ARCTIC OCEAN CIRCULATION
- going around at the Top of the World

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Welcome to the Arctic Ocean

The Arctic Ocean (Figure 1), the smallest of the world's five major oceans, is about 4000km (2500 miles) long and 2400km (1500 miles) wide, about the size of the continental USA. It lies entirely within the Arctic Circle, contains deep (~ 4500m) basins, the slowest spreading ridges in the world, and about 15% of the world's shelf seas [*Menard and Smith*, 1966], with the area of the Arctic shelves being almost half the area of the deep Arctic basins [*Jakobsson*, 2002].

The Arctic is most remarkable for its perennial (multiyear) sea-ice, which historically covered about half the Arctic Ocean [*Stroeve et al.*, 2007], although in recent years (2007 onwards, compared to the 1980s), warming of the Arctic has reduced the perennial sea-ice area by around 40% [*Nghiem et al.*, 2007] and thinned the mean ice thickness from ~ 3m to ~ 1.5m [*Kwok and Rothrock*, 2009]. The sea-ice, seasonally covering the entire Arctic Ocean, is one key to the remarkable quietness of the Arctic Ocean - it damps surface and internal waves and modifies transfer of wind momentum to the water. Sea-ice processes also profoundly influence ocean stratification, providing a fresher surface layer on melting, and a mixing of surface waters via brine rejection on freezing as the less salty ice forms from salt water. Note that at the temperatures of Arctic Ocean waters (typically less than 2ºC) density is primarily determined by salinity, not temperature (Figure 2).

What comes in and what goes out?

The Arctic Ocean plays two roles in the global ocean circulation - it provides an oceanic pathway between the Pacific and the Atlantic Oceans; and also takes an Atlantic input, modifies it, and returns it to the Atlantic [*Rudels and Friedrich*, 2000].

The only Pacific-Arctic gateway is the narrow (~ 85km wide) shallow (~ 50m deep) Bering Strait, through which about 0.8Sv ($1Sv=10^6m^3s^{-1}$) of water enters the Arctic. Properties of this inflow vary significantly seasonally, from about 0.4Sv, -1.9ºC, and 33psu in winter; to about 1.2Sv, greater than 2 ºC, and less than 31.9psu in summer [*Woodgate et al.*, 2005a]. (The dimensionless unit "psu" is used in this article to indicate salinities measured on the Practical Salinity Scale [*Lewis*, 1980]: numerically values are equivalent to parts salt per thousand parts water.)

The Atlantic inflow is generally saltier (> 34 psu), warmer (> 0ºC) and about 10 times greater in volume than the Pacific inflow. The Atlantic inflow enters through both the Fram Strait (~ 350km wide, ~ 2700m deep) and the Barents Sea (mostly via St Anna Trough, ~ 200km wide, 600m deep). For discussion and references, see [*Beszczynska-Möller et al.*, 2011]. The Fram Strait inflow is about 7Sv (also seasonally varying) [*Fahrbach et al.*, 2001], although complex recirculations in the strait return around half of that immediately to the south [*Rudels et al.*, 2000b]. The Barents Sea inflow is around 1Sv in summer and 3Sv in winter, and has been substantial modified during transit of the Barents Sea [*Schauer et al.*, 2002a].

The other inputs to the Arctic are volumetrically small – Eurasian and Russian rivers (~ 0.1Sv); precipitation minus evaporation (~ 0.06Sv) – but together contribute roughly 2/3rds of the freshwater entering the Arctic, the remaining 1/3rd coming from the Pacific inflow [*Aagaard and Carmack,* 1989; *Serreze et al.*, 2006]. (Since the Pacific inflow is fresher than the mean salinity of the Arctic Ocean, it freshens the Arctic: this freshening can be quantified as an equivalent volume of pure freshwater [*Aagaard and Carmack*, 1989].)

Outflows from the Arctic are all to the Atlantic, via either the western side of the Fram Strait (~ 9Sv [*Fahrbach et al.*, 2001]), or via the complex channels of the Canadian Archipelago (~ 1-2Sv [*Melling et al.*, 2008]).

All these flow estimates are approximate, with uncertainties typically about 25%. See [*Beszczynska-Möller et al.,* 2011] for a review.

The vertical structure of the Arctic Ocean - a layered approach to understanding the Arctic

The Arctic water column (Figure 2) can be considered as a stacking of mostly non-interacting layers, and categorized into typical western Arctic (Canadian Basin) or eastern Arctic (Eurasian Basin) profiles [*McLaughlin et al.*, 1996].

In regions of ice-cover both profiles typically have a thin (~ 5-10m thick) surface mixed layer, although in (increasingly common) ice-free regions, wind-driven mixed layers maybe more than twice as deep [*Rainville et al.*, 2011].

In most of the western Arctic (blue profiles in Figure 2), below the mixed layer are the Pacific Waters (PW) – a temperature maximum often less than 0ºC around 50-100m depth indicates Pacific Summer Waters (PSW); a deeper temperature minimum around freezing at about 100-150m depth indicates Pacific Winter Waters (PWW). Shallower temperature maxima (not in Figure 2), probably locally formed by solar heating, are observed in some regions [*Jackson et al.*, 2010; *Shimada et al.*, 2001]. Below the PW, Atlantic Waters (AW) form a temperature maximum (up to ~ 1ºC) at depths of around 200-400m. These are called Fram Strait Branch Waters (FSBW) since they come mainly from the Fram Strait inflow [*Rudels et al.*, 1994], although there is likely also some influence from the Barents Sea [*Rudels et al.*, 2000a; *Woodgate et al.*, 2001]. Below the FSBW, temperatures decrease and an inflexion point in temperature-salinity (TS) space (corresponding to enhanced European radionuclide tracers) mark waters of dominantly Barents Sea influence (Barents Sea Branch Waters, BSBW) [*Rudels et al.*, 1994; *Smith et al.*, 1999].

In the eastern Arctic (red profiles in Figure 2), the PW layers are absent. The AW are separated from the surface by a cold layer in which the salinity increases - a "cold halocline" [*Aagaard et al.,* 1981; *Rudels et al.*, 1996] - which is formed by either brine-rejection-driven convection topped off with fresher cold waters (convective halocline), or injection of cold salty shelf waters (advective halocline) [*Steele and Boyd*, 1998], the latter mimicking the influence of PWW. Throughout the Arctic, a cold halocline layer is important in providing a density barrier trapping AW heat at depth away from the ice.

Below the AW, the deep waters are colder and saltier than waters above, and are slightly warmer and saltier in the western Arctic than in the eastern Arctic (Figure 2). Remarkable here is the homogeneity of these bottom layers, which are often more than 1000m thick and topped with thermohaline staircases implying geothermal heating from below [*Timmermans et al.*, 2003].

Overall, most of the density stratification in the Arctic occurs in the upper ~ 150m, in the halocline and Pacific influenced layers (Figure 2). This density step is reflected in the circulation of the various layers - the upper layers (the PW) feel the effects of surface wind/ice drag and their circulation appears to be related to the circulation of the sea-ice and largely independent of topography, while below the density step (i.e., in the AW) the circulation appears strongly influenced by the bottom topography [*Jones*, 2001].

Circulation of Pacific Waters

Pacific Waters (PW) have three major influences on the Arctic, providing: - a) an important source of oceanic heat (~ 1/3rd of the Fram Strait heat flux), with influence on Arctic sea-ice [*Woodgate et al.*, 2010]; b) about 1/3rd of the freshwater flux into the Arctic with implications for Arctic stratification [*Aagaard and Carmack*, 1989; *Serreze et al.*, 2006], and c) a dominant source of Arctic nutrients [*Walsh et al.*, 1989]. Heat and freshwater fluxes vary substantially from year to year [*Woodgate et al.*, 2006; *Woodgate et al.*, 2010; *Woodgate et al.*, 2012]. Nutrient content (especially silicate, or nitrate:phosphate ratios [*Jones et al.*, 1998]) and TS properties are used to trace PW pathways in the Arctic.

PW (Figure 3) are found on the Canada Basin side of the Mendeleev Ridge, and episodically also in the Makarov Basin and up to the Lomonosov Ridge [*McLaughlin et al.*, 1996; *Swift et al.*, 2005]. It is probable, however, that their location reflects the changing position of the Transpolar Drift of sea-ice (which takes ice from Russia to the Fram Strait [*Rigor et al.*, 2002]) rather than the bottom topography. Historic hydrographic data [*Steele et al.*, 2004] suggest PSW distribution mirrors the state of the Arctic Oscillation (AO, an index of the primary mode of variability of northern hemisphere sea-level pressure [*Thompson and Wallace*, 1998]) - e.g., under high AO conditions, the Transpolar Drift sweeps more of the western Arctic resulting in a smaller Beaufort Gyre and less influence of PW in the eastern Arctic. This variability may also explain changes in the proportions of PW exiting the Arctic via the Canadian Archipelago and the Fram Strait [*Falck et al.*, 2005; *Jones et al.*, 2003].

Processes which move PW from the ~ 50m deep Chukchi Sea into the upper layers of the basin are still poorly quantified. The assumption that potential vorticity (PV) conservation constrains PW to flow along the Beaufort slope neglects important surface and bottom friction terms - indeed only about 1/3rd of the PW inflow is observed along the Beaufort slope [*Nikolopoulos et al.*, 2009], the rest having left the slope somewhere along the shelf break. PW ventilate much of the upper ~ 180m of the western Arctic, probably via wind-driven upslope/upcanyon upwelling, mixing and downwelling of AW over the shelves [*Woodgate et al.*, 2005c]. PW eddies are also common in the Canada Basin [*D'Asaro*, 1988; *Plueddemann et al.*, 1998; *Timmermans et al.*, 2008], likely with origins in instability of slope currents of Pacific water found along the Chukchi shelf break.

Pacific Waters exit the Arctic via the Fram Strait and the Canadian Archipelago, their high nutrients fueling ecosystems in the polynyas of the Archipelago [*Tremblay et al.*, 2002].

The various fates of the Atlantic Waters

Atlantic Waters (AW), volumetrically the largest inflow to the Arctic, provide a pan-Arctic boundary current system, the Arctic Ocean Boundary Current (AOBC) [*Rudels et al.*, 1999; *Woodgate et al.*, 2001]. AW provide a substantial reservoir of subsurface heat, and a "climate handshake” between the Arctic and the rest of the world ocean, being the northernmost loop of the global ocean circulation. AW are traced by their TS signature (particularly tracking an anomalous FSBW warming of the 1990s [*Quadfasel et al.*, 1993]); Cs and I from the European nuclear reprocessing plants [e.g., *Smith et al.*, 1999]; and CFCs [e.g., *Smethie et al.*, 2000].

TS and tracer data suggest the AOBC (Figure 4) follows topographic slopes cyclonically (anticlockwise in the northern hemisphere) around the basins and along the ocean ridges, with the core of the current lying between the ~500-3000m isobaths. The interior gyres are generally quiescent and sparsely populated with some deep eddies [*Aagaard,* 1989; *Rudels et al.*, 1994; *Woodgate et al.,* 2001].

In the Eurasian basin, the AOBC is equivalent barotropic (i.e., velocity well correlated at various depths [*Killworth*, 1992]), sluggish (order a few cm/s), and transports about 5Sv along the Eurasian continental slope and about 3Sv along the Lomonosov Ridge [*Woodgate et al.*, 2001]. Eddies are rare but dramatic - 40cm/s and 1000m in vertical extent [*Aagaard et al.*, 2008; *Woodgate et al.*, 2001]. The AOBC includes both FSBW and BSBW with the BSBW possibly deflecting the FSBW from the slope [*Schauer et al.*, 2002b] or stacking below the FBSW [*McLaughlin et al.*, 2002]. Recent observations suggest significant TS and energy seasonality [*Dmitrenko et al.*, 2009], implying aliasing complications when tracing AW pathways using summer-only hydrography. In the Canadian Basin, the AOBC is weaker, but still topographically steered in the Chukchi Borderland [*Shimada et al.*, 2004; *Woodgate et al.*, 2007]. Along the Beaufort slope, the AOBC is only poorly measured [*Aagaard*, 1984], but the implied cyclonic circulation of the boundary current opposes the anticyclonic circulations of ice and presumably Pacific Water in the overlying Beaufort Gyre. (Note the AOBC is defined as a pan-arctic transporter of AW, not to be confused with recent unhelpful namings of the Pacific Water slope current as “the Arctic boundary current” [*Nikolopoulos et al.*, 2009].) Further along the Canadian Archipelago, AOBC observations are extremely rare [*Newton and Sotirin*, 1997].

The physics of the AOBC are still debated, although proposed mechanisms relate generally to conservation of potential vorticity (PV). (PV has similarities to angular momentum. It depends on the rotation of the water, including rotation from the spinning earth, and the thickness of the layer considered. For details, see oceanography text books.) Various PV drivings have been suggested - the wind-stress in the Greenland Sea [*Nost and Isachsen*, 2003]; eddy-topography interactions (nicknamed “Neptune” in some computer models) [*Holloway and Wang*, 2009; *Nazarenko et al.*, 1998]; the PV of the Pacific and Atlantic inflows [*Yang*, 2005]; or some combination of factors, e.g., Barents Sea inflow and the Beaufort Gyre surface stress [*Karcher et al.*, 2007].

A remarkable feature of the AW TS structure is the presence of double diffusive intrusions (sometimes called “zigzags” due to their form in TS space [*McLaughlin et al.*, 2009; *Woodgate et al.*, 2007]), where differences in the molecular diffusivities of heat and salt drive interleaving layers perpendicular to the AOBC flow [*Carmack et al.*, 1998; *Woodgate et al.*, 2007 and references therein]. These layers have vertical dimension of 10-50m, but show coherence over the entire Arctic. Though velocities are small (order mm/s) they are a sizeable fraction of the mean flows of a few cm/s, and certainly in the Canadian Basin appear to be a major part of AOBC to basin interior exchange [*McLaughlin et al.*, 2009].

Concluding Remarks

It is remarkable that fundamental questions about Arctic circulation – as basic as water pathways and physical driving mechanisms – remain unanswered at this time. Since Arctic forcings and inflows are changing (with dramatic warming in Atlantic inflow to the Arctic [*Polyakov et al.*, 2005] and intermittent Pacific water warming [*Woodgate et al.*, 2010]), we should revise tacit assumptions about stationarity in the Arctic Ocean, and embrace non-linear processes gaining traction in lower latitudes [*Lozier*, 2010]. Moreover, if the summer sea-ice extent continues shrinking, processes of wind-driven mixing and internal waves may become dominant, increasing ocean energy levels, speeding currents, increasing eddies, and swamping the prior status quo of sluggish boundary currents, double diffusive processes and geothermal-driven thermohaline staircases. The quiet Arctic we have studied for decades may become a thing of the past, while instead we measure the spin-up of a wind-driven Arctic Ocean.

The implications are widespread [*ACIA*, 2004]. A warming ocean may destabilize glaciers, permafrost, and methane gas hydrates. Temperature, stratification, mixing and chemical changes herald challenges for various levels of the Arctic ecosystem. Water mass and albedo changes may affect local and global climate, including the meridional overturning circulation as Arctic waters precondition both Atlantic surface waters and the overflows. Ocean change may also influence sea-ice change, with numerous climate, societal and commerce impacts. To successfully predict Arctic change and quantify the implications thereof, and to design an efficient manner of observing the system, we require a better understanding and quantification of dominant processes within the Arctic Ocean. Such an understanding will be best achieved by combining observational, theoretical and modeling approaches.

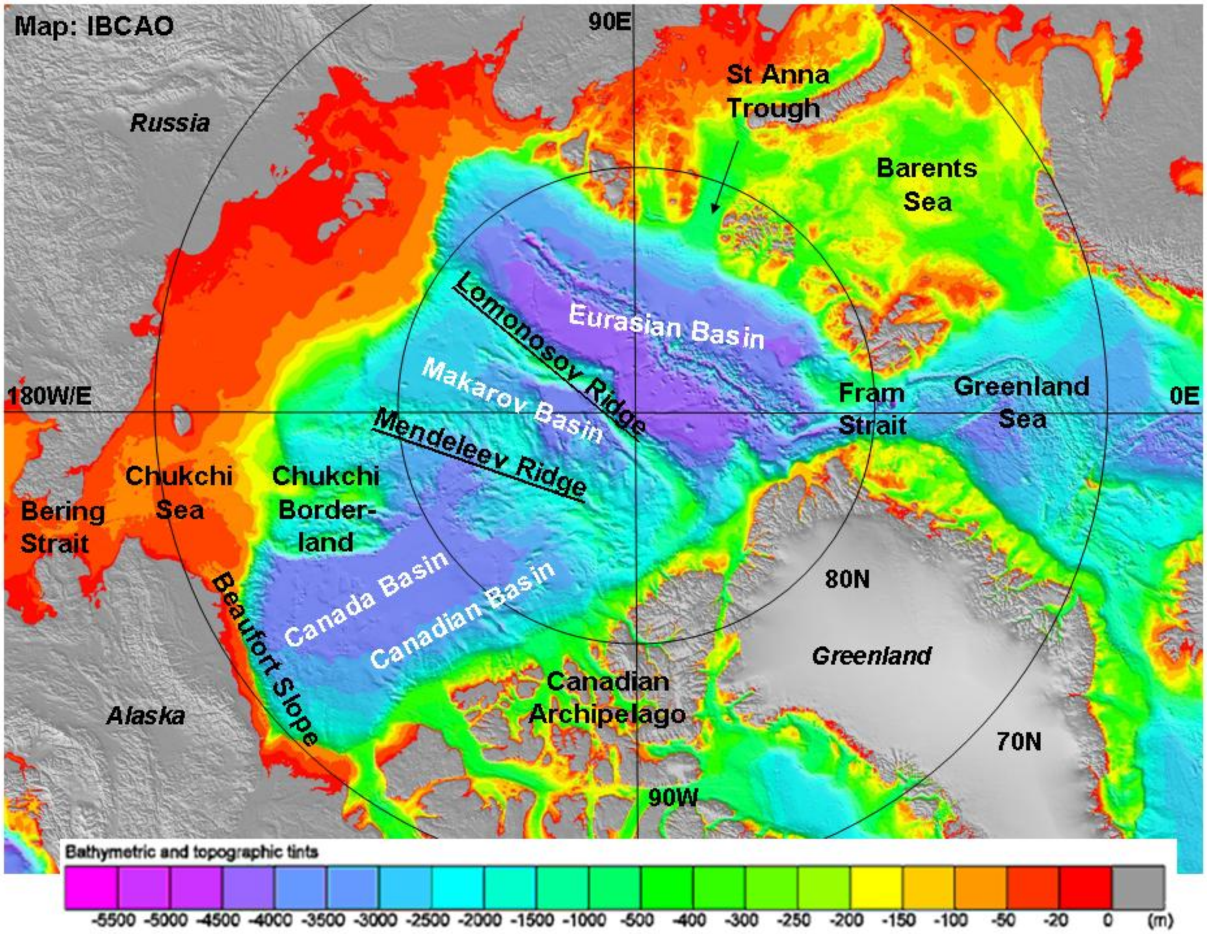

Figure 1: Map of the Arctic Ocean with topography from the International Bathymetric Chart of the Arctic Ocean (IBCAO) [*Jakobsson et al.*, 2000], indicating places named in the text. The term “western Arctic” refers to the Canadian Basin (itself the combination of the Canada and Makarov Basins) and the surrounding shelf seas. Similarly, the term “eastern Arctic” refers to the Eurasian Basin and surrounding shelf seas.

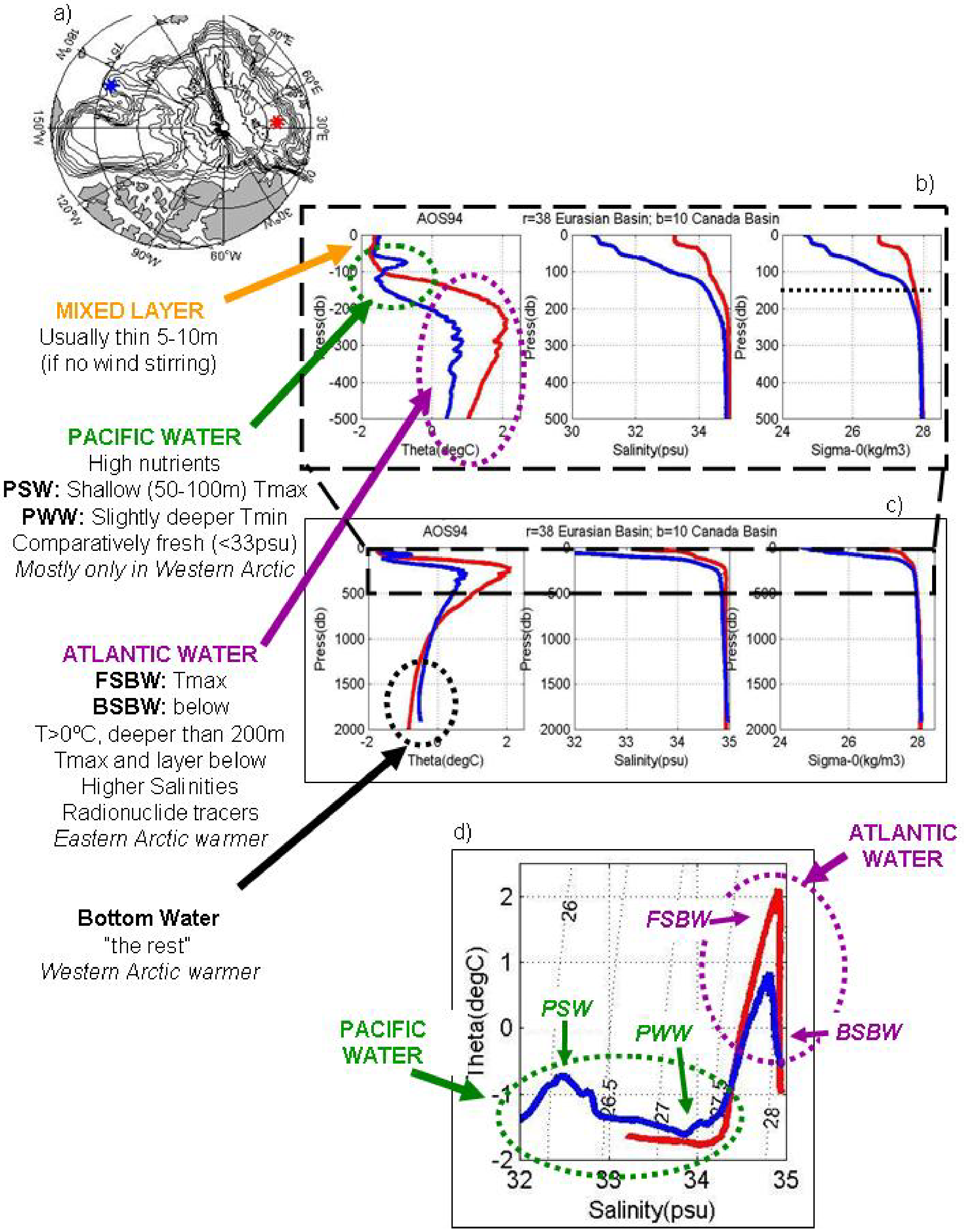

Figure 2: Examples of Arctic profiles, taken from the Arctic Ocean Section (AOS) 1994 [*Swift et al.*, 1997].

a) Schematic Arctic map indicating profile locations - red = a typical eastern Arctic profile (AOS station 38); blue = a typical western Arctic profile (AOS station 10).

b) and c) Profiles (with pressure) of potential temperature (theta), salinity, and the measure of density, sigma-0. (Potential temperature is the temperature a parcel of water would have if brought to the surface adiabatically. For the Arctic, it is up to ~ 0.3ºC colder than in situ temperatures. Sigma-0 is water density in kgm^{-3} minus 1000 kgm^{-3}, again for a parcel of water brought adiabatically to the surface.)

d) Potential temperature - salinity plot, marking water masses. Lines of sigma-0 (thin curved dotted lines) are almost vertical, indicating density is primarily determined by salinity at these temperatures.

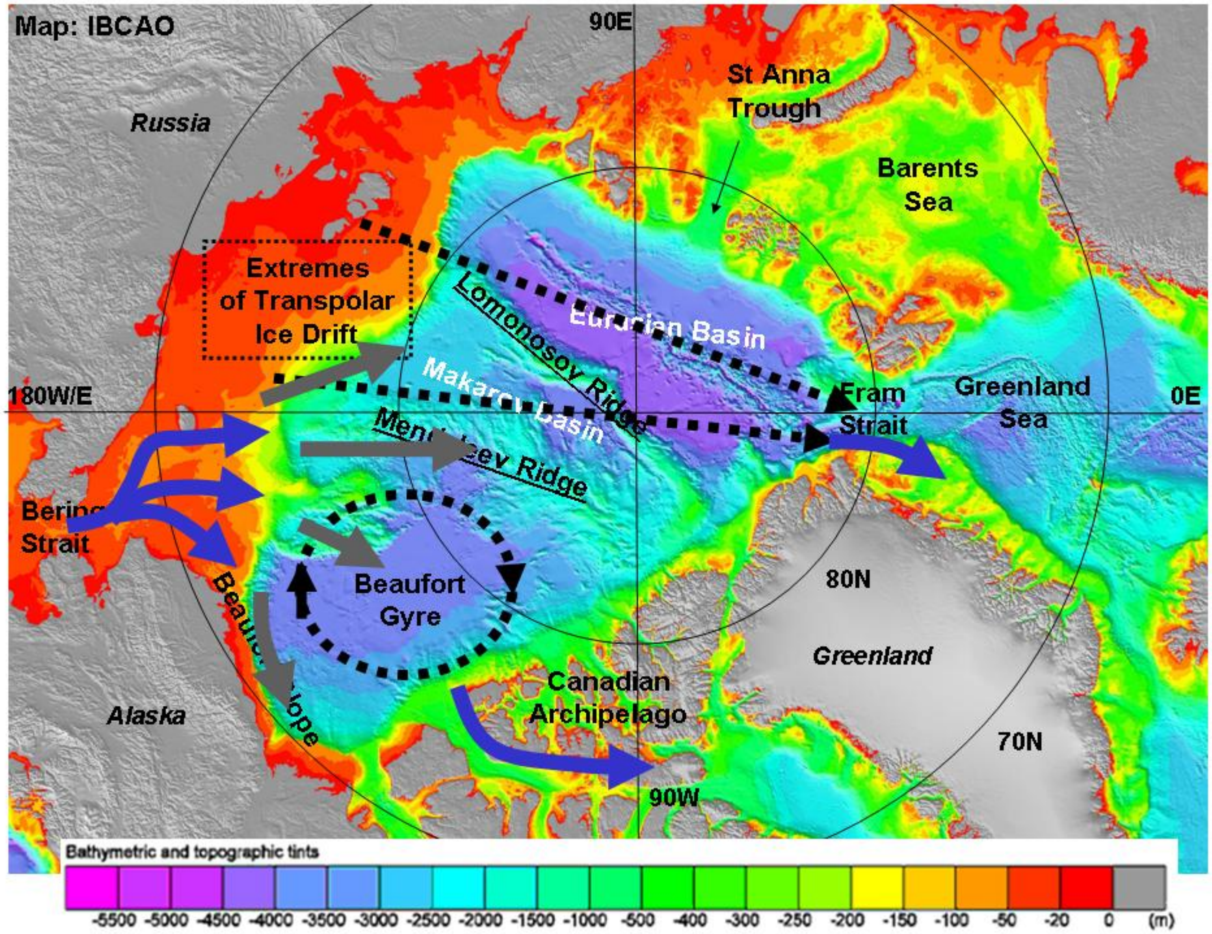

Figure 3: Schematic of Pacific Water Circulation. Dashed straight black arrows from Russia to Fram Strait indicate extremes of the Transpolar Drift of sea-ice under different Arctic Oscillation conditions [see e.g., *Rigor et al.*, 2002]. Dashed circle with arrows indicates anticyclonic circulation of sea-ice (and presumably Pacific Waters) in the Beaufort Gyre. Blue arrows entering through the Bering Strait (left) indicate the branches of Pacific Waters crossing the Chukchi Sea [*Woodgate et al.*, 2005b]. Dark grey arrows indicate possible pathways of Pacific Waters into the Arctic and along the Beaufort Slope. Blue arrows in the Fram Strait and the Canadian Archipelago indicate exit paths of Pacific Waters from the Arctic into the Atlantic.
Note arrows are schematic only.

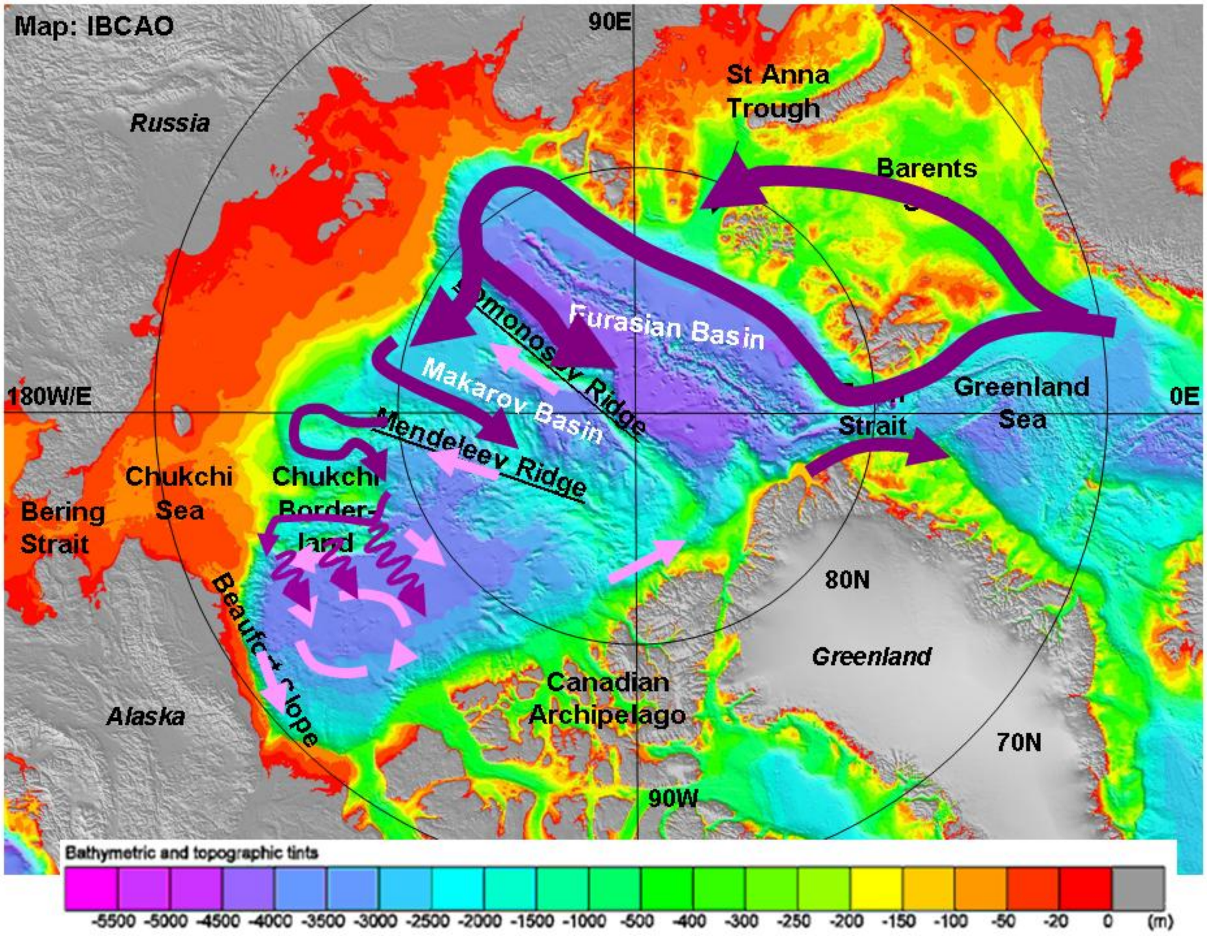

Figure 4: Schematic of Atlantic Water Circulation. Solid mauve lines (right) indicate Atlantic Waters entering through the Fram Strait and the Barents Sea, and the Arctic Ocean Boundary Current (AOBC) flowing cyclonically along the slope of the Eurasian Basin. The AOBC is split by the Lomonosov Ridge, with roughly half moving north along the ridge, and half entering the Makarov Basin [*Woodgate et al.*, 2001]. Beyond this thinner, lighter arrows indicate more uncertainty about the flow. AW flow around the Chukchi Borderland and are believed to continue cyclonically along the Beaufort slope although observations are sparse (pink arrows) [*Aagaard*, 1984]. Within the Beaufort Gyre, an anticyclonic flow may exist in the same sense as the sea-ice gyre above, opposing the AOBC flowing cyclonically along the slope [*Newton and Coachman*, 1974]. Squiggly lines extending from the Chukchi Borderland into the Basin indicate transfer of waters from the AOBC to the interior by double diffusive processes [*McLaughlin et al.*, 2009]. The AOBC is believe to continue cyclonically along the Canadian Archipelago [*Newton and Sotirin*, 1997] and exit the Arctic primarily through the Fram Strait. Note arrows are schematic only.

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