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The impact of the wind stress curl in the North Atlantic on the Atlantic inflow to the Norwegian Sea toward the Arctic

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[1] The Norwegian Atlantic Current (NwAC) through the Norwegian Sea serves as a conduit of warm and saline Atlantic water from the North Atlantic to the Arctic Ocean, an important factor for climate and ecology. In this study, we concentrate on how the North Atlantic wind stress curl (NAWSC) affects interannual variability on the major branch of the NwAC—the Norwegian Atlantic Slope Current (NwASC). Based on wind stress data from the NCEP reanalysis and estimated volume transport of the NwASC from current records during 1995–2003 in the Svinøy section (62°N), our analysis shows that the volume transport in the NwASC exhibits a maximum correlation of 0.88 with the zonally integrated NAWSC at 55°N 15 months earlier. Our findings reveal the NAWSC to be a major forcing for interannual variability of the NwASC in the range of 3.0- to 5.3 Sv (Sv = 10^6 m^3 s^{-1}). The 15 month time lag appears to be in accordance with a forced baroclinic Rossby wave in response to the local Ekman pumping changing the baroclinicity and strength of the North Atlantic Current (NAC). After being converted to a nearly barotropic shelf edge current along the Irish-Scottish shelf through interaction with bottom topography, it appears as a barotropic response downstream in the Svinøy section. This result suggests the possibility of predicting conditions influenced by the NwASC more than a year in advance, using the NAWSC as a proxy. *INDEX TERMS:* 4512 Oceanography: Physical: Currents; 4532 Oceanography: Physical: General circulation; 4516 Oceanography: Physical: Eastern boundary currents; 4215 Oceanography: General: Climate and interannual variability (3309). **Citation:** Orvik, K. A., and Ø. Skagseth, The impact of the wind stress curl in the North Atlantic on the Atlantic inflow to the Norwegian Sea toward the Arctic, *Geophys. Res. Lett.*, *30*(17), 1884, doi:10.1029/2003GL017932, 2003.

1. Introduction

[2] The Norwegian Atlantic Current (NwAC) through the Norwegian Sea (Figure 1), serves as a conduit of warm and saline Atlantic water from the North Atlantic to the Barents Sea and Arctic Ocean. A disruption of this transport may cause dramatic climatic-related changes, such as reduction of the Arctic ice cover [e.g., *Johannessen et al.*, 1999; *Rahmstorf*, 1999]. Quantifying and understanding the variability of the transport between these regions is thus important for our understanding of the climate system, both in Northern Europe and the Arctic. The large scale ocean circulation including the North Atlantic, is primarily wind driven and partly driven by thermal forces [*Veronis*, 1973; *Eden and Willebrand*, 2001]. In this study we concentrate on how the wind field affects the Atlantic inflow (AI) by investigating the connection between interannual variability of North Atlantic wind stress curl (NAWSC), and the major branch of the NwAC—the Norwegian Atlantic Slope Current (NwASC).

[3] The NwAC is a poleward extension of the western boundary current—the Gulf Stream (GS), transporting warm water to eastern polar regions [*Veronis*, 1973]. The GS, after separating from the western boundary, partly penetrates through the normal barrier formed by the vanishing of wind-stress curl and continues as the zonally, eastward flowing North Atlantic Current (NAC) associated with the Subpolar Front (SPF), after a retroflection at 50–52°N north of Newfoundland [*Rossby*, 1999]. After crossing the Mid Atlantic Ridge (MAR) at about 52°N, the NAC splits into two major branches [*Fratantoni*, 2001; *Reverdin et al.*, 2003]: (1) a western branch toward East Iceland where it partly enters the Norwegian Sea, (2) the eastward continuing zonal flow, upon encountering the Irish-Scottish shelf, appears to be constrained as a topographically trapped shelf edge current [*Burrows et al.*, 1999], entering the Norwegain Sea through the Faroe-Shetland Channel (FSC) as the eastern branch of the NwAC—the NwASC. The NwAC then continues as a two-branch current through the entire Norwegian Sea toward the Arctic [*Poulain et al.*, 1996; *Orvik and Niiler*, 2002]; (1) the western branch is a jet in the Polar Front that tends to feed the interior of the Norwegian Sea, (2) the eastern branch about 3500 km long, is a nearly barotropic shelf edge current (NwASC) along the Norwegian shelf. In this study we will concentrate on the NwASC which tends to flow into the Barents Sea and Arctic Ocean, and is thus the major link between the Atlantic and the Arctic.

[4] We will use long term series of volume transport estimates of the NwASC in the Svinøy section (Figure 1), calculated from moored current meter records, 1995–2003. The Svinøy section cuts through the AI just to the north of the FSC and is a suitable place to undertake a comprehensive study of the NwAC. In the Svinøy section the annual mean NwASC appears as a stable flow about 40 km wide over the steep slope (200–900) m, with mean velocity of about 30 cm/s [*Orvik et al.*, 2001].

[5] To date, short term variabilities of the NwASC have been studied; e.g. as current fluctuations with periods of

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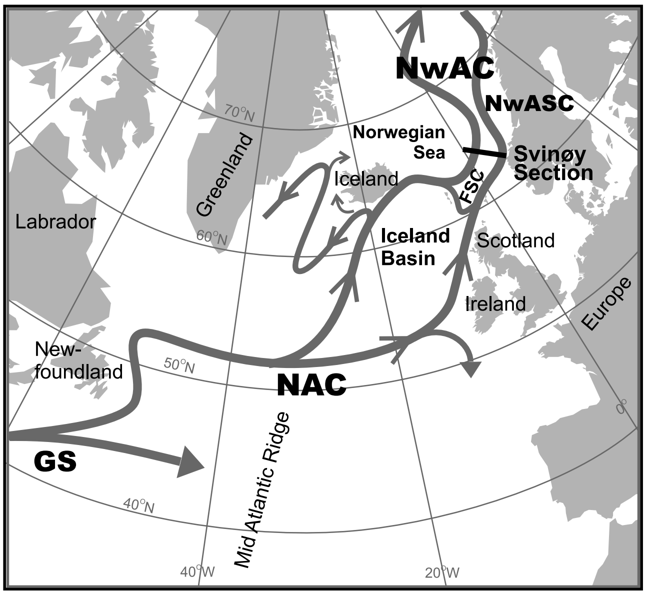

Figure 1. Map of the study area where solid lines outline the major pathways of Atlantic water in the North Atlantic, and into the Norwegian Sea toward the Arctic Ocean. Abbreviations are explained in the text (Based on *Poulain et al.* [1996], *Valdimarsson and Malmberg* [1999], *Fratantoni* [2001], *Orvik and Niiler* [2002], and *Reverdin et al.* [2003]).

2–3 days [*Mysak and Schott*, 1977; *Schott and Bock*, 1980], as seasonally varying [*Gould et al.*, 1985], and as response to wind in terms of free and forced continental shelf waves with periods up to one month [*Gordon and Huthnance*, 1987; *Skagseth and Orvik*, 2002]. *Mork and Blindheim* [2000] inferred from hydrography that geostrophic volume transport in summer was correlated with winter NAO index.

[6] In this study we concentrate on interannual variability (>1 year) of the NwASC, and in particular how the NAWSC affects the AI. In the light of classical Sverdrup theory, we test the hypothesis that long-term variability of the NwASC is affected by the NAWSC. For that purpose, we compare variability of the zonally integrated NAWSC with estimated volume transport of the NwASC for the 8-year period 1995–2003.

2. Data and Methods

[7] The study is based on measurements from moored current meters in the Svinøy section for the period April 1995–April 2003 (Figure 1), and monthly mean wind stress data from the NCEP reanalysis. According to *Orvik and Skagseth* [2003], the transport of Atlantic Water (AW) in the NwASC can be estimated by using one single current meter record in the core of the flow. This methodology is applied to construct the 8-year time series of the AW volume transport in Figure 2 showing consecutive time series of volume transport based on moving average filtering with 7, 30, 90, and 365-day cutoff periods.

[8] Based on the NCEP wind stress data the vertical component of monthly mean NAWSC is estimated at the mid points of the NCEP grid. The zonally integrated NAWSC (ZIWSC) is then estimated for latitude bands between 30°N and 75°N, and further averaged over 3 NCEP latitude bands of about 5 degrees. The integration starts from the eastern boundary and proceeds toward the western limit at 40°W, excluding land points and western continental slope regions. These ZIWSCs are then related to the volume transport of the NwASC.

[9] Prior to the analyses, the data are smoothed using a one-year moving average filter to remove seasonality. The filtered series of the NwASC and ZIWSC are then correlated as a function of latitude and time lag (Figure 3). To visualize the ultimate connection, the time series of the NwASC and ZIWSC at the point of maximum correlation in terms of latitude and time shift, are presented in Figure 4.

3. Results

[10] The 8-year time series of volume transport in Figure 2, show that the NwASC has fluctuations over a wide range of periods, from weeks to months, seasons and years. The overall mean is 4.2 Sv (1 Sv = 10^6 m^3 s^{-1}) with a (minimum, maximum) in the range of (1.0, 7.1) Sv and (3.0, 5.3) Sv on (1, 12)-month time scales. Most striking feature is the seasonal cycle with winter maxima and summer minima. It is noteworthy that in terms of interannual variability (Figure 2, lower panel), the annual mean

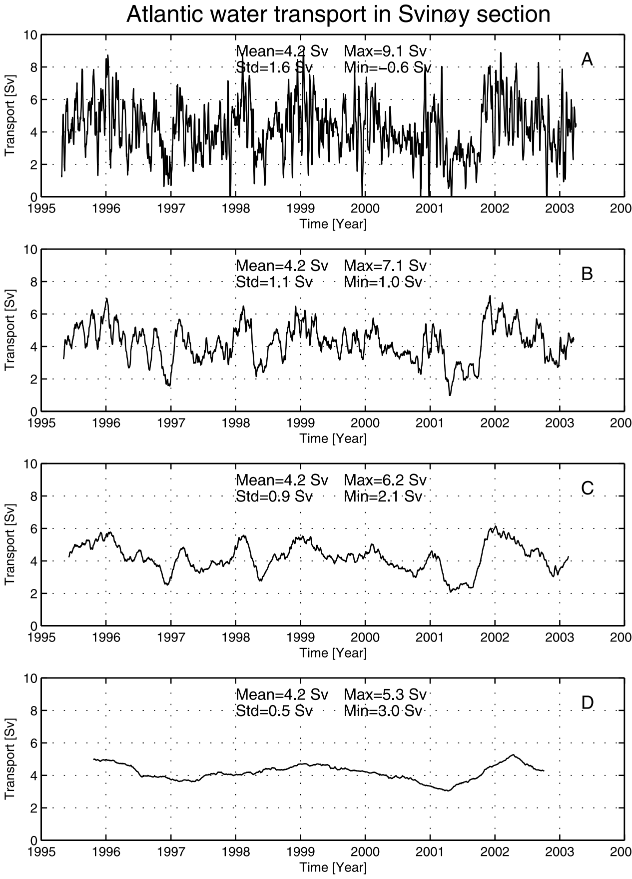

Figure 2. Time series of Atlantic water transport in the NwASC for the period 1995–2003; calculated from a linear regression model and consecutively filtered using moving average filter of [7, 30, 90, 365]- days. The filtered time series, [mean, min, max]- transport and standard deviation are shown in panel [A, B, C, D], respectively.

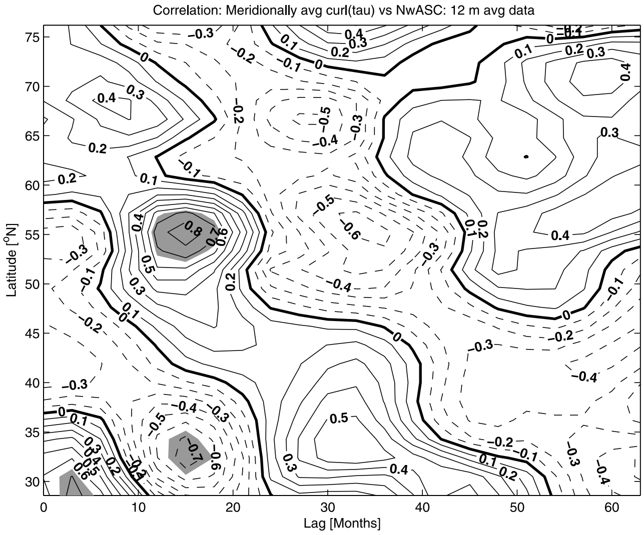

Figure 3. Correlation field for volume transport of Atlantic water in the NwASC vs. zonally integrated wind stress curl (ZIWSC) as a function of latitude and time lag. Positive lag means that variability of the NwASC trails those of the ZIWSC. The patched regions indicate correlation values significant at the 95% level for number of independent samples (n) = 7.

goes from an absolute minimum of 3.0 Sv in 2001 to an absolute maximum of 5.3 Sv in 2002, i.e., an 2.3 Sv (77%) increase over a one-year period, and subsequently decreases. There is no clear overall trend, and the annual means in 1995 are comparable with the absolute maximum in 2002.

[11] The correlation field displayed in Figure 3 shows a maximum of 0.88 between the ZIWSC at 55°N and volume transport in the NwASC, with a corresponding time lag of 15 months. This indicates that striking events in the NwASC at 62°N trail the ZIWSC at 55°N in the North Atlantic by 15 months. The minimum correlation of −0.75 at 32°N, also has a time lag of about 15 months. This substantiates the large scale characteristics of the atmospheric variability in the North Atlantic with opposite phase in terms of vorticity between the sub-polar and sub-tropical gyres.

[12] Figure 4 shows the normalized time series of the ZIWSC consistent with the correlation maximum of 0.88 at 55°N, and volume transport in the NwASC. For comparison, the ZIWSC time series is shifted 15 months ahead to fit the corresponding time lag in correlation. The striking coincidence of the time series agrees with the correlation field.

4. Discussion

[13] The statistical analysis reveals a strong connection between the ZIWSC at 55°N and the NwASC with a 15-month time lag (Figure 4). In that sense, the NAWSC appears to be a major forcing for interannual variability of the NwASC. The 15-month time lag suggests a baroclinic response in the SPF, and we attempt to substantiate how the NAWSC alters the baroclinic field and thus the strength of the NAC, resulting in a 15-month time lag of the barotropic NwASC in the Svinøy section.

[14] The northern North Atlantic has a complex structure with respect to bottom topography, water mass distribution and flow field. The SPF has a sharp density gradient suggesting a stable front with a baroclinic jet west of the MAR. After crossing the MAR, the NAC broadens in association with spreading of warm water in accordance with the splitting into two northward branches [*Fratantoni*, 2001; *Reverdin et al.*, 2003]. Interannual variability in the SPF is shown from hydrography transects by *Belkin and Levitus* [1996] and *Bersch et al.* [1999]. *Bersch et al.* [1999] showed an overall increase of the temperature and thickness of Atlantic water from 1995 to 1996, but most prominently in the Iceland Basin with a westward shift in the SPF.

[15] Concerning feasible mechanisms in light of classical Sverdrup theory on interannual timescales, a response will be close to a geostrophic equilibrium. This justifies the use of a quasi-geostrophic approach, examining how NAWSC-forcing through Ekman pumping alters the pressure field and thus the geostrophic balance. There will be both a barotropic and a baroclinic ocean response to changes in the NAWSC, where the ocean spin-up simply appears in terms of planetary waves. For the barotropic mode, the time taken for a long planetary wave to cross the Atlantic is about 3 days, giving the approximate adjustment time for the barotropic flow. For the baroclinic mode, the phase speed is of the order of 1/1000 of the barotropic wave resulting in a decadal adjustment [*Gill*, 1982, chapter 12]. *Gill and Niiler* [1973] showed that if planetary waves cannot propagate far compared with the scale of the forcing, the baroclinic response to the wind is simply a direct local response to Ekman pumping. Thus the 15-month time lag appears to be in accordance with a forced baroclinic Rossby wave in response to the local Ekman pumping. Consequently, variabilities in the NAWSC will be mirrored in the eastward flowing baroclinic NAC as it approaches the Irish-Scottish shelf. According to *Eden and Willebrand* [2001], interaction

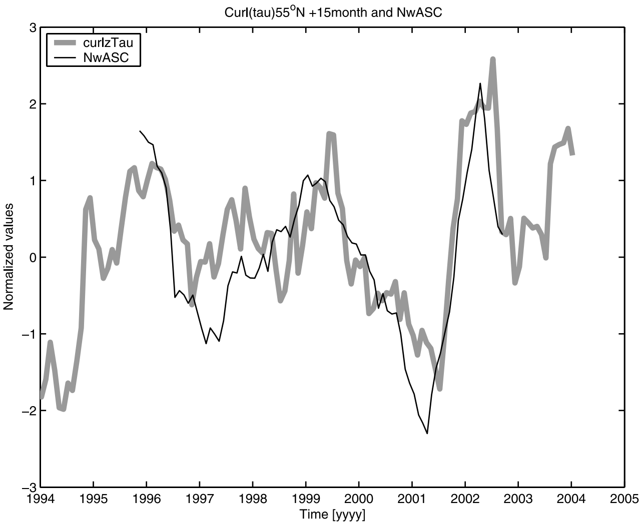

Figure 4. Time series representing the variability of the NwASC at zero lag and the ZIWSC at 55°N. An offset is subtracted from the ZIWSC time to illustrate the maximum correlation at 15 months time lag. The series are normalized by subtracting the means and dividing by the standard deviations.

of a baroclinic field with bottom topography results in a barotropic adjustment with a fast topographic wave signal. This compares with *Burrows et al.* [1999], showing an acceleration of the barotropic shelf edge current along the Scottish slope toward the FSC, entering the Norwegian Sea as the NwASC. Farther downstream the NwASC then passes the Svinøy section in terms of a 15-month delayed barotropic adjustment to the NAWSC at 55°N. This interpretation agrees with *Anderson et al.* [1979], who showed that interaction of the baroclinic field with bottom topography results in a delayed barotropic mode on baroclinic time scale.

[16] Our interpretation of the wind field influence on the SPF also agrees to some extent with *Bersch et al.* [1999]. Their explanation of the 1996 anomaly as due to a low NAO index and reduction of the upward Ekman pumping locally, compares with *Orvik et al.* [2001]. They found a strong connection between the NAO index and the NwASC for the period 1996–1999. High inflow events coincide with high NAO index and vice versa, indicating a fairly fast, barotropic response [*Willebrand et al.*, 1980]. In fact, the correlation between variability of the NAWSC and NwASC is consistent for the overall period 1995–2003, where the NwASC events trail the NAWSC by 15 months (Figure 4). Thus the 1996 anomaly in both the hydrography of the SPF [*Bersch et al.*, 1999] and the NwASC, trails a maximum NAWSC by 1–1 1/2 years. This justifies the view that the NAWSC is an important driving force for interannual variabilities of the NwASC manifested in an about 15-month delayed barotropic response in the Svinøy section.

5. Concluding Remarks

[17] This study substantiates the hypothesis that interannual variability of AI in the NwASC is forced by the NAWSC, where a complex baroclinic adjustment process results in a 15-month delayed barotropic response in the Svinøy section. Our result suggests the possibility of predicting conditions influenced by the NwASC more than a year in advance, using the NAWSC as a proxy. This can be important for weather predictions, planning of oil field operations, fish stock developments and ice cover in the Arctic. In that view, Figure 4 indicates an exciting development of the NwASC for the year ahead, revealing an increase of the NAWSC since late 2001. We have concentrated on the major AI branch—the NwASC. This is justified because this branch favours transport into the Barents Sea and Arctic Ocean, while the western branch appears to feed the interior Norwegian Sea. Because of the complexity of the physical processes hidden in the chain from the North Atlantic to the Svinøy section, our interpretation must be suggestive. In fact, a comprehensive study will be needed to better understand these processes, a challenge for future studies.

[18] **Acknowledgments.** This study is a contribution to the Svinøy section monitoring program, which was initiated in 1995 and is still in progress. The program was funded initially by the Norwegian Research Council (MareCog) and again partly from year 2000 (NOClim). For the period 1997 to 2000 the program was part of the EU-MAST-funded project Variability of Exchanges In the Northern Seas (VEINS). Thanks are also due to support from the Norwegian Deepwater Program (NDP) and Hans Jørgen Sætre in particular, making continuation of the monitoring program feasible, and for careful reading of the manuscript by Alastair Jenkins and two anonymous reviewers.

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