

Internal solitary waves as a global ocean hazard observed continuously by automated Sentinel-1 classification

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Abstract

Internal solitary waves (ISWs) are among the stratified ocean's most energetic features, with subsurface amplitudes exceeding 100 m and rapid current changes that threaten offshore infrastructure and underwater navigation and drive ocean mixing. Yet the observational record is a patchwork of regional case studies, recording where ISWs were found but not where they were sought in vain. Here we show that automated classification turns the Sentinel-1 wave-mode (WV) synthetic-aperture-radar (SAR) archive, acquired over the open ocean since 2014 and far too large to screen by hand, into a systematic ISW observing system. Applied to more than 4 million ocean vignettes harvested to September 2026, it brings more than 83% of the open ocean within observational reach and yields more than 19,000 expert-confirmed detections. Because imagery is classified within hours of acquisition, the system operates continuously, giving this hazard, to our knowledge, its first operational monitoring capability.

Introduction

Internal solitary waves (ISWs) are among the most energetic phenomena of the stratified ocean. Generated most commonly where tidal currents force stratified water over topography, though also by river and estuarine plumes and by frontal processes in shelf and coastal settings^{1,2}, they propagate as trains of large-amplitude nonlinear waves whose vertical displacements can exceed 100 m, reaching 38% of the water depth on the northern South China Sea slope, with vertical velocities of order 0.7 m s^{-1} — four orders of magnitude above typical open-ocean values — and along-wave currents of order 2 m s^{-1} ^{3,4}. Extreme events far exceed these figures: the strongest ISW so far reported, in the deep basin of the northern South China Sea, reached an amplitude of 240 m, carrying water from 300 m down to 540 m in 3,847 m of water, with a peak current of 2.55 m s^{-1} ⁵, and satellite inversions place spring-tide amplitudes above 150 to 200 m in several regions⁶. These properties make ISWs a recognised marine hazard: the occurrence is the hazard itself, exposure is set by the offshore infrastructure, shipping and submarine operations lying in their path, and risk by the vulnerability of those assets. They impose severe loads on offshore platforms, risers and pipelines, first documented as a threat to drilling operations in the Andaman Sea⁷, and pose a risk to underwater navigation, manned and autonomous, brought into focus by their hypothesised role in the loss of a naval submarine in Indonesian waters^{8,9}. ISWs generated in deep water also drive hazard at a distance: after propagating hundreds of kilometres they excite damaging seiches in coastal harbours, documented on the Caribbean coast of Puerto Rico and at Puerto Princesa on Palawan, where Sulu Sea waves arrive some 450 km from their generation site^{10,11,12,13}. A single large ISW event in the northern South China Sea can carry gigajoules of energy per metre of crest and drive turbulent dissipation orders of magnitude above background^{4,5}, resuspend shelf sediments¹⁴, and contribute to the diapycnal mixing that shapes ocean stratification¹⁵. ISWs may also mobilise seabed sediment on continental slopes, a process implicated in the turbidity currents that damage seafloor cables and pipelines¹⁶.

Because their surface signatures modulate sea-surface roughness, ISWs can be observed from space, and synthetic-aperture radar (SAR) is one of the most effective sensors for detecting them across the open ocean, being independent of cloud cover and daylight^{17,18,19}. In SAR imagery a wave train appears as alternating bright and dark bands, where the wave's surface currents converge and diverge and so enhance or suppress the centimetre-scale roughness to which the radar responds. Decades of SAR and in-situ work have established the phenomenology of ISWs in particular settings – the northern South China Sea^{17,4,5}, the Andaman Sea^{7,20}, the Mozambique Channel¹⁸, the Gulf of Oman²¹, the Mascarene Ridge, the Amazon shelf¹⁹, the Luzon Strait, and the Strait of Gibraltar, among others. That body of work established ISWs as a global-ocean phenomenon and characterised their generation, structure and energetics. It is the foundation any systematic survey rests on, supplying both the physical understanding of what a surface signature represents and the expert knowledge by which every detection reported here is confirmed.

Yet these studies share a structure: they are researcher-driven and place-based. A case study typically arises when an investigator expects ISWs, searches, finds them and publishes; the literature therefore maps successful searches rather than the distribution of the phenomenon. Coverage is consequently fragmented, clustering in a few intensively studied regions while much of the open ocean appears only in isolated studies, or not at all (Fig. 1a). With few exceptions the record is a patchwork of independent campaigns, each conditioned on where ISWs were already expected. It is shaped, too, by how results reach print: a survey that finds no waves is a null result, and null results are seldom published, so sightings accumulate while a record of where ISWs were sought and not found does not. No prior method has recorded both detections and non-detections, and regions are recognised as active only once someone looks: the Mozambique Channel was identified as intensely active only after SAR imagery of the region was first examined for that purpose¹⁸, and a comparable survey of the heavily trafficked Gulf of Oman appeared only recently²¹. Even the global atlases compiled from satellite and astronaut imagery^{22,23} are catalogues of where ISWs have been sighted, assembled from observations made where ISWs were expected. A systematic near-global survey of 21 months of MODIS sunglint imagery went further, reporting 3,581 wave occurrences and identifying activity in several regions where little had previously been described²⁴. It was systematic in method, conducted over a fixed period without a regional prior; its sample was not. Imagery was screened for sunglint before inspection and drawn from a near-real-time service rather than the mission archive, so the count was, as its author noted, a lower bound on what MODIS could detect; the detections span 45°S to 55°N because the sunglint ellipse does, not because the ocean does. Where the field of view is set by illumination and cloud, absence carries no information and occurrence cannot be expressed as a rate. A contemporaneous global survey is free of those conditions: a neural classifier was applied to 29 orbital cycles of SWOT sea-surface-height and roughness imagery, independent of cloud and illumination⁶, but the acquisitions that returned none are not reported, so occurrence again cannot be expressed as a rate. No ISW record has yet combined a sampling frame independent of the conditions that govern detectability with an analysis against the denominator that frame makes available.

This is not for want of data. The Sentinel-1 mission has acquired wave-mode (WV) SAR imagery — small images of nominally 20 km × 20 km — over the open ocean continuously since 2014, at a rate of order two thousand vignettes per day from a single satellite. A decade of such acquisition is an archive of exceptional density for ocean-surface observation. The obstacle has been analytical, not observational: this volume of imagery cannot be screened for ISW signatures by hand at the scale of the global ocean, continuously, and in near-real time. Until automated classification became reliable, imagery that could have constituted a global ISW survey remained unexploited. Automated classification is the single component that removes this bottleneck, making both the live stream and the decade-deep archive analysable, and turning data that already exists into a systematic survey. The enabler is artificial intelligence rather than a new source of observation.

Here we present the Internal Waves Service (IWS), an operational system run by the Atlantic International Research (AIR) Centre that applies automated classification to the Sentinel-1 WV archive to deliver a systematic, near-global ISW survey^{25,26}, whose first global maps, published in 2025, close the researcher-led period against which it is compared here. The survey concerns the open ocean, throughout the World Seas (IHO v3) ocean with marginal and enclosed seas excluded, which Sentinel-1 WV images by default. Internal waves on continental shelves and in marginal seas, where much of the prior SAR and in-situ literature is concentrated, are primarily covered by the mission's other imaging modes and lie outside this survey. The IWS is designed to observe internal waves across the whole ocean, but the archive analysed here is WV only.

What the IWS measures directly is the occurrence of SAR-detectable surface signatures; inferences about wave amplitude, energetics or hazard follow from the established relationship between those signatures and the underlying waves rather than from direct measurement. We (i) quantify how little of the ocean the prior literature examined; (ii) characterise the observational reach of the WV archive; and (iii) present a global, expert-confirmed ISW detection dataset — to our knowledge the first in which ISW occurrence is reported as a rate over classified acquisitions, with both detections and non-detections recorded against a known denominator, rather than as a catalogue of sightings selected by illumination, cloud cover or prior expectation^{22,24} or as detection counts from a phenomenon-blind archive whose sampling denominator is not carried through⁶. We then establish what continuous, near-global monitoring makes possible. The events we report are derived from an archive that is still growing and are therefore provisional; they can only increase as acquisition continues.

Results

Geographical confinement of the prior observational regime

We assembled a systematic bibliography of peer-reviewed ISW observational studies and geolocated every study with a recoverable spatial footprint, obtaining 92 papers describing 105 distinct study

regions spanning 1980 to 2026. The corpus is deliberately not restricted to open-ocean studies: much of the prior record concerns continental shelves and marginal seas, and those studies are retained because that concentration is itself the finding. Reach is nevertheless computed for the prior record and for the WV archive against the same open-ocean denominator, so the comparison is like-for-like over a shared extent; study regions lying wholly outside that denominator are reported separately.

The distribution is strongly skewed, clustering in a few intensively studied regions while much of the open ocean appears only in isolated studies, or not at all. Expressed as observational reach — the share of open-ocean cells (H3 resolution 2) containing at least one study — the prior record touches about 12% of the ocean (Fig. 1a). Nearly doubling the compilation during co-author review left this figure essentially unchanged, the added studies falling in the same shelves and marginal seas as those already held, so the concentration is a property of the record rather than of how exhaustively it was assembled. This record is not a prior monitoring system being improved upon; it is a retrospective aggregate of independent campaigns using diverse methods over four decades, and is best read as an upper bound on ISW observation to date rather than as a baseline of systematic coverage.

Near-global open-ocean coverage from a single instrument

The harvested Sentinel-1 SAR WV archive analysed here comprises 4,071,560 vignettes acquired between 2021-11-26 and 2026-09-11, of which 4,064,170 fall over open ocean after filtering. Observational reach — the share of open-ocean cells brought under observation — is more than 83% at H3 resolution 2 (Fig. 1b). Percentages throughout are approximations, quoted to the nearest whole per cent: the harvested WV archive is partial and still growing, and the prior-literature compilation, though thorough and systematic, cannot be guaranteed complete.

An H3 resolution-2 cell spans of order 10^5 km^2 , so reach denotes the share of the ocean within which a transiting ISW would be sampled, not the fraction of ocean area physically imaged (Supplementary Fig. 1). Compared with the prior literature's reach of about 12%, the archive's reach of more than 83% represents a qualitatively different observation coverage. This is a statement about observational breadth, not scientific value: the prior studies resolved process detail — vertical structure, energetics and in-situ dynamics — that a surface-signature survey cannot capture^{4,18}. This comparison applies to the researcher-led, place-based record; the contemporaneous SWOT-based global survey of ISW occurrence⁶ was submitted after the first IWS global maps^{25,26} and so falls outside the researcher-led record by the rule set out in Methods; it is addressed in the Discussion. Restricting both layers to the ocean that WV actually reaches leaves that contrast essentially unchanged, so it is not an artefact of comparing over different extents (Supplementary Fig. 2).

Crucially, WV acquisition is indifferent to where ISWs are expected: imagery is acquired wherever orbit and mode place it, recording non-detections as faithfully as detections. This removes the study-area selection bias of the prior regime and is what makes the discovery of previously unrecognised activity possible. The archive is also a single instrument applied consistently across the global ocean within a

few years, in contrast to the methodological patchwork of the prior record. The step-change is therefore not only one of extent but of kind: the same near-global lattice of acquisition positions is re-imaged on each orbital repeat cycle – nominally every 12 days from a single satellite, and more often as the constellation grows – continuously over years, whereas prior studies observed a given region once or across a single campaign. Coverage is thus wider, unconditioned on where ISWs were expected, and mechanically repeated through time rather than episodic and researcher-driven. Reach is provisional: the archive analysed here is a recent-years subset of a record reaching back to 2014, and it grows as harvesting continues.

A near-global, expert-confirmed record of internal-wave detections

Applying automated classification to the archive and subjecting candidate detections to expert review^{27,28} yielded 233,829 human-examined vignettes and 19,167 confirmed ISW detections (Fig. 2), so far. Because each confirmed detection has been reviewed by a human expert, the reliability of the confirmed set as true positives is high by construction; the open question is completeness, addressed below. The confirmed detections recover the major open-ocean centres of ISW activity already reported in the literature – among them the Amazon shelf break and the adjacent deep tropical Atlantic^{19,29,30,31,32}, the Mascarene Ridge³³, and the equatorial Pacific cold tongue^{34,35} – while also populating regions not previously documented. Figure 2b–e shows four of these detections in the WV imagery itself, spanning the tropics and both mid-latitude belts and including ocean no published study has examined. The ISW activity centres are delineated by a per-cell test against the global reviewed-set rate rather than by visual inspection of the map: 208 elevated cells resolve into 19 connected activity centres (hotspots), the six largest holding 74.5% of all confirmed detections (Supplementary Fig. 3). Eleven of the nineteen intersect no published study region and hold 4,549 confirmed detections between them. Because the survey is unconditioned on prior expectation, the resulting spatial distribution is interpretable as a first-order global view of apparent ISW occurrence – the occurrence of SAR-detectable surface signatures – across the open ocean, rather than a map of where observations have historically been concentrated. Because detectability depends on wind, sea ice and sampling geometry, a non-detection is not evidence that no ISW was present.

The detection dataset is produced in two tiers. Tier 1 is the model's classification of every WV vignette in the archive, without human intervention: each is scored by the detection model and flagged where the score exceeds a fixed decision threshold of 0.935, so tier 1 covers the archive uniformly. Tier 2 is the subset of those flags that a domain expert has reviewed, and is the record reported above. Measured on the live acquisition stream over a review window of 41,906 vignettes, tier 1 returned a precision of 0.79 at a recall of 0.67, with an area under the ROC curve of 0.933 (ref. 28). The model-detected tier is mapped beside the expert-confirmed one in Supplementary Fig. 4; the two profiles share their shape but not their level, the denominators being classified and reviewed vignettes respectively.

Near-real-time operation

A dedicated harvester follows the live acquisition stream (Fig. 3), taking each WV vignette as it is published and classifying it on arrival. The interval between sensing and availability in the IWS database has a floor of 1.0 h across the archive; in the current harvesting configuration the median is 3.0 h, with about 82% of held imagery available within six hours of sensing. Most of that interval is upstream publication at the Copernicus Data Space Ecosystem, which the service does not control; the service's own contribution is a small fraction of it. What matters operationally is the time between detection and the waves reaching coastal areas: internal solitary waves propagate at wave speeds of order 2 m s^{-1} (ref. 4), advancing some 7 km an hour, so a train imaged in the open ocean reaches a coast hundreds of kilometres away a day or more after the overpass. Detection within a median 3 h of sensing therefore precedes that arrival by a wide margin: the wave is identified while it is still at sea and still far from the coast it is travelling towards. Open-ocean detection at this latency is what an early-warning capability requires, and the system delivers it continuously rather than as a retrospective exercise. To our knowledge, the IWS is the first operational monitoring service for internal solitary waves^{25,26}.

Discussion

The Sentinel-1 WV archive, analysed automatically, converts a phenomenon known almost exclusively from scattered case studies into a systematic, near-global, continuously updated record. The transition is not from one coverage figure to a larger one but from one observational mode to another: from the researcher-led case study to the systematic survey. The closest precedent is the Argo float array, which took the ocean interior from sparse, regionally biased sampling to systematic and sustainable global coverage^{37,38} and, with satellite altimetry, made possible advances in ocean forecasting and climate modelling that sparse hydrography could not support. A systematic global ISW survey stands in the same relation to the prior ISW literature, and automated classification is what makes the existing imagery yield it.

That the change is delivered by AI-driven analysis of an existing, expanding archive rather than by new hardware is the essential point, and it generalises: any hazard whose signature is recorded in remote-sensing archives that already exceed manual analysis is a candidate for the same treatment.

The most consequential opportunity lies in the representation of ocean mixing. Diapycnal mixing driven by breaking internal waves influences ocean stratification and contributes to the ocean uptake and storage of heat and carbon, yet its spatial pattern spans orders of magnitude and is governed by the geography of internal-wave generation, propagation and dissipation^{15,39}. Parameterising this mixing in climate models remains a leading source of uncertainty, partly because the global distribution of internal-wave energy is itself poorly constrained by observation⁴⁰. Generation is increasingly well characterised; where the energy is finally dissipated is not^{41,42}. ISWs are the high-energy, strongly dissipative end of that field^{4,5}. Much of that dissipation occurs where they shoal and break over continental slopes⁴¹, which WV normally does not image, so this survey records where ISWs propagate through the open ocean rather than where they are dissipated. It still bears on the geography of

dissipation, since open-ocean breaking and interaction with deep topography dissipate ISW energy far from any coast. ISW breaking is one contributor among several to diapycnal mixing, so a global occurrence record constrains the distribution of one strong, highly localised term rather than the mixing field as a whole, and offers a validation target for the internal-tide-resolving simulations now used to estimate internal-wave energy⁴³.

More broadly, a continuously updated occurrence dataset is a standing validation resource. High-resolution global ocean models increasingly resolve internal tides and the conditions that generate ISWs; a survey unconditioned on expectation allows the question of whether ISWs are observed where models predict generation to be asked globally rather than at a handful of mooring sites. Near-real-time detection also distinguishes an operational monitoring service from a periodic climatology: the same detections that build the retrospective survey arrive soon enough after overpass to support hazard services, among them alerting offshore operators, informing vessel routing, and flagging conditions relevant to underwater acoustics and submersible operations^{44,8,9,45}, in regions where no in-situ monitoring exists. Translating the occurrence record into hazard exposure will require co-locating detections with shipping density, offshore installations and submarine-cable routes. Jackson²⁴ argued that the utility of a large satellite wave catalogue lay less in the sightings than in what could be derived from them: image pairs acquired minutes to hours apart yield propagation speeds accurate enough to invert for mixed-layer depth, buoyancy frequency and upper-ocean heat storage, and a catalogue dense enough in time permits statistical tests of whether season, year or environmental state modulates wave propagation. Neither followed from that survey, because a sample selected by illumination and cloud cover cannot support a rate. Both follow from a record in which every acquisition is classified and the denominator is known.

The survey also changes what can be said about where ISW hazard arises. The hazards documented to date are largely coastal and shelf-based, being loads on fixed installations, sediment resuspension and risk to submersibles operating over slopes, because that is where instrumented campaigns have been mounted. An open-ocean occurrence record bears on hazard in two further ways. First, ISWs are present across the deep ocean far more widely than the case-study record indicated, and the interactions this implies, with mesoscale features and where trains converge or meet topography in deep water, are largely uncharacterised; establishing where they occur is a prerequisite to assessing their effects. WV primarily samples the open ocean rather than continental shelves, so shelf and deep-ocean incidence cannot be compared from this archive. Second, waves detected in the open ocean are in many cases upstream of the shelves on which they will eventually shoal, detections over the Mascarene Ridge lying on propagation paths towards Madagascar and Mauritius³³, so an open-ocean survey observes waves before they reach the settings where damage occurs. That is the basis on which monitoring could offer lead time rather than only a retrospective record.

Apparent occurrence is strongly concentrated at low latitudes, falls to a minimum in the subtropics of both hemispheres, and rises again in the mid-latitudes, more strongly in the north, where the mid-latitude maximum is roughly three times its southern counterpart (Fig. 2). Three mechanisms plausibly

contribute, and the survey is placed to test rather than to settle them. Rotation is the most direct: the Coriolis term radiates ISW energy into inertia-gravity waves at a rate that increases with latitude, so waves both form more readily and persist longer at low latitudes, where the resonance parameter governing nonlinear steepening of the internal tide is correspondingly large^{46,47,48,49}. Consistent with this, the modelled ratio of supertidal to tidal baroclinic energy is enhanced in the tropics^{42,50}, and ISW trains in the Pacific cold tongue persist over unusually long distances³⁴. Stratification is the second: the strength and depth of the pycnocline set the waveguide an ISW propagates in, and both vary with latitude and with longitude: the thermocline is shallower in the eastern equatorial Pacific under the trade winds, and the pycnocline deeper in the central gyres of the Pacific and North Atlantic⁵¹. The third is observational and ours: detection requires an intermediate wind, and the mid-latitude storm-track belt is where that condition fails most often, so part of the poleward decline is a decline in detectability rather than in occurrence. This detectability decline cannot be separated from any real weakening of the waveguide by the same winds using the detections alone; doing so requires co-locating the occurrence record with modelled internal-tide energetics, stratification climatologies and per-acquisition wind, which this survey makes possible and we identify as the next step.

Internal solitary wave generation requires a stably stratified water column and a forcing capable of producing large isopycnal displacements; whether the disturbance evolves into a coherent ISW depends on the balance between nonlinear, dispersive and, in the fully nonlinear regime, nonhydrostatic dynamics. The most widespread mechanism is barotropic tidal flow over slopes, ridges and other pronounced topography, producing a low-mode internal tide that propagates away and may steepen and disintegrate into trains of shorter, nonlinear waves^{14,18,22,33}, equivalently a transfer of energy from the internal tide towards higher harmonics and ISW scales^{52,53}.

Where the forcing current approaches the long-wave phase speed, this transcritical regime can become resonant and generate large-amplitude waves directly, described with forced weakly nonlinear⁵⁴ and with fully nonlinear, nonhydrostatic models^{53,55}. It has been proposed for the equatorial Pacific cold tongue, where buoyant gravity currents along sharp fronts and tropical instability waves generate ISW trains^{34,35}. Figure 2 suggests such settings deserve wider consideration: deep-reaching western boundary currents and tropical jets produce localised convergence and substantial vertical displacement of density surfaces⁵⁶, documented in the Kuroshio Extension^{57,58} and Gulf Stream⁵⁹, though displacement alone does not demonstrate generation.

A third route, relevant in deep water, is nonlinear transfer from internal tidal beams into a strong pycnocline^{60,61,62,63,64,65}, which under deep-ocean tropical stratification can favour higher-mode, particularly mode-2, waves^{55,64}.

The case for automated, systematic observation strengthens as the observing landscape diversifies. The SWOT mission resolves the sea-surface-height and roughness signatures of ISWs, with detections reported off the Amazon shelf and in the Andaman Sea^{66,29,67} and occurrence and first-order amplitude

now mapped globally⁶, and the Sentinel-1 mission has continuity into the next decade. Optical sensors add complementary coverage: a 22-year internal-wave dataset for the northern South China Sea has recently been built from MODIS imagery by deep learning⁶⁸. Combining radar and optical streams would further strengthen a systematic monitoring capability. The two are complementary rather than competing, wide-swath altimetry inverting amplitude for the waves it detects while WV SAR establishes how often waves occur across a denominator of classified acquisitions. The volume and heterogeneity of ISW-relevant observation is rising across missions, and only automated methods can operationalise it.

The value of a global record extends beyond physical hazard. ISWs transport nutrients, larvae and heat across shelves^{69,70} and can buffer reef systems thermally, structuring nearshore ecosystems⁷¹. Across reefs in the western, central and eastern Pacific, temperature fluctuations associated with internal waves reduced cumulative heat exposure at the peak of the 2015–2016 El Niño by up to 88%, and how far that buffering persists depends on how internal-wave climates themselves respond to continued warming and strengthening stratification⁷¹. Whether ISW occurrence itself varies with climate state is a further question, one that classifying the full WV archive, and in time Sentinel-1's interferometric wide-swath imagery, would bring within reach. On shelves ISWs resuspend bottom sediment and transport it offshore⁷², a process that may also mobilise the resting cysts from which harmful algal blooms develop, though resolving that link would require observations at the waves' own space and time scales. They are also detected near ocean fronts and eddies²⁹, so a global occurrence map may identify where ISWs and upper-ocean dynamic features interact, and they interact with sea ice at high latitudes³⁶, a coupling of growing relevance in a changing polar ocean. Integrating systematic ISW observation into coordinated ocean-observing frameworks, alongside the Essential Ocean Variables⁷³, would make the record a durable community resource rather than a single product.

Several limitations bound these claims and define the work that remains. The survey is a sample, not a census: WV acquisition is near-global but non-uniform, set by orbit and mode, and the imaged-area and reach figures are provisional, rising as the archive, currently a recent-years subset of a record reaching back to 2014, is completed. Because WV primarily images the open ocean by default, internal waves on continental shelves and in marginal seas lie outside the present survey, and it is there that stratification is strong and the hazard to infrastructure and navigation most concentrated; extending the same automated classification to Sentinel-1's interferometric (IW and EW) modes is the route by which the IWS would reach the all-ocean coverage it is designed for. SAR detection is itself wind-dependent: the surface-roughness (Bragg) signature is legible only within an intermediate wind band, of order 3–9 m s⁻¹, being swamped by wind-driven roughness above it and, for want of a background to modulate, absent below it^{21,74}. WV acquisition extends into the persistently high winds of the storm-track latitudes, where the signature is often suppressed. The effect is directional: high winds can only cause an ISW to go undetected, never generate a spurious detection, so the survey undercounts in very calm and high-wind regions and the occurrence maps are a lower bound there rather than a biased estimate. Because the threshold is known, this can be mapped and bounded, and quantifying it globally from wind co-located with each acquisition is a planned refinement. The confirmed detections are expert-reviewed, so their

reliability as positives is high by construction; the open question is completeness. The classifier's recall, reported above, quantifies it at the model's operating point, which is set precision-first so that missed signatures are the expected cost of a low false-positive burden. Ice-covered and high-latitude seas are sampled sparsely. Whether the record can support a seasonal climatology, as distinct from a global occurrence map, depends on the temporal span accumulated per region rather than on the total number of vignettes, and is assessed as the archive grows. None of these caveats alters the central result: the difference between about 12% and more than 83% observational reach is a difference in kind.

For an ISW-based hazard recognised for more than four decades but observed only in fragments, the change is foundational. Automated classification makes an imagery stream acquired continuously since 2014, and still being acquired, tractable at the rate it arrives, so that where internal solitary waves occur becomes something observed as a matter of routine rather than reconstructed from campaigns. What the record assembled here establishes is the observational basis that the science of this hazard, and the services that depend on it, have until now lacked.

Methods

Sentinel-1 WV archive

Sentinel-1 acquires WV vignettes — small SAR images of nominally 20 km × 20 km — over the open ocean by default⁷⁵, and has done so continuously since the launch of Sentinel-1A in 2014. The acquisition rate is governed by the number of operating satellites rather than by any property of the ocean: Sentinel-1B (2016) was lost in December 2021, leaving an effectively single-satellite configuration until Sentinel-1C became operational in 2025, with Sentinel-1D following in 2026. WV is operated continuously, so the daily vignette rate scales approximately with constellation size and must be read per configuration rather than as a multi-year average (Fig. 3). The archive analysed here is the harvested subset available to the IWS at the time of writing (4,071,560 vignettes, 2021-11-26 to 2026-09-11) and continues to grow as harvesting proceeds; the source imagery is the Copernicus Sentinel-1 WV product. Represented as nominal 20-km footprints and counting overlapping passes once, these vignettes image about 39 million km² (Supplementary Fig. 1).

Acquisition geometry. WV images the same along-orbit positions repeatedly, and we characterised the spatial structure of those positions to inform how imaged area and reach are quantified. Grouping vignette centroids by snapping them to a 0.1° grid and merging eight-connected occupied cells into acquisition spots, the positions prove highly repeatable: the median 95th-percentile radius of repeat acquisitions about their spot centre is 0.33 km, far finer than the 20-km vignette footprint. They are also much denser than the nominal 100 km spacing of WV acquisitions along a single orbit track⁷⁵ — the median nearest-neighbour distance between distinct spots is 29.30 km (5th–95th percentile 16.8 to 54.1 km), and 92.8% of spots lie within 50 km of another. This density is the superposition of many regular but interleaved acquisition sequences — the two WV beams, ascending and descending passes, adjacent relative orbits and successive satellites — whose union is a dense, finely spaced field rather than a single

regular lattice. Consistent with this, the spot count does not stabilise as the grouping radius is varied: distinct positions are separated by a continuum of distances from below one kilometre upward, with no characteristic spacing at which a unique set of cells could be defined. Because the acquisition positions therefore cannot be reduced to a fixed grid, imaged area and observational reach are quantified on an imposed equal-area discrete global grid (H3; below) rather than on the acquisition positions themselves, making no claim that the analysis cells are the instrument's own footprints. These statistics are computed on the cleaned ocean archive — the same centroids used for the maps — and are provisional; they are essentially unchanged from an earlier analysis of a substantially smaller archive, indicating that the field is a stable property of the acquisition plan rather than an artefact of the present harvest (Supplementary Fig. 5).

Automated internal-wave classification

Each WV vignette is classified for the presence of an ISW surface signature by an automated image classifier. Classifier architecture, evolution and engineering including the processing pipeline are the subject of separate methodological papers^{27,28}. The detection model is applied uniformly to the live acquisition stream and to the archived imagery, so the same procedure produces both the retrospective survey and the operational product: each release of the detection dataset is produced by reclassifying the entire archive with a single model version, so that every vignette within a release is classified by the same model.

Detection uses a compact convolutional neural network trained from scratch on expert-labelled WV imagery drawn from this archive, rather than adapted from a general-purpose vision model. Its development and evaluation are reported in full in a separate methodological paper²⁸. The model is evaluated against the operational class prior — the heavily negative-skewed rate at which ISW signatures actually occur in the stream — and its operating point is set precision-first, subject to a floor on recall. Its discrimination was also tested on scenes whose acquisition footprints do not overlap any used in training, so the survey is not confined to regions resembling those the model learned from. The labelling protocol is common to both: domain experts assign each reviewed vignette one of three labels — Confirmed Positive, Confirmed Negative, or Inconclusive — and the training set is built from the confirmed classes, with positives augmented by 90°, 180° and 270° rotations (physically appropriate, as ISW surface signatures have no preferred orientation relative to the satellite look direction) and negatives, including reviewed false positives retained as decision-boundary examples. False positives and false negatives propagate asymmetrically into the survey. The classifier acts as a pre-screening filter: only predicted positives are routed to expert review, so false positives consume reviewer time but are human-classified as negative or inconclusive, whereas false negatives are never reviewed and enter the survey as undercount. That undercount is not fixed at the moment of first classification: each dataset release reclassifies the entire archive under the current model, so a signature missed on one pass is re-examined on the next and the survey's completeness improves as the model does. What reprocessing cannot recover is a signature the model fails on for reasons intrinsic to its appearance, which is missed

on every pass; training deliberately targets this residue, through the choice of negatives the model is required to discriminate against and through evaluation on the confusing cases rather than on the average one.

Expert review

Candidate detections are reviewed by domain experts. Review is queued by classifier confidence rather than sampled at random, so review coverage varies across the archive and is highest where the classifier fires most often. Reviewers can elect a threshold for a review session based on the model's classification score. A vignette is recorded as reviewed once an expert has examined it and as a confirmed positive once an ISW signature has been identified by at least one expert. The archive analysed here carries 233,829 reviewed vignettes and 19,167 confirmed positives; both counts are over open-ocean vignettes and grow as review continues. The review programme is the basis for the operational classifier-performance characterisation (false-positive and false-negative rates) to be reported with the final dataset. Reviewers judge each vignette on the geometry of the banding rather than on contrast alone. An ISW signature appears as a train of quasi-parallel, laterally coherent bright and dark bands, ordered in spacing along the train, with the bright and dark pairing consistent with surface convergence ahead of and divergence behind each wave. The features most often confused with it are atmospheric — gravity waves in the marine boundary layer produce comparably regular banding — together with wind streaks, surfactant slicks and ship wakes, each of which departs from that packet geometry in a characteristic way. A vignette that cannot be resolved on these grounds is labelled Inconclusive rather than forced to a decision, and Inconclusive vignettes do not enter the confirmed set.

Spatial extent and observational reach

Two distinct measures are reported. Imaged area is computed by representing each vignette as a nominal 20-km square about its centroid — the square has the correct area, and its orientation, which is not stored, does not affect area — and taking the deduplicated union of these footprints on an H3 resolution-7 grid. Observational reach is the occupancy of H3 cells, where a cell counts once if at least one sample falls within it, with the same resolution applied to both the literature and the WV layers; resolution 2 is used throughout, and the finer resolution 3 was computed as a sensitivity check. The choice of resolution 2 is an aggregation compromise: at planetary scale the survey must represent coverage in a single map, and because an ISW is a moving feature — propagating from tens of kilometres up to of order 10^3 km within its lifetime^{19,34} — a detection is evidence that ISWs transit a region, not only the point at which the vignette was imaged. Mapping detections only at their exact locations would itself misrepresent their reach. A resolution-2 cell (of order 10^5 km², edge length ≈ 180 km) is commensurate with that propagation scale in the regions where ISW activity concentrates, so that one occupied cell denotes an observed neighbourhood — a sensible unit at which to represent coverage without overstating the precision of any single detection. The open-ocean denominator is the World Seas

(IHO v3) layer with marginal and enclosed seas excluded (355,254,236 km²); seven literature regions falling outside this denominator are reported separately and not folded into the comparison. Antimeridian-crossing footprints are corrected, and on-land centroids are removed, before analysis.

Prior-regime corpus

A systematic bibliography of peer-reviewed ISW observational studies was assembled from the primary literature and from forward and backward citation tracing of anchor reviews^{3,22}, then expanded with region-specific searches to address geographic and temporal gaps, with title and DOI verification and deduplication. Studies reporting a recoverable spatial footprint were geolocated with bounding-box coordinates and a confidence rating; 92 papers describing 105 regions entered the coverage quantification. The prior record is defined by approach and bounded in time. It comprises the researcher-led literature — case studies, compilations and surveys that record where ISWs were found but not where they were sought and absent — up to the first global maps from a systematic survey that classifies every acquisition for presence or absence, published by the IWS in July 2025²⁵. Case studies of any date are included, since that approach has continued; surveys published after that date are contemporaries of the systematic approach rather than part of the record it replaces. On this rule the MODIS survey²⁴ enters as its six regional footprints, and the SWOT survey⁶, submitted in November 2025, enters none.

Acquisition latency and reproducibility

Acquisition-to-storage latency was computed from the sensing and storage timestamps over whole completed sensing days in the current configuration (median 3.0 h). All reported magnitudes are produced by a single audit-gated pipeline: each value carries provenance to its producing script and to the content hash of its input, and the registry is regenerated only when every recorded input hash matches the current inputs, so a stale producer cannot leak a number into the manuscript.

Use of AI tools

AI-assisted tooling was used in developing the software, including its test suite, and for paragraph-level rewriting during manuscript preparation; all experimental design, scientific decisions, and final content are the authors’.

Data availability

The expert-confirmed ISW detection dataset and the literature spatial-coverage dataset that support the findings of this study are available from the corresponding author on reasonable request and will be deposited in a public repository on publication. Live IWS detections are viewable at

<https://studio.iws.aircentre.org/explorer>. The source Sentinel-1 WV imagery is openly available from the Copernicus Data Space Ecosystem.

Code availability

The analysis pipeline (acquisition-rate, literature-coverage and coverage/reach computations, and the figure-generation scripts) is maintained under version control. It is available to editors and referees, and to qualified researchers on reasonable request from the corresponding author, and will be released publicly on publication.

Declarations

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Author contributions

J. Pinelo conceived the study, performed the analysis, generated the figures, and wrote the manuscript. J. Pinelo and A.S.F. led the development of the Internal Waves Service. J.d.S., J.G., and J.A.J. contributed to the development of the Internal Waves Service. A.S.F., J.d.S., and J.M. performed the expert review of detections. J. Pinelo and A.S.F. compiled the literature corpus and the spatial-coverage dataset. J.d.S. contributed text on internal solitary wave generation. M.B., M.S., J. Pineda, M.C., and K.T. contributed to the hazard framing and the interpretation of the occurrence patterns. J.A.J., D.V., J.M., C.G., F.C., A.L., G.F., A.C., and M.M. contributed to the revision process and commented on different manuscript versions. All authors edited the paper and approved the submission.

Competing interests

The authors declare no competing interests.

References

1. Mendes, R. et al. On the generation of internal waves by river plumes in subcritical initial conditions. *Sci. Rep.* 11, 1963; 10.1038/s41598-021-81464-5 (2021).
2. Bourgault, D., Galbraith, P. S. & Chavanne, C. Generation of internal solitary waves by frontally forced intrusions in geophysical flows. *Nat. Commun.* 7, 13606; 10.1038/ncomms13606 (2016).
3. Helfrich, K. R. & Melville, W. K. Long nonlinear internal waves. *Annu. Rev. Fluid Mech.* 38, 395–425 (2006).
4. Lien, R.-C., Henyey, F., Ma, B. & Yang, Y. J. Large-amplitude internal solitary waves observed in the northern South China Sea: properties and energetics. *J. Phys. Oceanogr.* 44, 1095–1115 (2014).
5. Huang, X. et al. An extreme internal solitary wave event observed in the northern South China Sea. *Sci. Rep.* 6, 30041; 10.1038/srep30041 (2016).
6. Zhang, X., Zhou, Y., Wang, X. & Li, X. Global distribution and amplitudes of internal solitary waves revealed by SWOT. *Sci. Adv.* 12, eaee0923; 10.1126/sciadv.aee0923 (2026).
7. Osborne, A. R. & Burch, T. L. Internal solitons in the Andaman Sea. *Science* 208, 451–460 (1980).
8. Wang, T. et al. Internal solitary wave activities near the Indonesian submarine wreck site inferred from satellite images. *J. Mar. Sci. Eng.* 10, 197; 10.3390/jmse10020197 (2022).
9. He, Z. et al. Investigations into motion responses of a suspended submersible in an internal solitary wave field. *J. Mar. Sci. Eng.* 12, 596; 10.3390/jmse12040596 (2024).
10. Giese, G. S., Hollander, R. B., Fancher, J. E. & Giese, B. S. Evidence of coastal seiche excitation by tide-generated internal solitary waves. *Geophys. Res. Lett.* 9, 1305–1308 (1982).
11. Giese, G. S., Chapman, D. C., Black, P. G. & Fornshell, J. A. Causation of large-amplitude coastal seiches on the Caribbean coast of Puerto Rico. *J. Phys. Oceanogr.* 20, 1449–1458 (1990).
12. Chapman, D. C. & Giese, G. S. A model for the generation of coastal seiches by deep-sea internal waves. *J. Phys. Oceanogr.* 20, 1459–1467 (1990).
13. Giese, G. S., Chapman, D. C., Collins, M. G., Encarnacion, R. & Jacinto, G. The coupling between harbor seiches at Palawan Island and Sulu Sea internal solitons. *J. Phys. Oceanogr.* 28, 2418–2426 (1998).
14. Quaresma, L. S., Vitorino, J., Oliveira, A. & da Silva, J. Evidence of sediment resuspension by nonlinear internal waves on the western Portuguese mid-shelf. *Mar. Geol.* 246, 123–143 (2007).
15. Whalen, C. B. et al. Internal wave-driven mixing: governing processes and consequences for climate. *Nat. Rev. Earth Environ.* 1, 606–621 (2020).
16. Talling, P. J. et al. Detailed monitoring reveals the nature of submarine turbidity currents. *Nat. Rev. Earth Environ.* 4, 642–658 (2023).
17. Alford, M. H. et al. The formation and fate of internal waves in the South China Sea. *Nature* 521, 65–69 (2015).

18. da Silva, J. C. B., New, A. L. & Magalhães, J. M. Internal solitary waves in the Mozambique Channel: observations and interpretation. *J. Geophys. Res.* 114, C05001; 10.1029/2008JC005125 (2009).
19. Magalhães, J. M., da Silva, J. C. B., Buijsman, M. C. & Garcia, C. A. E. 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 (2016).
20. Yang, Y. et al. Internal solitary waves in the Andaman Sea revealed by long-term mooring observations. *J. Phys. Oceanogr.* 51, 3251–3267 (2021).
21. Koohestani, K., Stepanyants, Y. & Allahdadi, M. N. Analysis of internal solitary waves in the Gulf of Oman and sources responsible for their generation. *Water* 15, 746; 10.3390/w15040746 (2023).
22. Jackson, C. An Atlas of Internal Solitary-like Waves and their Properties 2nd edn (Global Ocean Associates, 2004).
23. Klemas, V. V., Zheng, Q. & Yan, X.-H. Ocean internal wave observations using space shuttle and satellite imagery. *Geocarto Int.* 16, 53–58 (2001).
24. Jackson, C. Internal wave detection using the Moderate Resolution Imaging Spectroradiometer (MODIS). *J. Geophys. Res.* 112, C11012; 10.1029/2007JC004220 (2007).
25. Santos-Ferreira, A. M. et al. The Internal Waves Service Workshop: observing internal waves globally with deep learning and synthetic aperture radar. *Bull. Am. Meteorol. Soc.* 106, E1462–E1470 (2025); 10.1175/BAMS-D-25-0133.1
26. Pinelo, J. et al. IWS – Internal Waves Service: a world-first repository for planetary-scale internal solitary waves monitoring. *Proc. SPIE* 13666, 1366605 (2025); 10.1117/12.3069138
27. Pinelo, J. et al. Choosing an operational inference pipeline for internal solitary wave detection in Sentinel-1 SAR imagery: EVA02-Large+XGBoost versus SAR_CNN v2 (Lux.jl). Preprint at <https://doi.org/10.5194/egusphere-2026-1798> (2026). Under review for Geoscientific Model Development.
28. Pinelo, J., Gonçalves, J., Shukla, A. & Santos-Ferreira, A. Prior-matched evaluation of operational Earth-observation classifiers: a three-number reporting method demonstrated on Sentinel-1 internal-wave detection. Preprint at <https://doi.org/10.48550/arXiv.2607.07146> (2026). Submitted to Geoscientific Model Development.
29. Goret, C. et al. Internal solitary waves refraction and diffraction from interaction with eddies off the Amazon Shelf from SWOT. *Ocean Sci.* 22, 679–698 (2026).
30. Kouogang, F. et al. Turbulent dissipation along contrasting internal tide paths off the Amazon shelf from AMAZOMIX. *Ocean Sci.* 21, 1589–1608 (2025).
31. Santos-Ferreira, A. M. et al. 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; 10.3390/rs14030587 (2022).
32. da Silva, J. C. B. et al. Internal solitary wave parameters from SWOT KaRIn sea surface topography: a case study in the tropical Atlantic. *Sci. Remote Sens.* 12, 100307; 10.1016/j.srs.2025.100307 (2025).

33. da Silva, J. C. B., New, A. L. & Magalhães, J. M. On the structure and propagation of internal solitary waves generated at the Mascarene Plateau in the Indian Ocean. *Deep-Sea Res. I* 58, 229–240 (2011).
34. da Silva, J. C. B., Magalhães, J. M., Santos-Ferreira, A. M. & Huerre, R. Longevity of internal solitary waves in the Pacific Cold Tongue: synergies with SWOT. *Remote Sens. Environ.* 331, 115038; 10.1016/j.rse.2025.115038 (2025).
35. Santos-Ferreira, A. M., da Silva, J. C. B., St-Denis, B., Bourgault, D. & Maas, L. R. M. Internal solitary waves within the cold tongue of the equatorial Pacific generated by buoyant gravity currents. *J. Phys. Oceanogr.* 53, 2419–2434 (2023).
36. Hartharn-Evans, S. G., Carr, M. & Stastna, M. Interactions between internal solitary waves and sea ice. *J. Geophys. Res. Oceans* 129, e2023JC020175; 10.1029/2023JC020175 (2024).
37. Roemmich, D. et al. The Argo Program: observing the global ocean with profiling floats. *Oceanography* 22, 34–43 (2009).
38. Roemmich, D. et al. The technological, scientific, and sociological revolution of global subsurface ocean observing. *Oceanography* 34, 2–8 (2021).
39. MacKinnon, J. A. et al. Climate process team on internal wave-driven ocean mixing. *Bull. Am. Meteorol. Soc.* 98, 2429–2454 (2017).
40. Brüggemann, N. et al. Parameterized internal wave mixing in three ocean general circulation models. *J. Adv. Model. Earth Syst.* 16, e2023MS003768; 10.1029/2023MS003768 (2024).
41. Boegman, L. & Stastna, M. Sediment resuspension and transport by internal solitary waves. *Annu. Rev. Fluid Mech.* 51, 129–154 (2019).
42. Solano, M. et al. Nonlinear internal tides in a realistically forced global ocean simulation. *J. Geophys. Res. Oceans* 128, e2023JC019913; 10.1029/2023JC019913 (2023).
43. Zhao, Z., Alford, M. H., Giron, J. B., Rainville, L. & Simmons, H. L. Global observations of open-ocean mode-1 M2 internal tides. *J. Phys. Oceanogr.* 46, 1657–1684 (2016).
44. Gong, Q. et al. On the identification of internal solitary waves from moored observations in the northern South China Sea. *Sci. Rep.* 13, 3133; 10.1038/s41598-023-28565-5 (2023).
45. Yang, K.-C. et al. Anatomy of mode-1 internal solitary waves derived from Seaglider observations in the northern South China Sea. *J. Phys. Oceanogr.* 53, 2519–2536 (2023).
46. Helfrich, K. R. Decay and return of internal solitary waves with rotation. *Phys. Fluids* 19, 026601; 10.1063/1.2472509 (2007).
47. Stastna, M., Poulin, F. J., Rowe, K. L. & Subich, C. On fully nonlinear, vertically trapped wave packets in a stratified fluid on the f-plane. *Phys. Fluids* 21, 106604; 10.1063/1.3253400 (2009).
48. Grimshaw, R. H. J. & Helfrich, K. R. Rotation-induced nonlinear wavepackets in internal waves. *Phys. Fluids* 26, 056606; 10.1063/1.4879075 (2014).
49. Grimshaw, R. H. J., Helfrich, K. R. & Johnson, E. R. Experimental study of the effect of rotation on nonlinear internal waves. *Phys. Fluids* 25, 056602; 10.1063/1.4805092 (2013).

50. Buijsman, M. C. et al. Energetics of (super)tidal baroclinic modes in a realistically forced global ocean simulation. *J. Geophys. Res. Oceans* 130, e2025JC022460; 10.1029/2025JC022460 (2025).
51. Fiedler, P. C. & Talley, L. D. Hydrography of the eastern tropical Pacific: a review. *Prog. Oceanogr.* 69, 143–180 (2006).
52. Gerkema, T. & Zimmerman, J. T. F. Generation of nonlinear internal tides and solitary waves. *J. Phys. Oceanogr.* 25, 1081–1094 (1995).
53. Buijsman, M. C., Kanarska, Y. & McWilliams, J. C. On the generation and evolution of nonlinear internal waves in the South China Sea. *J. Geophys. Res. Oceans* 115, 2009JC005275; 10.1029/2009JC005275 (2010).
54. Grimshaw, R. & Helfrich, K. R. Internal solitary wave generation by tidal flow over topography. *J. Fluid Mech.* 839, 387–407 (2018).
55. da Silva, J. C. B., Buijsman, M. C. & Magalhães, J. M. 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 (2015).
56. Shao, M. et al. Observations of high-frequency internal waves near submesoscale fronts. *J. Geophys. Res. Oceans* 131, e2026JC023981; 10.1029/2026JC023981 (2026).
57. Kouketsu, S., Yasuda, I. & Hiroe, Y. Observation of frontal waves and associated salinity minimum formation along the Kuroshio Extension. *J. Geophys. Res. Oceans* 110, 2004JC002862; 10.1029/2004JC002862 (2005).
58. Kouketsu, S., Yasuda, I. & Hiroe, Y. Three-dimensional structure of frontal waves and associated salinity minimum formation along the Kuroshio Extension. *J. Phys. Oceanogr.* 37, 644–656 (2007).
59. Gray, P. C. et al. Evidence for kilometer-scale biophysical features at the Gulf Stream front. *J. Geophys. Res. Oceans* 129, e2023JC020526; 10.1029/2023JC020526 (2024).
60. Gerkema, T. Internal and interfacial tides: beam scattering and local generation of solitary waves. *J. Mar. Res.* 59, 227–255 (2001).
61. New, A. L. & da Silva, J. C. B. Remote-sensing evidence for the local generation of internal soliton packets in the central Bay of Biscay. *Deep-Sea Res. I* 49, 915–934 (2002).
62. da Silva, J. C. B., New, A. L. & Azevedo, A. On the role of SAR for observing local generation of internal solitary waves off the Iberian Peninsula. *Can. J. Remote Sens.* 33, 388–403 (2007).
63. Akylas, T. R., Grimshaw, R. H. J., Clarke, S. R. & Tabaei, A. Reflecting tidal wave beams and local generation of solitary waves in the ocean thermocline. *J. Fluid Mech.* 593, 297–313 (2007).
64. Grisouard, N., Staquet, C. & Gerkema, T. Generation of internal solitary waves in a pycnocline by an internal wave beam: a numerical study. *J. Fluid Mech.* 676, 491–513 (2011).
65. Mathur, M., Nadimpalli, J. R. & D'Asaro, E. A. Internal waves in a nonuniformly stratified ocean. *Annu. Rev. Fluid Mech.* 58, 383–411 (2026).
66. Cheshm Siyahi, V., Kudryavtsev, V., Chapron, B. & Collard, F. Novel insights on ocean internal waves: quantitative surface manifestations and upper ocean layer displacements from the Surface Water

- Ocean Topography Mission (SWOT) measurements. *Earth Space Sci.* 13, e2025EA004443; 10.1029/2025EA004443 (2026).
67. Zaron, E. D. Baroclinic tides observed by SWOT in the California Current. *J. Geophys. Res. Oceans* 131, e2025JC023119; 10.1029/2025JC023119 (2026).
68. Zhang, X. & Li, X. Constructing a 22-year internal wave dataset for the northern South China Sea: spatiotemporal analysis using MODIS imagery and deep learning. *Earth Syst. Sci. Data* 16, 5131–5144 (2024).
69. Scotti, A. & Pineda, J. Observation of very large and steep internal waves of elevation near the Massachusetts coast. *Geophys. Res. Lett.* 31, L22307; 10.1029/2004GL021052 (2004).
70. Garwood, J. C., Musgrave, R. C. & Lucas, A. J. Life in internal waves. *Oceanography* 33, 38–49 (2020).
71. Wyatt, A. S. J. et al. Heat accumulation on coral reefs mitigated by internal waves. *Nat. Geosci.* 13, 28–34 (2020).
72. Butman, B., Alexander, P. S., Scotti, A., Beardsley, R. C. & Anderson, S. P. Large internal waves in Massachusetts Bay transport sediments offshore. *Cont. Shelf Res.* 26, 2029–2049 (2006).
73. Task Team for an Integrated Framework for Sustained Ocean Observing. A Framework for Ocean Observing (UNESCO/IOC, 2012).
74. Santos-Ferreira, A. M., da Silva, J. C. B. & Srokosz, M. SAR-mode altimetry observations of internal solitary waves in the tropical ocean, part 2: a method of detection. *Remote Sens.* 11, 1339; 10.3390/rs11111339 (2019).
75. Torres, R. et al. GMES Sentinel-1 mission. *Remote Sens. Environ.* 120, 9–24 (2012).

Figures

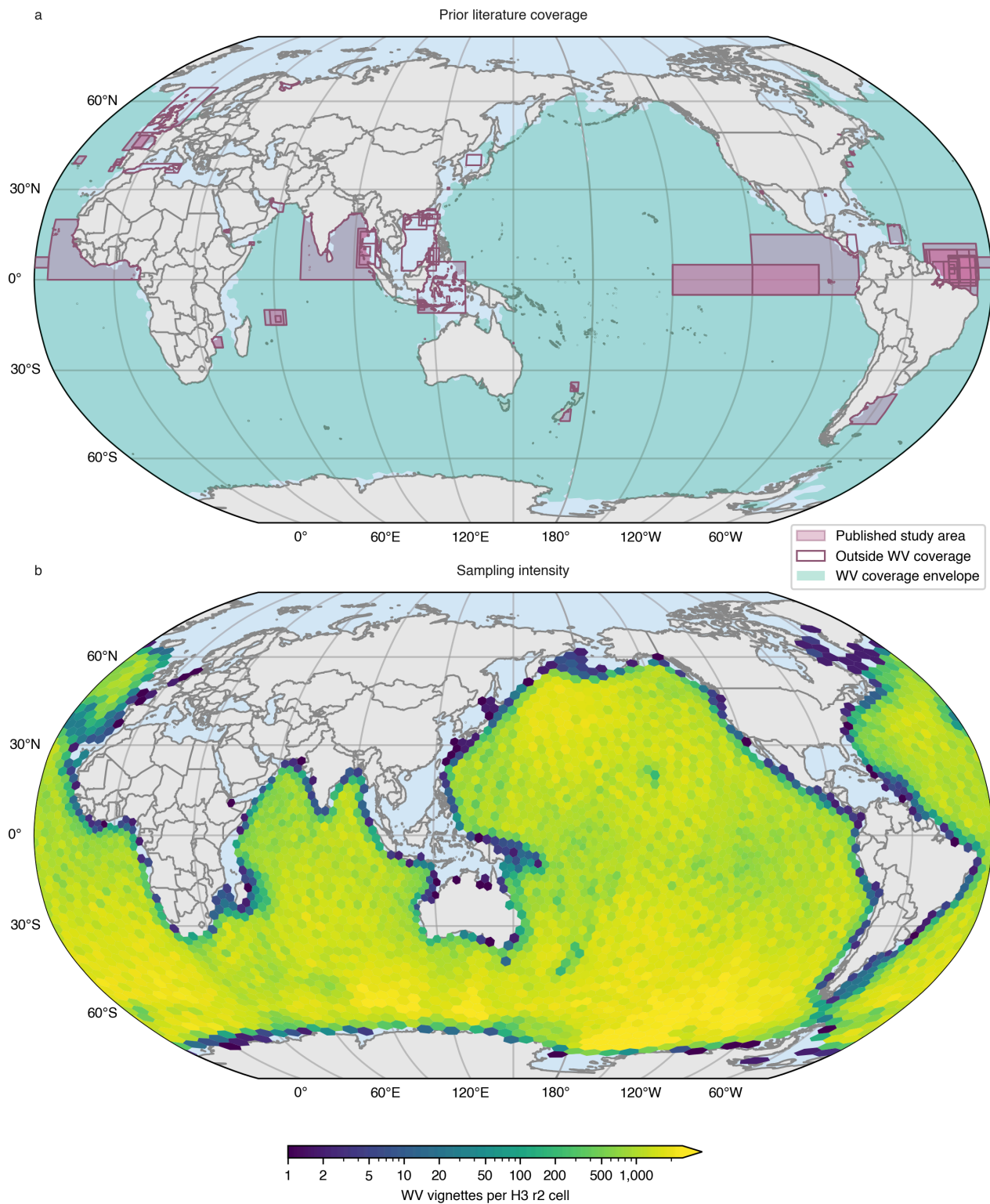


Figure 1

From a fragmented literature to a systematic global survey. a, Geolocated study regions of the prior ISW observational literature (92 papers, 105 regions; 1980–2026), drawn as their declared study-area footprints (reddish-purple boxes). Boxes are clipped to ocean, so land falling within a declared study area does not count towards the prior record's reach. Of these, 38 lie wholly outside the Sentinel-1 WV coverage envelope and are shown as outlines only. b, Sampling intensity of the analysed Sentinel-1 WV

archive: every ocean WV vignette (4,064,170) binned to equal-area cells of the H3 geospatial grid (resolution 2; each cell of order 10^5 km^2), colour giving the number of vignettes per cell on a logarithmic viridis scale.

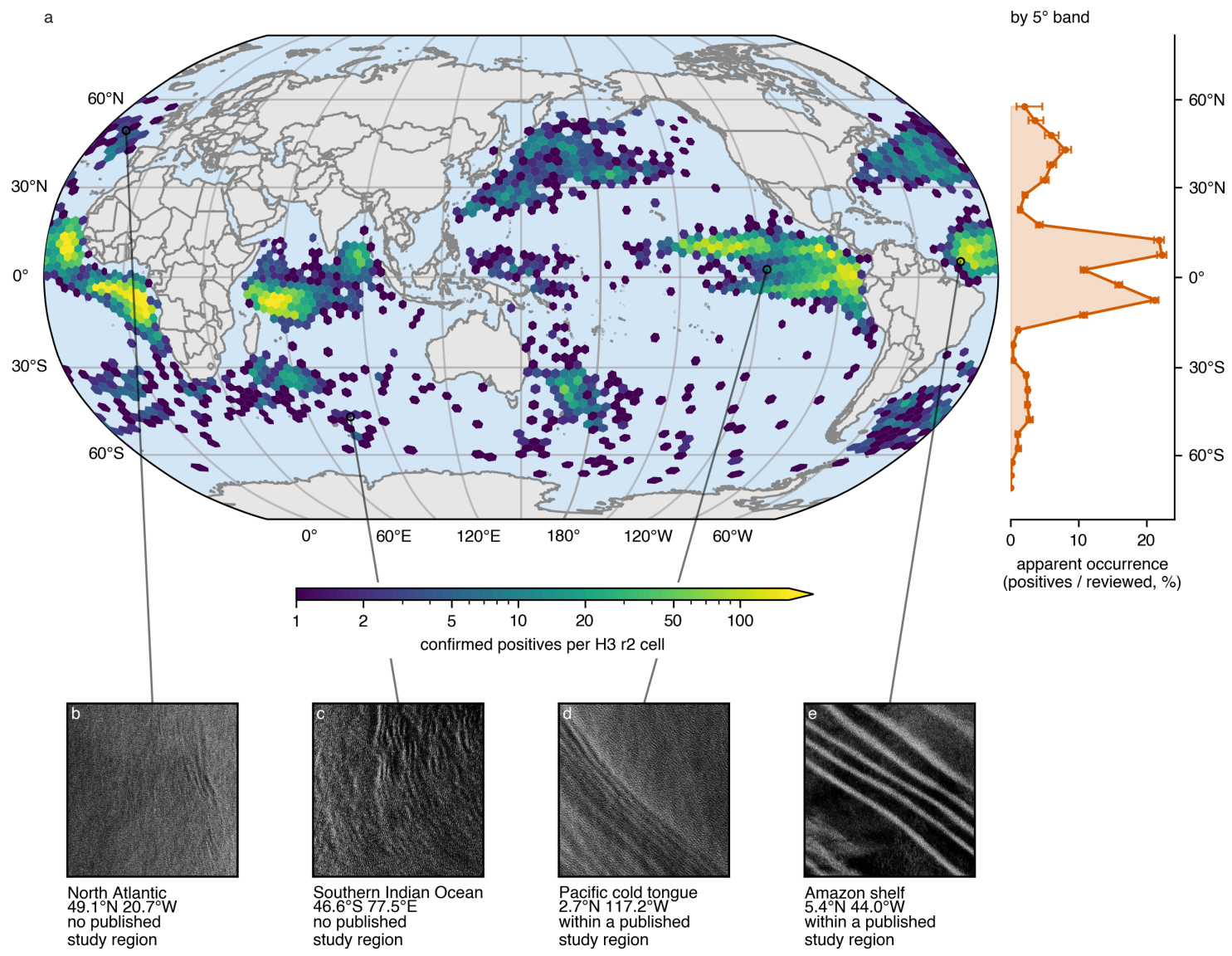


Figure 2

Global distribution, zonal profile and exemplar surface signatures of expert-confirmed SAR-detected internal solitary waves. a, Density of confirmed ISW detections (19,167 vignettes, from automated classification of the Sentinel-1 WV archive followed by expert review) aggregated to equal-area cells of the H3 geospatial grid (resolution 2), colour giving detections per cell on a logarithmic viridis scale. The profile along the right-hand edge shares the map's latitude axis and gives apparent occurrence by 5° latitude band, confirmed positives divided by the expert-reviewed vignettes in that band: vermilion markers, line and horizontal whiskers giving 95% Wilson score intervals, with a pale vermilion fill to the axis; bands holding fewer than 100 reviewed vignettes are omitted. The rate is apparent because factors other than ISW occurrence vary with latitude: high winds suppress the surface-roughness (Bragg)

signature²¹, sea ice masks the high latitudes³⁶, and review is queued by classifier confidence rather than sampled at random, so reviewed imagery is enriched in likely detections, not necessarily uniformly with latitude. b–e, Exemplar WV vignettes of confirmed ISW signatures, ordered left to right as their positions appear across a, each joined to its position by a grey leader line and circular marker: b, North Atlantic (49.1°N, 20.7°W); c, southern Indian Ocean (46.6°S, 77.5°E); d, equatorial Pacific cold tongue (2.7°N, 117.2°W); e, off the Amazon shelf (5.4°N, 44.0°W). Panels are VV-polarised amplitude in linear greyscale, each scaled to its own range, so brightness is not comparable between them; each spans about 20 km. Contains modified Copernicus Sentinel data (2023, 2024, 2026).

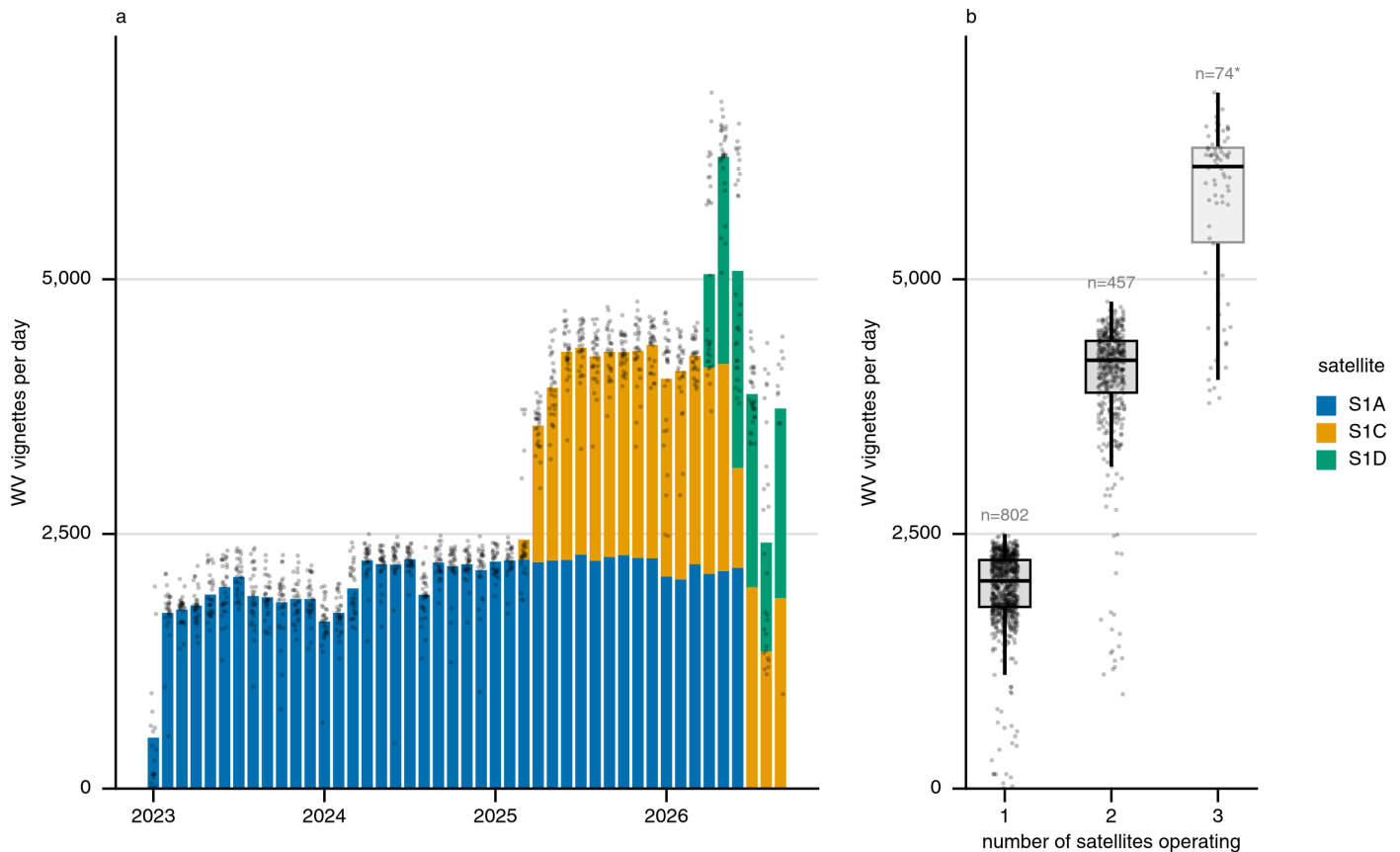


Figure 3

Acquisition characteristics of the Sentinel-1 WV stream. a, Monthly mean of the daily WV vignette rate, stacked by contributing satellite (Sentinel-1A blue, Sentinel-1C orange, Sentinel-1D green), with individual harvested-day totals overlaid as black points; months with fewer than five harvested days are omitted. b, Daily WV vignette rate grouped by the number of satellites operating that day, as box-and-whisker plots with the harvested-day totals overlaid (black points): the box gives the median and interquartile range, the whiskers the range excluding outliers, and n (harvested days) is given above each group. The rate scales with constellation size rather than trending in time; the three-satellite group is drawn muted and its n asterisked because it rests on few harvested days, following Sentinel-1D's 2026 commissioning.

Panel a begins in January 2023; WV harvesting before that date is discontinuous, and Sentinel-1B (retired 2021) falls outside the range shown.

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