Evidence from driftwood records for century-to-millennial scale variations of the Arctic and northern North Atlantic atmospheric circulation during the Holocene

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Abstract.

Different Holocene sea-ice drift patterns in the Arctic Ocean have been hypothesized by Dyke et al. from radiometric analyses of driftwood collected in the Canadian Arctic Archipelago. A dynamic-thermodynamic sea-ice model is used to simulate the modes of Arctic Ocean ice circulation for different atmospheric forcings, and hence determine the atmospheric circulations which may have accounted for the inferred ice drift patterns. The model is forced with the monthly mean wind stresses from 1968 (a year with very large ice export) and 1984 (very low ice export), two years with drastically different winter sea level pressure patterns and with different phases of the NAO index. The simulations show that for the 1968 wind stresses, a weak Beaufort Gyre with a broad Transpolar Drift Stream (TDS) shifted to the east are produced, leading to a large ice export from the Arctic. Similarly, the 1984 wind stresses lead to an expanded Beaufort Gyre with a weak TDS shifted to the west and a low ice export. These results correspond to the patterns inferred by Dyke et al. Based on the simulations, the driftwood record suggests that for centuries to millennia during the Holocene, the high latitude average atmospheric circulation may have resembled that of 1968, 1984 and today's climatology, with abrupt changes from one state to the other.

Introduction

Driftwood enters the Arctic Ocean from bank erosion by North American (NA) and Eurasian rivers as they traverse the boreal forests. The forest composition on either side of Bering Strait is different; NA wood is dominated by spruce, whereas wood from Siberia is dominated by larch. The logs are transported away from these sources by sea ice moving with the surface ocean currents, and several years later, some of them strand on the shores of the Canadian Arctic Archipelago (CAA), Greenland, Svalbard and Iceland (Figure 1). This process has been operating since the postglacial establishment of the boreal forests, about 10 ka BP. It has left a rich driftwood record that has been interpreted in terms of changing sea-ice drift patterns [*Dyke et al.*, 1997, hereafter DERJ97]. In this paper, we explore mechanisms for these changes in terms of atmospheric forcing. Figure 1

The pattern of annual mean sea-ice drift in the Arctic Ocean has two features (Figure 1): the anticyclonic Beaufort Gyre, and the Transpolar Drift Stream (TDS), extending from the Siberian coast to Fram Strait. NA spruce is delivered into the fringe of the Beaufort Gyre, which feeds into the right-hand side of the TDS. Siberian larch enters the center of the TDS and western Eurasian wood, mainly spruce and pine, enters the left-hand side. For this reason, DERJ97 interpreted the changes in driftwood delivery to the CAA and Baffin Bay as resulting from changes in the path of the TDS.

The driftwood record reveals changes of two sorts. First, the influx has not been constant in any one region. Rather, abrupt changes of influx, with low probabilities ($<$ 1%, [DERJ97]) of these being due to chance, are recognized. For example, during many intervals, incursion of wood to the CAA via the Beaufort Gyre is negatively correlated with incursion of wood to Baffin Bay via the West Greenland Current, delivery in one region occurs at the expense of delivery to the other. However, at other times, wood is delivered evenly to both regions. Second, the mix of spruce and larch has also changed. At times, only NA spruce arrived in the CAA; at other times, a nearly equal mix of spruce and Siberian larch arrived. The flux of wood to Baffin Bay was always dominated by spruce whereas the flux to Svalbard was dominated by larch. Mean sea-ice drift patterns suggest that spruce arriving in Baffin Bay could originate either from western North America or western Eurasia.

DERJ97 postulated three modes of wood transport in the Arctic Ocean to account for these changes in the driftwood record. In one mode, the conventional TDS is shifted to the west[1] resulting in a greatly expanded Beaufort Gyre, and wood delivery to the CAA. In another, the TDS is shifted to the east and all wood exits Fram Strait. In a third mode, the TDS is split to the north of Greenland and wood is delivered to both regions (Figure 1). If this hypothesis of a shifting TDS is correct, the driftwood record indicates that these different modes of circulation were each stable, or at least dominant, for centuries to millennia during the Holocene, and that the system is prone to switching.

In the following, we explore the validity of the hypothesis of postglacial oscillations of the TDS and we evaluate its paleoclimatic significance. In the next section, descriptions of the driftwood data and wood delivery routes are presented. Finally, the sea-ice model used to derive different modes of circulation is briefly described, and the model simulations showing sea-ice circulation patterns are presented and discussed for contrasting atmospheric forcing fields.

Data description and incursion history

A total of 299 driftwood samples from isostatically raised beaches of the CAA were analyzed by DERJ97. The ages of the samples range from 8.9 ka BP to the present,

[1]By "shifted to the west (east)", we mean that the TDS north of Greenland and north of Eurasia is shifted to the west (east). This leads to a TDS which mainly recirculates in the central Arctic (mainly exits through Fram Strait).

and typically have two standard-deviation error bars of 40 to 50 years. The main types of driftwood found are spruce and larch; however, pine also occurs, as well as rare hemlock, willow, birch and poplar. The present wood identification method, based on cell morphology, determines the wood genus, but not species of conifers, except pine. Therefore, it is not possible to distinguish NA wood from Eurasian wood. However, the relative abundance of the two main wood types (larch/spruce) is markedly different on the two continents and can be used to infer the origins of the driftwood, provided that the forest compositions remained similar during the Holocene. The western Canadian boreal forest achieved its modern composition about 6 ka BP. The boreal forest, west of Hudson Bay, is dominated by spruce, whereas larch is dominant in eastern Siberia, followed by pine (note that spruce is absent). Spruce increases westward in Siberia, but still accounts for less than 1 % south of the Laptev Sea. Spruce dominates in western Siberia south of the Kara Sea, but little or no wood from there can reach the CAA today. Some of this spruce could reach Baffin Bay, however.

Wood entering the Arctic Ocean will remain buoyant for approximately 12 months for larch and 17 months for spruce. Since several years are required for the wood to cross the Arctic Ocean, sea ice is the necessary transport mechanism for stranded wood in the CAA. For this reason, changes in quantity and type of wood delivered to a given region are interpreted as a change in sea-ice drift and upper ocean circulation pattern.

Most of the CAA can only receive wood from the north. In contrast, eastern Jones and Lancaster sounds, Smith Sound and eastern Baffin Island can receive wood either from the Arctic via Nares Strait or from Baffin Bay via the East and West Greenland Currents (Figure 1). Figure 2 shows a summary of the TDS excursions during the last 8.5 ka as derived by DERJ97 from the driftwood data. The position of the TDS seems to have shifted abruptly (40-to-50 year time scale) with century-to-millennial scale stable periods between shifts. Note that the time it takes for wood to travel from the Beaufort Sea to Baffin Bay is about 10 years, a fraction of the error bar on a driftwood

Figure 2

age. A large number of shifts occurred between 5 and 6 ka BP, and relatively stable periods occurred before 6.75 ka and in the Neoglacial period (4 - 0.25 ka BP). Another change in the TDS occurred about 250 a BP, which appears to coincide with a rapid environmental change in high-Arctic ecosystems [*Douglas et al.*, 1994,], and a sudden warming on Ellesmere Island [*Beltrami and Taylor*, 1995,].

Sea ice model

For large-scale simulation of the Arctic sea-ice cover forced by monthly averaged wind stress, both the advection and acceleration terms can be neglected in the two-dimensional sea-ice momentum equation. The remaining terms in the momentum equation include the wind stress on the top of the ice, the ocean drag, the internal ice stress term resulting from ice floe interations, the sea surface tilt term and the Coriolis term. The wind stress and ocean drag are obtained from a simple quadratic law with constant turning angle [*McPhee*, 1975,]. In this model, the sea ice is assumed to behave as a granular material in slow continuous deformation. The resistance of sea ice to compressive load is considered to be a function of its thickness and concentration, and its shear resistance is proportional to the internal ice pressure at a point. In divergent motion, the ice offers no resistance, and the floes drift freely. A detailed description of the sea-ice dynamic and thermodynamic models can be found in [*Tremblay and Mysak*, 1997].

Sea-ice model and simulation results

The sea-ice motion is determined from a balance between the wind stress on the top of the ice, the ocean drag, the internal ice stress resulting from ice floe interactions, the sea surface tilt and the Coriolis term. In this model, the sea ice is assumed to behave as a granular material in slow continuous deformation. A detailed description of the sea-ice dynamic and thermodynamic models can be found in [*Tremblay and Mysak*, 1997].

This model is used to determine whether a westward, split or eastward wood delivery route can be reproduced using wind patterns observed during the last 30 years. To do this, we analyze two anomalous years: 1968, a year with large ice export into the Greenland Sea; and 1984, a year with little ice export. During these two years, the large-scale sea level pressure (SLP) fields were very different (Figure 3a-b show the winter patterns). Figure 3a-b

The sea-ice model is applied to the Arctic Ocean and surrounding seas using a grid resolution of one degree latitude. The model is forced with monthly mean wind stresses, derived from the daily NMC sea level pressure analysis, steady but spatially varying ocean currents, and climatological monthly mean (1954-1989) air temperatures. The model was integrated for two periods of 8 years, first with 1968 and then with 1984 wind stress fields. This allowed a stable periodic seasonal cycle to be reached for each type of forcing using a one-day time step. In both runs, the ocean currents and air temperature were kept the same. In reality, the ice motion would in turn influence the ocean currents, and the mean sea level pressure and temperature fields; this fact is ignored in order to isolate the effect of wind forcing on the sea ice drift pattern. The September conditions produced in these two simulations were then used as initial conditions for two six-year runs with a passive tracer (representing driftwood) positioned at the center of each grid cell. The first run used 1968 monthly averaged wind stresses and the other used 1984 monthly averaged wind stresses. Tracer positions were recalculated at each time step, from the interpolated ice or upper ocean velocity vector at the tracer location. For ice concentrations in a grid cell below 50 %, the tracers are assumed to be carried by the water, and for ice concentrations above 50 %, they are assumed to be carried by the ice.

The results shown in Figure 3 include the SLP patterns for winter (DJF) 1968 and winter 1984, and spaghetti plots (passive tracer trajectories) resulting from the two six-year runs including the potential source regions for driftwood found in northern Baffin Bay and driftwood found in the central CAA.

In winter 1968, the Icelandic Low was weak and had two centers, one south of Greenland and one in the northern part of the Norwegian Sea (Figure 3a). A negative sea level pressure anomaly was also present in the central Arctic. These features helped produce surface winds north of Greenland which carried large quantities of ice out of the Arctic through Fram Strait [*Chapman and Walsh*, 1993,]. During this time, the TDS was broad and shifted to the east, resulting in a strong East Greenland Current and very cold temperatures in the northern North Atlantic [*Chapman and Walsh*, 1993,], while the Beaufort Gyre was mostly confined to the western Arctic (Figure 3c). Given this atmospheric circulation, driftwood originating from the Mackenzie Delta, the Alaskan, Siberian and Russian coasts will be carried out of the Arctic by the Beaufort Gyre and the TDS (Figure 3c). A few years later, the specimens would be found in northern Baffin Bay and the eastern part of the CAA, after being transported by the East and West Greenland Currents.

In winter 1984, the Icelandic Low had a single deep center situated around Iceland (Figure 3b), and the isobars over the central Arctic Ocean were oriented towards the CAA. This resulted in an expanded Beaufort Gyre, a weakened TDS shifted to the west and an even weaker East Greenland Current (Figure 3d). During this time, northern Europe was anomalously warm [*Chapman and Walsh*, 1993,]. Given this atmospheric circulation, driftwood from NA and East Siberian rivers would get caught in the Beaufort Gyre and strand on the beaches of the CAA via the currents which flow southeastward through the CAA channels to Baffin Bay. Driftwood from west Siberian and possibly European rivers would be found in Svalbard and northern Baffin Bay, provided there was sea ice to carry it.

Simulation results with monthly climatological (1959-1984) wind stresses (not shown here) resulted in a Beaufort Gyre and a TDS similar to the climatological ice drift pattern (Figure 1). Given this atmospheric circulation, driftwood of Eurasian origin is found on the coast of Svalbard and northern Baffin Bay and wood of NA origin is found in the CAA and northern Baffin Bay. Note, however, that the driftwood record is incapable of distinguishing between an interval of stable "split" configuration, and an interval of sub-century scale variability with several switches between the two "non-split" configurations; this is due to limitations in the dating precision.

It is interesting to note that the year 1968 coincided with a negative North Atlantic Oscillation (NAO) index [*Hurrell*, 1995,] while 1984 coincided with a positive NAO index. In general, a positive phase of the NAO is characterized by stronger mid-latitude westerlies, and anomalous easterlies north of Greenland [*Hurrell*, 1995, figure 1b]. The latter will contribute to an expanded Beaufort Gyre, a reduced TDS shifted to the west and a reduction in ice export into the Greenland Sea (Figure 3b-d). During a negative phase of the NAO, anomalous westerlies are present north of Greenland, resulting in a reduced Beaufort Gyre, a TDS shifted to the east and an increase in ice export into the Greenland Sea (Figure 3a-c). It is thus plausible that, in the last 10 ka, the atmospheric circulation resembled, in the mean, the positive NAO pattern during periods when mode 1 was dominant, the negative NAO pattern when mode 3 was dominant and today's climatology when mode 2 was dominant (Figure 2). A direct link between the NAO and ice export, however, remains to be demonstrated.

The above simulated sea-ice drift patterns can thus account for the driftwood delivery routes hypothesized by DERJ97. Furthermore, such sea-ice drift patterns can be produced by wind forcings of the type that have occurred during the past few decades. If the character of the Icelandic Low is the main determinant of these states, the Holocene Arctic driftwood record has broad significance to the high latitude paleoclimate.

Conclusions

Based on the age and type of driftwood samples collected on the raised beaches of the CAA, postglacial oscillations of the Transpolar Drift Stream have been hypothesized

[*Dyke et al.*, 1997,]. During the last 8.5 ka, long periods (from centuries to a few millennia) existed when wood of North American and Siberian origin was found on the beaches of northern Baffin Bay, a region mainly accessible via the East and West Greenland Currents, or on those beaches of the CAA, that are only accessible from the north and northwest through various channels and straits. From these observations, it was hypothesized that a small Beaufort Gyre and a broad TDS shifted to the east, or a large Beaufort Gyre and a TDS shifted to the west, were mainly responsible for the observed change in wood delivery.

Results from two six-year integrations of a coupled ocean-sea-ice model using widely different observed wind stress forcing fields lend support to this hypothesis, provided a given forcing field was stable over long periods. For wind forcing typical of 1968, large quantities of sea ice are exported from the Arctic to the Greenland Sea. Under these conditions, driftwood of North American, Siberian and Russian origin is transported by sea ice from the Arctic to the Greenland Sea via Fram Strait and eventually, is stranded on the beaches of Baffin Bay. For winds typical of 1984, driftwood of North American and Siberian origin is caught in a strengthened Beaufort Gyre and is stranded on the beaches of the central CAA. The driftwood record also suggests the possibility that for long periods (centuries to millennia) during the Holocene, the atmospheric circulation was varying around a mean state similar to that of the year 1968, the year 1984 and today's climatology, and abruptly changed from one state to the other. These two years produced drastically different ice export from the Arctic to the Greenland Sea and also corresponded to different phases of the NAO index. We are engaged in further studies to determine whether ice export and the NAO index are directly related. If the character of the Icelandic Low is the main determinant of these states, the Holocene Arctic driftwood record has broad significance to northern North Atlantic paleoclimate.

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References

Beltrami, H., and A. E. Taylor, Records of climatic change in the Canadian Arctic: towards calibrating oxygen isotope data with geothermal data, *Global and Planetary Change*, *11*, 127–138, 1995.

Chapman, W. L., and J. E. Walsh, Recent variations of sea-ice and air temperature in high latitudes, *Bulletin American Meteorological Society*, *74*, 33–47, 1993.

Douglas, M. S. V., J. P. Smol, and W. Blake Jr, Marked post-18th century environmental change in high-Arctic ecosystems, *Science*, *266*, 416–419, 1994.

Dyke, A. S., J. England, E. Reimnitz, and H. Jetté, Changes in driftwood delivery to the Canadian Arctic Archipelago: the hypothesis of postglacial oscillations of the transpolar drift, *Arctic*, *50*, 1–16, 1997.

Hurrell, J. W., Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679, 1995.

McPhee, M. G., Ice-ocean momentum transfer for the aidjex ice model, *AIDJEX Bulletin*, *29*, 93–111, 1975.

Tremblay, L.-B., and L. A. Mysak, Modelling sea ice as a granular material, including the dilatancy effect, *Journal of Physical Oceanography*, *27*, 2342–2360, 1997.

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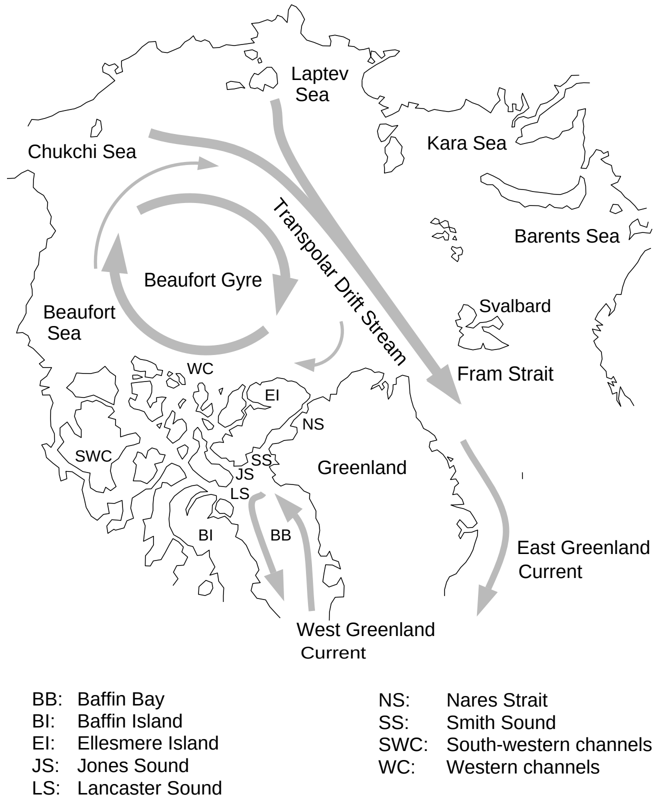

Figure 1. Map of the Arctic Ocean and the Canadian Arctic Archipelago (CAA)

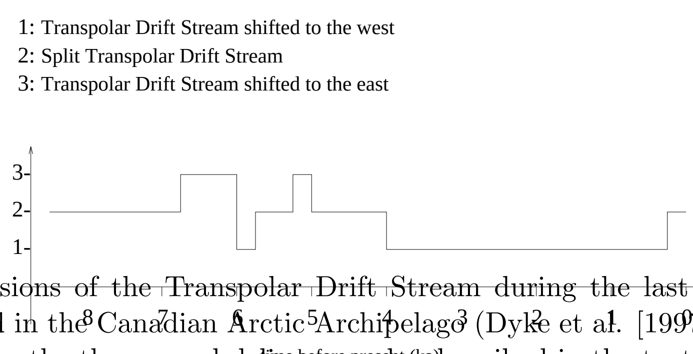

Figure 2. Excursions of the Transpolar Drift Stream during the last 8.5 ka inferred from driftwood collected in the Canadian Arctic Archipelago (Dyke et al. [1997]). The numbers 1, 2 and 3 correspond to the three wood delivery modes described in the text.

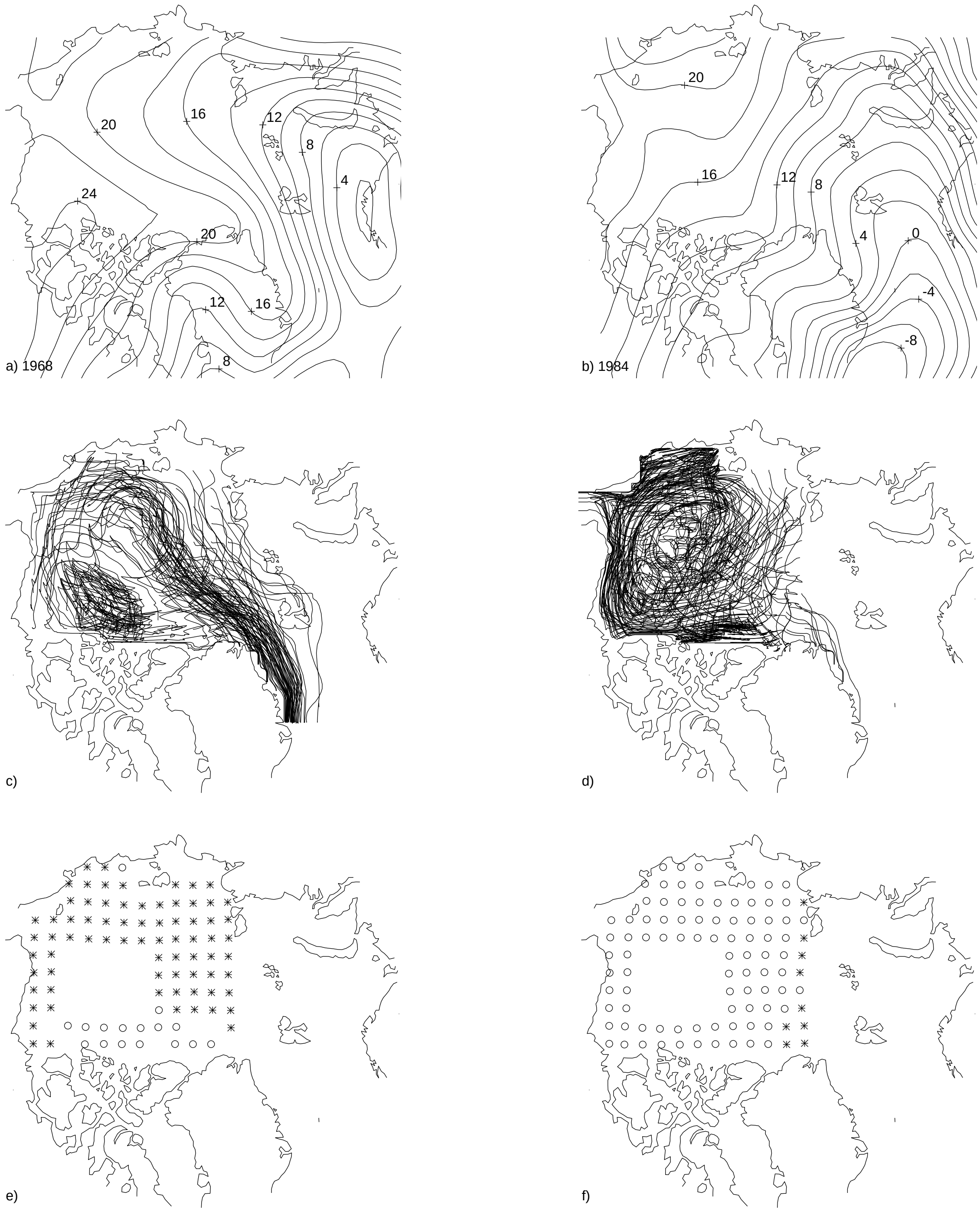

Figure 3. Winter sea level pressure pattern (mb - 1000 mb), spaghetti plot and driftwood sources for the years 1968 (a,c,e) and 1984 (b,d,f). In (e) and (f), the circles indicate source regions of driftwood for the central Canadian Arctic Archipelago (CAA) and the stars indicate the source regions for northern Baffin Bay.