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SHORT COMMUNICATION

EXAMINATION OF TRENDS IN HOURLY SURFACE PRESSURE IN CANADA DURING 1953–2003

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ABSTRACT

Hourly values of surface pressure recorded at 90 stations across Canada during 1953–2003 were examined. For each station, a linear trend was fitted to the data and a statistical *t*-test determined whether the trend was significant at the 5% level. Most of the stations located above 60 °N latitude reported a statistically significant decrease in winter pressure averaging −5.8 hPa over the 50 year period which is likely a manifestation of the Arctic oscillation (AO). This winter pressure decrease is slightly larger than that found in other studies that determined sea level pressure trends during 1948–1998 using reanalyzed datasets. The present work found fewer and weaker statistically significant trends for the northern stations during the other seasons. Very few stations in southern Canada had significant trends in any season. The data were also examined for possible inhomogeneities, but none that affected the aforementioned conclusions were found. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: pressure; Arctic; trends

1. INTRODUCTION

A number of studies have found evidence of global climate change (Hurrell, 2003; Intergovernmental Panel on Climate Change, 2001). For Canada, significant changes affecting temperature, precipitation and relative humidity have been documented during the past century (Zhang *et al*., 2000; van Wijngaarden and Vincent, 2004). These changes may be due to changes in global circulation patterns that cause one region to cool simultaneously as warming occurs elsewhere. For example, it has been known for centuries that mild winters in northern Europe coincide with severe winters in southern Greenland and vice versa (Sturm *et al*., 2003). This correlation arises from the so called North Atlantic Oscillation (NAO) whose strength is determined by the difference in pressures over Iceland and the Azores (Hurrell, 2003). A strong NAO indicates a strong high pressure center over the Azores and anomalously low pressure over Iceland. Trends of a stronger NAO in recent decades are believed to have reduced the severity of winter weather over most middle and high latitude Northern Hemisphere continental regions while northeastern Canada and southern Greenland have cooled (Thompson and Wallace, 2001; Ostermeier and Wallace, 2003).

In 1998, Thompson and Wallace suggested the NAO is part of a much larger oscillation, called the Arctic Oscillation (AO), affecting the entire Northern Hemisphere (Thompson and Wallace, 1998; Thompson and Wallace, 2000; Thompson *et al*., 2000; Deser, 2000; Ambaum *et al*., 2001). They reported a pressure decrease of 4 hPa over parts of the Arctic during winter over the period 1968–1997. A recent study (Gillett *et al*., 2003) also found a pressure decrease in the Arctic during the winter (Hurrell, 2003). They evaluated trends

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for sea level pressure using decadal mean data found using three datasets. These datasets resulted from a reanalysis of pressure measurements collected from a variety of sources and were generated by the Hadley Centre of the United Kingdom Meteorological Office (Basnett and Parker, 1997), the National Center for Environmental Prediction/National Center for Atmospheric Research NCEP/NCAR (Kalnay *et al*., 1996) and also included an updated 'Trenberth dataset' (Trenberth and Paolino, 1980). Data collected at various locations were interpolated permitting the reanalyzed data to have global coverage. Sea-level pressure trends found using the three datasets separately agreed except over Greenland and the Himalayas. The discrepancies are believed to arise because of differences in how sea level pressure was deduced from surface pressure. Over the Canadian Arctic during winter, sea level pressure was found to have decreased by 3 to 4 hPa during 1948–1998.

Considerable effort to model the AO and NAO is underway (Baldwin, 2001; Hurrell, 2003; Osborn, 2004; Rauthe *et al*., 2004). Some studies indicate an association with a cooling trend in the stratosphere from the 1960s to the 1990s (Shindell *et al*., 1999; Zhou and Miller, 2001), while other models do not find such a link (Fyfe *et al*., 1999). Recent work indicates that changes in winter Arctic pressure may be caused by human activity (Gillett *et al*., 2003). Gillett *et al*. considered the effects of increased concentrations of greenhouse gases and sulphate aerosols using four different global climate models. The simulated trends have a similar geographic pattern when compared to observations but have a smaller magnitude. For example, the models account for a pressure decrease over the Canadian Arctic during 1948–1998 of only 1–2 hPa.

Direct evidence of a decrease of sea level pressure in the central Arctic has been obtained using data collected from buoys in the Arctic Ocean. Average pressure during 1987–1994 was about 3 hPa lower than during 1979–1986 (Walsh *et al*., 1996). The largest decrease was observed during winter and likely affects the movement of Arctic ice (Rigor *et al*., 2001). A correlation between the AO and Arctic sea-ice cover has been found using monthly sea-ice data for the period 1901–1997 (Wang and Ikeda, 2000). It has been suggested that a stronger AO causes a greater inflow of Atlantic water into the Arctic Ocean. Submarine data indicates Arctic waters at depths between 200 and 800 m have warmed by 0.5–1 °C since the 1950s (Macdonald, 1996).

Nearly all of the work done to date has relied on a reanalysis of records of sea level pressure and geopotential height. For example, the NCEP/NCAR dataset interpolates various measurements to provide global data that are gridded on a 2.5° latitude × 2.5° longitude mesh. There has also been some work that has examined station records of pressure measurements. For example, mean monthly sea level pressure was examined for 51 stations located predominantly in the three prairie provinces of Canada, and indications that pressure decreased during the period 1956–1993 (Nkemdirimn and Budikova, 2001) were found. The trends were largest in winter and spring with northern stations experiencing the largest pressure change.

The objective of this work was to examine whether there were significant trends in pressure over Canada during the period 1953–2003. The analysis used station pressure data rather than sea level pressure since a variety of errors have been found in the records of sea level pressure that have been calculated from the measured station pressure (Graham and Slonosky, 2004). This work studied data collected at 90 stations located throughout Canada, which are listed in Table I. These were mostly airport stations that measure pressure hourly.

Digital records of climate data for the period 1953–2003 were retrieved from the National Climate Data and Information Archive of the Meteorological Service of Canada, Environment Canada. The database contains climate observations from several hundred stations across the country, with some data starting as early as the end of the 1890s. The 90 stations considered in this study were extracted from this database using the criteria that less than 0.1% of the data was missing. Hourly observations first began at airports in the late 1940s and early 1950s. These observations have been accumulated in digital form only since 1953. Pressure was recorded with a precision of 0.1 hPa using a mercury manometer (Atmospheric Environment Service Canada, 1961, 1970, 1976). The climate stations were operated by a variety of organizations including the Canadian Defense Department, the Meteorological Service of Canada and volunteer observers. Some stations, primarily in the Arctic, only became operational in the late 1950s and a few stations such as Mould Bay, Nunavut and Inukjuaq, Quebec were closed in the 1990s.

Table I. List of stations considered in this study

Station name	Latitude	Longitude	Observation period[a]	Data missing/incorrect (%)
Windsor A	42.27	82.97	–	<0.1
London A	43.03	81.15	–	<0.1
Yarmouth A	43.83	66.08	–	0.1
Sable Island	43.93	60.02	–	1.3
Shearwater A	44.63	63.5	–	0.2
Wiarton A	44.75	81.1	–	0.1
Greenwood A	44.98	64.92	–	0.1
Saint John A	45.32	65.88	–	0.1
Ottawa Int	45.38	75.72	–	<0.1
Sherbrooke A	45.43	71.68	1963–	<0.1
Fredericton A	45.87	66.53	–	0.1
Gore Bay A	45.88	82.57	–	0.3
Moncton A	46.12	64.68	–	0.1
Sydney A	46.17	60.05	–	0.2
Charlottetown A	46.28	63.13	–	0.2
North Bay A	46.37	79.42	–	<0.1
Sault Ste Marie	46.48	84.52	1962–	<0.1
St John's A	47.62	52.75	–	0.2
Val-D'Or A	48.05	77.78	1955–	<0.1
Bagotville A	48.33	71	–	<0.1
Thunder Bay A	48.37	89.33	–	<0.1
Bonavista	48.4	53.07	1960–	0.3
Stephenville A	48.53	58.55	–	2.7
Mont Joli A	48.6	68.22	–	<0.1
Victoria A	48.65	123.43	–	<0.1
Gander Int A	48.95	54.58	–	0.2
Abbotsford A	49.03	122.37	–	<0.1
Estevan A	49.22	102.97	–	<0.1
Kapuskasing A	49.42	82.47	–	<0.1
Lethbridge A	49.63	112.8	–	<0.1
Comox A	49.72	124.92	–	<0.1
Kenora A	49.78	94.37	–	<0.1
Brandon A	49.92	99.95	1958–	0.2
Winnipeg Int A	49.92	97.23	–	<0.1
Medicine Hat A	50.02	110.72	–	<0.1
Sioux Lookout A	50.12	91.9	–	<0.1
Daniels Harbour	50.14	57.34	–	5.4
Sept-Iles A	50.22	66.27	–	<0.1
Swift Current A	50.3	107.68	–	0.3
Regina A	50.43	104.67	–	<0.1
Port Hardy A	50.68	127.37	–	<0.1
The Pas A	51.1	100.05	–	<0.1
Calgary A	51.12	114.02	–	<0.1
Saskatoon A	52.17	106.72	–	<0.1
Wabush Lake A	52.93	66.87	1961–	<0.1
Quesnel A	53.03	122.52	–	0.3
Prince Albert A	53.22	105.67	–	<0.1
Sandspit A	53.25	131.82	–	0.2
Edmonton A	53.32	113.58	1961–	<0.1
Goose A	53.32	60.42	–	0.1

(*continued overleaf*)

Table I. (*Continued*)

Station name	Latitude	Longitude	Observation period[a]	Data missing/incorrect (%)
Cartwright	53.72	57.03	1955–	6.8
Prince George A	53.88	122.68	–	<0.1
Churchill A	53.97	101.1	–	<0.1
Prince Rupert A	54.28	130.45	1962–	0.1
Cold Lake A	54.42	110.28	1955–	<0.1
Schefferville A	54.8	66.82	–	0.2
Smithers A	54.82	127.1	–	<0.1
Kuujjuarapik A	55.28	77.77	1957–	<0.1
Peace River A	56.23	117.43	1955–	0.3
Fort St John A	56.25	120.73	–	<0.1
Fort McMurray A	56.65	111.22	–	<0.1
Kuujjuaq A	58.1	68.42	–	1.1
Inukjuaq	58.47	78.08	1953– 1995	31
Dauphin A	58.73	94.05	–	0.1
Fort Nelson A	58.83	122.6	–	<0.1
Fort Smith A	60.02	111.97	–	<0.1
Watson Lake A	60.12	128.82	–	0.2
Teslin A	60.17	132.75	–	1.5
Whitehorse A	60.72	135.07	–	<0.1
Hay River A	60.83	115.78	–	<0.1
Fort Simpson A	61.77	121.23	1964–	<0.1
Yellowknife A	62.47	114.43	–	<0.1
Mayo A	63.62	135.87	–	5.3
Iqaluit A	63.75	68.55	–	<0.1
Coral Harbour A	64.2	83.37	–	1.7
Baker Lake A	64.3	96.08	–	6.4
Norman Wells A	65.28	126.8	–	1.6
Broughton Island[b]	67.32	63.47	1961–	36
Cape Hooper[b]	68.28	66.48	1958–	36
Inuvik A	68.3	133.48	1961–	<0.1
Longstaff Bluff[b]	68.54	75.09	1958–	25
Hall Beach A	68.78	81.25	1956–	0.8
Cambridge Bay A	69.1	105.13	–	1.6
Cape Parry A	70.17	124.72	1956–	2.2
Clyde A	70.48	68.52	–	29
Sachs Harbour A	72	125.27	1957–	31
Resolute A	74.72	94.98	–	5.8
Mould Bay A	76.23	119.35	1953– 1996	43
Eureka	79.98	85.93	–	29
Alert[b]	82.52	62.28	–	60

[a] Only listed if data does not cover 1953–2003.
[b] Only four stations have significant numbers of obviously incorrect data: Alert (1155), Broughton Island (5049), Cape Hooper (5825) and Longstaff Bluff (4083).

2. METHODOLOGY

The hourly pressure data were first checked for obvious errors such as unphysical readings. For example, four stations in the Arctic reported several thousand pressure measurements exceeding 1200 hPa which were discarded as mentioned in Table I. The data were also checked whether pressure had changed by more than 3.9 hPa during any 2-h period. Less than 0.1% of the data consisted of such measurements and occurred

for stations in Newfoundland. This is not unexpected as the east coast of Canada is prone to strong storms causing sudden large pressure changes. The pressure trends were negligibly affected when such data were removed. The scarcity of incorrect measurements is not surprising given that pressure is relatively easy to measure compared to other atmospheric parameters and it is critical for aviation. Station records were examined and show that visits by external inspectors were carried out at least annually. Indeed, checking the proper calibration of the pressure instruments was the top priority on the list of instruments to be inspected.

Hourly data values of station pressure were averaged over four 6-h periods of the day (night 0–5 am, morning 6–11 am, afternoon noon–5 pm and evening 6–11 pm) as well as for each season to examine possible seasonal and diurnal trends. Seasons were defined as winter (December–February), spring (March–May), summer (June–August) and fall (September–November). This analysis accessed hourly data that are recorded for each date in the archives. There was no change in the aforementioned definitions of the seasons for each year of the analysis that encompassed the period from spring 1953 (March–May, 1953) until winter 2003 (Dec, 2002–Feb, 2003). In general, a myriad of factors affect a climatic variable potentially causing a nonlinear temporal dependence. It is not possible to predict the exact functional dependence as the various factors are not necessarily well understood or all are not even known (Zwiers and von Storch, 2004). It is therefore appropriate to fit a linear function to the data. This was done using a least squares fit and a t-test determined whether the linear trend was significant at the 5% level. A trendline was only fitted if 40 years of data were present.

3. RESULTS

Figure 1 shows data taken for Iqaluit, Nunavut for the four seasons. Clearly, winter and spring experience larger pressure changes during the 1953–2003 period compared to summer and fall. Figure 2 shows sample winter data for four coastal stations located in different climate regions of the country: Norman Wells (Northwest Territories), Iqaluit (Nunavut), St. John (New Brunswick) and Port Hardy (British Columbia). The two northern stations exhibit a downward pressure trend while the two southern stations show a slightly increasing trend.

The seasonal dependence of the pressure trends is shown in Figure 3. The trends found using data taken at different periods of the day were identical in every season. Significant seasonal differences are apparent and are summarized in Table II. Very few southern stations have statistically significant trends in any season. In addition, the few statistically significant trends that occur are not clearly clustered in a particular geographic region. There is a hint in spring of a slight overall pressure increase as 13 (4) stations report a statistically significant pressure increase (decrease) albeit out of a total 55 southern stations. In contrast, two-thirds of the

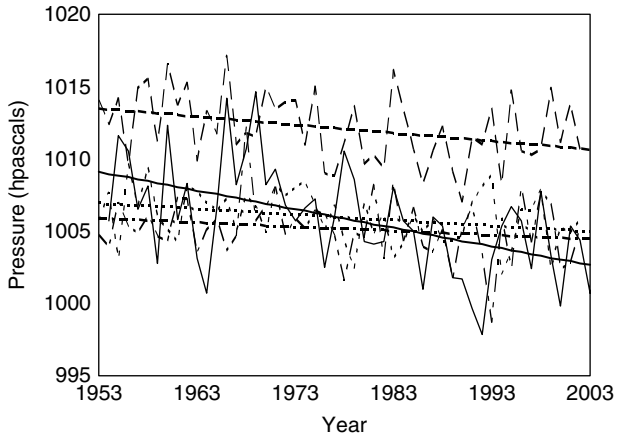

Figure 1. Seasonal pressure trends for Iqaluit located at latitude 63.75 °N. Symbols used are solid line for winter, large dashes for spring, small dashes for summer and dash dot for fall

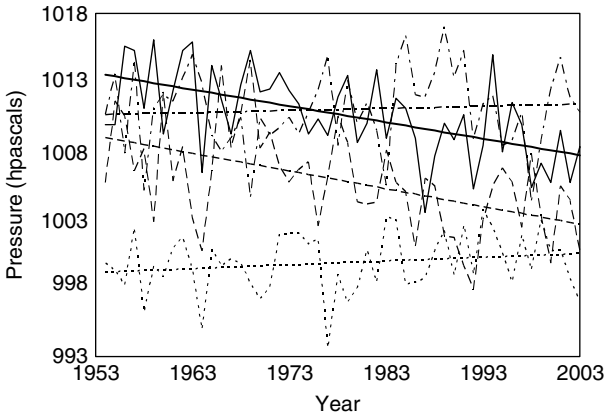

Figure 2. Trends in average winter pressure for Norman Wells (solid line), Iqaluit (large dashes), St. John (small dashes) and Port Hardy (dash dot)

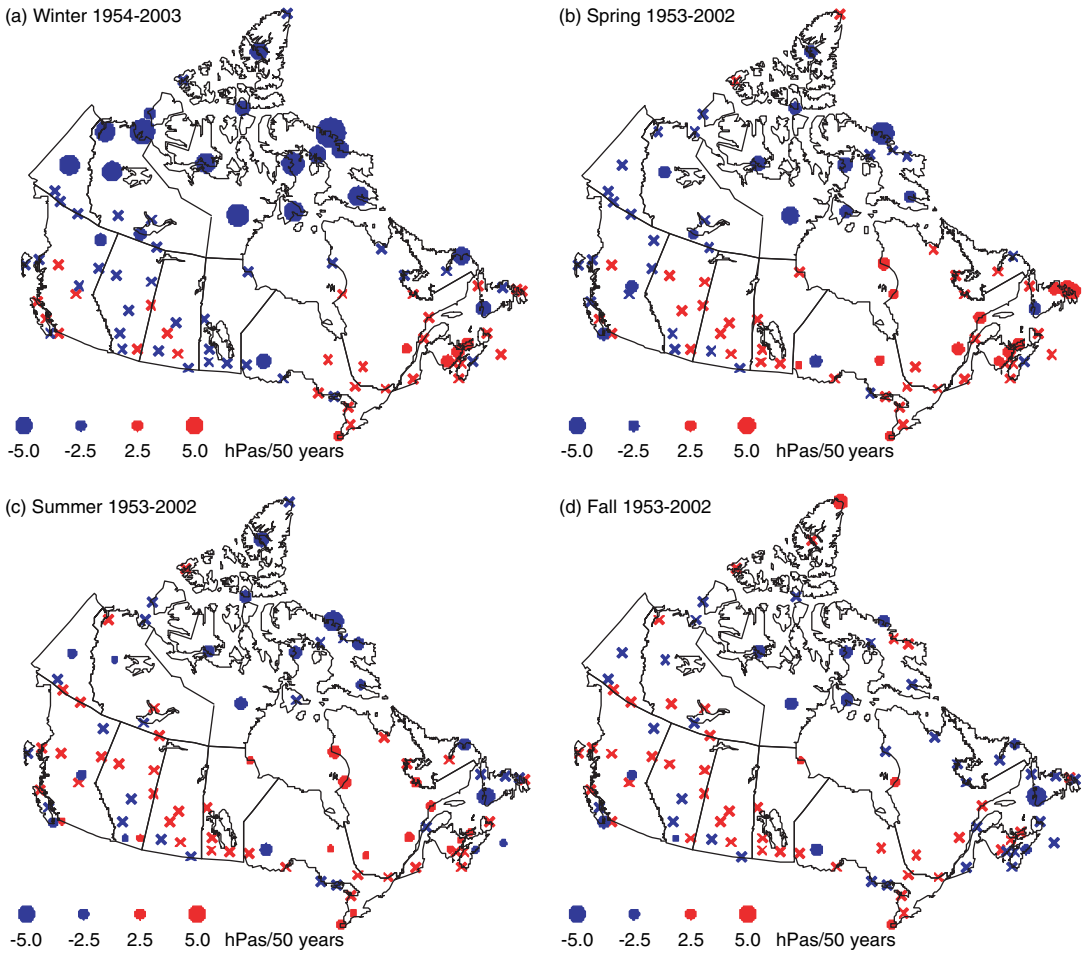

Figure 3. Pressure trends during 1953–2003 (a) winter, (b) spring, (c) summer and (d) fall. Red (blue) dots represent increasing (decreasing) pressure statistically significant at the 5% level. Crosses represent insignificant trends

northern stations experience significantly decreasing pressure in winter with an average pressure change of −5.8 hPa occurring over 50 years.

It is essential to carefully examine the data to check for possible inhomogeneities before concluding that the statistically significant pressure trends in the winter for Arctic stations may be a result of climate fluctuation or change. For example, changes in instruments and/or procedures have been shown to cause sudden decreasing steps in the determination of variables such as relative humidity (van Wijngaarden and Vincent, 2004). The seasonal averaged data of each individual station were therefore examined using two regression models. Model 1 is given by the following.

$$y_i = a_1 + b_1 t_i + e_i \tag{1}$$

Here, y_i is the seasonal surface pressure for year t_i and e_i is the residual. The estimate of the slope is given by b_1. The trends shown in Figure 3 resulted from applying Model 1 to the seasonal time series.

Model 2 was applied next to consider the existence of a potential step occurring at some unknown time in the time series.

$$y_i = a_2 + b_2 t_i + c_2 I + e_i \tag{2}$$

The estimate of the slope before and after the step is given by b_2 and c_2 is the step magnitude. The variable I is an indicator variable that takes the values 0 and 1, before and after the step year t_s respectively. The parameters a_2, b_2, c_2 and t_s were varied by the computer program to optimize the fit of Model 2 to the data.

Models 1 and 2 were compared using the following F-statistic to determine which model better fitted the data.

$$F = [SSE_1 - SSE_2]/[SSE_2/(n-3)] \tag{3}$$

Here, SSE_1 and SSE_2 are the sums of squared errors for models 1 and 2 respectively and n is the number of data points. Model 2 was accepted if the F-statistic exceeds the 95 percentile of the F-distribution with 1 and $n-3$ degrees of freedom (Neter *et al.*, 1985) while Model 1 was accepted otherwise. Step discontinuities

Table II. Trend dependence for stations north and south of 60 °N latitude. The brackets contain the average trends (hPa/50 years), which are only listed for the northern stations where a comparatively large fraction of the stations have statistically significant decreasing pressure trends during 1953–2003. Average trends are not listed for the southern stations since they would not be meaningful as most of these stations experience insignificant trends

Number of stations north of 60 °N latitude				
Season	Significant positive trend	Insignificant positive trend	Insignificant negative trend	Significant negative trend
Winter	0	0	8	16 (−5.8)
Spring	0	2	11	11 (−3.8)
Summer	0	6	8	10 (−2.9)
Fall	1	10	9	5 (−2.8)
Number of stations south of 60 °N latitude				
Season	Significant positive trend	Insignificant positive trend	Insignificant negative trend	Significant negative trend
Winter	5	29	27	4
Spring	13	35	13	4
Summer	15	29	14	7
Fall	3	31	24	7

were only found for a handful of stations. Only two stations, Ottawa and Stephenville, showed discontinuities occurring in the same year in all seasons. Cape Parry was the only Arctic station for which a step discontinuity was found during the winter. Hence, no evidence of inhomogeneities in the data that would affect the trend patterns shown in Figure 3 and summarized in Table II were found.

4. CONCLUSIONS

This study has found a statistically significant decrease in pressure during the period 1953–2003 in the Canadian Arctic. The decreasing trend is particularly evident in winter. Very few southern stations report significant trends in any season. This study encompassed a much larger geographic region and was taken over a considerably longer period of time than previous works, which used original station pressure data (Nkemdirimn and Budikova, 2001).

The magnitude of the pressure decrease for the Arctic stations in the winter is about 0.5% of the total atmospheric pressure. No inhomogeneities in the data that could account for this were found. Moreover, it is very unlikely that such a large trend could be caused by instrument malfunction. Pressure is a key parameter affecting aviation, and records show that strict instrumental checks/maintenance has been done at these primary airport stations on at least an annual basis.

The observed winter pressure decrease over the Canadian Arctic is slightly larger than that found in previous studies. One reason may be that the present work determined trends during 1953–2003, whereas Gillett *et al*., who used reanalyzed datasets, considered the period 1948–1998 (Gillett *et al*., 2003). This may indicate a strengthening of the AO. It is interesting that the winter pressure decrease over the Arctic found in this study as well as that obtained using the reanalyzed datasets are larger than those resulting from global climate models that simulate anthropogenic changes in the atmosphere during the last half century (Gillett *et al*., 2003). In conclusion, trends determined from surface pressure measurements not only test the reliability of reanalyzed datasets but also facilitate testing of climate models. Monitoring in northern regions such as Canada gives an indication of the strength of the AO, which has an important effect on the climate of the Northern Hemisphere.

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