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The alpha/beta ocean distinction: A perspective on freshwater fluxes, convection, nutrients and productivity in high-latitude seas

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Abstract

Stratification is perhaps the most important attribute of oceans with regards to climate and biology. Two simple aspects of the ocean's climate system appear to have a surprisingly important role in transforming waters that feed the global thermohaline circulation, dominating patterns of biogeochemical flux and establishing macroecological domains. First, largely because of meridional distillation (mainly due to the atmospheric transport of freshwater across the Isthmus of Panama) the North Pacific is fresher than the North Atlantic. Second, largely because of zonal distillation (e.g., warming and evaporation at low latitudes and poleward transport of latent heat and moisture by the atmosphere) the upper layers of subtropical seas are permanently stratified by temperature ($N_T^2 = g\alpha \mathrm{d}T/\mathrm{d}z > 0$; here called *alpha oceans*), while the upper layers of high-latitude seas are permanently stratified by salinity ($N_S^2 = g\beta \mathrm{d}S/\mathrm{d}z > 0$; here called *beta oceans*). The physical basis for the boundary separating alpha and beta oceans is unclear, but may lie in the thermodynamical equations published by Fofonoff [1961. Energy transformations in the sea. Fisheries Research Board of Canada, Report Series 109, 82pp]. Nevertheless, it is clear that the resulting thermohaline distributions establish a 'downhill journey' of low-salinity (and nutrient-rich) waters from the North Pacific to the Arctic and then into the North Atlantic. The Arctic Ocean—itself—acts a double estuary, whereby waters entering from the North Atlantic become either denser through cooling (negative estuary) or lighter by freshening (positive estuary) as they circulate within the basin and then return to the North Atlantic as a variety of components of the ocean's conveyor. Intermediate and deep waters generally form within cyclonic beta oceans in close proximity to alphas systems. Similar patterns of stratification, nutrients and biogeographical boundaries persist in the Southern Hemisphere. It is thus argued that this simple distinction—alpha versus beta oceans—provides a broad, conceptual framework for simple interpretation of key physical and biological processes and rates, including the impacts of climate variability.

Keywords: Stratification; Convection; Freshwater; Nutrients; North Atlantic/North Pacific; Productivity

1. Introduction

In their insightful paper Tully and Barber (1960) referred to the North Pacific as a great estuary. Weyl (1968) drew attention to the role of inter-basin

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freshwater transports across the Isthmus of Panama in ocean climate and circulation. Stigebrandt (1984) applied the estuarine analogy to explore the water exchange between the Pacific and Arctic Oceans. Completing this freshwater circuit, Aagaard and Carmack (1994) argued for the importance of freshwater egress from the Arctic into the North Atlantic in setting conditions for sites and rates of deep convection (see Fig. 1 for schema of the northern hemisphere's freshwater cycle). These basic ideas can, in fact, be expanded and applied to the high-latitude seas in *both* hemispheres. Quite simply, because low-latitude oceans gain heat while high-latitude oceans loose heat, and because water inexorably evaporates in warm regions and condenses in cold, the upper layers of subtropical seas are permanently stratified mainly by temperature ($N_T^2 = \alpha \mathrm{d}T/\mathrm{d}z > 0$; *alpha oceans*), while the upper layers of high-latitude seas are permanently stratified mainly by salinity ($N_S^2 = \beta \mathrm{d}S/\mathrm{d}z > 0$; *beta oceans*); here N_T^2 is the contribution to static stability due to temperature, N_S^2 is the contribution due to salinity, α is the coefficient of thermal expansion, β is the coefficient of haline contraction, T is temperature, S is salinity, and z is depth. Importantly, the transition from alpha to beta domains is generally abrupt. This distinction is further amplified by the non-linear equation of state whereby the magnitude of α decreases by roughly an order of magnitude between warmer alpha (large values) and colder beta (small values) ocean regimes.

This simple distinction (alpha versus beta oceans) plays a major role in shaping global climate and ocean zoogeography. This is because, as discussed below, alpha and beta oceans respond in markedly different ways and different time scales to atmospheric fluxes and thermohaline mixing processes (cf. Rooth, 1982). For example, in deep oceans sea ice can only form over beta oceans (cf. Bulgakov, 1962), an important point with regard to ice-albedo feedback mechanisms, and this is but one of the important differences in the structure and physical habitat afforded by stratification type. At the same time it is fair to point out that, owing to the locations of the largest oceanographic institutions, more process studies have been carried out in alpha than in beta oceans, and that some risk may accompany the transfer of rates, processes and algorithms determined in alpha oceans to their beta ocean counter parts. Canada, for example, is surrounded on three sides by three beta oceans that are linked to one another by freshwater fluxes through the Bering Sea and Canadian Arctic

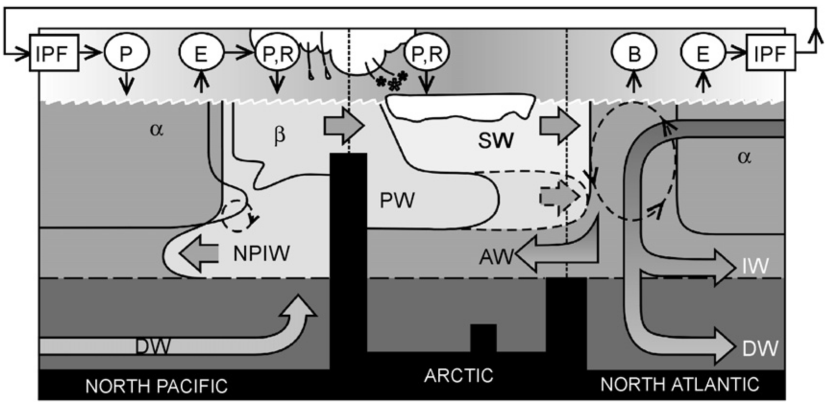

Fig. 1. Schema of the northern hemisphere ocean showing how the global imbalance of heat gain in low latitudes and heat loss at high latitudes is redressed by global fluxes of heat and freshwater. Zonal winds carry water vapor from the Atlantic to the Pacific across the Isthmus of Panama (IPF), contributing to a fresher Pacific than Atlantic. At the same time, net evaporation (E) occurs in the warmer alpha-type oceans and this moisture is transported meridionally poleward to the cooler beta-type oceans where it enters as net precipitation (P) and river runoff (R). While some excess freshwater in the beta domain of the Pacific is carried back to the alpha domain as North Pacific Intermediate Water (NPIW), the combined effects of zonal and meridional distillation result in higher long-term mean steric height in the Pacific and subsequent 'downhill' transport of Pacific Water (PW) into the Arctic Ocean and then North Atlantic. The Arctic Ocean, itself, acts as a double estuary in that incoming the Atlantic waters (AW) become both denser by cooling and buoyancy loss (B) (negative estuary) and lighter by freshening (positive estuary). Freshwater (buoyancy gain) is supplied by river input, net precipitation, ice melt and the inflow of relatively fresh Pacific Water. For conservation reasons this supply of freshwater must return equatorward; as surface water (SW) in beta-type seas and as intermediate water (IW) and deep water (DW) in alpha-type seas. Such flows that ensure the conservation of fresh water reflect many features of ocean structure and climate.

Archipelago; still, little or no ecosystem research has focused on this interconnectivity (but see Grebmeier et al., 2006).

Previous works have solidly built the case for recognizing the importance of stratification type in setting a framework for interpretation of diverse datasets. In a seminal work, Berger (1970) used an estuarine analogy, with the Atlantic as a negative estuary and the Pacific as a positive estuary, to explain the distribution of biogenic sediments in the global ocean. Rooth (1982) noted that while the dynamic response of the oceans to temperature and salinity forcing is indeed through their *combined* effects on density, the non-linearity of the equation of state and the different molecular diffusivities of heat and salt result in differential climatic feedback effects associated with temperature and salinity, respectively. Rooth (1982) and Welander (1986) added the point that diverse boundary conditions for heat and salt fluxes would strongly impact circulation. Warren (1983) explored stratification differences between the Atlantic and Pacific and proposed that reduced evaporation in the cooler North Pacific resulted in lower upper-layer salinities, and thus answered his own question, ''why is no deepwater formed in the North Pacific?''. Hopkins (2001) further noted that stabilizing (negative) feedback loops within the ocean's thermohaline system may also provide stability to the marine biotic environment. Still, variations in the release of freshwater reserves from Arctic and subarctic seas may alter the global ocean circulation (cf. Dickson et al., 1996; Wu et al., 2005; Bryden et al., 2005), and must thus be understood. The purpose here is to argue that an assessment of stratification type and its response to forcing is a fundamental prerequisite to understanding biogeochemical distributions, cycles and processes in the sea.

Empirical evidence also is given that the physical basis for boundaries separating alpha and beta oceans can be found in the thermodynamical conservation equations published in 1961 by a young researcher, Fofonoff, working under the direction of Tully at the Pacific Biological Station in Nanaimo, British Columbia; his equations express the energy and stability transformations during mixing due to the non-linear equation of state of sea water (e.g., cabbeling or the densification (volume contraction) that occurs whenever two differing water types are mixed; Fofonoff, 1961; E.B. Bennett, pers. comm.). Specifically, the large gradients of temperature *and* salinity prevalent at the alpha/beta boundary are conducive to densification upon mixing, sinking of the resulting dense water, and thus sustained convergence across the frontal boundary (cf. Garrett and Horne, 1978). The critical indication here is that the alpha/beta boundary, marked by a surface density maximum and local stability minimum (cf. Roden, 1970, 1975) is globally associated with the winter outcropping of the ~10 °C isotherm, a contiguous domain of maximum cabbeling; however, further theoretical confirmation is required.

Admittedly, there is always the risk that a conceptual generalization will at best admit exceptions and at worst be a gross oversimplification. Clearly, atmospheric and oceanic processes have been highly generalized. Meridional distillation (moisture transport by trade winds across the Isthmus of Panama) has been implicated as both key to the initiation of ice ages and North Atlantic Deep Water formation (Weyl, 1968; Zaucker et al., 1994; Weaver et al., 1999; Hasumi, 2002). While other processes may condition the existing interbasin salinity differences, the importance of freshwater transfer across the Isthmus of Panama is strongly supported in the paleo-record, which shows that the modern salinity difference was established concurrently with the closure of the Central American Seaway ~4 Myr ago (Haug et al., 2001). Zonal distillation (moisture transfer from low to high latitudes) is a highly complex and variable mechanism involving the steering of cyclone tracks by air/sea/land interactions (cf. Cohen et al., 2001; Hoskins and Hodges, 2002). The key role of the Asian Monsoon in supplying the northern moisture flux and thus the freshening the subarctic Pacific is discussed by Emile-Geay et al. (2003). Ocean circulation patterns within the alpha and beta domains are clearly more complex than treated here; as an example, McPhaden and Zhang (2002) discussed the wind-driven meridional overturning of the upper Pacific Ocean. Talley (2003) gave a comprehensive discussion of the complex overturning patterns of upper, intermediate and deep waters. Complex oceanic structures exist within the alpha and beta domains; for example, a rich variety of oceanic fronts formed by diverse processes (e.g., shelf-break currents, retroflexion, buoyancy-boundary currents, tidal mixing) extend poleward from alpha/beta boundaries (cf. Belkin and Gordon, 1996; Belkin et al., 2002; Belkin and Cornillon, 2003). Transfer of water mass properties across the alpha/beta boundary may be accomplished by oceanic eddies, such as the Kuroshio warm core rings that extend into Oyashio domain of the subarctic Pacific (Rogachev, 2000).

2. Physical structure—basis for the alpha/beta ocean distinction

Data used within the paper were collected on various WOCE cruises, from the 1990 to 1993 Russia/Canada/US International North Pacific Ocean Climate (INPOC) study, from the 1994 Trans-Arctic section, and from various cruises associated with the Canada/Japan/USA Canada Joint Western Arctic Climate (JWACS) and Beaufort Gyre Exploration (BGEP) programs. Oceanographic variables (potential temperature (θ), potential density (σ_θ) and stability (N^2, N_T^2 and N_S^2) were calculated from algorithms in UNESCO (1983). The Turner angle, an indicator of double-diffusive potential, is calculated as the four quadrant arctangent $\mathrm{Tu} = \tan^{-1}[\alpha \mathrm{d}T/\mathrm{d}z - \beta \mathrm{d}S/\mathrm{d}z,\ \alpha \mathrm{d}T/\mathrm{d}z + \beta \mathrm{d}S/\mathrm{d}z]$; see Ruddick, (1983). The advantage of using Tu over the more commonly used density ratio $R_\rho = \alpha \mathrm{d}T/\mathrm{d}z / \beta \mathrm{d}S/\mathrm{d}z$ is that it eliminates ambiguity in sign. Essentially, the water column is conducive to salt-finger instabilities for $45 < \mathrm{Tu} < 90$, is doubly stable for $45 < \mathrm{Tu} < -45$, and conducive to diffusive instabilities for $-45 < \mathrm{Tu} < -90$. The locations of the oceanographic sections are shown in Fig. 2.

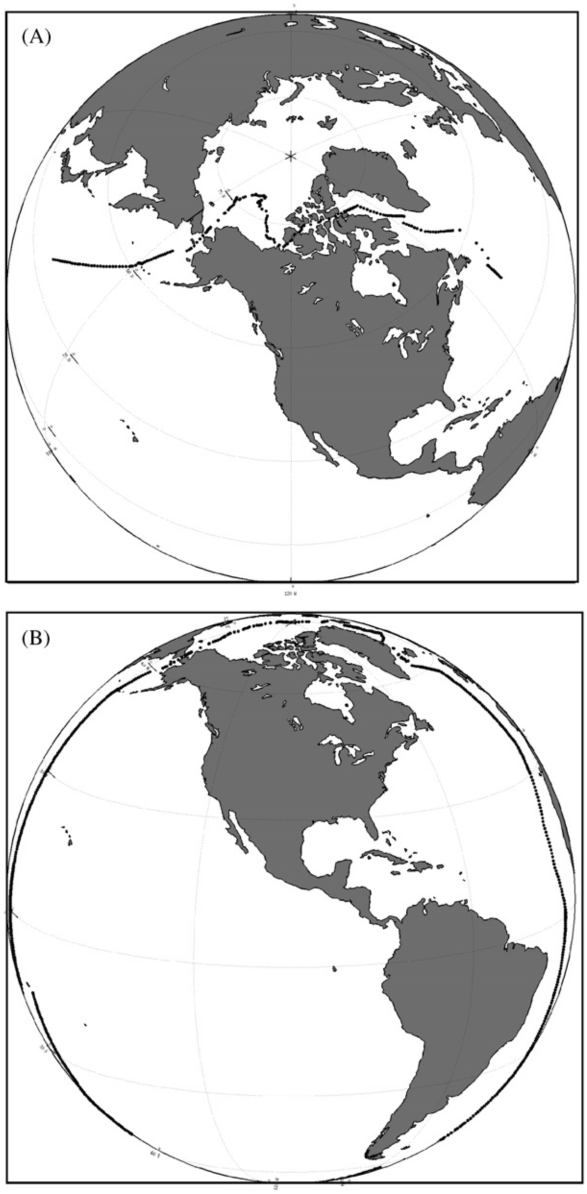

Fig. 2. Map of oceanographic stations used in the present study: (A) shows INPOC, WOCE, and JWACS data used in Figs. 3 and 6; (B) shows WOCE, AOS-94, Oden, Hudson and Polarstern data used in Fig. 7.

Oceanographic sections across the alpha/beta boundary in a variety of ocean regions are examined next. The North Pacific is a relatively straightforward example of the alpha/beta ocean classification (cf. Reid, 1965; Roden, 1970; Talley, 1993). Distributions of θ, S, σ_θ, N_T^2, N_S^2 and Tu along a meridional section extending from 32°N, 160°E to 51°N, 180°E obtained aboard the R/V *Priliv* in March 1992, as part of the INPOC study, are shown in Fig. 3. The key feature is the abrupt change in all water mass characteristics across the alpha/beta boundary (cf. Favorite et al., 1976). The temperature distribution shows the warm waters and permanent thermocline of the subtropical domain, the rapid upward bending of isotherms and outcropping within the frontal zone formed by the alpha/beta boundary and the weak vertical temperature gradients north of the frontal zone (Fig. 3A). Complex mesoscale structures are observed at temperatures in the transition domain between 10 and 6 °C. The salinity distribution shows salinities decreasing with depth to the south of the alpha/beta boundary, and increasing with depth to the north (Fig. 3b). A tongue of low-salinity intermediate water, North Pacific Intermediate Water (NPIW) is observed to spread south from the boundary region (see Talley, 1993; You et al., 2000, for discussions of source regions). A surface density maximum lies at the alpha/beta boundary between temperatures of about 10° and

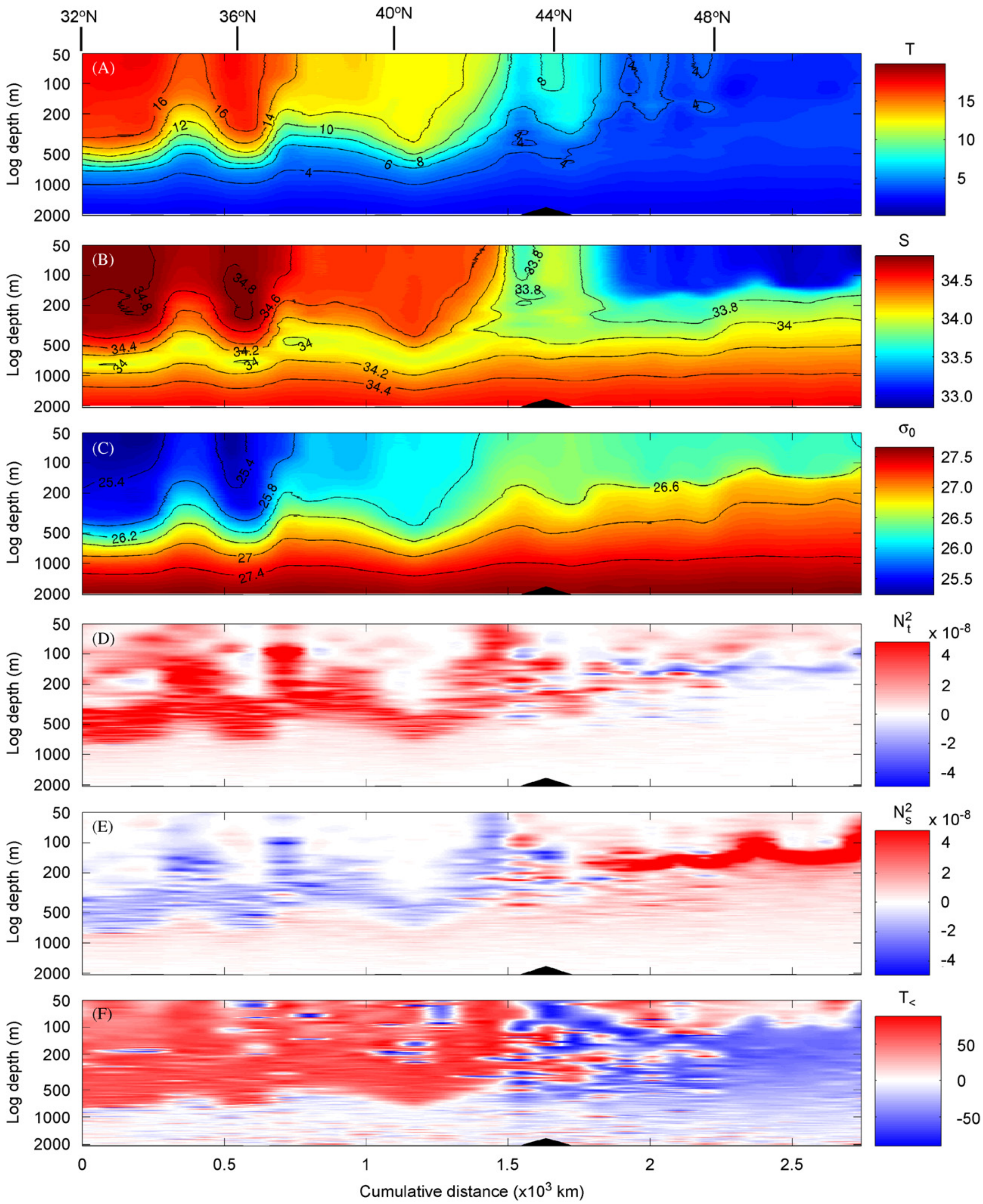

Fig. 3. Sections of (A) potential temperature, (B) salinity, (C) density, (D) N_T^2, (E) N_S^2 and (F) Tu along a meridional line in the western North Pacific in early spring; data from INPOC, R/V *Priliv*, spring 1992.

7 °C (Fig. 3C; cf. Roden, 1970). Waters south of the boundary are T-stable while those north of the boundary are T-unstable, while the reverse holds true for the salinity distribution (Fig. 3D and E, respectively); at the boundary both $\alpha \mathrm{d}T/\mathrm{d}z$ and $\beta \mathrm{d}S/\mathrm{d}z$ pass through their respective zero crossings. The section of Tu (Fig. 3F) shows the critical point that waters south of the boundary are conducive to salt-finger instabilities (Schmitt, 1981, for arguments based on constant R_i), while those immediately beneath the halocline north of the boundary are conducive to the diffusive instability (also see You (2002) for global mappings of Tu).

The alpha/beta boundary is also a domain wherein cabbeling due to *lateral* mixing is maximized (Talley and Yun, 2001; You, 2003). A North Pacific basin-wide suite of sea-surface T and S observations collected aboard the R/V *Priliv* in spring 1992 shows, when plotted as a T/S scatter diagram, two main mixing lines (Fig. 4): one that connects western subarctic surface waters (labelled WSAP) with subtropical surface waters (labelled STP) and one that connects eastern subarctic surface waters (labelled ESAP) also with subtropical surface waters. The two mixing lines support the idea of You et al. (2000) that NPIW is formed in *both* the Okhotsk Sea and Gulf of Alaska (see below). More importantly, with regards to the cabbeling mechanism, the mixing lines are not straight, but instead bend concave upwards; and since isopycnals are concave downwards, it follows that there must be a temperature range wherein mixing along such lines results in a surface maximum density. In this temperature range surface convergence and frontogenesis can be expected. As noted below, this temperature range is associated with the alpha/beta boundary in both hemispheres of the Atlantic and Pacific, and will be referred to here as the cabbeling temperature. For surface pressure and salinity ranges characteristic of the world ocean, the cabbeling temperature is near 10 °C, close to that of the equatorward boundary of subarctic (and subantarctic) fronts. As anecdotal evidence, naval oceanographers often will use, in the absence of other information, the 10 °C isotherm to define the real-time location of the subarctic front in the North Pacific for anti-submarine warfare purposes (J. Powell, pers. comm.), and this is also consistent with the observation of Belkin and Levitus (1996) of the subarctic front in the North Atlantic.

The resulting "bimodal" convection pattern (with cabbeling occurring year-round near 10 °C and thermal convection occurring only in winter) leads to the convergence of surface waters within the broad (100 km) boundary zone. Such convergence

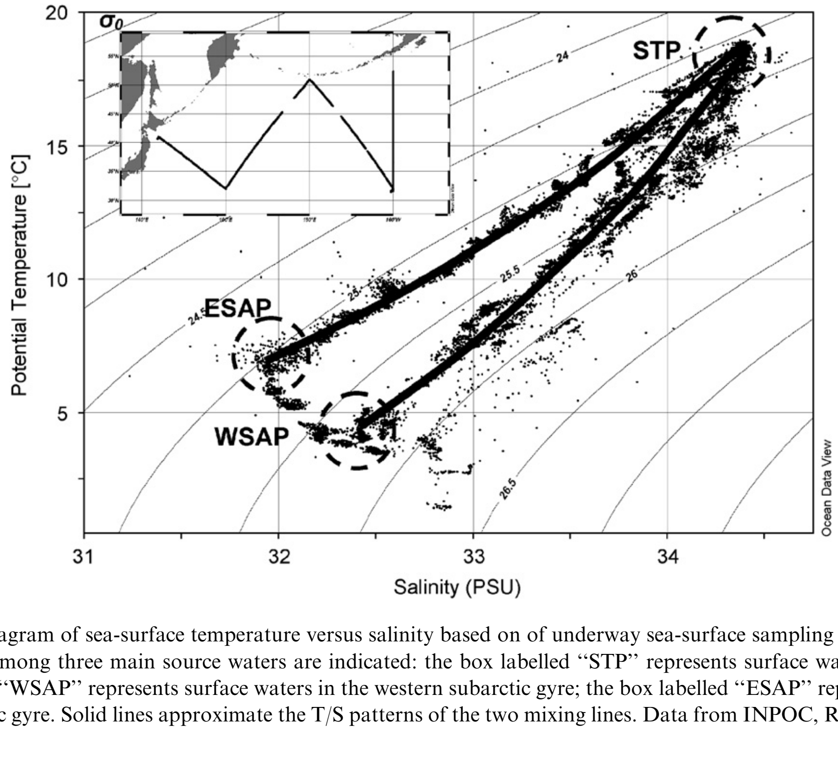

Fig. 4. Correlation diagram of sea-surface temperature versus salinity based on of underway sea-surface sampling in the North Pacific in spring. Mixing lines among three main source waters are indicated: the box labelled "STP" represents surface waters in the subtropical gyre; the box labelled "WSAP" represents surface waters in the western subarctic gyre; the box labelled "ESAP" represents surface waters in the eastern subarctic gyre. Solid lines approximate the T/S patterns of the two mixing lines. Data from INPOC, R/V *Priliv*, spring, 1992.

aids the subduction of low-salinity (high-latitude) waters below high-salinity (low-latitude) waters. Because such convergence and subduction is a convective feature associated with a surface density extremum, it can be considered as the oceanic analogy to the so-called *thermal bar* phenomenon, which drives convection in temperate lakes (Carmack, 1979). Within the alpha/beta boundary zone cabbeling occurs via a convective flux structure of interleaving layers of cold/fresh and warm/salty waters, particularly in the temperature range 10–6 °C (Fig. 5). The formation of thermohaline intrusions also raises the possibility for further energy extraction from double diffusive processes (Ruddick and Richards, 2003). Hence, for thermodynamic reasons the subarctic and subantarctic fronts and their attendant supply of low-salinity intermediate waters tend to form poleward of ~10 °C, regardless of variability in atmospheric forcing. Indeed, it is speculated that the ocean and the corresponding location of the ~10 °C isotherm steers the atmospheric wind field, with anticyclonic winds above alpha oceans and cyclonic winds above beta oceans, and thus that the relative position of this front and its control on the flux of water vapor and storage of freshwater in the upper layers of the ocean impacts climate and climate variability.

The subarctic Pacific thus consists of three parts: (a) a boundary region that separates the subtropical (alpha) and subarctic (beta) oceans; (b) an interior (beta) domain north of the transition zone that is stratified by a permanent halocline; and (c) a contiguous system of buoyancy boundary currents that transport continentally discharged fresh waters around the perimeter (cf. Royer, 1982; Weingartner et al., 2005). The subarctic system 'leaks' its excess freshwater poleward through Bering Strait (Coachman and Aagaard, 1966; Woodgate and Aagaard, 2005) and equatorward via the formation of NPIW (You, 2005) and the branching of the North Pacific Current (Favorite et al., 1976; Ingraham et al., 1998). Due to the wind field and cyclone tracks across the Pacific, the western continent (Asia) is a source of global-scale signals (e.g., aeolian-derived dust and iron, organochlorine contaminants) while the eastern continent (North America) may serve to capture such signals in the paleo-record (e.g. in snow, ice cores, tree rings) (Wilkening et al., 2000). It is noteworthy that anadromous salmon reside in the beta domain (that is, waters colder than 10–6 °C; cf. Welch et al., 1995, 1998), and use the system of contiguous buoyancy boundary currents along the coast of British Columbia and Alaska to assist in their migration (D. Welch, pers. comm.). Efforts to address the so-called regime-shift phenomena (e.g., Beamish et al., 2004) must take each of these components into consideration. For example, changes in the depth of the halocline have been observed, and this appears to impact on ocean production (Freeland et al., 1997). Decadal-scale variability in the branching structure of the North Pacific Current as it approaches the North American continent has been observed and modelled by Ingraham et al. (1998), and this too will impact both the freshwater budget of subarctic Pacific and the transport of productive

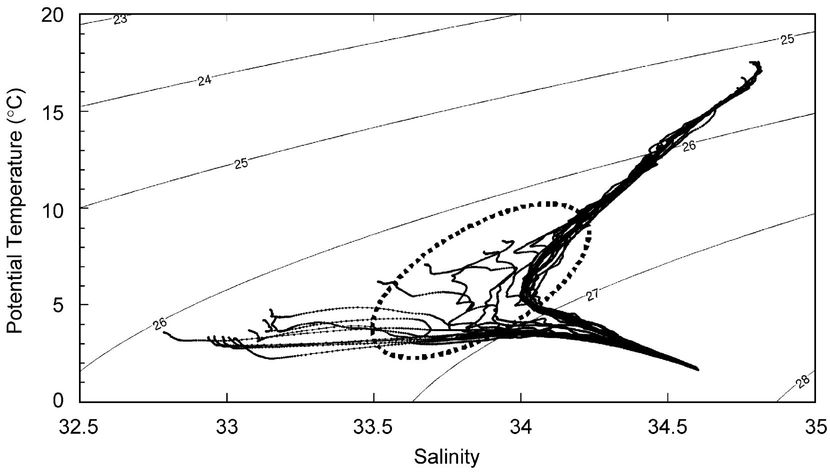

Fig. 5. Correlation diagram of potential temperature versus salinity for hydrographic lines crossing the western North Pacific. The dashed ellipse encloses the T/S domain of thermohaline intrusions. Data from INPOC (R/V *Priliv*, spring 1992).

subarctic waters to the coastal ecosystems of western Canada and the United States.

The stratification distinction extant in the North Pacific can be extended through the Arctic Ocean and Canadian Arctic Archipelago, and then into the North Atlantic, thus completely surrounding Canada and Alaska (Fig. 6). The temperature (Fig. 6A) section again shows the pronounced alpha/beta boundary in the North Pacific. (The shift to relatively warm water in the upper 50 m immediately north of the Bering Sea slope is due to the use of summertime WOCE data to complete this section.) As water passes through Bering Strait and enters the Arctic Ocean, temperatures rapidly decrease to less than 0 °C in the upper 200–300 m, representing the polar mixed-layer, the inflow of cold Pacific waters and the lower halocline. Within the Canada Basin of the Arctic Ocean the final branch of Atlantic Water is visible as temperatures above 0 °C; so again, colder fresher waters overlie warmer saltier waters. Temperatures remain low through the Canadian Arctic Archipelago and into Baffin Bay, but increase quickly upon passing through Davis Strait into the Labrador Sea. The Atlantic's alpha/beta boundary, formed by the northern edge of the eastward turning Gulf Stream, is visible at the right-hand side of the section. Note, anecdotally, that Smith et al. (1937) referred to this boundary as "the 10-degree wall".

The salinity section (Fig. 6B) reflects similar features to those discussed above. Also visible now is the relatively fresh, westward-flowing Alaska Stream in the northernmost part of the Pacific Ocean adjacent to the Aleutian Archipelago (Weingartner et al., 2005). The freshest waters occur in the Canada Basin and Canadian Arctic Archipelago. Salinities increase again as the section crosses the central Labrador Sea, decreases as it crosses back across the Labrador Current, and then increases abruptly upon encountering the subtropical waters carried by the Gulf Stream. The density section (Fig. 6C) shows surface density maxima in both the Pacific and Labrador Sea, and a surface density minimum extending fully across the salt-stratified Canada Basin. Waters equatorward of the alpha/beta boundary, marked by the 10 °C isotherm, are T-stable while those poleward of the boundary are T-unstable (Fig. 6D). The dominance of salinity stratification across the full span of the "Northern Ocean"—connecting the Pacific, Arctic and North Atlantic—is clearly shown in Fig. 6E. The section of Tu (Fig. 6F) underscores the fact that waters equatorward of the alpha/beta boundary are fundamentally conducive to salt finger instabilities while those of the Northern Ocean poleward of the boundary are conducive to the diffusive instability. At the boundary both $\alpha \mathrm{d}T/\mathrm{d}z$ and $\beta \mathrm{d}S/\mathrm{d}z$ pass through their respective zero crossings.

To complete the generalization proposed here, Fig. 7 shows a section that extends northward from the Pacific sector of the Southern Ocean, crosses the Arctic Ocean and extends southwards across the Atlantic Ocean to the Atlantic sector of the Southern Ocean. Evident here are sharp thermal fronts near 10 °C that separate the alpha and beta oceans in both hemispheres. Also evident is the freshening of surface waters within the equatorial current. Tongues of well recognized intermediate waters (e.g., NPIW, Antarctic Intermediate Water (AAIW) and Labrador Sea Water (LSW)) are observed to spread equatorward from the alpha/beta boundaries beneath alpha domains in both hemispheres. The dominance of temperature over salinity stratification in the alpha domains and vice versa for the beta domains is clearly evident on the global scale, and the Tu section re-emphasizes the role of salt fingering in alpha domains and diffusive instabilities in beta domains. The global pattern of the permanent pycnocline is thus one in which temperature and salinity contributions act in opposition to each other and thus permit enhanced flux due to double-diffusive transports.

3. Biogeochemical processes and distributions

The physical environments of the alpha and beta oceans differ, as do their interactions with the atmosphere. This is due in part to wind forcing and in part to the highly non-linear Clausius–Clapeyron equation (Rooth, 1982; Webster, 1994). This straight-forward fact has substantial consequences for the pelagic environment and biogeochemical processes and distributions. To comprehensively list these consequences is well beyond the scope of this paper; the goal here is to suggest that the distinction offers a useful backdrop against which to interpret oceanic processes and rates, and thus only a limited set of examples is given.

3.1. Intermediate water formation, salt balance and ventilation

It has been noted above that the intermediate waters of the Atlantic and Pacific in both hemispheres

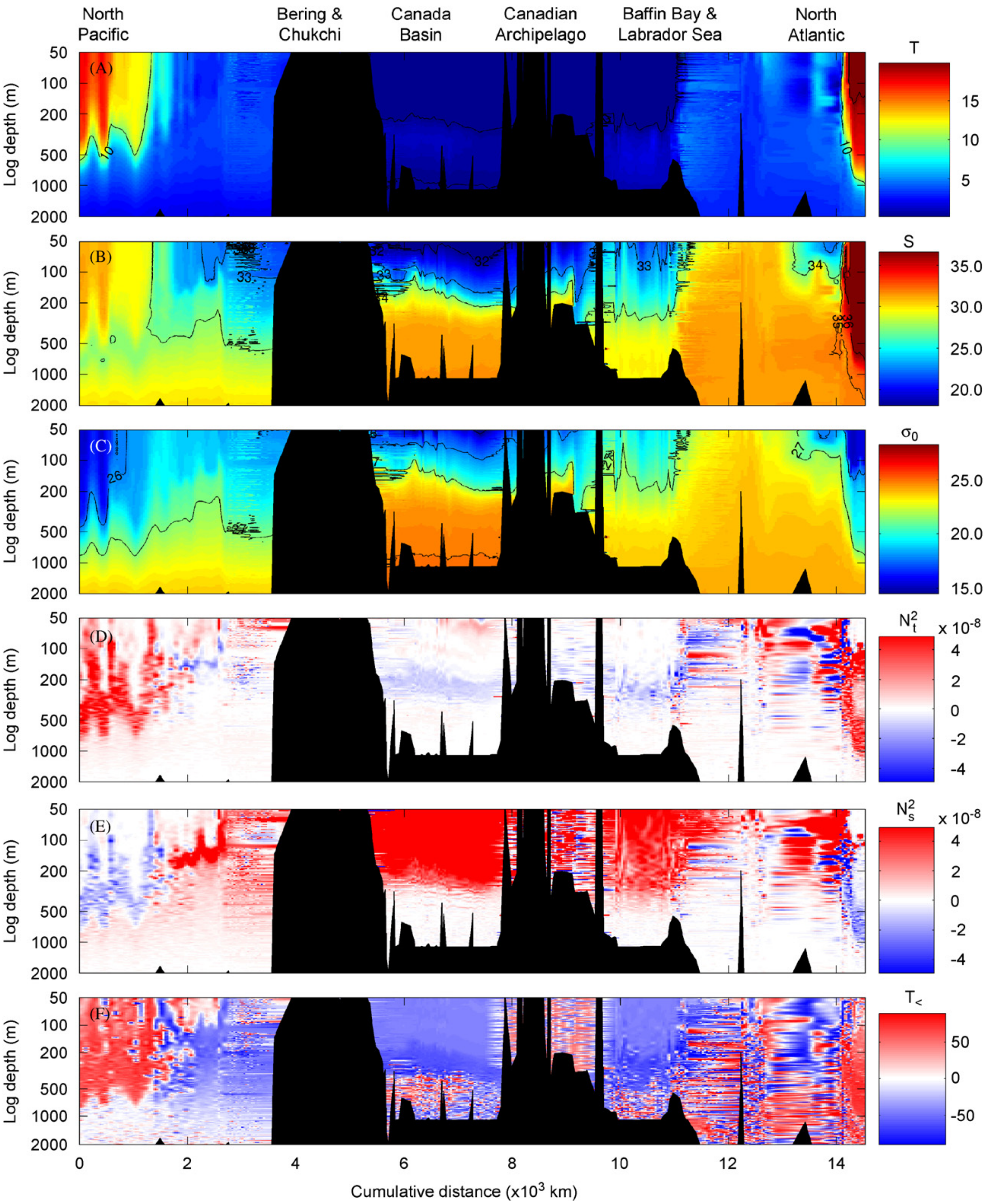

Fig. 6. Sections of (A) potential temperature, (B) salinity, (C) density, (D) N_T^2, (E) N_S^2 and (F) Tu along a section that extends from the North Pacific across the Bering Sea, Beaufort Sea, Canadian Arctic Archipelago, Baffin Bay, Labrador Sea and into the North Atlantic; data from WOCE and JWACS.

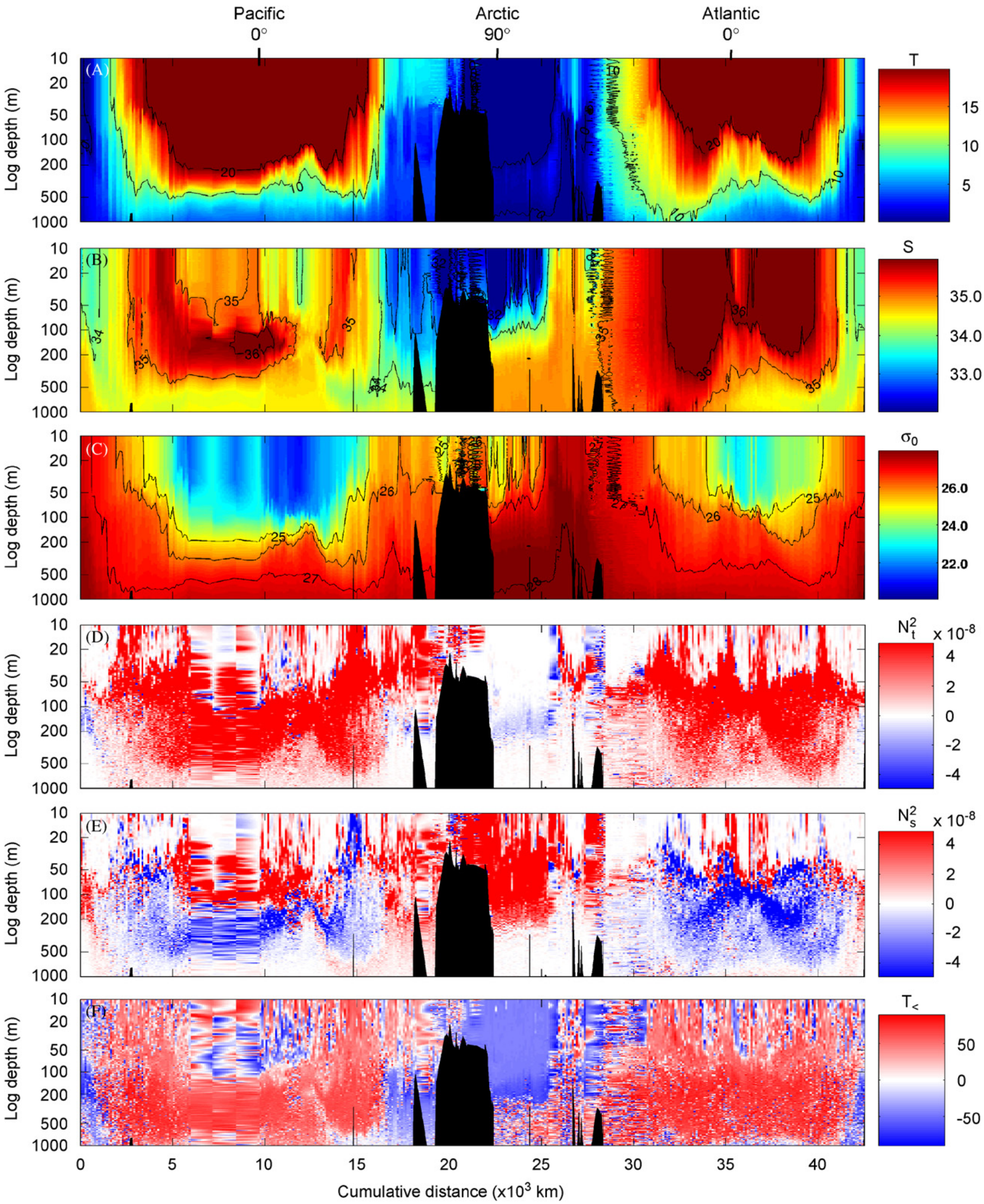

Fig. 7. Sections of (A) potential temperature, (B) salinity, (C) density, (D) NT2, (E) NS2 and (F) Tu along a section that extends northward from the Pacific sector of the Southern Ocean to the North Pole, and then extends southwards to the Atlantic sector of the Southern Ocean.

(e.g., NPIW, AAIW and LSW) appear to spread equatorward from source regions immediately poleward of the alpha/beta boundary. While these waters are drawn from beta oceans, it is the occurrence of special circumstances and preconditioning (e.g., weakened stratification within shelf or mid-gyre sources) that allows convection driven by heat loss to complete the process of water mass formation (Killworth, 1983; Bacon et al., 2003; Bailey et al., 2005). Such intermediate water flows are crucial in closing the freshwater loop; e.g. in replacing the freshwater lost to evaporation and poleward transport in the subtropical gyres. But, the subtropical gyres are anticyclonic (downwelling) systems, thus constraining the upward flux of low salinity intermediate water, and so how is the salt balance maintained? One possibility, noted above, is that the interflowing intermediate waters establish the requisite temperature and salinity gradients (e.g., Turner angle) required for salt fingering, with salinity imposing a destabilizing gradient against the stabilizing temperature gradient, and so salt is preferentially fluxed downwards out of the gyres and into the fresher intermediate waters, thus contributing to the global salt balance.

The intermediate waters also transport various biogeochemical properties, examples being nutrients and dissolved gasses. For example, Sarmiento et al. (2004a) argued that AAIW and, to a lesser extent NPIW, are the main agents of nutrient transfer to the upper water of the lower-latitude oceans. Another example involves the role of freshwater in constraining ventilation. Both AAIW and LSW serve to replenish dissolved oxygen, but NPIW does not serve to ventilate the North Pacific. One possible reason for this difference is that the Subarctic Pacific simply has 'too much' freshwater. As noted by Warren (1983) this explains why no deep water forms, and as noted by Reid (1965) this constrains the winter outcropping of the appropriate isopycnals in winter. How then does the source water of NPIW form? Talley (1993) called for a source in the Sea of Okhotsk, while You et al. (2000) and You (2005) supported the Okhotsk as one source and proposed a second source in the central Gulf of Alaska. The thermohaline mechanisms discussed above supports the latter proposal, and a hydrographic section across the Gulf of Alaska along 160°W (Fig. 8) appears to illustrate the You (2005) hypothesis. Here a tongue of warmer and relatively saline, subtropical water is seen to spread poleward from the alpha/beta boundary immediately beneath the subarctic halocline. Mid-way across the Gulf of Alaska, close to the site indicated by You (2005) as the second source region for NPIW formation, colder, low-salinity water is observed to subduct under the intruding tongue of saline water. Mixing between the two converging water masses, and associated cabbeling, may then result in a well-defined tongue of NPIW directed equatorward. As the formation appears to occur subsurface, and involves waters already depleted in oxygen, no strong ventilation signal ensues.

3.2. Nutrient distributions

Beta oceans coincide with cyclonic circulation; the North Pacific subarctic gyre system, Bering Sea, eastern Arctic gyre, Baffin Bay, Labrador, Irminger, Greenland, Norwegian, Icelandic seas, and gyres of the Southern Ocean all being examples. Indeed, the Equatorial Currents system, with elongated cyclonic gyres, and surface waters freshened by precipitation associated with the intertropical convergence zone, may also be considered a beta ocean (J.L. Reid, pers. com.). The sole exception to this pattern is the anticyclonic gyre of the Beaufort Sea below the atmospheric Beaufort High. As noted by Rooth (1982) the surface waters of such systems are wind-divergent with mean upwards Ekman pumping. It is not surprising then that they are likewise associated with the so-called high-nutrient–low-chlorophyll (HNLC) regimes and hypothesized to be iron limited (cf. Martin and Gordon, 1988; Cullen, 1991). To address the question, "is the alpha/beta ocean distinction relevant to the global distribution of nutrients in general, and to HNLC regimes in particular?", the global correlation of near-surface (~50 m depth) temperature and nitrate is examined using the same data set used to construct the globe encircling section. For the Pacific sector (Fig. 9A) nitrate values increase abruptly from near-zero values starting at temperatures near 15 °C, and continue to increase—in both hemispheres—to values near 30 μM at temperatures near 4 °C. Slightly elevated values also are observed at warmer temperatures corresponding to the equatorial domain, where salinity stratification and surface divergence also persist. At temperatures below 4 °C the surface waters of the two hemispheres diverge, with Southern Ocean waters remaining high and Northern Ocean waters decreasing. A similar pattern is observed in the Atlantic sector

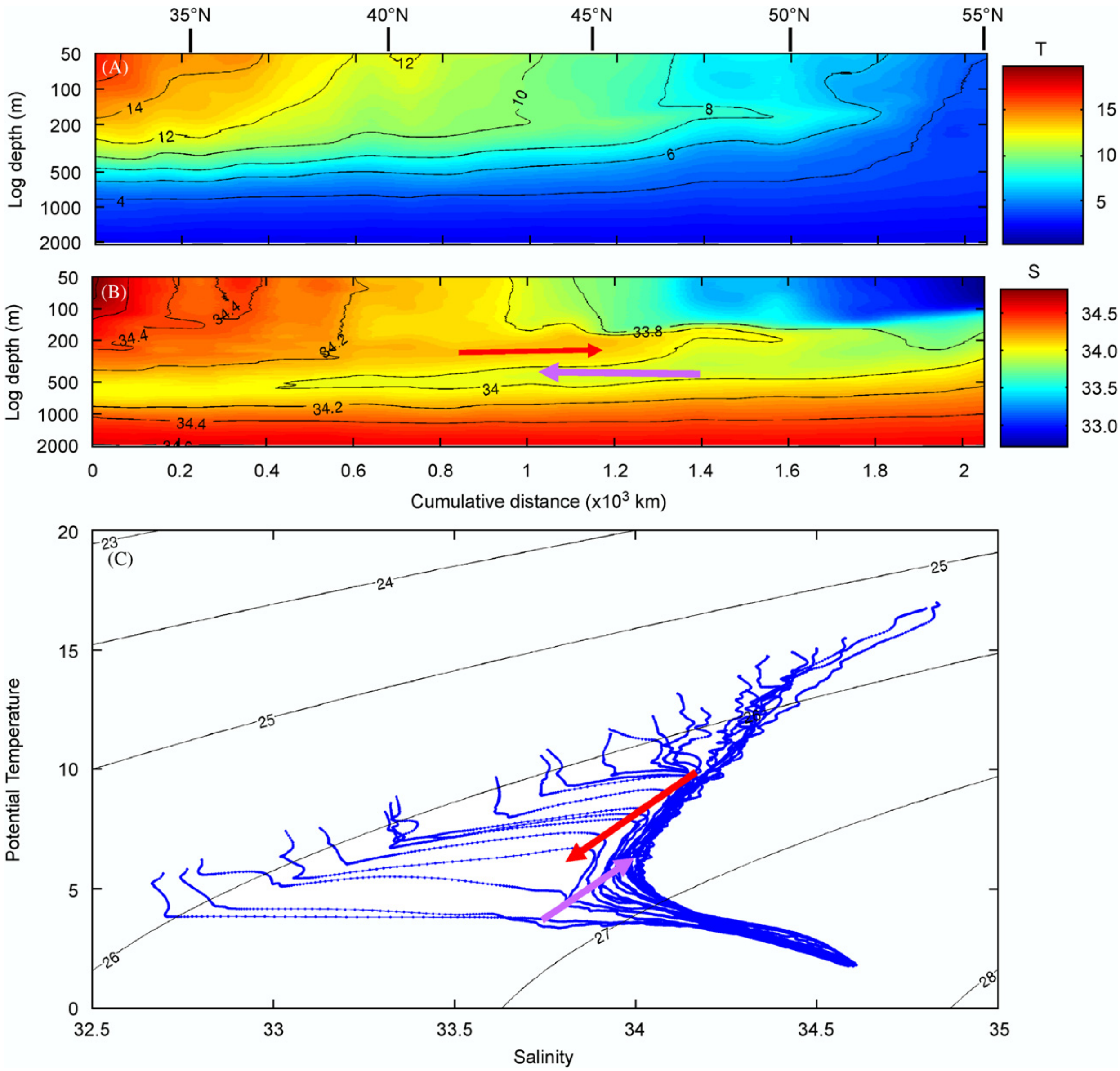

Fig. 8. Data illustrating the poleward spreading of NPIW water in the central Gulf of Alaska: (A) potential temperature, (B) salinity and (C) potential temperature versus salinity correlation diagram; red and purple arrows in (B) and (C) denote the spreading of warm and cold cores, respectively. Data from INPOC (R/V *Priliv*, line 4, 1992).

(Fig. 9B). The distinguishing feature of both correlation plots is the sharp break near 15 °C. At first this would not seem to relate to the alpha/beta boundary. Recall however, that the indicator temperature of the alpha/beta boundary corresponds to the surface outcropping of the ~10 °C isotherm in winter, and that most WOCE cruises in high latitudes were conducted in other seasons. A comparison of summer versus winter T/S correlation curves for the North Pacific (Fig. 10) shows that surface temperatures change, roughly, 5 °C from summer to winter (also see Reid, 1969). Subtracting 5 °C from the summer temperatures in Fig. 10 would move the break point to 10 °C, as has been hypothesized here. Regardless of details in the break-point temperature, the remarkable point here is that the break point is at the same temperature in the Atlantic and Pacific of both hemispheres *and* the slope $\Delta NO_3/\Delta T$ is identical. No explanation for the latter observation is offered,

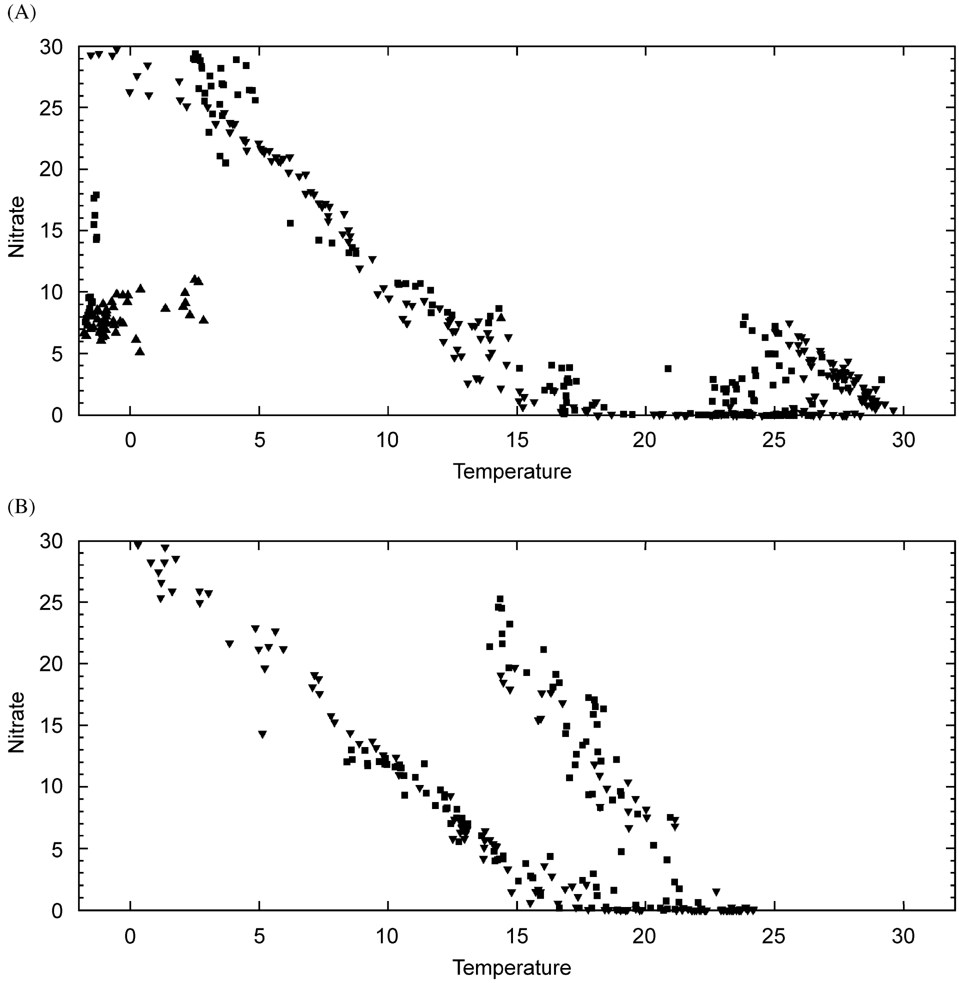

Fig. 9. Correlation diagrams for nitrate versus temperature for the near-surface waters of the (A) Pacific and (B) Atlantic oceans. Nitrate values are in μM. Data from WOCE.

although strong bottom-up control of nutrient utilization is indicated.

3.3. Convection and primary production

Nutrient supply and light, the primary criteria limiting primary production, are strongly controlled by the annual pattern of convection, and this relationship was quantified by Sverdrup (1953) to explain the annual phytoplankton cycles and year-to-year variations in the timing of the spring bloom. This hypothesis holds that the initiation and evolution of the spring bloom are determined by events that control the balance between the availability of nutrients, the amount of light available to phytoplankton cells, and losses due to respiration, sinking and grazing. Recently, however, Backhaus et al. (1999, 2003) have presented model results and field observation that challenge the mixing assumptions inherent in the Sverdrup formulation. They argue that convection is the mechanism that accounts for both the transport of phytoplankton spores to the surface throughout winter and for the early phases of the spring bloom. Well-structured convective cells, as opposed to turbulence, effectively 'incubate' phytoplankton by continuously re-exposing them to surface light conditions throughout the winter, and this allows the maintenance of active chlorophyll at much greater depths than are predicted by the Sverdrup model. This returns to the differences in convection patterns to be expected in alpha versus beta domains; oceans with thermal stratification allow much deeper convection along their poleward perimeters than oceans with

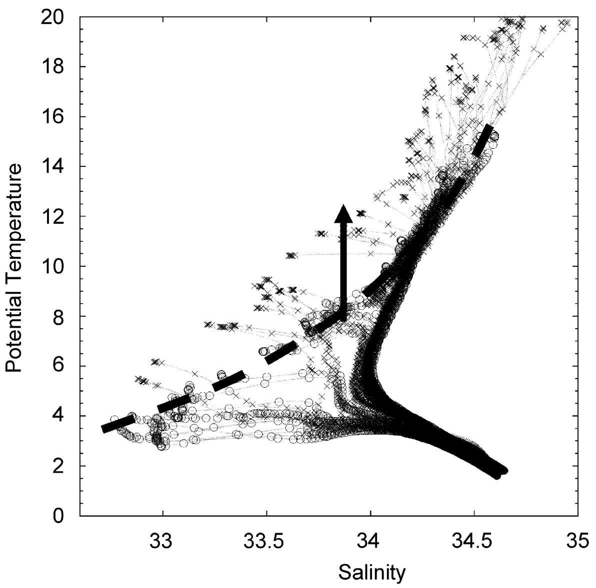

Fig. 10. Correlation diagrams of potential temperature versus salinity for late winter (circles) and summer (crosses) in the North Pacific; the dashed line approximates surface values observed in late winter. Data from INPOC (R/V *Priliv*, 1992).

haloclines. Indeed, this is shown clearly in the data of Backhaus et al. (2003; their Fig. 4) which shows evidence of convection reaching to 600 m or more in the North Atlantic southeast of Iceland (alpha domain) compared to less that 200 m in the Iceland sea north of Iceland (beta domain). While chlorophyll concentrations within these convective gyres are relatively low, they are sufficiently high to maintain an effective seed population for the subsequent bloom. It is, perhaps, counter-intuitive that the shallowest depths of winter convection are to be found in the upper layers of the Canada Basin, where wintertime convection is limited to 30 m or less by the strong halocline complex (McLaughlin et al. (2004). The severe constraint on the depth of winter convection by beta stratification likewise constrains the efficiency of nutrient replenishment, and likely caps the amount of annual new production in the Arctic Ocean (cf. Carmack et al., 2004).

The differing responses of the alpha and beta domains of the North Pacific to winter cooling and convection, based on the temperature/depth time series recorded by two representative Argo drifters, are shown in Fig. 11. Despite the fact that the drifter in the alpha domain lies approximately 800 km to the south of the drifter in the beta domain, the depth of winter convection there is roughly twice as deep as at the northern location. It is suggested that this difference in convective patterns plays a major role in setting the physical environment of North Pacific foodwebs; the impact of this difference on trophic phasing of phytoplankton and zooplankton is an overdue subject for research (cf. Parsons, 1988).

4. Summary and consequences of alpha versus beta stratification

It has been argued here that the alpha/beta boundary in *both* hemispheres of the Pacific and Atlantic is marked by surface density maxima at temperatures near 10 °C, a transition zone where both $\alpha \mathrm{d}T/\mathrm{d}z$ and $\beta \mathrm{d}S/\mathrm{d}z$ pass through their respective zero crossings. It is also a zone wherein the local surface density is maximum (cf. Roden, 1970) and cabbeling due to lateral mixing enhances water mass transformation (cf. Talley and Yun, 2001; You, 2003). This zone is called, regionally, by a number of names, but, in fact, each is a manifestation of the same structure, temperature range and, arguably, thermodynamic processes.

The critical importance of understanding physical–biological coupling is widely accepted (cf. Reid et al., 1978; Daly and Smith, 1993) except, perhaps, by the general fisheries management community (cf. Parsons, 1996). In this regard, the alpha/beta distinction may be of value from biogeographical (Longhurst, 1998) and macroecological (Li, 2002) perspectives. Another timely application is that of assessing the potential impacts of climate change. As Barber (1992) convincingly argues, the appropriate way to account for ocean biome differences is to take into account the fundamentally different large-scale physical processes that control nutrient supply. Applying these ideas to a climate-change analysis, Sarmiento et al. (2004b) note three classes of impacts that might arise from climate change: (1) warming (2) altered underwater light climate and (3) altered nutrient supply. They then identify seven oceanographic 'diagnostics' that influence these three impacts and that would allow comparison of various model predictions with field observations; these are (1) sea-surface temperature, (2) sea-surface salinity, (3) sea-surface density, (4) upwelling (evaluated at 50 m depth), (5) vertical density gradient, (6) mixed-layer depth and, finally, (7) extent of sea-ice cover. These seven diagnostics are all important criteria of the alpha/beta distinction. Finally, they identify, largely on the basis of SeaWiFS chlorophyll distributions, six major

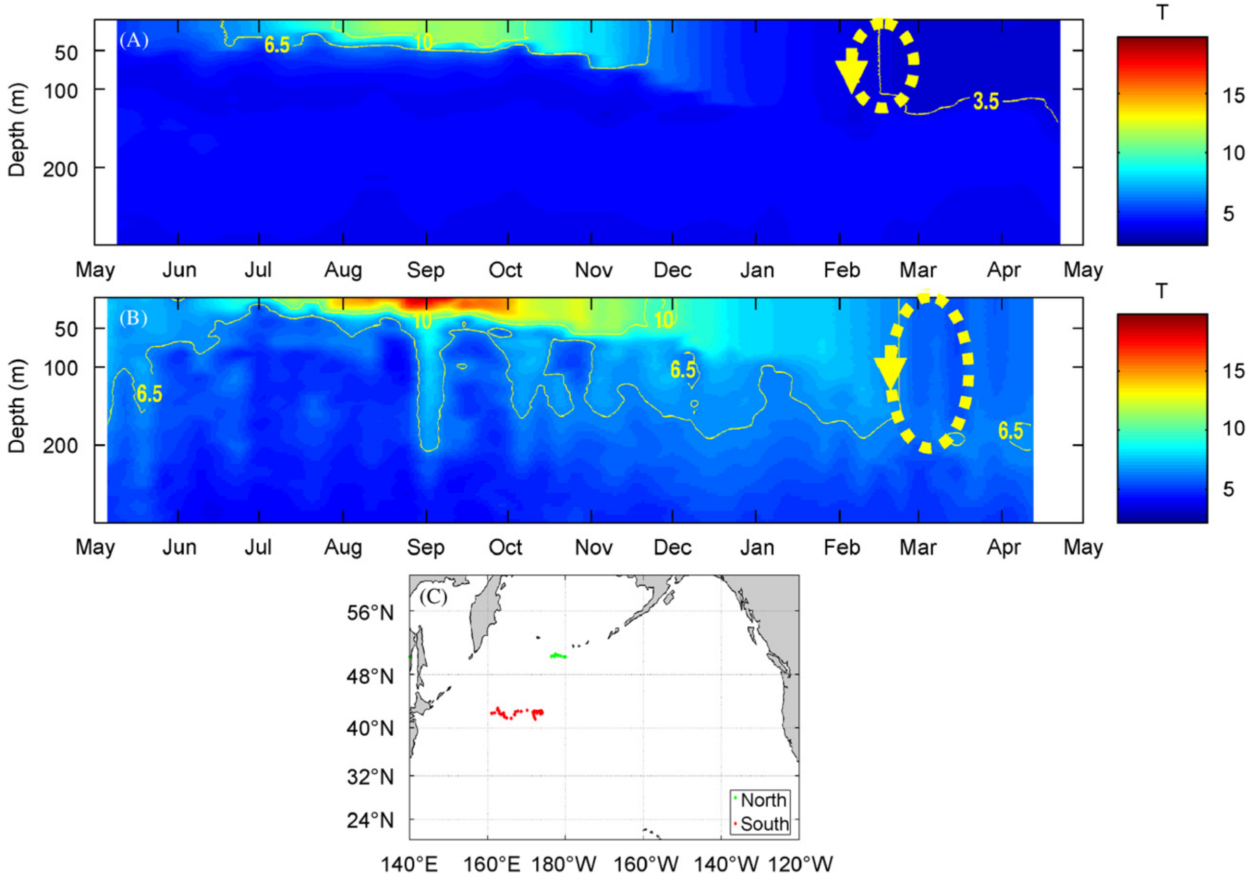

Fig. 11. Temperature versus depth time series from two Argo floats in the North Pacific for (A) a float in the beta (more northerly) domain and (B) a float in the alpha (more southerly) domain. The location of the floats is shown in (C). The dashed ovals depict the maximum depth of winter convection in both domains.

biomes, each of which can be linked to alpha or beta characteristics. They argue, correctly, that climate warming will impact not only the basic properties within each biome, e.g., the diagnostics, but will also shift the boundaries that separate biomes. Two of the biomes discussed by Sarmiento et al. (2004b) correspond to beta oceans, their subpolar and marginal sea ice biomes. The models they use show that relative surface areas and characteristics of these domains will change under scenarios of global warming. A third potential beta biome, the permanently covered polar pack-ice domain, is not included in their analysis, presumably because it is inaccessible to SeaWiFS sensors.

In summary, beta oceans have many important climatic and biological features that may distinguish them from their alpha ocean counterparts; for example:

- In the deep sea, sea ice can *only* form over beta oceans where the permanent halocline limits deep, thermally-driven convection (Bulgakov, 1962); hence these domains play a key role in determining the planetary albedo and ice/albedo feedback effects (Aagaard and Carmack, 1994). On palaeo time-scales, the build-up of freshwater in the surface layers of high-latitude seas and shifting of the alpha/beta boundary during the Pleistocene would be a prerequisite for sea-ice formation, and thus impact all processes associated with ice/albedo feedback. On modern time-scales, the biome of permanently-covered sea ice will certainly change under scenarios of global warming (ACIA, 2005).
- Beta oceans are typically rimmed by complex, buoyancy-driven boundary current systems, supplied by continental runoff, which serve to augment freshwater transport (cf. Royer, 1982; Weingartner et al., 2005). Such systems appear to be contiguous; an example is the system that begins with the Alaska Coastal Current off the

west coast Canada and Alaska, extends along the Alaska North Slope of the Beaufort Sea, flows through the Canadian Arctic Archipelago and connects to the Baffin and Labrador currents before entering the North Atlantic. A similar system follows the southern boundary of Greenland (Chapman and Beardsley, 1989; Bacon et al., 2002). Such flows and their timing aid anadromous fish in their migration from freshwater to marine environments (D. Welch, pers. com.). The extension of arctic outflows into the Labrador Sea and subarctic North Atlantic has clear biological consequences pertaining to the ecology of advection (cf. Drinkwater and Harding, 2001).

- Beta oceans in both hemispheres are characterized by permanently high surface nutrient levels (HNLC) and are thought to be iron-limited viz new production (Martin and Gordon, 1988; Cullen, 1991). The transition to HNLC conditions begins roughly where temperatures near 10 °C outcrop at the surface in winter marking the alpha/beta boundary. A similar argument might apply to the HNLC domains of equatorial current system, which are also influenced by salt stratification forced by strong net precipitation.
- The joint occurrence of low chlorophyll and high nutrients (LCHN) in beta oceans is also linked to greenhouse gas uptake issues in that beta oceans draw more CO_2 from the atmosphere (cf. Semiletov and Pipko, 1991). As such the relative surface area of alpha to beta seas (the α/β ratio) likely impacts on atmospheric CO_2 exchange, and thus plays a role in greenhouse gas levels. The covariance of paleo-temperatures and CO_2 levels in ice cores may indeed relate to the α/β ratio.
- Atmospheric pressure patterns reflect the underlying ocean structure. High-latitude lows are situated over beta oceans and they drive cyclonic gyres. The single exception to this is the coupled Beaufort High and Beaufort Gyre system, which, however, lies between two strong low-pressure systems (the Aleutian and Icelandic lows) and is a marine extension of the Siberian High. The spatial and temporal variability of such lows is well known to influence open-ocean upwelling rates, cyclone tracks, and atmospheric moisture transport patterns (cf. Ebbesmeyer et al., 1989).
- Since the zonal expansion and contraction of beta oceans ultimately determines the zonal position of the alpha/beta boundary and convective processes, the storage and release of fresh water in beta oceans may even set the conditions for glacial and interglacial events (Broecker, 1987; Khodri et al., 2003). Clearly, the switching from alpha to beta stratification plays a dominant role in Paleoclimate and paleoecology (Weyl, 1968; Moore et al., 1981; Weaver et al., 1999; Hillaire-Marcel and Bilodeau, 2000; Haug et al., 2001; de Boer and Nof, 2004; among others).
- Winter mixed-layer depths in beta oceans are less than in the alpha oceans immediately equatorward of the boundary. Because of the shallower winter mixed-layer, the amount of heating required to re-stratify the summer mixed-layer is less; and likewise the timing of the onset of summer stratification is less sensitive to variability in atmospheric forcing.
- Portions of the alpha/beta boundary (e.g., the northern boundary of the Gulf Stream) are recognized as maintaining both isopycnal outcropping and a potential vorticity (PV) front, where PV$\sim(f/\rho)\mathrm{d}\rho/\mathrm{d}z$, where f is the Coriolis parameter (Rajamony et al., 2001). Isopycnal outcropping serves to constrain cross frontal exchange, while a potential vorticity front is susceptible to baroclinic instability. This prompted the question posed by Bower et al. (1985): 'is the Gulf Stream a barrier or blender?'' The critical point here is that the vertical density gradient comprising PV changes from salt stratification to temperature stratification across the front. Thus winds directed along the alpha/beta boundary will, through a combination of buoyancy loss and frictional forces, preferentially remove PV from the alpha (equatorward) side of the front (Thomas, 2005).
- The alpha/beta boundary in the North Atlantic appears to limit the equatorward spreading of Great Salinity Anomaly events (Belkin, 2004).
- Beta oceans are occupied by unique planktonic communities. Beta ocean phytoplankton appear to be greater producers of DMS, an active agent in the global radiative budget. Beta ocean zooplankton appear to have adopted a life cycle that produces nauplii ready to graze as soon as the basic Sverdrup balance is met, thus excluding the spring phytoplankton bloom (Parsons and Lalli, 1988; Mackas and Tsuda, 1999). Perhaps this is because, as noted above, the timing of the onset of the summer stratification is less variable from year to year in beta oceans; thus there is less

uncertainty in the timing of the onset of primary production, and this might give an evolutionary advantage to zooplankton ready to graze immediately when primary production builds, that is, with tighter trophic phasing (Parsons, 1988).

- Beta oceans appear to be the domain of anadromous salmon. Again, the 10–6 °C isotherms form the key boundaries (Welch et al., 1995, 1998). These authors argue that salmon remain in colder waters for physiological reasons; however, an alternative and well-matched reason is that salmon have evolved a physiology that takes advantage of colder, beta oceans, simply because salmon leaving the beta ocean structure would loose the special suite of environmental cues-maintained by freshwater mixtures in and above the permanent halocline-that would be required for navigation back to home spawning sites. Other important commercial species that occupy beta oceans include the walleye Pollock (*Theragra chalcogramma*) and Pacific cod (*Gadus macrocephalus*) in the Pacific and the Atlantic cod (*G. morhua*) in the Atlantic.
- Changes in freshwater flux within beta-type oceans are now known to impact on circulation and downstream conditions in the North Atlantic (Dickson et al., 1996; Belkin, 2004; Curry and Mauritzen, 2005; Bryden et al., 2005; Peterson et al., 2006). It is *possible* that the so-called regime-shifts in fish productivity (Beamish et al., 2004) can be linked to beta ocean behaviour; for example, changes in the wind field and moisture transport patterns may alter freshwater storage in the North Pacific, the location of internal fronts, the transport of perimeter boundary currents, the stability of the halocline, and thus surface nutrient supply.

Obviously, beta oceans are not themselves laterally homogeneous, and important frontal systems and structures internal to northern and southern beta domains will play key ecological roles. Such fronts and structures may be subject to climate-scale variability (Belkin et al., 2002). As an ecological example, Grebmeier et al. (2006) show that on the Bering Sea shelf the retreat of a cold pool of near-bottom water, formed by ice formation and haline convection in winter, is (a) related to a local climate warming trend and (b) shifting the basic ecosystem from benthic to pelagic. McLaughlin et al. (1996) reported a large (~1000 km) shift in the location of a frontal domain separating Pacific-derived and Atlantic-derived water masses interior to the Arctic basin, with major consequences to stratification, mixing and the distribution of nutrients. Such internal re-arrangements are almost certain to be of ecological importance, and should be the subject of new, comprehensive, large-scale monitoring programs.

The intent here has been to characterize the mid-ocean regime, and the distinction may fail in alpha domains close to continental discharges of freshwater. In addition, there is a special exception to the above broad generalization. The upper layers of the equatorial seas, by virtue of their position below the moist, rapidly rising air masses over tropical seas, are also beta-type, and exhibit beta-type characteristics. These regions, unlike the high-latitude regions, are not required by thermodynamic laws to be beta-type, bounded by a maximization of cabbeling, and may contract or expand according to climate feedback considerations. Still, the pooling of freshwater in the equatorial beta-type regions drives the Indonesian throughflow (Andersson and Stigebrandt, 2005), preconditions El Niño events (Maes et al., 2003) and might, through cloud albedo feedback effects, be a mechanism for amplification of small fluctuations in the solar constant.

If not importantly, at least curiously, the arguments presented here border on the teleological, after Aristotle's 'final cause'—the *telos*—which roughly means that a cause or process has a final goal or purpose. Why are the stationary thermohaline structures (N_T^2, N_S^2, Tu) extant in the global ocean? The teleological reason is because they are exactly the structures that reflect and even optimize the 'job' of the ocean climate system; namely: (1) to redress the global heat imbalance by transporting water vapor (latent heat) polewards, thus forming the beta reservoirs; (2) to redress the global freshwater imbalance by returning low salinity (intermediate and deep) waters back to the alpha ocean reservoirs; and (3) establishing large-scale double-diffusive systems (with salt transport downwards in alpha oceans and heat transport upwards in beta oceans) that enhance transports required by the climate system. While verging on teleology, there is some reason to think that the physical climate system will continuously self-organize in an optimal fashion, and that ocean biota will continuously evolve, in a Darwinian manner, to best exploit these 'most-probable' habitats.

Regardless of philosophical arguments, it is doubtful that we will ever manage our marine resources until we grasp the basics principles of thermo-hydrodynamical habitats. Fish may live in a moving and changing environment; but some habitat states are simply more probable than others, and these most-probable states will shape the direction of evolution. Because of the emphasis of this volume, emphasis here has been on the Subarctic Pacific and Northern Ocean; however, the ideas of Fofonoff (1961) on energy transformations in the sea and of Bennett (1994) on optimal stationary structures in the ocean may provide a simple context for the study of climate and habitat issues associated with the beta and alpha oceans of both hemispheres. Likewise the arguments of Hopkins (2001) suggest that strong negative feedbacks in thermohaline systems enhance the inherent stability of these systems as habitats. Admittedly, as in the case of any new generalization, there is a tendency to over-extend its application. Still, it seems clear we must follow the lead of Claus Rooth (1982) and others (e.g. Weyl, 1968; Warren, 1983; Schmitt and Wijffels, 1993; Webster, 1994; Carmack, 2000) and accept that climate change and climate-related impacts on essential industries (e.g. fisheries, agriculture, water resources) are not strictly about temperature, but also (perhaps mainly!) about the flux, distribution and phase of freshwater components in the atmosphere and ocean. The impacts of such changes in freshwater disposition will alter both the properties *and* the boundaries of ocean biomes.

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