Trends in the Summer Northern Annular Mode and Arctic Sea Ice

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Abstract

The summer Arctic sea ice extent (SIE) during the period 1996−2008 had an accelerating trend of retreat. The difference of SIE between May and September has a significant correlation with the summer Northern Hemisphere Annular Mode (summer NAM). The summer NAM had a significant positive trend during the period 1958−1996, and a weak negative trend during the period 1996−2008. The atmospheric circulation during the recent period had a trend of anticyclonic circulation over the Arctic with easterly wind over the marginal seas. In addition, tropospheric warming was enhanced especially over the Arctic and near the ground surface.

1. Introduction

Summer Arctic sea ice has declined since the 1960s and reached record low levels in September 2007 (Stroeve et al. 2008). The time series of September sea ice extent (SIE) (Comiso and Nishio 2008) (Fig. 1) shows retreat following the maximum extent in 1996, which considerably accelerated over recent years with record lows in 2005, 2007 and 2008 (Comiso et al. 2008). Arctic SIE had a significant decreasing linear trend of −22% per decade from 1996 to 2008, compared with a weak decreasing linear trend of −3% per decade from 1979 to 1996 (These values are based on Fig. 1). Before 1979, Stroeve et al. (2008) showed that September SIE starts decreasing from the 1960s. Climate change is hypothesized to have occurred in the Arctic around 1996 and this change may affect the change in the decreasing trend of summer SIE.

Several mechanisms have been proposed to explain the decline of summer Arctic sea ice. In terms of oceanic forcing, enhanced Pacific warm water inflow to the Arctic Ocean and warming of the intermediate warm Atlantic water are possibly contributing to recent Arctic sea ice loss (Shimada et al. 2006; Polyakov et al. 2005). In terms of atmospheric forcing, the positive Arctic Oscillation (AO) in winter acts to reduce Arctic sea ice through the enhancement of sea ice outflow through Fram Strait (e.g., Rigor et al. 2002). The winter AO index had an increasing trend from the 1960s up until the mid 1990s, but the AO index has decreased since the mid 1990s (Overland and Wang 2005).Using drifting buoys, recent reduction of ice is linked with atmospheric circulation (Rigor et al. 2002; Inoue and Kikuchi 2007). Reduced cloudiness and enhanced downward radiation are discussed as causes for the extreme 2007 Arctic sea ice loss (Kay et al. 2008; Schweiger et al. 2008). Summertime atmospheric circulation also plays an important role in controlling the year-to-year variations of September sea ice: The summer anticyclonic circulation over the Arctic reduced sea ice by producing anomalous Ekman drift (Ogi and Wallace 2007). In fact, strong anticyclonic surface wind anomalies over the Arctic were observed during the summer of record-low SIE in 2007 and substantial Ekman drift of summer sea ice was observed by drifting buoys (Ogi et al. 2008). Hence, the change in the trend of atmospheric circulation between the previous period (before 1996) and the recent period (after 1996) is important for exploring the causes for the accelerated decline in summer Arctic SIE. In this paper, we focus on the summertime atmospheric circulation.

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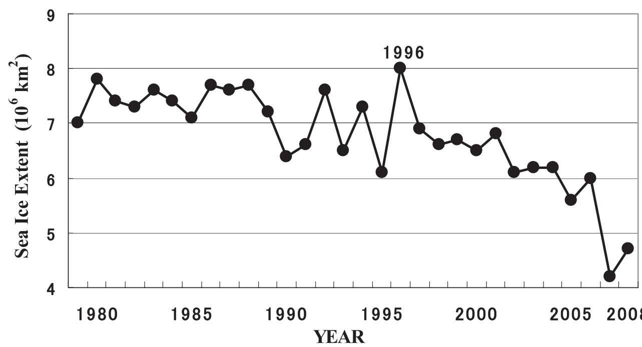

Fig. 1. September Arctic Sea ice extent from 1979 to 2008. Based on data described by Comiso and Nishio (2008). Unit is 10^6 km^2.

In summer, the dominant mode of variability in the Northern Hemisphere circulation is the summer Northern Hemisphere Annular Mode (summer NAM) (Ogi et al. 2004). Ogi et al. (2004) defined the NAM as the first empirical orthogonal function (EOF) mode derived from the zonally-averaged monthly geopotential height field from 1000 hPa to 200 hPa and poleward of 40°N in each month. The summer NAM has a smaller meridional scale compared to the conventional (annually calculated) NAM presented by Thompson and Wallace (2000). This summer NAM pattern is similar to the summer sea level pressure (SLP) anomaly pattern regressed on the index of May minus September SIE shown in Ogi et al. (2008). Hence, the trend of the summer NAM index is examined in this paper.

2. Data and method

SIE data from 1979 to 2008 is based on Comiso and Nishio (2008) and the time series of the summer NAM from 1958 to 2008 are taken from http://www.jamstec.go.jp/frsgc/research/d2/masayo.ogi/SVNAM.txt. For the atmospheric data, we used the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kistler et al. 2001). In this paper, linear trends in summer (June-July-August: JJA) atmospheric circulation during the period 1958−1996 and the period 1996−2008 are compared. The results did not change if the boundary year was taken as 1995 or 1997. Thus, the results do not depend critically on specific choice of the boundary year.

3. Results

The time series of the summer NAM index from 1958 to 2008 is shown in Fig. 2, together with the time series of May minus September SIE for the period 1979−2008. The summer NAM index (open squares) shows an increasing trend up to the 1990s and a decreasing trend afterward. The summer NAM trend from 1958 to 1996 was 0.537/decade, statistically significant at 99%. The trend is affected by low index values in the early 1960s, and the statistical significance reduces to 95% for the period 1965−

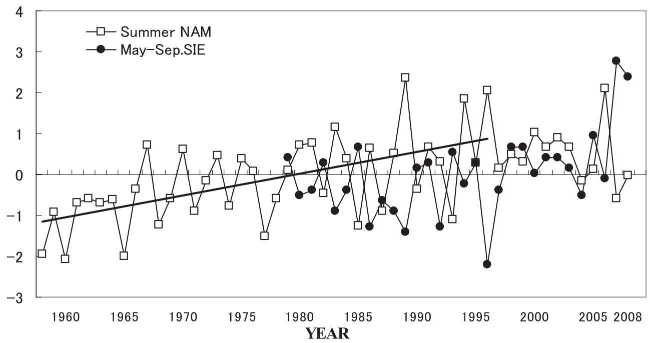

Fig. 2. Standardized time series of indices of summer (June-July-August) NAM from 1958 to 2008 (open squares) and May minus September sea ice extent from 1979 to 2008 (black circles). (Correlation coefficient (1979 −2008): R = −0.50, statistically significant at 99%) The average of May minus September sea-ice extent value is 6.68 × 10^6 km^2 and standard deviation is 0.76 × 10^6 km^2.

1996. The trend from 1996 to 2008 was −0.692/decade, which is not statistically significant possibly due to the short record length. The value of the May minus September SIE (black circles) index showed no significant trend before 1996, and was at a minimum in 1996. After 1996, the SIE index had a positive trend, which means seasonal melt accelerated. During the period 1979–2008, these two time-series had a negative correlation of R = −0.50, which is statistically significant at 99%.

In the following, summer atmospheric circulation trends between the period 1958–1996 and the period 1996–2008 are compared. Figures 3 (top) show the summer linear trends in geopotential height at 1000 hPa (Fig. 3a) and temperature at 850 hPa (Fig. 3b) from 1958 to 1996. Geopotential height had a negative trend over the Arctic Ocean and a positive trend over Eurasia, though the positive trend over central Eurasia is too large and seems to be unreliable (Inoue and Matsumoto 2004). This seesaw pattern is similar to the positive summer NAM pattern identified by Ogi et al. (2004). The summer temperature trend (Fig. 3b) was negative over the Arctic and positive over midlatitudes.

The linear trend in summer geopotential height at 1000 hPa from 1996 to 2008 (Fig. 3c) was opposite to that from 1958 to 1996, displaying a negative summer NAM pattern. The recent strong high-pressure trend over the Arctic was characterized by anticyclonic surface wind anomalies over the Arctic with easterly wind anomalies over the marginal seas. The dominance of summer anticyclonic circulation over the Arctic was similar to the results of Ogi et al. (2008), who demonstrated that reduced SIE in summer 2007 was produced by Ekman drift of sea ice out of the marginal seas to the central Arctic. The temperature trend for the period 1996–2008 (Fig. 3d) showed a strong warming trend over the Arctic and midlatitudes compared with the trend from 1958 to 1996 (Fig. 3b). The atmospheric trends before 1996 (Figs. 3a and

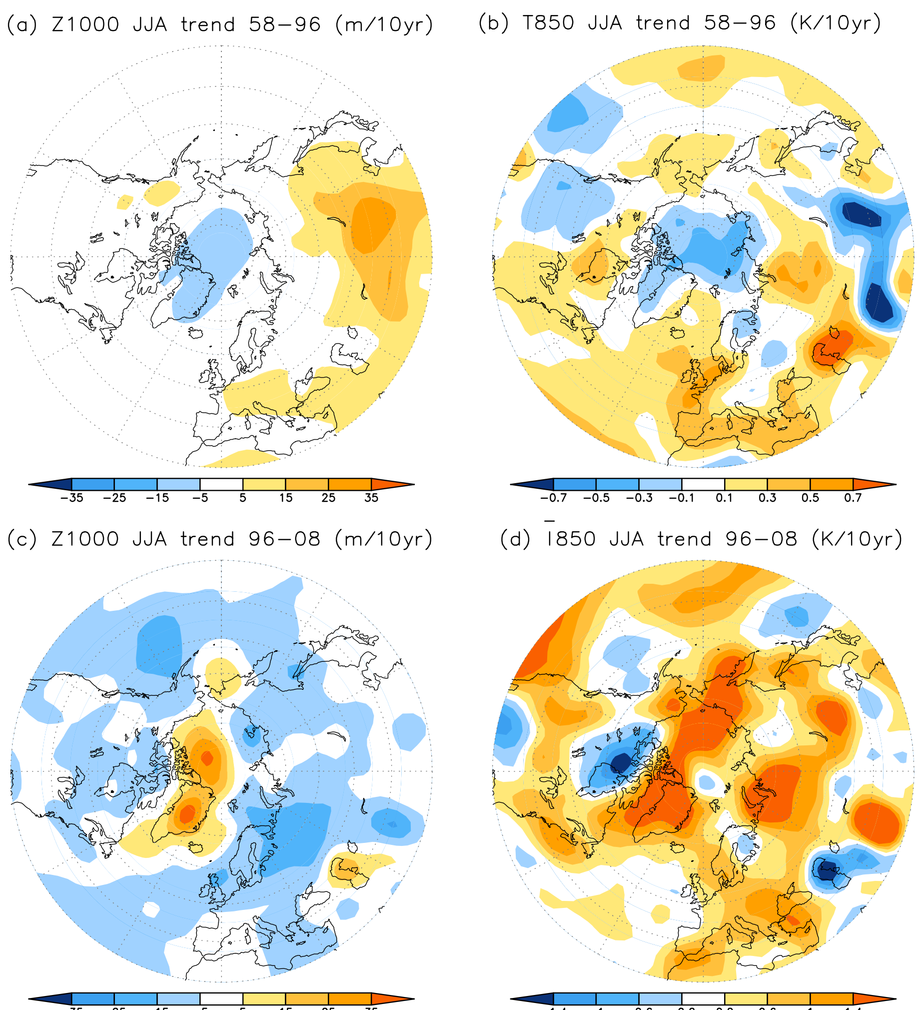

Fig. 3. JJA linear trends (top) from 1958 to 1996 and (bottom) from 1996 to 2008 for (a) and (c) 1000-hPa geopotential height, (b) and (d) temperature at 850 hPa. Linear trends are shown per decade. Contour intervals and vector scale are indicated in the scale bar.

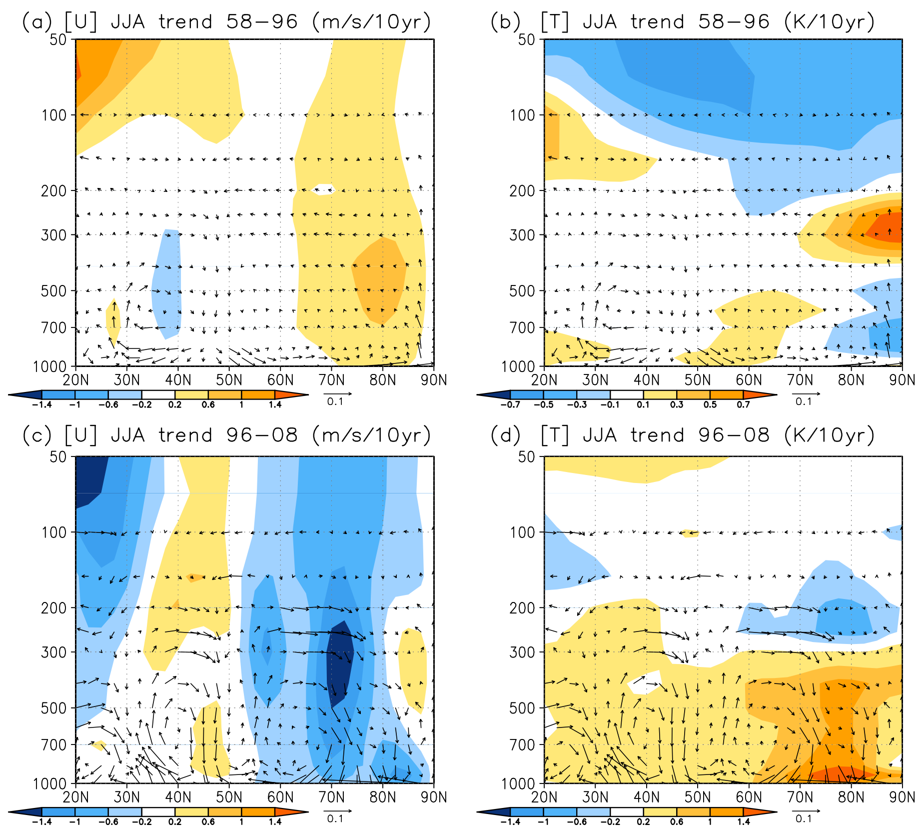

Fig. 4. Same as in Fig 3, but (a) and (c) zonal mean zonal wind (shading) and meridional circulation (vectors), (b) and (d) zonal mean temperature (shading) and meridional circulation (vectors).

3b) are statistically significant at 95% level, but the trends after 1996 (Figs. 3c and 3d) are not statistically significant.

Figure 4 shows the latitudinal-height cross-section of zonal mean zonal wind (Figs. 4a and 4c) and zonal mean temperature (Figs. 4b and 4d) trends for the periods 1958−1996 (top) and 1996−2008 (bottom). The trend in the zonal mean zonal wind from 1958 to 1996 (Fig. 4a) is characterized by a strengthening of high-latitude westerly winds from the ground surface to the lower stratosphere and the peak occurred at approximately 70−80°N, 300−700 hPa. The tropospheric temperature at 50−70°N increased and that over the Arctic region decreased (Fig. 4b). Strong warming near the Arctic tropopause (300 hPa) and strong cooling in the stratosphere are apparent. These temperature trends are consistent with the zonal wind trends from the viewpoint of thermal wind balance. The trends in meridional motion indicated by the arrows in Figs. 4a and 4b were dominated by rising motion near 30°N, northerly motion at 30−50°N, 300 hPa, and downward motion near 50°N. However, a rising motion near the pole was dominant in Arctic latitudes.

The trends during the period 1996−2008 for both zonal mean zonal wind and zonal mean temperature were quite different from those during the previous period. The recent trend in zonal mean zonal wind as shown in Fig. 4c is characterized by a strong easterly wind at 60−80°N from the surface to the lower stratosphere and the meridional motion (arrows in Fig. 4c) exhibits a strong downward trend near 70°N. The trend in EP flux divergence in the upper troposphere is generally consistent with the trend in zonal-mean zonal wind. The temperature trend (Fig. 4d) is dominated by strong warming over the whole northern troposphere. In particular, the polar region at 70−80°N showed a strong warming trend of 1 K/decade. The Arctic warming is also strong near the Earth's surface and the warming trend is more than 1.4 K/decade. In the stratosphere, the trend was weak except for the lower stratosphere at 70−80°N.

4. Summary and discussion

The decline in September SIE in the Arctic Ocean has accelerated considerably since 1996. We investigated changes in the trends of summertime atmospheric circulation between 1958−1996 and 1996−2008. We found that the seasonal sea ice retreat from May to September had good correlation with the summer NAM. When the summer NAM was negative, the sea ice retreat accelerated.

During the earlier period, the SLP over the Arctic Ocean was decreasing, while that over Eurasia was increasing, corresponding to the intensification of the subpolar westerly jet. These changes are consistent with an increasing summer NAM trend. The atmosphere over the Arctic Ocean was cooling and that over the midlatitudes was warming during this period.

During the recent period of 1996−2008, the trend in atmospheric circulation changed, i.e., the summer NAM had a negative trend. During the recent period, anticyclonic circulation over the Arctic Ocean tended to intensify and the subpolar westerly jet became weak. In addition, the polar atmosphere has displayed rapid warming. These changes probably caused the rapid sea ice loss after 1996, but the direct influence of atmospheric trend to sea ice needs to be studied. Feedback from sea ice to the atmosphere should be also studied in future work. Although we have focused on summer circulation in this paper, other factors such as winter circulation also contribute to summer SIE. This analysis will be discussed in a separate paper (Ogi et al. 2010).

The change in trends of the Arctic atmospheric circulation may be due to natural variability. Another possibility is the recovery of stratospheric ozone and associated slight warming in the lower stratosphere since 1996 (Liu and Wing 2009). There is some evidence that stratospheric ozone affects the summer NAM (Kuroda et al. 2008). Nakamura et al. (2009) found that the increase in summertime lower stratospheric ozone in midlatitudes caused negative summer NAM through both observational analysis and a climate model experiment. If this is the case, the stratospheric ozone might have triggered the change in trend of the summer NAM. Further studies are needed.

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