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Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies

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Abstract. Trends in seasonal and annual frequencies of 1000 mb and 500 mb closed low pressure centers, or "cyclones", over the 40 year period 1958-1997 are determined for latitudinal zones and regions of cyclogenesis. Statistically significant trends are found throughout the northern hemisphere and in the southern hemisphere tropics, though the trends vary by season. Opposite trends were observed at the two levels in some regions. No significant differences in cyclone frequencies were found when El Niño and La Niña years were compared. Cyclone frequencies in North America and Europe are poorly correlated with the North Atlantic Oscillation.

1. Introduction

The frequencies and characteristics of surface cyclones and anticyclones in a variety of regions have been studied by a number of investigators over the last two decades. For example, Colucci (1976) examined the winter cyclone frequencies over the eastern United States and adjacent western Atlantic, Sanders and Gyakum [1980] studied cyclogenesis in the northern hemisphere (NH) during 1976 and 1979, Roebber [1984] updated a climatology of explosive cyclones, Zishka et al. [1980] examined North America and surrounding ocean areas for January and July for 1950-1977, Harman [1987] determined mean monthly North America anticyclone frequencies from 1950-1979, Serreze et al. [1993] examined synoptic activity in the Arctic for 1952-1989, Serreze [1995] analyzed patterns of cyclone distribution, deepening rates, and cyclogenesis in the Arctic, Leighton [1994] presented monthly anticyclonicity and cyclonicity in the southern hemisphere (SH), and Agee [1991] examined the trends in cyclone and anticyclone frequency for the 20th century in the northern hemisphere, and correlated the trends warming and cooling periods.

Cyclones and anticyclones at 500 mb, like their surface counterparts, undergo pronounced interannual and seasonal variations in frequency, intensity, tracks, and deepening rates. From a meteorological perspective these systems are important because of their connection to upper-level circulation. For example, they can form blocking patterns and cutoff lows, causing a split in the zonal westerlies and obstructing smaller-scale disturbances associated with daily weather events [Parker et al., 1989]. In addition, the formation of rapidly intensifying 500 mb cyclones is often associated with intensifying surface low pressure systems [Alberta et al., 1991]. But there have been far fewer studies of 500 mb cyclone characteristics: Bell and Bosart [1989] examined the monthly, seasonal and interannual variability characteristics of the closed circulation center distributions for specific regions of the NH from 1963-77, Parker et al. [1989] investigated the 500 mb cyclones and anticyclones over the western half of the NH for the period 1950-1985, and Alberta et al. [1991] studied the rapid cyclogenesis and anticyclogenesis in the NH.

In this paper we extend the work cited above to a global scale for the 40-year period 1958-1997. Both "surface" (1000 mb) and mid-tropospheric (500 mb) cyclonic systems are examined. The analysis is limited to seasonal trends in cyclone frequencies for various geographical regions.

2. Data and Methodology

Twice daily, global 1000 mb and 500 mb geopotential height data from the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) 40-year Reanalysis Project [Kalnay et al., 1996] are used in this study. The data cover the period 1958-1997 with a grid resolution of 2.5° x 5° latitude-longitude.

Cyclone detection and tracking algorithms are automated and follow the methodology of Bell and Bosart [1989]. Closed cyclones are defined by having at least one closed 30 m contour around a central minimum value. If the geopotential height along lines extending from a grid cell increases 30 m or more before falling or reaching a distance limit, it is recorded as a closed cyclone. Cyclones are tracked individually over their lifespan. Each cyclone is found in subsequent grids until no further continuation is detected. The grid cell (cyclone center) of the first cyclone in a track is a position of cyclogenesis, and that of the last cyclone in a track is one of cyclolysis. Figure 1 gives an example of the identification results, showing 1000 mb cyclone centers in the northern hemisphere on June 30, 1958 at 0Z. In all analyses "frequency" is the total number of closed cyclone centers in all 12-hour grids. For example, if a region had 10 cyclone centers on one 12-hour grid and 12 on the next (some of which will be the same cyclones), then the frequency for that day in that region is 22.

High-latitude and midlatitude cyclones identified in this study are wave cyclones. Those detected in the tropical regions are primarily the large-scale thermal lows over India (summer monsoon) and Argentina, and might be more accurately labelled as "subtropical". Due to the relatively coarse resolution of the sampled data, hurricane frequencies are not well represented.

3. Trends in Cyclone Frequencies

Trends in cyclone frequencies were examined for broad latitude zones and regions of cyclogenesis. The latitude zones are

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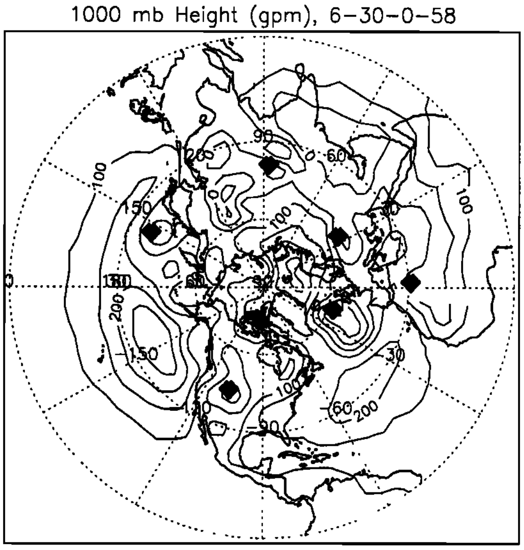

Figure 1. Automatically identified 1000 mb cyclone centers (diamonds) in the northern hemisphere on June 30, 1958 at 0Z.

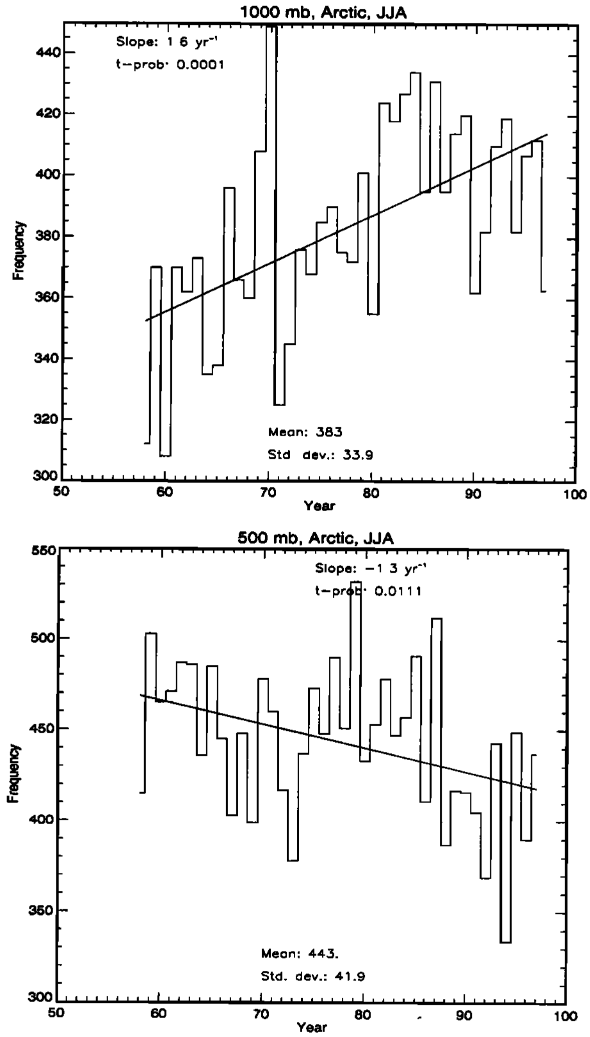

Figure 2. Trends in cyclone frequency at 1000 mb (top) and 500 mb (bottom) during the Arctic summer. The slope of the linear fit is the change in cyclone frequency per year and "t-prob" is its significance. Mean and standard deviations of frequency are given at the bottom of each plot.

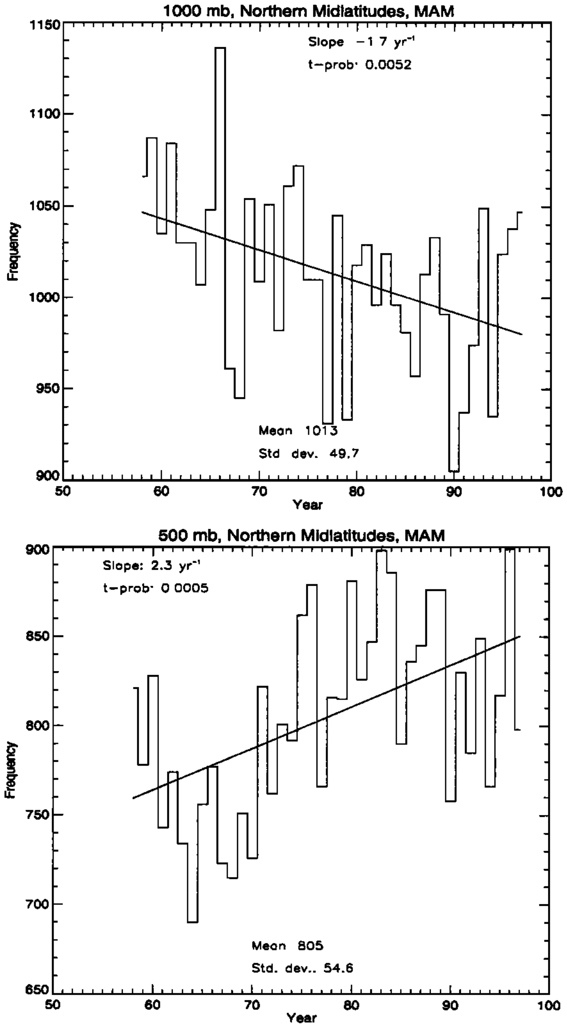

Figure 3. As with Figure 2 but for the northern midlatitudes during the spring.

0-30° (tropics), 30-60° (midlatitudes), and 60-90° (Arctic and Antarctic). Areas of high cyclogenesis frequencies include the southwestern U.S. (Rocky Mountain region), northeastern North America extending to Iceland, the Aleutian Islands in the North Pacific, northeastern Asia, the Mediterranean Sea, India, Argentina, and the Dome Argus region of Antarctica. The northern hemisphere midlatitude regions of cyclogenesis are the same as those identified by Bell and Bosart [1989].

Results for one season in the Arctic and northern hemisphere midlatitudes are shown in Figures 2 and 3 ("JJA" is June, July, August; "MAM" is March, April, May, etc.). The slope of the trend line, its statistical significance, and the mean and standard deviation of the number of cyclones per year are shown. These quantities are given for all latitudinal zones in both hemispheres in Table 1. The statistical significance is the result of a t-test of the linear regression coefficient. The table indicates that there are many statistically significant (level of significance less than 0.05) trends in cyclone frequencies at both atmospheric levels. For example, surface cyclone frequency in the Arctic has increased during all seasons (also observed by Serreze et al. [1997]), while surface cyclone frequency in the midlatitudes of both hemispheres has decreased. The only significant trend in the Antarctic is for the surface during the southern hemisphere summer.

Table 1. Cyclone Frequency Statistics for Six Latitude Zones. First Line: Trend (Cylones per Year) and its Significance (in Parentheses); Second Line: Mean Annual Frequency and its Standard Deviation (in Parentheses).

	December - February		March - May		June - August		September - November	
Latitude Zone	1000 mb	500 mb	1000 mb	500 mb	1000 mb	500 mb	1000 mb	500 mb
Arctic	1.2 (.009) 318 (38)	1.5 (.002) 359 (38)	1.1 (.01) 341 (35)	-0.3 (.29) 404 (38)	1.6 (.000) 383 (34)	-1.3 (.011) 443 (42)	0.8 (.04) 388 (34)	-0.5 (.210) 398 (41)
N. Midlatitude	-1.5 (.03) 912 (55)	-0.2 (.421) 630 (59)	-1.7 (.005) 1013 (50)	2.3 (.000) 805 (55)	-1.0 (.087) 736 (55)	2.5 (.000) 745 (54)	-0.5 (.222) 876 (45)	2.4 (.000) 635 (55)
N. Tropics	0.1 (.394) 67 (16)	0.9 (.002) 62 (22)	-1.7 (.000) 163 (35)	0.5 (.020) 53 (19)	0.5 (.117) 207 (30)	1.6 (.000) 98 (27)	0.2 (.270) 158 (27)	1.1 (.004) 104 (30)
S. Tropics	1.5 (.000) 198 (31)	1.6 (.000) 79 (28)	0.9 (.001) 115 (21)	1.2 (.000) 52 (23)	-0.2 (.160) 78 (16)	0.5 (.007) 38 (15)	-0.2 (.134) 123 (15)	0.6 (.000) 35 (14)
S. Midlatitude	-0.6 (.300) 582 (75)	-0.3 (.379) 288 (68)	-1.6 (.045) 618 (67)	0.8 (.098) 237 (43)	-3.4 (.000) 746 (67)	0.4 (.267) 249 (44)	-0.9 (.140) 587 (59)	1.8 (.000) 214 (41)
Antarctic	1.4 (.021) 386 (48)	0.4 (.208) 351 (35)	0.1 (.468) 518 (47)	0.5 (.147) 360 (33)	-0.1 (.447) 463 (55)	0.5 (.139) 355 (33)	-0.6 (.153) 476 (45)	0.4 (.128) 359 (38)

The northern tropics and subtropics have experienced a decrease in surface cyclones during the spring and an increase in 500 mb cyclones during all seasons. The southern tropics and subtropics show an increase in cyclone frequency in all seasons at both levels. The significant decrease in the frequency of closed surface lows over India may help explain the decreasing trend in precipitation over Sri Lanka between 1950 and 1990 observed by Suppiah [1997, his Figure 2].

Of particular interest are the opposite trends at the two levels for certain latitude zones and seasons, two of which are shown in Figures 2 and 3. Decreasing trends in 500 mb frequency but increasing trends at the surface (e.g., Figure 2) may be indicative of a trend toward shallower systems. Increasing frequencies at 500 mb may indicate longer-lasting cutoff lows and a long-term change in the amplitude of the jet stream, although the relative intensities of systems at both levels would have to be examined for this to be verified.

Statistically significant regional trends in surface cyclone frequencies have been observed for northeastern Asia (MAM, JJA, SON, decreasing), Argentina (JJA, decreasing), the Argus Dome area of Antarctica (JJA, increasing), and India (MAM, JJA, SON, decreasing). At 500 mb trends exist for northeastern North America (DJF, decreasing), the Aleutian Islands (DJF, decreasing), Argentina (all seasons, increasing), northeastern Asia (MAM, SON, increasing), and India (JJA, increasing).

4. El Niño - La Niña Differences and the NAO

Are there differences in cyclone frequencies during El Niño and La Niña years? To address this question, mean annual cyclone frequencies were determined for El Niño and La Niña years as identified by the NCEP climate Prediction Center. El Niño years are 1965, 1969, 1972, 1976, 1982, 1986, 1991, 1994, 1997; La Niña years are 1964, 1970, 1973, 1975, 1988, 1995. Years are defined to begin in October and continue through the following September.

An example of the results is shown in Figure 4 (top) for northwestern Europe (50-60°N, 10-30°E). The plot illustrates the frequency variability, where El Niño and La Niña years may have anomalously high or low frequencies. While there is a difference between cyclone frequencies during El Niño and La Niña years, it is not statistically significant (t-test for sample means). Over the 40-year period, El Niño years have a greater mean annual frequency than La Niña years in the Arctic and southern midlatitudes, but a lower value in all other latitudinal zones. This pattern applies to both levels. However, the only regions of cyclogenesis that show statistically significant differences are the Argus Dome area of Antarctica (both levels) and in the Aleutian Island area (at 500 mb), where El Niño years experience fewer cyclones than La Niña years.

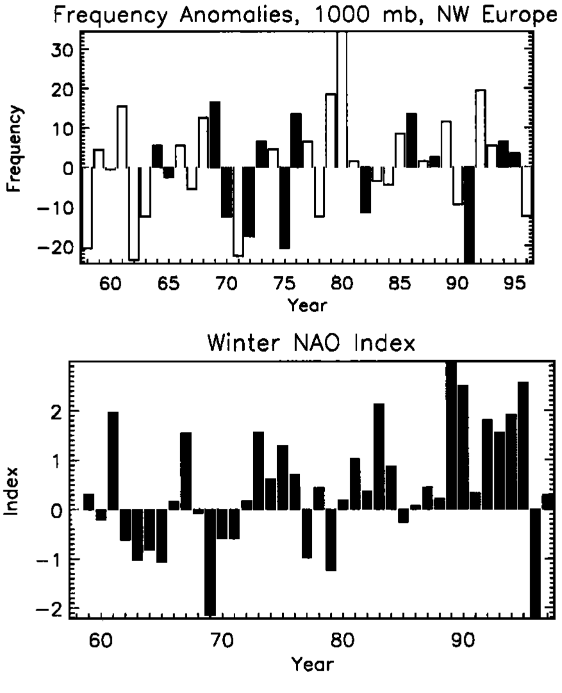

Figure 4. Yearly 1000 mb cyclone frequency anomalies for northwestern Europe (top), indicating El Niño (black), La Niña (grey), and neutral (white) years. The bottom plot gives the North Atlantic Oscillation index after Jones et al. [1997].

The relationship between cyclone frequencies and the North Atlantic Oscillation (NAO) was also examined for northeastern North America, northwestern Europe, and the Arctic. The NAO is the normalized pressure difference between the Azores and Iceland. A positive NAO index corresponds to strengthened westerly flow across the North Atlantic. The NAO index for the winter months is shown in Figure 4 with annual surface cyclone frequency anomalies for northwestern Europe. Though northwestern Europe is not an area of pronounced cyclogensis, cyclonic activity is important in that region, and its climate is affected by shifts in the NAO.

While there is some correspondence between extreme NAO index values and annual cyclone frequencies, overall the relationship is weak. This is also true for winter frequencies in both northwestern Europe and northeastern North America. There is, however, a stronger relationship between the NAO and Arctic surface cyclone frequencies in winter and spring (see also Serreze et al. [1997]). Upward trends through the 1980s and early 1990s correspond to generally positive NAO index values, and a decrease in frequencies in 1996 corresponds to a negative NAO index. From 1970 forward, local maxima/minima in cyclone frequencies appear to precede NAO maxima/minima by approximately three years. No such pattern was observed in the northwestern Europe and northeastern North America records. The three-year lag agrees with that observed by Lin and Derome [1998] in the correlation between the NAO and winter conditions over North America.

5. Summary and Conclusions

The zonal and regional frequencies of 1000 mb and 500 mb cyclones from 1958-1997 over the globe have been investigated, as have the effects of El Niño and the North Atlantic Oscillation on annual frequencies. Areas of cyclogenesis include the southwestern U.S., northeastern North America extending to Iceland, the Aleutian Islands, northeastern Asia, the Mediterranean Sea, India, Argentina, and the Dome Argus region of Antarctica.

Statistically significant trends in cyclone frequencies have been observed at 1000 mb and 500 mb in certain seasons for all regions and latitude zones. In some cases the trends at the two levels are of opposite sign. While differences in annual average frequencies for El Niño and La Niña years are apparent, the majority of the differences are not statistically significant. The North Atlantic Oscillation index is correlated with Arctic cyclone frequencies, but not with frequencies in northeastern North America or northwestern Europe.

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