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Arctic climate and atmospheric planetary waves

Donald J. Cavalieri and Sirpa Häkkinen

NASA Goddard Space Flight Center, Greenbelt, Maryland

Abstract. Analysis of a fifty-year record (1946-1995) of monthly-averaged sea level pressure data provides a link between the phases of planetary-scale sea level pressure waves and Arctic Ocean and ice variability. Results of this analysis show: (1) a breakdown of the dominant wave 1 pattern in the late 1960's, (2) shifts in the mean phase of waves 1 and 2 since this breakdown, (3) an eastward shift in the phases of both waves 1 and 2 during the years of simulated cyclonic Arctic Ocean circulation relative to their phases during the years of anticyclonic circulation, (4) a strong decadal variability of wave phase associated with simulated Arctic Ocean circulation changes. Finally, the Arctic atmospheric circulation patterns that emerge when waves 1 and 2 are in their extreme eastern and western positions suggest an alternative approach for determining significant forcing patterns of sea ice and high-latitude variability.

Introduction

In this paper we report on the variability of sea level pressure (SLP) planetary waves and relate these planetary-scale variations to some of the climatic changes observed in the Arctic over the last fifty years. In contrast to many recent Arctic climate studies that use EOF-defined indices such as the North Atlantic Oscillation (NAO), the Pacific North American (PNA), and Arctic Oscillation (AO), we examine the variability in the amplitude and phase of the longest atmospheric waves in the SLP field.

Recent studies of the Arctic climate system have identified seemingly significant changes over the last fifty years or so. Many of these studies have been regional in nature and have focused on the two primary centers of atmospheric low pressure, the Aleutian Low (AL) and the Icelandic Low (IL). The importance of these systems as drivers of regional sea ice variability is well established (for example, Agnew, 1993; Niebauer, 1998). Oscillations in the intensity of these two semi-permanent centers have been known for some time (Rogers and van Loon, 1979) and more recent studies have correlated the variability of the AL to high latitude hemispheric circulation patterns (Overland et al., 1999).

Analysis and Results

A zonal Fourier analysis of monthly-averaged sea level pressure over a fifty-year period (1946-1995) provides information on the variability of both the phase and amplitude of the planetary-scale waves at polar latitudes. The analysis was performed on each of three ten-degree latitude bands from 50° to 80° N for the winter months of December, January, and February. For each latitude band and for each of the first six zonal wave numbers we computed the wave amplitude expressed as a percent variance and the wave phase expressed in terms its longitudinal position. The focus of this study is on the variability of zonal waves 1 and 2 for the month of January when the wintertime circulation is well developed. These planetary-scale waves reflect changes in the strength and position of the three largest semi-permanent pressure systems that dominate Arctic climate variability: the IL, the AL and the Siberian High (SH).

Time series of the phases ($^{\circ}$E longitude) and amplitudes (% variance) for both wave numbers at the 70° - 80° N latitude band are presented in Figure 1a for January of each year. A 3-year running mean is also shown. For this latitude band, waves 1 and 2 explain over 80% of the variance 90% of the time. Only twice did the variance of wave 1 fall below 50%, in 1969 and in 1979. At these times waves 2, 3, and 4 show a corresponding increase in variance. The phase of wave 1 is generally between 150° - 200° E longitude corresponding to the average winter position of the SH pressure system. Notable exceptions occurred in 1966 and 1967, which preceded the minimum variance observed in 1969. The phase of wave 2 at this latitude shows large amplitude fluctuations until the mid 70's, although the variance explained by wave 2 is consistently less than 30%, except for 1969.

For the latitude band 60° - 70° N (Figure 1b), the fluctuations of wave 1 variance is much greater than at the latitude band 70° - 80° N, but nonetheless show minima in the mid to late 60's. There are a few exceptional events such as in 1966 when its variance drops to zero and its phase undergoes a rapid shift eastward. Other years with low variance (less than 20%) are 1955, 1963, 1967, 1969 and 1979. The time series of the wave 1 variance suggests an overall quadratic trend consisting of a decrease from 1946 to 1966, a decade long excursion between 1969 and 1979, and an increase from 1979 to 1995. Wave 2 phase also appears to have a low-frequency variation manifesting itself as an overall eastward drift, interrupted only by a westward shift from 1963 to 1972.

For the latitude band 50° - 60° N (not shown), both the wave 1 phase and variance time series exhibit a temporal pattern similar to but not as pronounced as the wave 1 variance pattern at 60° - 70° N. Wave 1 has an enhanced variance as well as an eastward phase shift from the late 60's to the mid 70's. The mean phase of wave 2 after the mid 1970's is further eastward than it was before the 70's. The variance explained by wave 2 at these latitudes is generally greater than that explained by wave 1 reflecting the greater strength of the AL and IL at these latitudes, in contrast to the 70° - 80° N latitude band (Figure 1a).

Discussion and Conclusions

Following the large-scale change in atmospheric circulation in the late 1960's, there was a significant shift in

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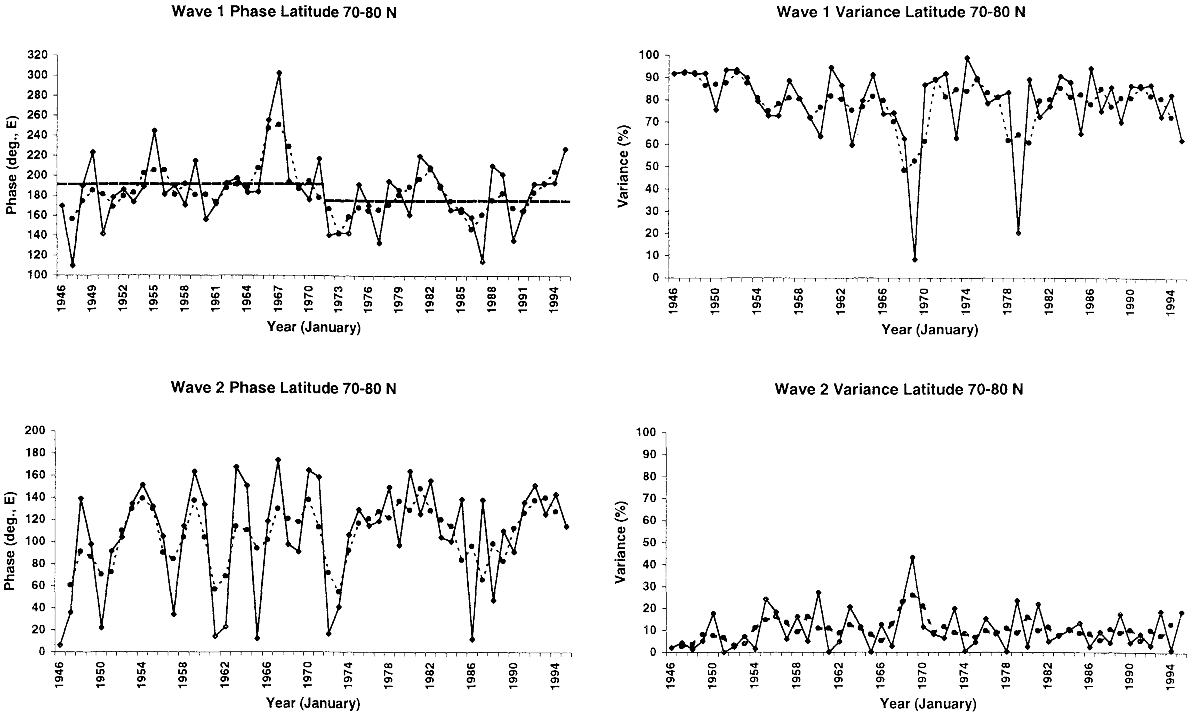

Figure 1a. January phases (°E) and variances (%) over the 50-year period for waves 1 and 2 for 70° - 80° N. The mean phase of wave 1 for 1946-1971 and for 1972-1995 are indicated by dashed lines.

the mean phase of wave 1 westward and a lesser shift in the phase of wave 2 eastward at 70° - 80° N (Figure 1a). The mean phase of wave 1 for the period 1972-1995 is 16° further westward in longitude than it was for 1946-1971 (Figure 1a). To test the statistical significance of this shift, we used the difference of means z-score statistic for a one-tailed test and found the difference in means to be at the 0.05 level of significance. That is, we are 95% confident that the two means are statistically different. The wave 1 phase shift occurred a few years later from 1976 to 1979 for the latitude band 50° - 60° N. Trenberth and Hurrell (1994) have discussed the climate shift in the late 1970's in the North Pacific sector. Niebauer (1998) showed that this same climate shift is observed in sea ice extent anomalies for the Bering and Chukchi seas and since the shift the AL has been moving even further east during El Nino conditions. The mean phase of wave 2 since 1971 has shifted eastward by 8°, 4°, and 2° for latitude bands 70° - 80° N, 60° - 70° N, and 50° - 60° N respectively, but none of these shifts are statistically significant.

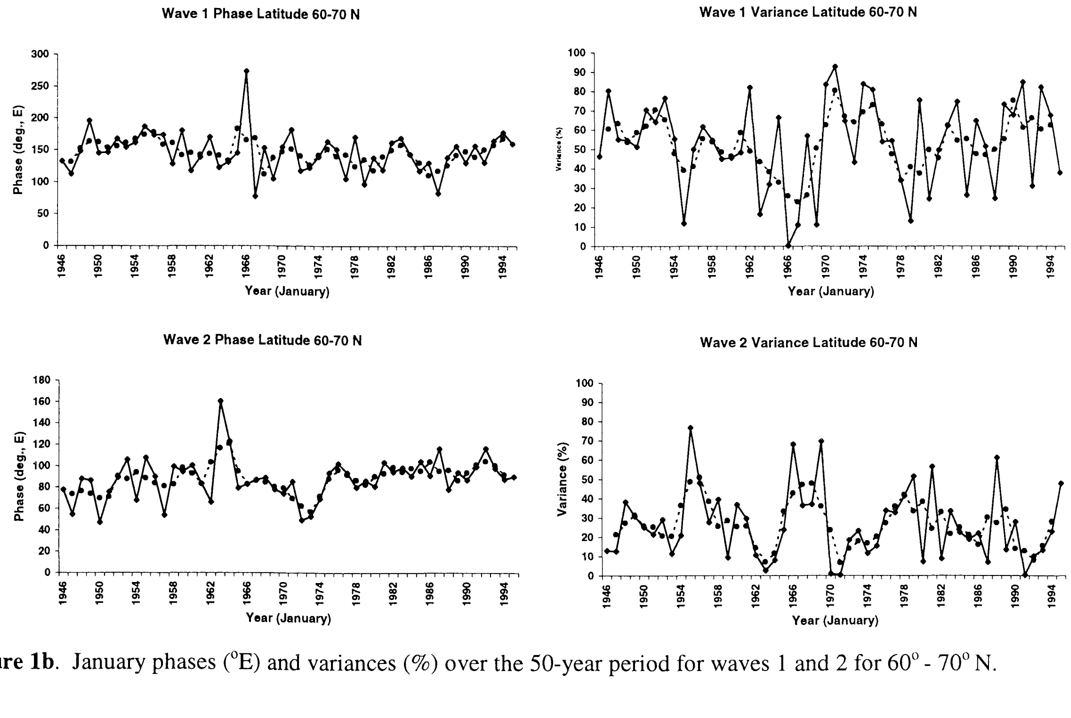

Figure 1b. January phases (°E) and variances (%) over the 50-year period for waves 1 and 2 for 60° - 70° N.

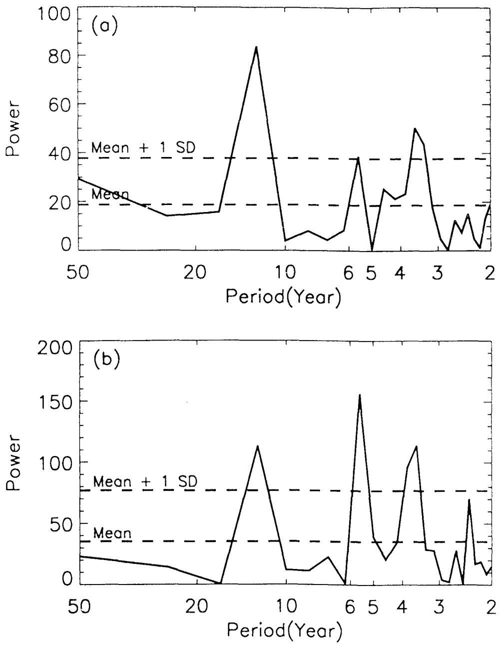

Figure 2. Power spectra of the January phase anomalies for (a) wave 1 and (b) wave 2 both for 70° - 80° N.

A power spectrum of the phase of waves 1 and 2 for the 70° - 80° N latitude band is shown in Figure 2 (the corresponding variance spectra peaks were not significant and the spectra are not shown). The spectra for the phases show strong concentrations of power at 3.6, 5.6, and 12.5 years for both waves 1 and 2. The 3.6-year period is likely related to atmospheric circulation changes associated with El Nino - SOI (Trenberth and Hurrel, 1994). The 5.6-year period also appears prominently in the observed variability of Arctic sea ice extent (Cavalieri et al., 1997) and given the well established association between the position of the three major semipermanent Northern Hemisphere pressure systems and sea ice extent variability, it is not surprising to find a common spectral component in both data sets.

Proshutinsky and Johnson (1997), in their study of simulated Arctic Ocean circulation, found two dominant modes of alternating circulation, one cyclonic and one anticyclonic each persisting for 5-7 years. The authors suggest that shifts from one regime to the other are forced by changes in the location and intensity of the IL and the SH. Averaging the phases of waves 1 and 2 individually for their years of simulated Arctic Ocean cyclonic and anticyclonic circulation, we find average phase differences of 25° longitude for wave 1 and 34° longitude for wave 2 for these two modes of circulation. The phases for the cyclonic years are more eastward. From applying a difference of means test we find that these differences are statistically significant at the 99% confidence level. During the anticyclonic years the IL is centered at about 40° W longitude and the SH stretches across the central Arctic Ocean extending into North America. In contrast, during the cyclonic years the IL extends into the Kara and Barents seas, but the strength of the SH over the central Arctic is weakened. These results clearly support the assertion by Proshutinsky and Johnson (1997) that these two

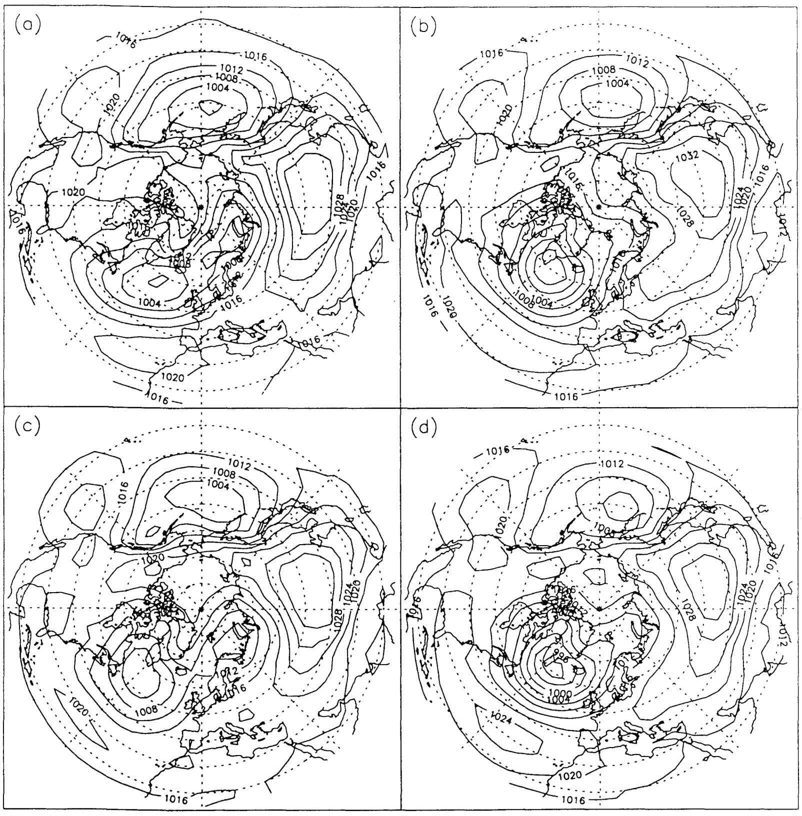

Figure 3. Mean January SLP maps for latitude band 70° - 80° N when (a) wave 1 phase is greater than the mean +1 SD, (b) wave 1 phase is less than the mean -1 SD, (c) wave 2 phase is greater than the mean +1 SD, and (d) wave 2 phase is less than the mean -1 SD.

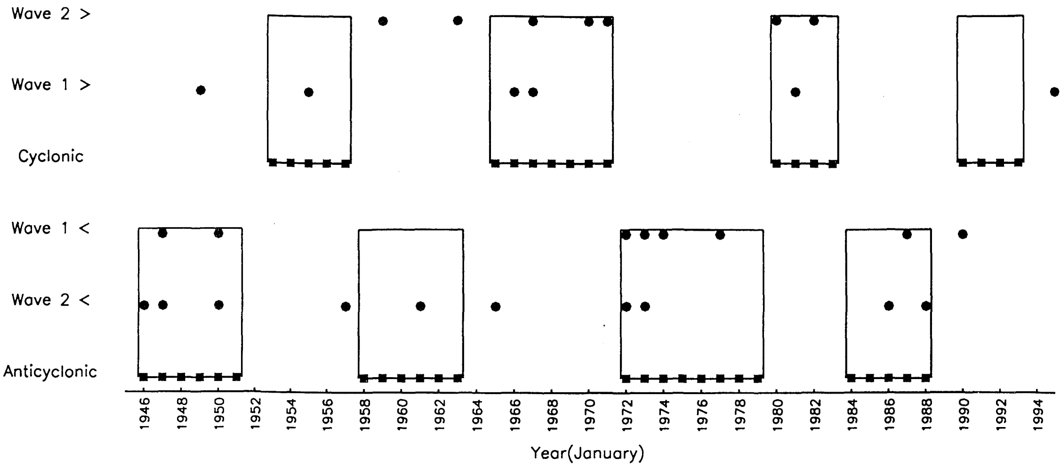

Figure 4. Occurrence of the Proshutinsky and Johnson (1997) simulated Arctic Ocean cyclonic and anticyclonic circulations (boxes), and of the phases of waves 1 and 2 (dots) both when the phases are greater than the mean + 1 SD and when the phases are less than the mean - 1 SD.

regimes are forced by the relative positions and intensity of the IL and the SH.

For the purpose of examining the relationship between the variabilities in the phases of waves 1 and 2 for the latitude band 70° - 80° N and the hemispheric SLP patterns, we averaged the SLPs for those years when the phase of wave 1 is greater than the mean plus one standard deviation (SD) and we averaged the SLPs for those years when the phase of wave 1 is less than the mean minus one SD. We followed the same procedure for wave 2. The results are shown in Figure 3. These SLP patterns are very similar to those obtained when averaging the SLP fields for the cyclonic (Figure 3a and 3c) and anticyclonic (Figure 3b and 3d) years of Arctic Ocean circulation (not shown). Years of occurrence of the simulated Arctic Ocean cyclonic and anticyclonic circulations (Proshutinsky and Johnson,1997), and the extreme positive and negative phases of waves 1 and 2 are illustrated in Figure 4. Using a chi-squared test we find that there is only a 1% chance that the occurrences between cyclonic circulation and extreme positive phases and between anticyclonic circulation and extreme negative phases are independent.

The SLP patterns shown in Figure 3a and 3c are consistent with the forcing needed for large ice exports from the Arctic to the Greenland and Norwegian Seas. The relationship between SLP patterns similar to Figure 3a and 3c and ice export has been demonstated by Häkkinen (1993) and Hilmer et al. (1998). They show a secondary low in the Barents Sea consistent with the extension of the IL. Ice export out of the Arctic can have a significant impact on the modification of the water masses especially in the subpolar gyre and on the thermohaline circulation (Mauritzen and Häkkinen, 1997). While the patterns shown in Figure 3a and 3c, based on the extreme eastward positions of the phases of waves 1 and 2, may share some of the features of a NAO pressure anomaly at low index phase, they clearly represent a separate dynamical entity due to the low pressure anomaly extending to the Barents Sea. One would expect that such a feature would be associated with a positive phase NAO where the storm track is located in the northernmost North Atlantic and over Scandinavia. On the other hand, the westward phase patterns of waves 1 and 2 (Figure 3b and 3d) display the classical positive phase NAO pattern. Based on these results, we suggest that it is principally the phases of the planetary SLP waves (waves 1 and 2) that drive low frequency Arctic Ocean and sea ice variability.

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D.J. Cavalieri, S. Häkkinen, Laboratory for Hydrospheric Processes, Code 971, NASA Goddard Space Flight Center, Greenbelt, MD 20771.
(email: Donald.J.Cavalieri.1@gsfc.nasa.gov)

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