Volume, Freshwater, and Heat Fluxes through Davis Strait, 2004–05*

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ABSTRACT

Davis Strait volume [{2.3 ± 0.7 Sv (1 Sv = 10^6 m^3 s^{-1}); negative sign indicates southward transport}], freshwater (−116 ± 41 mSv), and heat (20 ± 9 TW) fluxes estimated from objectively mapped 2004–05 moored array data do not differ significantly from values based on a 1987–90 array but are distributed differently across the strait. The 2004–05 array provided the first year-long measurements in the upper 100 m and over the shelves. The upper 100 m accounts for 39% (−0.9 Sv) of the net volume and 59% (−69 mSv) of the net freshwater fluxes. Shelf contributions are small: 0.4 Sv (volume), 15 mSv (freshwater), and 3 TW (heat) from the West Greenland shelf and −0.1 Sv, −7 mSv, and 1 TW from the Baffin Island shelf. Contemporaneous measurements of the Baffin Bay inflows and outflows indicate that volume and freshwater budgets balance to within 26% and 4%, respectively, of the net Davis Strait outflow. Davis Strait volume and freshwater fluxes nearly equal those from Fram Strait, indicating that both are significant Arctic freshwater pathways.

1. Introduction

Arctic waters flow into the North Atlantic through the Canadian Arctic Archipelago (CAA) and Fram Strait (Aagaard and Carmack 1989). Recent changes in the Arctic including increased air temperatures (e.g., Overland et al. 2008), enhanced sea ice loss (e.g., Wang and Overland 2009), increased Canadian river discharge (Déry et al. 2009), and ice-free CAA channels (Canadian Ice Service; available online at http://ice-glaces.ec.gc.ca/) suggest potentially large changes in volume, freshwater, and heat transports between the Arctic and North Atlantic Oceans. Variability in freshwater export through Davis Strait could impact North Atlantic deep convection (e.g., Våge et al. 2009), alter the strength of the Atlantic meridional overturning circulation (Holland et al. 2001), and affect western North Atlantic continental shelf ecosystems (Greene et al. 2008).

Davis Strait captures the CAA outflow after modification during its transit through Baffin Bay to the Labrador Sea (Fig. 1a). Arctic Ocean waters, entering northern Baffin Bay through Nares Strait and Jones and Lancaster Sounds, flow southward along Baffin Island through Davis Strait as the broad, surface-intensified Baffin Island Current (BIC; Tang et al. 2004; Cuny et al. 2005). Northward flow on the eastern side of Davis Strait consists of the fresh West Greenland Current (WGC) of Arctic origin on the shelf and warm, salty West Greenland Slope Current (WGSC) of North Atlantic origin on the slope. These inflowing waters, modified during their cyclonic circulation in Baffin Bay, join the BIC and exit western Davis Strait at depths typically >400 m. The net Baffin Bay outflow combines CAA flows, river runoff, sea ice, and inputs from Greenland and the North Atlantic. The smaller Fury and Hecla Strait component [0.1 Sv (1 Sv = 10^6 m^3 s^{-1} = 31 536 km^3 yr^{-1}) volume and 38 mSv (freshwater)] of the CAA outflow bypasses Baffin Bay and enters the Labrador Sea through Hudson Strait (Straneo and Saucier 2008).

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2. Data and methods

a. Data

A long-term monitoring program in Davis Strait began in September 2004. The 2004–05 program included 14 moorings (4 per shelf and 6 central moorings; Figs. 1b,c) north of the sill (640 m) at a maximum depth of 1040 m. Instrumentation measured velocity, temperature, and conductivity at 30 min and hourly intervals. On the Baffin Island shelf, a prototype iceberg-resistant mooring (IceCAT), consisting of a float and SBE37 MicroCAT inductively coupled to a bottom-mounted datalogger measured temperature and conductivity at 5-min intervals.

Currents were resolved parallel and orthogonal to the array line (77.3°); tidal variability was removed with a 34-h low-pass Butterworth filter and subsampled to obtain daily values; and missing data were filled by interpolation and extrapolation using archived data to produce full-depth temperature (T) and salinity (S; BIO; T and S data are available online at http://www.mar.dfo-mpo.gc.ca/science/ocean/) and along-strait velocity (V) profiles at each mooring (see appendix A of online supplement).

b. Objective mapping

Objective analysis (OA; Bretherton et al. 1976) was used to construct daily variable (=observed value – mean value) maps of V, T, and S fields using a Gaussian covariance function. Correlations calculated from hydrographic sections and mooring time series yielded horizontal decorrelation length scales of 20 (V) and 40 km (T and S). Slowly varying daily-mean fields were created using further low-passed data (10-day cutoff to reduce tidal and meteorological variability) and spatially averaged into domains defined by depth (0–150, 200–250, and 500 m) and location (e.g., the shelves and WGSC–BIC frontal zone). The mean and variable fields were mapped onto a regular, two-dimensional grid with 4-m cells at depths ≤150 m and 10-m cells at depths >150 m at a horizontal resolution of 5 km (see appendix B of online supplement).

c. Flux calculations

Daily volume, freshwater, and heat fluxes were averaged to compute monthly and annual fluxes. The reference salinity (34.8, mean Arctic Ocean salinity; Aagaard and Carmack 1989), sea ice salinity (5), and temperature (0°C) were chosen to maintain consistency with Cuny et al. (2005). Mooring deployment and recovery provided 10 days of data in September, insufficient to compute reliable flux estimates for that month. Monthly fluxes for September 2005 were estimated as the average of October 2004 and August 2005 values.

d. Uncertainties

Flux uncertainties were estimated as the sum of OA random error, standard error of the mean calculated using the Student’s t distribution with 95% confidence limits, and maximum range of flux estimates obtained
FIG. 2. Objectively analyzed monthly mean (a) along-strait velocity, (b) salinity, and (c) temperature. Gray lines indicate moorings, white dots indicate instrument locations for each property, and the pink bars indicate areas along the moored array that are covered by sea ice 60% of the month. The 34.8 salinity contour (dashed black line) and the 27 kg m$^{-3}$ isopycnal (black line) are noted in (b). Mean salinities $\geq 34.8$ were seen only in October. The boundaries of the four dominant water masses (see Fig. 3 for $\theta$–$S$ characteristics) are shown for October in (c).
using different approaches to compute the mean field. Additional uncertainties associated with the ice flux and estimation of the shelf and 0–100-m salinities were added to the freshwater flux uncertainty estimate. Sensitivity tests were performed to estimate flux variability associated with differences in mean field and sea ice flux.

3. Results and discussion

a. Current and water mass structure

Circulation during 2004–05 was dominated by northward flow on the West Greenland (WG) shelf and slope and southward flow over the remaining strait with weaker currents below 200 m (Fig. 2a). The surface-intensified (upper 200 m) southward flow extended eastward ~150 km from Baffin Island with a bimodal structure featuring strong flows over the slope, weaker currents approximately 100 km offshore, and maximum velocities at the BIC–WGSC front. The narrow (~50 km) WGSC had an average velocity magnitude 7 times greater than the WGC. Opposing currents in the BIC–WGSC front were strongest in autumn and winter and present in all months but April. A weak northward flow over the Baffin slope in December and January was also noted by Tang et al. (2004) and Cuny et al. (2005).

Following the definitions of Tang et al. (2004), four water masses are identified in Davis Strait and defined in Fig. 3. Arctic Water dominated the upper layers to depths approaching 200 m and extending to ~200 km from Baffin Island (Figs. 2b,c). Salinity increased ~0.4 from December to March in the upper 200 m with local ice formation (~1.25 m) accounting for only ~0.1 of the increase, with the remaining due to salt advection. The strong BIC–WGSC frontal zone, separating Arctic Water (AW) and transitional water (TrW) from West Greenland Irminger Water (WGIW), is evident over the slope. Maximum temperatures and salinities of the WGIW occurred in autumn, decreased until April and remained nearly constant until August, consistent with advection from the south (M. Stein 2009, personal communication). Recirculated WGIW influenced the temperature of TrW, but their temperature variations were not well correlated, possibly due to variations in recirculation and mixing time scales in Baffin Bay. The WGSW temperature had an annual cycle of ~6°C with a late summer maximum and March minimum. Salinity variations on the WGSW (autumn minimum, May maximum, and typically freshest at the coast) reflect melting Arctic sea ice advected from Fram Strait, local and advected runoff, and interactions with WGIW. Ice was present from November 2004 to July 2005 with peak coverage in February.

b. Annual and monthly fluxes

Mean volume, freshwater (including sea ice), and heat fluxes through Davis Strait, from October 2004 to September 2005, were ~2.3 ± 0.7 Sv, ~116 ± 41 mSv, and 20 ± 9 TW, respectively. Because autumn CTD data suggest that waters below the sill did not cross the strait, flux calculations were extended only to 640 m. Transport

FIG. 3. Davis Strait water masses defined using potential temperature (θ) and S: AW (red ellipse; θ < 1°C; S > 33.7) present in the western strait at depths <300 m, WGIW (blue ellipse; θ > 2°C; S > 34.1) along the WG slope, WGSW (green ellipse; θ < 7°C; S < 34.1), and TrW (magenta ellipse; θ < 2°C; S > 33.7) usually at depths >300 m. Water masses are illustrated using September 2004 (black squares) and September 2005 (gray circles) hydrographic data along the mooring line.
from 0 to 100 m was 39% (−0.9 Sv) of the net volume and 59% (−69 mSv) of the net freshwater fluxes. Shelf contributions were small: for WG, 0.4 Sv of volume, 15 mSv of liquid freshwater, and 3 TW of heat; the Baffin Island shelf accounted for −0.1 Sv, −7 mSv, and 1 TW. The heat flux estimates must be viewed with caution because the net volume flux is not zero (Schauer et al. 2008).

Net monthly volume and freshwater fluxes were southward year round with weak peaks in December–January and June (Fig. 4). Though not statistically significant, the peaks suggest transport may have been driven by advection (December–January) from the Arctic Ocean via the CAA and local (June) forcing related to the spring–summer Baffin Bay ice melt. A reasonable advection speed of 0.08–0.12 m s\(^{-1}\) is required for the broad June–August transport peak in Lancaster Sound (Prinsenberg et al. 2009) to have triggered the December–January transport peak at Davis Strait. Heat flux was strongest between October and December because of increased southward transport of cold BIC water and northward transport of warm WGSC water: it was nearly constant between January and August.

The September linearly interpolated volume and freshwater fluxes, −1.7 Sv and −99 mSv, agreed well with the geostrophic estimates from the hydrographic sections for 2004 (−1.9 Sv and −96 mSv) and 2005 (−2.6 Sv and −107 mSv), particularly for freshwater. The geostrophic transports were based on a ~1-day transect of the strait and neglect barotropic contributions, particularly large for the northward WGSC, which could account for the larger difference in volume transport.

Sea ice contributes significantly only to the freshwater flux. Kwok (2007) estimated that 360 × 10\(^3\) km\(^2\) of sea ice with an average thickness of 1–1.5 m was exported between November 2004 and May 2005. Assuming a thickness of 1.25 m, this implies 450 km\(^3\) of sea ice export, which, when combined with the estimate from Jordan and Neu (1982) of 17 km\(^3\) for June and July, yields 467 km\(^3\) yr\(^{-1}\) or 11 mSv of freshwater export through Davis Strait.

c. Water mass fluxes

Particular water masses dominate the heat and freshwater fluxes. The annual negative liquid volume flux (−4.2 Sv) consists of 50% (−2.1 Sv) AW and 40% (−1.7 Sv) TrW.
The fresher AW makes up 72% (−103 mSv) of the annual negative liquid freshwater flux (−143 mSv), whereas TrW contributes only 23% (−33 mSv). The annual positive heat flux (+30 TW) shows 37% (+11 TW) from AW, 37% (+11 TW) from WGIW, and 10% (+3 TW) from WGSW.

d. Comparisons to previous studies

These results extend the Davis Strait flux estimates beyond 1987–90 (Ross 1992) and are more robust. The 1987–90 estimates, based on six central strait moorings, lacked measurements shallower than 150 m and over both shelves, where the 2004–05 results indicate that 55% (73%) of the volume (liquid freshwater) transport occurs.

Three studies using the 1987–90 data adopted different approaches for extrapolating across the upper 150 m and either made highly uncertain estimates of shelf contributions (Cuny et al. 2005) or confined their analyses to the central strait (Loder et al. 1998; Tang et al. 2004). Differences in upper-layer extrapolation methods produced volume fluxes ranging from −3.3 to −2.6 (±1.2) Sv, liquid freshwater fluxes ranging from −120 to −92 (±34) mSv, and a heat flux (only Cuny et al. 2005) of 18 ± 17 TW. The freshwater transport from ice ranged from −21.3 mSv (873 km3 yr−1; Tang et al. 2004) to −12.9 mSv (528 km3 yr−1; Cuny et al. 2005).

The 2004–05 volume, liquid freshwater, and heat flux estimates (−2.3 ± 0.7 Sv, −105 ± 41 mSv, and 20 ± 9 TW) are within the uncertainties of the 1987–90 estimates (−2.6 ± 1 Sv, −92 ± 34 mSv, and 18 ± 17 TW; Cuny et al. 2005), but the WG shelf contributions differ substantially. The 2004–05 volume, freshwater, and heat flux estimates for the WG shelf (0.4 Sv, 15 mSv, and 3 TW) are less than half the 1987–90 estimates (0.8 Sv, 38 mSv, and 7 TW). Neglecting the fluxes over the WG shelf where Cuny et al. (2005) had no measurements, net southward volume and liquid freshwater fluxes have decreased between 1987–90 (−3.4 Sv and −130 mSv) and 2004–05 (−2.7 Sv and −120 mSv), not a statistically significant margin but nonetheless intriguing and contrary to expectations. The solid (ice) component of freshwater flux between 2004 and 2005 (−11 mSv) nearly matches the estimate from 1987 to 1990 (−12.9 mSv).

e. Baffin Bay budgets

Contemporaneous measurements across the primary pathways of Baffin Bay, combined with estimates of ice contributions, precipitation less evaporation (P-E), and historical data from Jones Sound, allow assessment of Baffin Bay volume and freshwater budgets (Table 1; see appendix C of the online supplement for details). Budgets close to within 0.6 Sv for volume and 5 mSv for freshwater: both are within the uncertainties of the estimates. These imbalances represent 26% and 4% of the net annual volume and freshwater transports through Davis Strait and provide a rough gauge of the array’s ability to monitor the fluxes. The larger volume flux imbalance may reflect decreased resolution below 200 m in

<table>
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<tr>
<th>Baffin Bay passages</th>
<th>Volume transport (Sv)</th>
<th>Freshwater transport (mSv)</th>
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<tr>
<td></td>
<td>Inflow</td>
<td>Outflow</td>
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<tr>
<td>Nares Strait (2003–06)</td>
<td>0.72 ± 0.11</td>
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<tr>
<td>Lancaster Sound (1998–2006)</td>
<td>0.7 ± 0.2</td>
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<tr>
<td>Jones Sound (1998–2002)</td>
<td>0.3 ± 0.1</td>
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<td>CAA Ice (1996–2007)</td>
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<td>Greenland Ice Sheet (1995–2007)</td>
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<td>P-E (1961–2001)</td>
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<tr>
<td>Baffin Island Runoff (1971–2000)</td>
<td>&lt;0.1</td>
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<tr>
<td>Davis Strait (2004–05)</td>
<td>1.7 ± 0.2</td>
<td>−2.3 ± 0.7</td>
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<td>Difference</td>
<td>−0.6</td>
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a From Münchow and Melling (2008) and Rabe et al. (2010).
b From Prinsenberg et al. (2009).
c From Melling et al. (2008).
d From Agnew et al. (2008) and Kwok (2005).
e From Mernild et al. (2009).
f From Canadian Climate and Data Information Archive (available online at http://www.climate.weatheroffice.ec.gc.ca), Jensen and Rasch (2008), National Climate Data Center (available online at http://www.ncdc.noaa.gov/oa/ncdc.html), Källberg et al. (2005), and Danish Meteorological Institute (available online at http://www.dmi.dk/dmi/index/gronland/klimanormaler-gl.htm).
g From Canadian Climate and Data Information Archive (available online at http://www.climate.weatheroffice.ec.gc.ca) and Water Survey of Canada (available online at geogratis.cgdi.gc.ca/geogratis/en/index.html).
Davis Strait (a larger fraction of the volume, relative to freshwater, flux is in the deeper layer) or interannual variability.

f. Comparison to Fram Strait

Net volume and freshwater transports through Davis Strait are similar in magnitude to those estimated for Fram Strait, the other major pathway connecting the Arctic and North Atlantic. Davis Strait net volume and freshwater fluxes are within the uncertainty of the Fram Strait estimates [−2.3 ± 4.3 Sv (Schauer et al. 2008; Rudels et al. 2008) and −119 ± 40 mSv (Rudels et al. 2008; Kwok et al. 2004); see appendix D of online supplement]. Estimates of volume and freshwater outflows for the Barents Sea (Skagseth et al. 2008; Ingvaldsen et al. 2004; Aagaard and Carmack 1989) and Hudson Strait (Straneo and Saucier 2008) indicate that Davis and Fram Straits combined account for 98% of the total volume and 84% of the total freshwater Arctic outflows.

4. Conclusions

Davis Strait, along with Fram Strait, represents a critical component of Arctic volume and freshwater budgets and an important input of freshwater for the subpolar North Atlantic. The 2004–05 fluxes are statistically similar to those calculated for 1987–90, though comparisons suggest a decrease of the volume transport for the central strait. Varying methodologies, observational coverage, and record length along with interannual variability create a somewhat disparate comparison, suggesting a reanalysis using common methodologies. Larger differences might have been expected given recent changes seen in the Arctic and CAA. Continued measurements are needed to monitor and understand any variability of the CAA outflow in response to Arctic change.

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