Revising the Bering Strait freshwater flux into the Arctic Ocean

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[1] The freshwater flux through the Bering Strait into the Arctic Ocean is important regionally and globally, e.g. for Chukchi Sea hydrography, Arctic Ocean stratification, the global freshwater cycle, and the stability of the Atlantic overturning circulation. *Aagaard and Carmack* [1989] estimated the Bering Strait freshwater flux as 1670 km^3/yr (relative to 34.8 psu), assuming an annual mean transport (0.8 Sv) and salinity (32.5 psu). This is ~1/3rd of the total freshwater input to the Arctic. Using long-term moored measurements and ship-based observations, we show that this is a substantial underestimate of the freshwater flux. Specifically, the warm, fresh Alaskan Coastal Current in the eastern Bering Strait may add ~400 km^3/yr. Seasonal stratification and ice transport may add another ~400 km^3/yr. Combined, these corrections are larger than the interannual variability observed by near-bottom measurements and near-surface measurements will be necessary to quantify this flux and its interannual variability. **Citation:** Woodgate, R. A., and K. Aagaard (2005), Revising the Bering Strait freshwater flux into the Arctic Ocean, *Geophys. Res. Lett.*, *32*, L02602, doi:10.1029/2004GL021747.

1. Introduction

[2] The only Pacific gateway to the Arctic Ocean is the narrow (~85 km wide), shallow (~50 m deep) Bering Strait at the far northern end of the Pacific Ocean (Figure 1). The Diomede Islands divide the Bering Strait into two channels. Flow through the western channel, which is in the Russian Exclusive Economic Zone (EEZ), is dominated by the nutrient-rich Anadyr waters (from south of the strait) which are generally saltier and colder than the waters of the Bering Shelf [*Coachman et al.*, 1975, hereinafter referred to as C75]. The Bering Shelf waters, along with the Alaskan Coastal Current (ACC) (both from south of the strait), make up the flow in the eastern channel. The warm, fresh ACC is present in the eastern strait every year at least in summer/autumn [*Paquette and Bourke*, 1974; *Ahlnäs and Garrison*, 1984] whilst the cold, fresh Siberian Coastal Current (from north of the strait) is present only occasionally in the western Bering Strait [*Weingartner et al.*, 1999]. North of the strait, the bottom topography diverts some of the nutrient-rich Anadyr waters into the US EEZ for a short distance (near site A3, Figure 1).

[3] The Bering Strait throughflow, ~0.8 Sv northwards in the annual mean, is highly variable and reversible, with weekly transport variability between ca. −2 to 3 Sv, and seasonal variability in transport and near-bottom water properties of ca. 0.3 to 1.3 Sv; −1.8 to 8°C; and ~31 to 34.5 psu [*Roach et al.*, 1995]. The mean flow is often attributed to a pressure-head difference between the Pacific and Arctic oceans [e.g., *Coachman and Aagaard*, 1966]. The variability is highly correlated with the local wind [e.g., *Coachman and Aagaard*, 1981] which in the mean actually opposes the pressure-head forcing [*Woodgate et al.*, 2005, hereinafter referred to as Wetal]. Interannual temperature and salinity variability is also substantial, although so far no statistically significant change has been found in the annual mean volume transport.

[4] The throughflow has a profound influence not only on the adjacent Chukchi Sea (C75; Wetal), but also on the thermal structure, the nutrient loading, and the freshwater budget of the Arctic Ocean [e.g., *Shimada et al.*, 2001; *Steele et al.*, 2004; *Walsh et al.*, 1989; *Aagaard and Carmack*, 1989, hereinafter referred to as AC89]. It is also important globally. Theoretical and modeling studies indicate that the fluxes through the Bering Strait play an important role in the salt and freshwater cycles of the world oceans [*Wijffels et al.*, 1992; *Huang and Schmitt*, 1993; AC89], to the extent of having a controlling influence on the Atlantic meridional overturning circulation [e.g., *Reason and Power*, 1994; *Goosse et al.*, 1997; *Wadley and Bigg*, 2002], the strength of the deep western boundary currents and the separation point of the Gulf Stream from the American coast [*Huang and Schmitt*, 1993], and possibly also world climate [*DeBoer and Nof*, 2004].

[5] AC89 estimated the Bering Strait freshwater flux (relative to 34.8 psu) as 1670 km^3/yr (0.053 Sv) by assuming an annual mean transport (0.8 Sv) and salinity (32.5 psu). Whilst the transport estimate was based on multi-month moored measurements and is confirmed by current measurements from 1990–1994 [*Roach et al.*, 1995], the salinity is fairly arbitrarily inferred from mainly summer measurements in the 1960s and 1970s.

[6] We present here year-round moored near-bottom measurements from 1990–2004 (Figure 2) from four moorings in the Bering Strait region (Figure 1). Not all moorings were deployed all years. Moorings A1 and A2 monitor near-bottom (i.e., ~9 m above bottom) water properties and flows in the center of the western and eastern channels respectively. The water properties at A3, north of the strait, represent some combination of eastern and western channel waters. The currents at all three sites are highly correlated (r = 0.95; Wetal). Mooring A4 samples the Alaskan Coastal Current (see below). Measurements at A1, A2 and A3 yield a ca. 14-year Bering Strait mean of near-bottom salinity of 32.5 ± 0.3 psu and, assuming no velocity shear, a mean transport of 0.8 ± 0.1 Sv. However, near-shore moorings (A4) and CTD sections (Figures 3 and 4) indicate that both velocity and salinity vary significantly across the strait and in the

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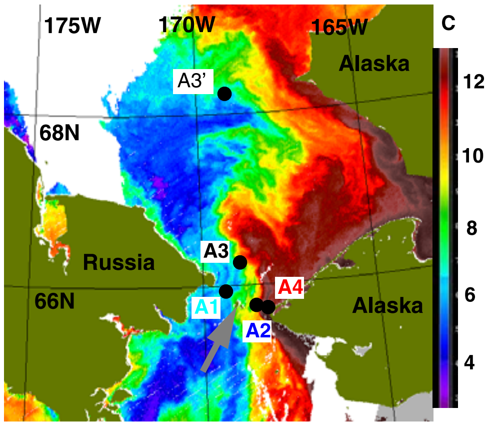

Figure 1. The Bering Strait region, with mooring locations (A1 - 65.90°N 169.43°W, water depth 50 m; A2 - 65.78°N 168.59°W, 53 m; A3 - 66.29°N 168.97°W, 56 m; A3′ - 68.17°N 168.97°W, 59 m; A4 - 65.75°N 168.26°W, 59 m) as black dots, showing sea surface temperature for 26th August 2004 (MODIS/Aqua level 1 image courtesy of Ocean Color Data Processing Archive, NASA/Goddard Space Flight Center). Arrow marks the Diomede Islands ~65.8°N 168°W. White areas indicate clouds.

vertical, and this substantially alters the prior estimate of freshwater flux.

2. The Alaskan Coastal Current (ACC)

[7] During ice-free months (May–October), clouds permitting (~15% of the time), satellite imagery (Figure 1) can track the warm surface temperatures of the buoyant (warm and fresh) Alaskan Coastal Current (ACC) in the eastern Bering Strait and Chukchi Sea [*Paquette and Bourke*, 1974; *Ahlnäs and Garrison*, 1984]. C75 show this current to be in the strait at least from early summer to late autumn, with anchored stations recording maximum flows of 170 cm/s on the eastern side of the strait, an intensified northward surface flow that is also known to local shipping.

[8] Summer/autumn CTD/ADCP sections of the eastern channel of the Bering Strait from years 2000–2004 (e.g., Figure 3) consistently show this ~10 km wide, 40 m deep, generally coastally trapped current to be in its core ~3 psu fresher and 4°C warmer than the central strait. Note the ACC waters are considerably fresher than C75's definition of Alaskan Coastal Water (ACW), i.e., all waters fresher than 32.1 or 32.4 psu, a salinity range which includes almost all the water in Figure 3. Thus, although the ACC is classic ACW, by no means is all ACW in the buoyant ACC.

[9] The front marking the ACC (right of the 31.5 psu contour in Figure 3) suggests by geostrophy a ~1 m/s surface-intensified current and this is confirmed by ship's ADCP data (not shown). The first year-round measurements within the ACC, (temperature and salinity at 39 m and water velocity in 2 m bins from 34 m to 14 m depth at site A4 from July 2002 to 2003), indicate such shears are common, with hourly velocities at 14 m depth peaking at 150 cm/s, exceeding the central strait near-bottom velocity by almost 100 cm/s (Figure 4). The multi-day events (found from late April to late December) correlate well (r = 0.7) with the local winds and coincide with sizeable (up to 3 psu and 5°C) temperature and salinity differences between near-bottom measurements at A2 and A4 (e.g., Figure 4). Between January and late April, when near-bottom temperatures at A2 and A4 are at freezing and salinities at A2 and A4 are very similar and increasing (Figure 4) suggestive of vertical water homogenization by ice formation (Wetal), the velocity shear is much less, and more consistent with a surface wind- (or ice-) driven Ekman spiral, which is order 5 cm/s over this depth range for a typical 10 m/s wind, or 10–20 cm/s for a typical storm wind speed of 20 m/s. Thus, although no year-round upper layer salinity measurements are available within the ACC, we hypothesize the fresh

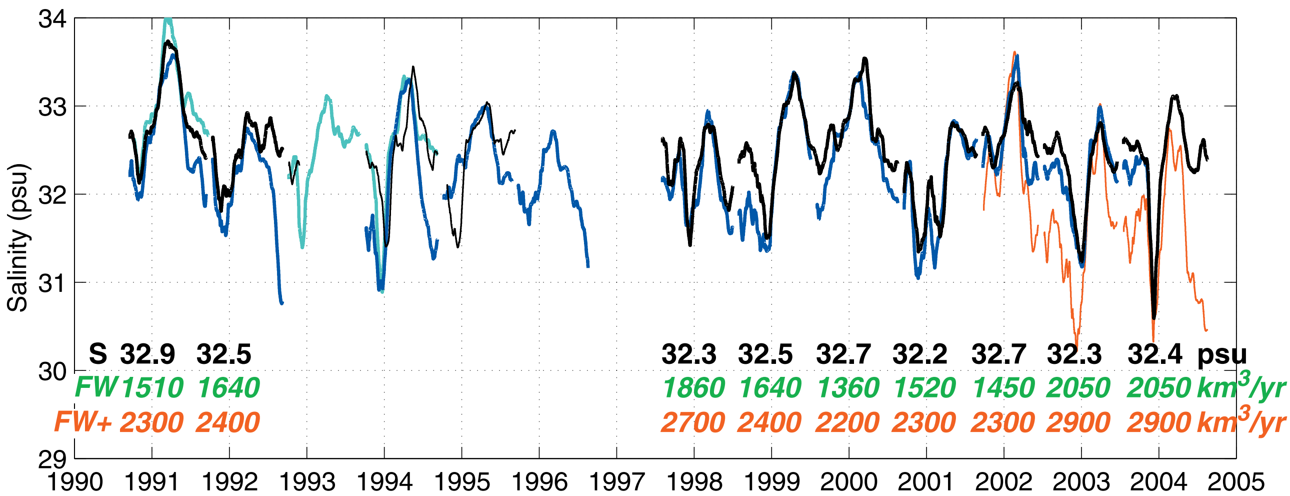

Figure 2. Thirty-day running mean of hourly time series of salinity ~9 m above bottom at sites A1 (western channel, cyan), A2 (eastern channel, blue), A3 (north of the Bering Strait, black), and A4 (the Alaskan Coastal Current, red). Not all moorings are deployed each year. Between summer 1992 and summer 1995, A3′ (thin black line) was deployed instead of A3 (see Figure 1). Record mean (i.e., ~annual mean from summer to summer) salinities (S, black) (errors ~ 0.2 psu) and freshwater transports (errors ~ 300 km^3/yr) are estimated from A3 records, assuming no stratification in velocity or density (FW, green) and with the correction of 800 km^3/yr (FW+, red).

ACC was present in the strait until late December 2002 and returned in late April 2003.

[10] Based on summer/autumn CTD/ADCP sections from 2000 to 2003, we can estimate the instantaneous transports of the ACC. A 10 km wide, 40 m deep current of the wedge-like form of Figure 3 with 1 m/s mean velocity and 30 psu mean salinity has a volume transport of 0.2 Sv and a freshwater transport (relative to 34.8 psu) of 0.03 Sv. Using the annual mean velocity at 15 m depth at A4 of 40 ± 4 cm/s, we estimate an annual mean volume transport for the ACC of 0.08 Sv with errors (including those in estimates of width and depth) at least 0.02 Sv. Lacking year-round shallow salinity measurements, we note that in the CTD sections the vertical salinity gradient at A4 is about twice that between A4 and A2 and use annual mean salinities at A2 (32.1 ± 0.2 psu) and A4 (31.5 ± 0.3 psu) to estimate a mean salinity for the ACC as 30.3 ± 0.5 psu and thus obtain a freshwater transport estimate ~0.007 to 0.014 Sv, equivalent to between 220 and 450 km^3/yr, i.e., ~20% of the AC89 freshwater estimate. Such an annual volume is easily obtainable from freshwater sources to the south, e.g. the highly seasonal Yukon River outflow (order 200 km^3/yr, calculated from C75) and the freshwater transport of the Alaska Coastal Current in the Gulf of Alaska (order 1000 km^3/yr) [*Weingartner et al.*, 2005].

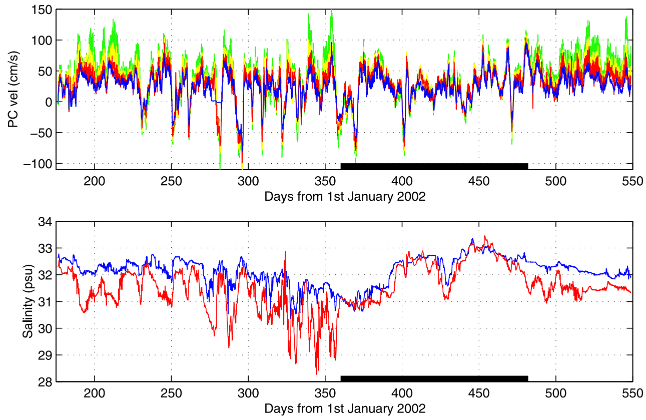

Figure 4. Hourly time series data from A2 and A4 for July 2002 to 2003. (Top) Principal component of velocity (~northward velocity) at A2 (47 m, blue) and A4 (34 m, red; 24 m, yellow; and 14 m, green). (Bottom) Salinity at A2 (48 m, blue) and A4 (39 m, red). Thick black line marks times when near-bottom temperatures at A2 and A4 are at the freezing point (days 360 to 482, i.e., late December 2002 to late April 2003).

3. Effects of Vertical Stratification and Ice Transport

[11] Aside from the ACC, two other freshwater terms are neglected by the analysis of AC89. The first is the water column stratification. Although no derivation was given of the mean salinity (32.5 psu) used by AC89, it matches the 14-year mean near-bottom salinity estimated from A1, A2 and A3 (Figure 2). In summer/autumn, CTD measurements (not shown) indicate the Chukchi is approximately a 2-layer system, a warmer, fresher layer overlying a colder, saltier layer, with a salinity step ~1 psu. Wetal argue the similar magnitude of freshening found at depth in autumn at moorings throughout the Chukchi is due to wind and surface cooling mixing this fresher layer down to the near-bottom layers. Assuming conservatively that stratification is only present for half the year, we estimate that near-bottom salinities overestimate the water column mean salinity by order 0.5 psu. This corresponds to a freshwater transport of 0.01 Sv, i.e., ~350 km^3/yr, again order 20% of the AC89 estimate.

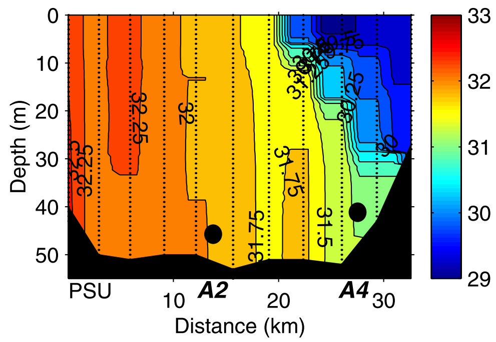

Figure 3. July 2003 CTD salinity section across the eastern channel of the Bering Strait from the Diomede islands (left) to Alaska (right). Black dots indicate moored instrument locations. Note the fresh (warm) ACC on the Alaskan coast.

[12] The second term is the contribution of sea-ice, taken as 24 km^3/yr and thus negligible by AC89. A moored ADCP from 1990–1991 just north of the Bering Strait (65.84°N 168.62°W) measured ice-thickness and velocity simultaneously, yielding (assuming a flow width of 75 km) an annual mean northward ice transport of 130 ± 90 km^3/yr, despite almost two months of net southward ice flux. Assuming a salinity of 7 psu, this is equivalent to a freshwater transport of order 100 ± 70 km^3/yr, indicating the ice could contribute ~10% of the annual freshwater flux.

4. Interannual Variability 1990–2004

[13] The interannual variability in annual mean salinity and freshwater transport estimated from near-bottom measurements (Figure 2) is smaller than these corrections. However, the near-bottom salinity and velocity still determine the dominant part of the freshwater transport. Although there are many caveats to this calculation, it appears the mean salinity was higher in 1990–1991 than in subsequent years (Figure 2). This is mitigated however by variations in velocity, which dominate the variability of the freshwater flux. To within errors, the freshwater flux shows little significant variation over the data period, although there is a suggestion of increased freshwater flux since 2002 (Figure 2).

5. Conclusions

[14] Consideration of the contribution of the Alaskan Coastal Current (~220–450 km^3/yr), the stratification in the central Bering Strait (~350 km^3/yr) and the ice transport (~100 km^3/yr) increases the *Aagaard and Carmack* [1989]

estimate of the Bering Strait freshwater flux by ∼800 km^3/yr from 1670 km^3/yr (0.05 Sv) to ∼2500 km^3/yr (0.08 Sv), with uncertainty of order ±300 km^3/yr (0.01 Sv). This makes the Bering Strait freshwater transport 75% of the AC89 estimate of river runoff into the Arctic Ocean and comparable to their estimate of ice export through the Fram Strait.

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