BAMS
Meeting Summary

The Internal Waves Service Workshop: Observing Internal Waves Globally with Deep Learning and Synthetic Aperture Radar

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The Internal Waves Service Workshop

What: This workshop gathered leading experts in satellite remote sensing, oceanography, and artificial intelligence to advance the development of the Internal Waves Service (IWS)—the first global, operational platform for automatic detection of internal solitary waves (ISWs) from synthetic aperture radar (SAR) imagery. The participants reviewed the current state of internal wave research, shared technical advances, and defined priorities for future collaboration.

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Where: Angra do Heroísmo, Azores, Portugal

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1. Introduction

Oceanic internal solitary waves (ISWs) are long, powerful, nonlinear subsurface waves that propagate along sharp density gradients, typically near the seasonal or permanent pycnocline (Helfrich and Melville 2006). They can exceed 100 m in amplitude at depth, with periods from minutes to under an hour, producing strong vertical velocities (>0.5 m s^{-1}) and localized shear currents. ISWs are usually generated from linear internal tides that steepen into solitary waves, typically when barotropic tidal flows displace stratified layers over sloping topography. When forcing is strong enough, baroclinic energy can quickly cascade into nonlinear waves. Other mechanisms include wind forcing, gravity currents, and interactions with mesoscale oceanic features (e.g., Buijsman et al. 2010; Jackson et al. 2012; Lamb 2014; da Silva et al. 2015). ISWs often appear in wave trains of solitons (Apel et al. 1975; Osborne and Burch 1980; Alford et al. 2015), ranked by amplitude and visible in high-resolution satellite observations in optical, altimeter, and synthetic aperture radar (SAR). Given the ocean's vastness and limited in situ observations, satellite remote sensing has long been key to ISW monitoring. The advent of satellites equipped with SAR in the 1980–90s revolutionized ISW research by providing high-resolution, two-dimensional, day-and-night, all-weather observations of surface signatures (Fu and Holt 1982; Alpers 1985). However, identifying these waves in satellite imagery remains labor-intensive due to the sheer volume of data. To address this challenge, the Internal Waves Service (IWS) was conceived, a deep learning–based system that automatically detects and logs internal wave events, making the data openly accessible. To promote the IWS and gather feedback, the Atlantic International Research Centre (AIR Centre) organized the IWS Workshop 2025 (IWS-W25), held on 3–4 April 2025 in Angra do Heroísmo, Azores, Portugal. The event gathered 15 invited researchers, oceanographers, and data service providers from institutions across Europe and North America to discuss IWS development. The IWS initiative aims to enhance detection, forecasting, and understanding of internal wave dynamics, which are critical for advancing operational oceanography and climate research. Currently, it uses SAR Wave (WV) mode data from the European Space Agency's (ESA's) Sentinel-1 satellite mission, offering near-real-time, global, open-ocean coverage with a latency of approximately four days. Expert-validated deep learning algorithms classify ISWs, supporting the first operational, long-term global ISW monitoring service.

2. State of the art and developments reported at the workshop

ISWs are major contributors to ocean mixing, energy dissipation, and vertical transport processes across the ocean (Garrett and Munk 1979; Alford 2003; Simmons et al. 2004; Zhao and Alford 2009; Waterhouse et al. 2014). Their dynamics, global distribution, and climatic impacts are increasingly studied using satellite remote sensing, in situ observations, and numerical modeling. To support systematic, large-scale detection and analysis, the IWS was developed—the first operational, free, global service dedicated to ISWs, to our knowledge.

The IWS is a collaborative initiative developed by a multidisciplinary team of researchers and technologists working across several international institutions. Led by the AIR Centre (Portugal) and codeveloped by a team of international experts in oceanography, Earth observation, and artificial intelligence (AI), the IWS aims to provide an operational, global-scale system for the detection and analysis of internal waves using satellite data. At present, the service assimilates Copernicus Sentinel-1 SAR images acquired in WV mode and automatically classifies them according to the presence or absence of ISWs. WV mode collects 20 km × 20 km vignettes with 5-m resolution every 100 km at two incidence angles along the satellite orbit. The ISW detection system leverages an expert-curated dataset of internal waves in several deep-ocean regions which was used to develop a state-of-the-art machine learning model that is capable of classifying SAR images as depicting or not ISWs. The service involves a comprehensive data pipeline that sources the images, classifies them automatically, and sends the positives to be validated by an expert. As the dataset of confirmed internal waves expands, the model is retrained, increasing its performance. Images are stored in S3-compatible cloud storage, and associated metadata (confidence, time, location) in a Structured Query Language (SQL) database for efficient access. This infrastructure enables near-real-time image classification and is scalable to handle the large data volumes generated by Sentinel-1, which collects parsimonious WV mode vignettes along its 100-min orbit, covering up to 75 min of acquisition time per orbit depending on the satellite track and operational plan. The images classified as positive by the machine learning model and validated by an expert are subsequently mapped on a web platform (https://services.aircentre.org/iw/map). Figure 1 (top) shows global validated ISW detections to date. This aggregation of internal wave events will, over time, highlight spatial and temporal hotspots. Currently, the dataset covers the global satellite acquisitions starting in September 2024, with an extended 5-yr archived data record available specifically for the equatorial Pacific Ocean region. The red points in Fig. 1 mark detection centroids; green points correspond to SAR WV mode vignettes displayed below, showing ISW surface signatures as alternating bright and dark bands in wave packets.

The scientific importance of ISWs underscores the value of services like the IWS. ISWs influence the thermohaline circulation (Whalen et al. 2020) and force coastal ecosystems, often delivering offshore nutrient-rich deep waters (Pineda 1991). Nonlinear internal waves and bores can alter local conditions, causing or mitigating events such as hypoxia, acidification, or extreme heating (Palumbi et al. 2014; Wyatt et al. 2020) and influence fertilization and larval transport (Crimaldi and Zimmer 2014; Pineda et al. 2024). In the open ocean, regions of frequent and intense ISW activity, known as hotspots, are evident in global maps such as Jackson (2007), which is based on nearly 2 years of global analysis of Terra/Aqua National Aeronautics and Space Administration (NASA) satellites. These include the Mascarene Ridge of the Indian Ocean (da Silva et al. 2015), the South China Sea (Alford et al. 2015), off the Amazon shelf (Magalhães et al. 2016), and the Pacific cold tongue (PCT; see Santos-Ferreira et al. 2023). Recent numerical modeling efforts (Solano et al. 2023) show that, particularly in the tropics, the combination of strong surface-intensified stratification and weak Coriolis forces promotes the nonlinear steepening of internal tides into solitary waves. In many of these ISW hotspots, such as the PCT, upper-ocean shear currents coinciding with strong stratification create conditions close to "marginal instability" (Miles 1961; Smyth et al. 2013). Large-amplitude ISWs, which produce intense shears near the pycnocline, may nudge shear even further to unstable conditions, causing overturning and strong mixing. These processes may significantly impact climate (see e.g., Warner and Moum 2019). Santos-Ferreira et al. (2023) propose that in the PCT, ISWs generated by buoyancy-driven gravity currents linked

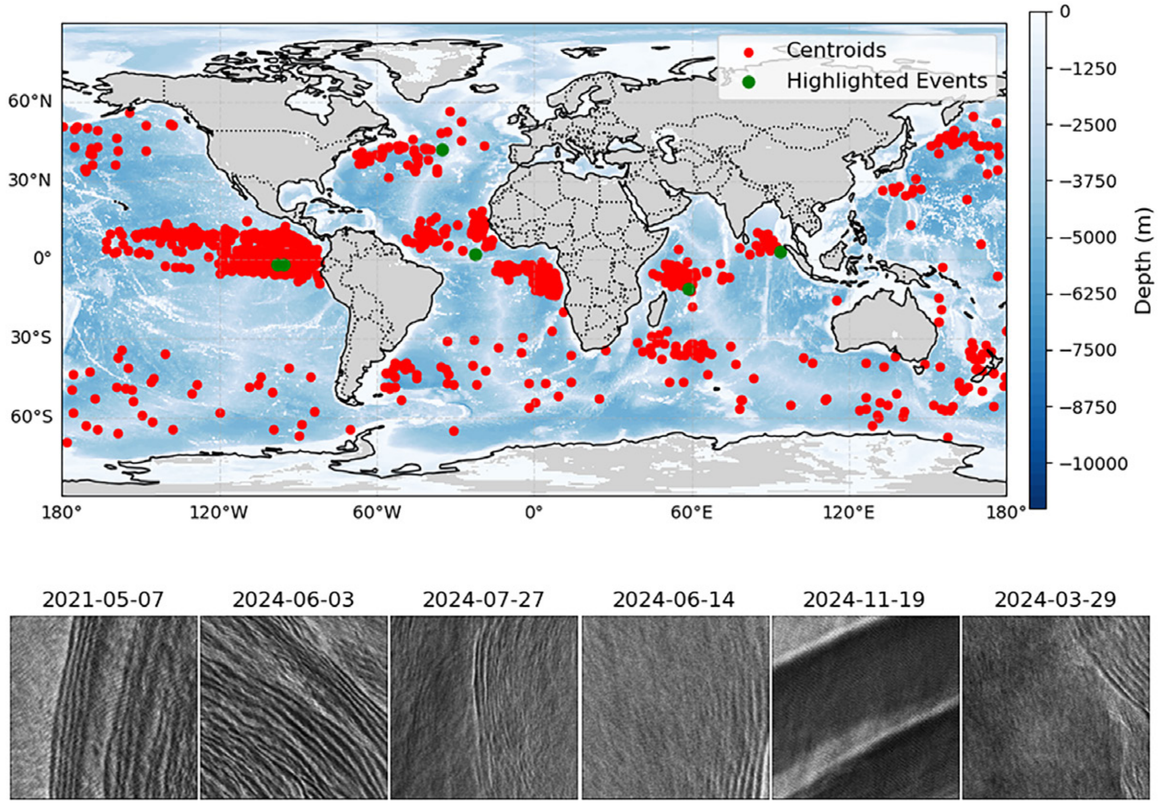

Fig. 1. (top) Global distribution of validated ISW detections from Sentinel-1 WV mode imagery. Red dots mark centroids of ISW events from the past 7 months (since September 2024), with a 5-yr extended dataset for the equatorial Pacific (2020–24). Green dots show the locations of SAR vignettes below. (bottom) SAR WV-mode vignette examples from those locations, showing typical ISW surface signatures as alternating bright and dark bands forming wave packets. Images are ordered left to right, matching the green dots above.

to tropical instability waves propagate through strong shear zones, enhancing vertical mixing and potentially reinforcing the El Niño–Southern Oscillation (ENSO) feedback loop during La Niña years or regular other years, possibly with global-scale ramifications in climate.

During the workshop, ISWs in the equatorial Pacific Ocean, within ±10°N for 5 years, were presented (see global map in Fig. 1), revealing a hotspot whose ISW origins, characteristics, and impacts on climate are just beginning to unfold. Long-crested ISWs exceeding 300 km are abundant in the PCT and are believed to be generated by buoyant gravity currents, themselves originating from tropical instability waves' dynamics (see e.g., Santos-Ferreira et al. 2023; Warner et al. 2018). The longevity of these waves was measured from satellite synergy with Surface Water and Ocean Topography (SWOT) to be on average 20 h, with a maximum of 72 h, the waves being, therefore, capable of propagating across the full meridional length of the PCT. This suggests ISWs may convey information between the north and south equatorial fronts by transporting mass and momentum (da Silva et al. 2025a). The new SWOT mission could advance the retrieval of key ISW parameters, precisely mapping at high resolution both sea surface roughness and height anomalies (ssha). New methods are being developed to retrieve the 3D structure of ISWs based on SWOT Ka-band radar interferometer (KaRIn) measurements of ssha and our knowledge of ocean stratification and dynamics (Siyahi et al. 2025, manuscript submitted to *J. Geophys. Res. Oceans*; da Silva et al. 2025b). This represents a major step in satellite synergy for ISWs and highlights the timely growth of the IWS.

Advances in SAR oceanography, particularly the insights gained over the past decade from continuous datasets provided by off-nadir SAR systems such as Sentinel-1, were also reported. These highlight the ability of SAR to capture surface expressions of internal waves associated with phenomena such as surface wave breaking, currents, and eddies (Johannessen et al. 2005; Chapron et al. 2005; Johannessen et al. 2008). The radar imaging model (RIM) (Kudryavtsev et al. 2005) was highlighted as a key tool for analyzing SAR imagery and disentangling the contributions from different ocean surface processes. The importance of dual-polarization SAR for distinguishing Bragg scattering from wave breaking was emphasized (section 3.2 in Fan et al. 2019), along with the benefits of combining SAR with other sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS) and SWOT. Although SWOT is not a conventional SAR imager but an across-track SAR interferometer operating in quasi-specular geometry, its synergy with traditional SAR missions offers complementary perspectives for ocean surface and internal wave studies. Emphasis was placed on the synergy between SWOT, optical missions (Sentinel-3 and Sentinel-2), nadir altimeters, other acquisition modes of Sentinel-1, such as the Interferometric Wide (IW) and ExtraWide (EW) swath modes, and future SAR missions like Radar Observing System for Europe at L-band (ROSE-L), which will feature full-polarization capabilities, and NASA–ISRO SAR (NISAR). Simulations and case studies demonstrated how internal waves interact with wind and surface currents, and how SAR can be used to investigate internal wave dynamics, including those generated by mesoscale features. The need for targeted validation campaigns was strongly emphasized, particularly those capable of linking satellite-detected surface expressions to subsurface oceanic properties.

Workshop discussions extended beyond internal wave detection. Unsupervised machine learning is being used to identify submesoscale ocean eddies in SAR imagery (Vincent et al. 2023), revealing potential synergies between the automated detection of internal waves and other features (Wang et al. 2019). Global ocean simulations have provided insights into the generation and distribution of supertidal internal waves (periods < 9 h). Sites of strong supertidal energy flux coincide with regions of observed ISW activity in SAR imagery, particularly in the tropics where strong stratification and weak Coriolis effects prevail (Solano et al. 2023). The generation of these waves is hypothesized to result from resonant wave–wave interactions (Buijsman et al. 2025), in agreement with theoretical predictions (Wunsch 2017; Baker and Sutherland 2020). Such findings help explain the formation of ISWs in regions like the Amazon off-shelf region and underscore the importance of resolving internal wave processes in global circulation models (Forget et al. 2015a,b; Su et al. 2018; Forget 2024). The combined effects of ISWs and surface wind forcing were also investigated for their role in enhancing vertical mixing in the coastal ocean (Magalhães et al. 2025, manuscript submitted to *Cont. Shelf Res.*). Using in situ data collected over the Portuguese shelf in 2019 within the framework of the HABWAVE project (https://habwave.campus.ciencias.ulisboa.pt/) and simulations with the Massachusetts Institute of Technology General Circulation Model (MITgcm), this study showed that wind can amplify shear instabilities associated with ISWs, particularly at midwater-column depths. Results suggest that the interaction between ISWs and moderate wind regimes leads to more frequent overturns and convective mixing [also possibly including enhanced surface wave breaking as documented in Magalhães et al. (2021) and Santos-Ferreira et al. (2022)]. These findings highlight the importance of considering wind–wave interactions in models of ocean mixing and stratification. Beyond their physical impacts, internal waves play an important role in shaping biological processes. Surface convergence zones associated with internal wave activity can influence larval transport and biological patchiness in coastal ecosystems (Pineda et al. 2024). Field studies in the Gulf of Maine showed consistent accumulation of lobster larvae and zooplankton in these ephemeral features, with notable differences observed inside versus outside the convergence zones.

Regarding new satellite missions, SWOT, Harmony, and the proposed SEASTAR concept (Martin et al. 2024) offer valuable opportunities for monitoring surface manifestations of ISWs and offer deeper understanding of the relationship between surface signatures and subsurface processes. Harmony is an approved ESA Earth Explorer mission, scheduled for launch in December 2029, and will provide pseudopolarimetric bistatic measurements (López-Dekker et al. 2021). OSCAR, an airborne demonstrator developed with ESA support, was specifically designed to inform and de-risk the SEASTAR mission. Although SEASTAR was not ultimately selected to fly, OSCAR produced encouraging results, demonstrating the ability to resolve fine-scale 2D frontal structures of total surface currents and winds under highly dynamic ocean conditions (Martin et al. 2024; McCann et al. 2024). One of the key innovations was the use of 90° azimuth diversity, which is crucial for capturing the complex interactions between wind, currents, and surface waves, and other geophysical phenomena like internal waves that manifest in SAR. These developments highlight the growing interest in systematic satellite-based cataloging of internal waves and reinforce the importance of complementary observation strategies beyond SAR alone, to fully capture and understand internal wave dynamics.

3. Major outcomes and future work

The IWS-W25 workshop led to several key outcomes and strategic recommendations, all centered on advancing the Internal Waves Service into a robust, comprehensive, and operational platform. A major consensus emerged around the need to continuously expand a high-quality, curated global dataset of Sentinel-1 WV mode images containing ISWs, covering data since the launch of *Sentinel-1A* in 2014 to the present and into the future, now ensured by the successful launch in December 2024 and current operation of *Sentinel-1C* alongside *Sentinel-1A*. This dataset is fundamental for algorithm development, training, expert validation, and long-term monitoring of ISWs globally. Participants also emphasized the importance of preparing the system for future satellite missions such as ROSE-L (expected launch in 2028), which will inherit and enhance the WV mode legacy, offering increased temporal resolution. Given that WV mode acquisitions have limited spatial coverage, especially over coastal and shelf areas, the integration of data from Sentinel-1's Interferometric Wide (IW) mode was considered a crucial next step. Looking beyond detection, the community identified internal wave image segmentation as a vital capability. Segmentation methods will enable the precise localization of wave fronts and extraction of key physical parameters such as distance between wave crests and crest length, supporting improved quantitative analyses. The workshop highlighted promising synergies between SAR and SWOT observations. For specific regions such as off the Amazon shelf and the Banda Sea, where it is known that large-amplitude ISWs are common, the synergy can be used to estimate internal wave amplitudes (Siyahi et al. 2025, manuscript submitted to *J. Geophys. Res. Oceans*; da Silva et al. 2025b) and, when combined with interpacket separation, provide and validate phase speeds.

Finally, strong emphasis was placed on community engagement and coordination. All participants reaffirmed their involvement in the ongoing development of the IWS. The formation of dedicated thematic working groups focusing on data curation, AI model development, and science applications was proposed as a concrete next step (Glaser et al. 2024; Kerdreux et al. 2025). These groups will support collaborative publications and are expected to reconvene in follow-up workshops within 12–18 months, ensuring continuity, innovation, and shared scientific advancement.

The Internal Waves Service represents a significant step forward in the operational observation providing foundations for the understanding of internal wave dynamics at a global scale. By combining the power of satellite Earth observation, AI, and expert knowledge, the IWS is not only enabling the scientific community to better track and characterize these features in vast datasets, but also laying the groundwork for improved forecasting, climate modeling, and marine services. The collaborative efforts initiated at the IWS-W25 workshop mark the beginning of a long-term vision: to build an open-source, scalable, and evolving platform that empowers both science and society. This long-term strategy is aligned with the evolution of the Copernicus program, building on Sentinel-1 and preparing for future missions such as ROSE-L and Harmony. Recent advances in AI also invite a reexploration of historical missions like *Environmental Satellite* (*Envisat*), offering potential to extract internal wave signals from archived SAR data. By connecting past, present, and future missions, the IWS is well-positioned to deliver lasting scientific and societal value.

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References

Alford, M. H., 2003: Improved global maps and 54-year history of wind-work on ocean inertial motions. *Geophys. Res. Lett.*, **30**, 1424, https://doi.org/10.1029/2002GL016614.

——, and Coauthors, 2015: The formation and fate of internal waves in the South China Sea. *Nature*, **521**, 65–69, https://doi.org/10.1038/nature14399.

Alpers, W., 1985: Theory of radar imaging of internal waves. *Nature*, **314**, 245–247, https://doi.org/10.1038/314245a0.

Apel, J. R., H. M. Byrne, J. R. Proni, and R. L. Charnell, 1975: Observations of oceanic internal and surface waves from the earth resources technology satellite. *J. Geophys. Res.*, **80**, 865–881, https://doi.org/10.1029/JC080i006p00865.

Baker, M. E., and B. R. Sutherland, 2020: The evolution of superharmonics excited by internal tides in non-uniform stratification. *J. Fluid Mech.*, **891**, R1, https://doi.org/10.1017/jfm.2020.188.

Buijsman, M. C., Y. Kanarska, and J. C. McWilliams, 2010: On the generation and evolution of nonlinear internal waves in the South China Sea. *J. Geophys. Res.*, **115**, C02012, https://doi.org/10.1029/2009JC005275.

——, and Coauthors, 2025: Energetics of (super)tidal baroclinic modes in a realistically forced global ocean simulation. *J. Geophys. Res. Oceans*, **130**, e2025JC022460, https://doi.org/10.1029/2025JC022460.

Chapron, B., F. Collard, and F. Ardhuin, 2005: Direct measurements of ocean surface velocity from space: Interpretation and validation. *J. Geophys. Res.*, **110**, C07008, https://doi.org/10.1029/2004JC002809.

Crimaldi, J. P., and R. K. Zimmer, 2014: The physics of broadcast spawning in benthic invertebrates. *Ann. Rev. Mar. Sci.*, **6**, 141–165, https://doi.org/10.1146/annurev-marine-010213-135119.

da Silva, J. C. B., M. C. Buijsman, and J. M. Magalhães, 2015: Internal waves on the upstream side of a large sill of the Mascarene Ridge: A comprehensive view of their generation mechanisms and evolution. *Deep-Sea Res. I*, **99**, 87–104, https://doi.org/10.1016/j.dsr.2015.01.002.

——, J. M. R. Magalhaes, A. M. Santos-Ferreira, and R. Huerre, 2025a: Longevity of internal solitary waves in the Pacific cold tongue: Synergies with SWOT. SSRN Electron. J., https://doi.org/10.2139/ssrn.5196730.

——, J. M. Magalhães, A. Bosser, R. Huerre, A. Koch-Larrouy, C. Goret, S. Diallo, C. R. de Macedo, and A. C. Silva, 2025b: Internal solitary wave parameters from SWOT KaRIn sea surface topography: A case study in the tropical Atlantic. SSRN, https://doi.org/10.2139/ssrn.5349432.

Fan, S., V. Kudryavtsev, B. Zhang, W. Perrie, B. Chapron, and A. Mouche, 2019: On C-band quad-polarized synthetic aperture radar properties of ocean surface currents. *Remote Sens.*, **11**, 2321, https://doi.org/10.3390/rs11192321.

Forget, G., 2024: Digital twins for ocean robots. *Proc. JuliaCon Conf.*, **6**, 164, https://doi.org/10.21105/jcon.00164.

——, J.-M. Campin, P. Heimbach, C. N. Hill, R. M. Ponte, and C. Wunsch, 2015a: ECCO version 4: An integrated framework for non-linear inverse modeling and global ocean state estimation. *Geosci. Model Dev.*, **8**, 3071–3104, https://doi.org/10.5194/gmd-8-3071-2015.

——, D. Ferreira, and X. Liang, 2015b: On the observability of turbulent transport rates by Argo: Supporting evidence from an inversion experiment. *Ocean Sci.*, **11**, 839–853, https://doi.org/10.5194/os-11-839-2015.

Fu, L.-L., and B. Holt, 1982: *Seasat Views Oceans and Sea Ice with Synthetic-Aperture Radar.* Jet Propulsion Laboratory, 200 pp.

Garrett, C., and W. Munk, 1979: Internal waves in the ocean. *Annu. Rev. Fluid Mech.*, **11**, 339–369, https://doi.org/10.1146/annurev.fl.11.010179.002011.

Glaser, Y., J. E. Stopa, L. M. Wolniewicz, R. Foster, D. Vandemark, A. Mouche, B. Chapron, and P. Sadowski, 2024: WV-Net: A foundation model for SAR WV-mode satellite imagery trained using contrastive self-supervised learning on 10 million images. arXiv, 2406.18765v1, https://doi.org/10.48550/arXiv.2406.18765.

Helfrich, K. R., and W. K. Melville, 2006: Long nonlinear internal waves. *Annu. Rev. Fluid Mech.*, **38**, 395–425, https://doi.org/10.1146/annurev.fluid.38.050304.092129.

Jackson, C., 2007: Internal wave detection using the Moderate Resolution Imaging Spectroradiometer (MODIS). *J. Geophys. Res.*, **112**, C11012, https://doi.org/10.1029/2007JC004220.

——, J. C. B. da Silva, and G. Jeans, 2012: The generation of nonlinear internal waves. *Oceanography*, **25** (2), 108–123, https://doi.org/10.5670/oceanog.2012.46.

Johannessen, J. A., V. Kudryavtsev, D. Akimov, T. Eldevik, N. Winther, and B. Chapron, 2005: On radar imaging of current features: 2. Mesoscale eddy and current front detection. *J. Geophys. Res.*, **110**, C07017, https://doi.org/10.1029/2004JC002802.

——, B. Chapron, F. Collard, V. Kudryavtsev, A. Mouche, D. Akimov, and K.-F. Dagestad, 2008: Direct ocean surface velocity measurements from space: Improved quantitative interpretation of Envisat ASAR observations. *Geophys. Res. Lett.*, **35**, L22608, https://doi.org/10.1029/2008GL035709.

Kerdreux, T., A. Tuel, Q. Febvre, A. Mouche, and B. Chapron, 2025: Efficient self-supervised learning for Earth observation via dynamic dataset curation. arXiv, 2504.06962v2, https://doi.org/10.48550/arXiv.2504.06962.

Kudryavtsev, V., D. Akimov, J. A. Johannessen, and B. Chapron, 2005: On radar imaging of current features: 1. Model and comparison with observations. *J. Geophys. Res.*, **110**, C07016, https://doi.org/10.1029/2004JC002505.

Lamb, K. G., 2014: Internal wave breaking and dissipation mechanisms on the continental slope/shelf. *Annu. Rev. Fluid Mech.*, **46**, 231–254, https://doi.org/10.1146/annurev-fluid-011212-140701.

López-Dekker, P., and Coauthors, 2021: The Harmony mission: End of phase-0 science overview. *2021 IEEE Int. Geoscience and Remote Sensing Symp. (IGARSS)*, Brussels, Belgium, Institute of Electrical and Electronics Engineers, 7752–7755, https://doi.org/10.1109/IGARSS47720.2021.9554896.

Magalhães, J. M., J. C. B. da Silva, M. C. Buijsman, and C. A. E. Garcia, 2016: Effect of the North Equatorial Counter Current on the generation and propagation of internal solitary waves off the amazon shelf (SAR observations). *Ocean Sci.*, 12, 243–255, https://doi.org/10.5194/os-12-243-2016.

——, W. Alpers, A. M. Santos-Ferreira, and J. C. B. da Silva, 2021: Surface wave breaking caused by internal solitary waves. *Oceanography*, **34** (2), 166–176, https://doi.org/10.5670/oceanog.2021.203.

Martin, A. C., C. P. Gommenginger, D. Andrievskaia, P. Martin-Iglesias, and A. Egido, 2024: Performance of the Earth Explorer 11 SeaSTAR mission candidate for simultaneous retrieval of total surface current and wind vectors. *Remote Sens.*, **16**, 3556, https://doi.org/10.3390/rs16193556.

McCann, D. L., and Coauthors, 2024: A new airborne system for simultaneous high-resolution ocean vector current and wind mapping: First demonstration of the SeaSTAR mission concept in the macrotidal Iroise Sea. *Ocean Sci.*, **20**, 1109–1122, https://doi.org/10.5194/os-20-1109-2024.

Miles, J., 1961: On the stability of heterogeneous shear flows. *J. Fluid Mech.*, **10**, 496–508, https://doi.org/10.1017/S0022112061000305.

Osborne, A. R., and T. L. Burch, 1980: Internal solitons in the Andaman Sea. *Science*, **208**, 451–460, https://doi.org/10.1126/science.208.4443.451.

Palumbi, S. R., D. J. Barshis, N. Traylor-Knowles, and R. A. Bay, 2014: Mechanisms of reef coral resistance to future climate change. *Science*, **344**, 895–898, https://doi.org/10.1126/science.1251336.

Pineda, J., 1991: Predictable upwelling and the shoreward transport of planktonic larvae by internal tidal bores. *Science*, **253**, 548–549, https://doi.org/10.1126/science.253.5019.548.

——, C. K. Tepolt, V. Starczak, P. Alatalo, and S. Shapiro, 2024: Concentration and condition of American lobster postlarvae in convergences. *Fish. Oceanogr.*, **33**, e12657, https://doi.org/10.1111/fog.12657.

Santos-Ferreira, A. M., and Coauthors, 2022: Effects of surface wave breaking caused by internal solitary waves in SAR altimeter: Sentinel-3 Copernicus products and advanced new products. *Remote Sens.*, **14**, 587, https://doi.org/10.3390/rs14030587.

——, J. C. B. Silva, B. St-Denis, D. Bourgault, and L. R. M. Maas, 2023: Internal solitary waves within the cold tongue of the equatorial Pacific generated by buoyant gravity currents. *J. Phys. Oceanogr.*, **53**, 2419–2434, https://doi.org/10.1175/JPO-D-22-0165.1.

Simmons, H. L., S. R. Jayne, L. C. S. Laurent, and A. J. Weaver, 2004: Tidally driven mixing in a numerical model of the ocean general circulation. *Ocean Modell.*, **6**, 245–263, https://doi.org/10.1016/S1463-5003(03)00011-8.

Smyth, W. D., J. N. Moum, L. Li, and S. A. Thorpe, 2013: Diurnal shear instability, the descent of the surface shear layer, and the deep cycle of equatorial turbulence. *J. Phys. Oceanogr.*, **43**, 2432–2455, https://doi.org/10.1175/JPO-D-13-089.1.

Solano, M. S., M. C. Buijsman, J. F. Shriver, J. Magalhaes, J. C. B. da Silva, C. Jackson, B. K. Arbic, and R. Barkan, 2023: Global characterization of supertidal internal waves from realistic simulations. *J. Geophys. Res. Oceans*, **128**, e2023JC019913, https://doi.org/10.1029/2023JC019913.

Su, Z., J. Wang, P. Klein, A. F. Thompson, and D. Menemenlis, 2018: Ocean submesoscales as a key component of the global heat budget. *Nat. Commun.*, **9**, 775, https://doi.org/10.1038/s41467-018-02983-w.

Vincent, G., K. Pak, D. Martinez, E. Goh, J. Wang, B. Bue, B. Holt, and B. Wilson, 2023: Unsupervised SAR images for submesoscale oceanic eddy detection. *IGARSS 2023—2023 IEEE Int. Geoscience and Remote Sensing Symp.*, Pasadena, CA, Institute of Electrical and Electronics Engineers, 4567–4570, https://doi.org/10.1109/IGARSS52108.2023.10282488.

Wang, C., and Coauthors, 2019: Classification of the global Sentinel-1 SAR vignettes for ocean surface process studies. *Remote Sens. Environ.*, **234**, 111457, https://doi.org/10.1016/j.rse.2019.111457.

Warner, S. J., and J. N. Moum, 2019: Feedback of mixing to ENSO phase change. *Geophys. Res. Lett.*, **46**, 13 920–13 927, https://doi.org/10.1029/2019GL085415.

——, R. M. Holmes, E. H. M. Hawkins, M. S. Hoecker-Martínez, A. C. Savage, and J. N. Moum, 2018: Buoyant gravity currents released from tropical instability waves. *J. Phys. Oceanogr.*, **48**, 361–382, https://doi.org/10.1175/JPO-D-17-0144.1.

Waterhouse, A. F., and Coauthors, 2014: Global patterns of diapycnal mixing from measurements of the turbulent dissipation rate. *J. Phys. Oceanogr.*, **44**, 1854–1872, https://doi.org/10.1175/JPO-D-13-0104.1.

Whalen, C. B., C. de Lavergne, A. C. Naveira Garabato, J. M. Klymak, J. A. MacKinnon, and K. L. Sheen, 2020: Internal wave-driven mixing: Governing processes and consequences for climate. *Nat. Rev. Earth Environ.*, **1**, 606–621, https://doi.org/10.1038/s43017-020-0097-z.

Wunsch, S., 2017: Harmonic generation by nonlinear self-interaction of a single internal wave mode. *J. Fluid Mech.*, **828**, 630–647, https://doi.org/10.1017/jfm.2017.532.

Wyatt, A. S., J. J. Leichter, L. T. Toth, T. Miyajima, R. B. Aronson, and T. Nagata, 2020: Heat accumulation on coral reefs mitigated by internal waves. *Nat. Geosci.*, **13**, 28–34, https://doi.org/10.1038/s41561-019-0486-4.

Zhao, Z., and M. H. Alford, 2009: New altimetric estimates of mode-1 M_2 internal tides in the central North Pacific Ocean. *J. Phys. Oceanogr.*, **39**, 1669–1684, https://doi.org/10.1175/2009JPO3922.1.