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Burchard, Hans; Alford, Matthew; Chouksey, Manita; Dematteis, Giovanni; Eden, Carsten; Giddy, Isabelle; Klingbeil, Knut; Le Boyer, Arnaud; Pietrzak, Julie; More Authors

DOI
10.1175/BAMS-D-24-0082.1

Publication date
2024

Document Version
Final published version

Published in
Bulletin of The American Meteorological Society

BAMS
Meeting Summary

Linking Ocean Mixing and Overturning Circulation

Hans Burchard,[a] Matthew Alford,[b] Manita Chouksey,[a,d] Giovanni Dematteis,[c] Carsten Eden,[d] Isabelle Giddy,[e] Knut Klingbeil,[a] Arnaud Le Boyer,[b] Dirk Olbers,[h] Julie Pietrzak,[f] Friederike Pollmann,[d] Kurt Polzin,[g] Fabien Roquet,[e] Pablo Sebastia Saez,[d] Sebastiaan Swart,[e] Lars Umlauf,[a] Gunnar Voet,[b] and Bethan Wynne-Cattanach[b]

KEYWORDS:
Eddies;
Inertia–gravity waves;
Meridional overturning circulation;
Mixing;
Ocean circulation;
Turbulence

11th Warnemünde Turbulence Days on Linking Ocean Mixing and Circulation at Various Scales

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

When: 17–20 September 2023

Where: Rostock, Germany

DOI: 10.1175/BAMS-D-24-0082.1
Corresponding author: Hans Burchard, hans.burchard@io-warnemuende.de
In final form 25 March 2024

AFFILIATIONS: [a] Leibniz Institute for Baltic Sea Research Warnemünde, Rostock, Germany; [b] Scripps Institution of Oceanography, University of California San Diego, La Jolla, California; [c] Dipartimento di Fisica, Università degli Studi di Torino, Torino, Italy; [d] Institut für Meereskunde, Universität Hamburg, Hamburg, Germany; [e] Department of Marine Sciences, University of Gothenburg, Gothenburg, Sweden; [f] Department of Hydraulic Engineering, Technical University of Delft, Delft, Netherlands; [g] Woods Hole Oceanographic Institution, Woods Hole, Massachusetts; [h] Department of Oceanography, Institute of Environmental Physics, University of Bremen, Bremen, Germany

1. Introduction

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 mixing and 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 semienclosed 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 organized on a biannual basis with the 11th WTD taking place during 17–20 September 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.

2. 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. It is often argued that mixing is the driver of overturning circulation, 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 comparably 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 these 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.

3. 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? Diffusive tracer fluxes are a good indicator of mixing, because they are specific for each individual tracer and require turbulence and tracer gradients. Often, also (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). This definition of variance decay as mixing is also consistent with turbulence theory that assumes stirring to increase the microstructure tracer variance and mixing to dissipate it (Umlauf and Burchard 2005; Thorpe 2007; Moum 2021). In the ocean, many instabilities act to produce stirring, forming a spectrum of turbulent patterns linking the mesoscale to the Batchelor scale 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, and thermobaricity). In ocean models, numerical mixing due to discretization errors in the advection terms results in numerical mixing (Maqueda and Holloway 2006; Burchard and Rennau 2008; Klingbeil et al. 2014) that needs to be considered when analyzing effective mixing in models.

b. What is overturning circulation? Mixing can set up circulations that cross mean isopleths. The question of how to define overturning circulation is far from trivial due to the potential choices of coordinates and mean isopleths. What we intend by overturning circulation is that the flow loops vertically over itself as opposed to being 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 circulation typically results from the superimposition of various intricate circulation patterns generated by different processes such as Ekman pumping, eddy transport, or boundary dynamics. The overturning streamfunction obtained by integrating bottom up the basinwide meridional transport provides a natural proxy. The vertical integration is usually done using depth coordinates, although the use of density coordinates is also popular. With 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 section 4c). The water mass transformation (WMT) framework links the overturning streamfunction to diasurface 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). This provides a useful framework for identifying the WMT mechanisms of cabbeling and double diffusive convection (Thomas and Shakespeare 2015; Evans et al. 2018). Later, also the direct link of WMT to mixing in terms of integrated 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. Each coordinate space has its pros and cons, and it is usually through their combination that a faithful picture emerges.

4. Overturning and mixing processes in different scales and regimes

a. Large-scale overturning circulation. 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 odds 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 4d), and 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 and 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 the Atlantic and Pacific Oceans.

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 cannot 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. A more nuanced view of southern-wind-driven upwelling appears called for.

Mesoscale eddies stir properties along isopycnals and are decisive in contributing to both dynamics and tracer distributions. Non-eddy-resolving models used, for example, in climate studies, typically employ a diffusion tensor having both advective [antisymmetric, Gent et al. (1995)] and diffusive [symmetric, Redi (1982)] parts. A. Chouksey et al. (2022) demonstrate the sensitivity of ocean circulation in coarse models to isopycnal diffusivity, which is changed along with different formulations of surface forcing, and show that the isopycnal diffusion not only controls the uptake of carbon and other tracers but is also as important as the surface fluxes in shaping the 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-dimensional description of the open-ocean WMT 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 water mass 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 $\mathcal{O}(100)\,\mathrm{m\,day}^{-1}$ (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, manuscript submitted to *J. Phys. Oceanogr.*). The 3D internal tide breaking processes, captured by moored estimates of diapycnal fluxes K. L. Polzin et al. (2024, personal communication), appear 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 WMT (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 WMT and circulation (Walin 1977) were developed for the Baltic Sea, a large nontidal fjord-type estuary. The overturning circulation in the Baltic (the Baltic Haline Conveyor Belt; Döös et al. 2004) consists of sporadic bottom saltwater 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. Estuarine circulation is commonly thought of as inflow of salty water and outflow of brackish water into semienclosed 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 characterized 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 view 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 WMT 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 (TPFs) generate internal waves ahead of them that can lead to substantial mixing, e.g., in the near- to midfield of the Columbia River plume (Kilcher and Nash 2010). Recently, Rijnsburger et al. (2018, 2021a,b) showed trapping of TPFs and the presence of internal solitary waves (ISWs) ahead of TPFs in the near- to midfield 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 TPFs and ISWs 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 contributes to maintaining the large-scale overturning circulation (Talley 2013; Cimoli et al. 2023). This process can be understood as (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 turns, by shear or convective instabilities (Staquet and Sommeria 2002), into turbulent kinetic energy. A major forcing is provided by the interaction of tides or nonoscillatory flows with the seafloor (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). Surface wind stress forces mixed-layer inertial oscillations of about 0.3 TW globally (Alford 2001; Rimac et al. 2013; Alford 2020; von Storch and Lüschow 2023), but only a fraction of that propagates into the interior. Another forcing mechanism includes spontaneous loss of balance by shear instabilities (Vanneste 2013; Alford et al. 2013b; Chouksey et al. 2018). Idealized studies estimated 0.3-TW input (Brüggemann and Eden 2015; Sugimoto and Plougonven 2016), although recently a weak role of spontaneous loss of balance was found using more precise flow decomposition methods (Eden et al. 2019a; M. Chouksey et al. 2022, 2023).

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 semiempirical finescale parameterizations (Polzin et al. 2014). These parameterizations have recently found solid theoretical grounding (Eden et al. 2019c; Dematteis et al. 2023) and appear to apply roughly in the ocean interior (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 (Dematteis et al. 2023; Lozovatsky et al. 2023). The finescale parameterizations are also used in the Internal Wave Dissipation, Energy, and Mixing (IDEMIX) parameterization for wave mixing and mean flow effects in both ocean and atmosphere (Olbers and Eden 2013, 2017; Eden and Olbers 2017; Quinn et al. 2020).

Wave interaction with mesoscale eddies could represent another internal wave energy source, particularly in eddy-rich environments (Mtfller 1976; Polzin 2010), although the scattering of waves by resonant interactions without energy transfers but toward larger wavenumbers might be the more important effect (Kafiabad et al. 2019; Cox et al. 2023; Savva et al. 2021). Saez et al. (2024) introduce the Internal Wave Energy Model (IWEM) based on the radiative transfer equation to resolve the spectral energy balance between waves and mesoscale 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

$\mathcal{O}(10)^{-7}$–$\mathcal{O}(10)^{-5}\,\mathrm{m^2\,s^{-1}}$. Further, Eden et al. (2019b) derive mixed Rossby–gravity wave–wave interactions from kinetic equations under the weak interaction assumption (Hasselmann 1962). Based on that, it can be shown that energy by nonresonant wave–eddy interactions could be important for energy transfers 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.

5. 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. What is needed for better understanding is a simple, self-consistent analytical model for the overturning. Small-scale tracer mixing requires the resupply of tracer gradients by the large-scale circulation, and the resulting diascalar fluxes are required to close the overturning circulation.

Besides giving answers, some general questions were formulated at the WTD:

- 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 do they contribute to exchange flow?
- Can we directly quantify the relation between mixing and overturning circulation on different scales?
- How do wave–wave and wave–eddy interactions determine the energy transfers between waves and eddies and the resulting mixing?
- What is the role of nonlinearities of the equation of state on mixing and overturning circulation?

The presentations and discussions during the 11th 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 program, all abstracts, and photos can be found at https://www.io-warnemuende.de/wtd-2023.html.

Acknowledgments. The organizers of the 11th Warnemünde Turbulence Days are grateful for the financial support from the Collaborative Research Center TRR 181 Energy Transfers in Atmosphere and Ocean, funded by the German Research Foundation under Project 274762653. We thank all the workshop participants for their contributions and inspiring discussions. Special thanks go to Berit Recklebe from IOW for the successful organization of the meeting.

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