The Competition of Tidal Mixing and Freshwater Forcing in Shaping the Outflow from Hudson Strait

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LONG-TERM GOALS

River discharge, precipitation and, in the high-latitudes, melt water from sea-ice or glaciers give rise to fresh and buoyant plumes which flow along topographic margins. These plumes form in coastal environments and are subject to a variety of processes, including tidal mixing and surface forcing, which rapidly modify their properties and their structure. We investigate how tidal mixing, surface forcing and a variable fresh water source act to modify a fresh, buoyant plume using a combination of observations, theory and numerical models.

OBJECTIVES

- Investigate the spatial characteristics of the plume from the moored data including its vertical structure, fresh water content, the bottom boundary layer, and the freely propagating internal tides.
- Investigate the tidal to interannual variability in the flow and better understand its relation to the tidal forcing as well as the local and remote wind-forcing and buoyancy forcing.
- Expand the theory for a buoyant gravity plume over sloping topography to include strong mixing.

APPROACH

A new and unique set of measurements from Hudson Strait, one of the most tidally energetic straits in the world and an important channel for freshwater transport into the North Atlantic is available to us to address our objectives (Figure 1). The 3-year moored data set, which includes high resolution property and velocity profiles, as well as optical backscatter and fluorometer data, is ideal to look at the interplay of the variable stratification, driven by input of freshwater, and the mixing driven by the

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tides, two competing mechanisms controlling the physical and biochemical properties of many estuaries and straits. Our analysis focuses on the barotropic and baroclinic tides, the bottom boundary layer, and the buoyant current and on their spatial and temporal variability.

WORK COMPLETED

1. Barotropic tide

Using a global tidal assimilation model, TPXO, Egbert and Ray (2001) found that the region around Hudson Bay dissipates more tidal energy than any other region of the world's ocean. Regional tidal models are run with a higher resolution and are available from Gary Egbert's group. Here we have compared the global model and the Atlantic Ocean (AO) and Hudson Bay (HB) models, available on http://www.oce.orst.edu/research/po/research/tide.

The mooring records allow us to calculate the barotropic energy fluxes. The elevation (pressure) and currents associated with the barotropic tides are computed using least-square fit on multi-year time series from the moorings. The resulting barotropic energy flux vectors (Figure 2a) agree reasonably well with the TPXO HS regional model.

The M2 barotropic energy flux divergence (Figure 2b) shows a strong divergence in Hudson Strait, indicating that the barotropic tide is losing most of its energy in the strait itself. In fact, integrating the divergence in the strait, and in the whole Hudson Bay system west of the mooring lines (~70°W), it appears that the tide gains energy in Hudson Bay and Foxe Basin, partly compensating for the losses in the Strait. This result, consistent for all TPXO models, is surprising and somewhat in disagreement with the model of Saucier et al., 2004 (Pierre St-Laurent, personal communication), which has similar total dissipation west of the moorings (-123 GW), but most of this dissipation occurring in Foxe Basin rather than in the Strait. The choice of topography in the models appear to be critical.

Table 1: Tidal dissipation in the Hudson Bay system and in Hudson Strait, from the Hudson Bay TPXO regional model (1/12° resolution), the TPXO Arctic Ocean model (1/12° resolution), and the global TPXO6.2 model (1/4° resolution). Hudson Strait is defined as the domain show in Figure 2a (61° to 65N, 77° to 70°W) and the Hudson Bay system is all the domain west of 70°W.

	Regional HB model	Regional AO model	TPXO6.2
Hudson Bay system (west of 70°W)	-127 GW	-139 GW	-103 GW
Hudson Strait only	-269 GW	-239 GW	-226 GW

Based on the actual depths recorded at the CTD stations (Figure 3a, red), a square channel appears to be a good approximation of the bathymetry of the Hudson Strait – better in fact than the Smith and Sandwell bathymetry used in tidal models (Figure 3a, blue).

Problems with the topography that TPXO uses – brings questions to the total tidal dissipation in Hudson Strait / Hudson Bay. Indeed, Arbic et al. 2007 showed that changing the geography of the Hudson Bay system can have big impacts on the global tidal dissipation, and far reaching effect.

2. Subtidal Variability

Beyond the tidal variability, the buoyant plume in Hudson Strait exhibits a high degree of variability on a range of subtidal scales. We investigated the variability of the two dominant signals, the seasonal and 2-3 day variability, using a combination of data, numerical models and idealized models. Our goal here is to understand what physical mechanisms contribute to shaping the outflow on these timescales. This work has been carried out in collaboration with a graduate student at the University of Quebec, Rimouski, Pierre St-Laurent who has been running a high-resolution regional model of the Hudson Bay System and with David Sutherland, a post-doc first in Woods Hole and then at the University of Washington, Seattle.

RESULTS

1. Barotropic tide

To independently calculate the M_2 tidal dissipation in the Hudson Bay system, we assume that the elevation of the surface tide is given by the superposition of an incoming Kelvin wave, propagating eastward along the northern side of the strait, and a reflected Kelvin wave propagating westward along the south shore (Drinkwater, 1988).

$$\eta(x,y,t) = \eta_I + \eta_R, \text{ where}$$

$$\eta_I = \eta_0 \exp(-i\omega t)\cdot\exp(-ikx)\cdot\exp\left(\frac{+(y+L/2)}{R_0}\right), \text{ and}$$

$$\eta_R = R\cdot\eta_0 \exp(-i\omega t)\cdot\exp(-ikx)\cdot\exp\left(\frac{-(y-L/2)}{R_0}\right).$$

Here η_0 is the incident wave surface elevation, x and y is the along- and cross-strait distances, respectively (centered in the middle of the strait), k is the wavenumber in the along-strait direction (determined by the dispersion relation), ω is the M_2 frequency, L is the strait width, and R is the reflection coefficient. R_0 is the external Rossby radius given by

$$R_0 = \frac{\sqrt{gH}}{f} \approx 4.55\times10^5 \text{ m},$$

with the depth of the strait H = 350 m, and g and f are the gravitational acceleration and the Coriolis frequency, respectively. Because we also have velocity information at the mooring sites, we can further constrain the model. For a Kelvin wave,

$$u(x,y,t) = \frac{gk}{\omega}\eta(x,y,t)$$

η_0 and R are both unknown complex numbers, determined via a least-square fit using the amplitude and phase of the barotropic surface elevation and velocity at the mooring sites.

The 3 mooring data, and in particular the phase lag between velocity and surface displacement determine the parameters of the incoming and reflected wave. We find that the reflection coefficient is 0.38, showing that the incoming M_2 tide is much greater than the reflected tide. This model predicts that 81 GW are dissipated in the Hudson Bay system (west of the mooring line). For reference, we find that the incoming Kelvin wave carry 94 GW into the strait.

This number is 20-45% smaller than the estimates from the regional and global TPXO models (Table 1).

2. Subtidal Variability

Beyond the seasonal cycle that results from the strongly seasonal river input, the buoyant plume in Hudson Strait is characterized by a series of discrete pulses (particularly pronounced during the fall/winter season) which occur on average every four and half days (Figure 4). An analysis of the characteristics of these pulses showed them to be anticyclonic, surface-trapped eddies (Figure 5) that account for roughly 40% of the total volume transport and 50% of the fresh water transport. We investigated the origin of these eddies both using data from Hudson Strait and Bay as well as using the regional numerical model (Saucier et al. 2004) and found them to be associated with the passage of storms across Hudson Bay. By exerting a strong influence on the relatively slow boundary current of Hudson Bay, wind patterns associated with these weather events control the release of freshwater from the mouth of Hudson Bay into Hudson Strait. These results represent a shift from viewing buoyant plumes as simple, continuous boundary currents and highlight the strong variability associated with the freshwater release from an upstream marginal sea. They are important because of their strong impact on stratification and their coherent nature – which enables water properties to be carried downstream without substantial modification.

FUTURE WORK

Baroclinic tide and bottom boundary layer

With the better knowledge of the barotropic tide, the next step is to investigate the baroclinic signal we observe at the moorings. In the next few months (grant expires in March 2010), we will study the tidal bottom Ekman layer and the internal tide.

Eddy Generation at the Mouth of Hudson Bay

We are presently working with both data and the numerical model to investigate the exact mechanism for fresh, eddy generation at the mouth of Hudson Bay and, furthermore, whether it is modified by the seasonal ice-cover.

IMPACT/APPLICATIONS

TRANSITIONS

RELATED PROJECTS

REFERENCES

Arbic, B. K., P. St-Laurent, G. Sutherland, and C. Garrett, 2007: On the resonance and influence of the tides in Ungava Bay and Hudson Strait. *Geophys. Res. Lett.*, **34**, L17606, doi:10.1029/2007GL030845.
Egbert, G. D., and R. D. Ray, 2001: Estimates of M2 tidal dissipation from TOPEX/Peseidon altimeter data. *J. Geophys. Res*., **106**, 22475-22502.

Saucier, F. J., S. Senneville, S. Prinsenberg, F. Roy, G. Smith, P. Gachon, D. Caya, and R. Laprise, 2004: Modelling the sea ice-ocean seasonal cycle in Hudson Bay, Foxe Basin and Hudson Strait, Canada. *Climate Dynamics*, **23**, 303–326, doi:10.1007/s00382-004-0445-6

PUBLICATIONS

We are currently working on a paper focusing on the barotropic tide in Hudson Strait. Several papers addressing the subtidal variability of the Hudson Strait outflow are about to be submitted to a special issue volume on the Hudson Bay System edited by R. MacDonald:

Sutherland, D., F. Straneo, S. Lentz, E. Boss, 2010: Observations of fresh anticyclonic eddies in the Hudson Strait outflow, *J. Mar. Res, (in preparation)*

St-Laurent, P., Straneo, F., Dumais, J.-F., and Barber, D. G., 2010. On the residence time of freshwater in Hudson Bay and the export of freshwater to the Labrador Sea using a 3-D model. *J. Mar Res* (in preparation)

Straneo, F. , D. Sutherland, P. St. Laurent, S. Dery, 2010. Subtidal variations in the freshwater and heat transport from Hudson Bay 2004-2007, *J. Mar. Res*, (in preparation).

Portions of this work will be presented at the 2010 Ocean Science Meeting in Portland, Oregon.

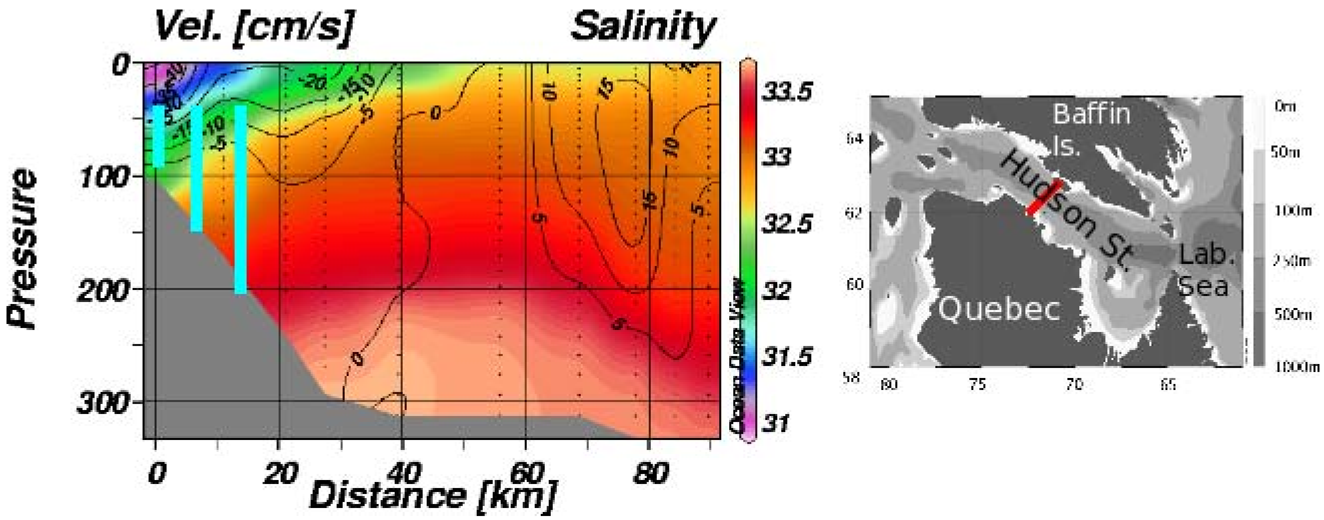

Figure 1: Left Panel: Salinity section across Hudson Strait (from hydrographic data). The geostrophic velocity (referenced to the bottom) is overlaid (black contours) showing the outflow towards the Labrador Sea on the southern side (fresh outflow) and a weakly stratified inflow on the northern side. Also shown as vertical lines are the locations of the three moorings maintained from August 2004. Right Panel: Hudson Strait bathymetry and location of the hydrographic and mooring section shown.

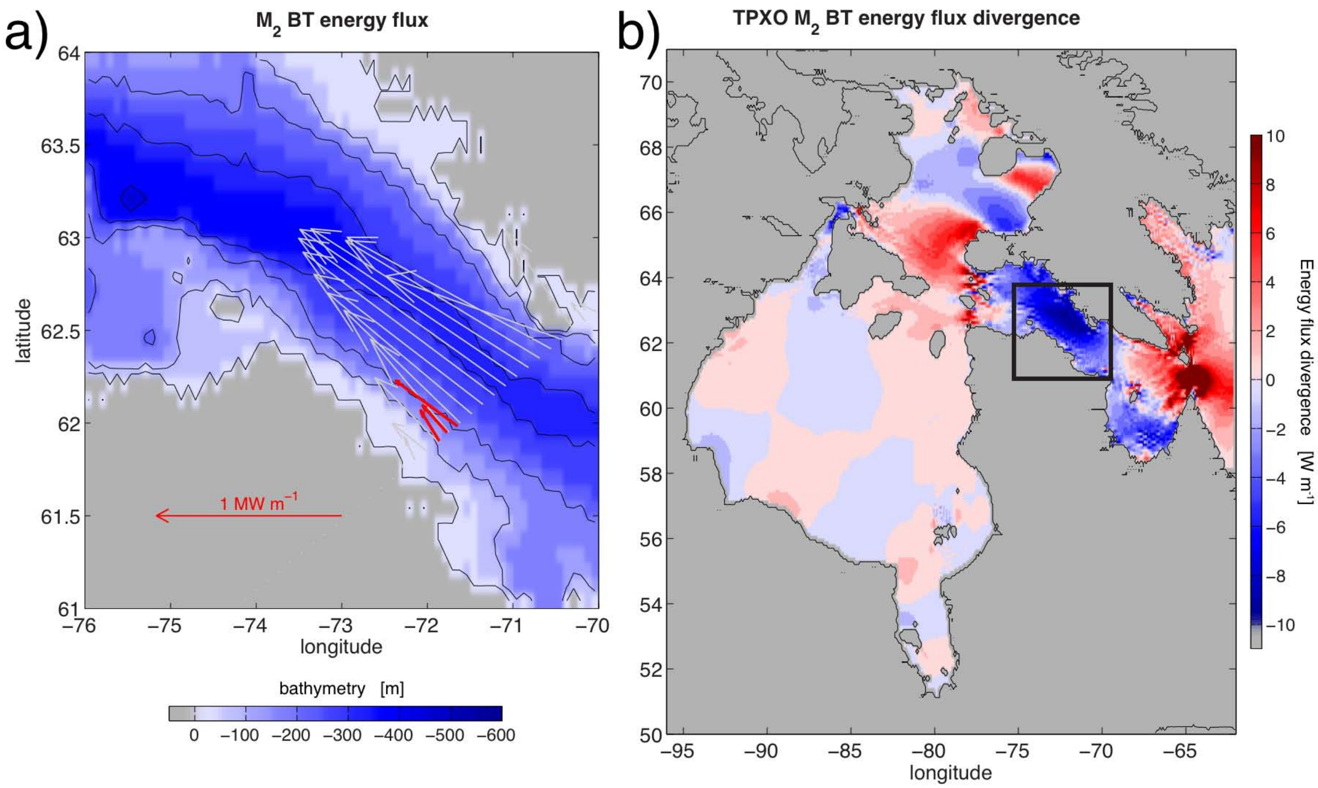

Figure 2: (a) M2 barotropic energy flux vectors from the TPXO model (gray) and from the TPXO Hudson Bay regional model (gray) along the mooring line. (b) M2 Barotropic energy flux divergence from TPXO

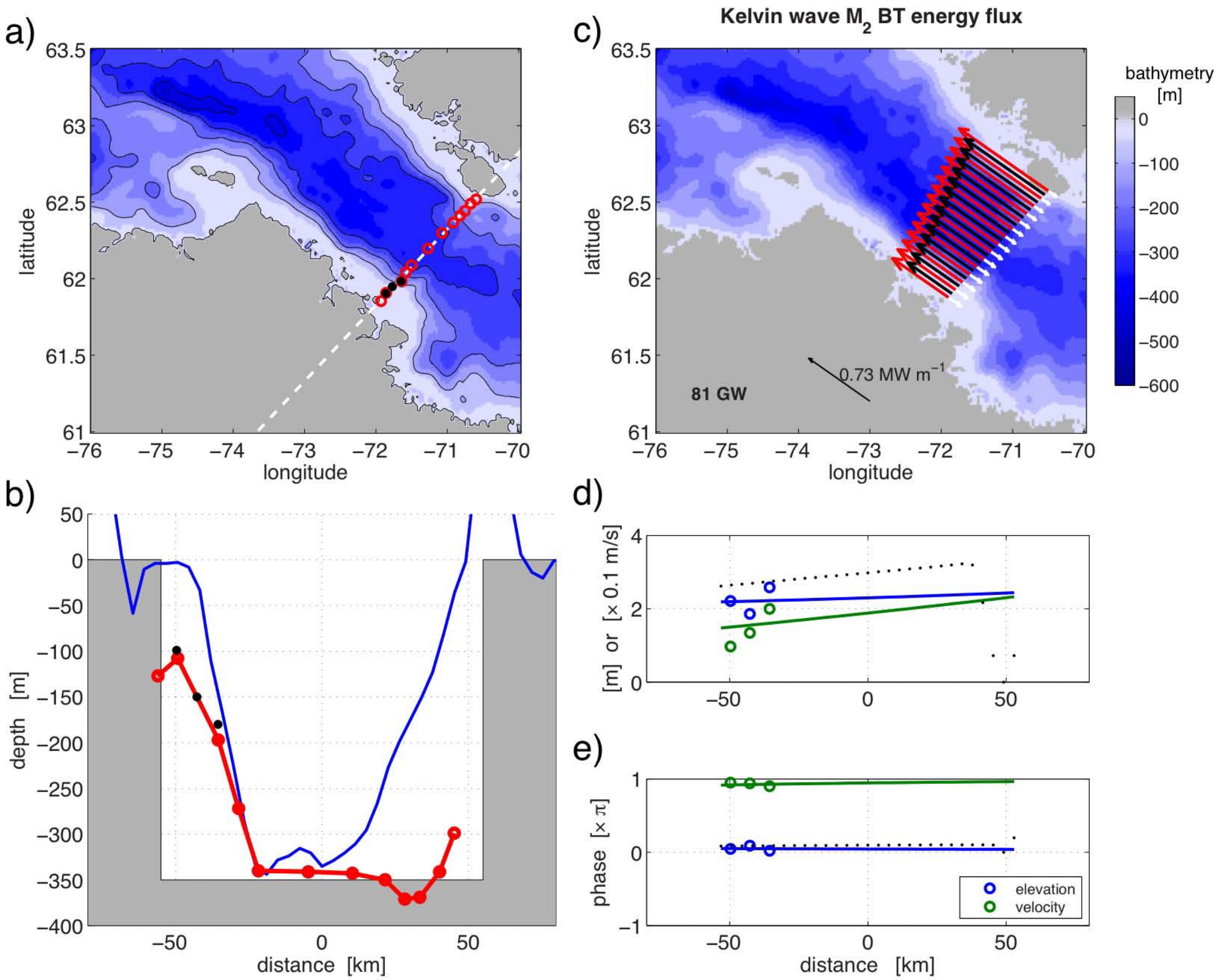

Figure 3: (a) Map of Hudson Strait, showing the location of the moorings (black), CTD stations (red), and of the cross-strait line chosen for the Kelvin Wave calculation. (b) Bathymetry of Hudson Strait, showing in the Smith and Sandwell bathymetry used in the TPXO models (blue), the actual depth at each CTD stations (red) and moorings (black). (c) Barotropic energy flux from the Kelvin wave model, showing the incident (red), reflected (white), and total (black) fluxes. (d) Amplitude and (e) phase of the barotropic elevation (blue) and velocity (green) from the moorings (circles) and the Kelvin wave model (lines).

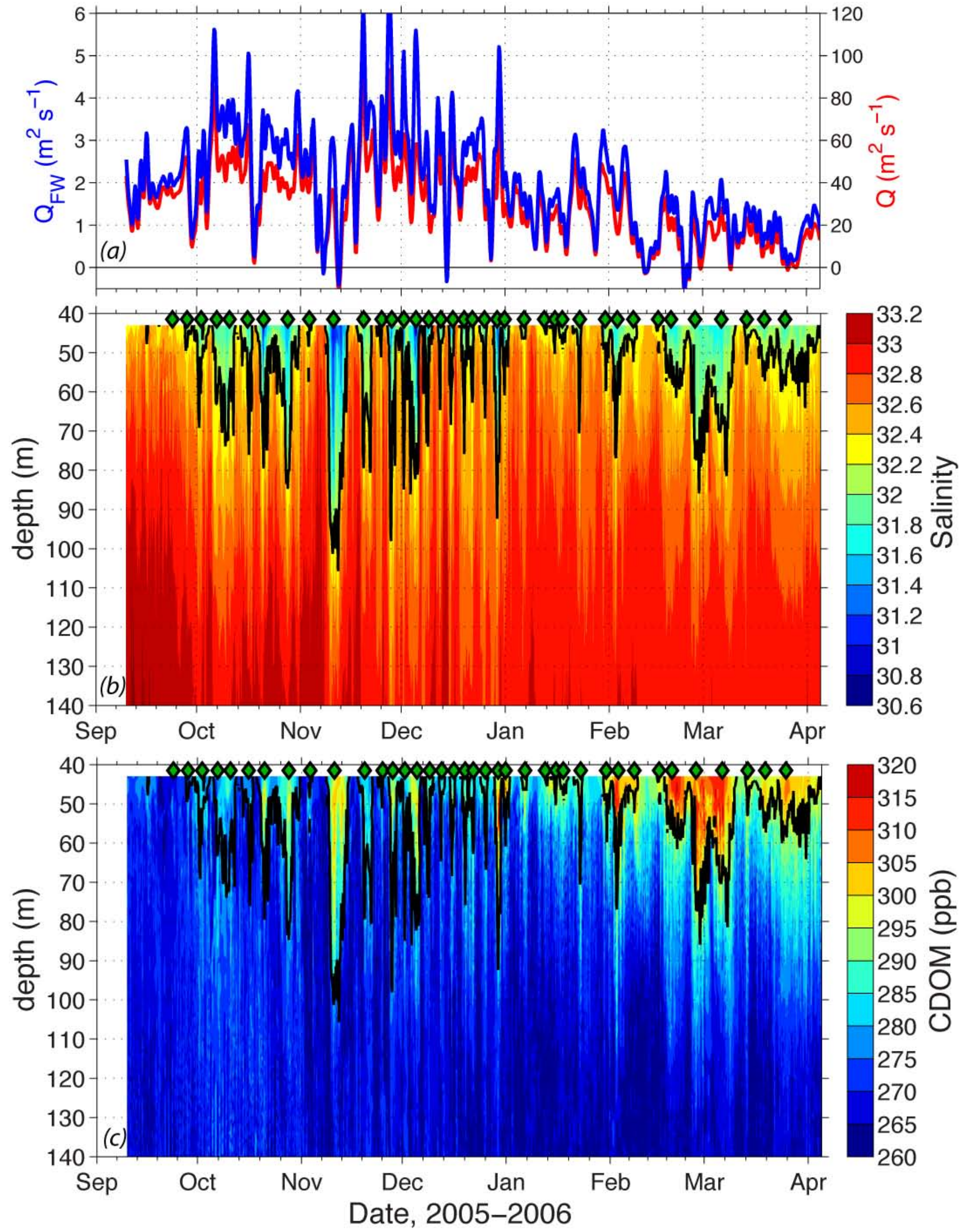

Figure 4. (a) Observed freshwater transport (per unit width, relative to S = 34.8, in blue) and volume transport (per unit width, red) of the Hudson Strait outflow, calculated at mooring A. (b) Salinity record from the moored profiler (MMP) at mooring A with the 32.2 isohaline contoured (black) and individual low-salinity events indicated (green diamonds). (c) Same as in b but for CDOM (colored dissolved organic matter), with the 32.2 isohaline contoured (black).

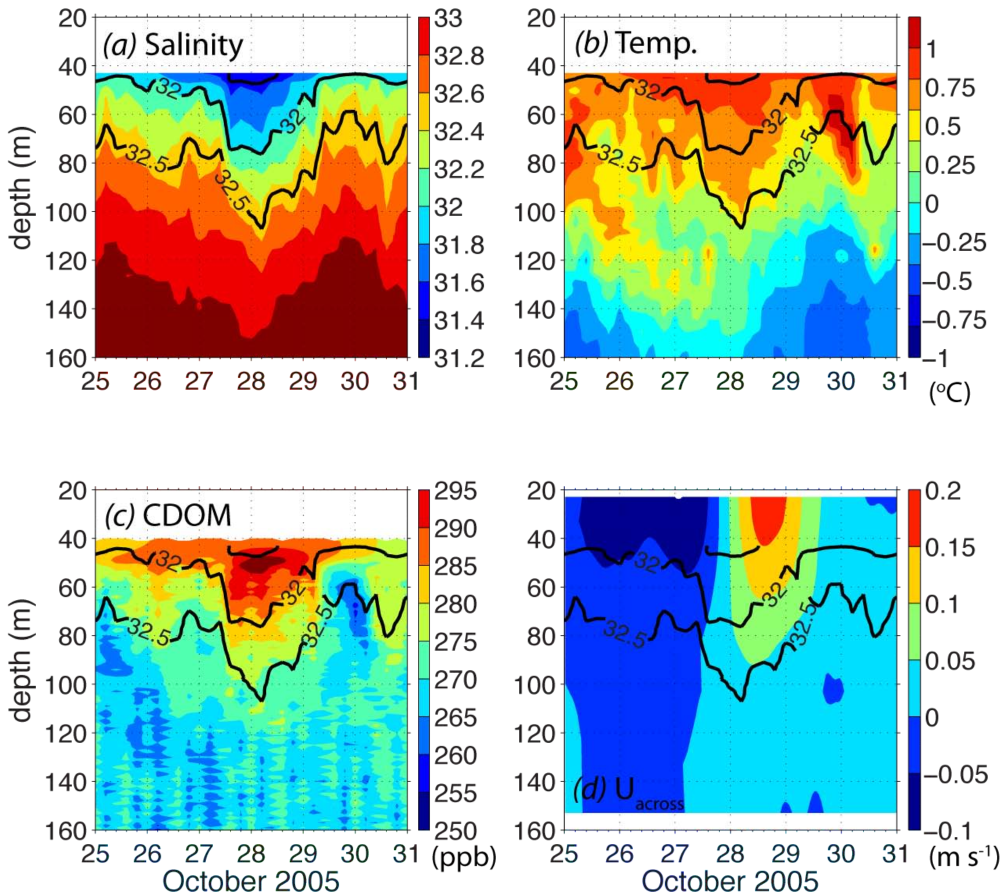

Figure 5. (a) Observed salinity record from the Strait during a typical eddy event that occurred in late October 2005. Select isohalines (black lines: 31.5, 32, 32.5) are indicated similarly across all panels. (b) Same as in a, but for temperature. (c) Same as in a, but for CDOM record. (d) Across-strait velocity (U_{across} < 0 is onshore) for the same time period as in a-c, from the ADCP.