, the results presented here show that upper-tropospheric positive vorticity advection is favorable for maintaining or increasing cyclone intensity as indicated by the negative correlation with pressure. They also concluded that cyclone development usually does not occur unless a secondary low-level warm air advection maximum is coupled with the one in the upper-troposphere.

In the study by Elsberry and Kirchoffer (1988), upper-level wind speeds were directly related to large pressure falls. The moderate strength cyclones from the current study show that wind speeds at the mid-levels (400 and 500 mb) correlate negatively with pressure tendency (-.26 to -.32). As in the case with thermal advection, there are some similarities in the findings, but the level at which the indicators should be assessed comes into question. In the moderate cyclone subsample, 850 mb wind speeds and 400 mb wind speeds when combined with 700 mb vorticity are weakly correlated with pressure change.

One or more of the following reasons may explain the relatively low correlations found in this study:

1) There are non-linear relationships between atmospheric variables and pressure change.

2) The variance not accounted for by the correlations may be explained with the inclusion of other processes such as diabatic effects, boundary-layer influences, and other sub-synoptic scale influences.

3) The large number of weak cyclones (51%) and those with positive pressure tendency (53 %) may have influenced the results. It is possible that dominant processes, which may appear in only strong, deepening cyclones, are smoothed out in a large sample. Previous studies have used primarily cyclones in the deepening phase.

4) Short-term fluctuations in the atmosphere act to reduce correlations and explained variances. Surface pressure responds also to smaller scale influences that are not incorporated into the RAOB database.

5) Errors may have been made in extracting the exact latitude and longitude of the cyclone center from the surface analyses. Sparseness of upper-air data coupled with inexact coordinates has the potential of producing errors in the estimates of the variables at the real cyclone center. Since an interpolation scheme is used to evaluate the variables at the specified coordinates, the exact values cannot be determined, so some error is likely in the estimates. However, a systematic bias in the values obtained is unlikely.

As a reading of the relevant literature suggests, there is uncertainty in terms of what the primary forcing mechanisms are for cyclogenesis. It is likely that a variety of dynamic and thermodynamic processes all play some role, and that this is dependent on cyclone stage, sign of pressure tendency, and location of the cyclone.

Acknowledgments

Sincere thanks to Joseph R. Cermak III for his programming the Enhanced Upper-Air Diagnostics program used in this study. The authors also wish to thank Dr. Peter Chen for assistance related to statistics and Mrs. Jeremi Harnack for editorial assistance. This project received funding from the New Jersey Agricultural Experiment Station via project number 07141.

Authors

Dr. Harnack is a Professor at Rutgers University in the Department of Environmental Sciences. His teaching and research interest is in synoptic meteorology and climatology, with an emphasis on the nature, cause, and prediction of storms on the synoptic- and mesoscale. He earned his BS degree from Rutgers University, and the MS and Ph.D. degrees from the University of Maryland, all in meteorology.

Mr. Woo is currently employed as an assistant to the State Climatologist for New Jersey, after being a Teaching Assistant in the Department of Environmental Sciences at Rutgers University and a weather forecaster for Weather Services Corporation. He earned his BS and MS degrees in meteorology from Rutgers University.

References

Bjerknes, J., 1940: The deepening of extra-tropical cyclones, *Quart. J. Roy. Meteor. Soc.*, 66, 57-59.

Businger, S., 1995: Cool season cyclogenesis and associated mesoscale weather, *Reviews of Geophysics*, 907-915.

Byers, H.R., 1940: Divergence and deepening of extratropical cyclones, *Quart. J. Roy. Meteor. Soc.*, 66, 61-67.

Davis, C.A., and K.A. Emanuel, 1991: Potential vorticity diagnosed cyclogenesis, *Mon. Wea. Rev.*, 119, 1929-1953.

Elsberry, R.L., and P.J. Kirchoffer, 1988: Upper-level forcing of explosive cyclogenesis over the ocean based on operationally analyzed fields, *Wea. Forecasting,* 3, 205-216.

Foster, M.J., 1988: Upper-air analyses and quasi-geostrophic diagnostics for personal computers, unpublished technical memo, 35 pp. [available from Scientific Services Division, Southern Region, NOAA/National Weather Service, Fort Worth, TX.].

Gyakum, J.R., P.J. Roebber, and T.A. Bullock, 1992: The role of antecedent surface vorticity development as a conditioning process in explosive cyclone intensification, *Mon. Wea. Rev.,* 120, 1456-1489.

Hines, K.M., and C.R. Mechoso, 1991: Frontogenesis processes in the middle and upper troposphere, *Mon. Wea. Rev.*,119, 1225-1241.

Krishnamurti, T.N., 1968: A study of a developing wave cyclone, *Mon. Wea. Rev.*, 96, 208-217.

Lupo, A.R., P.J. Smith, and P. Zwack, 1992: A diagnosis of the explosive development of two extratropical cyclones, *Mon. Wea. Rev.*, 120, 1490-1523.

Panofsky, H.A., 1944: The effect of vertical motion on local temperature and pressure tendencies, *Bull. Amer. Meteor. Soc.*, 25, 271-275.

__________, and G.W. Brier, 1958: *Some Applications of Statistics to Meteorology*, The Pennsylvania State University, University Park, PA, 224 pp.

Reed, R.J., M.T. Stoelinga, and Y-H. Kuo, 1992: A model aided study of the origin and evolution of the anomalously high potential vorticity of the inner region of a rapidly deepening marine cyclone, *Mon. Wea. Rev.*,120, 893-913.

Rolfson, D.M., and P.J. Smith, 1996: A composite diagnosis of synoptic scale extratropical cyclone development over the United States, *Mon. Wea. Rev.*,124, 1084-1099.

Ruscher, P.H., and T.P. Condo, 1996: Development of a rapidly deepening extratropical cyclone over land, 2. Thermodynamic aspects and the role of frontogenesis, *Mon. Wea. Rev.*, 124, 1633-1647.

Sanders, F., 1986: Explosive cyclogenesis in the west-central North Atlantic Ocean, 1981-1984. Part I: composite structure and mean behavior, *Mon. Wea. Rev.,* 114, 1781-1794.

_________, 1993: Upper-level geostrophic diffluence and deepening of surface lows, *Wea. Forecasting*, 8, 339-344.

Schwartz, B.E., and M. Govett, 1992: A hydrostatically consistent North American Radiosonde Data Base at the Forecast Systems Laboratory, 1946-present. NOAA Tech. Memo. ERL FSL-4. [Available from NOAA/ERL/FSL, 325 Broadway, Boulder, CO 80303].

Wash, C.H., R.A. Hale, P.H. Dobos, and C.G. Wright, 1992: Study of explosive and nonexplosive cyclogenesis during FGGE, *Mon. Wea. Rev.*,120, 40-51.

Zehnder, J.A., and D. Keyser, 1991: The influence of interior gradients of potential vorticity on rapid cyclogenesis, *Tellus,* 43A, 198-212.

Zwack, P., and B. Okossi, 1986: A new method for solving the quasigeostrophic omega equation by incorporating surface pressure tendency data, *Mon. Wea. Rev.*, 114, 655-666.

WEATHER - IT