The Global Ocean Observing System: Oceans of Data for Earth System Predictions

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"If you like your 7-day weather forecast, thank an oceanographer." – Craig McLean, Acting Chief Scientist, United States National Oceanic and Atmospheric Administration (NOAA), House Committee on Science, Space, and Technology Subcommittee on Environment, June, 2021.

The ocean affects us all. It covers over two-thirds of the Earth's surface. It impacts our daily live and broad range of economic sectors – from agriculture and marine and coastal activities to tourism, construction and insurance. As a key component of the climate system it has a direct influence on weather patterns all over the globe, also for areas thousands of kilometers from the nearest coastline. Those are just a few of the reasons, the Global Ocean Observing System (GOOS) is critical to improving WMO products and services.

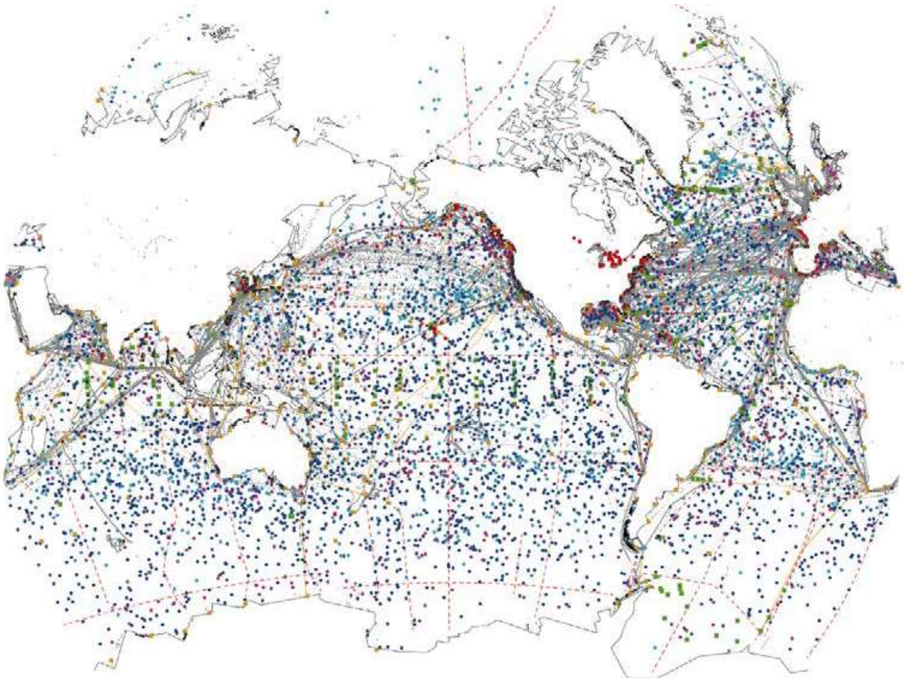
Ocean observations are needed to fulfill the WMO mandate to support the delivery and use of high-quality, authoritative weather, climate, hydrological and related environmental information and services by its Members for the improvement of the well-being of all nations. In particular, as society faces the impacts of climate change, more ocean data will be needed to better adapt and forecast extreme weather and climate events such as drought, flooding, wildfires, heatwaves and tropical cyclones.

The importance of ocean data was underlined in the findings of the recent Assessment Report from the Intergovernmental Panel on Climate Change (IPCC AR6[1], August 2021). Observed changes in several ocean parameters that impact phenomena such as heatwaves, hurricane frequency and inundation figure prominently in the report. Since 1980, sea surface temperature has risen 0.6 °Celsius (C), contributing to an excess of ocean heat content, to a roughly doubled frequency in marine heat waves which have also become more intense, and to sea level rise, while Arctic ice decreases. Before 2050, the Arctic Ocean is likely to be practically ice-free during the seasonal sea-ice minimum. Ocean acidification is increasing as a result of the uptake of carbon dioxide emissions and spreading deeper into the ocean, driving changes in saltwater chemistry.

In the current context, it is difficult to overstate the importance of GOOS as the global system for sustained observations of the ocean. Co-sponsored by WMO, the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the UN Environment Programme (UNEP) and the International Science Council (ISC), this program leads, support and coordinates long-term, sustained ocean observing for climate, operational services and ocean health. For three decades, GOOS has been coordinating in situ observations via a broad range of global, national and regional ocean observing initiatives, projects and systems.

Today, evolving and innovating the GOOS system in line with an Earth system approach, and in line with the WMO strategic plan, is critical to improving the weather, climate and water services and products of WMO Members. To support GOOS efforts to evolve and innovate, this article provides five recommendations. These recommendations, if

1 Working Group I Sixth Assessment Report



See *in situ* networks table for map legend. OceanOPS data source as of June 2021: operational platforms latest location (Argo, DBCP, AniBOS, VOS, ASAP); fixed platforms location (GLOSS, HF radars, OceanSITES); reference lines (GO-SHIP, SOOP); sampled sites (OceanGliders). Dashed lines for GO-SHIP and SOOP have not been sampled after Covid-19 impact; dots for VOS and ASAP show May 2021 observations. Symbols size is not to scale, in the map they are exaggerated to an order of hundreds kilometers for readability.

Ship based meteorological measurements - SOT/VOS
Ship based aerological measurements - SOT/ASAP
Ship based oceanographic measurements - SOT/SOOP-XBT
Sea level gauges - GLOSS
Drifting and polar buoys - DBCP
Moored buoys - DBCP
Long-term time series sites - OceanSITES
Profiling floats - Argo
Repeated transects - GO-SHIP
OceanGliders
HF radars
Biogeochemistry & Deep floats - Argo
Animal borne ocean sensors - AniBOS

implemented, will not only help GOOS adopt an Earth system approach, but will also accelerate the application of ocean observations and data delivery into WMO operations for improving weather and climate forecasts, especially for extreme events.

1. Augment the WMO Global Basic Observing Network (GBON) with a *global basic ocean observing system*. This "basic" oceans observing system would be designed to meet WMO's priority needs for observations and data sharing; to focus on pathways to sustain implementation; and to evolve in accordance with both operational and scientific drivers.
2. Engage with and support the GOOS *Ocean Observing Co-Design Programme* in order to build a system that fits the needs of WMO services; for example, developing a WMO-use area focused *exemplar* project.
3. Adopt FAIR (findability, accessibility, interoperability, and reusability) data principles for ocean data, to accommodate the diversity in ocean observing systems and data management systems.
4. Enhance connection, cooperation and coordination between the appropriate National Meteorological and Hydrological Service (NMHS) points of contact and the GOOS National Focal Points.
5. Increase cooperation and coordination between IOC GOOS Regional Alliances (GRA) and WMO Regional Associations (RA) to improve the design and collection of ocean observations for WMO applications.

GOOS has been gradually creating an extensive global system of ocean observations since 1991, based on contributions from a large number of organizations and governments, from which nations all over the world benefit. In its first two decades, GOOS focused more narrowly on development to support climate science and to serve as the observational backbone for operational forecast systems. In 2012, its success, coupled with growing concerns about the health of oceans and demand for information products to help nations manage their ocean economies, sparked development of the visionary Framework for Ocean Observing (FOO). GOOS has since led the implementation of FOO with the goal of serving users across climate, operational services and ocean health sectors, with ever more focus on coastal and regional seas.

GOOS has worked interactively with the ocean observing community to define both Essential Ocean Variables (EOVs) and Essential Climate Variables (ECVs) based on assessments of feasibility and impact. Observations of both EOVs and ECVs are crucial for providing scientific assessments of climate change and the health of the environment, to enable environmental prediction and adaptation to climate change, and to support more effective protection of ecosystems. (ECVs are discussed in more detail in Article 5.)

Sustainability and reliability of EOV data dissemination are of importance for the delivery of ocean services. The approximately 30 EOVs are roughly equally distributed between the areas of physical, biogeochemical and biological/ecosystem. The physical EOVs are identified as "Core Data'' in the draft WMO *Unified Data Policy*, which means that Members shall exchange them; while all other BioGeoChemical (BGC) and bio/eco EOVs are classified as "Recommended Data", and as such should be exchanged by Members to support Earth system monitoring and prediction efforts.

Today, the GOOS Observation Coordination Group (GOOS OCG), along with the WMO-IOC Joint Centre for Oceanography and Marine Meteorology in situ Observations Programmes Support (OceanOPS), together strengthen and coordinate activities

	Implementation	WMO delivery services			
	Status [1]	Climate	Ocean health [2]	Extreme weather events [3]	Weather forecast
Profiling floats - Argo Biogeochemistry & Deep floats - Argo	★★★ ★ Emerging	✓	✓		✓
Drifting and polar buoys - DBCP	★★★	✓		✓	✓
Moored buoys - DBCP	★★★	✓		✓	✓
Ship based meteorological measurements - SOT/ VOS	★★	✓		✓	✓
Ship based oceanographic measurements - SOT/SOOP-XBT	★★	✓			✓
Ship based aerological measurements - SOT/ASAP	★	✓			✓
Sea level gauges - GLOSS	★★★	✓		✓	✓
Animal borne ocean sensors - AniBOS	Emerging	✓			✓
Repetead transects – GO-SHIP	★★★	✓	✓		
Long-term time series sites - OceanSITES	★★	✓	✓		
HF radars	Emerging	✓		✓	✓
OceanGliders	★ Emerging	✓	✓	✓	✓

(1) Status: status vs network's target.

(2) Ocean health area regroup the observations supporting the assessment of the biological and geochemical status of the ocean.

(3) Extreme weather events encompass heat waves, hurricanes and floods.

*Profiling floats: Now an array of 4 000 autonomous floats profiling the ocean to 2 000 m, sampling temperature and salinity for climate, seasonal forecasts and ocean heat content assessment / * Deep and BGC missions are emerging to extend the capacity of floats in depth (to 6 000 m) and Biogeochemical observations*

Drifting and polar buoys: An array of 1 500 drifting buoys that observe surface atmospheric pressure, temperature and currents over the global ocean and are indispensable for global to regional weather forecasts.

Moored buoys: Network of about 400 moored buoys that observe multiple atmospheric and oceanographic parameters, mainly in coastal and tropical areas, for regional weather forecast and ocean operations.

Ship based meteorological measurements: A large fleet of voluntary observing ships that measure marine meteorological parameters for marine weather forecasting and safety at sea, the records go back 150 years and are also used in climate research.

Ship based oceanographic measurements: The Ship of Opportunity Program focuses on underway measurements from voluntary observing ships, including XBT temperature profiles to 1 000 m depth, sea surface temperature, salinity and pCO_2*, on repeated transects or reference lines.*

Ship based aerological measurements: The Automated Shipboard Aerological Programme collects upper-air profile data for operational applications and global climate studies, using voluntary ships.

Sea level gauges: A network of 290 sea level observing stations supporting high-quality long-term time series of sea level for climate research, marine operational user, and hazard warnings.

Animal borne ocean sensors: A network of instruments deployed on marine animals to provide ocean profiles of temperature and salinity, as well as and behavioural data for sustainable management.

Repeated transects Research vessels providing high quality, data collected to the full depth and width of the ocean, on reference lines repeated every decade. They are the benchmark for instruments calibration, climate studies such as carbon cycle studies and marine biogeochemistry and fuel many scientific applications.

across 12 global ocean observing networks. This enormously complex undertaking includes almost 10 000 operational observing platforms, all committed to deliver freely available data, at a quality and latency that is fit for user applications. Observational data include above-ocean atmospheric variables (such as sea surface pressure, sea surface temperature, humidity and wind stress) from every oceanic region, including under-sampled areas (such as the poles and the Southern Ocean). These 12 global and complementary ocean observing networks are operated by more than 80 countries. They include ships, both academic and merchant, surface and subsurface mobile instruments, and fixed platforms.

A technical coordination team at OceanOPS supports the implementation of the global system through integration and harmonization of metadata – basic information about data that makes it easier to find and use. This metadata management allows for accurate monitoring of ongoing global ocean observing activity and ensures that data and metadata can be delivered to stakeholders.

The GOOS OCG, on the other hand, supports the global system through work with the 12 international ocean observing networks to build common strategies across eight areas, which include data management, best practices, metrics, capacity development and requirements. These common strategies act to strengthen the 12 networks, help pilot the system's growth and develop cross-platform implementation.

Regional bodies also play a role in managing GOOS. The GOOS Regional Alliances (GRA), established by the GOOS Regional Council in 1994, have the mandate to connect "Global to Regional to National level". The WMO reform process paved a way via the new WMO-IOC Joint Collaborative Board (JCB) for GRAs and WMO Regional Associations (RAs) to work together on common issues connecting ocean to meteorology.

A note on satellite observations: while this paper focuses on the in situ oceans observing component, it is also important to recognize the impact of very significant investments in ocean observations from space. Since the launch of the first Earth observing satellites in the late 1970s, there has been a tremendous development of remotely sensed ocean data, from altimetry, ocean colour and sea-surface temperature to salinity. The importance of remote sensing data for ocean services cannot be overstated, particularly as they are able to fill gaps in the in situ observing system. For instance, remote sensing data of chlorophyll and temperature are used to fill the gaps in the sparse ocean CO_2 observations to reach the coverage needed to estimate global fluxes of CO_2.

A fundamental aim of GOOS is that ocean data are delivered efficiently: that is, with appropriate latency, quality and with sufficient metadata, ideally adhering to the FAIR principles (Findable, Accessible, Interoperable, Reusable), to the services and users that need it, in a freely and openly available manner. This is no easy task. The ocean observing system is diverse, with a large range of actors delivering data to a large set of data portals designed for different purposes. Although the FAIR data principles are essentially a prerequisite for WMO operational services, they are still not widely implemented for many of the ocean data streams, particularly for the delayed mode data. In response, one of eleven strategic objectives in the GOOS 2030 Strategy calls for FAIR ocean data.

Efficient GOOS data delivery is a key objective that cannot be met without a smoothly functioning, and appropriately connected and funded, data management system. To support such a data management system, GOOS relies on cooperation with the International Oceanographic Data Exchange (IODE) and the Ocean Data and Information System (ODIS) as well as the WMO Information System (WIS). In particular the development of WIS2.0 (see Article 4) offers great potential to radically improve the dissemination of ocean data to an ever larger user group.

Challenges and opportunities

GOOS currently faces a number of challenges and opportunities that are pushing it to innovate and evolve. Resolving these in ways that integrate ocean observation systems into an Earth system approach, and in line with the WMO strategic plan, is critical to improving the weather, climate and water services and products of WMO Members.

A major challenge for both providers and users of ocean observations is to determine which efforts really need to be sustained on a continued basis, and then to establish a commitment for sustained funding and operational support for those. To respond to this challenge, there is a need to extend and build partnerships for the ocean observing enterprise, and to explore development of a global basic oceans observing system.

Experimental or mission-based ocean observation systems are justifiable normally for a finite period to address a research challenge or to meet a specific need. However, there has been a tendency to develop dependency on research-funded systems that fill a specific gap in measurement or coverage and to consider them as de facto operational systems. The number of players in the ocean observing space drives this diversity of applications and (growing) demand, and vice versa, and contributes to the richness of observations that, if shared, add value to many other domains. However, this diversity can also lead to a lack of coordinated focus on ocean observing priorities, particularly at national levels where the funding largely originates and competition for resources is rife. Additionally, the ongoing use of research funding to support de facto operational systems puts a burden on the research community, since those funds are then not available for new research.

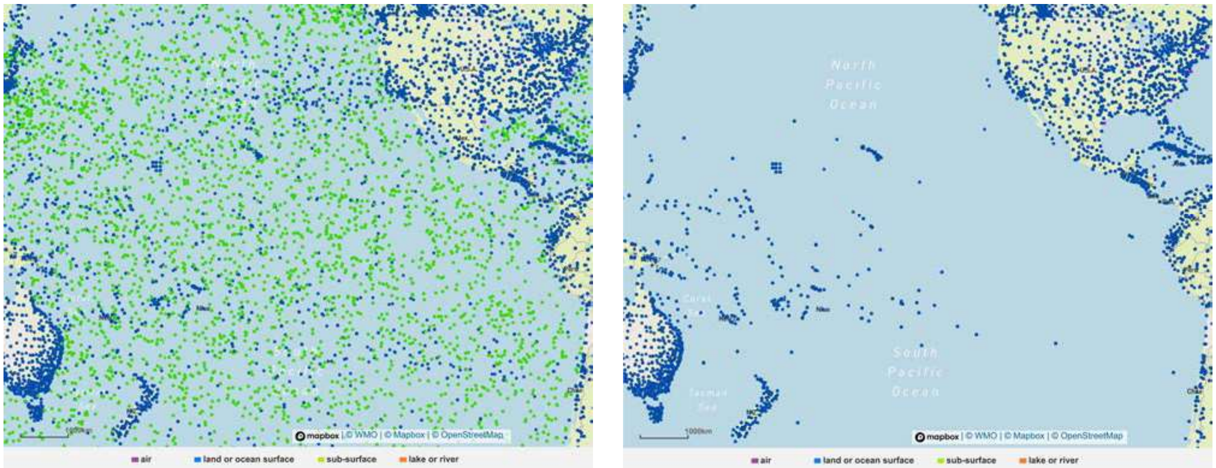
There is no magic bullet that will deliver new ocean observations funding to support a transition to operations. However, building stronger links between WMO-affiliated national agencies and IOC-affiliated institutions could yield mutual benefits in terms of greater collaboration, increased efficiency and reduction of duplication. Additionally, there is a need to develop an open process, tools and infrastructure to coordinate and prioritize user requirements and assess system capability in order to deliver in a platform-independent manner. A clearer delineation of which elements of global (and, by extension, regional and national) ocean observing systems might constitute an irreducible basic ocean observing system would support better decision-making by the entities who lead development of observing systems. Such entities (for example satellite operators) seek to secure ongoing funding commitments to operate and maintain them for the long term and (often) to freely share the data with the global community. Their fundraising and development work should build on EOVs and other identified ocean data priorities, as well as upon initiatives already underway.

GOOS as well as the WMO-IOC partnership embraces the full breadth of applications of ocean observations. These range from understanding, modelling and predicting the state and structure of the oceans in order to better manage the threats, hazards, productivity and sustainability of the ocean environment, to understanding the role that the oceans play as an integral part of the overall Earth system, across all timescales.

This broad range of applications means that both sustained, ongoing ocean observations and mission-based ocean observations are needed (as outlined in the GOOS 2030 Strategy). Again, however, some prioritization would be helpful. The formalization of a tiered approach to the ocean observing system should be explored, featuring as its foundational component a global basic ocean observing system. Such a global basic ocean observing system would be designed to meet priority needs for observations and data sharing; would evolve and innovate in accordance with operational and science drivers; and would focus on pathways to sustained implementation.

Addressing barriers related to national sovereignty of the seas is another important consideration in design and implementation of a global ocean observing system. The 2019 WMO driven "Ocean-Safe" workshop highlighted the importance of facilitating access to Exclusive Economic Zones (EEZs), in particular, for making and sharing subsurface measurements critical for operational applications like weather forecasting and safety of life at sea. The Argo program, the most abundant source of subsurface observations, has facilitated access for instruments deployed in high seas that drift into an EEZ, but not for deployments directly into an EEZ, which inevitably limits its global data coverage. Bilateral requests for marine scientific research clearance, needed six months ahead of operations, are today mostly not accommodated; and impractical for autonomous instruments deployed from a wide range of multinational opportunities, including from third parties. There is a need to facilitate these critical observations, possibly building on the Argo notification scheme to guarantee transparency for coastal states.

At the same time, a series of opportunities beckon, most notably the WMO *Unified Data Policy*. This substantial update of WMO data policy provides a once-in-a-lifetime opportunity for the ocean research community. It would provide this community with much greater free and unrestricted access to data from non-traditional sources (e.g. weather, atmosphere and cryosphere data) that impact ocean services and research via applications such as coupled modelling. In addition, access to WIGOS and WIS tools will support increased discoverability, standards, station IDs, and exchange that will benefit the objectives of both WMO and the ocean observing community. The WMO *Unified Data Policy* will also lead to increased recognition of data providers through the attribution of research data used for operational purposes. Finally, the revised policy also has the potential to influence national policies, thereby opening up inter-agency sharing and coordination of ocean data at national levels.



WMO OSCAR Surface Maps Without and with GOOS Ocean Observations

Although the WMO Observing Systems Capability Analysis and Review Tool (OSCAR) calls for surface observations, we are missing 2/3rds of the Earth's surface if we do not include Ocean data. Augmenting GBON with ocean observations is the way forward to improve climate and weather services for lives, livelihoods and properties. In this Figure, the tropical Pacific Ocean region of El Nino, the need to include ocean data into a unified system is obvious, green dots on the right panel are ocean observations.

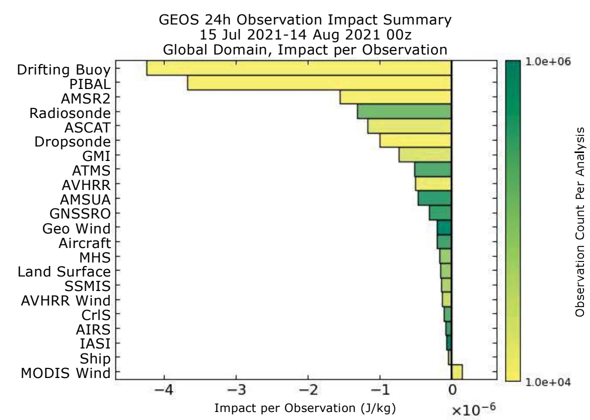
Additionally, cutting-edge projects like *OpenGTS* offer the opportunity to enhance access to free met-ocean data. Such projects will demonstrate the benefits of an integrated and collaborative approach to strategic areas like open data access, met-ocean forecast and environmental warnings. The implementation plan of the WIS2.0 endorsed *OpenGTS* as a demonstration project, and embraces activities that may benefit the WMO community for wider and more comprehensive data accessibility.

A number of additional opportunities have arisen through other international data management projects. To optimize the diversity of funding and satisfy requirements from ocean observing agencies, GOOS is participating in multiple other international data management efforts, which seek to harmonize data and metadata management internationally and to develop a global strategy and unified implementation plan. OCG, OceanOPS, IODE and WMO all play a role in this work. This strategic coordination capacity is supported by the GOOS infrastructure and has already demonstrated fruitfulness and efficiency. It is worth highlighting, in particular, the Ocean Best Practices project, which aims to improve uptake of observations as well as data and meta data.

Practical successes to help improve services

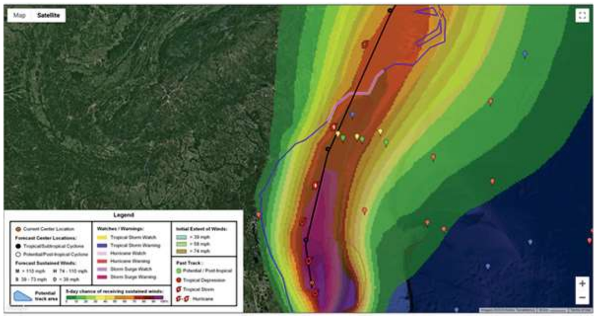
Ocean observations are fundamental to achieve weather ready and climate smart nations. Several examples below demonstrate how ocean data are, or could be, used to deliver more accurate weather forecasts.

- Sea level pressure (SLP) observations acquired by drifting buoys are essential in Numerical Weather Predictions (NWP) delivered by meteorological agencies around the world.
- The *Barometer Upgrade Program* of the Data Buoy Cooperation Panel, supported by NOAA's Global Drifter Program, allows users from the



Sea Level Pressure (SLP) Observations
Impact on Improving Numerical Weather Predictions (NWP)

In situ ocean surface drifter sea level pressure (SLP) observations are extremely valuable for anchoring the global surface pressure field and contribute significantly to NWP skill. Forecast sensitivity observation impact analysis (graph) indicates that the SLP drifters provide the largest per-observation contribution to skill.

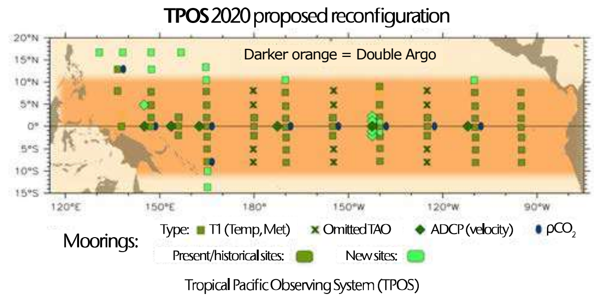


NOAA's Efforts to improve hurricane intensity forecasts were applied in August 2020 to Hurricane Isaias deploying in situ gliders, drifters, and Argo floats

meteorological community to measure sea-level air pressure in their areas of interest; the users simply pay the incremental cost of adding a barometer port and pressure sensor to a standard drifter.

- Progress has been made in the prediction of extreme events by using ocean data. Multiple types of ocean observation stations – drifters, OceanGliders, Argo floats and moored buoys – collect ocean data along the projected tracks of tropical cyclones for real-time assimilation into NWP models.
- Since 2020, North Atlantic Hurricanes are providing real cases for NOAA, allowing the agency to evaluate the ocean component of the full end-to-end hurricane forecast data flow.
- Similarly, India's Meteorological Department (IMD), working with India's National Institute for Ocean Technology, is delivering time-series observations from a network of moored data buoys to help improve forecasts of the track and intensity of cyclones. The high-frequency subsurface ocean temperature observations are extremely useful for the accurate estimation of upper-ocean heat content, and for understanding the role of the ocean in the intensification of tropical cyclones.
- The Tropical Pacific Observing System (TPOS) is being updated as a co-designed atmospheric and oceanic observing system in support of atmospheric teleconnections studies – the studies of how climate anomalies are related to each other at large distances – as well as operational forecasting.

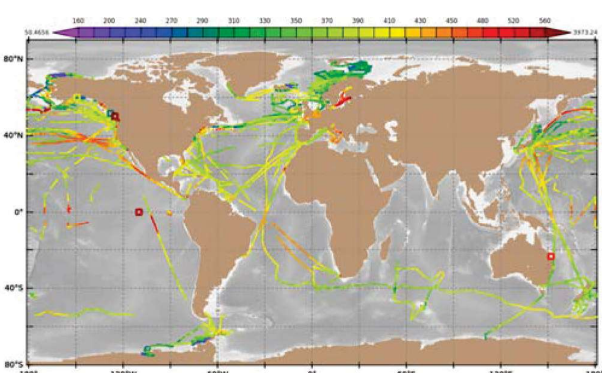
Regarding climate, ocean data are essential to effective prediction, but outstanding data needs remain. The level of carbon dioxide in the atmosphere has increased by about 50% since pre-industrial time; this is the primary driver of climate change. The ocean has taken up an estimated 45% of the cumulative fossil fuel emissions. It is critical to closely monitor the flux of CO_2 between ocean and



TPOS is a multinational met-ocean observing system designed to measure the subsurface and surface ocean and the atmosphere spanning the tropical Pacific from approximately 10°S to 10°N. TPOS seeks to accelerate advances in technology, understand and predict tropical Pacific variability, and inform policymakers and benefit society.

atmosphere and the accumulation rates of carbon in the interior ocean. However, there are large gaps in the required observations, particularly due to the large seasonal variability in surface ocean CO_2, and the observing effort is currently only weakly coordinated. Data on ocean carbon are currently mainly available through community-driven data products: SOCAT (the Surface Ocean CO_2 Atlas) is focusing on surface carbon data, whereas GLODAP (the Global Ocean Data Analysis Project) is delivering interior ocean carbon data.

The common denominator to success and progress in the examples above is collaboration between ocean institutes and meteorological agencies. Without technical, operational, financial and political partnerships, these accomplishments would not be possible. Cooperation between atmospheric and oceanographic communities at all levels is a prerequisite to any effort toward improving weather and climate services.



The Surface Ocean CO_2 Atlas (SOCAT) is a synthesis product for quality-controlled, surface ocean fCO_2 (fugacity of carbon dioxide) observations.

Ocean Observing Co-Design Process

We need additional ocean observations; but we also need to make sure funding is spent wisely and to establish clear priorities for future investments in ocean observations. Breaking down the silos between ocean institutes and meteorological agencies is critical to providing the largest possible impact of investments, and to effectively advocate for ocean observations at the highest political level. It will also accelerate the application of ocean observations and data delivery into WMO operations, thereby helping Members improve weather and climate forecasts, especially for extreme events.

A promising development is the GOOS *Ocean Observing Co-design*, one of the programs endorsed by the United Nations Ocean Decade. Co-design seeks to engage ocean institutes and meteorological agencies to jointly build the process, infrastructure and tools needed to evolve a truly integrated ocean observing system.

GOOS Co-Design will develop a more user-focused process to design and implement a large range of ocean observations by integrating with the modelling, forecast and services communities. Co-design of a *fit-for-WMO* ocean observing system will require that WMO experts work in close collaboration with GOOS colleagues at every step along the value chain pictured below. *Exemplar* projects, such as extreme event forecasting or carbon accounting, are selected to assess the observations required to deliver improved WMO forecasts.

The WMO *Unified Data Policy* has the potential to influence national policies that will open up inter-agency sharing and coordination of ocean data at national levels. Combined with Systematic Observations Financing Facility (SOFF) investments and partnerships, it is now possible for the first time to augment existing ocean observations into GBON to the inclusion of the remaining 2/3rds of the earth's surface. Co-designing, co-investing, and co-advocacy together will help developing the appropriate ocean observing capacity to deliver the climate and weather forecasts required to support short- and long-term decision-making in the context of climate change.