nature geoscience

LETTERS

PUBLISHED ONLINE: 3 MAY 2009 | DOI: 10.1038/NGEO518

Observed sources and variability of Nordic seas overflow

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The overflows from the Nordic seas maintain the deep branch of the North Atlantic Ocean's thermohaline circulation[1,2], an important part of the global climate system[3,4]. However, the source of these overflows, and of overflow variability, is debated: proposals include open-ocean convection, dense-water production on the Arctic shelves and the gradual transformation of Atlantic water as it circulates the periphery of the Nordic seas and the Arctic Ocean[2,5,6]. Here we analyse time series of observed ocean temperature and salinity between 1950 and 2005. We find that the progression of thermohaline anomalies on interannual to decadal timescales does not support a systematic response of the overflow properties to convective mixing in the Greenland Sea as has been suggested[7,8]. Instead, anomalies in temperature and salinity that leave the northern seas at the Denmark Strait have travelled along the rim of the Nordic seas from inflow to overflow. Furthermore, the Faroe–Shetland Channel reflects the variability of an overturning loop within the Norwegian Sea that has not been observed previously. We thus conclude that the Atlantic water circulating in the Nordic seas is the main source for change in the overflow waters.

The Atlantic Ocean is understood to be an important mediator of climate variability and change[3]. The main source of the southward flow of North Atlantic deep water is the overflow of dense water across the Greenland–Scotland ridge, which separates the Nordic seas from the Atlantic Ocean[1] (Fig. 1). The generation of overflow water is a matter of much debate. Proposed contributing processes and source regions are: open-ocean convection, primarily in the central Greenland Sea, dense water produced on the Arctic shelves and the gradual transformation of Atlantic water as it circulates the periphery of the Nordic seas and the Arctic Ocean[2,5,6]. The state of the source regions can be related to the state of the overflows in two different ways: (1) prognostically through the degree of co-variability between the overflows and the sources upstream and (2) diagnostically through the decomposition of overflow into source waters. Observation-based descriptions so far have generally assessed the hydrography from individual cruises or climatology[5,6], and are thus concerned with diagnosis and the overflow composition of a steady state. The prognostic issues of variability, change and potential predictability[9] remain unexplored in the long-term instrumental record.

Identifying the observed co-variability between overflows and sources—or the lack thereof—is the purpose of this study. To this end, a recently compiled comprehensive hydrographic database for the Nordic seas[10] is used to construct time series of salinity and temperature for overflows and sources from 1950 to 2005 (Fig. 2).

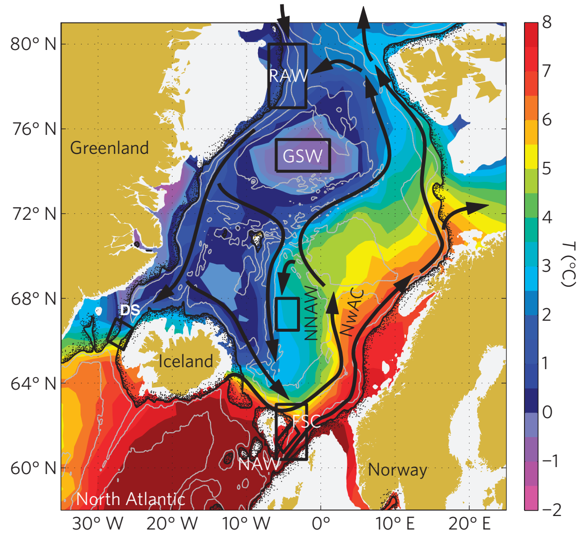

Figure 1 | Climatological temperature of the Nordic seas at 200 m depth. The arrows indicate the pathways from warm and saline Atlantic inflow to dense overflow. Isobaths are given for every 1,000 m, and the thick 'pebbly' line at 500 m depth marks the continental slopes. Note the narrow gaps restricting the overflows.

Note that corresponding time series of volume fluxes cannot be constructed as current measurements are relatively few and limited to recent years[11,12]. The regions and water masses extracted from the observations are restricted by the bounding boxes in Fig. 1 and further discussed in the Methods section. Greenland Sea water (GSW) represents the product of intermediate or deep open-ocean convection that fills the interior basins of the Nordic seas[13], whereas return Atlantic water (RAW) is part of the more direct cyclonic loop from inflow of North Atlantic water (NAW) to dense overflow[5]. RAW is carried by the East Greenland current from the Fram Strait to the Denmark Strait, and the current entrains GSW en route[6].

The above description is well established, but it has also been suggested that Denmark Strait overflow water (DS) is predominantly provided by a more eastern pathway rooted in the convective Iceland Sea[14]. This alternative mode of operation is not reflected in our database as time series specifically constructed for the Iceland Sea (not shown) were found to be less representative of overflow variability than what is described below for GSW, the main convective product in the Nordic seas. This alternative is therefore not further pursued herein.

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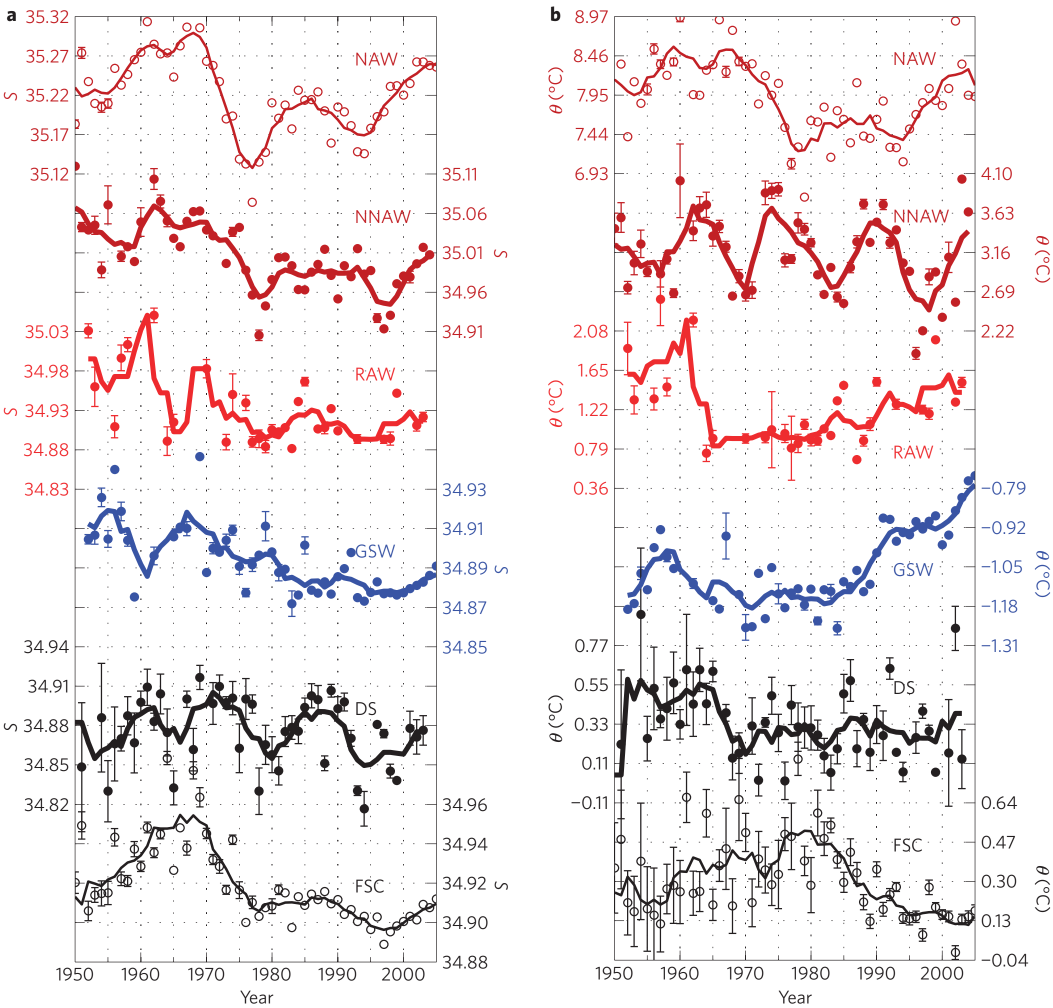

Figure 2 | The observational time series. a, Salinity S. **b**, Potential temperature θ. Water masses are labelled, data points are annual means and curves correspond to 5-year running means. Time series are normalized such that the vertical grid spacing is the standard deviation of the corresponding annual time series. Error bars show the error estimates of the annual means, $\sigma_m = \sigma/\sqrt{N-1}$, where σ is the standard deviation for the N observations within a year.

The overflow waters that do not leave through the Denmark Strait continue southeast to exit mainly through the Faroe–Shetland Channel along its western slope. Faroe–Shetland Channel overflow water (FSC) is also supported by the shorter pathway through the Jan Mayen Channel, which connects the Greenland Sea directly to the Norwegian Sea[2,15]. There is also a shallow overflow between Iceland and the Faroe Islands, but this relatively weak outlet[2] is not considered herein.

An extra source for FSC can plausibly be found in the topographically steered retroflection from the western branch of the Norwegian Atlantic current[16] (NwAC; Fig. 1). The resulting Norwegian North Atlantic water (NNAW) is sufficiently cold to have overflow density (Fig. 2), and it is a main water mass in the slope region north of the Faroe Islands[17]. This location, where the other two pathways to the Faroe–Shetland Channel also converge, is the entry point for the overflow water that constitutes FSC (ref. 18). Our inclusion of NNAW in the analysis provides a first quantification of this possible source.

The gradual transformation in Fig. 2—from warm and saline inflow to cold and relatively fresh overflow—is the result of the large oceanic heat loss and freshwater input in the Nordic seas and Arctic Ocean. All water masses show the regional freshening of the three decades before 1995 (ref. 19), but salinities increase notably thereafter, particularly for NAW (refs 12, 20). The freshening trend in the Denmark Strait is weak compared with the almost regular decadal fluctuations there. The 'great salinity anomaly'[21] is seen in RAW and DS around 1965, and in NAW, NNAW, RAW and DS in the second half of the 1970s. The interannual to decadal variability is also broadly reflected in the observed temperatures, but cooling trends corresponding to the long-term freshening are generally less distinct or absent. GSW exhibits a strong warming after 1980, whereas the overflows do not.

With this unique collection of observational time series at hand, it is possible to quantify objectively to what extent the overflows manifest the thermohaline variability of the sources upstream. We do this by cross-correlations, a simple and common way to assess the possible progression of anomalies through a collection of time series. The lagged peak correlations between the detrended versions of the annual time series in Fig. 2 are given in Table 1. We emphasize that the analysis includes the most commonly suggested sources for overflow in the Nordic seas[2,5,22]. One would therefore expect overflow variability that is not accounted for by Table 1 to be partly stochastic. Extra variability due to, for example, other sources or nonlinear relations, is not considered herein. The latter is however represented to the extent that it contributes to variable overflow compositions as diagnosed in Fig. 4.

Starting with the Denmark Strait, the main overflow from the Nordic seas, we find no significant correlation with GSW for potential temperature, and there is only a weak negative correlation for salinity. A signature of the water mass transformation taking