Tide mediated warming of Arctic Halocline by Atlantic Heat Fluxes over Rough Topography

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The largest oceanic heat input to the Arctic results from inflowing Atlantic water, which is at its warmest for 2,000 years[1,2], yet the fate of this heat remains uncertain[3]. This is partly because the water's relatively high salinity, and thus density, lead it to enter the Arctic Ocean at intermediate depths. A key pathway linking the Atlantic water heat to overlying, colder waters, and ultimately to the sea surface, is vertical cross-gradient mixing. Mixing is generally weak within the Arctic Ocean basins, with very modest heat fluxes (0.05 – 0.3 Wm^{-2}) arising largely from double diffusion[4-8]. However, previous, geographically limited observations have indicated substantially enhanced turbulent mixing rates over rough topography [9-14]. Here we present new pan-Arctic microstructure measurements of turbulent kinetic energy dissipation which further demonstrate that the enhanced

continental slope dissipation rate, and by implication vertical mixing, varies significantly with both topographic steepness and longitude, while appearing insensitive to sea-ice conditions. Tides are identified as the main energy source supporting this enhanced dissipation, which generates vertical heat fluxes of more than 50 Wm^{-2}. As sea ice declines, the increased transfer of momentum from the atmosphere to the ocean will likely expand mixing hotspots in the future Arctic Ocean.

Atlantic water (AW) enters the Arctic Ocean at depths between 40 and 200 m, and its core is ~ 4°C warmer than the overlying cold, fresher halocline and surface mixed layer water, as illustrated by the temperature profiles in figure 1. As the boundary currents of the Arctic Ocean circulate cyclonically around the basin, the interface between the AW and the overlying waters is progressively eroded by mixing[1,15]. The density difference across this interface, the AW thermocline, is the major barrier to upward heat flux, such that in the absence of vertical turbulent mixing, only a small fraction of the AW heat can reach the sea surface or sea-ice directly[1]. This paper will focus on vertical mixing across the AW thermocline. Measurements of profiles of the rate of dissipation of turbulent kinetic energy (ε) are presented, from which cross-gradient mixing rates are estimated, for locations covering much of the seasonally ice-free Arctic Ocean: see map in figure 1. The measurements include transects taken across the shelf break north of Svalbard through dense ice cover in autumn 2008, and spring and early summer of 2010 and 2011, and more open water conditions in the summers of 2012 and 2013 (transect 1 in figure 1). Further transects were made across the continental slope north of Severnaya Zemlya (transect 2), the Laptev Sea (transects 3 & 4) and the East Siberian Sea (transect 5) during the ice-free September 2007, and through 100% first year ice cover in October 2008. Cross-slope transects were made in the largely ice-free Canada Basin (transects 6 and 7) in the summer of 2012. The measurements span the upper 500 m of the water column and fully resolve the AW thermocline.

The average dissipation rate across the AW thermocline varies significantly with bathymetry (figure 2a). Within the central Arctic Ocean (over bathymetry > 2000m) average values of between ~ $5x10^{-10}$ and 2×10^{-9} W kg^{-1} are observed: close to (but above) the instrument noise level, and in agreement with previously published estimates[4,6,8,9]. It is interesting to note that these very low levels of ε appear insensitive to sea ice cover. The observed values are substantially lower than background values reported for intermediate depths in the central Atlantic and Pacific Ocean basins (~ 10^{-8} W kg^{-1})[16,17], and are often not sufficiently energetic to drive significant turbulent mixing[4,6]. A consequence of the very low levels of turbulence is the formation of thermohaline staircases which link the AW to the cold, fresh overlying waters (figure 1 – grey profile). The staircases arise from the competing impacts of the temperature and salinity gradients on density, and the greatly differing molecular diffusion rates for heat and salt. These unique phenomena support vertical exchange of heat through double diffusion but with relatively weak resulting across-gradient heat fluxes (0.05 – 0.3 W m^{-2}) [4-7]. The double diffusive fluxes together with weak dissipation associated with the internal wave field[8] are insufficient to explain the observed cooling of the AW as it passes through the Arctic Ocean[1, 6, 18].

In contrast the new observations in figure 2a show that profile-averaged ε within the AW thermocline is enhanced by up to two orders of magnitude over the continental slope regions (i.e. depths between 200m – 2000m), when compared to the values for the central Arctic Ocean. The largest values are found over the continental slope to the north of

Svalbard with no apparent dependence on sea ice conditions. Here, the observed dissipation rates of $3 – 20 \times 10^{-8}$ W kg^{-1} are sufficiently energetic to drive significant turbulent mixing and thus prevent the formation of thermohaline staircases (figure 1, red and black profiles). Similarly enhanced values have been reported for the Yermak Plateau region further to the west [9, 11], as well as the region north of Svalbard [10]. Figure 2b shows that the enhancement of the AW thermocline averaged ε appears to be related to the local topographic slope, with the largest values of ε observed above the steepest topography. Enhanced ε values (~ 10^{-8} W kg^{-1}) are also observed further to the east, over the continental slope poleward of the Severnaya Zemlya islands. Here the slope-enhanced values of AW thermocline ε are comparable to those observed at intermediate depths at lower latitudes over rough topography, such as the mid-ocean ridge systems[16, 17] and the continental shelf breaks[19]. There is also a modest enhancement over the Canada Basin continental shelf break (average ε ~ 3×10^{-9} W kg^{-1} compared to central Canada Basin average values of $<10^{-9}$ W kg^{-1}). Previous observations of water column structure in this region have revealed the absence of thermohaline staircases over this slope, an indicator of significant turbulent mixing at intermediate depths[5]. The new observations reveal that, whilst the AW thermocline averaged ε appears insensitive to sea ice cover and bathymetry, there is significant variation with both local topographic slope and location around the Arctic Ocean margins.

Two sources of kinetic energy are usually implicated in driving turbulent mixing in the ocean: wind and tide[20]. Recent studies have suggested increased momentum transfer from the wind to the ocean associated with declining seasonal sea ice cover potentially leading to increased mixing[21-23]. The results presented here provide no evidence that the AW thermocline-averaged ε is sensitive to sea ice conditions in locations where observations were made in varying ice conditions, implying the wind is of lesser importance in supplying energy to mixing at intermediate depths. However, the observed longitudinal variation in transect mean dissipation (ϵ_{AW} - obtained by averaging the profile-integrated ε, for the AW thermocline, for all profiles taken over the continental slope in each transect) does correlate with the tidal energy dissipation rate, *D* (figure 3). This is computed as the difference between the rate of work by the tide-generating force and the divergence of the energy flux[24] using tidal elevations and velocities from the TPXO8 inverse solution[25,26] . Based on this correlation, the observed transect mean ε accounts for 12% of the total tidal energy dissipation rate ($r = 0.67$). The conclusion is that the energy supporting much of the enhanced dissipation observed along the continental slopes, poleward of the Svalbard and Severnaya Zemlya archipelagos, is of tidal origin. The most significant deviation between ϵ and D is found for transects 6 and 7, in the ice free Canada Basin. These measurements were made in the immediate aftermath of the unprecedented “Great Arctic Cyclone” of 2012 where wind forcing may be an additional contributory factor. Previous geographically-limited studies have suggested enhanced mixing near rough topography[9-14], but these new observations provide the first circumpolar evidence for the control of AW mixing rates by the interaction between the tide and rough topography.

At lower latitudes the cascade of energy from tides to turbulence is facilitated by the generation of a freely-propagating linear internal tide which results from stratified tidal flow over rough topography. However, the new measurements were taken poleward of the critical latitude (74.5° N) beyond which the rotation of the Earth prohibits freely propagating waves at the dominant semidiurnal (M_2) tidal frequency. Consequently tidally-generated internal waves at these latitudes are thought to have properties inherent to lee waves[27] which have short temporal and spatial scales, related to the local topography and stratification, and tend to be dissipated rapidly leading to local turbulent mixing[28]. It is likely that large variability in ϵ_{AW} north of Svalbard (as indicated by the 95% confidence interval in figure 3) is a consequence of the temporal and spatial variability of the tidal processes generating the turbulence[19, 29].

The dissipation rates are combined with the observed water column stratification in the calculation of a diffusion coefficient which is then used to estimate the magnitude of the heat fluxes across the AW thermocline resulting from turbulent mixing. Using information from 84 profiles, collected during 5 observational campaigns in the region between 2008 and 2013, an average heat flux across the AW thermocline of 22±2 W m^{-2} is estimated for the continental slope poleward of the Svalbard and Severnaya Zemlya archipelagos. Heat fluxes of more than 50 Wm^{-2} are calculated from individual profiles. These heat fluxes are over 2 orders of magnitude greater those reported for the central Arctic Ocean, although they operate over a more limited area. The localised nature of the enhanced AW heat fluxes will therefore lead ultimately to spatial inhomogeneity in the Arctic Ocean – sea ice system response to climate change with impacts on sea ice cover and heat transfer with the atmosphere enhanced in the vicinity of rough topography.

The new observations confirm the paradigm of a predominately double-diffusive central Arctic with weak mixing, whilst contrasting it to the more turbulent continental slope regions where the tides interacting with steep topography act to control the rate of turbulent mixing. We note that the observed turbulent mixing is a result of relatively modest tidal currents. Model studies suggest that retreating seasonal sea ice coverage will result in an increased transfer of momentum from the atmosphere to the ocean[22, 23] whilst observations show the spin-up of the wind-driven Canada Basin gyre circulation[21] and enhanced currents due to near-inertial waves[30] in response to declining sea ice cover. The acceleration of the currents resulting from these processes have the potential to grow the geographic extent of turbulent mixing to other regions of rough topography where at present flows are too weak to induce lee wave formation. Hence, the coupling of these large and small-scale processes will likely drive the expansion of mixing hotspots, and so increase local AW heat fluxes, which will in turn feedback on the already declining Arctic sea ice and increase momentum transfer between the atmosphere and the ocean.

Methods:

i) Turbulent dissipation rate measurements:

The profiles of the rate of dissipation of turbulent kinetic energy (ε) are made using a loosely-tethered free-fall velocity microstructure profiler (Rockland VMP500 model) deployed by the Bangor University team and a loosely-tethered ISW MSS 90L microstructure profiler by the Norwegian Polar Institute (Tromsø) team. The instrument is deployed from a ship and takes profiles of velocity microstructure together with temperature and salinity down to near the sea bed, or up to 500 m depth in deeper water. The rate of dissipation of turbulent kinetic energy is then calculated for depth bins (Δz) of approximately 1 m size using assumptions of stationarity and homogeneity[29]. At each station reported, 1 or 2 profiles were made over a period of approximately 1 hour with longer time series (up to 6 hours) collected by the NPI in the vicinity of the shelf break at 30°E.

The profile-averaged ε values shown are the station averages for the AW thermocline. The vertical depth limits for the AW thermocline are defined, for each cast, as the region from the temperature minimum in the cold overlying water down to the AW temperature maximum (for example see bold section of the temperature profile on figure 1). The number of profiles used ranged from 1 to 12. Full details of the number of profiles collected for each location, during each visit, are given in table 1 in supplementary information.

The transect-mean AW thermocline dissipation, ϵ_{AW}, shown in figure 3 is obtained by averaging the profile integrated dissipation, for the AW thermocline, for all profiles (n) taken over a continental slope transect. ie.

$$\epsilon_{AW} = \frac{1}{n}\sum_{1}^{n}\sum_{AW_t} \varepsilon \Delta z$$

The number of profiles (n) used for each point ranges from 2 to 23, all averages represent temporal means over several days, for each transect. A measure of variability in both station-average ε (fig 2) and transect-mean ϵ_{AW} (fig 3) is obtained by bootstrapping the individual 1 m depth bin values of ε across the Atlantic water thermocline, for appropriate stations. The variability is shown on figures 2 and 3 as the 95% confidence interval.

(ii) Topography:

Topography used in the comparisons presented in figure 2 was extracted from the GEBCO (General Bathymetric Chart of the Oceans) data base http://www.gebco.net/.

The GEBCO database incorporates IBCAO (International Bathymetric Chart of the Ocean) data for the Arctic region.

(iii) Heat Flux calculation method:

Eddy diffusivity, K_z, and heat flux estimates were calculated for the AW thermocline using a layer averaged method. For each profile an average ε is calculated for the layer together with the buoyancy frequency N, where $N^2= -(g/\rho_0)\,\partial\rho/\partial z$. The layer mean values are then combined to form a turbulent diffusivity, $K_z=0.2\varepsilon/N^2$. Heat fluxes (F_h) are then estimated using K_z and the layer mean temperature gradient, $\Delta T/\Delta Z$, where $F_h=-\rho_0\, c_p\, K_z\, \Delta T/\Delta Z$[29], ρ_0 a reference density, c_p is specific heat capacity and ΔZ layer thickness.

The AW thermocline heat flux for the slope region north of Svalbard and Severnaya Zemlya (longitudinal range 16-31E) is an average value made from estimates for 84 profiles, collected during 5 observational campaigns in the region between 2008 and 2013. The largest values for individual profiles exceed 50 Wm^{-2}.

iv) **Tidal Dissipation Calculation**:

The tidal energy dissipation rate, *D*, can be expressed as a local balance between the work rate by the tide generating forces (*W*) and the tidal energy flux (P)[24]:

$$D = W - \nabla \cdot \mathrm{P}$$

where *W* and P are defined as

$$W = g\rho\langle \mathrm{U} \cdot \nabla(\eta_{eq} + \eta_{SAL})\rangle$$

$$\mathrm{P} = -\mathrm{g}\rho\langle \mathrm{U}\eta\rangle$$

Here, $\langle \quad \rangle$ denote time-averages, U is the tidal transport vector, η is the tidal elevation, η_{eq} is the equilibrium tidal elevation, η_{SAL} is the self-attraction and loading elevation, g is gravity and ρ is a reference density. The tidal amplitudes and currents from the TPXO8 database are combined with the astronomical forcing to calculate the tidal energy flux and work rate from which the tidal energy dissipation rate for the principle tidal constituents in the region, the semi-diurnal M2 and S2 and the diurnal K1 and O1 constituents, is calculated.

Microstructure data: Access to the microstructure data used in the paper may be requested. The Bangor VMP data presented in this paper may be requested from the British Oceanographic Data Centre, National Oceanography Centre, Liverpool, UK (http://www.bodc.ac.uk/). Request “ASBO and TEA-COSI microstructure data”. The MSS data used may be requested from the Norwegian Polar Institute (e-mail: arild.sundfjord@npolar.no).

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Figure Legends:

Figure 1: Map of the Arctic Ocean showing the bathymetry and the location of the microstructure profiler measurements. Marker shape indicates the sea ice conditions during those measurements (O – open water/ low ice cover, Δ - significant (> 70%) ice cover). The colours refer to the geographical location of the measurements (consistent with figures 2 and 3). The numbers refer to transects shown in figure 3.

Typical temperature profiles are shown for the continental slope region (black in open water and red under sea ice) and for the central Arctic Ocean (grey) to the north of Svalbard.

Figure 2: Variation of profile average dissipation with bathymetry and topographic slope.

(a) Profile-average dissipation rate, ε, in the AW thermocline, plotted against bathymetry. Variability is indicated by the 95% confidence interval. For clarity the confidence interval is not shown when it is smaller than the plotted symbol used. Following figure 1 the colour indicates the geographical location of the measurements whilst the shape shows the sea ice conditions.

(b) Profile-averaged dissipation in the AW thermocline plotted against the slope of the topography below.

Figure 3: Transect-mean integrated AW dissipation, ϵ, against longitude. The colours and the transect numbers refer back to figure 1, whilst the marker shape indicates the sea ice conditions (as per figure 1). The variability is indicated by the 95% confidence interval.

The blue line is the rate of tidal energy dissipation, D, computed as the difference between the work done by the tide generating force and the divergence of the tidal energy flux.

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