Quaternary Science Reviews 191 (2018) 89–100

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A model to interpret driftwood transport in the Arctic

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ARTICLE INFO

Article history:
Received 7 December 2017
Received in revised form
27 April 2018
Accepted 2 May 2018

Keywords:
Driftwood
Proxy system models
Reconstruction
Holocene
Sea ice
Arctic ocean

ABSTRACT

Driftwood is frequently used to estimate past changes of sea ice extent and circulation in the Arctic. Nevertheless, driftwood observations are difficult to interpret because of the potentially complex relation with climate change. In order to determine the origin of the observed changes, we built a driftwood transport model (DTM) simulating the driftwood trajectories from the boreal forest to Arctic coasts. The model is driven by three main variables, which are the sea ice velocity, concentration and the sea surface current velocity that can be derived from observations or climate model outputs (e.g. from a General Climate Model – GCM). Overall, the DTM model agrees with the observations, although this comparison needs to be taken with caution because of the sparse data and the uncertainties of driftwood provenance. Through simulations performed with the DTM model, we confirm the strong influence of the variability of the atmospheric circulation on the spatial driftwood distribution. Model simulations of the Mid-Holocene period driven by six GCMs show that small local changes in sea ice circulation – a westward shift in the Transpolar Drift and a reduced Beaufort Gyre during the Mid-Holocene compared to the present period – suffice to explain the driftwood landing change during the Mid-Holocene, with a non-negligible contribution from reduced sea ice concentration. Consequently, a change in driftwood deposit should not be directly interpreted as large modifications in atmospheric circulation and the complexity of the response of driftwood trajectories to past climate changes clearly highlights the interest of using a model to interpret driftwood records.

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1. Introduction

Driftwood represents a unique record that can provide information on sea ice state over several millennia (Hellmann et al., 2017; Funder et al., 2011; Nixon et al., 2016; Dyke et al., 1997). Driftwood from boreal (Canadian and Siberian) forests enters in the Arctic Ocean via river systems because of natural processes such as shoreline erosion or storms. For Siberia, timber originating from industrial activities is also currently an important source of driftwood (Eggertsson, 1993; Hellmann et al., 2013). The woods transported to the Arctic Ocean are trapped into sea ice and then follow sea ice drift. Driftwood can then be transported on long distances before being deposited on Arctic coasts.

The Siberian driftwood is directly transported by the Transpolar Drift (TPD) – a strong current from the Siberian coasts to Fram Strait and later along the eastern coasts of Greenland. The Canadian driftwood is generally incorporated into the Beaufort gyre (BG) – an anticyclonic circulation located north of the Beaufort sea – before reaching the TPD. The journey of Canadian driftwood across the Arctic is therefore 6–7 years long while the minimum duration of Siberian driftwood transport is 2–3 years (Rigor et al., 2002; Funder et al., 2011). However, the speed and direction of sea ice drift are not the only elements to take into account. Sea ice melting and reduced ice extent play also a large role in the driftwood transport as once driftwood is released from sea ice, it becomes waterlogged and eventually sinks far from the shores (Eggertsson, 1993; Häggblom, 1982). Driftwood transport across the Arctic is thus several years long and driftwood is an indicator of the presence of the multiyear pack sea ice (sea ice that is several years old; Funder et al., 2011; Dyke et al., 1997).

It seems well established that the main source of driftwood found on the Arctic coasts is presently the Siberian forests (Eggertsson, 1993, 1994; Hellmann et al., 2013, 2017, 2015). The first reason is that the voyage from Canada is more precarious because

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Abbreviations: General Climate Model, (GCM); Proxy system model, (PSM); Driftwood transport model, (DTM); Beaufort Gyre, (BG); Transpolar Drift, (TPD); Mid-Holocene, (MH); North Atlantic Oscillation, (NAO).

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https://doi.org/10.1016/j.quascirev.2018.05.004
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the Canadian driftwood must make a detour in BG before reaching the TPD, increasing the probability to sink in the Arctic Ocean (Funder et al., 2011). Furthermore, a larger amount of driftwood comes from the Siberian rivers (compared to Canadian rivers) because of a significant loss of industrial timber (Eggertsson, 1993; Hellmann et al., 2016). Driftwood is found in many locations in the Arctic but observations show that four different regions display the highest occurrence: Ellesmere Island, Greenland, Svalbard and Iceland (Hellmann et al., 2017). Driftwood of Siberian origin dominates in all regions but Greenland (England et al., 2007; Hellmann et al., 2017; Eggertsson, 1993; Funder et al., 2011). Assigning a specific source for each driftwood is complicated as some tree species are present both on Siberian and Canadian sides (Hellmann et al., 2017). Detailed analyses of macroscopy and microscopy, driftwood anatomy and species composition allow a decrease in the driftwood origin uncertainties (Hellmann et al., 2013; Hole and Macias-Fauria, 2017). Moreover, the driftwood sampling is not usually often representative of the total amount deposited in each region because of: the use of driftwood by the local population (Alix, 2005; Wheeler and Alix, 2004), wood decay caused by fungal colonisation making difficult the species determination (Hellmann et al., 2013) and heterogeneous geographic coverage of sampling. Furthermore, the lack of driftwood deposit can be interpreted as the presence of perennial landfast sea ice preventing driftwood from being released on the shore (Kelly and Bennike, 1992; Hole and Macias-Fauria, 2017; Funder et al., 2011). Observations of driftwood deposit have been used to reconstruct changes in sea ice extent and circulation in the Arctic over several thousand years (Hole and Macias-Fauria, 2017; Funder et al., 2011; Bennike, 2004; Dyke et al., 1997). Nevertheless, because of the complex interpretation of the driftwood observations, the available information is often qualitative.

One additional difficulty is that driftwood transport is influenced by both changes in sea ice circulation and concentration. Such a complex dependence is standard in palaeoclimatology. Generally, the climatic variables (sea ice velocity and concentration in our study) can be derived from observations (driftwood occurrence and position in our analysis) using an inverse procedure (e.g. Sachs et al., 1977; Evans et al., 2013). Nevertheless, the inverse procedure may be ill-conditioned because of the multi-variate and non-linear nature of the link between paleoclimatic observations and the climatic variables of interest (Evans et al., 2013; Dee et al., 2015).

An alternative solution is to use a proxy system model (PSM) which predicts the measured quantity on the basis of our current understanding of the processes that lead to the observations and estimates the climatic or environmental forcings (Evans et al., 2013; Dee et al., 2015). In other words, a PSM transposes in a mathematical program the mechanical processes by which climate information is recorded and then observed in the archives (Dee et al., 2015). PSMs improve the interpretation of the signal recorded in archives and isolate the contribution of individual processes in the sensor response. Furthermore, PSMs facilitate the comparison of model results to observations by simulating the directly observed variable using climate model results as inputs. This approach is currently developed for several archives including speleothems, ice cores and woods (e.g. Evans et al., 2013; Dee et al., 2015).

In this study, we propose a PSM for the driftwood transported by sea ice. The model is designed to study the influence of thermodynamic and dynamic changes on driftwood deposits. The next section presents the driftwood transport model (DTM). This first part is accompanied by a short evaluation of fields used to drive the DTM model. The experiments performed with the DTM model are described in section 3. Then, in section 4, two applications of the DTM model are presented. The first application consists in the study of the impact of a change in the atmospheric circulation on the driftwood distribution. In the second application, the DTM is driven by the results of six climate models for the mid-Holocene in order to improve our understanding of past sea ice changes and to illustrate from a practical example the interest of the approach.

2. Model description

2.1. Transport model

The main equation of the driftwood transport model (DTM) is

$$\mathbf{v}_i(t) = \frac{d\mathbf{x}_i(t)}{dt} \tag{1}$$

$\mathbf{x}$ and $\mathbf{v}$ are the position and velocity of each simulated wood (i ranging 1 to n, the total number of simulated woods), respectively. t is the time. Equation (1) is discretised using the forward Euler method:

$$\mathbf{x}_i(t+1) = \mathbf{x}_i + \mathbf{v}_i(t) \times \Delta t \tag{2}$$

The model time step Δt is one day. As long as sea ice concentration is higher than a threshold (referred to as ice_{thr} in the DTM model), woods drift with sea ice (driftwood velocity is equal to sea ice velocity). When sea ice concentration is lower than the threshold, woods follow the ocean surface currents (driftwood velocity is equal to the ocean surface velocity) for a limited duration equal to the ice_{time} parameter before woods sink (Eggertsson, 1993).

The DTM model can be driven by the sea ice velocity and ocean currents derived from large-scale models. However, those present large biases in sea ice velocity near the shores because of their coarse resolution which does not allow a correct representation of the coastal processes. The local processes related to small scale circulation, tides, the landfast ice that blocks the driftwood beaching (Wadhams, 2000), etc., which contribute to the trapping of woods by the ice and to their release on the coast, are not represented in the simulated trajectories. In order to remove this bias in sea ice velocity due to coastal processes, the coastal regions are not explicitly included in the DTM model. Woods are assumed to be released at a prescribed distance from the coast and be deposited on the coast when they are actually at some distance from it (referred to as $coast_{thr}$ in the DTM model). After calibration tests, we have chosen the effective depart zone as a 100 km band located 300 km from the coast. Within this band, the initial driftwood positions are randomly generated due to the high uncertainty in these positions.

Only ”active” driftwood is retained in the simulations. A driftwood is active when it does not go directly back to land (typically when the winds are blowing towards the shore). Moreover, if the distance between the initial and arrival positions is too small (1000 km), driftwood is not taken into account since it is not linked to large-scale sea ice patterns but local processes (Hole and Macias-Fauria, 2017).

The DTM model includes three main parameters for which values are uncertain and difficult to estimate from observations, namely $coast_{thr}$, ice_{thr} and ice_{time}. To select adequate values of these parameters, we have performed simulations with the DTM model driven by the outputs of the NEMO-LIM sea ice model (Nucleus for European Modelling of the Ocean and Louvain-la-Neuve sea Ice Model; Barthélemy et al., 2015; see section 2.2) varying each of these parameters in a reasonable range ($coast_{thr}$: 75 km and 150 km; ice_{thr}: 5%, 10%, 15% and 25%; ice_{time}: 15 days and 45 days; see Table A1 for the details of the calibration simulations). Compared with Eggertsson (1993), the tested values for the ice_{time} parameter are relatively small as the transport duration of the wood from the continent to the open ocean and the drift duration before the beaching are not taken into account.

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