

# The relationship between summer sea ice extent in Hudson Bay and the Arctic Ocean via the atmospheric circulation

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## Abstract

The trends and interannual variations of summer sea ice extents (SIEs) in both Hudson Bay and the Arctic Ocean are investigated in association with variations in atmospheric circulation and air temperature. The summer SIE variabilities of both Hudson Bay and the Arctic Ocean are well correlated and have a strong negative trend. The negative SIE trends are associated with a summer atmospheric circulation pattern that is characterized by positive anomalies over the Arctic Ocean and negative anomalies over mid-latitudes. The trends are also connected with warm air temperatures over mid- and high-latitudes. The atmospheric circulation and air temperature regressed on the summer SIEs in both Hudson Bay and the Arctic Ocean are quite similar to these trend patterns. On the other hand, the year-to-year variations of the detrended summer SIEs in both Hudson Bay and the Arctic Ocean are not correlated. The summer atmospheric circulation and air temperature over the Arctic Ocean have contributed to the detrended summer Arctic Ocean SIE. In contrast, the detrended summer Hudson Bay SIE is controlled by atmospheric circulation and air temperature in the previous spring.

**Keywords:** Hudson Bay sea ice; Arctic Ocean sea ice; atmospheric circulation; air temperature; trend and interannual variation

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## 1. Introduction

Arctic Sea Ice Extent (SIE) has declined over the entire Arctic Ocean since the passive microwave record began in 1979. Both its trend and the interannual variability of Arctic sea ice are associated with atmospheric circulation and air temperature variabilities (Deser *et al.*, 2000; Rigor *et al.*, 2002; Ogi and Wallace, 2007; Serreze *et al.*, 2009; Screen and Simmonds, 2010; Walsh, 2014). The negative trend in the Arctic sea ice has been accelerating since the mid-1990s (Comiso *et al.*, 2008; Deser and Teng, 2008), and the atmospheric circulation and surface wind forcing have caused changes of the Arctic sea ice trend (Screen *et al.*, 2011; Ogi and Rigor, 2013). The influence of recent low Arctic SIE is not only limited to the Arctic climate change but has also impacted climate variabilities and changes in mid-latitudes with atmospheric variations (e.g., Honda *et al.*, 2009; Orsolini *et al.*, 2011; Bhatt *et al.*, 2013; Ogi *et al.*, 2015).

Hudson Bay is one of the world's largest inland seas. It becomes seasonally ice-covered during winter and becomes ice-free during summer. Recently, however, warming sea surface temperatures over the Bay and surrounding area have caused the ice pack in Hudson Bay to change; in particular sea ice in Hudson Bay now breaks up earlier during spring and forms later

in fall, ultimately creating a longer open water season and relative decline in the ice pack thickness and extent (Galbraith and Larouche, 2011; Hochheim and Barber, 2014). Changes to the ice cover in Hudson Bay have affected the marine ecosystem, specifically, biological and biogeochemical processes through all trophic levels (e.g. Estrada *et al.*, 2012; Hoover *et al.*, 2013; Hare *et al.*, 2014; McCall *et al.*, 2015). Trend and interannual variability in Hudson Bay waters are controlled by both large-scale atmospheric variability (Wang *et al.*, 1994; Mysak *et al.*, 1996; Qian *et al.*, 2008) and wind anomalies surrounding Hudson Bay (Hochheim *et al.*, 2011; Hochheim and Barber, 2014).

Several previous studies (Qian *et al.*, 2008; Hochheim *et al.*, 2011; Bhatt *et al.*, 2013; Ogi *et al.*, 2015) have implied a relationship between SIEs in Hudson Bay and the Arctic Ocean, and suggested that the overlying atmospheric circulation patterns are responsible for this connection. To test this hypothesis, we analyze the relationship between SIEs in Hudson Bay and the Arctic Ocean across the interannual and multidecadal time scales.

## 2. Data

The annual mean summer [July to September (JAS)] SIEs in both Hudson Bay and Arctic Ocean were

calculated from 1979 to 2013 using daily sea ice concentration fields from the National Snow and Ice Data Center ([http://nsidc.org/data/smmr\\_ssmi\\_ancillary/area\\_extent.html#smmr\\_ssmi](http://nsidc.org/data/smmr_ssmi_ancillary/area_extent.html#smmr_ssmi)). Sea ice concentrations were derived from passive microwave data using the Bootstrap sea ice algorithm (Comiso, 2000). The SIEs in Hudson Bay and Arctic Ocean are hereafter referred to as 'Hudson Bay SIE' and 'Arctic Ocean SIE'. The Hudson Bay SIE index includes James Bay, Foxe Channel and Hudson Strait. The Arctic Ocean SIE index includes only the Arctic Ocean without the Greenland Sea, Kara and Barents Seas (Figure 1, Northern Regions in NSIDC webpage).

Atmospheric fields of sea level pressure (SLP) and air temperature at 850-hPa (T850) were used from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset from 1979 to 2013 (Kalnay *et al.*, 1996). Within this study 'spring' and 'summer' are defined as April to June (AMJ) and JAS, respectively.

### 3. SIE trends in Hudson Bay and the Arctic Ocean

Summer SIEs in both Hudson Bay (dotted line) and the Arctic Ocean (solid line) have declined since the start of the observational record in 1979 (Figure 1(a)). The two time series fluctuate similarly and are well correlated ( $R = 0.61$ ,  $p < 0.01$ ) across the 35-year time series. The SIEs in Hudson Bay and the Arctic Ocean have retreated following respective maximum extents in 1992 and 1996. Between 1979 and 1992 there was a positive trend of 0.184% per decade in relative SIE within Hudson Bay, whereas between 1992 and 2013 the linear trend is  $-0.701\%$  per decade. In the Arctic Ocean, SIE declined at  $-0.463\%$  per decade from 1979 to 1996, and the rate of decline nearly tripled to  $-1.568\%$  per decade between 1996 and 2013.

Figure 1(b)–(e) shows summer SLP and T850 regressed on the summer SIEs in Hudson Bay and the Arctic Ocean. The SLP regression patterns associated with SIEs in both Hudson Bay (Figure 1(b)) and the Arctic Ocean (Figure 1(c)) show positive anomalies over the Arctic Ocean and Greenland and negative anomalies over mid-latitudes. It is known that September Arctic Ocean SIE variations are associated with anticyclonic circulation anomalies over the Arctic Ocean (Ogi and Wallace, 2007; Screen *et al.*, 2011). In this study, we show that the summer Hudson Bay SIE variations are associated with the negative and positive anomalies between mid- and high- latitudes. The atmospheric circulation pattern is quite similar to the pattern associated with the summer Arctic Ocean SIE. The pattern correlation between Figure 1(b) and (c) is  $R = 0.93$  (poleward of  $50^\circ\text{N}$ ).

The relationship between summer T850 patterns and the summer Hudson Bay (Figure 1(d)) and Arctic Ocean (Figure 1(e)) SIEs is characterized by warm

anomalies throughout the Northern Hemisphere, especially positive anomalies over the Arctic Ocean (pattern correlation is  $R = 0.83$ ). Significant positive trends in air temperature have occurred throughout the Northern Hemisphere during recent years (Walsh, 2014). Increasing air temperatures over the Arctic Ocean have been associated with reduced Arctic Ocean SIE, while increasing air temperatures over Hudson Bay are commensurate with significant negative trends in sea ice concentration within Hudson Bay (Hochheim *et al.*, 2011).

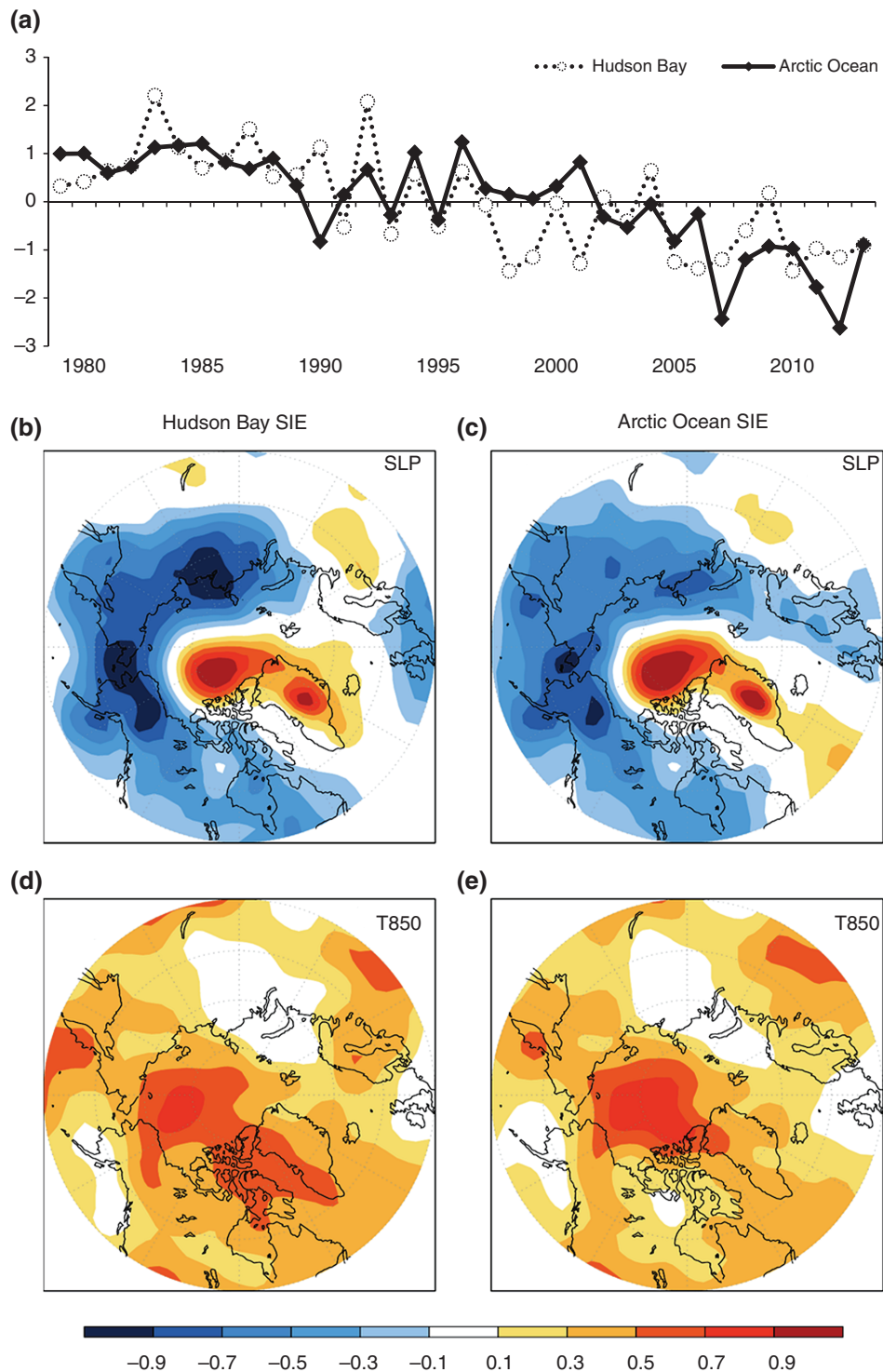
To assess the influence of atmospheric trends on the SIEs, we present the summer linear trends in SLP and T850 from 1979 to 2013 (Figure 2). The SLP trend shows a positive trend over the Arctic Ocean and Greenland and a negative trend over mid-latitudes (Figure 2(a)). The T850 trend is positive across the northern hemisphere (Figure 2(b)). The trend patterns for both SLP and T850 are quite similar to the regression patterns associated with SIEs in both Hudson Bay and the Arctic Ocean (Figure 1). Therefore, the relationship between Hudson Bay and Arctic Ocean SIE trends appears to be connected with the positive SLP anomalies over the Arctic Ocean and the warm temperature anomalies over mid- and high-latitudes.

### 4. The interannual variations of SIEs in Hudson Bay and the Arctic Ocean

In this section, we describe the year-to-year variations of SIEs in Hudson Bay and the Arctic Ocean, and associate them with atmospheric patterns. The detrended summer SIEs in Hudson Bay (dotted line; Figure 3(a)) and Arctic Ocean (solid line; Figure 3(a)) are poorly related with a low correlation coefficient of  $R = 0.15$ .

Figure 3(b)–(e) shows the summer SLP and T850 regressed on the detrended summer SIEs in Hudson Bay and the Arctic Ocean. The SLP regression patterns associated with Hudson Bay (Figure 3(b)) and the Arctic Ocean (Figure 3(c)) are positive anomalies over the Arctic Ocean and Greenland and negative anomalies over mid-latitudes. However, the SLP anomalies associated with the detrended Hudson Bay SIE are weaker than the anomalies correlated with the Hudson Bay SIE (Figure 1(b)). On the contrary, the positive anomalies associated with the detrended Arctic Ocean SIE are strong and more widespread over the Arctic Ocean compared with the anomalies associated with the Arctic Ocean SIE (Figure 1(c)). The pattern correlation between Figure 3(b) and (c) is  $R = 0.68$  (poleward of  $50^\circ\text{N}$ ), which is lower than the correlation ( $R = 0.93$ ) of between Figure 1(b) and (c) including a trend.

The T850 patterns associated with the detrended SIEs in Hudson Bay (Figure 3(d)) and the Arctic Ocean (Figure 3(e)) show warm anomalies over the Arctic Ocean (pattern correlation is  $R = 0.44$ ). However, the T850 anomalies associated with the detrended Hudson Bay SIE are weaker than the anomalies associated with the detrended Arctic Ocean SIE. The interannual

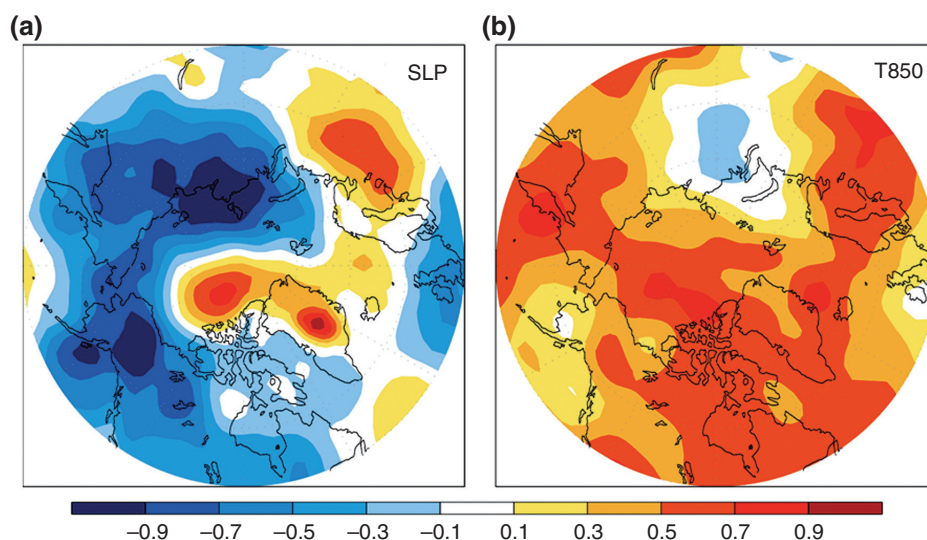


**Figure 1.** (a) The time series of the standardized indices of the summer SIEs in Hudson Bay (dotted line) and the Arctic Ocean (solid line) from 1979 through 2013. (b–e) Summer SLP regressed on the inverted summer SIEs in (b) Hudson Bay and (c) the Arctic Ocean for 1979–2013. (d and e) As in b and c, but summer T850.

variations in September Arctic Ocean SIE have been attributed to changing patterns of summer anticyclonic circulation anomalies and summer air temperature over the Arctic Ocean (Ogi and Wallace, 2007; Screen *et al.*, 2011). The summer atmospheric circulation with the detrended September SIE is similar to summer Arctic Oscillation pattern defined by Ogi *et al.* (2004). Our results are consistent with Ogi and Wallace (2007) and

Screen *et al.* (2011) in the sense that the year-to-year variation of summer Arctic Ocean SIE is controlled by the summer anticyclonic circulation and air temperature.

However, the interannual variation of the Hudson Bay SIE might be less controlled by the summer atmospheric circulation and temperature. Hochheim and Barber (2014) showed that spring (AMJ) SIE and



**Figure 2.** Linear trends in summer from 1979 to 2013 for (a) SLP (hPa) and (b) T850 (C°).

breakup data over Hudson Bay are highly correlated with spring air temperatures and spring surface winds over North and East of Hudson Bay. Based on weekly ice charts from the Canadian Ice Service Digital Archive, Tivy *et al.* (2011) showed that summer ice cover in Hudson Bay from 1966 to 2008 has a large negative trend, and that the summer sea ice cover is linked to spring air temperature in Hudson Bay. These previous results suggest that the atmospheric and temperature anomalies in the previous months may influence the summer Hudson Bay SIE. Thus, we investigate further the inter-seasonal relationship between the summer Hudson Bay SIE and atmospheric patterns of the previous months.

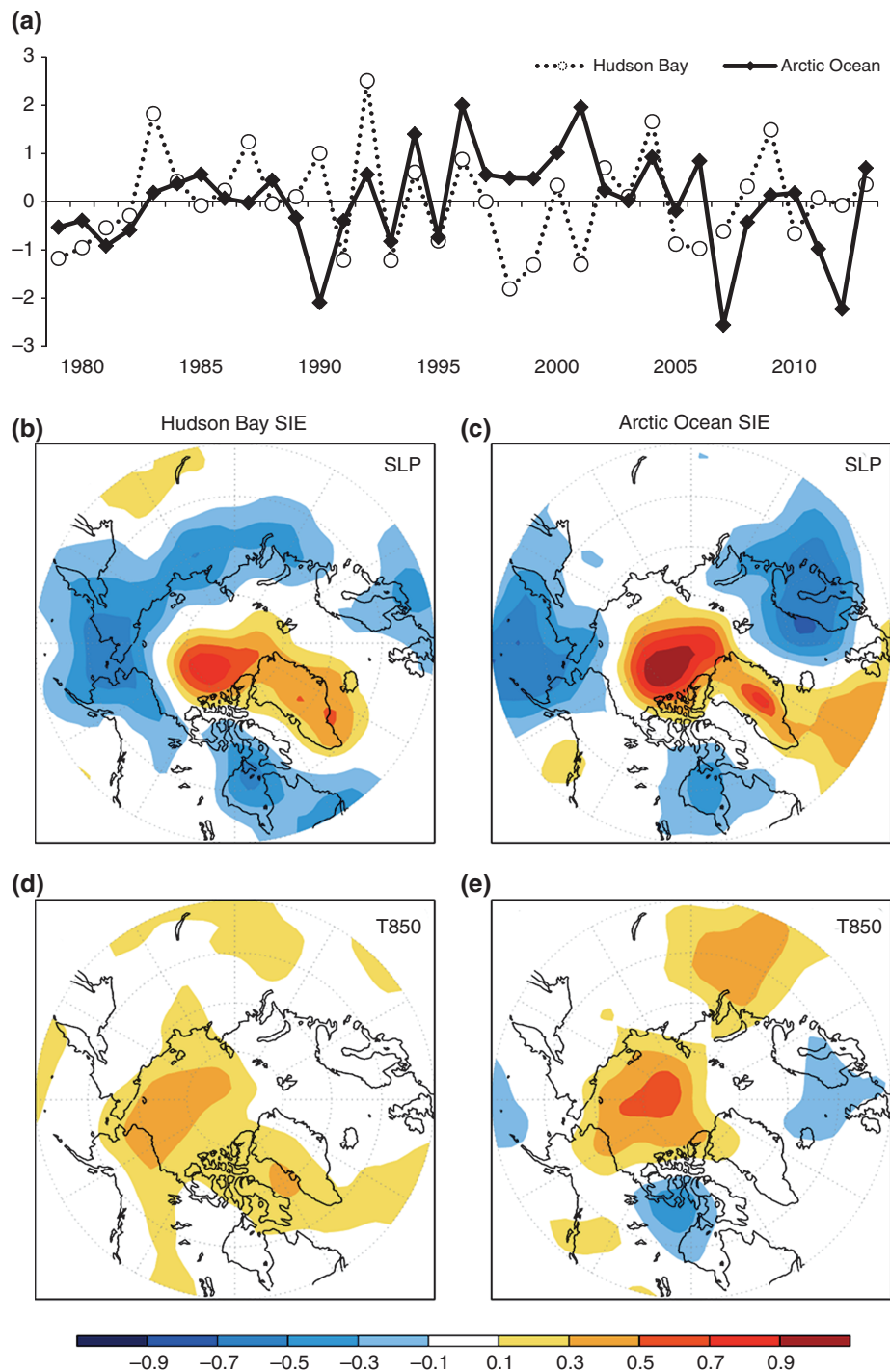
Figure 4 shows the spring SLP and T850 regressed on the detrended Hudson Bay SIE in the following summer. The spring SLP patterns (Figure 4(a)) have strong negative anomalies over the Bering Sea and a seesaw pattern between mid- and high-latitudes over the North Atlantic Ocean similar to the North Atlantic Oscillation pattern. The T850 patterns have strong positive anomalies over Hudson Bay (Figure 4(b)). The result reveals that the spring air temperature anomalies tend to be warmer over Hudson Bay when the Hudson Bay SIE during summer is lower than normal.

Figure 5 shows the time series of the detrended spring T850 over Hudson Bay (green box; Figure 4(b)) together with the inverted detrended Hudson Bay SIE in the following summer. The interannual variation shows a good correlation ( $R = 0.67$ ,  $P < 0.01$ ). Because the Hudson Bay SIE in spring coincides with the melting season, open water appears over the Hudson Bay in spring. The surface in Hudson Bay is capable of absorbing energy from the sun, and then releases this heat back to the atmosphere. As a result, the variations of the Hudson Bay SIE in spring are linked to the spring air temperatures. The Hudson Bay SIE variabilities in spring associated with the spring air temperature may influence the summer Hudson Bay SIE conditions. The correlation coefficient of the detrended Hudson

Bay SIEs between spring and summer is positively correlated ( $R = 0.50$ ,  $P < 0.01$ ). The variation in spring SIE is almost the same as June SIE since Hudson Bay in April and May is still covered with sea ice. As a result, the spring air temperature influences the Hudson Bay SIE in the following summer. As shown by the stronger correlations over Hudson Bay region in Figure 4(b) than in Figure 3(d), the spring variabilities of the air temperature as preconditions are more important for the interannual variations of the summer Hudson Bay SIE than the influence of the summer atmosphere and air temperature.

## 5. Discussion and conclusions

We have investigated the trends and the year-to-year variations in summer SIEs in Hudson Bay and the Arctic Ocean. The summer SIEs in both Hudson Bay and the Arctic Ocean have strong negative trends. The summer SLP pattern associated with SIEs in Hudson Bay and the Arctic Ocean including the negative trend is characterized by positive anomalies over the Arctic Ocean and Greenland and negative anomalies over mid-latitudes. The summer T850 pattern is warmer than normal over mid- and high-latitudes. The SLP and the T850 anomalies associated with SIEs in both Hudson Bay and the Arctic Ocean are similar to the summer atmospheric circulation and air temperature trend patterns. The trends of atmospheric circulation and air temperature over the Arctic Ocean are correlated with the Arctic SIE (Ogi and Yamazaki, 2010; Ogi and Rigor, 2013). The Hudson Bay sea ice recently began to break up earlier in spring. The trends in the breakup dates agreed with the temperature trends at the weather stations situated along Hudson Bay (Gagnon and Gough, 2005; Vincent *et al.*, 2015). These atmospheric circulation and air temperature trends have controlled the SIE trends in both Hudson Bay and the Arctic Ocean. As a

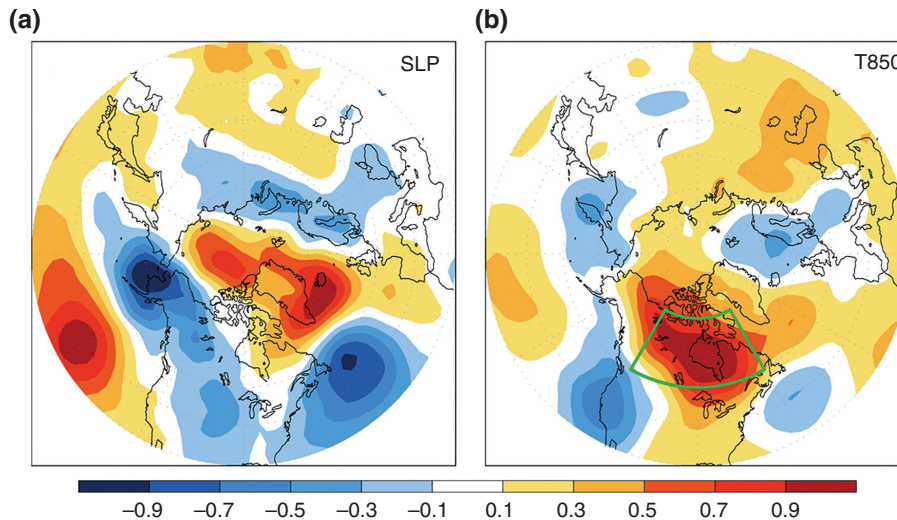


**Figure 3.** (a) As in Figure 1 but detrended summer SIEs in Hudson Bay (dotted line) and the Arctic Ocean (solid line). (b–e) As in Figure 1 but regressed on the inverted detrended summer SIEs in Hudson Bay and the Arctic Ocean.

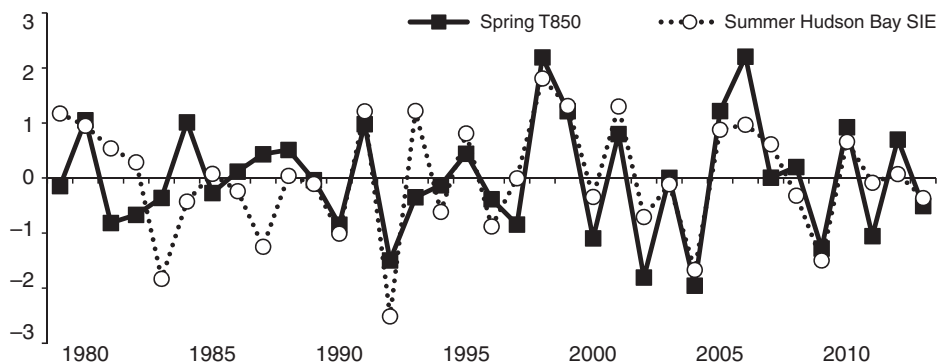
result, the summer SIEs between Hudson Bay and the Arctic Ocean are strongly positively correlated.

In contrast, the interannual variation between Hudson Bay and the Arctic Ocean using the detrended summer SIE show a weak correlation. The summer SLP pattern associated with the detrended SIEs in both Hudson Bay and the Arctic Ocean is reflective of the anticyclonic circulation over the Arctic Ocean. However, the atmospheric anomalies associated with the detrended Hudson Bay SIE (Figure 3(b)) are weaker than the anomalies associated with the detrended Arctic

Ocean SIE (Figure 3(c)). The summer SLP correlated with the detrended Arctic SIE (Figure 3(c)) shows strong positive anomalies over the Arctic Ocean as compared with the anomalies correlated with the Arctic SIE (Figure 1(c)). It is known that the summer anticyclonic circulation and air temperature anomalies over the Arctic Ocean are associated with the year-to-year variation of the September Arctic SIE (Ogi and Wallace, 2007; Ogi *et al.*, 2016). The summer anticyclonic circulation over the Arctic Ocean has favored enhanced sea ice export from the Arctic toward Fram Strait. Ogi *et al.*



**Figure 4.** Spring (a) SLP and (b) T850 regressed on the inverted detrended summer Hudson Bay SIE. Green box is 240°–300°E and 50°–70°N.



**Figure 5.** The time series of the standardized indices of the detrended spring T850 over Hudson Bay (green box in Figure 4(b), black squares) and the inverted detrended summer Hudson Bay SIE (open circles) (correlation coefficients,  $R = 0.67$ ).

(2016) indicated that the summer atmospheric circulation associated with the September Arctic SIE in both the original and detrended data is similar to the summer AO pattern, although the recent strong anticyclonic circulation has a greater influence on the recent low Arctic SIE than the seesaw pattern of the summer AO.

In this study, we showed that the year-to-year variation of the detrended summer Hudson Bay SIE is influenced by the atmospheric anomalies in the previous spring. The spring SLP pattern associated with the summer Hudson Bay SIE shows negative anomalies over the Bering Sea and a seesaw pattern over the North Atlantic Ocean similar to the North Atlantic Oscillation (Figure 4(a)). The spring T850 associated with the detrended summer Hudson Bay SIE shows warm anomalies over Hudson Bay (Figure 4(b)). In the spring, the surface air temperature surrounding Hudson Bay and the wind forcing over the North Atlantic Ocean and the Hudson Bay accounted for the interannual variation in the Hudson Bay SIE (Hochheim and Barber, 2014). The spring open water in Hudson Bay is capable of absorbing solar heat that can be released back to the atmosphere. As a result, the variations of the Hudson Bay SIE in spring are

linked to the spring air temperatures. The Hudson Bay SIE variabilities in spring may influence the summer Hudson Bay SIE conditions. As a result, the summer Hudson Bay SIE is associated with the atmosphere and the air temperature in the previous spring.

In this paper, we clearly show that the trend of the summer SIE in Hudson Bay and the Arctic Ocean are strongly correlated via the summer atmospheric conditions and temperature trends. On the other hand, the year-to-year variations of these SIEs show little correlation, because the interannual variation of summer Arctic Ocean SIE is influenced by the summer atmosphere and temperature over the Arctic Ocean. Instead, the interannual variation of the summer Hudson Bay SIE is influenced by the atmosphere and air temperature in the previous spring. This teleconnection is important if we are to understand the linkages between the high Arctic Ocean sea-ice cover, the lower latitude Hudson Bay ice cover, and the climate drivers affecting both regions.

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