Atlantic Water Transport and Temperature Anomalies Through the Nordic Seas Towards the Arctic Ocean

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Main points

I. A dynamical measure of the Norwegian Atlantic Slope Current (NwASC) from Sea Surface Heights (SSHs) is developed

II. The flow of Atlantic water into the Arctic is found to be regionally regulated by the atmospheric circulation

III. Warm anomalies towards the Arctic Ocean propagate as response to an increase in the flow in the Southern Norwegian Sea

Introduction

The Nordic Seas are fed by warm and saline water from the Gulf Stream/North Atlantic Current as the upper limb of the meridional overturning circulation portrayed in Fig. 1. The main heat conveyor of the Atlantic inflow through the Nordic Seas and towards the Arctic is the Norwegian Atlantic Slope Current (NwASC). This is a topographically-steered nearly barotropic current and is thought to respond directly to the wind field over the Nordic Seas through Ekman dynamics.

Recent studies have explored the variability of ocean heat content, and they seem to agree on that both air-sea fluxes and advective processes control hydrographic anomalies in the Nordic Seas. Based on a dynamical transport measure from SSHs, we here explore an alternative mechanism, i.e. whether warm anomalies in the Nordic Seas are caused by an increase of the northward flow in the southern Norwegian Sea, rather than by advection of "warm packets" from the North Atlantic.

Figure 1. **A schematic representation of the large-scale pathways of Atlantic water in the northern North Atlantic and the Nordic Seas including the bathymetry (shading). Abbreviations in black denote current systems, and white denote regions. The focus is on the Norwegian Atlantic Slope current (NwASC); the main flow branch of Atlantic water linking the North Atlantic to the Arctic and Barents Sea (cf. the inset).**

Data and Methodology

The SSHs used in this study are based on the globally gridded (1/3°x1/3°) and Mercator-projected absolute dynamic topography at weekly resolution (provided by AVISO). This weekly data set from October 1992 to December 2012 is temporally averaged to form monthly fields. As an altimetrically-based dynamical indicator of the NwASC at time t, we will use the difference in absolute dynamic topography between the 500- and 900-m isobaths. At discrete points along the NwASC, denoted by the cuvilinear coordinate s, the equivalently barotropic flow can be approximated as

$$\Psi(s,t) = (g/f)\Delta_H \eta(s,t)\mathcal{H}_{700},$$

where g is the acceleration of gravity, f the Coriolis parameter, and $\mathcal{H}_{700}$ the arithmetic mean of the isobath range and $\Delta_H \eta(s,t)$ the dynamic height difference in the direction normal to the isobaths. Thus, $\Psi(s,t)$ is proportional to integrated geostrophic surface velocity between the isobaths and can simply be interpreted as an along-stream dynamical measure of the NwASC.

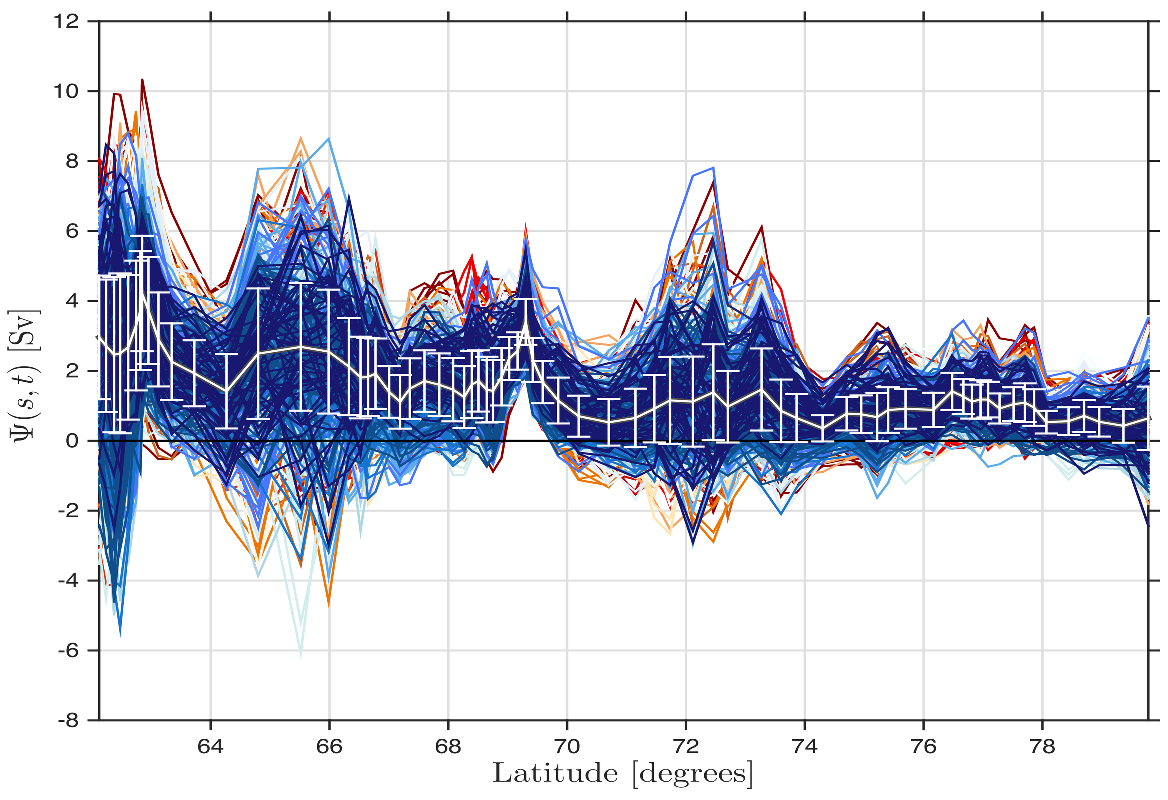

Figure 2. **The transport proxy along the NwASC as a function of latitude. The thin colored lines represent the raw weekly transport between 1992 and 2012. The gray line is the time-mean transport and the associated vertical bars indicate the spread. Note that due to baroclinic effects, the time mean barotropic transport varies along-stream.**

Results

The SSH and Mean Sea Level Pressure (MSLP) spatial patterns linked to the variability of the Fram Strait Branch (FSB) west of Spitsbergen are identified. On monthly timescales, we note a strong positive correlation along the shelf-edge zone of Norway and in the Barents Sea (Fig. 3a). The relationship to the SSH within the Nordic Seas is weak, suggesting that the flow along the FSB is mainly driven by positive SSH anomalies in the Barents Sea. The nodes of the Icelandic low and the Azores high are misplaced as compared to the traditional North Atlantic Oscillation and hence not applicable as a driver (Fig. 3b). On interannual timescales, a positive correlation encircling Svalbard becomes more distinct, suggesting that the FSB is regionally regulated (Fig. 3c). This is consistent with the MSLP pattern that develops on interannual timescales (Fig. 3d) and through Ekman transport leads to an anticyclonic circulation anomaly over the northern Barents Sea and around Svalbard, which enhances the FSB transport. The results reported here are novel since earlier studies have suggested that the entire NwASC is driven by the same NAO-type atmospheric conditions. Our results show wind-induced patterns that are distinctively different from those driving the transport in southern Norwegian Sea.

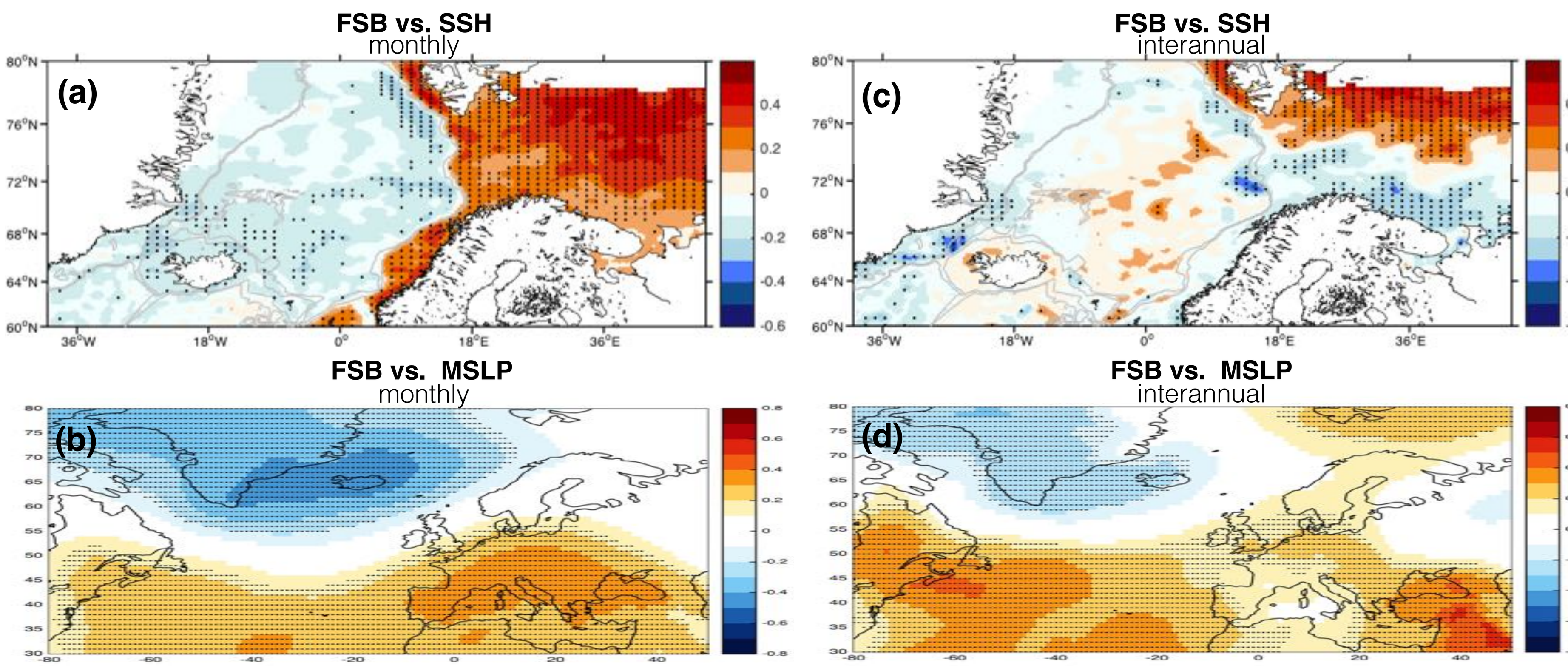

Figure 3. **Correlation of the FSB transport proxy anomalies and the SSH/MSLP anomaly (de-seasoned and detrended) on (a/c) monthly, and (b/d) interannual time scales. Black stipplings represent grid points that are significant at the 95% confidence level (p-value < 0.05) assessed based on a two-sided t-test. The positive SSH/MSLP anomaly over the Northern Barents Sea and Svalbard appears to be important for the FSB. The MLSP is retrieved from ERA-interim.**

Figure 4 shows the evolution of a composite temperature anomaly (T') along the NwASC following an increased transport in the southern Norwegian Sea. At zero-lag, we observe T' at 300-600 m depth. After 2 months, a T' s found in the vicinity of Lofoten (not shown). After 6 months, the T' is between 200 and 300 m depth, but the entire column shows a warming. After 12 months, the T' is predominantly located along the FSB and has a vertical extent from the surface down to ~300 m.

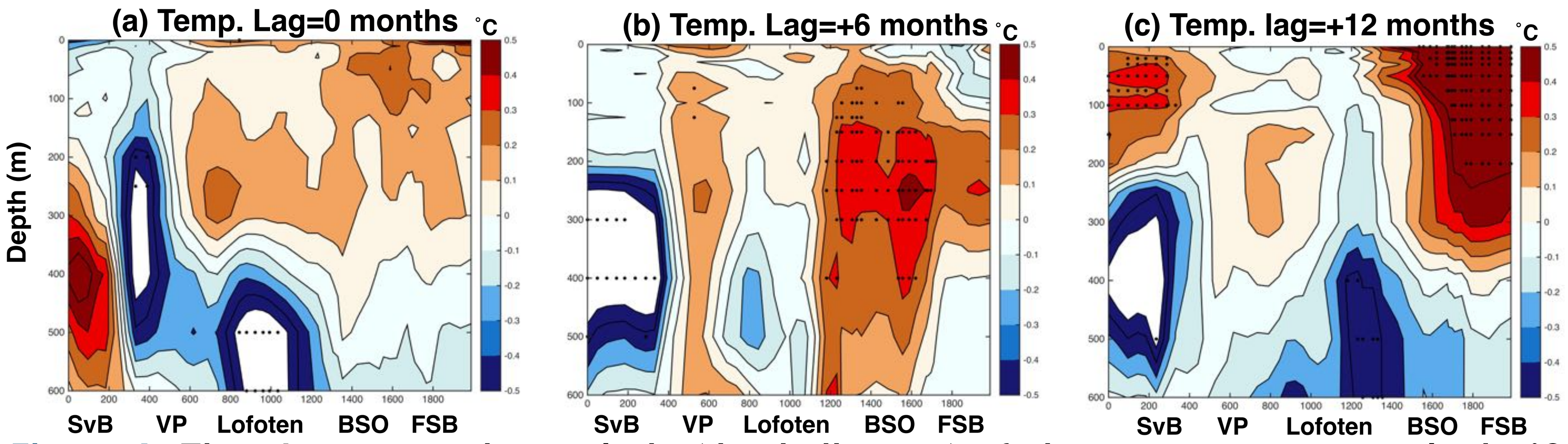

Figure 4. **Time Lag composite analysis (depth-distance) of the temperature anomaly, in °C, following the main core of Atlantic water in the Nordic Seas and towards the Fram Strait. The composite is based on transport proxy events in southern Norwegian Sea, defined as months exceeding 1 standard deviation. Positive lags are evaluated at (a) zero-lag, (b) 6-months and (c) 12-months. Black stipplings represent grid points that are significant at the 95% confidence level (p-value < 0.05) assessed based on a two-sided t-test. The regions are invoked to simplify the orientation along the NwASC (cf. Fig. 1). The temperature anomaly is found around BSO at 6 months, and along FSB at 12 months, where it is amplified. The temperature data is retrieved from the National Oceanographic Data Center (NODC).**

Conclusions

- The variability of the FSB is influenced by wind-induced Ekman transport centered around Svalbard and northern Barents Sea. Thus, the fractionation of Atlantic water transport towards the Arctic between the Fram Strait and Barents Sea branches is largely modulated by regional atmospheric patterns while the NAO plays a minor role. Based on the proposed mechanism, a good proxy of the Atlantic inflow into the Arctic Ocean may simply include the use of SSHs from altimetry along with regional atmospheric pressure variations.
- The composite warm anomaly reaching the FSB at roughly 12 months is generated after anomalous transport events in the southern Norwegian Sea. To the best of our knowledge, little evidence has been presented that connects changes in the transport and hydrography. We believe that the combination of transport in the southern Norwegian Sea using altimetry and temperature fluctuations in the Nordic Seas can be used to qualitatively predict warm anomalies moving towards the Arctic Ocean, which could be a valuable addition to the forecast skill of the statistical Arctic sea-ice models.
- Locally generated hydrographic anomalies in the Norwegian Sea are important for the heat/salt transport that enters the Arctic Ocean.