

# SCOR Working Group Proposal for “Standardizing Practices for Isopycnal Composition Estimates (SPICE)”

**Title:** Standardizing Practices for Isopycnal Composition Estimates

**Acronym:** SPICE

## Summary/Abstract

The ocean is stratified by density, yet temperature, salinity, and other tracers vary significantly along density surfaces. This density-compensated variability, commonly referred to as *spice*, is widely used to characterize water masses, diagnose isopycnal stirring, and interpret tracer transport across physical oceanography, ocean acoustics, and biogeochemistry. However, *spice* lacks a consistent definition. Existing formulations differ in their dependence on the equation of state, reference conditions, spatial resolution, and disciplinary context, making results difficult to compare across studies and limiting scientific synthesis. This working group will establish a unified framework for defining and applying *spice* across oceanographic contexts. We will compile and compare existing formulations, identify where they converge or diverge across regimes and scales, and assess their implications for interpreting along-isopycnal variability. Building on this synthesis, we will develop a community best-practice framework, including a decision flowchart to guide the selection of appropriate diagnostics. Key deliverables include a peer-reviewed synthesis paper, an open-access toolbox, and a georeferenced database of studies and observational contexts. By standardizing *spice* diagnostics, this effort will improve interpretations of tracer transport, support model development, and strengthen interdisciplinary applications.

## 1. Scientific Background and Rationale

### What is *spice*?

The ocean is stratified by density, but temperature, salinity, and other tracers can vary substantially along density surfaces. Along-isopycnal tracer variability is widely used across physical oceanography, ocean acoustics, and biogeochemical tracer studies to characterize water mass properties (e.g., Flament 2002), track stirring along isopycnals (e.g., Klymak et al., 2015), and assess the role of lateral gradients in tracer budgets (e.g., Echols and Riser, 2020). The density-compensated along-isopycnal variability of temperature and salinity (T-S) has often been referred to as *spice*, a term coined by Munk (1981): a warm salty parcel is “spicy” compared to a cold fresh parcel at the same density.

*Spice* is invoked across physical oceanography, acoustics, and biogeochemistry as a tracer of water mass origin and modification, a diagnostic of isopycnal stirring, and an indicator of susceptibility to double-diffusive instabilities. Identifying *spice* variability decouples heat

transport from diapycnal mixing. Recent work on water mass transformations shows that isopycnal mixing of heat likely dominates diathermal heat transport in high-latitude oceans, with first-order implications for the ocean's role as a heat engine in the climate system (Fernández-Castro *et al.*, 2026). In ocean acoustics, spice-induced sound speed anomalies, invisible to density-based measurements, affect acoustic travel time, coherence, and scattering, with direct relevance to acoustic tomography and underwater communication (Munk and Wunsch 1998). Along-isopycnal variability has implications beyond T-S, including for the transport of biogeochemical tracers such as oxygen and nutrients across ocean basins (Font *et al.*, 2026; Oglethorpe *et al.*, 2023). Nutrients and dissolved gases, like spice, are strongly influenced by isoneutral stirring. Variability in spice, therefore, reflects pathways of redistribution and provides insight into their lateral spreading along isopycnal surfaces. Despite this cross-disciplinary relevance, spice lacks a consistent definition, creating a significant impediment to scientific synthesis, limiting our ability to compare results across regions, datasets, and models.

### **The problem of multiple definitions**

Despite its broad utility, spice has been defined, estimated, and interpreted in multiple ways across studies. Different formulations depend on the choice of equation of state, reference density, spatial resolution, and the scale of interest. As a result, what is considered “along-isopycnal variability” in one framework may include vertical displacements or unresolved density changes in another. The processes that generate and modify spice complicate its interpretation. Mechanisms such as isopycnal stirring and shear dispersion can produce compensated T-S structures at different length scales (Jaeger *et al.*, 2020), linking spice variability to mesoscale and submesoscale dynamics (e.g., Kunze *et al.*, 2015). At the same time, spice gradients can influence stratification and drive double-diffusive processes, indicating that spice is not always dynamically passive (Middleton *et al.*, 2021). It can actively participate in mixing and energy pathways, particularly in regions where density compensation enhances susceptibility to double diffusion (Ikeda and Nagai, 2026), and recent measurements show that these processes can significantly modify heat fluxes (Fine *et al.*, 2018; Sanchez-Rios *et al.*, 2024).

The challenge to define spice becomes more pronounced across regimes. In the mixed layer and frontal regions, observations suggest that lateral T-S variability can be strongly density-compensated, allowing spice anomalies to persist even as density gradients are reduced (e.g., Rudnick and Ferrari, 1999). In contrast, in the ocean interior, the tight relationship between temperature and salinity in stratified environments raises questions about the mechanisms that help sustain distinct gradients (Schmitt, 1999; Legg and McWilliams, 2000). The degree of compensation that these gradients contribute to the density structure can be quantified by the density ratio  $R_\rho = \alpha\Delta\Theta/\beta\Delta S$ , for  $\alpha\Delta\Theta$  the change in temperature, and  $\beta\Delta S$  the change in salinity, both scaled by their effect on density, where  $\alpha$  is thermal expansion coefficient and  $\beta$  the haline contraction coefficient. When  $R_\rho \approx -1$ , temperature and salinity vary in opposition with no net density signature (Rudnick and Ferrari, 1999). Density can be used to classify regions where high variability of spice may occur. These differences highlight that the definition of spice and how it is applied are inherently scale- and regime-dependent.

Current methods to estimate spice can be broadly separated into two categories: (1) estimates based on the nonlinear equation of state, such as spiciness (McDougall and Krzysik, 2015) and spicity (Huang et al, 2018), which differ in how orthogonality to density is defined and can behave differently in high-latitude or deep-ocean conditions: (2) local anomaly approaches that linearize the equation of state around a reference T-S value (Dzieciuch, Munk and Rudnick, 2004). All approaches depend on choices of thermal expansion and haline contraction coefficients and on how the reference mean is estimated, whether temporal or spatial, and at what resolution (Klymak *et al.*, 2015). In Table 1, we present three different definitions. Spice is reported inconsistently, sometimes as an anomaly relative to a regional mean, and sometimes as an absolute value, further limiting comparability across studies.

Table 1: Example of spice definitions across different studies. Where  $\alpha$  = thermal expansion coefficient,  $\beta$  = haline contraction coefficient, and EOS = equation of state.

Definition	Equation	Author
Spice ( $\tau$ ) orthogonal to density isolines on $\theta$ - $S$ plane. Constant $\alpha$ , $\beta$ (locally valid).	$\Delta\tau = \alpha\Delta\theta + \beta\Delta S_A$	Veronis (1972) Munk (1981) Dzieciuch et al. (2004)
Isopycnal variations of spice proportional to compensating T-S contributions to density; nonlinear EOS (TEOS-10).	$\int_{\sigma} d\tau = 2 \int_{\sigma} \beta dS_A = -2 \int_{\sigma} \alpha d\theta$	McDougall & Krzysik (2015) Timmermans & Jayne (2016)
Signed distance from a <u>section T/S isopycnal</u> mean. Not globally invariant.	$\gamma = \text{sgn}(T - \bar{T}) \left( \alpha^2(T - \bar{T})^2 + \beta^2(S - \bar{S})^2 \right)^{\frac{1}{2}}$	Klymak et al. (2015)

Different disciplines also define spice according to their needs. For example sound speed depends on temperature and salinity in ways not captured by density alone. Acousticians have also developed their definition of spice (Dzieciuch, Munk and Rudnick, 2004; Colosi and Rudnick, 2020) to interpret sound speed anomalies that produce measurable acoustic signals, with direct implications for acoustic tomography, underwater communication, and the interpretation of acoustic observing systems.

The issues surrounding the definition of spice extend directly to modeling and prediction. Ocean models often under-resolve fine-scale T-S variability, particularly the compensated structures generated by mesoscale stirring that cascade tracer variance to small scales (Smith and Ferrari, 2009). This has implications for tracer transport, mixing parameterizations and coupled processes such as acoustics, where small changes in T-S structure can significantly alter sound speed. Without a consistent framework for defining and interpreting spice, progress in understanding and correcting these model deficiencies will remain limited.

## Why standardizing spice will move the science forward

The lack of a consistent definition of spice currently limits our ability to compare results across studies, synthesize observations across regions, and evaluate models against observations. As a result, key questions about along-isopycnal transport and tracer variance at various scales remain difficult to answer quantitatively at global scale. Despite the widespread use of spice as a diagnostic, key questions remain unresolved. Establishing a standardized framework for defining spice will enable:

- Consistent intercomparison across datasets collected at different scales and in different density regimes,
- Standard diagnostics for model evaluation,
- Quantitative budgets of along-isopycnal transport, enabling separation of lateral stirring from diapycnal mixing in heat, salt, and biogeochemical tracer budgets,
- Improved interpretation of acoustic observations, where spice-driven sound speed variability can affect the signal but lacks a unified framework for comparison with physical oceanography.

This working group aims to establish consistent definitions, diagnostics, and decision criteria to enable calculations and intercomparisons across disciplines and scales that are currently not possible. By bringing together observational, theoretical, and modeling perspectives, the group will identify best practices, clarify terminology, and produce open-access tools and guidance that serve the broader community beyond the SCOR support term.

## 2. Terms of Reference

- 1) **Compile existing spice formulations across fields:** Document the different methods used to interpret spice in physical oceanography, acoustics, and biogeochemistry, including the theoretical foundations, assumptions, domains of applicability, and sensitivity to reference state, spatial resolution, and ocean domain.
- 2) **Compare spice definitions across compiled classification:** assess where definitions and estimates are consistent and where they diverge, with explicit attention to interdisciplinary applications, including ocean acoustics and biogeochemical tracer transport.
- 3) **Develop a community best-practice framework:** Provide guidance on when spice is the appropriate diagnostic, how to choose among formulations, and a decision flowchart based on scientific objective, ocean region, and data type.
- 4) **Compile a georeferenced database of relevant studies and observational contexts:** Characterize the relationship between spice variability and the density ratio across ocean regimes, providing a community resource to guide future intercomparison and observational design
- 5) **Identify priorities for improving the representation of compensated T-S variability in ocean models and spice budgets:** Evaluate implications for tracer transport, mixing parameterizations, tracer budgets, and climate projections.

### 3. Deliverables

- 1) **Peer-review synthesis paper:** A comprehensive review of spice definitions, terminology, and applications across disciplines (ToR 1-3)
- 2) **Best-practice framework document with decision flowchart.** A community guideline document for selecting and applying spice diagnostics across regimes and disciplines (ToR 2-3)
- 3) **Open-source toolbox** (MATLAB/Python) implementing recommended spice diagnostics, enabling consistent, reproducible calculation of along-isopycnal variability across observational and model datasets, with documented workflows for common use cases (e.g., tracer variance budgets, acoustic interpretation, model evaluation). (ToR 2,3)
- 4) **Georeferenced community database of studies and key observational datasets across ocean regimes that focus on along-isopycnal variability**, including classification by scale and dynamical regime, designed to enable intercomparison of diagnostics and to assess the dynamical relevance of spice variability (ToR4)
- 5) **Community wiki hosted on GitHub:** central access hub for the toolbox, database, documentation and training materials (ToR 1-4)
- 6) **White paper on future observational and modeling needs:** Identifying requirements for resolving spice variability and constraining its role in transport and mixing (ToR 5).

### 4. Working plan

The Working Group (WG) is structured into three phases over four years (2027-2030). The plan is to first establish a common diagnostic and conceptual framework, then evaluate and apply the framework across regimes, and finally synthesize and produce community-facing tools. Each phase is aligned with specific Terms of Reference (ToR) and Deliverables (D).

The WG will meet monthly via virtual meetings and convene in person at key international conferences. To efficiently address the ToR, the WG will organize into subgroups focused on (i) definitions and theory, (ii) diagnostics and implementation, (iii) interdisciplinary applications.

#### **Phase 1 Synthesis and standardization (January 2027- June 2028)**

*(Addresses ToR 1-3; initiates D1, D2, D4, D5)*

Phase 1 establishes a common conceptual and diagnostic framework for spice by synthesizing existing definitions and identifying key inconsistencies across disciplines.

#### ***January – June 2027 (Monthly meetings)***

The WG will conduct a coordinated literature synthesis spanning physical oceanography, acoustics, and biogeochemistry. A structured classification system will be developed to

categorize studies by definition, scale, dynamical regime, and application. This classification will provide the foundation for all subsequent comparisons and products.

Actions:

- Draft a classification system based on a thorough literature review
- Launch the community hub platform (D5) as a central repository for WG outputs
- Define the structure and metadata standards for the georeferenced database (D4)
- Begin populating the database with key studies and datasets

### ***July – December 2027 (Monthly meetings)***

Using the compiled literature and developing classification system, the WG will compare existing definitions and diagnostics of spice across datasets and regimes (ToR 2). Subgroups will evaluate how methodological choices (e.g. reference state, equation of state) affect interpretation.

This stage focuses on identifying key inconsistencies and establishing a common language across disciplines.

Actions:

- Propose a session and workshop for Ocean Sciences 2028
- Begin drafting the synthesis paper (D1), including the classification and intercomparison
- Initiate development of the best-practice framework and decision flowchart (D2)

### ***January – June 2028 — Monthly meetings + OSM 2028***

Building on this synthesis, the group will develop a best-practice framework that includes a decision flowchart for selecting and applying spice diagnostics. The framework and flowchart will be shared on the WG Github website (D4). The Ocean Sciences 2028 workshop will be used to gather community feedback and test the clarity and applicability of the framework.

Actions:

- Circulate an internal draft of the synthesis paper (D1)
- Solicit feedback on the draft best-practice framework and flowchart (D2)
- Expand and publicly share the initial version of the database (D4) via the GitHub hub (D5)

### **Phase 2: Applications Across Disciplines (July 2028 – December 2029)**

*(Addresses ToR 3–4; finalizes D1–D4; advances D5)*

Phase 2 evaluates the developed framework in Phase 1 across regimes and applications, with emphasis on its behavior as a passive versus dynamically active tracer (ToR 3-4).

### ***July 2028 – April 2029 (Monthly meetings + EGU general assembly)***

The WG will engage with the broader community, including acoustics, biogeochemistry, and modeling groups, to test and refine the framework developed in Phase 1. This phase ensures that the framework is not limited to physical oceanography but is applicable across disciplines.

Actions:

- Refine the best-practice framework and flowchart based on community feedback (D2)
- Develop the open-source toolbox implementing recommended diagnostics (D3)
- Expand the georeferenced database with community-contributed studies and datasets (D4)
- Finalize and submit the synthesis paper (D1)
- Propose a session/workshop for Ocean Sciences 2030

### ***May – December 2029 (Monthly meetings)***

The WG will use the georeferenced database to examine how spice variability depends on spatial scale, stratification, and dynamical regime. Particular focus will be placed on identifying conditions under which spice departs from passive behavior and contributes to mixing processes. These efforts will result in a structured technical synthesis of the dynamical role of spice, which will inform both the framework and subsequent synthesis products.

Actions:

- Release Version 1 of the toolbox (D3) and database (D4)
- Finalize documentation and workflows within the community hub (D5)
- Initiate a Special Issue in a scientific journal to collect community applications and case studies

### **Phase 3: Spice in a Changing Ocean (January – December 2030)**

*(Addresses ToR 5; completes D5–D6)*

Phase 3 integrates results and translates findings into community-facing products, with emphasis on implications for modeling and future observational strategies (ToR 5).

### ***January – June 2030 (Monthly meetings + OSM 2030)***

The group will evaluate implications for ocean models, including how unresolved compensated T-S variability affects tracer transport, mixing parameterizations, and predictive capability. Key observational and modeling gaps will be identified. The OSM session will showcase the group's outputs and gather final community input.

Actions:

- Draft the white paper on observational and modeling needs (D6)

- Assemble contributions for the Special Issue

**July – December 2030 (Monthly meetings)**

Final deliverables will be completed, including publication of the synthesis paper and best-practice framework, as well as release of the database and toolbox. A perspective document will be developed outlining priorities for future observations and model development. All resources will be integrated into a publicly accessible GitHub-based platform.

Actions:

- Release final versions of the toolbox (D3) and database (D4)
- Submit the white paper (D6)
- Integrate all outputs into the GitHub community hub (D5) for long-term public access
- Submit the Special Issue

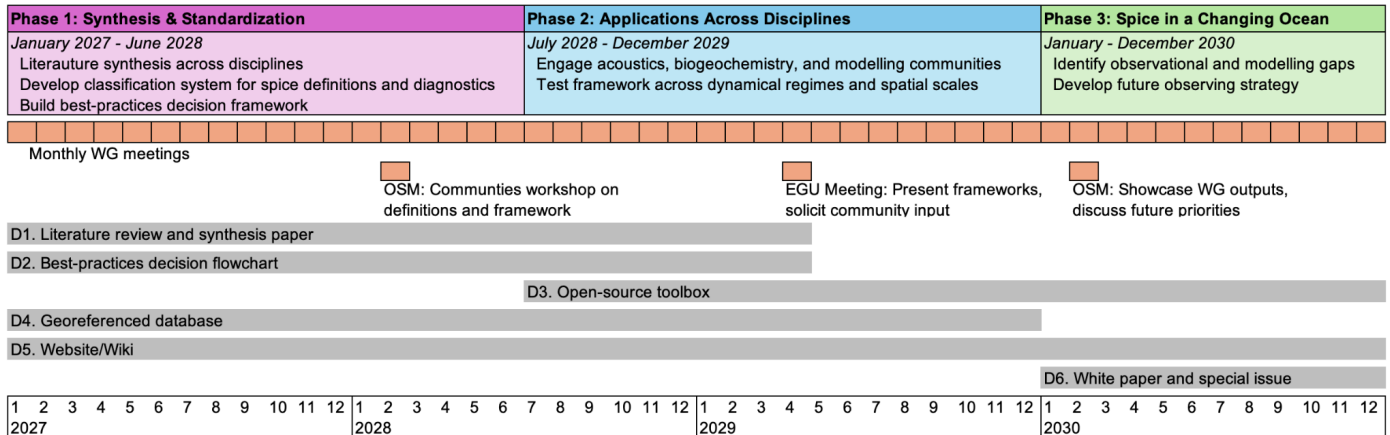


Figure 1: Gantt chart of the working plan over four years.

## 5. Capacity Building

A central goal of this working group is to make spice diagnostics transparent, accessible, and usable across disciplines. This WG aims to remove barriers for students and early career scientists who are starting to do research related to this field and for researchers outside the temperature-salinity (T-S) variability community, including acousticians, biogeochemists, climate modelers, and observational scientists, who often rely on spice-adjacent quantities without clear guidance.

### Open-access tools and reproducible workflows

A primary capacity-building deliverable of the WG is an open-source spice toolbox implemented in Python or MATLAB with comprehensive documentation and worked tutorial notebooks. The toolbox will be designed from the outset for accessibility to researchers without an advanced background in nonlinear thermodynamics or scientific computing: all functions will include

clearly documented inputs, outputs, and underlying assumptions, and the accompanying decision flowchart will guide users to the appropriate formulation for their application. Tutorial notebooks will span common use cases, computing spice from shipboard CTD profiles, from Argo float data, from glider observations, and from model output, and will include worked examples covering diverse ocean environments: the tropical thermocline, the Arctic halocline, thermohaline fronts, and the mixed layer. The toolbox will be developed with version control (GitHub), a formal test suite, and community contribution guidelines, ensuring it can be maintained and extended by the community after the WG concludes. All materials will be hosted on a permanent open-access repository with a DOI.

### **Online platform and guided learning**

The WG will develop an online platform integrating the database, toolbox, and best-practice framework. This platform will be designed to guide users through selecting and applying spice diagnostics, with step-by-step workflows tailored to scientific objectives, region, and data type.

Using the georeferenced database, users will be able to reference back to past studies, compare diagnostic approaches, and access additional context for how spice has been used across different regimes. To support adoption, we will develop training materials, including webinar series and guided workbooks that walk users through the decision framework and demonstrate applications across disciplines. These resources will be targeted toward students, early-career researchers, and scientists entering the field from adjacent disciplines.

### **Community engagement and dissemination**

To encourage adoption of the framework and tools, the working group will organize a special issue in a peer-reviewed journal focused on applications of spice and along-isopycnal variability. Contributors will be encouraged to apply the proposed framework and diagnostics, providing real-world examples of its use across different regions and disciplines. In addition, the working group will organize community workshops at major international meetings (e.g., Ocean Sciences, EGU) to present progress, solicit feedback, and provide hands-on training in the application of the framework and toolbox.

### **Inclusive and collaborative working environment**

The working group is composed primarily of early-career scientists who are committed to open science, transparency, and collaboration. This structure supports both capacity building within the group and broader community engagement. At the first meeting, the group will establish clear guidelines for participation, including expectations for open discussion, respectful feedback, and inclusive collaboration. Creating an environment where members feel comfortable asking questions, challenging assumptions, and contributing ideas is essential to achieving the group's goals.

Subgroups will be formed to encourage participation across expertise areas and career stages, ensuring that all members contribute to both scientific and community-facing outputs.

## 6. Working Group composition

The working group comprises 10 full members from 8 countries. The group is composed predominantly of early-career researchers, with six members within ten years of receiving their PhD, with expertise ranging from physical oceanography, ocean acoustics, biogeochemistry, and numerical modeling. While three full members are based at US institutions, their inclusion is essential for the group's interdisciplinary mandate. In particular, John Colosi (WHOI) represents unique expertise linking physical oceanography to ocean acoustics. Few researchers work at the intersection of physical oceanography and ocean acoustics at this level, and his inclusion ensures the working group's framework is built from the outset with acoustic applications in mind, rather than added as an afterthought. This directly supports ToR 3 and the white paper deliverable targeting interdisciplinary communities. We truly appreciate SCOR's commitment to representation in working groups. We aimed for our committee to be composed of individuals from diverse backgrounds seldom represented in our field.

### Full Members of Working Group

Name	Gender	Years since degree*	Institution (Country)	Expertise relevant to the proposal
Ailin Brakstad	F	3	University of Bergen (Norway)	Water mass transformation
John Colosi	M		Woods Hole Oceanographic Institution (USA)	Acoustics and spice variability
Nicole Couto (Co-Chair)	F	8	Scripps Institution of Oceanography (USA)	Finescale observations
Bieito Fernández Castro	M	10	University of Southampton (UK)	Microstructure and biogeochemical tracers
Estel Font	F	1	Southern Ocean Carbon-Climate Observatory (South Africa)	Finescale dynamics and biogeochemical tracers
Leo Middleton (Co-Chair)	M	4	University of Gothenburg (Sweden)	DD instability and spice spectra
Takeyoshi Nagai	M		Tokyo University of Marine Science and Technology (Japan)	Submesoscale dynamics
Enric Pallàs-Sanz	M		Centro de Investigación Científica y de Educación Superior de Ensenada (Mexico)	Glider observations in the Gulf of Mexico

Angel Ruiz-Angulo	M		University of Iceland (Iceland)	High-Latitude oceanography, mesoscale dynamics
Alejandra Sanchez-Rios (Co-Chair)	F	7	University of Hawai'i Mānoa (USA)	Double diffusion observation, microstructure measurements

\*Years since degree included for members within ten years of completing their PhD.

### **Associate Members of Working Group**

<b>Name</b>	<b>Gender</b>	<b>Years since degree*</b>	<b>Institution (Country)</b>	<b>Expertise relevant to the proposal</b>
Effie Fine	F	6	Scripps Institution of Oceanography (USA)	Thermal diffusivity parameterization, mixing
Izzy Giddy	F	2	University of Cape Town (South Africa)	Upper ocean variability
Sjord Groeskamp	M		Royal Netherlands Institute for Sea Research (Netherlands)	Ocean mixing and energetics
Takashi Ijichi	M		University of Tokyo (Japan)	Internal wave-driven mixing, fine-scale variability
Jennifer MacKinnon	F		Scripps Institution of Oceanography (USA)	Spice variance, finescale observation Internal waves

\*Years since degree included for members within ten years of completing their PhD.

## **7. Working Group contributions**

### **Full members**

*Ailin Brakstad* contributes observational expertise on water mass transformation in the Nordic Seas, a region where spice anomalies are particularly pronounced and well documented. Her work in high-latitude spicy water masses provides an important counterpoint to tropical and subtropical-focused studies within the group.

*John Colosi* provides a critical and underrepresented perspective: the relationship between along-isopycnal T-S variability and ocean acoustics. Very few researchers bridge physical oceanography and underwater acoustics at this level, and including this perspective ensures the working group's framework accounts for one of the most operationally significant applications of spice.

*Nicole Couto* contributes expertise in finescale and microstructure measurements, including data processing software development for microstructure instruments. Her observational focus is on bottom boundary mixing, submesoscale instabilities and the strategies needed to resolve submesoscale variability.

*Bieito Fernandez Castro* offers expertise in turbulent mixing, microstructure measurements from autonomous profiling floats, water-mass transformations and biogeochemical tracer dynamics. His combination of physical and biogeochemical perspectives, and experience with autonomous observing platforms, strengthens both the observational and interdisciplinary dimensions of the working group.

*Estel Font* provides expertise in underwater glider observations, water-mass transformation, and physical-biogeochemical coupling in oxygen minimum zones and upwelling boundary systems. As an early-career scientist working at the interface of physical and biogeochemical oceanography, she broadens the scope of spice applications beyond T-S dynamics.

*Leo Middleton* brings theoretical and numerical expertise in double diffusion, finescale parameterizations, and turbulence, with a focus on how compensated T-S structures drive diapycnal mixing. His work on the active role of spice in mixing dynamics is central to ToR 3, and his experience with parameterization schemes positions him to lead the modeling assessment.

*Takeyoshi Nagai* brings expertise across submesoscale dynamics, near-inertial waves, double diffusion, subduction, and tracer transport, with a strong combination of observational and theoretical contributions. His broad command of the processes that generate, modify, and destroy spice variance at multiple scales makes him uniquely suited to synthesize across the working group's themes.

*Enric Pallàs-Sanz* brings expertise in high-resolution observational oceanography, focusing on submesoscale dynamics, heat fluxes, and water mass transformation from glider and in situ observations. His work in the Gulf of Mexico, a region with distinct temperature–salinity structure, provides a key link between along-isopycnal variability and the processes that redistribute heat and tracers.

*Angel Ruiz-Angulo* brings expertise in high-latitude overturning dynamics, dense water formation, and the role of small-scale mixing processes in shaping large-scale circulation, particularly in the Iceland and Greenland Seas. He provides a process-oriented perspective on how turbulence, convection, and boundary interactions modify and redistribute spice during water mass transformation, linking finescale mixing to basin-scale structure.

*Alejandra Sanchez-Rios* brings expertise in heat and salt fluxes, double diffusion, and along-isopycnal mixing, particularly in temperature and salinity fronts such as Kuroshio current and Gulf Current. Her work on the interplay between spice anomalies, density ratio, and double-diffusive instabilities motivates several of the core questions this working group aims to address.

### **Associate members**

Associate members are established researchers who have engaged with along-isopycnal temperature-salinity variability in some dimension of their work, whether through observations, theory, or modeling, and whose broader expertise strengthens the working group's scope and reach. Their role is not to lead working group activities but to provide targeted feedback, connections to related programs and communities, and mentorship for early-career members. Associate membership also serves as a mechanism for geographic and disciplinary outreach: the current list spans South Africa, Japan, the Netherlands, and the United States, and we are actively working to confirm additional representation from India, where a growing community works on Bay of Bengal spiciness and water mass transformation in the Indian Ocean. We expect to add one or more Indian Ocean–focused Associate members before the working group formally convenes. This working group maintains strong international representation: the majority of its members are based outside the United States, spanning Europe, Asia, Africa, and Latin America, with geographic balance across Full members designed to capture perspectives from high-latitude, boundary current, and Southern Ocean regimes.

## **8. Relationship to other international programs and SCOR Working Groups**

### **SCOR Working Group 160: ATOMIX**

The proposed WG is thematically complementary to ATOMIX (WG160), which developed best practices for estimating the turbulent kinetic energy dissipation rate ( $\epsilon$ ) from velocity-based sensors. ATOMIX explicitly excluded the estimation of thermal variance dissipation rate ( $\chi$ ) partially because along-isopycnal T-S variability complicates its interpretation: in density compensated environments,  $\chi$ -derived mixing estimates are contaminated by lateral stirring of thermohaline intrusions and thus don't always reflect diapycnal mixing. This WG will directly address how along-isopycnal T-S structure affects our ability to obtain turbulence estimates from tracer variance, providing guidance that complements the ATOMIX framework where it left off. The ATOMIX model, including benchmark datasets, a wiki, a community best practices guides, and a peer-reviewed synthesis paper, provides an excellent template for our proposed framework.

### **SCOR Working Group 168: 4D-BGC**

The 4D-BGC Working Group (WG 168) is developing four-dimensional gridded data products of ocean interior biogeochemical properties from BGC-Argo observations. Along-isopycnal T-S structure governs much of the lateral tracer transport in the ocean interior; a consistent spice framework will improve the physical interpretation of 4D-BGC products and help distinguish isopycnal stirring from diapycnal mixing in biogeochemical budgets.

## **Global observation networks**

Phase 2 of the WG's activities - testing and applying the spice diagnostic framework across ocean regimes and disciplines - will draw extensively on global observation networks including Argo, GO-SHIP, and OceanGliders. Core Argo T-S profiles offer near global coverage of the upper two kilometers of the ocean at temporal and spatial scales required to characterize spice variability across dynamical regimes. The expanding BGC-Argo array additionally co-locates biogeochemical measurements with T-S profiles, directly supporting the WG's investigation of along-isopycnal transport. The OceanGliders program is similarly growing as a globally coordinated network of autonomous observations that especially excels in near-coastal regions where there are fewer Argo floats.

Where Argo coverage is sparse (at full ocean depth, in boundary current systems, and at high latitudes) GO-SHIP repeat hydrographic sections provide the high-quality, full-depth T-S observations needed to characterize spice in the abyssal ocean. GLODAP provides biogeochemical data from the GO-SHIP network and other cruises, synthesized into quality-controlled, globally consistent data products that can be used to test the diagnostics as they apply to tracer variability along isopycnals.

WG members Brakstad, and Fernandez-Castro hold direct connections to the Argo and GO-SHIP communities and will serve as liaisons to these programs.

## **The UN Ocean Decade**

The proposed working group aligns with Challenges 8 (create a digital representation of the ocean) and 9 (skills, knowledge, technology, and participation for all) of the United Nations Decade of Ocean Science for Sustainable Development. The georeferenced database directly supports Challenge 8, and the open-source toolbox, and best practices guide support Challenge 9, bringing the peer-reviewed synthesis and special topics papers to an even broader audience.

## **9. Key References**

Colosi, J.A. and Rudnick, D.L. (2020) "Observations of upper ocean sound-speed structures in the North Pacific and their effects on long-range acoustic propagation at low and mid-frequencies," *The Journal of the Acoustical Society of America*, 148(4), pp. 2040–2060. Available at: <https://doi.org/10.1121/10.0002174>.

Dzieciuch, M., Munk, W. and Rudnick, D.L. (2004) "Propagation of sound through a spicy ocean, the SOFAR overture," *The Journal of the Acoustical Society of America*, 116(3), pp. 1447–1462. Available at: <https://doi.org/10.1121/1.1772397>.

Echols, R. and Riser, S.C. (2020) "Spice and Barrier Layers: An Arabian Sea Case Study." Available at: <https://doi.org/10.1175/JPO-D-19-0215.1>.

Fernández-Castro, B. *et al.* (2026) "Global Observational Estimates of Thermohaline Transformations by Interior Ocean Mixing." Available at: <https://doi.org/10.1175/JPO-D-25-0265.1>.

Fine, E.C. *et al.* (2018) "Microstructure Observations of Turbulent Heat Fluxes in a Warm-Core Canada Basin Eddy," *Journal of Physical Oceanography*, 48(10), pp. 2397–2418. Available at: <https://doi.org/10.1175/JPO-D-18-0028.1>.

Jaeger, G.S. *et al.* (2020) "How Spice is Stirred in the Bay of Bengal," *Journal of Physical Oceanography*, 50(9), pp. 2669–2688. Available at: <https://doi.org/10.1175/JPO-D-19-0077.1>.

Klymak, J.M. *et al.* (2015) "Along-isopycnal variability of spice in the North Pacific," *Journal of Geophysical Research: Oceans*, 120(3), pp. 2287–2307. Available at: <https://doi.org/10.1002/2013JC009421>.

Legg, S. and McWilliams, J.C. (2000) "Temperature and Salinity Variability in Heterogeneous Oceanic Convection." Available at: [https://journals.ametsoc.org/view/journals/phoc/30/6/1520-0485\\_2000\\_030\\_1188\\_tasvih\\_2.0.co\\_2.xml](https://journals.ametsoc.org/view/journals/phoc/30/6/1520-0485_2000_030_1188_tasvih_2.0.co_2.xml) (Accessed: September 16, 2024).

McDougall, T. and Krzysik, O. (2015) "Spiciness," *Journal of Marine Research*, 73(5). Available at: [https://elischolar.library.yale.edu/journal\\_of\\_marine\\_research/408](https://elischolar.library.yale.edu/journal_of_marine_research/408).

Sanchez-Rios, A. *et al.* (2024) "Characterization of Mixing at the Edge of a Kuroshio Intrusion into the South China Sea: Analysis of Thermal Variance Diffusivity Measurements." Available at: <https://doi.org/10.1175/JPO-D-23-0007.1>.

Smith, K.S. and Ferrari, R. (2009) "The Production and Dissipation of Compensated Thermohaline Variance by Mesoscale Stirring," *Journal of Physical Oceanography*, 39(10), pp. 2477–2501. Available at: <https://doi.org/10.1175/2009JPO4103.1>.

## Appendix

Relevant publications for each of the committee members

### Ailin Brakstad

M. Årthun, A. Brakstad, J. Dörr, H.L. Johnson, C. Mans, S. Semper, and K. Våge, 2025. 'Atlantification drives recent strengthening of the Arctic overturning circulation'. *Science Advances*, 11 (28). DOI: [10.1126/sciadv.adu1794](https://doi.org/10.1126/sciadv.adu1794)

K. Svingen, A. Brakstad, K. Våge, W.J. von Appen, and L. Papritz, 2023. 'The Impact of Cold-Air Outbreaks and Oceanic Lateral Fluxes on Dense-Water Formation in the Greenland Sea from a 10-Year Moored Record (1999-2009)'. *Journal of Physical Oceanography*, 53 (6), 1499-1517. <https://doi.org/10.1175/JPO-D-22-0160.1>

A. Brakstad, G. Gebbie, K. Våge, E. Jeansson, and S.R. Ólafsdóttir, 2023. 'Formation and pathways of dense water in the Nordic Seas based on a regional inversion.' *Progress in Oceanography*, 212. <https://doi.org/10.1016/j.pocean.2023.102981>

J. Huang, R.S. Pickart, R.X. Huang, P. Lin, A. Brakstad, and F. Xu, 2020. 'Sources and upstream pathways of the densest overflow water in the Nordic Seas'. *Nature Communications* 11 (1), 1-9. <https://www.nature.com/articles/s41467-020-19050-y>

A. Brakstad, K. Våge, L. Håvik, and G.W.K. Moore, 2019. 'Water mass transformation in the

Greenland Sea during the period 1986-2016'. *Journal of Physical Oceanography* 49 (1), 121-140. <https://doi.org/10.1175/JPO-D-17-0273.1>

### **John Colosi**

John A. Colosi, Heriberto J. Vazquez, Bruce Cornuelle, Peter F. Worcester, Matthew A. Dzieciuch; Estimation of surface layer and Pacific summer water properties from acoustic transmissions in the Beaufort duct using a tomographic array during 2016–2017. *J. Acoust. Soc. Am.* 1 October 2023; 154 (4\_supplement): A133. <https://doi-org.eres.library.manoa.hawaii.edu/10.1121/10.0023030>

Edward L. Richards, John A. Colosi; Observations of ocean spice and isopycnal tilt sound-speed structures in the mixed layer and upper ocean and their impacts on acoustic propagation. *J. Acoust. Soc. Am.* 1 October 2023; 154 (4): 2154–2167. <https://doi-org.eres.library.manoa.hawaii.edu/10.1121/10.0021311>

John A. Colosi, William Zinicola-Lapin; Sensitivity of mixed layer duct propagation to deterministic ocean features. *J. Acoust. Soc. Am.* 1 March 2021; 149 (3): 1969–1978. <https://doi-org.eres.library.manoa.hawaii.edu/10.1121/10.0003821>

John A. Colosi, Timothy F. Duda, Ying-Tsong Lin, James F. Lynch, Arthur E. Newhall, Bruce D. Cornuelle; Observations of sound-speed fluctuations on the New Jersey continental shelf in the summer of 2006. *J. Acoust. Soc. Am.* 1 February 2012; 131 (2): 1733–1748. <https://doi-org.eres.library.manoa.hawaii.edu/10.1121/1.3666014>

Murat Kucukosmanoglu, John A. Colosi, Peter F. Worcester, Matthew A. Dzieciuch, Daniel J. Torres; Observations of sound-speed fluctuations in the Beaufort Sea from summer 2016 to summer 2017. *J. Acoust. Soc. Am.* 1 March 2021; 149 (3): 1536–1548. <https://doi-org.eres.library.manoa.hawaii.edu/10.1121/10.0003601>

### **Nicole Couto**

Alford, M. H., Le Boyer, A., Ren, A. S., Voet, G., Bellerjeau, C., Whalen, C. B., Hall, B., & Couto, N. (2025). Observations of Turbulence Generated by a Near-Inertial Wave Propagating Downward in an Anticyclonic Eddy. *Geophysical Research Letters*, 52(6), e2024GL114070. <https://doi.org/10.1029/2024GL114070>

Alford, M. H., Wynne-Cattanach, B., Le Boyer, A., Couto, N., Voet, G., Spingys, C. P., Castro, B. F., Forryan, A., Garabato, A. C. N., & Haren, H. van. (2025). Buoyancy Flux and Mixing Efficiency from Direct, Near-Bottom Turbulence Measurements in a Submarine Canyon. *Journal of Physical Oceanography*, 55, 97-118. <https://doi.org/10.1175/JPO-D-24-0005.1>

Couto, N., Alford, M. H., MacKinnon, J., & Mickett, J. B. (2020). Mixing Rates and Bottom Drag in Bering Strait. *Journal of Physical Oceanography*, 50(3), 809-825. <https://doi.org/10.1175/JPO-D-19-0154.1>

Couto, N., MacKinnon, J. A., Simmons, H. L., & Alford, M. H. (2025). Near-bottom baroclinic and

submesoscale instability at the Chukchi shelfbreak. *Journal of Physical Oceanography*.  
<https://doi.org/10.1175/JPO-D-24-0161.1>

Le Boyer, A., Couto, N., Alford, M. H., Drake, H. F., Bluteau, C. E., Hughes, K. G., Naveira Garabato, A. C., Moulin, A. J., Peacock, T., Fine, E. C., Mashayek, A., Cimoli, L., Meredith, M. P., Melet, A., Fer, I., Dengler, M., & Stevens, C. L. (2023). Turbulent diapycnal fluxes as a pilot Essential Ocean Variable. *Frontiers in Marine Science*, 10.  
<https://www.frontiersin.org/articles/10.3389/fmars.2023.1241023>

## **Bieito Fernández Castro**

Fernández Castro, B., Groeskamp, S., Broullón, E., Clément, L., Evans, D.G., Naveira Garabato, A.C., Williams, R.G. (2026) Global Observational Estimates of Thermohaline Transformations by Interior Ocean Mixing. *Journal of Physical Oceanography*. Early online (23 Feb 2026). Doi:10.1175/JPO-D-25-0265.1

Broullón, E., Fernández Castro, B., Naveira Garabato, A.C., Clément, L., Oltmanns, M., Williams, R.G. (2026) Isopycnal Stirring and Diapycnal Mixing in the Eastern North Atlantic Inferred from Argo Observations. *Journal of Physical Oceanography*, 56(3), 627–641.  
Doi:10.1175/JPO-D-25-0090.1

Oglethorpe, K.†, Fernández Castro, B., Spingys, C.P., Naveira Garabato, A.C., Williams, R.G. (2025) The Role of Mesoscale Eddy Stirring and Microscale Turbulence in Sustaining Biological Production in the Subtropical Gyres. *Global Biogeochemical Cycles*, 39(9), e2024GB008180. Doi:10.1029/2024GB008180

Fernández Castro, B., Naveira Garabato, A.C., Mazloff, M.R., Williams, R.G. (2025) Sources, Pathways, and Drivers of Sub -Antarctic Mode Water Formation. *AGU Advances*, 6(2), e2024AV001449. doi:10.1029/2024AV001449.

Fernández Castro, B., Fernández Román, D., Ferron, B., Fontela, M., Lherminier, P., et al. (2024) Isopycnal Eddy Stirring Dominates Thermohaline Mixing in the Upper Subpolar North Atlantic. *JGR: Oceans*, 129(9), e2023JC020817. Doi:10.1029/2023JC020817.

## **Estel Font**

Font, E., Portela, E., Swart, S., & Queste, B.Y. (submitted). Disentangling physical and biological drivers of mode water oxygen change above an oxygen minimum zone.

Font, E., Portela, E., Swart, S., Pinto-Juica, M., & Queste, B.Y. (2026). Spatiotemporal scales of mode water transformation in the Sea of Oman. *Ocean Sci.*, 22, 387401.  
<https://doi.org/10.5194/os-22-387-2026>

Font, E., Swart, S., Vinaychandran, P.N., & Queste, B.Y. (2025). On mode water formation and erosion in the Arabian Sea: Forcing mechanisms, regionality, and seasonality. *Ocean Sci.*, 21, 13491368. <https://doi.org/10.5194/os-21-1349-2025>.

Font, E., Swart, S., Bruss, G., Sheehan, P.M.F., Heywood, K.J., & Queste, B.Y. (2024). Ventilation of the Arabian Sea oxygen minimum zone by Persian Gulf Water. *Journal of Geophysical Research: Oceans*, 129, e2023JC020668. <https://doi.org/10.1029/2023JC020668>

Font, E., Queste, B.Y., & Swart, S. (2022). Seasonal to intraseasonal variability of the upper ocean mixed layer in the Gulf of Oman. *Journal of Geophysical Research: Oceans*, 127, e2021JC018045. <https://doi.org/10.1029/2021JC018045>

### **Leo Middleton**

Middleton, L., Wu, W., D'Asaro E. A., Johnston, S., Rudnick, D., Tarry, D., Poulain, P. M., Farrar, J. T., Berta, M., Shcheribina, A., Mahadevan, A. (2025). Observations of a splitting ocean cyclone resulting in subduction of surface waters, *Science Advances*

Middleton, L., Davis, P.E., Nicholls, K.W., and Taylor, J.R. (2022). Double-Diffusion as a Driver of Turbulence in the Stratified Boundary Layer under George VI Ice Shelf, *Geophysical Research Letters*

Middleton, L., Fine, E., Alford, M., Mackinnon, J. and Taylor, J.R. (2021). Estimating Dissipation Rates Associated with Double-Diffusion, *Geophysical Research Letters*

Middleton, L., Vreugdenhil, C.E., Holland, P.R. and Taylor, J.R. (2021). Numerical Simulations of Melt-Driven Double-Diffusive Fluxes in a Turbulent Boundary Layer beneath an Ice Shelf, *Journal of Physical Oceanography*

Middleton, L. and Taylor J.R. (2020). A general criterion for the release of background potential energy through double diffusion, *Journal of Fluid Mechanics: Rapids*

### **Takeyoshi Nagai**

Ikeda, Y., & Nagai, T. (2026). Intense isopycnal stirring and double-diffusion contributing to microscale variance in the Kuroshio Extension front. *Journal of Geophysical Research: Oceans*, 131, e2025JC022933. <https://doi.org/10.1029/2025JC022933>

Duran Gomez, G.S., Nagai, T. (2025) Submesoscale Eddy induced nitrate upwelling and effect on biological production in the upstream Kuroshio Current. *Sci Rep* 15, 22618. <https://doi.org/10.1038/s41598-025-05269-6>

Nagai, T., Hasegawa, D., Tsutsumi, E. et al. (2021) The Kuroshio flowing over seamounts and associated submesoscale flows drive 100-km-wide 100-1000-fold enhancement of turbulence. *Commun Earth Environ* 2, 170. <https://doi.org/10.1038/s43247-021-00230-7>

Nagai, T., Tandon, A., Kunze, K. & Mahadevan (2015) A. Spontaneous generation of near-inertial waves by the Kuroshio Front. *J. Phys. Oceanogr.* 45, 2381–2406.

Nagai, T., R.Inoue, A.Tandon, and H.Yamazaki (2015), Evidence of enhanced double-diffusive convection below the main stream of the Kuroshio Extension, *J. Geophys. Res. Oceans*, 120, 8402–8421, doi:10.1002/2015JC011288.

### **Enric Pallàs-Sanz**

Gentil, Mathieu & de Marez, Charly & Pallàs-Sanz, Enric & Bosse, Anthony & Tenreiro, Miguel & Laxenaire, Rémi. (2025). High-Resolution Observations Unveil (Sub)Mesoscale Heat Fluxes Shaping Upper-Ocean Heat Content. 10.22541/essoar.176530386.66262066/v1.

Gentil, M., Pallàs-Sanz, E., Middleton, L., Ruiz-Angulo, A., Meunier, T., Durante, G., et al. (2024). Distribution, mixing, and transformation of a Loop Current Ring waters: The case of Gulf of Mexico. *Geophysical Research Letters*, 51, e2024GL110845. <https://doi.org/10.1029/2024GL110845>

Márquez-Artavia, A., Pallàs-Sanz, E., & Tenreiro, M. (2024). On the seasonal cycle of phytoplankton bio-optical properties inside a warm core ring in the Gulf of Mexico. *Journal of Geophysical Research: Oceans*, 129, e2023JC020837. <https://doi.org/10.1029/2023JC020837>

Pérez, J. G. C., Pallàs-Sanz, E., Tenreiro, M., Meunier, T., Jouanno, J., & Ruiz-Angulo, A. (2022). Overturning instabilities across a Warm Core Ring from glider observations. *Journal of Geophysical*

Sosa-Gutiérrez R., Pallàs-Sanz E., Jouanno J., Chaigneau A., Candela J., & Tenreiro M. (2020). Erosion of the subsurface salinity maximum of the Loop Current Eddies from glider observations and a numerical model. *Journal of Geophysical Research: Oceans*, 125, e2019JC015397. <https://doi.org/10.1029/2019JC015397> *Research: Oceans*, 127, e2021JC017527. <https://doi.org/10.1029/2021JC017527>

### **Angel Ruiz**

Durante, G., Sheinbaum, J., Domínguez-Guadarrama, A., Jouanno, J., Hiron, L., Send, U., Verdugo-Ortega, H. and Ruiz-Angulo, A., 2026. Frontal-driven water-mass transformation in a western boundary current: Evidence from the Yucatan current. *Geophysical Research Letters*, 53(5), p.e2025GL119064.

De Marez, C., Ruiz-Angulo, A. and Gula, J., 2025. Mesoscale induced vertical fluxes over the Iceland-Faroe ridge. *Geophysical Research Letters*, 52(13), p.e2025GL115520.

De Marez, C., Vives, C.R., Portela, E. and Ruiz-Angulo, A., 2025. Mesoscale ocean processes: The critical role of stratification in the Icelandic region. *Journal of Geophysical Research: Oceans*, 130(6), p.e2025JC022664.

Gentil, M., Pallàs-Sanz, E., Middleton, L., Ruiz-Angulo, A., Meunier, T., Durante, G., Tenreiro, M., Allis Estrada, S.N. and Sheinbaum, J., 2024. Distribution, mixing, and transformation of a Loop Current Ring waters: The case of Gulf of Mexico. *Geophysical Research Letters*, 51(23), p.e2024GL110845.

Thomas Meunier, Miguel Tenreiro, Enric Pallàs-Sanz, Jose Ochoa, Angel Ruiz-Angulo, Esther Portela, Simò Cusí, Pierre Damien, and Xavier Carton. Intrathermocline Eddies Embedded Within an Anticyclonic Vortex Ring. *Geophysical Research Letters*, 45(15):7624–7633, aug 2018.

### **Alejandra Sanchez-Rios**

Hilditch, J. P., Bergentz, K., Northcott, D., Luko, C. D., Sanchez-Rios, A., et al. (2025). Observations of subduction, downward heat flux and dense filament collapse in the northern

Gulf of Mexico. *Journal of Geophysical Research: Oceans*, 130(11), e2025JC022570.  
<https://doi.org/10.1029/2025JC022570>

Sanchez-Rios, A., Shearman, R. K., Lee, C. M., Simmons, H. L., St. Laurent, L., et al. (2024). Characterization of mixing at the edge of a Kuroshio intrusion into the South China Sea: analysis of thermal variance diffusivity measurements. *Journal of Physical Oceanography*.  
<https://doi.org/10.1175/JPO-D-23-0007.1>

Sanchez-Rios, A., Shearman, R. K., Klymak, J., D'Asaro, E., & Lee, C. (2020). Observations of cross-frontal exchange associated with submesoscale features along the North Wall of the Gulf Stream. *Deep Sea Research Part I*, 163, 103342. <https://doi.org/10.1016/j.dsr.2020.103342>

Ballard, M. S., Sanchez-Rios, A., Taylor, R. T., Duda, T. F., Brakstad, A., Fer, I., et al. (submitted). Hydrographic variability and sound-channel dynamics in the Nordic Seas: implications for predicting acoustic arrival structure.

Dias Luko, C., MacKinnon, J. A., Waterhouse, A. F., Sanchez-Rios, A., et al. (submitted). Heat convergence at submesoscale salinity fronts boosts sea surface temperature, air-sea heat fluxes and downward heat transport.