Earth and Planetary Science Letters 435 (2016) 84–93

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Norwegian fjord sediments reveal NAO related winter temperature and precipitation changes of the past 2800 years

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ARTICLE INFO

Article history:
Received 31 May 2015
Received in revised form 2 December 2015
Accepted 14 December 2015
Available online 30 December 2015
Editor: M. Frank

Keywords:
NAO
Marine Sediments
Trondheimsfjord
Norway

ABSTRACT

The North Atlantic Oscillation (NAO) is the leading mode of atmospheric circulation variability in the North Atlantic region. Associated shifts of storm tracks, precipitation and temperature patterns affect energy supply and demand, fisheries and agricultural, as well as marine and terrestrial ecological dynamics. Long-term NAO records are crucial to better understand its response to climate forcing factors, and assess predictability and shifts associated with ongoing climate change. A recent study of instrumental time series revealed NAO as main factor for a strong relation between winter temperature, precipitation and river discharge in central Norway over the past 50 years. Here we compare geochemical measurements with instrumental data and show that primary productivity recorded in central Norwegian fjord sediments is sensitive to NAO variability. This observation is used to calibrate paleoproductivity changes to a 500-year reconstruction of winter NAO (Luterbacher et al., 2001). Conditioned on a stationary relation between our climate proxy and the NAO we establish a first high resolution NAO proxy record (NAO_{TFJ}) from marine sediments covering the past 2800 years. The NAO_{TFJ} shows distinct co-variability with climate changes over Greenland, solar activity and Northern Hemisphere glacier dynamics as well as climatically associated paleo-demographic trends. The here presented climate record shows that fjord sediments provide crucial information for an improved understanding of the linkages between atmospheric circulation, solar and oceanic forcing factors.

1. Introduction

The climate in northern Europe is strongly influenced by the relatively warm northward flowing North Atlantic Current and the NAO, which is the dominant mode of atmospheric circulation in the North Atlantic region (Hurrell, 1995). The NAO is defined by the atmospheric sea level pressure difference between two opposed centres, the Icelandic Low and the Azores High, which determine the strength and direction of the westerly winds (Wanner et al., 2001). It swings between two phases: a positive (negative) NAO generates periods of warmer (colder) and wetter (drier) climate conditions in north-western Europe (Wanner et al., 2001). The NAO varies on timescales ranging from seasons to decades and is most pronounced during winter (Dec–Mar).

Instrumental time series are too short to reveal NAO responses to long term internal and external climate forcing with confidence. Paleo-NAO records based on historical-, tree ring- or ice core data are shorter than ∼950 years (Ortega et al., 2015; Trouet et al., 2009), and contain large uncertainties for the pre-industrial period (Lehner et al., 2012; Pinto and Raible, 2012; Schmutz et al., 2000). General challenges for winter NAO reconstructions are its possible non-stationarity, and its high variability on very short time scales requiring high resolution winter paleoclimatic records. Only the latter can provide the essential knowledge for NAO prediction and quantification.

The Norwegian coastal area is consistently influenced by the NAO (Lehner et al., 2012; Nesje et al., 2000). General high sedimentation rates in Norwegian fjords, together with the possibility to quantify environmental parameters such as seawater exchange and freshwater input, offer an excellent opportunity for studying local responses to short-term variability in the northern hemisphere's climate.

The most important factors regulating primary productivity in fjords are insolation, temperature, wind-driven vertical mixing, and

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http://dx.doi.org/10.1016/j.epsl.2015.12.003

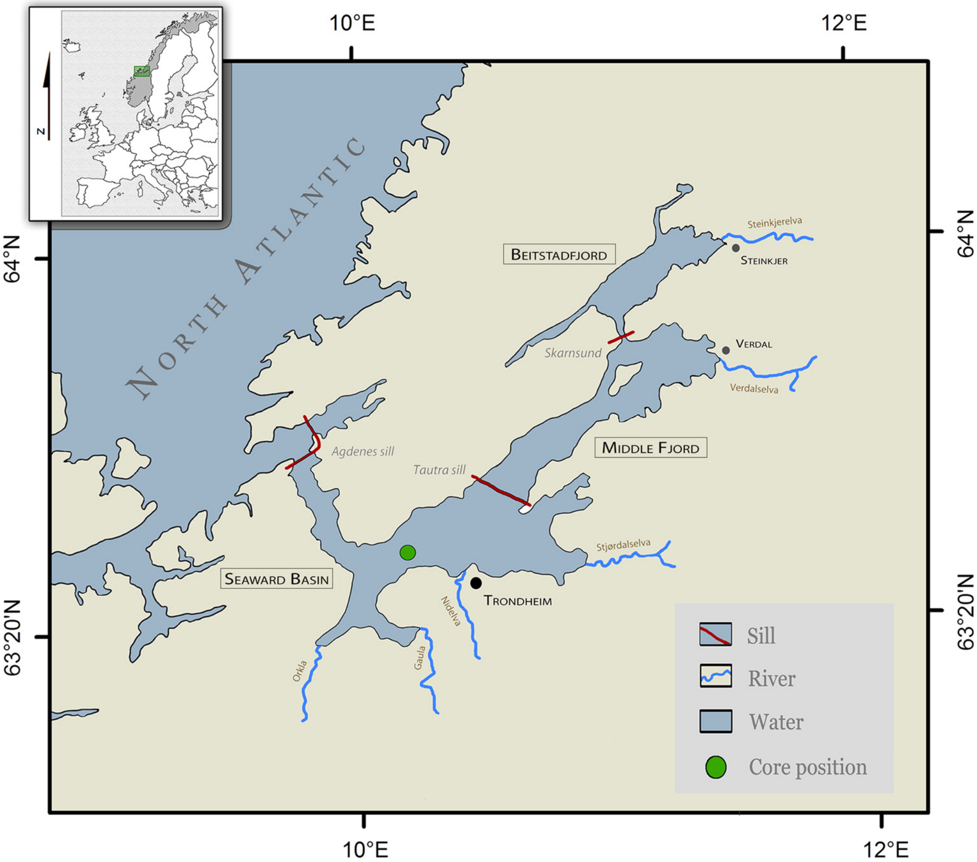

Fig. 1. Study area. The temperate Trondheimsfjord is located in the central part of Norway and with a length of approximately 135 km, it is the third longest fjord in the country. The six main rivers (blue lines) enter the fjord from the south–east and three sills, Agdenes Sill, Tautra Ridge and Skarnsund (red lines) divide the Trondheimsfjord into four main basins: Stjørnfjord, Seaward Basin, Middle fjord and Beistadfjord. The average tide in the Trondheimsfjord is 1.8 m, the average water depth is 165 m and the maximum water depth (620 m) is found at the mouth of the Seaward basin. The position of the sediment cores MD99-2292 and MC99 (water depth ∼500 m) is marked by a green point. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

freshwater runoff i.e. nutrient supply (e.g. Fe, N, P) (Sakshaug and Myklestad, 1973; Öztürk et al., 2002). The NAO has a strong impact on physical climate parameters, such as wind, temperature and precipitation in Norway. It thereby influences ecological dynamics in marine and terrestrial systems and changes in the phytoplankton production in terms of timing of reproduction and population dynamics (Drinkwater et al., 2003). In particular, the annual spring bloom, most likely the strongest primary productivity event in fjords, is triggered by the strength of spring river discharge due to snow melt (Sakshaug and Myklestad, 1973; Öztürk et al., 2002). During this period autotrophic production (algae growth) and heterotrophic consumption (algae feeders) are uncoupled, resulting in dense phytoplankton populations and large amounts of aggregated particles reaching the seafloor, nourishing the benthic population (Drinkwater et al., 2003; Kristiansen et al., 2001).

We investigated the geochemical records of two sediment cores recovered from the Trondheimsfjord, central Norway (Fig. 1): the piston core MD99-2292, and the multi-core MC99-3 (hereafter referred to as MC99) which have a temporal sampling resolution of 1.8–25 years. As schematically illustrated in Fig. 2 we show that $CaCO_3$ and Ca/Si are primary-productivity proxies that faithfully record NAO variability during the past 50 years. This observation is used to calibrate Trondheimsfjord paleoproductivity changes to a 500-year reconstruction of winter NAO (Luterbacher et al., 2001). Assuming that the observed relation between the NAO and our regional climate proxy remains stationary, we provide a first high resolution NAO-related proxy record from marine sediments covering the past 2800 years.

2. Material and methods

2.1. Sampling and analytics

Two sediment cores, MD99-2292 and MC99 were recovered at the same site in the Trondheimsfjord Seaward Basin (Fig. 1). The 31 m long sediment core MD99-2292 (water depth 486 m, 63°28′62″N, 10°11′63″E) was collected during the IMAGES V/MD114 cruise by the RV "Marion Dufresne" in 1999. Prior to sediment sampling 23 elements (Al, Si, S, Cl, Rh, K, Ca, Ti, Cr, Mn, Fe, Cu, Zn, Ga, Br, Rb, Sr, Y, Zr, Cd, Ba, Sn, Nb) were measured in the first six meters of the MD99-2292 in 0.5 cm steps using an Avaatech X-ray fluorescence (XRF) core scanner hosted at EPOC, CNRS/University of Bordeaux, France. X-ray images using the SCOPIX system were taken at the same institution. Subsequently, sediment slices (1 cm deep, 7 cm wide, 1.5 cm long) were taken in 4 cm intervals for further analysis. Six sand layers, between 3 and 8 cm thick, in various core depths (Supplementary Table S1) were identified by changes in grain size, geochemistry as well as in X-ray images. As these six sand layers represent short term sedimentation events due to gravitational mass movements these intervals have been removed from all data series. The short (26 cm) multi-core MC99 (5.5 cm diameter) was collected by the research vessel "Seisma" in April 2011 (water depth 504 m, 63°28′37″N, 10°11′37″E). To prevent disturbance of the sediment record during transport, the core was sliced in 1 cm intervals aboard the