The Unfinished Map

Why we govern the ocean on a vanishingly small sample,
and a distributed, self-correcting approach to observing the Indian Ocean

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Abstract

We make decisions about the ocean-the largest and most consequential system on Earth-from a sample so sparse it would be judged inadmissible in almost any other science. Less than one-thousandth of one percent of the deep seafloor has ever been seen by a human eye or camera; most deep-ocean observation has been carried out by a handful of wealthy nations; and the Indian Ocean-which has absorbed a disproportionate share of the planet's added heat and governs a monsoon on which more than a billion people depend-remains among the least-observed basins of all. This observation deficit, I argue, is not fundamentally a problem of reach but of method and economics-and both have quietly changed. I set out an approach to observing the Indian Ocean built on two premises. The first is that the ocean should be known the way a brain knows the world: through a continuously running model corrected by measurement only where it is uncertain-a case for data assimilation and prediction over the impossible ambition of measuring everything. The second is that the in-situ observing platform the field has waited for is already at sea, in the form of the artisanal fishing fleet-a route to dense, low-cost, participatory ocean sensing across a data-poor basin. I describe the scientific basis for this approach, the inference techniques that let a single modest sensor payload report on far more than it directly measures, the specific case for beginning in India and the Indian Ocean, and-at length, and without flattery-the problems that make it hard. This is not a report of results. It is a research and engineering programme, and an invitation to improve it or to refute it.

1 The unfinished map

We possess complete topographic maps of the Moon, of Mars, and of Venus. Each was surveyed, in the span of a few missions, to a resolution of roughly a hundred metres: the lunar surface is mapped over more than ninety-eight percent of its area, Mars in full from hundreds of millions of laser measurements, Venus across more than ninety-eight percent of its surface by a single spacecraft in the early 1990s [1, 2, 3]. We do not possess such a map of the floor of our own ocean. As of 2024, modern high-resolution mapping covered about a quarter of the seabed-26.1 percent, up from six percent in 2017 [4]-and even the most recent figures place it below a third [5]. NASA, announcing a new effort to infer seafloor shape from satellite gravity, put the matter plainly: there are better maps of the Moon than of the bottom of the sea [6].

Mapping, though, flatters us. To map the seabed at low resolution is to know its gross shape; it is not to have seen it. The fraction of the deep seafloor that has actually been observed-looked at, by a human or a camera, in seventy years of submersibles and remotely operated vehicles-is, by a 2025 estimate in *Science Advances*, less than one-thousandth of one percent: an area about the size of the American state of Rhode Island. The authors note that even if their estimate were wrong by a factor of ten, less than one-hundredth of one percent of the deep seafloor would have any visual record at all [7]. We have looked at more of other planets than of the planet we live on.

It is tempting to read these numbers as a story about difficulty-the deep is dark, crushing, and far away, and so of course we have not been-and to leave it there. That reading is comfortable and incomplete. The deep is difficult, but the more uncomfortable fact is what we do in spite of how little we have seen. We set fishing quotas, draw marine protected areas, model the carbon the ocean draws down, forecast the monsoon, and site the infrastructure of a blue economy now valued in the trillions [8], all on the basis of a sample so small and so skewed that no journal would accept it as representative of anything. This paper is about that sample, about why it has stayed small, and about a way to enlarge it that has only recently become possible.

2 The scandal of the sample

The first thing wrong with our knowledge of the ocean is not its quantity but its bias. The same 2025 analysis that produced the figure above examined roughly forty-four thousand deep-sea dives conducted since 1958 and found that more than sixty-five percent of them took place within two hundred nautical miles of just three countries-the United States, Japan, and New Zealand-and that five wealthy nations account for ninety-seven percent of all deep-sea submergence observations [7]. The instrument through which humanity has examined its largest habitat has been pointed, overwhelmingly, at the coastlines of a few rich states. We are not merely undersampling the ocean; we are extrapolating the whole of it from a handful of well-studied corners.

Nowhere is this clearer, or more consequential, than in the Indian Ocean. Consider a single fact, which I have not been able to get out of my head since I found it. The global satellite estimate of ocean primary productivity-the rate at which marine plant life turns sunlight and carbon dioxide into the base of the entire ocean food web, and a quantity that feeds directly into our understanding of fisheries and the carbon cycle-rests on an algorithm calibrated against in-situ measurements. Of the 1,698 calibration stations underlying that global product, not one lies in the Indian Ocean [9]. The maps of Indian Ocean biology that scientists, managers, and governments rely on are, in effect, guesses imported from other seas.

This would be a curiosity if the Indian Ocean were a backwater. It is the opposite. Though the smallest of the tropical oceans, it has accounted for roughly thirty percent of the increase in global ocean heat content over the past two decades-and yet, the regional observing community reports, its own heat budget remains uncertain, because the observations needed to close it do not exist [9]. The basin warms faster than almost anywhere, stores a vast share of the planet's added energy, and drives the monsoon on which the food security of more than a billion people turns; and we observe it least. The richest data are gathered where the stakes, in human terms, are arguably lowest, and the thinnest data where they are highest. That inversion is the scandal at the centre of this paper.

3 Why the gap persists

If the value of observing the ocean is so plain, why does the gap endure? Because every existing way of closing it runs into the same wall: the ocean is opaque to the instruments that are cheap, and transparent only to the ones that are expensive and few.

Satellites are the cheap instrument, and they are extraordinary-but they see a skin. Altimeters and scatterometers measure the height, wind, and waves of the sea surface, and lose accuracy within five to ten kilometres of the coast, precisely where most fishing and most people are [10]. More fundamentally, no satellite can see beneath the surface: the subsurface temperature and salinity structure that determines currents, stratification, and the distribution of life must be inferred, never directly observed, from orbit. The ocean, as the acoustic-tomography literature likes to put it, is largely transparent to sound but opaque to light [11].

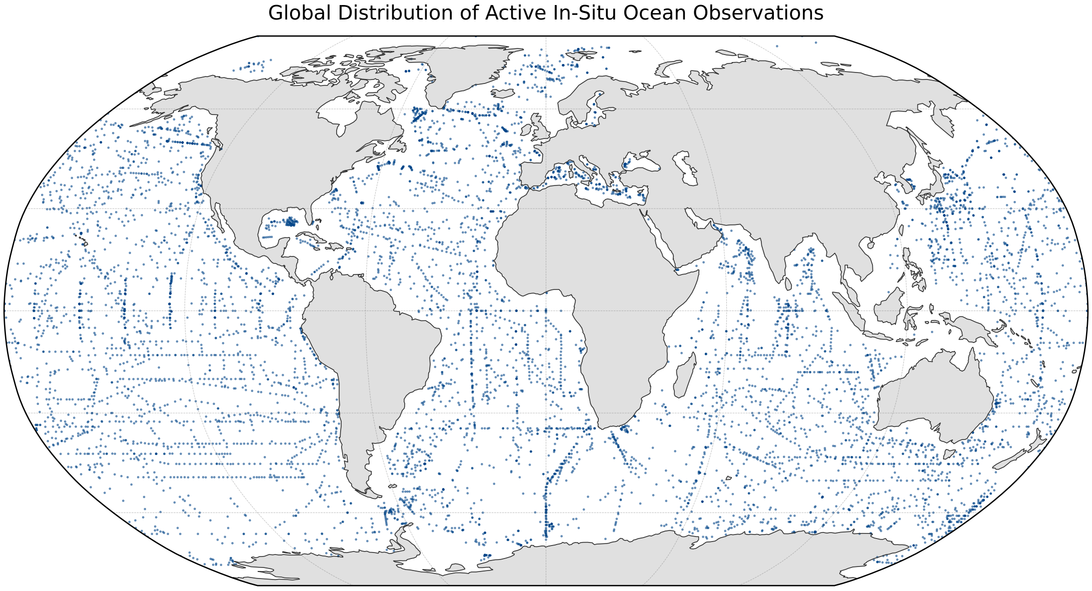

Figure 1: Spatial density of in-situ ocean observations, highlighting the data-sparsity of the Indian Ocean relative to the North Atlantic and North Pacific. [Produced from public Argo / observation-density data.]

The expensive instruments see beneath the surface, and there are not enough of them. The Argo program-the single greatest achievement of in-situ ocean observation-maintains close to four thousand autonomous floats, which between them have returned some three million profiles; sustaining the array requires five to six hundred new floats deployed every year [12]. Four thousand floats sounds like a multitude until one remembers the size of the ocean: the array was designed for roughly one float per three-degree square of sea, each profiling from two thousand metres to the surface once every ten days [13]. That is a magnificent climatology and a coarse nowcast; it was never meant to resolve a coastline, a shelf, an eddy, or a day. The deeper ocean below two thousand metres is sampled more sparsely still. Research vessels, the other deep instrument, cost on the order of thirty to sixty thousand US dollars per day to operate [14]; a moored deep-ocean buoy array of a few dozen nodes was estimated, decades ago, to cost tens of millions of dollars to build and millions a year to run, before ship time [15]. One does not observe a basin continuously with instruments priced like spacecraft.

There is a subtler obstacle as well, and honesty requires naming it early. Even where data exist, turning them into knowledge of the coastal ocean is genuinely hard: nearshore dynamics couple tides, waves, river discharge, and groundwater in ways that are, in the words of one mission white paper, "not well known and difficult to model" [10], and the assimilation methods that work in the open ocean strain in the shallows. I return to this in Section 9. For now the point is structural: the field has been caught between an instrument that is cheap and blind and instruments that see but cannot scale. The gap is not a failure of effort. It is the shape of the trade-off.

4 A different premise: read the ocean, do not measure it

The conventional response to undersampling is to ask for more sensors. It is the right instinct and the wrong primary strategy, because no affordable number of sensors will ever fill a volume of 1.3 billion cubic kilometres. The premise I want to propose instead is borrowed not from oceanography but from neuroscience.

A brain does not measure the world. The optic nerve delivers a startlingly thin stream of data; the brain spends most of its effort running a predictive model of reality and using the senses to correct that model where it errs. This idea-predictive coding-happens to describe, almost exactly, the most powerful technique in operational oceanography and meteorology, which is data assimilation: a physical model predicts what a sensor *should* read, the sensor reports what it *does* read, and the difference is used to nudge the entire model toward truth, after which it predicts forward again [11]. The model carries the physics into the gaps between observations. The observations keep the model honest.

I take this premise seriously and literally. The object I propose to build is not a dataset but a continuously running, self-correcting model of the Indian Ocean-a digital twin in the working sense of the term, of the kind that European efforts such as the Digital Twin of the Ocean and Destination Earth are pursuing at the planetary scale [16]. Two consequences follow, and they are the reason the premise matters.

First, such a system can give an answer everywhere, including where it has no sensor, because the physics interpolates; a pure data service goes silent outside its coverage. Second, and less obviously, the model knows where it is ignorant. A well-posed assimilation system produces not only a best estimate but an estimate of its own uncertainty at every point. That uncertainty field is a map of ignorance-and therefore a targeting system. It tells you exactly where another observation would buy the most knowledge. Sparse data, under this premise, stops being only a weakness and becomes a way of steering: the observing effort can be directed, continuously, at the places the model is least sure of. The structure is shown in Figure 2.

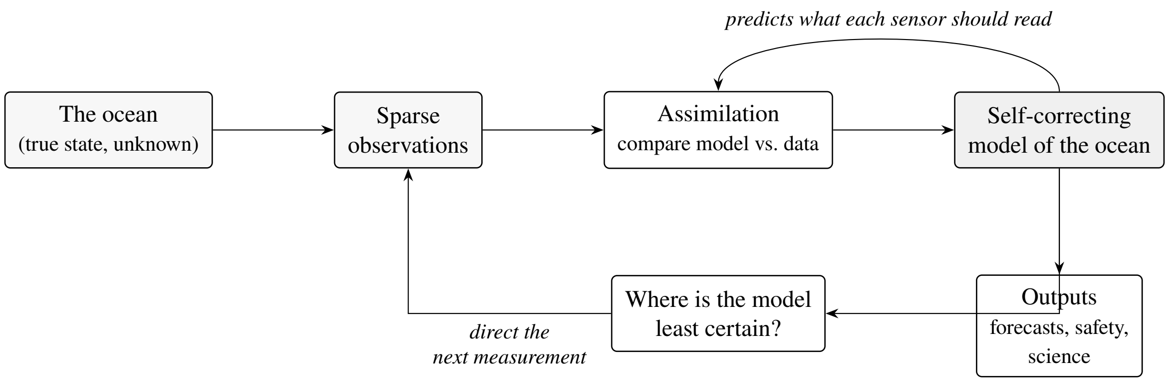

Figure 2: The premise in one diagram. Observations correct a running model rather than constituting the product; the model fills the gaps with physics, predicts what each sensor should read, and-crucially-reports where it is uncertain, which directs the next measurement. The observing network becomes a steerable sense organ rather than a fixed grid.

None of this is magic, and I will not pretend the hard part is solved. Coastal assimilation, as already noted, is one of the genuinely unsolved problems of the field. But the premise reframes the whole enterprise. The question is no longer “how do we measure the ocean,” which has no affordable answer, but “how do we keep a model of the ocean honest, and how do we feed it the corrections it most needs,” which has a tractable one-provided the corrections can be gathered cheaply and from the right places. Which brings me to the second premise.

5 The observers are already there

The platform the field has been waiting for is not a new fleet of autonomous vehicles, though those are valuable. It is the fleet that already exists. Every day, hundreds of thousands of fishing vessels go to sea-into the nearshore and shelf waters that satellites cannot resolve and research ships cannot afford to patrol, at night, under cloud, in every season. They are already where the data are missing. They simply carry no instruments and record nothing.

This is not a speculative idea; it is an established method that has never been pursued at the scale or in the places that matter most. The International Hydrographic Organization runs a Crowdsourced Bathymetry program built precisely on depth data volunteered by fishing, recreational, and commercial vessels, and that volunteered data is part of how the global seabed map is being completed [17]. The older tradition of "ships of opportunity"-the Voluntary Observing Ship scheme-has gathered marine meteorological data from merchant vessels for over a century, though its fleet has shrunk from around seven thousand seven hundred ships to roughly four thousand and remains dominated by developed-nation vessels [18]. The recent private networks point the same way with newer hardware: Sofar Ocean's distributed buoys return on the order of 1.5 million real-time observations per day and have logged tens of millions of observation-hours, from small solar-powered units cheap enough to be deployed from a modest boat [19, 20]; in one naval exercise, ten Saildrone surface vehicles covered 130,000 nautical miles over 2,700 mission-days and registered 116,000 unique maritime contacts [21]. The lesson of these efforts is consistent: distributed, low-cost platforms can now rival traditional programmes in the sheer volume of ocean they observe.

And yet each leaves the same gap open. The crowdsourced and voluntary-ship schemes ride mostly on commercial and developed-world traffic. The private networks deploy their own expensive hardware, concentrate in the global north, and answer to commercial coverage maps. None of them is built on the artisanal fleets of the global south, and none is built for the Indian Ocean. The very place with the thinnest data and the highest human stakes-the basin with no productivity calibration station of its own, fished by a fleet that is overwhelmingly small and traditional-is the place no one is instrumenting. That is the gap this initiative, which I am calling Thalwag, exists to close.

The approach is mutualistic by necessity, not sentiment. A sensor that its host resents is a sensor that gets removed, ignored, or fed bad data; the cheapest way to ruin a crowdsourced network is to give its participants nothing. So the design principle is that a fisher must receive more than the data is worth to us: real safety in dangerous weather, a means of calling for help, and genuine information about the sea, in exchange for measurements they choose to share. The fishers are not a resource to be extracted. They are the first beneficiaries and the first partners, and the system is, in the most literal sense, an instrument built out of their daily presence on the water.

6 Eight ways to read an ocean

The objection to a modest sensor payload is obvious: a fishing boat cannot carry an oceanographic laboratory, so how can it report on chemistry, biology, geology, and physics at once? The answer is that it need not measure each thing directly. The ocean broadcasts information about itself continuously, and a small number of well-chosen signals, read cleverly, reconstruct a great deal. What follows is a vision-level account of the leverage available; it is deliberately not an implementation. For each, I state honestly whether the underlying science is established, emerging, or speculative, drawing on the cited literature.

1. **The ocean is equations, not a list.** Temperature, salinity, and pressure are not three facts among hundreds; from them, a century of physics yields density, sound speed, stratification, and mixing without further measurement. One does not sense stratification-one senses T, S, p and computes it. *(Established.)*

2. **One instrument, many meanings.** A single hydrophone is not a "sound sensor": read well, the underwater sound field carries rainfall rate, wind speed, the passage and class of ships, the calls of marine life, distant earthquakes, and the ring of gas escaping the seabed. Quantitative "acoustic rain gauges" that infer rainfall from the sound of raindrops on the sea surface have decades of validation [23]. *(Established for several quantities; emerging for others.)*

3. **The ocean is a messenger.** Sound travels thousands of kilometres in the deep sound channel, and currents carry the chemical and thermal signature of a distant source past a fixed sensor. One need not be at a phenomenon to detect it; one stands where the ocean delivers it. *(Established.)*

4. **A cup of water is a census of life.** Every organism sheds DNA into the sea. Sequencing the environmental DNA in a litre of seawater can detect more species than a diver survey while matching

diver-measured abundance for common ones-turning a sample bottle into a biodiversity instrument [22]. *(Established and maturing fast.)*

5. **The medium itself is a sensor.** The travel time of sound across a stretch of ocean encodes the average temperature and current along its path, so many crossing acoustic paths can image the interior of a volume rather than a point; ambient-noise interferometry extracts structure even from the sea's own background sound [11]. *(Established in research; emerging at fleet scale.)*
6. **The surface betrays the deep.** Sea-surface height, roughness, and colour carry the fingerprints of what lies beneath-internal tides and waves, fronts, and the base of the food web-so satellite signatures can be inverted, partially, into subsurface information [24]. *(Established for detection; emerging for full inversion.)*
7. **Fields reveal what is buried.** A ferrous object on the seabed-a wreck, a pipeline, an anchor-perturbs the local magnetic field, so a vessel carrying a magnetometer is a moving detector of buried things; satellite gravimetry detects large-scale ocean and sub-surface mass changes from orbit [25, 26]. *(Established for object detection and large-scale mass; speculative for fine sub-seafloor resource mapping.)*
8. **Find the rare by never not-looking.** Shipwrecks, lost objects, and submerged sites are needles in an ocean; one cannot afford to search for them. But millions of boat-days are a passive, ambient survey, and a model that watches for anomalies can flag a candidate and send the one expensive asset-a vehicle, a diver-only to the promising square. *(The component techniques are established; the fleet-scale system is the proposal.)*

Table 1 summarises the leverage and its maturity. The honest reading is that most of these are established science individually; what is unproven, and what this initiative must earn, is their combination at scale, on cheap shared hardware, in a difficult basin. The inference layer does most of the work, but it does not make confirmation free: knowing where a wreck probably is, or what the deep temperature field likely is, still ends with an asset in the water. The contribution is to aim that asset precisely instead of searching blind.

Signal / method	**What it can yield**	**Maturity**
Coupled $T/S/p$	density, sound speed, stratification, mixing	Established
Passive acoustics	rain, wind, ships, marine life, quakes, seeps	Established / emerging
Downstream sampling	distant chemical and thermal sources	Established
Environmental DNA	biodiversity census from a water sample	Established
Acoustic tomography / interferometry	interior temperature and current fields	Research / emerging
Surface-signature inversion	internal waves, fronts, subsurface hints	Established / emerging
Magnetometry & gravimetry	buried objects; large-scale mass anomalies	Established / speculative
Fleet-scale anomaly search	rare and hidden targets, then confirm	Proposed

Table 1: Reading an ocean from modest hardware: the leverage, and an honest statement of its scientific maturity.

7 Why India, why now, why this basin

Three things make this the right place and the right moment, and only one of them is sentiment.

The basin needs it most. The case of Section 2 is, at bottom, the case for the Indian Ocean: the fastest-warming, most human-critical, least-observed of the tropical oceans, calibrated for some global products by data from everywhere except itself [9]. If distributed observation is worth doing anywhere, it is worth doing here first.

India has the fleet, and the human stakes are real. India's marine capture fishery landed about 3.49 million tonnes in 2022 from some 166,333 vessels, and the fleet is structurally artisanal: by older estimates roughly two-thirds of craft are traditional, and the small-scale sector that constitutes most of the daily presence on the water lands only a small fraction of the catch [30, 31]. That same daily presence is, today, almost entirely uninstrumented-and almost entirely unprotected. When Cyclone Ockhi struck in late 2017, official and community counts of the dead and missing diverged sharply, with church sources reporting hundreds still missing against far lower official figures-a discrepancy that exists because India has no single authoritative record of fishers lost at sea [32]. The country's flagship fisheries scheme, the Pradhan Mantri Matsya Sampada Yojana, with an outlay of about twenty thousand crore rupees, explicitly includes communication and tracking devices, sea-safety kits, and insurance [33]; the Draft Blue Economy Policy names marine data, warning systems, and coastal livelihoods as national priorities [34]. The policy intent exists. What is missing is the system.

The economics have changed. A decade ago this proposal would have required a state. It no longer does. The hardware has collapsed in cost-Sofar's evaluation by NOAA describes compact, solar-powered, easily deployable units operating for months [19, 20]-and so has the compute: AI weather models such as GraphCast and GenCast, and ECMWF's AIFS, now match or beat the best operational physics models on many measures and run a global medium-range forecast in minutes on a single accelerator, with code and weights released openly [27, 28, 29]. The model layer, in other words, is becoming a free input rather than a moat, and the foundational data-Argo, Copernicus, INCOIS-are open. For the first time, a small, focused effort can stand on a stack of open sensors, open data, and open models and attempt something that once needed a national agency. The window is real, and it is also, by the same logic, open to others; the advantage goes to whoever builds the trust and the data first.

8 One system, three purposes

It would be possible to describe what I propose as three separate things-a fisher-safety service, an ocean-science platform, and an ocean-intelligence enterprise-but that would mistake its structure. They are one system, and the dependencies run in a single loop. The safety service is what persuades fishers to participate and what makes the network grow; the network is what feeds the model and the science; the model and the science are what make the resulting ocean intelligence valuable to those who can pay for it; and that value is what funds the safety service, which is given freely. Doing the public good is not a charitable adjunct to the enterprise. It is the thing that builds the one asset-a trusted, dense, real-time presence in an unobserved sea-that nothing else can cheaply replicate.

Two commitments hold the structure together, and I state them here because they are load-bearing rather than decorative. The first is openness: the science and the methods are public, because an institution that aspires to be the trusted reference for a basin earns that trust by being checkable, and because giving science away is how one becomes the standard others measure against. The second is neutrality, secured structurally-the public-good mission and the data commons held by a body whose charter protects them, distinct from the commercial activity they make possible-so that the trust on which everything rests cannot be quietly traded away. I describe these arrangements in detail elsewhere; here it is enough to say that the design treats trust as the central asset and protects it accordingly.

9 What is genuinely hard

A position paper that lists only its hopes is a brochure. The following problems are real, several are unsolved, and an honest reader should weigh the idea against them. I have drawn the strongest versions of these objections from the same literature that supports the proposal.

Bad data can make a model worse. Biofouling begins the moment a sensor enters the sea; biofilms form, and reliable measurement eventually becomes impossible, with mitigation able to slow but not prevent the process-a problem especially acute for low-cost sensors meant to run unattended for months [35]. Crowdsourced data compound this: the hydrographic guidance for volunteered bathymetry warns that such data arrive with unknown offsets, uncertain calibration, and variable positional accuracy, and must have their quality and uncertainty explicitly assessed before use [17]. Ingesting heterogeneous fleet data naively could degrade a model rather than improve it. The approach therefore lives or dies on quality control, calibration strategy, and fouling-aware design, and these are not afterthoughts.

Coastal assimilation is hard in its own right. As noted in Section 3, the nearshore couples processes that are poorly observed and difficult to model, and the assimilation methods that succeed in the open ocean lose skill in the shallows [10]. Some of the most valuable waters to observe are also the hardest to model well; progress here will be incremental, and overpromising would be dishonest.

Adoption is a harder problem than electronics. The cautionary evidence is local and pointed: a study of small-scale motorised craft in northern Kerala found high adoption of mobile phones and GPS but that distress-alert beacons were "not effectively used," limited by cost, awareness, and perceived usefulness [36]. A device can be technically excellent and socially dead. Worse, a data-gathering device on fishers' boats can be perceived-even when it is nothing of the sort-as surveillance, or as extraction from a vulnerable community. Earning genuine, informed participation is anthropological work, and it is at least as hard as the engineering.

A fleet network could reproduce the very bias it means to cure. The deep-sea record is skewed toward rich nations; the voluntary-ship fleet is skewed the same way [7, 18]. A network that simply rode the best-equipped vessels would continue to under-sample the small-scale coastal fisheries that most need attention, unless those fleets are deliberately and primarily targeted. The equity that motivates the project is not automatic; it has to be designed in, and defended.

Operational uptake is not guaranteed. Even high-quality new data can sit unused if national forecasting centres lack the staff and time to build the error models, assimilation operators, and quality-control pipelines that heterogeneous streams require; the operational-modelling community is candid that limited understanding of the relationship between observed and unobserved variables already constrains forecast improvement [16]. Producing data is necessary and far from sufficient; the harder institutional work is making it usable.

I do not regard these as reasons not to try. I regard them as the actual content of the work-the problems whose solution *is* the contribution-and any version of this initiative that waves them away should be distrusted, including mine if it ever does.

10 An invitation

The argument of this paper is short enough to restate in a paragraph. We make large decisions about the ocean on a sample that is tiny and badly biased; the Indian Ocean, which matters most, is observed least, to the point of having no calibration station of its own behind some of the global products that describe it. The deficit is not mainly about reach but about method and cost, and both have changed: a self-correcting model can carry physics into the gaps and tell us where our ignorance is greatest, and the platform that can feed it cheaply, in the right places, is already at sea in the form of the fishing fleet-if, and only if, that fleet is treated as a partner that benefits, and the genuinely hard problems of data quality, coastal modelling, adoption, equity, and operational uptake are taken as the work rather than wished away.

I am building this, under the name Thalwag, from the coast of Kerala, beginning small. I am a final-year student of naval architecture and ship building, not yet the world's foremost authority on any of the disciplines this touches-nor do I need to be to see that the thing has not been built and ought to be. What I am certain of is the shape of the gap and the seriousness of the stakes. This document is a position, not a proof; its purpose is to be argued with. If you are a scientist who can sharpen the method, an institution whose data or mandate this serves, or a reader who thinks the premise is wrong, I would rather hear from you than not. The map is unfinished. It need not stay that way.

A note on this document

This is a position paper and a preprint. It has not been peer-reviewed, it reports no original experimental results, and it is deliberately confined to the level of approach and rationale rather than implementation. Every quantitative claim is referenced; readers are encouraged to consult the primary sources directly, and any error of fact is mine and worth correcting. Figures of ocean mapping and observation change over time-the seabed-mapped fraction in particular rises year on year-so the specific percentages should be read as of the cited dates.

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