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Detection of deep overflows with satellite altimetry

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Abstract. In-situ observations downstream of the sills in the Faroe Bank Channel and Denmark Strait show large temperature and current variability of the overflows with time-scales of a few days. These fluctuations are associated with meso-scale eddies and have an impact on sea surface height. This is confirmed by observations from the TOPEX/POSEIDON and ERS 1+2 satellites that show substantial enhancement of eddy kinetic energy and sea level variability immediately downstream of the sills.

Introduction

The overflows of dense bottom water from the Nordic Seas into the North Atlantic through Denmark Strait (DS) between Iceland and Greenland and through the Faroe Bank Channel (FBC) south of the Faroe Islands are important sources for North Atlantic Deep Water, which is a main constituent of the global thermohaline circulation [*Dickson and Brown,* 1994].

On seasonal and longer time-scales the overflows are fairly stable with estimated transports of $2.9 \cdot 10^6$ m^{3}s^{-1} through the DS and $1.7 \cdot 10^6$ m^{3}s^{-1} through the FBC [*Dickson and Brown,* 1994; *Hansen and Østerhus,* 2000]. However, both overflows exhibit large fluctuations in temperature and current velocities with periods of a few days downstream of the sills [*Smith,* 1976]. Infrared imagery and drifter trajectories in the DS have associated this variability with meso-scale eddies [*Bruce,* 1995; *Krauss,* 1996]. On the left, down-slope side of the overflow plume cyclonic eddies predominate, but anticyclonic eddies up-slope of the plume are also present. Model simulations have shown that cyclonic eddies in the DS are associated with surface depressions of up to 7 cm [*Jiang and Garwood,* 1996] and have been used to verify generating mechanisms such as baroclinic instability [*Smith,* 1976] and vortex tube stretching [*Krauss and Käse,* 1998]. Laboratory experiments of a dense overflow plume on a sloping bottom have also confirmed that different mechanisms can generate baroclinic eddies [*Whitehead et al.,* 1990].

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Previous studies of overflow eddies employing remote sensing techniques have used passive infrared imagery [*Bruce,* 1995]. These suffered from very poor data return due to persistent cloud cover and relied on a gradient in the sea surface temperature (SST) (which is not present in the FBC) to detect the eddies.

In this paper we present evidence that the large fluctuations in temperature and current velocities associated with eddies in overflows have an impact on the sea surface height (SSH). The SSH variability can be observed by the TOPEX/POSEIDON and the ERS 1+2 altimetry satellites. The observations are obtained by radar measurements and are thus not limited to cloud free times. The repeat cycles of the satellites are 10 days and 35 days, respectively, which certainly does not allow to resolve these fluctuations of 2-5 days period. However, second order statistics of this high-frequency variability, that is the variance of the SSH fluctuations and the SSH slopes, can be estimated within 90 % after only 20 measurement cycles. These statistics reveal strong SSH variability downstream of the DS and the FBC along the path of the overflows.

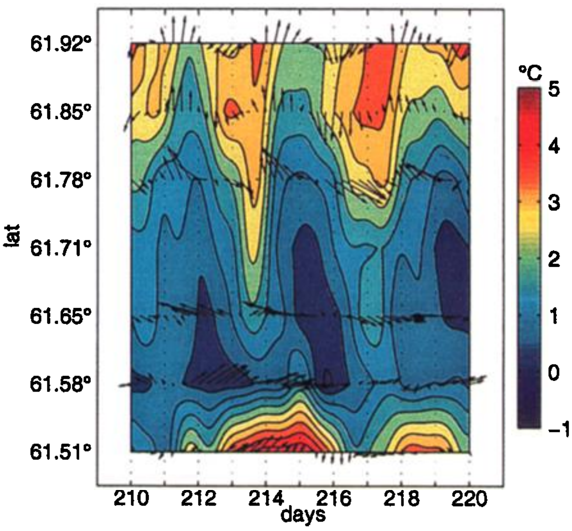

Figure 1. Time-Latitude plot of near bottom temperatures (colors) and band-passed filtered (2-8 days) currents (arrows). Data are from 7 moorings about 140 km downstream of the FBC (see Figure 3 for location). The maximum arrow represents a current anomaly of ~ 30 cm/s.

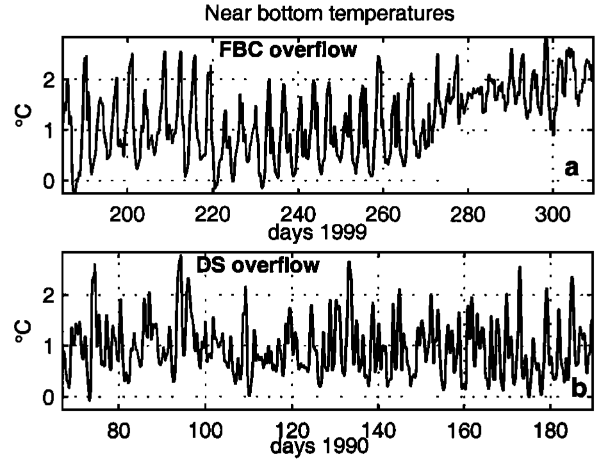

Figure 2. Time series of temperature from instruments moored downstream of the sills in the two overflows studied here. Tides and inertial oscillations have been filtered out, a: Half hourly values from FBC, b: Hourly values from DS (data courtesy of R. R. Dickson).

In-situ observations

Observations of the FBC overflow from an array of moored current meters 140 km downstream of the sill show the near bottom temperatures and currents to vary by more than 3°C and 50 cm/s, respectively (Figure 1). The mooring array, oriented north-south, intersected the overflow plume and its core can be identified as water $\leq$3°C. Temperature and flow fields are clearly correlated and show a train of meso-scale eddies. The fluctuations are a general feature of both overflows (Figure 2). The dominating periods during the four months of observations were 2.8 days for the DS and 3.5 days for the FBC.

To estimate the vertical extent of the fluctuations and the associated steric height variability, conductivity-temperature-depth (CTD) profiles downstream of the FBC were used. During a cruise in August-September 2000, 42 CTD profiles were taken during 5 repeats of the section 30 km from the sill (Figure 3). The repeat profiles containing some overflow water show variability in the steric heights with a standard deviation of up to 2.9 cm. Along the mooring array (Figure 3) 30 CTD profiles were available from four cruises in different years. The profiles containing the overflow plume show a steric height variability of up to 2.0 cm calculated over the deepest 500 m. The variability can be attributed to the 3-4 day fluctuations and showed up during all of the four years. In the DS, observations are available from the Dohrn Bank and the Overflow 1973 mooring arrays [*Dickson and Brown,* 1994; *Smith,* 1976]. No short term repeat CTD profiles were available to us and we estimate the variability of the plume thickness and the associated steric height variability from the temperature records of the central mooring in each array. The two moorings contained 3 instruments each in the vertical. The thickness of the plume in the Dohrn Bank array varied between 20 and 550 m, corresponding to a standard deviation in steric height of 1.9 cm. In the central Overflow 1973 mooring the plume thickness ranged from 100-350 m, resulting in a slightly higher steric height variability of 2.1 cm, due to larger temperature variations.

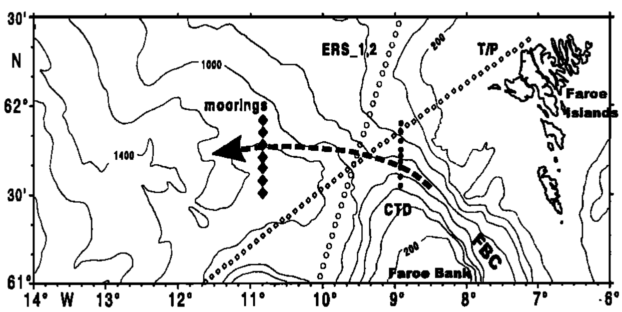

Figure 3. Bathymetry of the Faroe Bank Channel (FBC) and location of satellite ground tracks, T/P 32 (open diamonds) and ERS 405 (open circles). Also shown is the mooring array 140 km downstream of the sill (filled diamonds) and the CTD section 30 km away from the sill (filled circles).

Table 1. Eddy kinetic energy downstream of the sills from near bottom moorings ($\hat{K}_e = \langle u'^2 + v'^2 \rangle/2$) and from nearby T/P tracks (K_e). The data used in the DS are from the Overflow 1973 mooring array, the Dohrn Bank 1990 and from the Angmassalik array (see *Smith* [1976] and *Dickson and Brown* [1994]). Current meter data from inside the FBC are from B. Hansen, *personal communication* [2000].

Sill	Number of moorings	Dist. from sill, km	Moorings $\hat{K}_e$ cm^2/s^2	T/P K_e cm^2/s^2
DS	4	55	309-635	525
	5	160	59-263	250
	22	480	24-131	200
FBC	1	0	70	
	2	30	213-375	300
	6	140	77-210	

Eddy kinetic energies calculated from near bottom current meters moored along the path of the two overflows are listed in table 1. The variability associated with the overflows has its maximum some 30-60 km after the sill and decreases rapidly further downstream.

Results from altimetry data

The altimetry data used in this study are processed by the Pathfinder team[1] and consist of 232 T/P repeat cycles (interval 9.92 days, Sep 1992 – Dec 1998) and 66 ERS 1+2 repeat cycles (interval 35 days, April 1992

[1] http://neptune.gsfc.nasa.gov/ocean.html

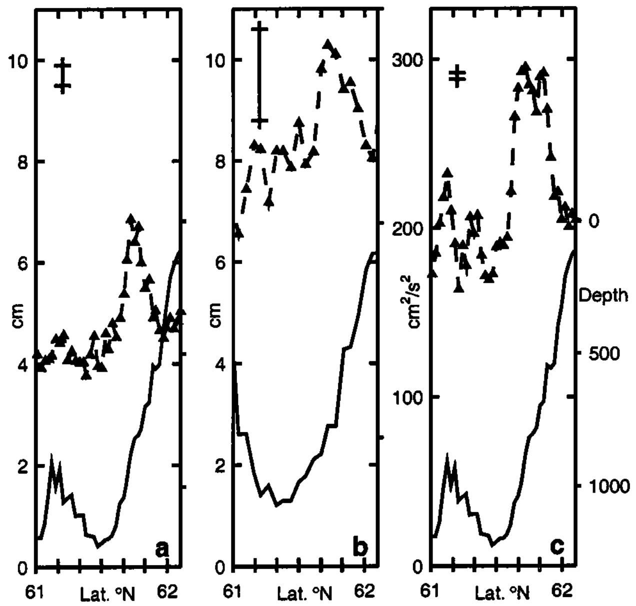

Figure 4. Results from TOPEX/POSEIDON track 32 (a+c) and ERS track 405 (b). a: Standard deviation of SSH (dashed) from T/P observations. b: as (a) but for ERS data. c: Time mean eddy kinetic energy from the T/P observations. The solid lines indicates the along track bottom topography taken from Etopo5.

– Aug 1998). The ERS record contains a gap of ~ 15 months and an overlap of ~ 10 months and is corrected for an offset between the missions. An accuracy of ≤ 5 cm has been obtained for individual measurements with the T/P satellite [*Fu et al.,* 1994] whereas the ERS satellites in general have slightly higher measurement errors. A set of edit criteria set by the Pathfinder team and a 3-σ filter was applied to the data before the SSH variability was calculated. Only results based on a minimum of 100 observations for T/P and 30 for ERS are shown in the subsequent sections. This allows to estimate the statistics of the fluctuations within 97 and 93 %, respectively. The time mean eddy kinetic energy is calculated as:

$$K_e = (\frac{g}{f})^2 \langle (\frac{\partial \eta}{\partial s})^2 \rangle \quad (1)$$

where η is the sea surface height anomaly, s the along track distance, $\langle \cdot \rangle$ denotes time average, f is the Coriolis parameter and g is gravity. Equation 1 gives twice the eddy kinetic energy from the cross track geostrophic surface velocity which corresponds to the total kinetic energy under the assumption of local isotropy. Isotropy in eddy kinetic energy was confirmed by the current meter observations downstream of the sills.

Error bars are calculated under the assumption that we only consider changes from the along track sea level. Orbit errors and errors in the corrections applied to the data have much larger spatial scales than the signal from the overflow plumes (see e.g. *JGR 101, Special issue* [1994]). The measurement errors are therefore taken as the instrumental noise of ~ 2 cm for the T/P and ~ 5 cm for the ERS data. The number of independent observations used for the calculation is 100 for T/P and 30 for ERS, according to the criteria of minimum observations.

Faroe Bank Channel

The T/P and ERS 1+2 satellite ground tracks closest to the FBC (Figure 3) cross the mean path of the overflow plume about 50 km downstream of the sill. Enhanced SSH variability associated with the overflow can be detected by both the T/P and the ERS altimetry satellites (Figure 4) and amounts to about 3 cm above background level, which is significant for both satellites. The location corresponds to where the ground track crosses the overflow plume.

The peak in variability is more distinct in the T/P data due to a combination of more observations and higher accuracy of the individual observations. Figure 4c also displays that enhanced K_e is observed over the plume. With no along track smoothing prior to the gradient calculation, the increase in the TOPEX observations is ~ 75 cm^2/s^2. Groundtracks to the west of those in Figure 3 are located ~ 110 km further downstream for the TOPEX/POSEIDON and ~ 40 km for the ERS 1+2 data. No significant enhancement of surface variability was seen in these groundtracks and they are therefore not shown here.

Denmark Strait

The high latitude of the DS close to the turning latitude of the T/P satellite makes the data favorable for this study. The ground tracks are closely spaced and oriented almost east–west, perpendicular to the overflow, and the K_e results can be gridded without introducing large errors. An objective gridding routine with a second order Markov covariance model was used in the gridding of K_e calculated from equation 1. The

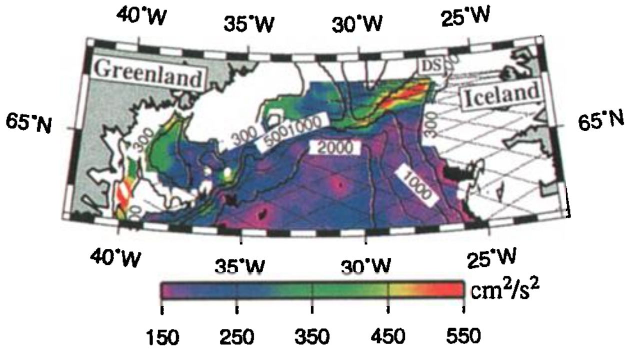

Figure 5. Gridded eddy kinetic energy (K_e) derived from T/P observations for the Denmark Strait (DS) overflow region (color). Overlaid are the original tracks on which the grid is based. Only observations from water depths ≥300 meters have been used.

distribution of K_e with the ground tracks overlaid (Figure 5) displays enhancement downstream of the sill in the DS ($\sim$ 66.2° N). Immediately downstream of the sill, the peak is centered in the DS, but further downstream the enhanced K_e shifts to the west and follows the Greenland continental slope. The increase in K_e extends $\sim$ 150 km downstream from the sill.

Discussion

The overflow regions downstream of the DS and the FBC exhibit significant increase in SSH variability and K_e close to the sills. The regions coincide with the mean locations of the plumes in areas where the overflows experience large bottom slopes and where high meso-scale eddy activity is observed. The small spatial scales of the elevated variability in SSH are in agreement with the scales of the overflow plume and the generated eddies. SSH variability from insufficient subtraction of the tides, inverse barometer effect or high–frequency wind driven barotropic motion occur on larger scales and contribute only to an increased background noise level. Also, the possible SSH variability induced by a combination of geoid variability and displaced satellite repeat ground tracks was investigated and found to be minimal. The observed increase in SSH variability from the altimetry satellites is in agreement with in-situ observations downstream from the sills. Discrepancies in the strength of the signal may be due to the presence of barotropic eddies, which are not included in the steric height estimate and which cause additional surface variability in the altimetry observations.

In the FBC maximum meso-scale variability, both in-situ and in the altimeter data, is seen around 30 km downstream of the sill. The poor spatial satellite coverage does not allow to draw detailed patterns, but 130 km further downstream K_e and SSH variability are below detection level.

The situation with the satellite coverage is much better for T/P in the DS. In agreement with in-situ observations the variability of the DS overflow plume is largest very close to the sill and decreases rapidly downstream. It is consistent with recent model results [*Käse and Oschlies,* 2000] that the maximum in eddy kinetic energy is found in the center of the strait very close to the sill and shifts to the Greenland slope further downstream. Eddies along the Greenland slope have been observed as far downstream as 62°50′ N [*Bruce,* 1995], but in the altimetry observations the associated variability that far downstream is too small to be detected. The DS overflow is not a simple two-layer exchange flow as the FBC overflow. Changes in the position of the East Greenland current together with contamination from sea ice may contribute to the variability. However, examination of AVHRR SST data revealed that the maximum SST variability associated with frontal processes was located downstream of the maximum in SSH variability, suggesting that the effect is minimal.

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