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Teleconnection between the Arctic Oscillation and Hudson Bay river discharge

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[1] Rising surface air temperatures in response to anthropogenic forcing are intensifying the global hydrologic cycle. Some of the more dramatic signs of climate change are increasing precipitation, evaporation, and freshwater discharge in continental river basins draining to high-latitude oceans. At regional scales, however, an acceleration of the hydrologic cycle is not always detected. In contrast to its major Eurasian counterparts, the North American Hudson Bay Basin experienced a 15% decline in river runoff between 1964 and 1994. It is shown that the Arctic Oscillation explains with statistical significance up to 90% of the recent variability in Hudson Bay river discharge. This study reveals the important role of large-scale atmospheric phenomena such as the Arctic Oscillation in regulating the terrestrial hydrologic budget. The ability of weather and climate models to represent these interannual to decadal scale phenomena governs their predictions of the surface water budget's future state in a changing climate. *INDEX TERMS:* 1833 Hydrology: Hydroclimatology; 1836 Hydrology: Hydrologic budget (1655); 1860 Hydrology: Runoff and streamflow; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology. **Citation:** Déry, S. J., and E. F. Wood (2004), Teleconnection between the Arctic Oscillation and Hudson Bay river discharge, *Geophys. Res. Lett.*, *31*, L18205, doi:10.1029/2004GL020729.

1. Introduction

[2] The Arctic Oscillation (AO), also known as the Northern Hemisphere annular mode, composes the primary mode of interannual variability in the Northern Hemisphere [*Thompson and Wallace*, 1998, 2001]. The leading empirical orthogonal function (EOF) of mean sea-level pressure (SLP) north of 20°N during winter defines the AO's reference state. For a given time period, a projection of the SLP field onto the leading EOF characterizes the AO index, a measure of its intensity. A positive AO index value implies positive SLP anomalies at mid-latitudes and negative SLP anomalies at high-latitudes. This pattern induces a stronger than usual zonal flow that affects Northern Hemisphere meteorological conditions [*Thompson and Wallace*, 2001]. Increasing surface air temperatures (SATs), permafrost temperatures, precipitation, and evaporation over most of Eurasia and North America between the 1960s and 1990s accompany a positive trend in the AO index [*Thompson and Wallace*, 1998; *Walsh*, 2000; *Serreze et al.*, 2000, 2002; *Stieglitz et al.*, 2003]. A 7% increase (+128 $\mathrm{km^3\ yr^{-1}}$) in river runoff for the six largest Siberian river basins between 1936 and 1999 [*Peterson et al.*, 2002] is also associated with increasing AO index values.

[3] In contrast to its major Siberian counterparts, the Hudson Bay Basin (which includes the James Bay and Ungava Bay basins, hereafter referred to as HBB) experienced a 15% ($-106\ \mathrm{km^3\ yr^{-1}}$) decrease in measured discharge from 1964 to 1994 (S. J. Déry et al., Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964–1994, submitted to *Journal of Climate*, 2004). The HBB drains an area of $3.7 \times 10^6\ \mathrm{km^2}$ in North America and its freshwater discharge of $\sim 950\ \mathrm{km^3\ yr^{-1}}$ equates one fifth of the total annual river runoff to the Arctic Ocean [*Shiklomanov et al.*, 2000]. Ocean currents transport the HBB discharge to the Labrador Sea such that it affects high-latitude oceanographic, atmospheric, cryospheric, and biologic processes [*Sutcliffe et al.*, 1983; *LeBlond et al.*, 1996]. For 1968–2001, the HBB had a mean annual SAT of −2°C and approximately 30% (155 $\mathrm{kg\ m^{-2}}$) of its total annual precipitation of 550 $\mathrm{kg\ m^{-2}}$ fell as snow. Continuous and discontinuous permafrost exists within the HBB above 60°N [*Woo*, 1986].

[4] The recent decline in measured HBB discharge suggests evidence of a changing hydrologic cycle in this region. The principal objective of this study is to explore the nature of these changes; specifically, we investigate the existence of a teleconnection between large-scale atmospheric anomalies and river runoff anomalies to high-latitude oceans with a focus on the HBB hydrologic cycle during the past few decades. This will provide crucial information on the processes that need to be resolved by regional and global climate models to accurately predict the future state of the terrestrial water budget.

2. Methods

[5] For this study, the model-based European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data set provides global meteorological data of SAT, precipitation, evaporation, and river runoff as generated by a numerical weather prediction model using a constant analysis framework [*European Centre for Medium-Range Weather Forecasts*, available online http://data.ecmwf.int/data/d/era40_daily/, 2004]. The ERA-40 data used here include 6-hourly values of SAT, precipitation, evaporation, and river runoff for 1968–2001 on a 2.5° latitude by 2.5° longitude horizontal grid. This data set derives from the ECMWF numerical weather prediction model using a fixed analysis scheme. A subset of 80 model grid cells

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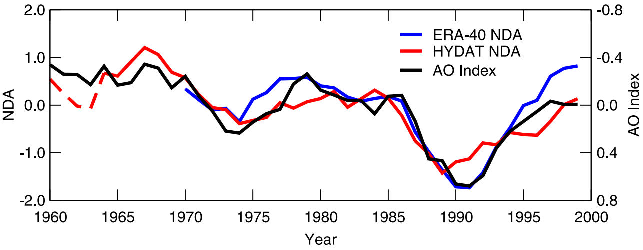

Figure 1. Five-year running means of the annual values of the AO index and of the normalized discharge anomalies (NDA) for the HBB between 1958 to 2001. NDA values are based on observational (HYDAT) and model (ERA-40) data. The dashed line represents the portion of the observed NDA time series inferred from *Shiklomanov et al.* [2000].

covering 3.5 × 10^6 km^2 represents the HBB. The ERA-40 precipitation and river runoff data at high northern latitudes prior to 1968 suffer large negative biases and are omitted in this study [*Betts et al.*, 2003]. A systematic underestimate also exists in the ERA-40 snow water equivalent data for Canada during 1990–1994 that reduces the modeled streamflow [*Betts et al.*, 2003]; however, the ERA-40 runoff data are not corrected to remove this bias since its effects on the results are minimal. Furthermore, the accuracy of the ERA-40 hydrologic cycle for 1968–2001 in HBB was verified using observed discharge rates from Environment Canada's Hydrometric Database (HYDAT) [*Government of Canada*, available online http://www.msc.ec.gc.ca/wsc/hydat/H2O/index_e.cfm, 2004] and observed precipitation from the Climate Research Unit (CRU) of the University of East Anglia [*New et al.*, 2000]. An analysis of 5-year running means of ERA-40 and HYDAT river discharge anomalies demonstrate their high level of agreement (correlation of 0.84, with probability <0.001). Monthly values of ERA-40 and CRU precipitation data also agree well (correlation of 0.96, with probability <0.001). The ERA-40 data set therefore provides spatially and temporally consistent meteorological fields that are reliable for the data sparse HBB. Hence the ERA-40 data set is selected as our source of meteorological data for the HBB and the remainder of the Northern Hemisphere.

[6] We also investigated the possibility of using the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data [*Kalnay et al.*, 1996]; however, the annual discharge rates for the HBB are more than twice the observed values and display little interannual variability. An alternative to the original NCEP/NCAR Reanalysis data set is its derivative, the NCEP-U. S. Department of Energy (DOE) Reanalysis II [*Kanamitsu et al.*, 2002]. Despite some improvements over the NCEP/NCAR Reanalysis, HBB river runoff inferred from NCEP-DOE Reanalysis II exhibits interannual variability that is nearly four times greater than observed and only covers the period 1979-present.

[7] Measured discharge rates for 42 HBB rivers from 1964 to 2001 are extracted from HYDAT (Government of Canada, http://www.msc.ec.gc.ca/wsc/hydat/H2O/index_e.cfm, 2004). These measurements cover 80% of the HBB and are divided by contributing area for comparison with the ERA-40 data. Dams, diversions, and reservoirs affect several HBB rivers including the Nelson, Churchill, Moose, and La Grande [*Vörösmarty and Sahagian*, 2000]. For example, the first phase of the James Bay hydroelectric complex involved the construction of several large reservoirs on La Grande Rivière between 1979 and 1986 [*Messier et al.*, 1986]. The total estimated capacity of these reservoirs is 182 km^3 of water (International Lake Environment Committee, http://www.ilec.or.jp/database/database.html, 2004). Filling of the reservoirs therefore accounts for a mean reduction of 23 km^3 yr^{-1} in river runoff to HBB during that period. The diversion of the Churchill River to the Nelson River system in 1976/1977 raised the water level of Southern Indian Lake by 3 m and its volume by 7 km^3. We added the water used to fill these reservoirs to the total annual observed discharge rates into HBB since this anthropogenic effect is omitted in the ERA-40 data. After 1980, the flow of La Grande Rivière is determined using a data set of monthly discharge rates corrected to remove the artificial control of upstream reservoir levels (R. Roy, unpublished data, 2004). This data set of observed river runoff constructed by Hydro-Québec provides the best estimate of the natural flow of La Grande Rivière after the construction of the James Bay hydroelectric complex. However, the regulation of water in other river systems and its contribution to HBB discharge is not quantified owing to the lack of precise mass flux data. This may account for some of the discrepancies between observed and ERA-40 discharge anomalies (see section 3). The network of HBB river gauges degrades appreciably prior to 1964. Discharge anomalies for 1958–1963 are therefore inferred from an alternate data set generated from the available HYDAT river runoff rates and correlation techniques [*Shiklomanov et al.*, 2000].

[8] The HYDAT database provides spatially and temporally integrated discharge rates at the outlet of 42 rivers that drain HBB whereas the ERA-40 provides instantaneous discharge rates for each ECMWF grid cell since the model excludes a river routing scheme. Thus to compare the annual observed and modeled discharge rates, a running mean of 5 years is chosen. For consistency, we also employ a 5-year moving average when comparing the meteorological fields with the AO index. The dominant timescale (2.4 to 9.0 years) of the AO further justifies this choice [*Robertson et al.*, 2001].

[9] The annual normalized discharge anomalies, defined as the difference between the annual and the mean annual discharge rates divided by its standard deviation, are computed for each time series of meteorological variables. These data are compared to a time series of the annual AO index values obtained from the Climate Diagnostics Center (National Oceanic and Atmospheric Administration, available online http://www.cdc.noaa.gov/ClimateIndices/, 2004).

3. Results

[10] Figure 1 shows that the ERA-40 discharge anomalies correspond well to measured river runoff anomalies (correlation of 0.84 for 1968–2001). The observations display decreasing HBB freshwater discharge from 1967 to 1975, then a nearly steady trend until 1985 when a significant decrease in river runoff occurs over 5 years. This is followed by a trend reversal with increasing river discharge over the next decade as measured in HBB. The time series

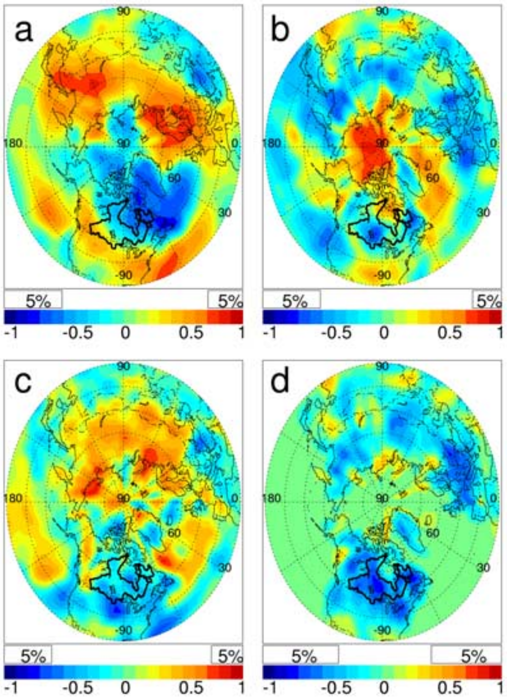

Figure 2. The correlation coefficient between the five-year running means of the annual values of the AO index and the ERA-40 grid point values of annual (a) mean SAT, (b) total precipitation, (c) total evaporation, and (d) total river runoff. The range of values significant at the 5% level, inferred from a two-tailed *t* test, is indicated on each color bar. The bold outline denotes the HBB.

of ERA-40 discharge anomalies shows similar behavior, with the exception that the model produces lower river runoff anomalies between 1990 and 1993 and higher river runoff anomalies between 1995 and 1999 than are observed. A potential source for these discrepancies is the regulation of water in artificial reservoirs, an anthropogenic process that is not resolved by the ECMWF model. Despite these differences, the observed and modeled discharge anomalies are both significantly correlated to the time series of the AO index over 1968–2001 (correlation coefficients of −0.88 and of −0.95, respectively, with probability values <0.001 in each case). For the period 1958–2001, the correlation coefficient between observed discharge anomalies and the AO index remains significant at −0.86. Hence the AO explains 75–90% of the variance in HBB river runoff anomalies.

[11] Figure 2 presents the correlation coefficients between the annual values of the AO index and the ERA-40 annual values of SAT, precipitation, evaporation, and river runoff at each model grid cell in the Northern Hemisphere. Significant negative correlations between the AO and SAT exist over Canada and Greenland whereas significant positive correlations prevail over Scandinavia, Siberia, and the western Atlantic Ocean. During the positive (negative) phase of the AO, northeastern regions of North America, including the HBB, experience cooler (warmer) than average SATs and northern Eurasia experiences warmer (cooler) than average SATs.

[12] Significant positive correlations between the modeled precipitation and the AO index are found over the Arctic Basin and, to a lesser degree, over the North Atlantic Ocean and Iceland. Prominent negative correlations are situated over the Eurasian and North American continents. The positive phase of the AO favors evaporation over northern Eurasia but hinders evaporation over most of North America.

[13] The interplay between precipitation and evaporation yields the amount of water available for river runoff over the land surface. The final panel in Figure 2 illustrates the significant negative correlation between the AO index with the ERA-40 discharge rates over nearly all continental regions of the Northern Hemisphere. A striking aspect of this plot is the limited regions where a positive correlation between the AO and the modeled river runoff appears in the Northern Hemisphere. The most prominent negative correlations between the AO and river runoff coincide with the HBB. Discharge is restricted to the land surface such that zero correlations are found over the oceans.

[14] Figure 3 provides correlations between the AO index and the normalized anomalies of the four main meteorological variables examined in this study. The meteorological data represent ERA-40 annual means or totals that are areally-averaged over the HBB for each of the 34 years of interest. The slope of the linear regression between the AO index and precipitation is greater (in absolute terms) than for evaporation. Thus the river runoff anomalies computed by the ECMWF model are driven more so by changes in precipitation than by evaporation. Although the AO corresponds only moderately to precipitation and evaporation, the interplay between these two processes on the land surface yields river discharge rates that are highly correlated to the AO. A notable characteristic of the correlations is a tendency for the meteorological data to cluster more closely along the linear regressions during the positive phase of the AO. This signifies that atmospheric

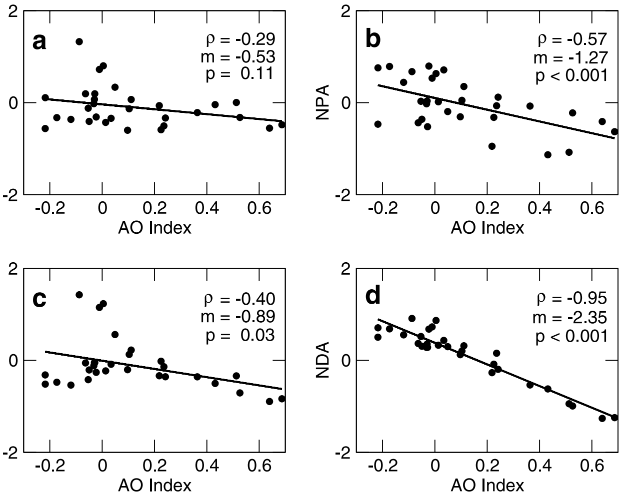

Figure 3. Relationship between the five-year running means of the annual values of the AO index and the ERA-40 annual (a) normalized SAT anomalies (NTA), (b) normalized precipitation anomalies (NPA), (c) normalized evaporation anomalies (NEA), and (d) normalized discharge anomalies (NDA) for the HBB between 1968 and 2001. The correlation coefficients (ρ), slopes (m), and probability values (p) for the linear regressions (solid lines) are also indicated.

and land surface processes in HBB are more tightly coupled to the positive phase of the AO rather than its negative phase.

4. Concluding Discussion

[15] This study provides evidence of a teleconnection between the AO and HBB river discharge operating at interannual to decadal timescales. The simulation of HBB river runoff by the ECMWF model reproduces the salient features of observed river discharge rates that correlate well with the AO. Although a statistical link between the AO and the observed and modeled streamflow in HBB is established, research into the physical mechanism is needed. *Thompson and Wallace* [2001] provide some insights on the possible mechanism driving this teleconnection. They show that the climatological SLP pattern during the negative phase of the AO favors northeasterly winds that advect relatively warm, moist air from the Labrador Sea to the HBB. In contrast, the positive phase of the AO is associated with a SLP pattern that generates a northwesterly flow which advects relatively cool, dry air from the Canadian Archipelago to the HBB. The source area of the dominant air masses affecting the HBB dictate its precipitation, evaporation, and river runoff. This suggests a direct link between the AO and the HBB terrestrial water budget. In a future study, the authors plan to further study this relationship through a comprehensive water budget study for the HBB that includes the role of atmospheric moisture convergence onto the basin during the alternating phases of the AO.

[16] The representation of regional trends and variability in the hydrologic cycle by regional and global climate models is therefore regulated by their ability to simulate interannual to decadal scale oscillations such as the AO. The current generation of climate models generally has difficulty representing the intensity of this phenomenon [*Moritz et al.*, 2002]. This yields uncertainty in the regional predictions of the state of the hydrologic cycle and highlights the need to better comprehend the mechanisms driving the AO. It has been hypothesized that the AO is an internal mode of variability in the climate system [*Baldwin*, 2001; *Feldstein*, 2002]. Others have found that an external forcing such as sea surface temperature anomalies in the North Atlantic Ocean or snow cover anomalies in Siberia can excite the atmosphere into a state resembling the AO [*Robertson*, 2001; *Gong et al.*, 2003]. Future efforts involving coupled atmospheric/oceanic/land surface models supported by precise observations are necessary to better understand the role of the AO on the global hydrologic cycle and its potential future state.

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