MEETING SUMMARIES

CLIMATE RECORDED IN SEAWATER

A Workshop on Water-Mass Transformation Analysis for Ocean and Climate Studies

Sjoerd Groeskamp, Casimir de Lavergne, Ryan Holmes, Veronica Tamsitt,
Ivy Frenger, Christopher C. Chapman, Emily Newsom, and Geoffrey J. Stanley

The opacity of seawater prevents radiation from penetrating into the ocean interior. Surface waters accumulate solar radiation, augmenting their buoyancy relative to deeper waters. Solar heating thus strengthens vertical stability and restrains vertical mixing of the ocean. These effects tend to shelter interior waters from atmospheric forcing, and to favor the ocean's layering into distinct, stable water masses.

AFFILIATIONS: Groeskamp and Stanley—School of Mathematics and Statistics, University of New South Wales, Sydney, New South Wales, Australia; Lavergne—LOCEAN Laboratory, Sorbonne Université, CNRS-IRD-MNHN, Paris, France; Holmes—School of Mathematics and Statistics, Climate Change Research Centre, and the Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, New South Wales, Australia; Tamsitt—Climate Change Research Centre, University of New South Wales, Sydney, New South Wales, and Centre for Southern Hemisphere Oceans Research, Oceans and Atmosphere, CSIRO, Hobart, Tasmania, Australia; Frenger—GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany; Chapman—Oceans and Atmosphere, CSIRO, Hobart, Tasmania, Australia; Newsom—Department of Physics, University of Oxford, Oxford, United Kingdom

CORRESPONDING AUTHOR: Sjoerd Groeskamp, sjoerdgroeskamp@gmail.com

DOI:10.1175/BAMS-D-19-0153.1

In final form 23 May 2019

FIRST WORKSHOP ON WATER-MASS TRANSFORMATION ANALYSIS FOR OCEAN PHYSICS, BIOGEOCHEMISTRY, AND CLIMATE

What:	An international cohort of oceanographers, marine biogeochemists, and climate modelers gathered to expand the use of water-mass transformation diagnostics in studies of ocean physics, biogeochemistry, and climate. Led by early-career scientists, the group laid out avenues to leverage growing oceanic observational databases and new model capabilities, using fundamental understanding of the ocean's layering.
When:	4–6 February 2019
Where:	Sydney, New South Wales, Australia

Water masses acquire their core properties at the surface, receiving an imprint of atmospheric tracers and climatic conditions at the time. They then spread in the ocean interior, where they serve as a climate record, eroding only slowly through weak mixing with surrounding waters.

The water-mass transformation (WMT) framework exploits this basic understanding of ocean physics. It complements traditional Eulerian and Lagrangian methods by framing circulation in terms of moving "layers" rather than stationary "boxes" (i.e., Eulerian) or moving "particles" (i.e., Lagrangian). Essentially, WMT measures volume changes of layers due to various processes. Layers are traditionally defined by pairs of tracer surfaces, such as temperature or buoyancy surfaces. The approach has several advantages: i) volume changes are the integrated result of irreversible transformations by (but not limited to) air–sea fluxes and ocean mixing: they ignore reversible adiabatic displacements that have little climatic relevance and often introduce noise; ii) WMT allows inferences of integral quantities that are difficult to measure, such as basin-scale mass or heat transports, from more accessible quantities such as temperature and salinity distributions; and iii) in theory, any property of interest can be considered to define layers and be analyzed, for example, anthropogenic carbon or oxygen.

Increased spatial and temporal coverage of hydrographic observations—largely owing to Argo floats deployed since 2000—and improved mapping of air–sea fluxes and ocean mixing rates have stimulated a recent resurgence in the use of the WMT framework. Examples include analyses of water-cycle changes (Skliris et al. 2016), Southern Ocean overturning (Abernathey et al. 2016; Pellichero et al. 2018), abyssal circulation (de Lavergne et al. 2017), and thermodynamic constraints on global ocean circulation (Newsom and Thompson 2018). We believe that the framework has further untapped potential, particularly for biogeochemistry and climate applications.

The workshop aimed to specify avenues to fulfill this potential. About 40 scientists with diverse backgrounds (physical oceanography, biogeochemistry, climate dynamics) and expertise (observations, theory, and modeling) gathered to share viewpoints, identify challenges, and instigate projects. Three days, divided equally between presentation and discussion sessions, allowed lively and productive exchanges within and across disciplines. The outcomes of the discussion sessions are summarized below.

AN OLD PROBLEM: SUBDUCTION AND VENTILATION. The ocean is a vast reservoir of heat and carbon. What controls the rate of uptake and the time scale of storage by the ocean of such climatically important tracers? Oceanic storage depends crucially on the rates and locations at which tracers of the surface mixed layer, in contact with the atmosphere, are transferred into the ocean interior. Quantifying subduction and ventilation—the injection of mass and tracer into the ocean interior—is both a pressing and long-standing challenge in oceanography.

The WMT framework can be used to estimate subduction rates using knowledge of the surface hydrography, air–sea exchanges, and near-surface mixing (Walin 1982; Marshall 1997). However, several challenges hinder progress. First, large uncertainties in estimates of air–sea fluxes, particularly in polar regions, are apparent in the discrepancies between different reanalysis and in situ products (e.g., Valdivieso et al. 2017). These uncertainties imply large error bars in derived subduction rates. Second, effective subduction occurs only when mass is transferred across the depth of the annual deepest (wintertime) mixed layer. Accounting for the zoo of mixing processes taking place above that depth is often a delicate task. Third, the use of temperature (or buoyancy) coordinate system only allows us to deduce subduction rates between pairs of temperature (or buoyancy) surfaces: desirable information about the geography of subduction is lost. Fourth, to infer ventilation of a specific tracer, diffusive tracer fluxes—in addition to the tracer flux carried with the subducting water mass—must be evaluated.

We propose several strategies to overcome these challenges. One avenue consists of using models to derive a transfer function that links the surface to the ocean interior, encapsulating effects of mixing above the annual maximum mixed layer depth. This transfer function is inaccessible from observations on a global scale, but it can be assessed from a model simulation by comparing actual subduction rates to those implied by air–sea fluxes alone. The function would be diagnosed for small intervals of potential density within coherent regions in the model. Subduction rates derived from air–sea-flux reanalysis products can then be multiplied by the transfer function to obtain refined estimates of effective subduction rates.

A second avenue consists of using multiple tracers to constrain the magnitude and geography of subduction and ventilation. For example, by diagnosing surface WMT in two coordinate variables whose isosurfaces are not aligned, it may be possible to map subduction in longitude–latitude space. Furthermore, in some regions, measurements of numerous tracers are available (e.g., chlorofluorocarbons or trace elements) that combined can constrain mass and tracer fluxes into the ocean interior. By performing budgets of multiple tracers in the mixed layer, estimates of subduction and ventilation rates are achievable. The rapidly growing GEOTRACES (www.geotraces.org) and Biogeochemical-Argo (BGC-Argo; Johnson and Claustre 2016) databases increase the feasibility of such budgets.

Progress may also be achieved by approaching the problem from below. For some tracers (e.g., buoyancy or chlorofluorocarbons), it may be easier to quantify WMT in the deep ocean, where there is less temporal variability in the tracer fields and fewer processes leading to WMT. The requirement for matching transformation in the upper ocean can then be used to narrow uncertainties in subduction and ventilation processes. Such bottom-up constraints on subduction are becoming attainable thanks to recent advances in the mapping of mesoscale and small-scale mixing in the ocean interior (Whalen et al. 2012; Cole et al. 2015; de Lavergne et al. 2019; Busecke and Abernathey 2019).

WATER AND BIOGEOCHEMICAL CYCLES.

Buoyancy and temperature are preferred coordinate variables for WMT studies as buoyancy surfaces align with the preferred direction of flow, while temperature surfaces allow tracking of heat transport. We explored the potential of using alternative coordinate variables (e.g., nitrate or salinity; Badin and Williams 2010; Zika et al. 2015), as well as the potential of combining buoyancy-based WMT with biogeochemical tracer budgets (Iudicone et al. 2011; Groeskamp et al. 2019).

Examination of volume changes of isohaline layers—that is, WMT in a salinity coordinate system—has allowed quantification of the intensification of the atmospheric hydrological cycle over 1950–2010 (Skliris et al. 2016). Continuing near-synoptic coverage of the upper 2 km of the ocean by Argo floats offers prospects for probing interannual to decadal variability in the water cycle. These strategies could also be applied to understanding cycling and trends of dissolved oxygen, including volume trends of oxygen minimum zones. For example, by combining observations and models, shifts in the distribution of ocean volume in different oxygen classes may be examined and attributed to physical and biochemical processes.

The WMT framework in a buoyancy coordinate system can be extended to include biogeochemical tracer conservation budgets. The resulting description of the total tracer change between two buoyancy surfaces integrates physics and biogeochemistry to provide a process-based understanding and quantification of tracer circulation, as exemplified for natural and anthropogenic carbon by Iudicone et al. (2016), Groeskamp et al. (2016), and Zhai et al. (2017). Such budgets can aid in quantifying poorly constrained biogeochemical source/sink terms by separating them from better-constrained terms. Application of this method to observations and/or data-constrained models emerged as an important target, with a focus on Southern Ocean carbon and nutrient cycles and the evolution of oxygen minimum zones.

Perhaps the most frontier application explored was the combination of the WMT framework with novel marine "omics" data. Microbial metabolic functions are central to setting the distribution of ocean biogeochemical tracers and these functions are determined by the genetic machinery available to the microbial community (Coles et al. 2017). As such, describing the ocean's distribution of genes and the markers for their expression and activity (collectively deemed "omics") may ultimately provide a mechanistic approach to predicting many biogeochemical tracer gradients from more fundamental determination of sources and sinks. With ever-increasing sampling frequency and density for ocean omics, the combination of these data with the circulation obtained from WMT could become a powerful tool for linking ocean physics with biogeochemistry.

OCEAN AND CLIMATE MODELING.

Implementing WMT diagnostics in numerical models allows for quantification and interpretation of key processes, aiding model intercomparison and evaluation. Modeling studies that embraced this approach have provided insights on the structure and drivers of ocean circulation, as well as information on model numerics and biases (e.g., Downes et al. 2015; Holmes et al. 2019). Models also fill spatiotemporal gaps in observed patterns of WMT (e.g., Cerovečki and Mazloff 2016) and to project future changes. Nevertheless, technical challenges and limitations often prevent a more systematic utilization of WMT diagnostics in model analyses.

Challenges include spatial and temporal discretization issues, defining tracer surfaces, closing tracer budgets, and the need for specialized online diagnostics. For example, when implementing buoyancy-based WMT diagnostics, one requires an appropriate buoyancy binning method, which in turn requires choices of bin size, remapping scheme, and measure of buoyancy. Buoyancy is commonly measured using potential density, but this is appropriate only in a limited space near the chosen reference pressure. Online calculation of globally accurate buoyancy surfaces remains a major hurdle and an active area of research (Stanley 2019).

The delicate choice of buoyancy measure hides a more general limitation of water-mass analysis applied to model oceans: how to define consistent water-mass boundaries that allow interpretation of simulated trends, comparison with observations, and comparison across models. The task is most demanding when air–sea fluxes and water-mass boundaries evolve rapidly, as occurs under twenty-first-century high-emissions scenarios. In such cases, water-mass definitions that combine several hydrographic properties (e.g., Sallée et al. 2013), rather than relying only on buoyancy, may provide a more robust framework of analysis.

A powerful tool to reveal geographical hotspots of WMT are Lagrangian particle trajectories in combination with WMT diagnostics (Tamsitt et al. 2018). However, attendees experimenting with this approach have highlighted issues with tracer budgets along Lagrangian trajectories: for example, the temperature difference between the initial and final locations of a Lagrangian particle can differ substantially from the thermal forcing and mixing integrated along the particle's trajectory. The numerical underpinning of such discrepancies was discussed, as were methods to align Lagrangian methods with the WMT framework.

Discussions also highlighted a lack of shared tools and recommendations to implement WMT diagnostics. It was decided to publicly release software for implementing/applying WMT methods, together with example studies and reference diagnostics, in order to facilitate uptake of these methods by both modelers and observationalists. Efforts to standardize diagnostics applicable to observations and models should ultimately enable WMT-based model comparison exercises. Such exercises are an important avenue to further our understanding of the physical and biogeochemical processes represented in climate-scale models.

CONCLUSIONS. The ocean's role in climate and ecosystems involves a rich tapestry of physical and biogeochemical processes. Quantification and simulation of these processes and their interplay are essential to reach a holistic understanding of past and future climate and ecosystem changes. To this end, it is vital that our community continues to build interdisciplinary research strategies. This meeting aimed to foster such strategies, bringing diverse expertise together to reflect on the potential of a framework—water-mass transformation—which weaves together ocean dynamics, thermodynamics, biogeochemical processes, and interactions with the atmosphere, cryosphere, and solid Earth.

Discussions allowed identification of the possibilities offered by the framework to tackle prominent questions, of bottlenecks that restrain its application, and of avenues to clear bottlenecks and catalyze progress. Studies initiated by the meeting will contribute to address targeted questions and to overcome challenges. Several tasks underway will also materialize outcomes. A website hosting sample code, scientific illustrations, and a forum is under construction to establish an inclusive community of users. A tutorial presentation is being prepared for online posting and for upcoming conferences to introduce the method to a wider audience. The organization of a follow-up meeting, to be held in April 2021 in Italy, has started.

ACKNOWLEDGMENTS. The authors thank Bernadette Sloyan and Stephen Griffies for reading and checking the content of this summary, and all participants for their contributions to the meeting. We acknowledge support from the School of Mathematics and Statistics and ARC Centre of Excellence for Climate Extremes of the University of New South Wales, Sydney, Australia. Sjoerd Groeskamp, Ryan Holmes, Casimir de Lavergne, and Geoffrey J. Stanley acknowledge support from the Australian Research Council Grant FL150100090. A repository can be found online (https://github.com/water-mass-transformation-tools).

REFERENCES

Abernathey, R. P., I. Cerovecki, P. R. Holland, E. Newsom, M. Mazloff, and L. D. Talley, 2016: Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nat. Geosci.*, **9**, 596–601, https://doi.org/10.1038/ngeo2749.

Badin, G., and R. G. Williams, 2010: On the buoyancy forcing and residual circulation in the Southern Ocean: The feedback from Ekman and eddy transfer. *J. Phys. Oceanogr.*, **40**, 295–310, https://doi.org/10.1175/2009JPO4080.1.

Busecke, J. J. M., and R. P. Abernathey, 2019: Ocean mesoscale mixing linked to climate variability. *Sci. Adv.*, **5**, eaav5014, https://doi.org/10.1126/sciadv.aav5014.

Cerovečki, I., and M. R. Mazloff, 2016: The spatiotemporal structure of diabatic processes governing the evolution of Subantarctic Mode Water in the Southern Ocean. *J. Phys. Oceanogr.*, **46**, 683–710, https://doi.org/10.1175/JPO-D-14-0243.1.

Cole, S. T., C. Wortham, E. Kunze, and W. B. Owens, 2015: Eddy stirring and horizontal diffusivity from Argo float observations: Geographic and depth variability. *Geophys. Res. Lett.*, **42**, 3989–3997, https://doi.org/10.1002/2015GL063827.

Coles, V. J., and Coauthors, 2017: Ocean biogeochemistry modeled with emergent trait-based genomics. *Science*, **358**, 1149–1154, https://doi.org/10.1126/science.aan5712.

de Lavergne, C., G. Madec, F. Roquet, R. M. Holmes, and T. J. McDougall, 2017: Abyssal ocean overturning shaped by seafloor distribution. *Nature*, **551**, 181–186, https://doi.org/10.1038/nature24472.

——, S. Falahat, G. Madec, F. Roquet, J. Nycander, and C. Vic, 2019: Toward global maps of internal tide energy sinks. *Ocean Modell.*, **137**, 52–75, https://doi.org/10.1016/j.ocemod.2019.03.010.

Downes, S. M., and Coauthors, 2015: An assessment of Southern Ocean water masses and sea ice during 1988–2007 in a suite of interannual CORE-II simulations. *Ocean Modell.*, **94**, 67–94, https://doi.org/10.1016/j.ocemod.2015.07.022.

Groeskamp, S., A. Lenton, R. Matear, B. M. Sloyan, and C. Langlais, 2016: Anthropogenic carbon in the ocean—Surface to interior connections. *Global Biogeochem. Cycles*, **30**, https://doi.org/10.1002/2016GB005476.

——, S. M. Griffies, D. Iudicone, R. Marsh, A. J. G. Nurser, and J. D. Zika, 2019: The water mass transformation framework for ocean physics and biogeochemistry. *Annu. Rev. Mar. Sci.*, **11**, 271–305, https://doi.org/10.1146/annurev-marine-010318-095421.

Holmes, R. M., J. D. Zika, and M. H. England, 2019: Diathermal heat transport in a global ocean model. *J. Phys. Oceanogr.*, **49**, 141–161, https://doi.org/10.1175/JPO-D-18-0098.1.

Iudicone, D., K. B. Rodgers, I. Stendardo, O. Aumont, G. Madec, L. Bopp, O. Mangoni, and M. Ribera d'Alcala', 2011: Water masses as a unifying framework for understanding the Southern Ocean carbon cycle. *Biogeosciences*, **8**, 1031–1052, https://doi.org/10.5194/bg-8-1031-2011.

——, ——, Y. Plancherel, O. Aumont, T. Ito, R. M. Key, G. Madec, and M. Ishii, 2016: The formation of the ocean's anthropogenic carbon reservoir. *Sci. Rep.*, **6**, 35473, https://doi.org/10.1038/srep35473.

Johnson, K., and H. Claustre, Eds., 2016: The scientific rationale, design and implementation plan for a biogeochemical-Argo float array. Biogeochemical-Argo Planning Group Tech. Rep., 65 pp., https://doi.org/10.13155/46601.

Marshall, D., 1997: Subduction of water masses in an eddying ocean. *J. Mar. Res.*, **55**, 201–222, https://doi.org/10.1357/0022240973224373.

Newsom, E. R., and A. F. Thompson, 2018: Reassessing the role of the Indo-Pacific in the ocean's global overturning circulation. *Geophys. Res. Lett.*, **45**, 12 422–12 431, https://doi.org/10.1029/2018GL080350.

Pellichero, V., J.-B. Sallée, C. C. Chapman, and S. M. Downes, 2018: The Southern Ocean meridional overturning in the sea-ice sector is driven by freshwater fluxes. *Nat. Commun.*, **9**, 1789, https://doi.org/10.1038/s41467-018-04101-2.

Sallée, J. B., E. Shuckburgh, N. Bruneau, A. J. S. Meijers, T. J. Bracegirdle, Z. Wang, and T. Roy, 2013: Assessment of Southern Ocean water mass circulation and characteristics in CMIP5 models: Historical bias and forcing response. *J. Geophys. Res. Oceans*, **118**, 1830–1844, https://doi.org/10.1002/jgrc.20135.

Skliris, N., J. D. Zika, G. Nurser, S. A. Josey, and R. Marsh, 2016: Global water cycle amplifying at less than the Clausius-Clapeyron rate. *Sci. Rep.*, **6**, 38752, https://doi.org/10.1038/srep38752.

Stanley, G. J., 2019: Neutral surface topology. *Ocean Modell.*, https://doi.org/10.1016/j.ocemod.2019.01.008, in press.

Tamsitt, V., R. Abernathey, M. Mazloff, J. Wang, and L. Talley, 2018: Transformation of deep water masses along Lagrangian upwelling pathways in the Southern Ocean. *J. Geophys. Res. Oceans*, **123**, 1994–2017, https://doi.org/10.1002/2017JC013409.

Valdivieso, M., and Coauthors, 2017: An assessment of air–sea heat fluxes from ocean and coupled reanalyses. *Climate Dyn.*, **49**, 983–1008, https://doi.org/10.1007/s00382-015-2843-3.

Walin, G., 1982: On the relation between sea-surface heat flow and thermal circulation in the ocean. *Tellus*, **34**, 187–195, https://doi.org/10.3402/tellusa.v34i2.10801.

Whalen, C. B., L. D. Talley, and J. A. MacKinnon, 2012: Spatial and temporal variability of global ocean mixing inferred from Argo profiles. *Geophys. Res. Lett.*, **39**, L18612, https://doi.org/10.1029/2012GL053196.

Zhai, P., K. B. Rodgers, S. M. Griffies, R. D. Slater, D. Iudicone, J. L. Sarmiento, and L. Resplandy, 2017: Mechanistic drivers of reemergence of anthropogenic carbon in the equatorial Pacific. *Geophys. Res. Lett.*, **44**, 9433–9439, https://doi.org/10.1002/2017GL073758.

Zika, J. D., N. Skliris, A. J. G. Nurser, S. A. Josey, L. Mudryk, F. Laliberté, and R. Marsh, 2015: Maintenance and broadening of the ocean's salinity distribution by the water cycle. *J. Climate*, **28**, 9550–9560, https://doi.org/10.1175/JCLI-D-15-0273.1.