Linking ocean mixing and overturning circulation

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ABSTRACT:

Begin of info box

11th Warnemünde Turbulence Days on *Linking ocean mixing and circulation at various scales*

What: 45 participants from 10 countries met to discuss about contemporary issues of marine turbulence with focus on the linkage between mixing and overturning circulation on all scales (`https://www.io-warnemuende.de/wtd-2023.html`).

When: September 17-20, 2023

Where: University of Rostock, Germany

End of info box

Walter Munk, in his famous *abyssal recipes*, showed more than half a century ago that the strength of the global overturning circulation is closely linked to diapycnal mixing. Since then, oceanographic research has succeeded in identifying more and more processes generating the mixing required to drive the global overturning circulation: internal-wave mixing, boundary mixing, wake eddies, gravity currents, double diffusion, and many more. The same dependence was also observed in other marine systems at smaller scales, including marginal and semi-enclosed seas and estuaries. Numerical models describing these mechanisms often include discretization errors that become evident in particular in the form of spurious *numerical* mixing, which may trigger artificial circulation patterns at all scales.

The Warnemünde Turbulence Days (WTD, `http://www.io-warnemuende.de/wtd.html`) have been established in 2003 to provide a regular international forum for discussing new developments in marine turbulence. Since then, the WTD have been organised every other year such that in 2023 we organised the 11th WTD that took place during September 17-20, 2023 in Rostock. We invited contributions discussing all aspects of mixing in the ocean, especially, however, those that focus on the relation of mixing and circulation at all relevant scales.

1. Context

Here we report on the presentations and discussions that occurred during the WTD workshop. The topic *Linking ocean mixing and circulation at various scales* provided the common thread of discussions, with a special focus on the overturning circulations, i.e. circulations in the vertical plane involving density transformations. Often, the notion *Mixing is the driver of overturning circulation* was advanced, but it was in general agreed that both are interdependent, and that the notion of *driver* is ambiguous and should be used with caution. Many of the discussions were also guided by the scale-specific differences of ocean dynamics, specifically to find out what can be learned for basin-scale dynamics from the relatively simple functioning of estuaries. In this report we do therefore highlight characteristics of mixing and overturning circulation on different regimes and scales.

The tank experiments of Sandström 1908 illustrated more than a century ago how an ocean forced only by surface buoyancy fluxes would produce a very weak and shallow stratification with minute overturning rates controlled by the molecular diffusion across the sharp thermocline. While the applicability of these experimental results to the real ocean is debatable (Coman et al. 2006), the central importance of mechanically-forced interior mixing in maintaining deep density gradients is now well established (Munk 1966; Munk and Wunsch 1998). This has led some authors to assert that the ocean circulation is powered by winds and tides, and that it is *not driven by the difference in density between equator and pole* (Paparella and Young 2002). However, this seems to be at odds with the simple observation that overturning circulations are greatly shaped by the surface buoyancy forcing (Kuhlbrodt et al. 2007).

On the estuarine scale, the basic theory was already laid out by Knudsen (1900) who quantified exchange flows on smaller scales. He mentioned mixing in his paper, but a quantitative connection between exchange flow and mixing, based on the principles of Knudsen (1900) was only formulated by MacCready et al. (2018). The beauty and simplicity of estuarine theories of mixing and exchange flow is the possibility to map the dynamics into salinity coordinates.

2. Diagnostics

Approaches to the key question *Is mixing driving overturning circulation?* do strongly depend on the definitions of both *mixing* and *overturning circulation*. For each of them numerous concepts exist as shown below.

a. What is mixing?

In the ocean, turbulent diffusivity (Munk 1966; St Laurent and Thurnherr 2007) or dissipation rate are often used as measures of mixing, following the Osborn (1980) relation that links both together via the buoyancy frequency. Both quantities are however not suitable measures for mixing on their own, since they would typically show large values in well-mixed regions such as in the surface and bottom mixed layers (where mixing is expected to be low). Moreover, both quantities do not indicate which tracer is mixed. Diffusive tracer fluxes do not have this disadvantage, because they are specific for each individual tracer. Often, (twice) the product of tracer flux and tracer gradient is defined as *mixing*, as it quantifies the *local tracer variance decay* (Burchard et al. 2009). Under the eddy diffusivity assumption, it results in twice the eddy diffusivity times the square of the tracer gradient, i.e., it is non-negative and vanishing for zero turbulence and zero tracer gradient. This definition of variance decay as mixing is also consistent with turbulence theory that assumes stirring to increase the micro-structure tracer variance and mixing to dissipate it (Umlauf and Burchard 2005; Thorpe 2007; Moum 2021). Many instabilities act to produce stirring, forming a spectrum of turbulent patterns linking the mesoscale to the microscale at which diffusion operates. Some rely on rotation, such as barotropic and baroclinic instabilities, some act at finer scale such as the Kelvin-Helmholtz instability or the static instability, while others rely on mechanisms specific to seawater (e.g., double diffusion, cabbeling, thermobaricity).

b. What is overturning circulation?

The question of how to define overturning circulation is far from trivial. Like the word *overturn* implies, it should involve a flow that loops vertically over itself as opposed to a circulation that would be purely horizontal. Most overturning circulations involve exchanges of heat, salt and other biogeochemical tracers between the surface and the ocean interior, making them of relevance to ecosystems and the climate.

Overturning circulations typically results from the superimposition of various intricate circulation patterns generated by different processes such as wind pumping, eddy transport or boundary dynamics. The overturning streamfunction obtained by integrating bottom up the basin wide meridional transport provides a natural proxy. The vertical integration is usually done using depth coordinates, although the use of density coordinates is also popular. Interior flows being preferentially oriented along neutral surfaces, the latter choice helps to distinguish the diabatic (mixing-driven) component of the overturning. Salinity coordinates are often applied to quantify the overturning circulation and exchange flow in estuaries (Knudsen 1900; MacCready 2011, and Sec. 3c). The water-mass transformation (WMT) framework links the overturning streamfunction to dia-surface volume transports associated with diffusive fluxes across isosurfaces of water mass properties (Groeskamp et al. 2019). The original integral framework has been developed in salinity space (Walin 1977), but can be extended to temperature-salinity space (Döös et al. 2012). Later, also the direct link of water mass transformation to mixing in terms of tracer variance decay (MacCready et al. 2018; Burchard 2020), and local formulations (Winters and D'Asaro 1996; Wang et al. 2017; Klingbeil and Henell 2023) have been presented. For streamfunctions and the WMT framework each coordinate space has its pros and cons, and it is usually through their combination that a faithful picture emerges.

3. Overturning and mixing processes in different scales and regimes

a. Large scale overturning circulation

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Large scale overturning circulations rely on a balance between several key processes, involving mixing on a wide range of spatial and temporal scales. The simplistic picture of a deep convective flux in the high-latitude being balanced by a vertical diffusive flux across a thermocline is at odd with the insufficient amount of mixing seemingly available in the ocean interior (Munk and Wunsch 1998). To resolve this apparent conundrum, two main threads have been followed: one focusing on searching the "missing mixing" that led to intense observational efforts (e.g. Polzin 2009) and a renewed understanding of internal wave dynamics (section 3d); the other highlighting the role of the Southern Ocean providing a conduit for the overturning flow (Toggweiler and Samuels 1998). A new paradigm has since emerged that is best encapsulated in the model of Nikurashin and Vallis

(2012), involving a balance between interior mixing, high-latitude convective mixing, together with wind-driven upwelling and eddy transports in the Southern Ocean (Cessi 2019).

However, the key dynamics of the laterally closed parts of the overturning circulation in particular in the Atlantic Ocean – the AMOC – are still not understood (Straub 1996; Brüggemann et al. 2011). It is clear that the zonal pressure difference at the boundaries balances the AMOC, but it is also clear that the north-south pressure or density gradient should not be part of the AMOC dynamics as in the model by Nikurashin and Vallis (2012) and several others. The key to understand the AMOC might be the (dissipative) processes in the western boundaries, but for which simple consistent models are still missing. The missing understanding of the AMOC is reflected (and could be resolved) by missing consistent models of the zonally averaged properties of Atlantic and Pacific ocean.

Furthermore, the surface buoyancy forcing leading to deep convection is not independent of the ocean circulation itself, as is often assumed. This is a consequence of the nonlinear nature of the equation of state, making the impact of heat fluxes on the buoyancy a function of surface temperature (Roquet et al. 2022; Caneill et al. 2022). This means that freshwater and heat forcings can not be treated as independent forcings separately acting on the ocean buoyancy, but should be seen as coupled. This coupling is also strong during sea ice formation, as the heat loss generates a salt flux in the ocean, and in the subtropics, as the evaporation generates a surface cooling.

Southern wind-driven upwelling has been invoked as the major driver of the return path of the deep water, closing the overturning cells and explaining why the global overturning is deep (Marshall and Speer 2012; Cessi 2019). However, this interpretation has recently been challenged by Klocker et al. (2023) who found that a deep-reaching overturning can be generated in the absence of Ekman pumping and with moderate interior mixing, as long as there is a differential heating on either side of a Southern Ocean-like open channel. In parallel, Miller et al. (2020) showed that Southern wind-driven upwelling alone fails to explain the mid-depth exponential ocean stratification, arguing that boundary-intensified mixing is still needed to explain observations. While these studies do not conflict with the idea that Southern wind-driven upwelling is an important control of the global overturning circulation, it calls for a more nuanced view on its overall role.

The geostrophically balanced mesoscale eddies are omnipresent in the ocean and mix properties along isopycnals. This eddy-induced isopycnal mixing becomes most pronounced in eddy-rich regions, as e.g. the western boundary currents and in frontal regions such as the Antarctic Circumpolar Current (ACC). Climate models and coarse ocean models do not resolve mesoscale eddies, and consequently still rely on eddy parameterizations, usually involving a diffusion tensor consisting of an advective (antisymmetric) and a diffusive (symmetric) part. The advective part is often parameterized with the Gent–McWilliams (GM) closure (Gent et al. 1995), whereas the diffusive part of the mixing tensor can be interpreted as turbulent mixing of properties along isopycnal surfaces, and is often parameterized with the isotropic, so-called Redi scheme (Redi 1982) involving a single scalar isopycnal diffusivity. While the role of the eddy-advective part is well studied, the role of eddy-diffusive part has not garnered much attention. Recently, however, Chouksey et al. (2022) have shown the sensitivity of ocean circulation to isopycnal diffusivity using a non-eddy-resolving global ocean configuration and changing isopycnal diffusivity along with different formulations of surface forcing. The results in Chouksey et al. (2022) show that the strength of isopycnal diffusion not only controls the uptake of carbon and other passive tracers, but is also as important as the surface fluxes in shaping the circulation in the ocean. The results emphasize that both the advective and diffusive eddy effects are crucial to the large scale ocean circulation.

b. Regional scale overturning circulations

Ocean basin-scale observations of bottom-enhanced dissipation rates ε (Polzin et al. 1997; Waterhouse et al. 2014) signaled that a one-dimension description of the open-ocean water masses transformations could not explain the upwelling branch of the global overturning circulation as previously thought (Munk 1966; Ferrari et al. 2016). Resolution of this conundrum requires rejecting standard eddy diffusive closures for internal wave-driven boundary layers and-or properly accounting for complex topography in watermass budgets (Polzin and McDougall 2022).

A recent observational effort within a canyon on the eastern slope of the Rockall Trough (the Boundary Layer Turbulence and Abyssal Recipes Experiment) set out to directly observe the near-bottom water-mass transformation using dye and tracer releases and a suite of microstructure profilers and moored turbulence measurements. The dye, released ~ 10 m above the seafloor, experienced rapid diapycnal upwelling equivalent to $\mathcal{O}(100)$ m day^{-1} (Wynne-Cattanach et al. 2024). However, tidally resolving observations from microstructure profilers do not find mixing efficiencies nor stratification that decrease to zero as required by 1D models (Alford et al. 2024). The 3D internal tide breaking processes, captured by moored estimates of diapycnal fluxes Polzin et al. (2024), appears to be of vital importance to the observed upwelling.

The Samoan Passage in the tropical South Pacific is one of the major global channel flows connecting ocean basins. As hypothesized for other abyssal ocean passage flows (Bryden and Nurser 2003), it is a site of intense water mass transformation (Alford et al. 2013a) and thus intricately links turbulent mixing processes with topography (Voet et al. 2015; Carter et al. 2019) and large-scale meridional density gradients. Recent work has shown the importance of topographic lee waves for the detailed dynamics of turbulent mixing via momentum redistribution at one of the major Samoan Passage sills (Voet et al. 2023).

The earliest works on exchange flows of water masses (Knudsen 1900) as well as water mass transformation and circulation (Walin 1977) were developed for the Baltic Sea, a large non-tidal fjord-type estuary. The overturning circulation in the Baltic (the *Baltic Haline Conveyor Belt*; Döös et al. 2004) consists of sporadic bottom salt water inflows from the North Sea into the deep basins, freshwater supply due to major rivers and net precipitation, and the outflow of brackish surface waters created by mixing. Local hotspots of this diahaline overturning circulation have been recently investigated by Henell et al. (2023).

c. Estuarine circulation and river plumes

At the meeting, there were intense discussions about the different characteristics of mixing and exchange flow between estuaries and larger ocean scales. Here, the estuarine and river plume perspective is briefly given.

Estuarine circulation is commonly thought of as inflow of salty water and outflow of brackish water into semi-enclosed coastal water bodies, generally driven by freshwater inflow from rivers (MacCready and Geyer 2010; Geyer and MacCready 2014). The brackish water outflow is a product of turbulent mixing between the river water and the inflowing ocean water, such that estuaries can be characterised as *mixing machines* Wang et al. (2017). Estuarine exchange flow may also be viewed in relation to an isohaline rather than to a fixed transect (Li et al. 2022; Reese et al. 2024), a procedure that gives a horizontal rather than a vertical view.

Estuaries (including fjords) discharge fresher waters into their coastal ocean (Hetland 2005) typically forming river plumes downstream. Mixing processes and water mass transformation within river plumes control how estuarine waters ultimately enter the ocean. Wind and tides advect and mix river plumes. In shallow frictional river plumes, such as the Rhine river plume, mixing is further dominated by tidal straining and wind straining (de Boer et al. 2006, 2008; Fischer et al. 2009; Rijnsburger et al. 2016).

Moreover, tidal plume fronts (TPF's) generate internal waves ahead of them that can lead to substantial mixing, e.g. in the near to mid-field of the Columbia river plume (Kilcher and Nash 2010). Recently Rijnsburger et al. (2018, 2021a,b) showed trapping of TPF's and the presence of Internal Solitary Waves (ISW's) ahead of TPF's in the near to mid-field plume of the Rhine river plume and their significant role in dispersion and transport of freshwater, in agreement with Horner-Devine et al. (2015). It is important to understand the contribution of TPF's and ISW's to mixing in river plumes.

d. Interior mixing by wave-eddy and wave-wave interactions

Small-scale turbulent diapycnal mixing caused by breaking internal waves contribute to maintaining the large-scale overturning circulation (Talley 2013; Cimoli et al. 2023). The understanding of this process breaks down to: (i) A forcing problem, detailing the large-scale sources of internal wave field, and (ii) A dynamical problem, describing the energy cascades from internal waves toward small scales until it breaks by shear or convective instabilities (Staquet and Sommeria 2002) and turns into turbulent kinetic energy (TKE).

A major forcing is provided by the interaction of tides or non-oscillatory flows with the sea-floor (Musgrave et al. 2022), generating internal tides or lee waves, respectively, with an energy input of about 1 TW (Egbert and Ray 2000; Nycander 2005) or 0.2-0.75 TW (Nikurashin and Ferrari 2011; Wright et al. 2014). Another major forcing is the wind stress fluctuations at the ocean surface (Thomas and Zhai 2022), forcing near-inertial waves with about 0.3 TW globally (Alford 2001; Rimac et al. 2013; Alford 2020; von Storch and Lüschow 2023). Additional mechanisms include spontaneous loss of balance (Vanneste 2013; Alford et al. 2013b; Chouksey et al. 2018) and shear instabilities of the balanced flow (Chouksey et al. 2022), with the global input from the former estimated at 0.3 TW from idealized studies (Brüggemann and Eden 2015; Sugimoto and

Plougonven 2016), although a precise representation of these processes in realistic ocean models remains a challenging feat and poses several open questions.

Recent progress on (i) involves estimating the direction of the barotropic-to-baroclinic energy transfer (Pollmann and Nycander 2023) and the consistent representation of lee wave drag in ocean general circulation models (Eden et al. 2021). The dynamical problem (ii) involves nonlinear wave-wave interactions, described via the internal wave kinetic equation (Olbers 1976; Müller et al. 1986) and is the basis for the semi-empirical finescale parameterizations (Polzin et al. 2014). These parameterizations have recently found solid theoretical grounding (Eden et al. 2019b; Dematteis et al. 2023) and apply quite ubiquitously in the ocean interior (in an averaged sense) (Waterhouse et al. 2014; Whalen et al. 2015; Pollmann et al. 2017), but are known to be incorrect in certain regions (Waterman et al. 2014) and have yet to be applied in regions with strong eddies or currents (Dematteis et al. 2023; Lozovatsky et al. 2023).

Addressing wave-eddy interactions, Müller and Briscoe (2000) and Natarov and Müller (2005) proposed the Internal Wave Action Model (IWAM) based on the radiative transfer equation (Müller and Olbers 1975) within the WKBJ approximation, but without practical applicability. Olbers and Eden (2013) proposed IDEMIX (Internal wave Dissipation, Energy and MIXing) as a parameterized solution applicable to ocean and atmosphere (Quinn et al. 2020) including wave-mean flow interactions (Olbers and Eden 2017; Eden and Olbers 2017). Building on IWAM, Sebastia Saez et al. (2024) introduce the Internal Wave Energy Model (IWEM) to resolve the spectral energy balance between waves and meso-scale eddies (with depth-varying stratification) in its full form. They show a nontrivial wave energy gain outside and decay within the eddy due to wave-eddy interactions, and enhanced wave dissipation by vertical refraction at eddy rims with vertical diffusivities of O(10^{-7}) to O(10^{-5}) m^2/s. Further, scale-separated stationary geostrophic flow effects on small-amplitude waves are studied using a diffusion equation (Kafiabad et al. 2019; Cox et al. 2023), whereas Savva et al. (2021) derived a kinetic equation using the Wigner transform for resonant interactions under constant stratification. Both approaches reveal an eddy-induced ”diffusion of wave action” towards larger wavenumbers at constant frequency, enhancing TKE production and mixing. From weak turbulence theory (e.g. Nazarenko (2011)), Eden et al. (2019a) derive the kinetic equation under the weak interaction assumption (Hasselmann 1966) for mixed Rossby–gravity wave–wave interactions. Recently, Olbers et al. (2024) show that energy cannot be exchanged by resonant but by non-resonant wave-eddy interactions, provided the wave and eddy fields show horizontal anisotropy. The question of energy exchange between internal tides and mesoscale eddies, lying at the brink of the WKBJ limit, remains open.

4. Discussion

During the meeting, there were vivid discussions about the relation between mixing and overturning circulation. It was concluded that the question whether mixing drives the overturning circulation, is that of a chicken-and-egg problem: Both are interdependent and can only exist together. Small-scale tracer mixing requires the resupply of tracer gradients by the large-scale circulation, and the resulting dia-surface fluxes are required to close the overturning circulation.

Besides giving answers, some general questions were formulated, among others:

- What are the roles of wave-wave and wave-eddy interaction and nonlinearities of the Equation of State on mixing and overturning circulation?
- What is the role of small-scale mixing in the bottom boundary layer of the ocean on the large-scale overturning circulation and where are the mixing hotspots?
- Where and when do the most important mixing events occur in estuaries and river plumes and on which time scales does this contribute to exchange flow?
- Can we directly quantify the relation between mixing and overturning circulation on different scales?

The presentations and discussions during the 11$^{\text{th}}$ Warnemünde Turbulence Days contributed to all these questions and brought new insights that we have reported about in this short meeting summary. By doing so, a wide range of scales and processes was bridged. More information about the meeting including the programme, all abstracts and photos can be found at `https://www.io-warnemuende.de/wtd-2023.html`.

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