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14. ABSTRACT The Northern Arabian Sea Circulation - autonomous research (NASCar) experiment (2015-2019) focused on the upper-ocean dynamics in the Arabian Sea and its relationship with the Indian Ocean monsoons and regional climate in general. During NASCar, fully autonomous oceanographic observations were conducted with a coordinated array of robotic instruments, including surface drifters, Seagliders, and several types of profiling floats. Reported here is an overview of an investigation of small-scale water mass interleaving, subduction, and barrier layer formation at thermohaline fronts in the interior Arabian Sea conducted as part of NASCar.						
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Final Technical Report for award #N00014-15-1-2317

Arabian Sea Fronts and Barrier Layers

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ABSTRACT

The Northern Arabian Sea Circulation – autonomous research (NASCar) experiment (2015–2019) focused on the upper-ocean dynamics in the Arabian Sea and its relationship with the Indian Ocean monsoons and regional climate in general. During NASCar, fully autonomous oceanographic observations were conducted with a coordinated array of robotic instruments, including surface drifters, Seagliders, and several types of profiling floats. Reported here is an overview of an investigation of small-scale water mass interleaving, subduction, and barrier layer formation at thermohaline fronts in the interior Arabian Sea conducted as part of NASCar.

LONG-TERM GOALS

The long-term goal of the Northern Arabian Sea Circulation – autonomous research (NASCar) DRI was to understand the upper-ocean dynamics in the Arabian Sea and its relationship with the Indian Ocean monsoons and regional climate in general.

OBJECTIVES

The primary objective of this project was to characterize small-scale watermass interleaving, subduction, and barrier layer formation at thermohaline fronts in the interior Arabian Sea.

Specific science questions were:

1. What combination of air-sea interactions and upper-ocean physical processes control mixed layer properties and upper ocean water mass modification in the interior of the Arabian Sea?
2. What are the scales, structure, and seasonality of these processes? How do they relate to semi-annual or monsoonal cycles?
3. What are the distributions of “special cases” (“barrier” and “compensated” layers)? How are they formed, where do they go, and how do they disappear?
4. What role do the barrier layers play in warm pool formation and monsoon initiation?

APPROACH

The Arabian Sea largely remains inaccessible to oceanographic vessels due to the piracy and ensuing UNOLS and USCG restrictions. Therefore, NASCar has adopted “cooperative autonomy” as the primary technical approach for studying the Arabian Sea interior (Centurioni et al., 2017). A broad array of autonomous instruments, including Surface drifters, Seagliders, and several types of profiling floats, was deployed in 2016-2017 with the help of US Naval Oceanographic Office (NAVO). This

autonomous array was operated collaboratively by the NASCar sciences team, with the aim to produce overlapping, comprehensive, and complementary observations.

ACCOMPLISHMENTS

Developing the “Mixing Bowl” working hypothesis

During the October 2016 meeting in Seattle, the NASCar Interior working group formulated the “mixing bowl” scientific concept for the Northern Arabian Sea. According to this concept, the processes of horizontal filamentation and vertical interleaving between the Bay of Bengal freshwater and the high salinity Northern Arabian Sea waters set the upper-ocean structure in the basin interior. Admixture of fresh water shoals the mixed layers, leading to SST feedback amplification that triggers the onset of the monsoon in April-May; mixing away of low salinity water during the monsoon season is key to resetting the monsoon cycle. Occurrence of barrier layers are seen as collateral phenomena in a wider class of thermohaline fine structure created by stirring and interleaving processes acting on disparate water masses in this region. We hypothesize that this fine structure is observable, and that it can provide insights into the mesoscale/sub-mesoscale dynamics that drive water mass modification in the Northern Arabian Sea. Subsequent research addressed various aspects of this hypothesis.

Analysis of historic observations of Arabian Sea water mass interleaving

In preparation for the NASCar fieldwork, the historic record of over 70,000 ARGO float profiles in the Arabian Sea and broader Northern Indian Ocean over the past 16 years was analyzed. The focus of the analysis was characterization of temporal and spatial variability of fine-scale water mass interleaving indicative of submesoscale subduction. Insight into the variability of the vertical layering can be gained from analysis of diapycnal spiciness curvature (DSC), a sensitive and robust indicator of interleaving activity (Shcherbina et al. 2015; Shcherbina et al. 2009); high values of DSC indicate vertical interfaces between interleaving water masses. The DSC climatology derived from ARGO observations reveals a broad maximum of interleaving activity in the Northern Arabian Sea (Fig. 1a). Active interleaving is typically observed following periods of mixed layer deepening associated with the winter and summer monsoon seasons (Fig. 1b,c). Interleaving tends to form a persistent peak at densities slightly deeper than the maximum mixed layer extent. This behavior supports the hypothesis that the observed interleaving is created by strongly-sheared three-dimensional submesoscale stirring associated with seasonal restratification of deep mixed layers. Unlike mixed layer depths (MLDs) in previously studied regions (Shcherbina et al. 2015), the Arabian Sea MLD exhibits two annual maxima: one in February – March and one in July – August, corresponding to the winter and summer monsoons. Interestingly, in the northern part of the basin (north of approximately 15°N), interleaving is produced predominantly during the *winter* mixed layer restratification. Conversely, in the central Arabian sea, restratification of the *summer* mixed layers produces the stronger interleaving peak, which, however, is shorter-lived. The reason for this difference is under investigation: it may be associated with variability of monsoonal surface forcing or differences in large-scale water mass structure north and south of the Arabian Sea Salinity Front (see below).

Characterization of barrier layers associated with the Arabian Sea Salinity Front (ASSF)

In 2016, two NASCar Seagliders occupied meridional transects in the central Arabian Sea and south of Sri Lanka (Fig. 2). In May, the eastern transect (along 60°E) crossed a frontal zone separating Arabian Sea High Salinity Water (surface salinity >36.2) to the north-west and fresher Bay of Bengal Water ($S < 35.8$) to the south-east – the Arabian Sea Salinity Front (ASSF, Fig. 3). The ASSF is purely a salinity feature, with no significant cross-front temperature gradient (Fig. 3b). As a result, water mass subduction across the ASSF is expected to create prominent barrier layers (BL) in the central Arabian Sea (de Boyer Montégut et al. 2014). Indeed, a 12-meter thick BL associated with an upper-pycnocline temperature inversion was observed by the Seaglider at the ASSF in mid-May (Fig. 4). The characteristic two-step structure of the temperature profile is indicative of recent subduction of relatively saltier and slightly warmer water from the north. As the summer monsoon develops in July – September, ASSF subduction is expected to intensify, creating thicker barrier layers at this location and further east.

Coordinated Lagrangian cluster observations

To address the “mixing bowl” hypothesis in the Central Arabian Sea, a subset of NASCar autonomous instruments were deployed as a coordinated multi-platform Lagrangian cluster. The site selection for the cluster deployment was guided by the analysis of historic Argo float observations (see above). Deployment region (box “c” in Fig. 1a) was chosen so as to offer the best chances of observing intense watermass interleaving during the spring intermonsoon season (February-April).

The Lagrangian cluster, consisting of two ALAMO profiling floats (PI: S. Jayne) and two Seagliders (PI: C. Lee), was deployed on 4 March 2017 by a NAVO vessel near the requested target. It was embedded in a large-scale deployment of autonomous instruments along the 1,300-km line crossing the interior Northern Arabian Sea from northwest to southeast. The ALAMO floats were set up to profile continuously between the surface and 300 m every 2 hours, thus following the mean upper-ocean (mixed layer and upper pycnocline) advection. Remarkably, the floats stayed within a few kilometers of each other throughout the duration of their 50-day 325-km drift through the Northern Arabian Sea (Fig. 5). The two Seagliders followed the drift of the target floats, navigating a 20 km × 20 km “bowtie” pattern in the Lagrangian frame of reference while profiling to 1,000 m every 4 to 5 hours. The Seaglider sampling schemes were complementary to those of the ALAMO floats, providing the synoptic three-dimensional context for the high-resolution float measurements.

Keeping the Seagliders in synchronized formation moving with the ALAMO floats was the main operational challenge of the experiment. Together with the APL Seaglider team, we developed an automated navigation system that a) ingested telemetry of the floats and the gliders in real time, b) made a statistical forecast of the reference frame translation, c) calculated the transformation of the survey pattern from the Lagrangian frame to geographic coordinates, and d) transmitted the updated navigation information to the gliders. The resulting tracks of the Seagliders in the Lagrangian frame of reference were fairly accurate (Fig. 6), owing to the rather simple and predictable mesoscale advection and weak wind forcing experienced by the cluster. An animation showing the progress of the coordinated Lagrangian cluster can be viewed at <https://youtu.be/WveJDHalS3g>.

Joint operation of floats and gliders during NASCar enabled comprehensive observation of the evolution of upper-ocean thermohaline structure in the central Arabian Sea. Successful completion of this coordinated multi-platform Lagrangian experiment was an important milestone in our continuing development of the “cooperative autonomy” concept.

Analysis of water mass interleaving

Coordinated Lagrangian cluster observations revealed rich thermohaline interleaving in the upper 300 m throughout the interior Arabian Sea region (Figs. 7, 8). These quasi-synoptic multi-platform observations allowed characterization of spatial scales of thermohaline variability without the typical detriment of space-time aliasing. Isopycnal decorrelation length scales of thermohaline variability were found to be 5–8 km, confirming its submesoscale nature. Vertical scales of interleaving features were 10–30 m.

Unexpectedly, strong submesoscale variability was found to extend well within the main pycnocline: The strongest isopycnal thermohaline variability was observed in two distinct layers at potential densities of 25.05 and 26.56 kg/m³, with mean isopycnal depths of 125 and 270 m, respectively. According to Monthly Isopycnal & Mixed-layer Ocean Climatology (MIMOC), these density layers do not outcrop anywhere in the basin at any time, except perhaps the Gulf of Oman where the mixed layer potential density reaches 25.03 kg/m³ in February. Therefore, formation of the observed horizontal thermohaline patchiness and vertical interleaving cannot be attributed to upper-ocean submesoscale processes, such as mixed-layer instability (MLI). Alternative origins of the observed submesoscale thermohaline variability are under investigation.

Upper-ocean currents tracked by the ALAMO profiling floats during the coordinated experiment in the interior Arabian Sea were relatively slow (~0.1 m/s) and steady, showing no signs of intense (sub-) mesoscale turbulence. Lateral dispersion was also weak: two floats stayed within a few kilometers of each other throughout their 50-day, 325 km drift. This suggests that the pronounced submesoscale variability observed in the Arabian Sea interior was “fossil,” i.e., created some time earlier and, potentially, elsewhere.

The interior Arabian Sea is generally characterized by inverted salinity stratification (salinity decreasing with depth) down to at least 1,000 m, which creates favorable conditions for salt fingering. Unstable salinity stratification was found to be further enhanced at the submesoscale interleaving interfaces, producing characteristic “saw tooth” profiles with straight segments and sharp cusps in temperature – salinity (T–S) space (Fig. 9). The straight segments on a T–S diagram corresponded to thermohaline stratification marginally unstable to salt fingering (typical Turner angles of 55–70°, density ratios of 2.1–5.7). This evidence suggests that the observed thermohaline interleaving structures may have been modified by double-diffusive mixing during the time elapsed since their initial formation.

A simple one-dimensional numerical model of double-diffusive mixing was developed. The model demonstrates the evolution of initially smooth thermohaline stratification into a saw-tooth profile similar to that observed in the Arabian Sea (Fig. 10). Simulations also predict the concentration of

remnant thermohaline stratification near the critical values of the Turner angle (or density ratio) with time, although the actual values depend on the double-diffusive parameterization used.

In parallel, we studied the watermass interleaving pathways in the fields of the MIT MSEAS numerical model, provided by NASCar collaborators P. Lermusiaux and P. Haley. This high-resolution (~2 km) nested model produced qualitatively similar interleaving features (Fig. 11), which were confirmed to be filaments of salinity (or spice) stirred by mesoscale and submesoscale flow. The range of thermohaline variability in the model compared favorably with that observed. The model, however, did not reproduce the sharp asymmetric distribution of properties across the interleaving layers observed in the field. This comparison illustrates the effects of small-scale mixing processes (specifically, double diffusion), which may be underrepresented even in state-of-the-art numerical models.

IMPACT

This work contributes an important regional counterpoint to the previous and ongoing studies of water mass interleaving and barrier layer formation in other areas of the World Ocean (e.g., Shcherbina et al. 2009; Shcherbina et al. 2015). Scientific understanding of the fine-scale upper-ocean processes gained in this project is informing the planning and execution of follow-on projects, such as the ONR Coherent Lagrangian Pathways from the Surface Ocean to Interior (CALYPSO) Departmental Research Initiative.

PUBLICATIONS AND PRESENTATIONS

Anderson, J., S.R. Jayne, A.Y. Shcherbina, L. Rainville, C.M. Lee (2020). Upper ocean temperature and salinity variability and compensation in the Arabian Sea. 2020 Ocean Sciences Meeting, 16-21 February 2020, San Diego, California, USA.

Anderson, J., S.R. Jayne, A.Y. Shcherbina, L. Rainville, C.M. Lee (TBD). Upper ocean temperature and salinity variability and compensation in the Arabian Sea. *Geophys. Res. Lett.*, in preparation.

Centurioni, L.R., V. Hormann, L.D. Talley, I. Arzeno, L. Beal, M. Caruso, P. Conry, R. Echols, H.J.S. Fernando, S.N. Giddings, A. Gordon, H. Graber, R.R. Harcourt, S.R. Jayne, T.G. Jensen, C.M. Lee, P.F.J. Lermusiaux, P. L'Hegaret, A.J. Lucas, A. Mahadevan, J.L. McClean, G. Pawlak, L. Rainville, S.C. Riser, H. Seo, A.Y. Shcherbina, E. Skillingstad, J. Sprintall, B. Subrahmanyam, E. Terrill, R.E. Todd, C. Trott, H.N. Ulloa, and H. Wang (2017). Northern Arabian Sea Circulation-Autonomous Research (NASCar): A research initiative based on autonomous sensors. *Oceanography*, 30(2):74–87, doi: 10.5670/oceanog.2017.224.

Lermusiaux, P.F.J., P.J. Haley Jr., S. Jana, A. Gupta, C.S. Kulkarni, C. Mirabito, W.H. Ali, D.N. Subramani, A. Dutt, J. Lin, A.Y. Shcherbina, C.M. Lee, and A. Gangopadhyay (2017). Optimal planning and sampling predictions for autonomous and Lagrangian platforms and sensors in the northern Arabian Sea. *Oceanography*, 30(2):172–185, doi: 10.5670/oceanog.2017.242.

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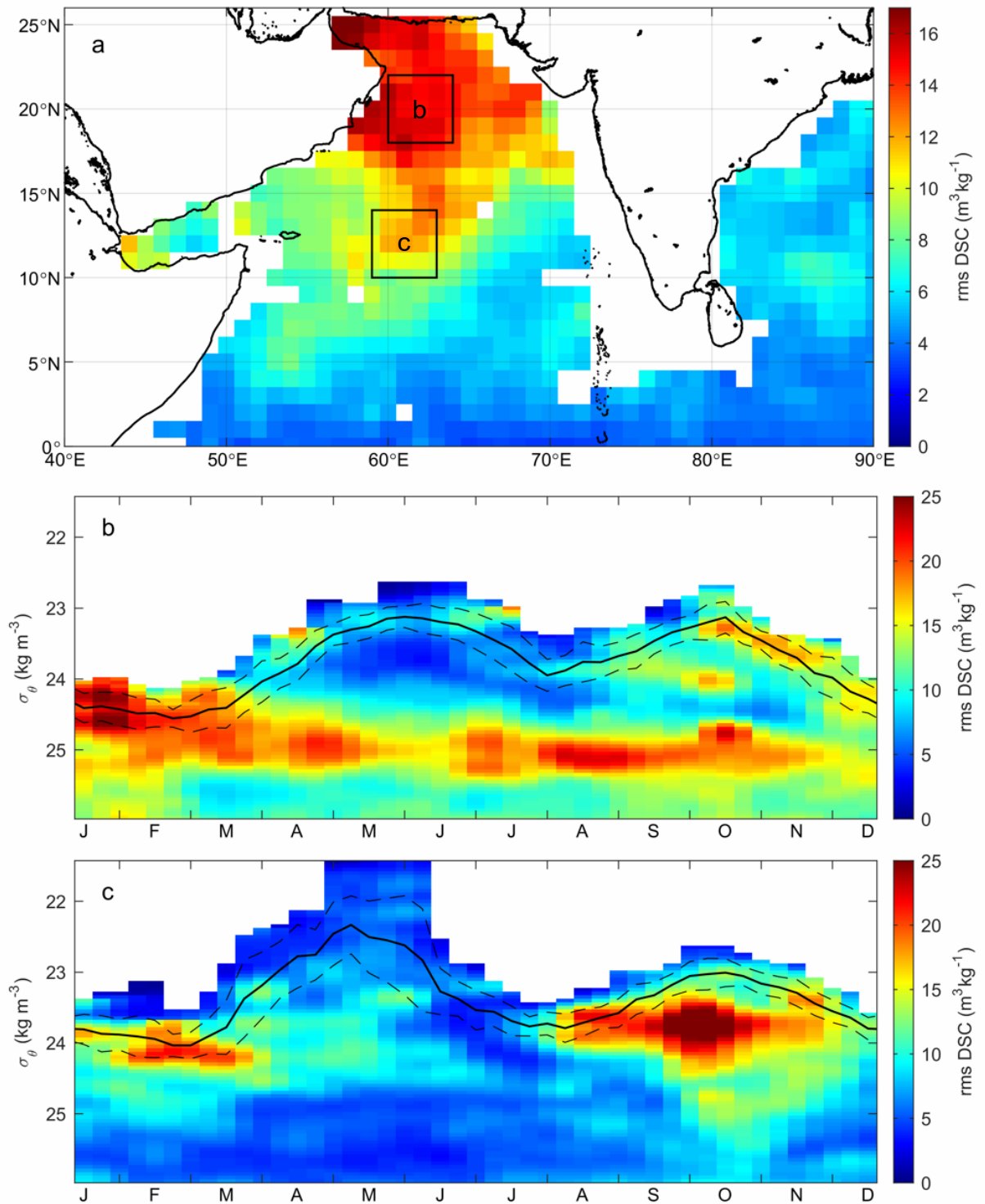


Fig. 1 Climatology of water mass interleaving in the Arabian Sea derived from 16 years (2000 – 2016) of ARGO profiling float observations. (a) Spatial distribution of root mean square (rms) diapycnal spiciness curvature (DSC) in the 21–25.5 kg m⁻³ potential density range. (b, c) Examples of seasonal cycle and density distribution of rms DSC in 2°×2° boxes centered at (b) 20°N, 62°E and (c) 12°N, 61°E. The locations of the boxes are marked with black rectangles in (a). Black solid and dashed lines in (b) and (c) indicate the mean and \pm one standard deviation of mixed layer density, respectively.

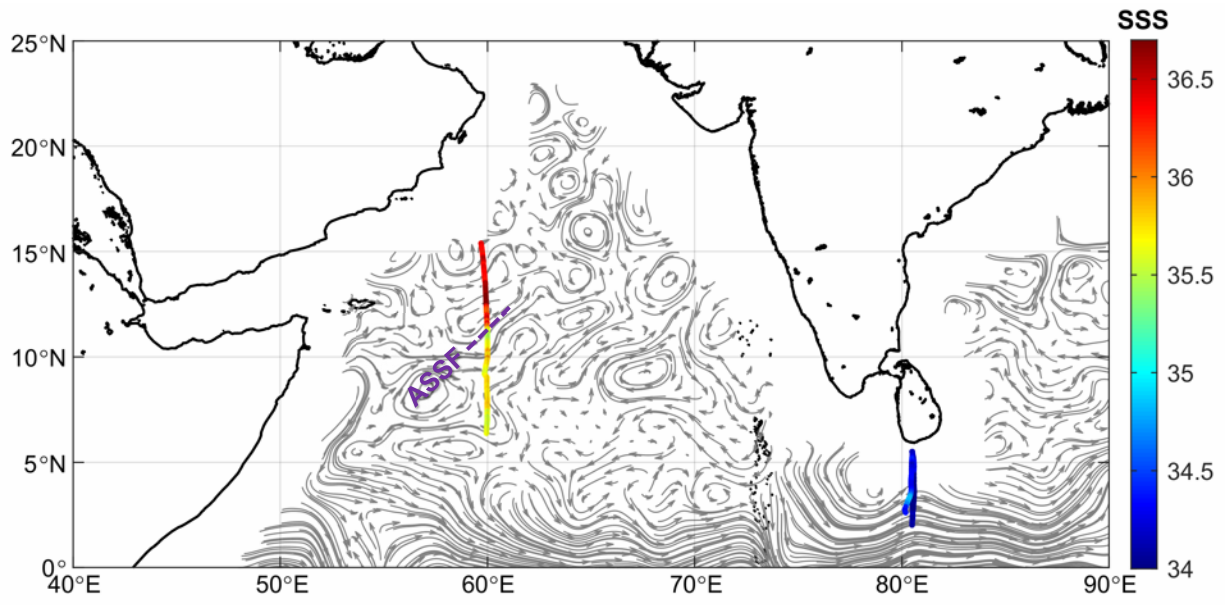


Fig. 2 NASCAR Seaglider observations in April – June 2016, colors indicating near-surface (5–15 m average) salinity. Grey arrows represent mean surface circulation in May 2016 derived from satellite altimeter and scatterometer data (OSCAR, courtesy of ESR). Upper-ocean structure along the 60°E transect is shown in detail in Fig. 3. The dashed purple line shows the location and likely orientation of the Arabian Sea Salinity Front (ASSF).

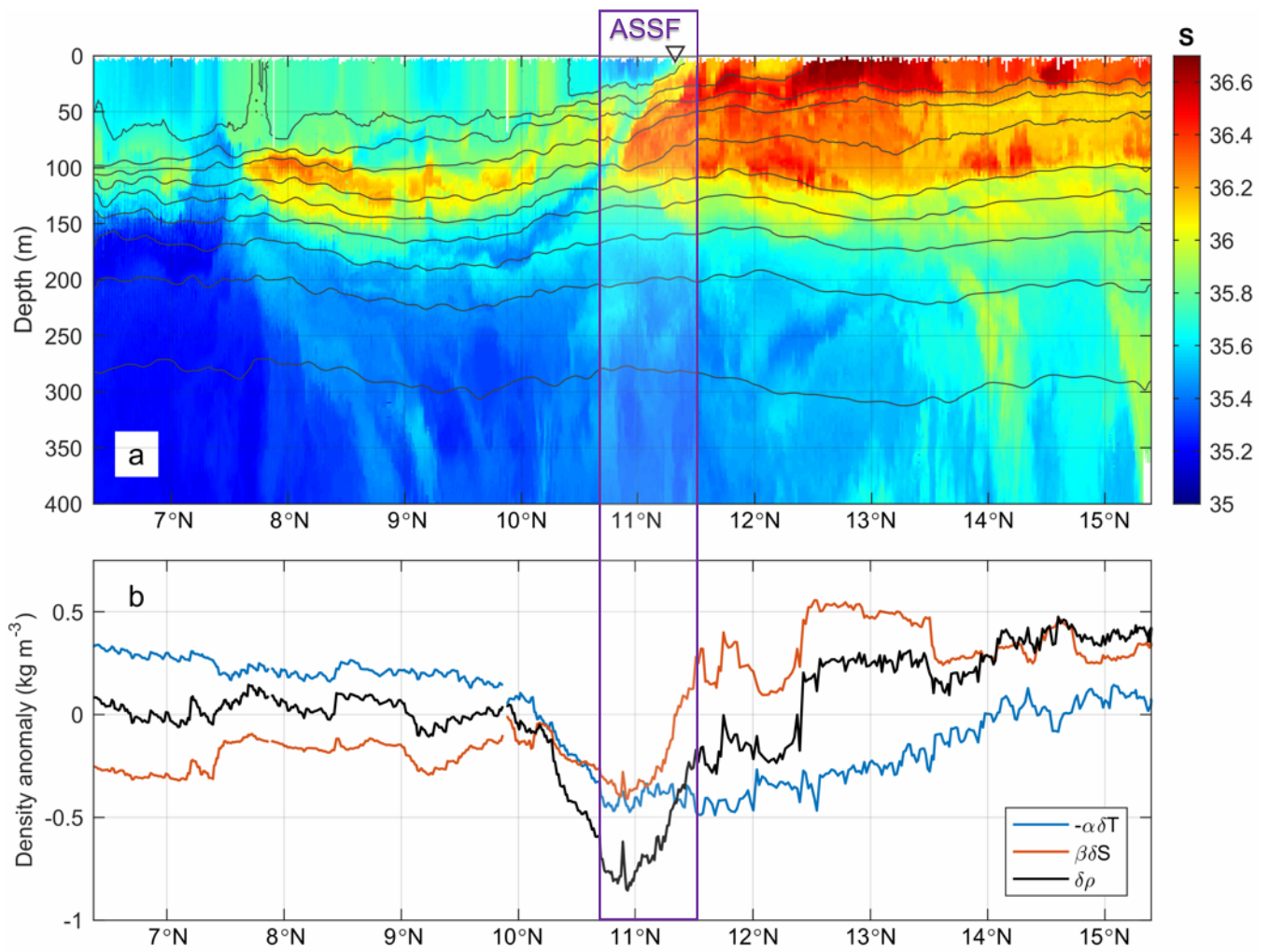


Fig. 3 (a) Salinity along the 60°E section observed with a NASCar Seaglider in April – June 2016. Grey isopycnal contours at 0.5 kg m^{-3} interval are overlaid. The purple rectangle marks the crossing of the Arabian Sea Salinity Front (ASSF) near 11°N. The black triangle marks the location of the profile shown in Fig. 4. The section extent is shown in Fig. 2. (b) Near-surface (5–15 m average) thermohaline variability along the section. Contributions of temperature (blue) and salinity (orange) to density variations (black) are shown.

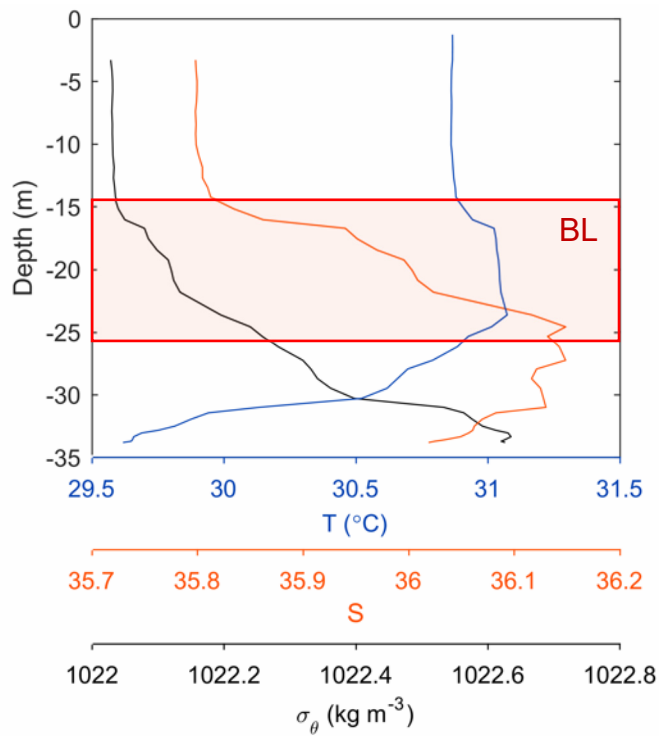


Fig. 4 Profiles of temperature (blue), salinity (orange) and density (black) at the ASSF. Note the 12-m thick barrier layer (BL) and the associated temperature inversion at 15–25 m depth. The profile location is marked in Fig. 3.

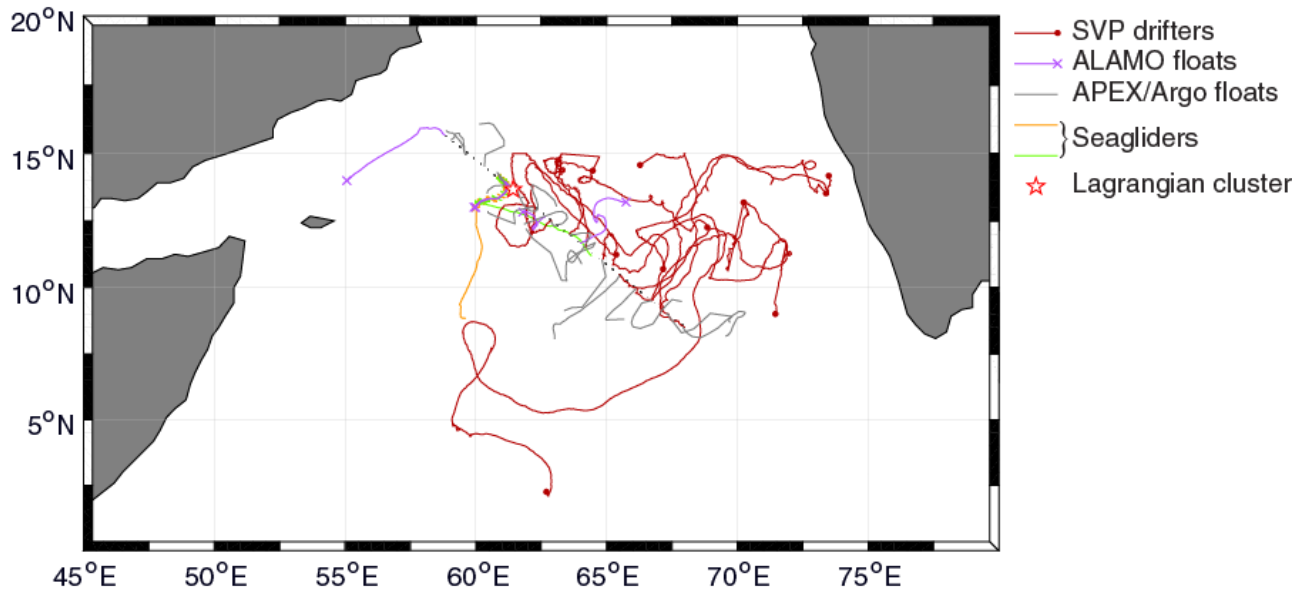


Fig. 5 Trajectories of autonomous instruments deployed for the Northern Arabian Sea interior study in March 2017 (as of 15 June 2017). The red star marks the deployment site of the coordinated Lagrangian cluster.

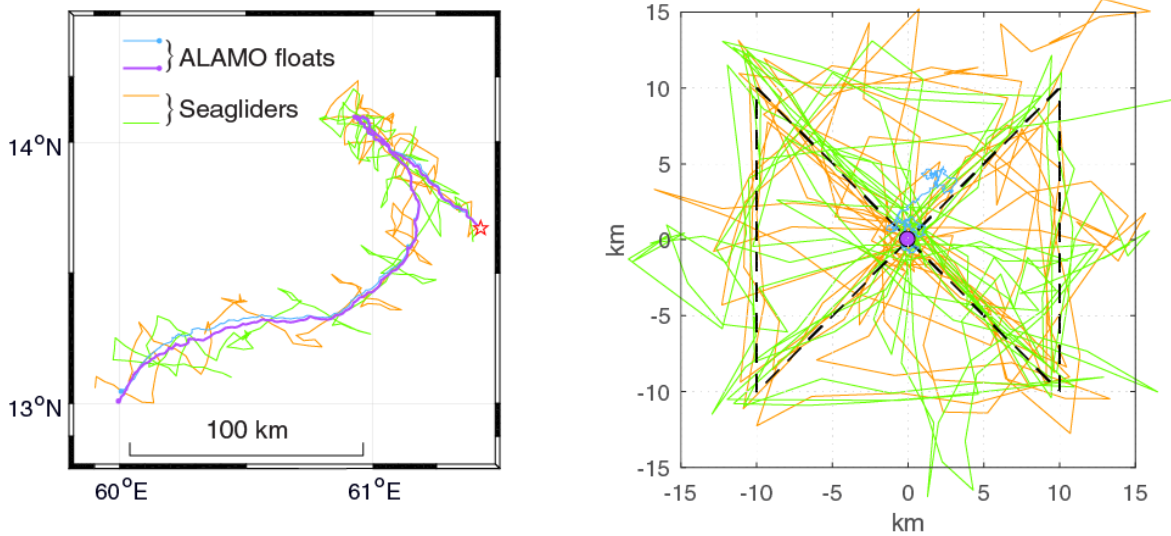


Fig. 6 Trajectories of the ALAMO floats and the Seagliders during the NASCar coordinated Lagrangian drift (4 March – 23 April 2017) in geographic coordinates (left) and in a Lagrangian frame of reference moving with one of the floats (right). During the drift, Seagliders aimed to navigate a “bowtie” pattern (black dashed lines) with respect to the target float.

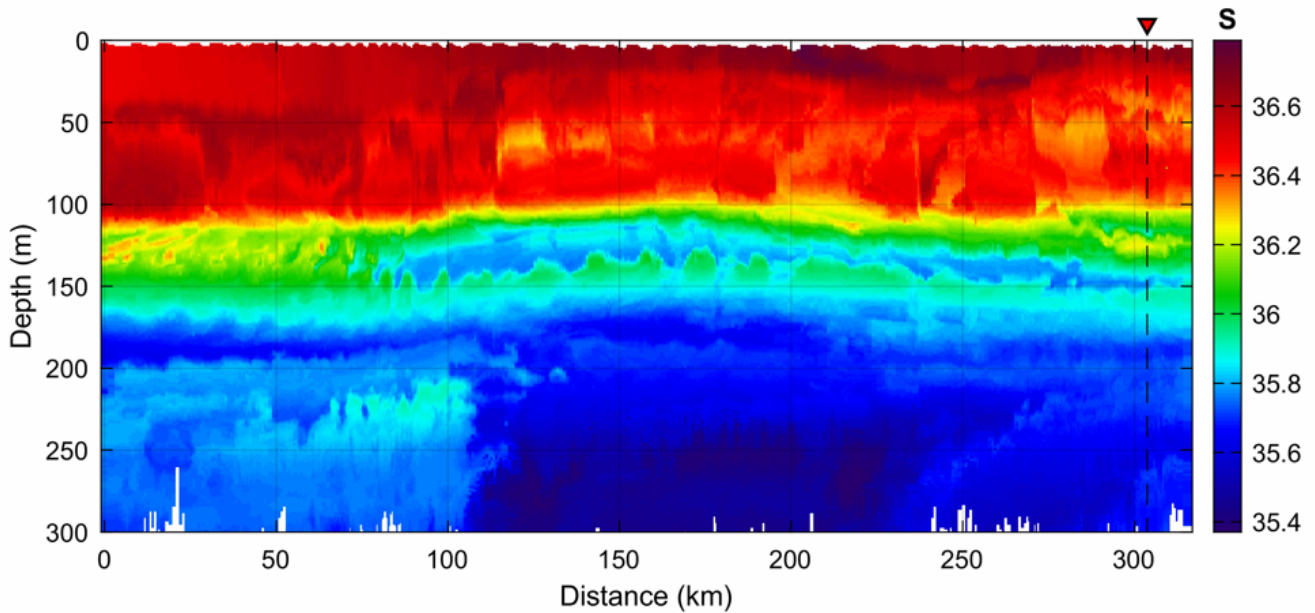


Fig. 7 Evolution of upper-ocean salinity fine structure observed by one of the ALAMO floats during the 50-day coordinated multi-instrument autonomous experiment in the interior NAS. Vertical coordinate is the semi-Lagrangian (isopycnal) depth. Numerous interleaving layers are clearly visible. Profiles at a location marked with a red triangle are shown in Fig. 8.

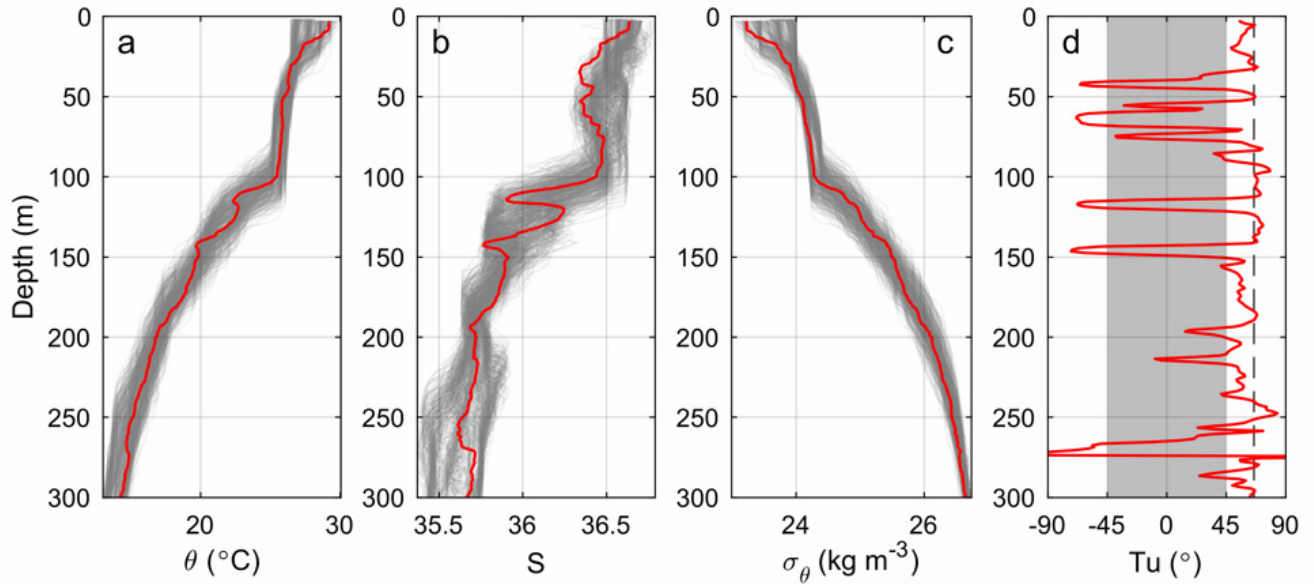


Fig. 8 Characteristic vertical profiles of (a) potential temperature, (b) salinity, (c) potential density, and (d) Turner angle, $Tu = \tan^{-1}[(\alpha\theta_z + \beta S_z)/(\alpha\theta_z - \beta S_z)]$, where α and β are the coefficients of thermal expansion and saline contraction, respectively. Turner angle value of 66° is marked in (d) for the reference. In (a)–(c) the envelope of the profiles over the course of the 50-day ALAMO float deployment is shown in grey, with one profile highlighted in red; location of the highlighted profile is marked in Fig. 7.

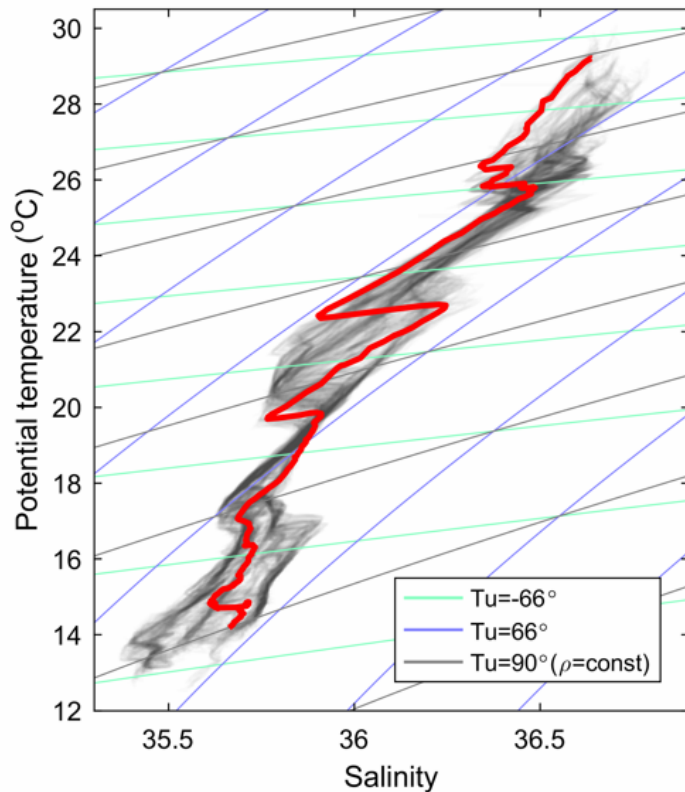


Fig. 9 Characteristic temperature-salinity (T-S) diagram observed during the coordinated multi-instrument autonomous experiment in the interior of the Northern Arabian Sea. The envelope of the profiles over the course of the 50-day ALAMO float deployment is shown in grey, with one profile highlighted in red; location of the highlighted profile is marked in Fig. 7.

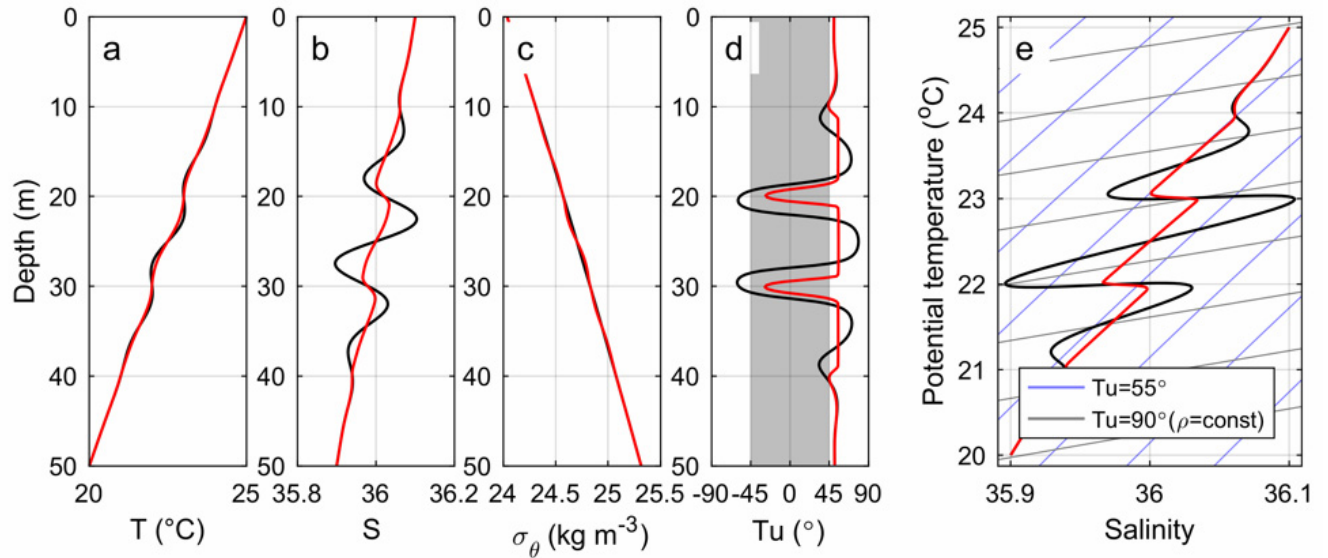


Fig. 10 Simulated evolution of thermohaline structure over the course of 10 days due to double-diffusive mixing. Initial (black) and final (red) profiles of (a) temperature, (b) salinity, (c) potential density, (d) Turner angle, and (e) T-S diagram are shown.

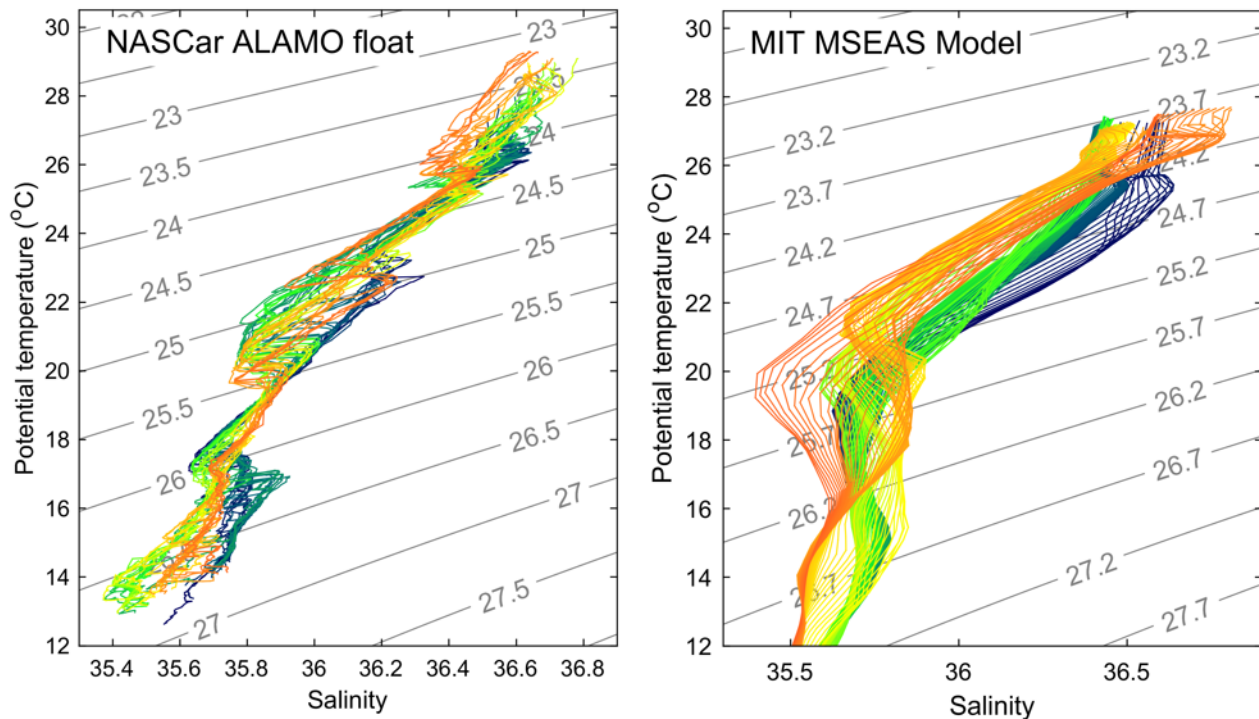


Fig. 11 Comparison of thermohaline interleaving structures in the interior Arabian Sea according to NASCar profiling ALAMO float observations (left) and MIT MSEAS numerical model (right, courtesy of P. Lermusiaux).