ARCTIC CLIMATE AND ATMOSPHERIC PLANETARY WAVES

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The significance of this paper is that it suggests an alternate approach to determine significant forcing patterns of sea ice and Arctic Ocean variability on decadal and centennial time scales. 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. Our analysis shows: (1) a breakdown of the dominant wave 1 pattern in the late 1960's at high latitude, (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.

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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 to determine 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 we computed the percent variance explained by each of the first six waves and their phase expressed in terms of 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 and variances for both wave numbers at all three latitude bands are presented in Fig. 1 for January of each year. A 3-year running mean is also shown. For the latitude band 70° - 80° N, waves 1 and 2 explain over 80% of the variance 90% of the time (Figure 1a). 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 120°-180° 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 20%, except for 1968.

For the latitude band 60° - 70° N (Fig. 1b), wave 1 variance is much more variable at this latitude than at 70° - 80° N, but nonetheless shows minima in the late to mid 60's. There are a few exceptional events such as in 1966 when its variance drops to zero and its phase undergoes a rapid eastward phase shift. Other years with extremely 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 recovery between 1969 and 1979, and an increase from 1979 to 1995. (Except for the interruption in the 1970's, the time series of the wave 1 variance during the 50-year period is suggestive of a 50- or 100-year cycle.) 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 (Fig. 1c), both the wave 1 phase and variance time series show a temporal pattern similar to but not as pronounced as the wave 1 variance pattern at 60° - 70° N with an enhancement of variance and an eastward shift of phase from the late 60's to the mid 70's. There appears to be a slight eastward trend in the phase of wave 2. The mean phase of wave 2 after the mid 1970's is further eastward than it was before the 70's. Drops in the variance of wave

2 coincide with the increases in the variance of wave 1, a characteristic even more apparent at 70° - 80° N (Fig. 1a).

Discussion and Conclusions

Following the large-scale change in atmospheric circulation in the late 1960's, there was a significant shift in the mean phase of wave 1 westward and a lesser shift in the phase of wave 2 eastward (Fig. 1a) at 70° - 80° N. The mean phase of wave 1 shifted about 19° westward in longitude from about 1972 on through the remainder of the 50-year period and is significant at the 0.1 level. Examination of Fig. 1b suggests that this phase shift occurred a few years later (about 1976) 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 results here show the phase of wave 2 for the latitude band 60° - 70° N has undergone a long-term drift since the mid 70's. A similar drift for the same time period is evident in the phase of wave 2 for 50° - 60° N. (Fig. 1c).

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 and these differences are statistically significant at the 1% level. The January mean SLP map for the anti-cyclonic years is shown in Figure 3a, whereas the January map for the cyclonic years is shown in Figure 3b. During the anti-cyclonic years the IL is centered at about 40° W longitude and the SH stretches across the central Arctic Ocean extending into North America (Fig. 3a). 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 (Fig. 3b). These results clearly support the assertion by Proshutinsky and Johnson (1997) that these two 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 at 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 4. These SLP patterns are very similar to those obtained when averaging the SLP fields for the cyclonic and anticyclonic years of Arctic Ocean circulation (Fig. 3).

The SLP patterns shown in Fig. 4a and 4c are consistent with the forcing needed for large ice exports from the Arctic to the Greenland and Norwegian Seas. Ice export out of the Arctic can have a significant impact on the modification of the water masses especially in the subpolar gyre. This has been demonstrated in models to have an influence on thermohaline circulation (Mauritzen and Häkkinen, 1997). Observations show that significant heat content changes in the subpolar waters occurred at the end of the 1960's and in the early 1980's. Both of these events were accompanied by large ice outflows as simulated by numerical models (Häkkinen, 1995; Hillmer et al. 1998; Arfeuille et al. 2000; Häkkinen and Geiger, 2000). These studies have tried to link these ice export events to the NAO index, but with mixed success. Since the models do not give a consensus result on this linkage, one has to question whether the NAO is responsible for the large ice export events. The analysis in the aforementioned studies do agree that the pressure pattern responsible for the largest ice events consists of an Icelandic Low extending to the Barents-Kara Seas with perhaps a secondary low and a high pressure anomaly over Greenland. While the patterns shown in Figures 4a and 4c, 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 (Fig. 4b and d) display the classical positive phase NAO pattern. Based on the results presented here, we suggest that the variability in the amplitudes and phases of the planetary SLP waves (waves 1 and 2) serves as the mechanism driving Arctic Ocean and sea ice variability on decadal to centennial time scales. These changes in the long waves are driven by zonal flow-wave interactions and by relative changes in the diabatic heating of oceans and land masses.

Acknowledgments

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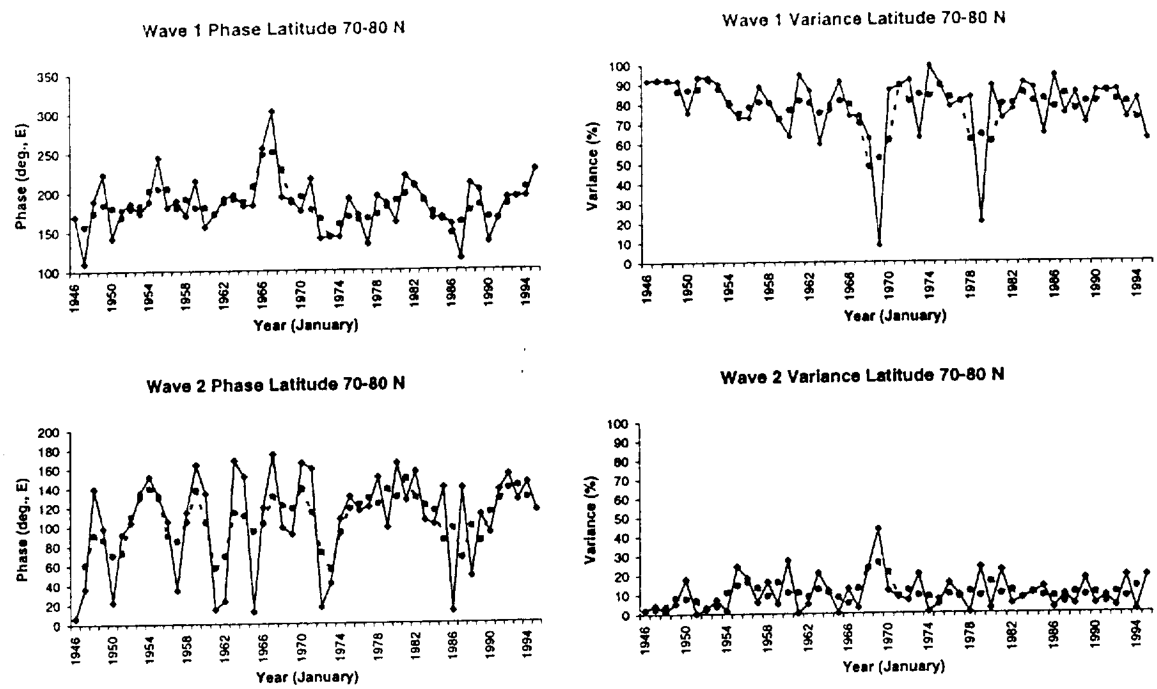


Figure 1.a January time series over the 50-year period of the phase in degrees longitude and percent variance explained by wavenumbers 1 and 2 for the latitude bands 70° - 80° N.

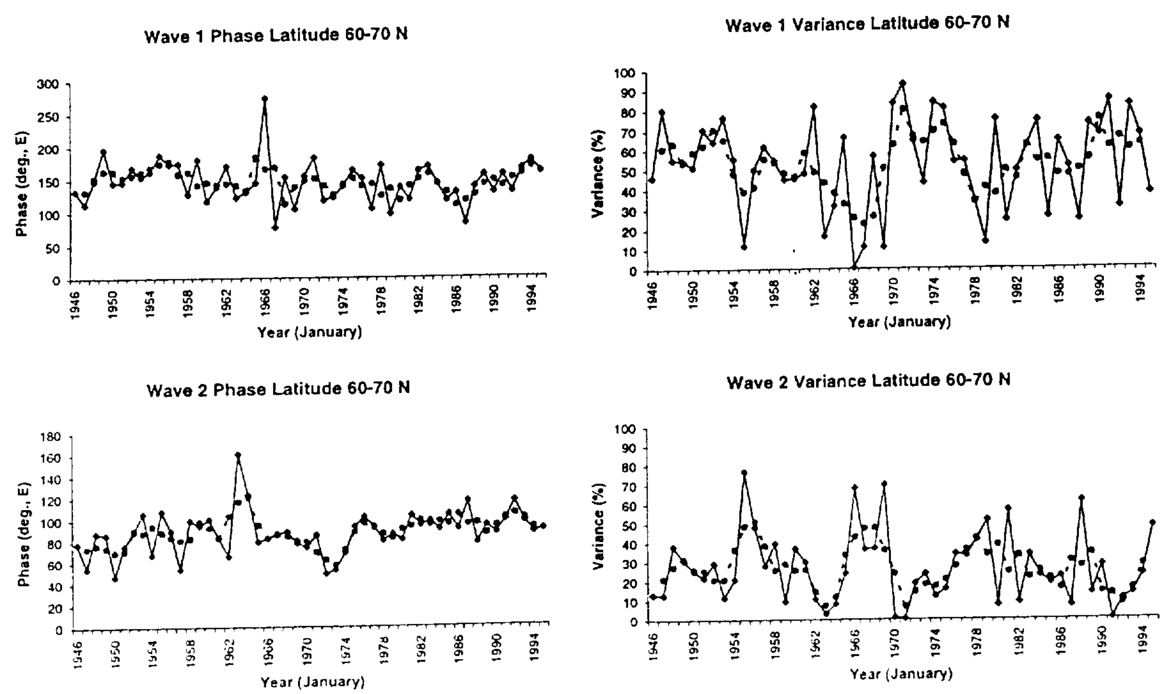


Figure 1.b January time series over the 50-year period of the phase in degrees longitude and percent variance explained by wavenumbers 1 and 2 for the latitude bands 60° - 70° N.

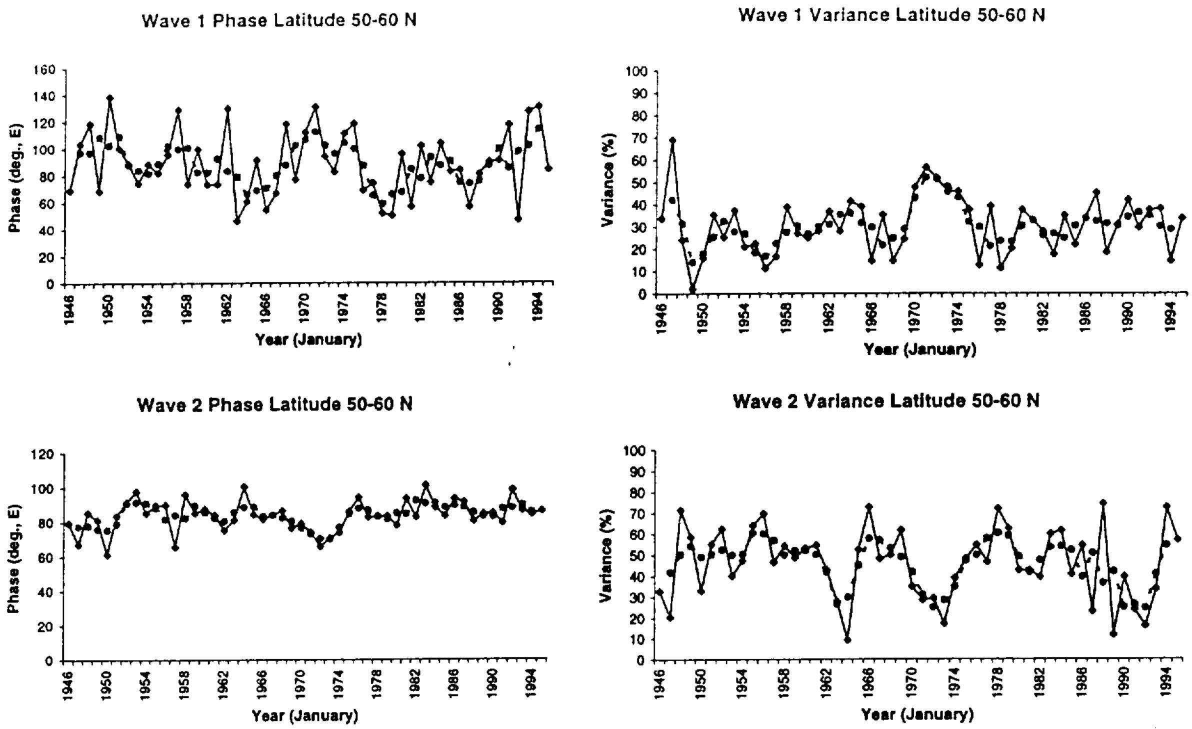


Figure 1.c January time series over the 50-year period of the phase in degrees longitude and percent variance explained by wavenumbers 1 and 2 for the latitude bands 50° - 60° N.

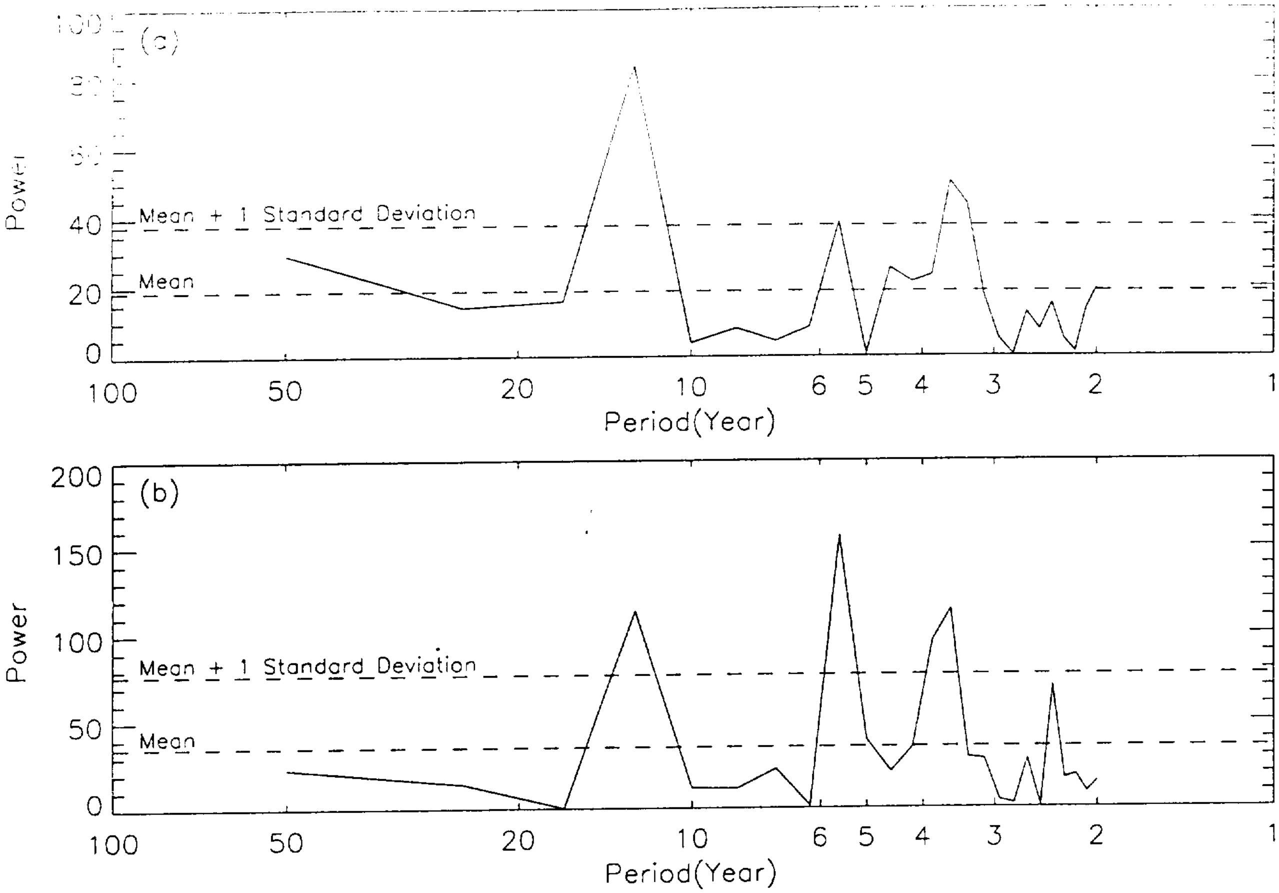
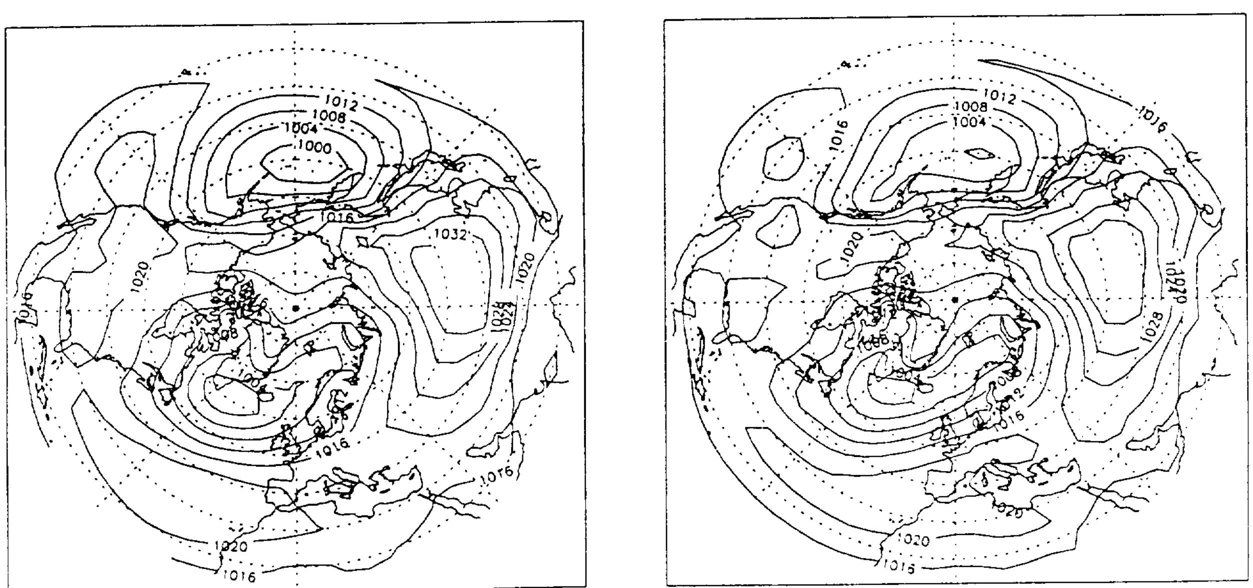


Figure 2. Power spectra of the January phase anomalies for (a) wave 1 and (b) wave 2 both for the latitude band 70° – 80° N.



(a) (b)

Figure 3. Mean January SLP maps for (a) anti-cyclonic and (b) cyclonic years of simulated Arctic Ocean circulation.

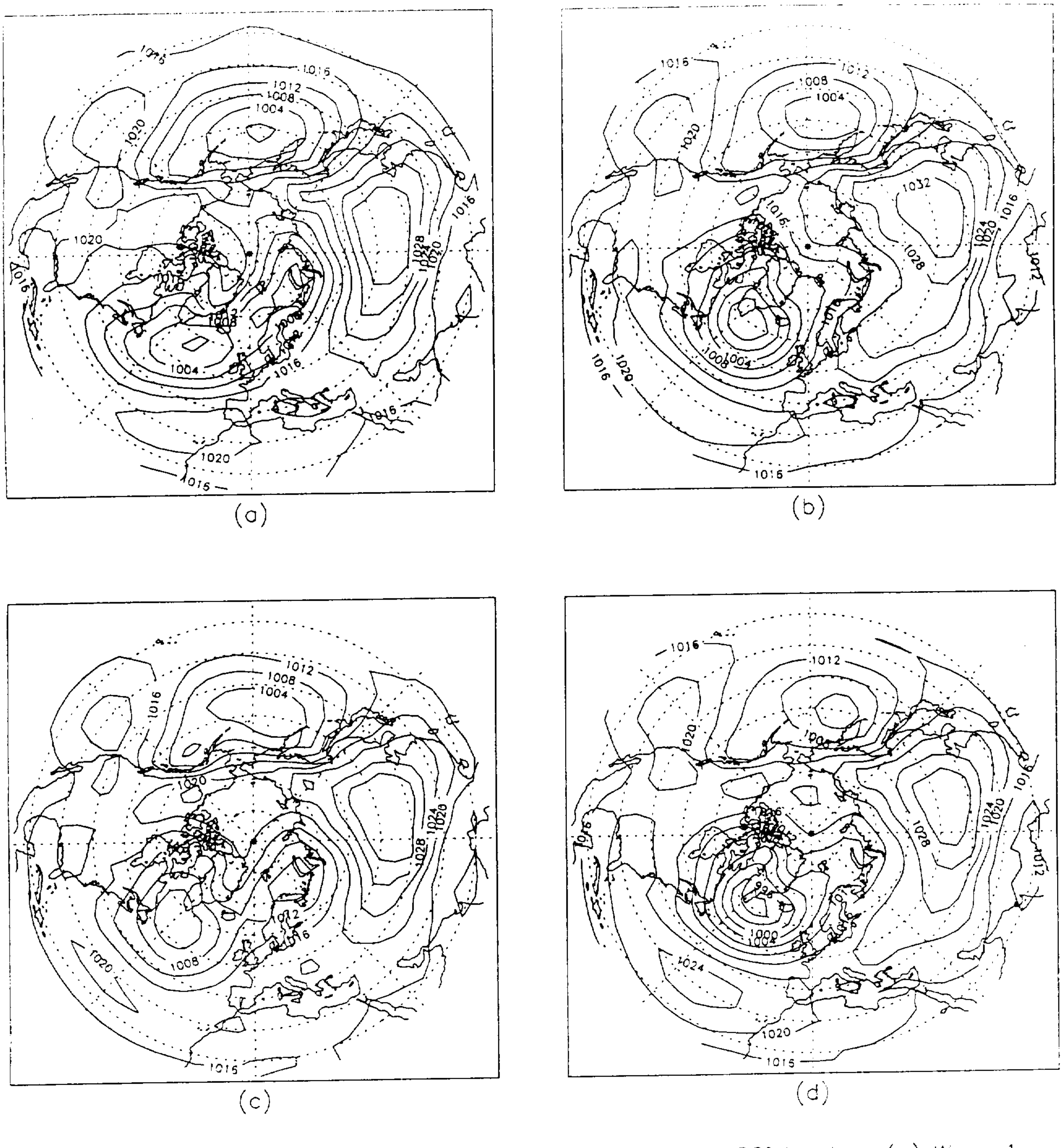


Figure 4. Mean January SLP maps for latitude band 70° – 80° N when (a) Wave 1 phase is greater than Mean + 1 SD, (b) Wave 1 phase is less than Mean – 1 SD, (c) Wave 2 phase is greater than Mean + 1 SD, and (d) Wave 2 phase is less than Mean – 1 SD.