Heat flux variations in the eastern Norwegian Atlantic Current toward the Arctic from moored instruments, 1995–2005

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[1] An extraordinary warming of the Atlantic inflow to the Norwegian Sea toward the Arctic is observed over the last decade. In light of that we investigate the seasonal and interannual variations of the heat flux in the eastern Norwegian Atlantic Current (NwASC) using moored temperature (T)- and current (v) measurements in the Svinøy section (62°N); 1995–2005. By splitting the heat flux anomaly $(vT)'$ into $v'\overline{T}$ and $\overline{v}T'$ ($\overline{T}$, $\overline{v}$: 10-year means; $v'T'$ negligible), we examine the relative contributions from variations in v and T. The dominating seasonal signal coincides almost completely with $v'\overline{T}$, whilst $\overline{v}T'$ has a minor modulating effect. On the interannual timescale the heat-flux anomaly also coincides with $v'\overline{T}$, while $\overline{v}T'$ contributes significantly to the long term trend. There is a downward 10-year trend in the velocity field of 3.9 cm s^{-1} (12%), combined with a 1°C increase in temperature, resulting in a constant heat flux. **Citation:** Orvik, K. A., and Ø. Skagseth (2005), Heat flux variations in the eastern Norwegian Atlantic Current toward the Arctic from moored instruments, 1995–2005, *Geophys. Res. Lett.*, *32*, L14610, doi:10.1029/2005GL023487.

1. Introduction

[2] Recent findings show dramatic climate changes in the Arctic with temperature increase and melting of glaciers and sea ice [*Arctic Climate Impact Assessment*, 2004]. These changes are presumed to be related to variability of the poleward transport of heat through the ocean and atmosphere. In light of that, this study is motivated by an extraordinary warming of about 1°C over the last 10 years of the Atlantic inflow to the Norwegian Sea (NS), in the core of the eastern Norwegian Atlantic Current (NwAC). The NwAC is a poleward extension of the Gulf Stream, and serves as a conduit of warm and saline Atlantic water (AW) from the North Atlantic (NA) to the Barents Sea (BS) and Arctic Ocean (AO). As illustrated in Figure 1, the North Atlantic Current (NAC) splits into two branches in the eastern NA and then enters the NS close to the eastern coast of Iceland and through the Faroe-Shetland Channel (FSC) [*Fratantoni*, 2001; *Orvik and Niiler*, 2002]. It then continues as the two-branch NwAC through the entire NS toward the AO [*Poulain et al.*, 1996; *Orvik and Niiler*, 2002]. The western branch is a jet in the Polar Front that tends to feed the interior of the NS resulting in a southward recirculation toward the Fram Strait (FS). The eastern branch - the Norwegian Atlantic Slope Current (NwASC) – is an approximately 3500 km long, nearly barotropic shelf edge current along the Norwegian shelf break that tends to flow into the BS and AO. From this point of view, the NwASC is the major link between the NA and AO, and BS.

[3] The NwASC shows a coherent along-stream structure at longer timescales, with a nearly simultaneously-responding flow field from the shelf edge west of Ireland to the Fram Strait [*Skagseth et al.*, 2004]. Variations in this flow are found to be strongly linked to the wind field, both directly [*Skagseth*, 2004; *Skagseth et al.*, 2004], and indirectly [*Orvik and Skagseth*, 2003a]. In fact, on 1–12 month time scales, along-slope current variations appear as a quasi-steady, direct response to the large-scale wind field [*Skagseth et al.*, 2004], whilst on interannual time scales the variations are driven by the wind stress curl in the NA with a 15 month time lag [*Orvik and Skagseth*, 2003a]. In contrast to the flow field, temperature and salinity anomalies on annual to interannual timescales propagate slowly through the system, with a typical time lag between the FSC and FS of 1–2 years [*Furevik*, 2001].

[4] To date, long-term time series of temperature and salinity relevant to the NwAC have mostly been obtained from standard hydrographic sections, operated just a few times a year with poor resolution [*Mauritzen*, 1996; *Blindheim et al.*, 2000; *Mork and Blindheim*, 2000; *Furevik*, 2001]. In that aspect, standard hydrographic observations in the FSC show a remarkable temperature and salinity increase in the AW since 1990 [*Turrell et al.*, 2003]. Using current meter records, *Schauer et al.* [2004] estimated the heat flux into the AO in the FS, while *Ingvaldsen et al.* [2004] studied the flow in the entrance to the BS.

[5] In this study we will concentrate on the starting point of the conduit of AW through the NS in the Svinøy section near its entrance to northern areas; about 300 km downstream from the FSC. In the Svinøy section monitoring program we now have reached a milestone of ten years of moored temperature and current measurements (1995–2005). These long-term observations give us the opportunity to investigate variabilities of the flow on both seasonal and interannual timescales. We will concentrate on what is presumed to be the most important contribution for climate change in the AO, variations of the heat flux in the NwASC.

2. Data and Methodology

[6] Figure 2 shows an overview of the bottom profile and a composite of the mooring sites occupied during the

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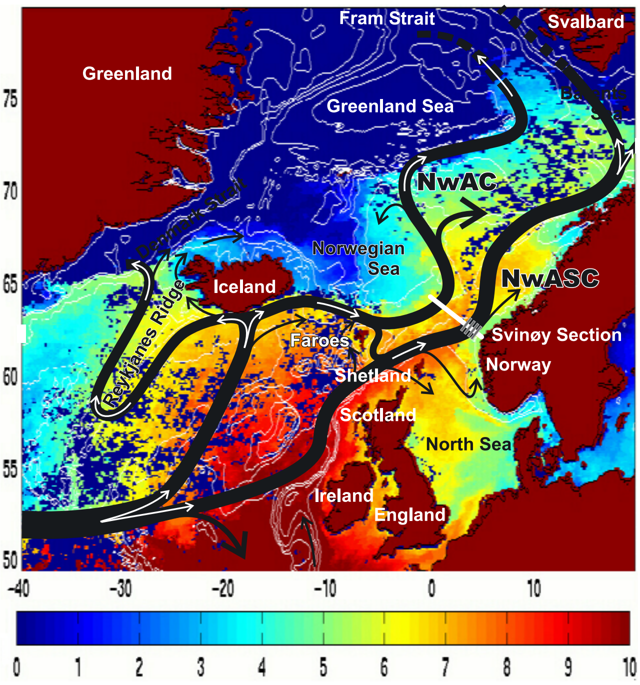

Figure 1. Schematic of the major pathways of near-surface Atlantic water in the northern North Atlantic and Norwegian Sea toward Arctic in the context of superimposed sea surface temperature from AVHHR image in March. The straight line show the Svinøy section where the mooring sites are indicated in the NwASC. Abbreviations are explained in the text.

monitoring program 1995–2005 in the slope of the Svinøy section. Figure 2 also shows the annual mean temperature- and along-slope velocity field (1997–1998) obtained from an array of 15 Aanderaa RCM7 current meters on 4 mooring lines that capture the entire NwASC. We will utilize the current and temperature measurements from mooring S1 (Figure 2). This is because S1 is located in the core of the NwASC with an annual mean current of about 30 cm/s and mean temperature through the water column of 7°C [*Mork and Blindheim*, 2000; *Orvik et al.*, 2001]. We use hourly records from the current meters at 100m and 300m depths, and an overview of data recovery is

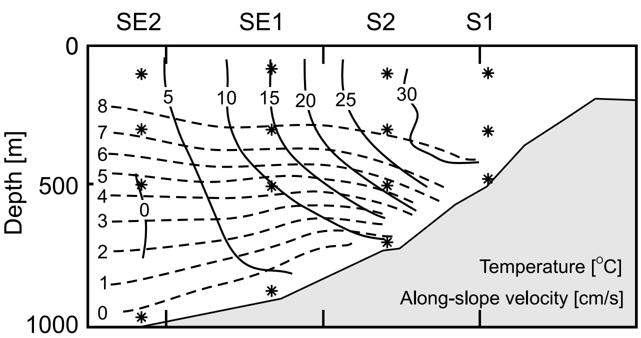

Figure 2. One-year mean along-slope current (full lines) and temperature (dashed lines) 1997–1998 in the NwASC. Mooring sites and bottom profile are shown.

Table 1. Data Overview of Current Measurements 1995–2005

ID	Lat/Lon	Inst depth(m)	Start–Stop	Total Days (Stop–Start)	Data Recovery (%)
S1-100	62°48′N	100	22 Apr 1995–	3640	98
S1-300	04°15′E	300	9 Apr 2005		92

given in Table 1. According to *Orvik and Skagseth* [2003b], the volume flux of AW in the NwASC can be estimated by using a single current meter record from S1. Accordingly; a single current record from the respective depths of 100 m or 300 m will mirror the volume flux of the NwASC. We improve confidence of the estimates from the single current meter methodology by combining the 100 m and 300 m records in an average current time series. Before calculation of the mean current, the gaps in each time series are filled by applying linear interpolation and using the mean of the data with similar length before and after the gaps to avoid aliasing [*Kushnar and Wallace*, 1989]. Onto the linear interpolation we add the contribution from the seasonal cycle, estimated from the data. To optimize the data for seasonal and interannual time scales, we apply moving-average low pass filters with 90-day (3 months) and 365-day (1 year) cut-off periods to the original time series.

[7] By applying the commonly-used assumption that inflowing AW is cooled to about 0°C before returning to the NA, the heat flux of the NwASC through the Svinøy section is given by $Q = \int_S c_p \rho v T ds$, where ρ is density of sea

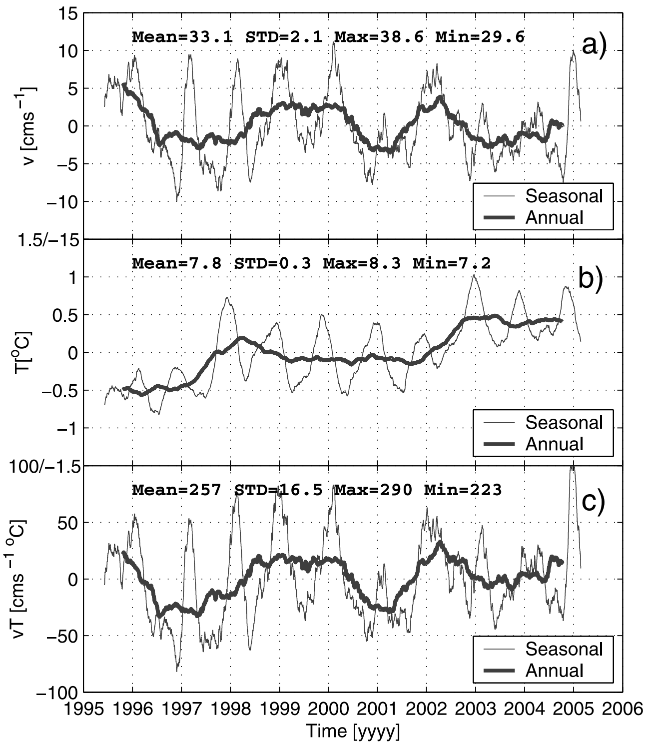

Figure 3. Time series of T(a), v(b), vT(c) anomalies in the core of the NwASC for the period 1995–2005. The hourly records are filtered by using boxcar moving average filter of 3- and 12 months. The [mean, min max] and standard deviations are shown in each panel, respectively.

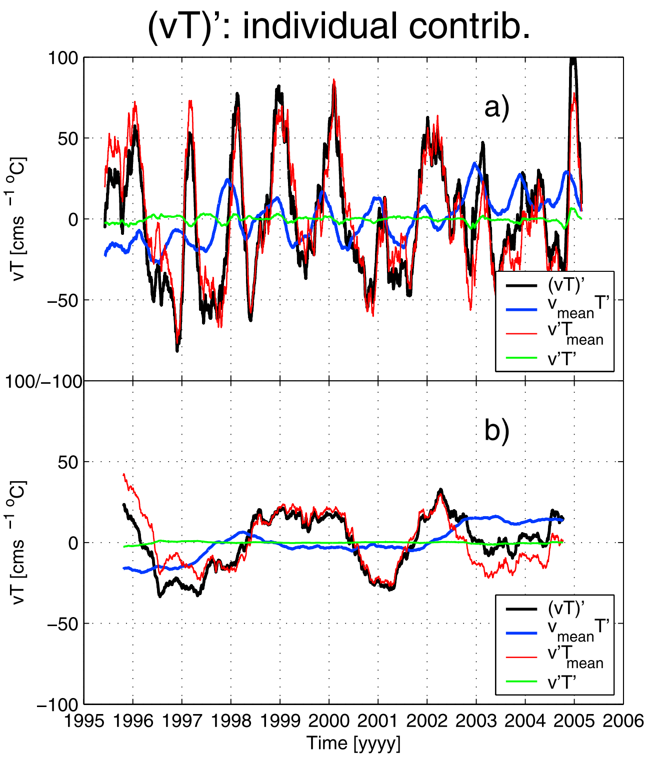

Figure 4. Time series of the vT anomalies as $(vT)' = \bar{v}T' + v'\overline{T} + v'T'$ for the period 1995–2005. For comparison, each term is presented in conjunction with the full anomaly $(vT)'$, as 3-months (a) and 12-months (b) filtered time series.

water, c_p the specific heat capacity (3985 J kg^{-1} K^{-1}), T the temperature of the AW, and v the along-slope current velocity perpendicular to the area S of the flow (NwASC). Since the volume flux $V = \int_S v ds$ of the NwASC can be determined by using a single current meter record, and the area S appears to be constant [*Orvik and Skagseth*, 2003b], it is justifiable to use the 100/300 m mean current time series (v) to determine variations of volume flux and the product vT for variations of the heat flux with reference to the 10-year averages $\bar{v}$ and $\overline{T}$. In considering anomaly variation, we split the total quantities v, T and vT into a 10-year average and an anomaly part $v = \bar{v} + v'$, $T = \overline{T} + T'$, and $vT = \overline{vT} + (vT)'$, where $(vT)' = \bar{v}T' + v'\overline{T} + v'T'$. Since the 300 m current meter on S1 is located in the core of the AW, we use this temperature record as representative for T in conjunction with the average current speed v. With reference to the 10-year means $\overline{T}$, $\bar{v}$ and $\overline{vT}$, the anomaly variables T', v' and $(vT)'$ are displayed in Figure 3 as 90- and 365-day moving average time series. In Figure 4 time series of the relative contribution from each term is presented. To detect possible trends in the time series we use a linear regression model y (T, v, vT) = a * t + b, where a gives the trend per year; t is time and b an offset (Table 2).

3. Results

[8] The time series of current anomalies v' in Figure 3a is superimposed on a 10-year mean current of 33.1 cm s^{-1} with variations in the range of about (−10, 12) cm s^{-1} on 3-month timescale and (−3.8, 5.2) cm s^{-1} annually ie. (−11, 15)%. On the 3-month timescale, the most striking feature of the flow is the annual cycle with winter maxima and summer minima, and amplitude of about 10 cm s^{-1}, except for the period 2002–2004, where the amplitude is halved (4 cm s^{-1}), but then followed by an extreme winter event in 2005. On the interannual timescale, the one-year moving average time series in Figure 3a shows variations with amplitude of (2–4) cm s^{-1}. The absolute maximum occurred around 1995, and there is an apparent periodicity of 3–4 years superimposed on a minor downward trend over the 10-year period.

[9] The temperature anomaly (T') in Figure 3b also shows a prominent seasonal cycle with amplitude of 0.5°C about the 10-year mean of 7.8°C. The annual cycle is manifested in a maximum temperature in December (early winter) and minimum in the autumn. Compared with observations at 100 m depth (not presented), there is downward time lag of about 1 month, and a 50% reduction of amplitude. This finding is in accordance with common understanding of the vertical propagation of the seasonal signal in the ocean. On interannual time scale, the most striking feature is an overall temperature increase over the 10-year period of about 1°C. This warming trend appears to be related to two prominent events; a temperature increase of 0.6°C from 1997 to 1998, followed by a gradual decrease of 0.3°C, and then a second abrupt increase of 0.6°C from 2002 to 2003. Comparing Figures 3a and 3b, there appears to be no coincidence between current and temperature, rather the contrary on interannual time scales. This is shown as temperature increase combined with a decrease in the current in late 2002, and *vice versa* in 1996–1998. This is in accordance with the non-significant correlation coefficient of 0.29 between v' and T'. Comparing the seasonal signals of v' and T', there is an apparent lag of about 2 months, where the flow trails the temperature signal. But in spite of an annual cycle both in the temperature and current, there is no apparent resemblance, either on monthly or interannual timescales, i.e. the strong seasonality in the flow in 1997/98 coincides with an extraordinary weak seasonal signal in the temperature.

[10] The heat flux variability, shown by the $(vT)'$ anomaly in Figure 3c, has a correlation coefficient of 0.88 with v' and 0.37 with T', respectively. This confirms a significant similarity between the v and vT time series, where variations in v dominate the heat flux, while temperature variations appear to have minor effects. This is in accordance with Figure 3, particularly on interannual timescales, where the time series of $(vT)'$ and v' have an overall resemblance, with respect to both periodicity and amplitude pattern. However, the temperature variations appear to modulate the heat flux compared with the volume flux

Table 2. Application of the Linear Regression Model y (T, v, vT) = a * t + b to Show Trend in the Time Series[a]

Var	a (year^{-1})	p-Value
T	0.097°C	$5*10^{-3}$
v	−0.39 cm s^{-1}	0.25
vT	0.26 cm s^{-1} °C	0.91

[a]Where t is time and b an arbitrary coefficient; a gives the trend per year and p the probability of a outside the range [0, 2a].

on longer timescales. This is demonstrated in Figure 4, where time series of each anomaly term are presented in conjunction with $(vT)'$. On the 3-month timescale, the dominating seasonal signal coincides almost completely with the $v'\overline{T}$ term, whilst the $\overline{v}T'$ term appears to have a minor modulating effect in spite of a distinct phase shift of about 2 months, and $v'T'$ is negligible. On the interannual timescale, Figure 4 shows that the $(vT)'$-variations are strongly connected to the $v'\overline{T}$ term, while the $\overline{v}T'$ term contributes significantly to the long term trend of the heat flux. This is manifested in a negative contribution for the 1995–1997 period and a positive contribution for the period 2003–2005. This temperature modulation of the heat flux thus compensates for an apparent downward trend in volume flux, resulting in a constant heat flux over the 10-year period. Table 2 indicates a downward trend in the velocity field of 0.39 cm s^{-1} $year^{-1}$, i.e. a 3.9 cm s^{-1} decrease over 10 years, while there is no trend in the heat flux.

4. Discussion and Concluding Remarks

[11] The volume flux of the NwASC has fluctuations over a wide range of periods, from weeks to months, seasons and years [*Orvik and Skagseth*, 2003a]. In this study we restrict the investigation to seasonal and interannual variations by examining the variations of the volume and heat flux over the 10-year period in terms of v', T' and $(vT)'$ anomalies. With reference to a mean volume flux of 4.2 Sv (1 Sv = 10^6 m^3 s^{-1}) [*Orvik and Skagseth*, 2003a], the annual volume flux anomalies turn out to be in the range of (−0.46, 0.63) Sv or in total (3.7, 4.8) Sv. The $\overline{vT}$ average in Figure 3 corresponds to an overall heat flux of 133 TW (T = 10^{12}) with anomalies is in the range of (−16.0, 14.6) TW, and in total between 117 TW and 148 TW. The variations reflect a 25% span between minimum and maximum heat flux in conjunction with a 30% span in volume flux and an about 1°C range in temperature.

[12] As shown in Figure 4, there appears to be a remarkable similarity between time series of v' and $(vT)'$, both on seasonal and interannual timescales, while there is less coincidence between temperature and flow variations. The splitting of the heat flux anomaly $(vT)'$ into $v'\overline{T}$ and $\overline{v}T'$ terms indicates the relative contributions from variations in current and temperature on the heat flux. The remarkable coincidence between variations of heat flux $(vT)'$ and the term $v'\overline{T}$ both on seasonal and interannual time scales confirms the fact that heat flux variations of the NwASC on these time scales are determined by variations of the volume flux. The seasonality of the NwASC is a quasi-steady, direct response to the large-scale wind field [*Skagseth et al.*, 2004], while the interannual variations are strongly connected to the wind stress curl in the NA 15 months earlier [*Orvik and Skagseth*, 2003a]. In that perspective, the absolute $(vT)'$ maximum event in Figure 3c corresponding to a heat flux of 148TW appeared in conjunction with a striking volume flux in 2002. It is noteworthy that this extreme heat flux event coincides with an extraordinarily high spawning of herring in the vicinity of the NwASC, and subsequent recruitment in 2002 (O. Misund, personal communication, 2005). Since this extreme event is strongly connected with the wind force in the NA 15 months earlier, it may be possible to predict future events.

[13] According to Figure 4, temperature variations in terms of $\overline{v}T'$ contribute significantly on longer timescales in modifying the heat flux trend. This effect is also manifested in Table 2, which shows a minor downward trend in volume flux over the 10-year period, whilst there is no significant decrease in heat flux. So there is a paradox, in that there is no increasing trend in the heat flux over the 10-year period, in spite of a 1°C temperature increase. This finding confirms the dominating influence of the volume flux in determining variations of the heat flux carried by the NwASC. The striking temperature increase appears to be independent of variations in the flow, so a relevant question is: what causes this striking temperature increase? Presumably the underlying mechanisms are complex, and are thus beyond the scope of this study. In any case there will be a challenge for e.g. modelers to determine whether their models capture the measured changes, and furthermore, whether they can incorporate the causal mechanisms in their models.

[14] **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 and partly from 2000 (NOClim) by the Norwegian Research Council, and for the period 1997–2000 as part of the EU-MAST-funded project VEINS. Since 2000 support from the Norwegian Deepwater Program (NDP) has made continuation of the monitoring program feasible. Thanks are due to Hans Jørgen Sætre (NDP), and Alastair Jenkins for careful reading of the manuscript.

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