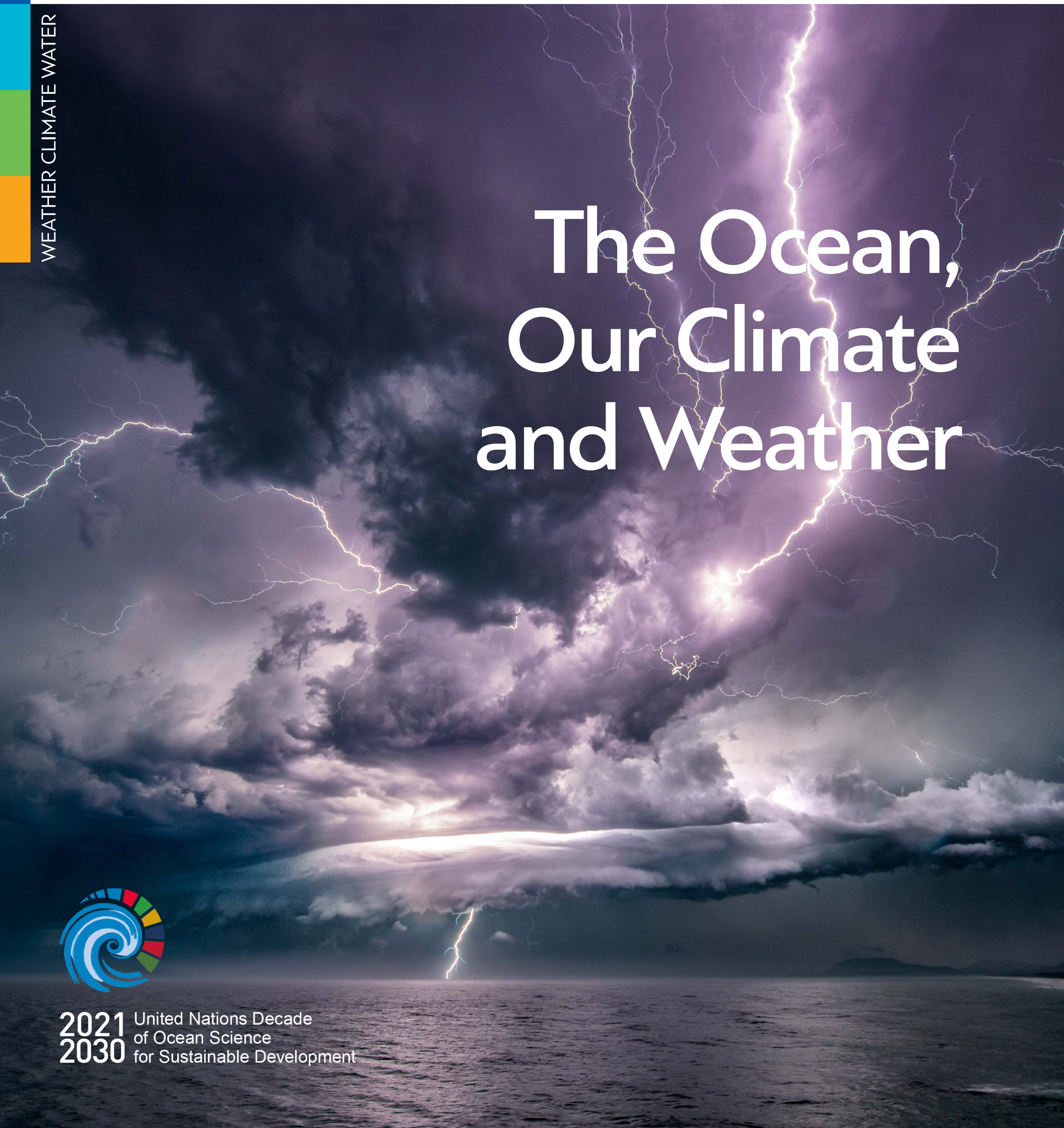
WORLD
METEOROLOGICAL
ORGANIZATION

BULLETIN

Vol. 70 (1) - 2021

WEATHER CLIMATE WATER



The Ocean, Our Climate and Weather

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

WMO BULLETIN

The journal of the World Meteorological Organization

Volume 70 (1) - 2021

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Deputy Secretary-General E. Manaenkova
Assistant Secretary-General W. Zhang

The WMO Bulletin is published twice per year in English, French, Russian and Spanish editions.

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	Surface mail	Air mail
1 year	CHF 30	CHF 43
2 years	CHF 55	CHF 75

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Front cover photo: Will Eades, Port Macquarie, Australia

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Foreword
Professor Petteri Taalas

World Meteorological Day marks the anniversary of the World Meteorological Organisation celebrated on the 23 March each year. This year, we celebrate the theme "The Ocean, Our Climate and Weather."

The theme is a reminder that the origin of WMO – and its predecessor, the International Meteorological Organisation – is linked to maritime history. As ships crossed the open ocean for trade, transport and exploration in the 1800s, the exchange of weather information at sea was critical for a safe voyage. This was the birth of international collaboration in meteorology. Indeed, Matthew Maury, the U.S. Naval Officer, oceanographer and meteorologist who initiated the First International Meteorology Conference in Brussels in 1853, is fondly referred to as the "Father of Modern Oceanography and Naval Meteorology."

Ocean and atmosphere exchange is a critical component to understand climate and weather processes. In a time of increasingly intense and frequent natural hazards, when people are starting to feel the impacts of climate change – many of which are ocean related – it is more important than ever to understand and appreciate the symbiotic links between oceanography and meteorology as WMO implements its Earth System approach.

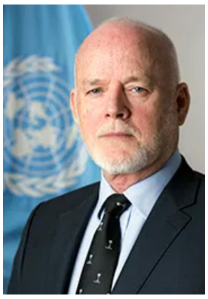
The WMO annual State of the Global Climate report, shows that 2020 was one of the three warmest years on record, despite the developing La Niña cooling in the Pacific Ocean. Many countries experienced prolonged droughts that extended fire seasons throughout the world, exacerbating wildfires – the devastation in Australia, for example, was linked to ocean temperatures influencing drier seasonal climate patterns. Warm ocean temperatures helped fuel a record Atlantic hurricane season, and unusually intense tropical cyclones in the Indian and South Pacific Oceans. The storm surge damage in these areas demonstrated the power of the ocean and its devastating impact on coastal communities. Non-tropical ocean storms also continued to wreak havoc aboard ships, with additional losses of life and cargo at sea. In 2020, the annual Arctic sea-ice minimum was among the lowest on record. Polar communities suffered abnormal coastal flooding, and sea ice hazards as a result of melting ice.

In understanding the ocean, and providing ocean related services, the WMO appreciates the many strong partnerships crucial for supporting our Members to strength met-ocean and climate services. The International Maritime Organization (IMO), the International Hydrographic Organization (IHO) and UNESCO's Intergovernmental Oceanographic Commission (IOC) are three key partners, of many, to this effort.

In celebrating World Meteorological Day with an ocean theme, WMO is also marking the start of the United Nations Decade of Ocean Science for Sustainable Development (2021 to 2030) with this special 'ocean' edition of the WMO Bulletin. Within, you'll find a very interesting and impressive compilation of the breadth of ocean activities that WMO, Members and partners are progressing.

In parallel to this, WMO is a Nominating Agency for the prestigious Earthshot Prize (2021 to 2030), which encourages solutions to support the much-needed work in understanding the ocean and climate for sustainable development. Together, around the world, I look forward to working with you all, with the high energy, innovation and commitment by Members, partners and civil society in progressing our knowledge, understanding and services for "The Ocean, Our Climate and Weather."

Petteri Taalas
Secretary-General
World Meteorological Organization


UN Photo/Mark Garten

Foreword
Ambassador Peter Thomson

Coming from an island community and having lived through many an extreme weather event, I have the highest of respect for meteorologists. I often find myself humming that memorable Simon and Garfunkel line, "I get all the news I need on the weather report"; so first up, on behalf of mariners at risk, vulnerable coastal dwellers, rain-dependent farmers, and so many others, I want to thank all you weather-people for the great work you do on our behalf.

An upbringing on a volcanic island in the South Pacific also provided me with direct observation of the hydrologic cycle and first-hand experience of the inextricable link between Ocean and Climate. It was clearly evident, even to a youthful mind, how the ocean was driving our water cycle, weather, and climate; how it was responsible for delivering the gentle rain that greened our fields, and how from time to time its powerful energy unleashed incredibly destructive storms.

It still amazes me that – though the ocean covers over 70% of the planetary surface and harbours the majority of life on this planet – so much of our economic and scientific endeavour has just ignored the ocean. In fact, the great majority of the ocean's properties remain unknown to science and we are only scratching the surface of the potential benefits of the sustainable blue economy. The time has come for us to change all that for the better, always ruled by the principle of sustainability, in the process bringing greater respect and balance to our relationship with the ocean.

In these times of looming Climate Crisis, the United Nations Secretary General Antonio Guterres has said that humanity has been waging a war against Nature and that it's time for us to make peace. What is clear to me now, is that the ocean's best interests must be fully represented at the peace table. Along with the energy of the sun, the ocean is the great regulator, thus we must give it the full respect it requires of us.

To understand what is expected of us, we must learn and understand more. The ocean has been absorbing over 90% of the heat trapped by increasing greenhouse gas emissions. This has warmed its waters, leading to marine heatwaves, death of coral, melting ice and rising sea levels. The better we understand the interplay between the ocean, weather and climate, the better we can predict and prepare for weather and climate hazards both on land and in the ocean.

At the beginning of 2021, we began the United Nations Decade of Ocean Science for Sustainable Development, during which we expect to witness a huge upsurge of knowledge about the ocean. I have no doubt that WMO commitments to the Decade's success will play a big part in our reaching the Decade's agreed goals of achieving a safe, predicted and transparent ocean.

I commend the contributors to this Bulletin for their descriptions of the good works being carried out around the world; and on behalf of all those dedicated to maintaining a healthy ocean, I thank WMO for the choice of "the ocean, our climate and weather" as its theme for this year's World Meteorological Day.

Peter Thomson
United Nations Secretary-General's
Special Envoy for the Ocean

The Ocean, weather, climate and the Earth system – new approaches and looking forward together

By Louis W. Uccellini, U.S. National Oceanic and Atmospheric Administration (NOAA), Director, National Weather Service; Permanent Representative of the U.S. to the WMO, and Co-Chair of the WMO-IOC Joint Collaborative Board (JCB)

WMO/Bruno Gonçalves

"If you like your 7-day weather forecast, thank an Oceanographer." - Craig McLean[1]

As a meteorologist, I've grown quite fond of this quote. I refer to it frequently when I'm explaining to people the tremendous changes that have taken place in the meteorological community in recent years. I think it captures the essence of our growing understanding that weather, water, climate and oceans are all inextricably linked, and so our work as individual meteorological and hydrological agencies, as well as our collaborative work together, must now reflect an Earth System Science (ESS) approach. The "Earth system" approach looks at the planet as a whole, linking the atmosphere, the ocean and hydrosphere, the terrestrial realm, the cryosphere and even the biosphere. Each of these affects the others, and understanding the oceans is integral to our ability to predict our Earth System.

A depiction of the Earth System Science framework linking the atmosphere, ocean, hydrosphere, and cryosphere while including the fundamental biological and chemical contributions and the effects of human factors.(Image courtesy of University Corporation for Atmospheric Research)

Historic changes

An outcome of this shift is an historic and significant change in the way meteorologists do their jobs and accomplish their mission. Thanks to rapid technological advancements and the proliferation of scientific data and information at our fingertips, we have moved from making basic forecasting predictions to providing faster, more accurate, impact-based forecasts, and products and services tailored to the needs of our users and partners as they make decisions. These decisions address society's increasing vulnerability to extreme weather, water and climate events, all influenced by accelerating global climate change. In addition, the world's demand for environmental intelligence is increasing, often across multiple disciplines. This increases the importance of integrating our forecasts and decision support across the weather, water and climate continuum.

As society becomes increasingly vulnerable to extreme weather, water and climate events, the need to take a more integrated ESS approach becomes ever more essential. The demand for increasingly useful, accessible and authoritative meteorological, hydrological and oceanographic information and services is growing as we collectively seek to implement smart mitigation and adaptation decisions by citizens, governments at all levels, and international institutions. These information and services are critical to support national agendas for disaster risk reduction and climate adaptation as well as to build resilience to the impacts of high impact weather, climate and water extremes. They also provide an essential underpinning to support the development and implementation of National Adaptation Plans under the Paris Agreement of the United Nations Framework Convention on

1 NOAA, Assistant Administrator for Oceanic and Atmospheric Research; U.S. Representative to the IOC; and Member of the WMO Research Board

UN Photo/Mark Garten

Closing ceremony of the 21st session Conference of Parties (COP21) of the United Nations Framework Convention on ClimateChange (UNFCCC) after the historic adoption of the Paris Agreement.

Climate Change UNFCCC) and other UN system needs for humanitarian and crisis management.

In response to these challenges, the WMO is in the process of historic change. In 2019, the 18th World Meteorological Congress adopted several critical decisions to position the Organization and its Members to break down bureaucratic and disciplinary stovepipes to better serve societal needs. One decision was the adoption of a WMO Strategic Plan, which sets a new course for the WMO – ensuring its relevance for decades to come by establishing a framework within which Members can successfully address these needs. By 2030, the WMO envisions a world where all nations, especially the most vulnerable, are more resilient to the socio-economic consequences of extreme weather, climate, water and other environmental events; and underpin their sustainable development through the best possible services, whether over land, at sea or in the air. Reflecting an integrated and inclusive approach, the new Strategic Plan:

- Advances an Earth System, fully-coupled approach to science and technology

- Advances understanding of stakeholder needs and improving service delivery

- Embraces the evolution and growth in partnerships and capacity development that enhance the observation, forecast and service abilities of WMO Members – including the growing private sector.

Through this process, WMO elevated the ocean as an essential component of the Earth System. Members welcomed this and agreed for WMO to move forward with a strategic approach ensuring that the work across a broad spectrum of ocean-related activities are connected within WMO and reach across essential partnerships.

WMO and Ocean Partnerships

Embracing an integrated, Earth System approach also means that the ocean and atmosphere communities need to work closer together and collaborate across the entire value chain, which includes the areas of observations, data management, modelling and forecasting, and services delivery. This value chain is underpinned by multidisciplinary research as well as capacity building. In support of this commitment (also in 2019), the 18th Congress and the 13th Session of the Intergovernmental Oceanographic Commission (IOC) of UNESCO created the WMO-IOC Joint Collaborative Board (JCB). The JCB is an advisory and coordination body to promote high-level collaboration and broad engagement of the relevant bodies of the WMO and IOC with the intent to work together to advance our mutual objectives.

The JCB is now developing a Joint Strategy to maintain, strengthen and promote links among the weather, climate and ocean communities in order to achieve the Visions of both the WMO and the IOC.

Within that Strategy, we see opportunities to work collaboratively to improve the scientific dialogue and interdisciplinary services to make them more accessible to developing countries. In addition, we see opportunities to jointly advance the global observation and numerical modelling system to provide a foundation for efficiently addressing the increasing requirements for decisions related to a wide range of applications, from maritime safety and transport, to agriculture, energy, health and water resource management.

The JCB is well-positioned to provide an opportunity to enhance coordination and cooperation among the well-established regional bodies of the WMO and the IOC such as the WMO Regional Associations and the Global Ocean Observing System (GOOS) Regional Alliances. The National Meteorological and Hydrological Services (NMHSs) of WMO Member States and Territories and National Oceanographic Institutes will now have an opportunity to collaborate more closely to improve weather forecasts, including for extreme events. In addition, the partnerships with other UN bodies – for example, the International Maritime Organization (IMO) for shipping and the Food and Agricultural Organization (FAO) for fisheries – can be harnessed to promote broader understanding among the coastal states on ocean data collection and science driven sustainable actions. The UN Decade of Ocean Science for Sustainable Development 2021-2030 will offer another opportunity to demonstrate the transformative role of the ocean in weather forecasts.

I believe we can successfully meet these global challenges by proceeding in a spirit of partnership among the many disciplines across the physical and social sciences. We must take advantage of advances in our field to ensure all Members have the capabilities to effectively respond to increasing vulnerability to extreme weather water and climate events. Together, we can position ourselves to deliver the science and services necessary for mitigating impacts of extreme events and protecting lives and livelihoods globally.

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Collaborating for a better future

By Sarah Grimes, WMO Secretariat

"Individually we are one drop; but together we are an ocean." – Ryunosoke Satoro

Sharing a common goal is the basis for strong partnerships. WMO, as the United Nations specialized agency for weather, climate and water, works towards enhanced comprehension of the Earth System, including the important links between ocean, climate and weather. A better understanding of the world in which we live will help, amongst others, to improve weather forecasts, to gauge the impacts of climate change and to manage water resources. These skills, in turn, will help countries to strengthen their ability to keep lives and property safe from natural hazards – reducing the risk of disaster – and to maintain viable economies. Toward this, WMO functions in a shared space with diverse partners to implement and support various high level international frameworks. These include the United Nations Sustainable Development Goals, the Sendai Framework for Disaster Risk Reduction, the Paris Agreement of the United Nations Framework Convention on Climate Change and the International Safety of Life at Sea Convention, amongst many.

In working across this shared space, partnerships are vital. Within the United Nations family, WMO and other agencies with ocean focused activities form UN-Oceans. This interagency mechanism boosts the coordination, coherence and effectiveness within the participating organizations with other international organizations. The United Nations Decade of Ocean Science of Sustainable Development, which started in January 2021, will heighten the close collaboration within UN-Oceans and other partners for harnessing further synergies to pool ideas and proactively advance solutions for the sustainable development of the ocean.

WMO is proud to collaborate across a broad spectrum of partners toward the mutual goal of supporting countries and serving the common good. The articles that follow spotlight three of WMO's principal ocean partners: the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the International Maritime Organization (IMO) and the International Hydrographic Organization (IHO).

CBD CMS CTED DESA DOALOS ESCAP FAO IAEA ILO IMO IOC ISA ODA

OHRLLS UNCTAD UNDP UNEP UNESCO UNFCCC UNHCR UNIDO UNITAR UNU UNWTO WMO World Bank

The UN-Oceans is made up of many participating agencies, collaborating to strengthen the collective efforts of ocean activities.

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IMO

The IMO and WMO – Providing weather information to support safe navigation

By Heike Deggim, Director, Maritime Safety Division, IMO Secretariat

"What maximum winds are expected in the storm area?" That is one of Standard Marine Communication Phrases under the International Maritime Organization (IMO) that officers in charge of navigation on ships, whatever their nationality, must be able to use and understand in English.

The world's 60 000 ocean going cargo ships are operated by some 1.6 million seafarers, traversing the globe and carrying 11 billion tons of trade annually which represents 80% of global trade.[1] High winds, waves, fog and storms can be encountered on every voyage – weather that impacts the safety of navigation. This was recognized in the first International Convention for the Safety of Life at Sea (SOLAS), adopted in the wake of the infamous 1912 *Titanic* disaster. The 1914 SOLAS treaty established the international ice patrol, active to this day, to monitor icebergs in the North Atlantic and included a "Code for the transmission by Radiotelegraphy of Information Related to Ice, Derelicts and Weather."[2]

IMO – established in 1948 as a specialized agency of the United Nations to develop standards for safe, environment-friendly, secure and efficient shipping – adopted and updated the SOLAS Convention, which now has 166 Contracting Governments, representing 98.98% of global shipping by tonnage.[3] The SOLAS Safety of Navigation chapter[4] sets out the Contracting Governments obligations to issue and disseminate weather information, forecasts and warnings and encourages ships to collect and exchange meteorological data. The SOLAS chapter on radiocommunications contains the provisions of the Global Maritime Distress and Safety System (GMDSS) and requires ships to have equipment on board to receive and transmit distress alerts, maritime safety information, search and rescue related communications and other general radiocommunications.

Today, the close cooperation between IMO, WMO and the International Hydrographic Organization (IHO) ensures that ships have automatic access to maritime safety information. This includes navigational warnings, meteorological warnings and forecasts through the IMO/WMO Worldwide Met-Ocean Information and Warning Service (WWMIWS)[5] and the World-Wide Navigational Warning Service (WWNWS)[6]. The three

1 Review of Maritime Transport 2020

2 Text of the Convention for the Safety of Life at Sea. Signed at London, January 20, 1914. Source: Open Library.

3 IMO Status of Treaties

4 SOLAS regulation V/5, in particular, refers to WMO publication WMO No.9, Information for Shipping (Volume D) through resolution A.528(13).

5 IMO/WMO Worldwide Met-Ocean Information and Warning Service – Guidance Document (resolution A.1051(27), as amended)

6 World-Wide Navigational Warning Service (resolution A.706(17), as amended) https://wwwcdn.imo.org/local-resources/en/KnowledgeCentre/IndexofIMOResolutions/MSCResolutions/MSC.469(101).pdf

Seafarers on ships (Photo: Simon LeBrun)

Organizations coordinate to provide maritime safety information,[7] undoubtedly contributing to safer voyage planning.

WMO works closely with IMO to support greater use of digitalization to integrate data on weather forecasts and related information into maritime services in the context of "e-navigation." Their goal is to harmonize the collection and integration of marine information to support safety and security at sea and the protection of the marine environment. The main focus is on harmonizing the format and structure of maritime services, taking user needs into account, leading ultimately to the implementation of improved and more efficient technical services.

IMO is aware that the scarcity of data from vast areas of the ocean (so-called data-sparse areas) to support basic weather forecasting, the provision of marine meteorological and oceanographic services and climate analysis and research is a problem for both meteorology and oceanography. It encourages mariners to participate in the WMO Voluntary Observing Ships (VOS) Scheme that welcomes sea-going vessels to join in the gathering of marine meteorological and oceanographic observations to support forecasting, climate change studies and research applications.[8] Today, over 4 000 ships are registered in VOS; with 2 740 identified operationally in 2020, that have submitted more than 2.5 million observations (Source: OceanOps, 2021). The reports from these ships are at times the only data available for remote areas, such as the polar regions.

Weather contributes to ships lost

Over the past decades, the number of large ships lost at sea has fallen from 130 in 2010 to 41 in 2019 – with a rolling average of 95[9]. This progress is widely attributed to improvements in shipping safety over the years due, among other things, to wider implementation of IMO treaties, an increased focus on safety management (IMO's International Safety Management Code was adopted in 1994) and more stringent global training standards (under IMO's STCW[10] training treaty). IMO has also been leading capacity building work to support increased coordination of port State controls – the process by which States inspect ships arriving in their ports to ensure standards are maintained. A mandatory Member State Audit Scheme is being rolled out to assess States' abilities to meet their

7 Promulgation of Maritime Safety Information (resolution A.705(17), as amended)

8 Participation in the WMO voluntary observing ships scheme (MSC.1/Circ.1293/Rev.1)

9 Allianz Global Corporate & Specialty's (AGCS) Safety and Shipping Review 2020

10 International Convention on Standards of Training, Certification and Watchkeeping, 1978

responsibilities as flag, port and coastal States and to offer technical assistance to fill any capacity gaps.

Nonetheless, casualty statistics reveal that "bad weather" is reported as a contributing factor in one in five ships losses.[11] While the investigation into any accident may shed light on the precise chain of events leading to a loss, there is a clear need for IMO, WMO and IHO to continue to work together to explore ways to further improve accuracy and timeliness of weather forecasting and its transmission.

The challenges ahead

Climate change has led to more frequent extreme weather events, threatening livelihoods, particularly in vulnerable communities. The maritime sector needs to be aware of increased risks to shipping and ports from more intense storms.

The IMO and WMO held the first joint Symposium on Extreme Maritime Weather: Towards Safety of Life at Sea and a Sustainable Blue Economy in 2019. Key areas for urgent attention were identified, including the need for maritime users to better understand meteorological and ocean data.[12] There are particular challenges for ships trading in polar regions and for ships not subject to mandatory IMO standards, such as small coastal cargo ships, large pleasure yachts and fishing vessels. There may be an abundance of commercial weather data available via mobile devices, but users need to know which data is authoritative.

Such issues must be addressed. The world has focused on more immediate challenges during the COVID-19 pandemic but it is now looking ahead to a sustainable recovery. Throughout 2020 and into 2021, seafarers and shipping have continued to deliver vital goods, including food and medical supplies, in the face of huge logistical challenges, in particular regarding global crew changes. Ensuring the safety of those seafarers against a variety of risks, including weather risks, must be a priority, as those seafarers are essential to global supply chains and economies worldwide.

Weather data and forecasting will always be key for shipping. IMO looks forward to continued cooperation with WMO in the coming years, to build on the systems established to date and ensure the resilience and responsiveness of met-ocean data for shipping.

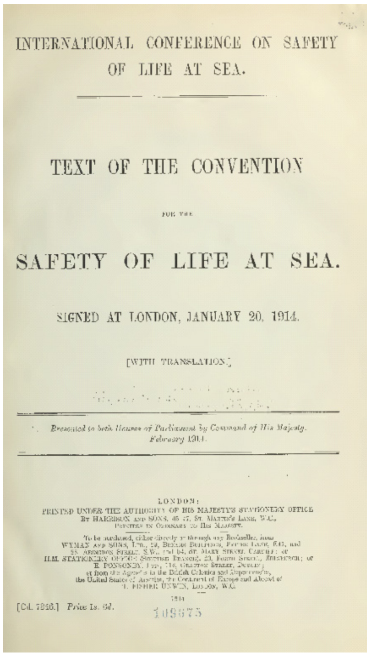
11 Allianz Global Corporate & Specialty's (AGCS) Safety and Shipping Review 2020 www.agcs.allianz.com/news-and-insights/news/safety-shipping-review-2020.html

12 public.wmo.int/en/media/news/wmo-imo-symposium-addresses-extreme-maritime-weather

The IHO and WMO – over a century of collaboration

By David Wyatt, Assistant Director, International Hydrographic Organization (IHO)

The catastrophic sinking of the *SS Titanic* on the night of the 14/15 April 1912 was the catalyst for many innovations, initiatives and regulations that the maritime community now take for granted. One of the most significant outcomes of the tragedy was the establishment of the International Conference that drafted the original text of the Convention for the Safety of Life at Sea (SOLAS), which was signed in London on 20 January 1914.


INTERNATIONAL CONFERENCE ON SAFETY OF LIFE AT SEA.

TEXT OF THE CONVENTION

FOR THE

SAFETY OF LIFE AT SEA.

SIGNED AT LONDON, JANUARY 20, 1914.

[WITH TRANSLATION.]

Presented to both Houses of Parliament by Command of His Majesty. February 1914.

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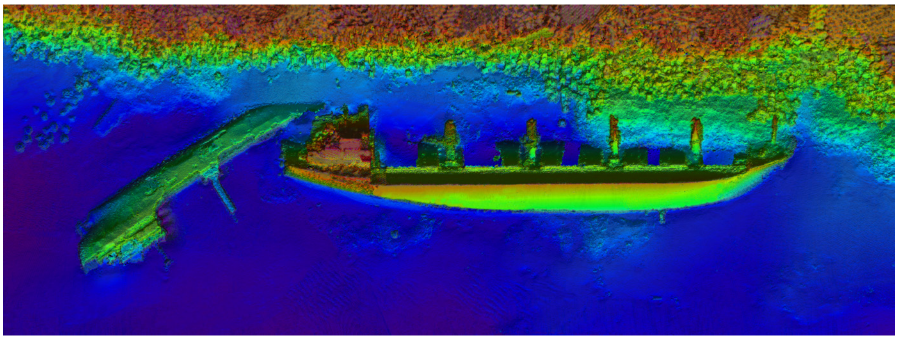
The Convention for the Safety of Life at Sea (SOLAS), signed in London on 20 January 1914

Several articles in the Convention cover the requirement for ships to be fitted with instruments to receive safety broadcasts, in particular information on ice and the weather. It is not surprising that the initial SOLAS requirements were very much focused on the provision of ice and meteorological information and obliged ships to provide information concerning ice and derelicts to other ships and authorities ashore, although weather details were optional. The text included particular instructions on the ice, derelicts and weather information that should be provided but less so information related to navigation and charting.

The International Hydrographic Bureau, now known as the International Hydrographic Organization (IHO), and the Meteorological Congress, now the World Meteorological Organization (WMO), worked closely together from the time of the first SOLAS Convention in 1914 to maintain, develop and refine maritime safety information (MSI). MSI covers both navigational warnings, and meteorological forecasts and warnings to ensure the safety of navigation and safety of life at sea. The cooperation between the two Organizations has led to a harmonization of procedures and regulations and the standardization of warning message formats for ease of transmission and clarity of understanding by the maritime customer.

The Radio Navigation Warning Service was developed to fulfil the SOLAS requirement for ships to receive safety broadcasts. It was the forerunner of the International Maritime Organization's (IMO) Global Maritime Distress and Safety System (GMDSS), the IHO/IMO World-Wide Navigational Warning Service and the WMO/IMO Worldwide Met-Ocean Information and Warning Service. This cooperation continues with the operational implementation into the GMDSS of new mobile satellite service providers recognised by the IMO.



Two boats colliding caused a double ship wreck off the coast of Constanta, Romania (Kongsberg Maritime)

Ocean floor data

The IHO and WMO have other common interests and goals, including the provision of accurate early warning information to coastal communities, which remains a considerable challenge. WMO and the Intergovernmental Oceanographic Commission (IOC) of UNESCO have both supported their members to develop models to predict the impacts of coastal inundations including from tsunamis and storm surge; however, the lack of complete high-resolution depth data for coastal zones, particularly coastal areas shallower than 1 000 metres, degrades the accuracy of these models. Depth data, and the information it provides about the seafloor, is also central to a better understanding of other ocean processes.

The IHO has several initiatives aimed at increasing the depth data of the ocean floor:

- a citizen science initiative, known as Crowdsourced Bathymetry (CSB), and
- a joint IHO/IOC General Bathymetric Chart of the Oceans (GEBCO) Project and its subordinate Nippon Foundation-GEBCO Seabed 2030 Project.

All these initiatives aim to provide a complete picture of the ocean floor from its deepest parts to the very edge of the land – information that is a vital foundation dataset for models created by WMO and IOC Members. As shape of the seafloor influences ocean circulation, which in turn has an impact on the climate and the atmosphere, the depth data could also be used to refine and improve the accuracy of climate change impact models.

Delivering as one

There is also a strong human element to the IHO and WMO collaboration. As part of the Joint[1] Capacity Building Coordination effort, the IHO and WMO identify and enact opportunities to develop and build capacity amongst the developing coastal states and small island developing states (SIDS). Their collaboration focuses in particular on the Caribbean, Indian Ocean, Pacific Islands and the coastal states of Africa. The United Nations "delivering as one" approach is at the centre of this coordinated effort to maximize the impact of limited resources and to ensure sustainability of the states to meet the objectives of the IHO and WMO as well as their obligations related to SOLAS, United Nations Convention on the Law of the Sea (UNCLOS) and other international instruments.

In the century that has passed since the sinking of the *Titanic*, the titles of the Organizations have changed and the methods have evolved, however, the goals and objective have remained the same: safety of navigation, safety of life at sea and protection of the marine environment. These will be the corner stones of IHO/WMO collaboration going forward. The digital world promises further breakthrough and developments for the navigational and meteorological information overlays that display on bridge systems and inform life-saving decisions.

1 IHO, IMO, WMO, IOC-UNESCO, International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), International Atomic Energy Agency (IAEA), International Federation of Surveyors (FIG), International Marine Pilot's Association (IMPA)

From ocean and atmosphere interaction to IOC and WMO cooperation

By Vladimir Ryabinin, Executive Secretary, Intergovernmental Oceanographic Commission; Assistant Director General, UNESCO

United Nations Educational, Scientific and Cultural Organization

Intergovernmental Oceanographic Commission

The theme of the 2021 World Meteorological Day highlights the inherent links and long-term cooperation between oceanography and meteorology. Two centuries ago, considerations of the safety of marine navigation were the decisive motivation for calling the first conference on marine meteorological observations. Held on 23 and 25 August 1853 in Brussels, the conference initiated common planning and cooperation between national meteorological offices. During the Crimean War, the Great Balaklava storm wreaked severe damage on the allied fleet on 14 November 1854. Soon after, it was understood that it would have been possible to predict the storm had there been a timely exchange of weather observations. Continued consultations resulted in 1879 in the establishment of the International Meteorological Organization, converted into the WMO on 23 March 1950, the date that we now celebrate as the World Meteorological Day.

The paths of development for meteorology and oceanography to their present state have been different. When the WMO Convention came into effect in 1950, the community of hydrometeorological services obtained a legal basis to sustainably and regularly conduct standard observations based on a mandate for coordinated service delivery. Not long after, the landmark concept for the World Weather Watch, the first WWW, was proposed in 1963. This quantum leap was crucial, and subsequent improvements have brought us today to a world that benefits from solid day-to-day meteorological services, even without fully realizing the scale of that achievement and the complexity of the system behind it.

Progress on ocean science has been different. Ocean research has been largely based on curiosity and the quest for discovery, earlier the interest was geographic, later scientific. The role of the ocean and ocean science for practical aspects of life has been undervalued historically, until recently. At the celebration of the 60th anniversary of IOC-UNESCO in 2020, one of its former Presidents, Geoff Holland, recalled that the need for real-time oceanographic data exchange was not obvious even in the 1980s.

We now live in the geological epoch of Anthropocene. Human influence on the planet has increased to the level of geological factors. The United Nations 2030 Agenda for Sustainable Development defines 17 Sustainable Development Goals (SDGs) to survive and live prosperously and in dignity in our epoch. Each of them is dependent on science, including the Earth System science and its atmospheric, hydrologic and ocean components. The success of UN organizations and agencies in supporting people and peoples – and of Member States of IOC and Members of WMO – requires focus on our common delivery for sustainability, co-design, good division of labour, equitable partnerships and the engagement of talent from the academic community working in the Earth System science.

A successful collaboration

Collaboration between IOC and WMO has been very intensive almost since the birth of IOC on 14 December 1960. The milestones have been multiple. I remember following the progress of the joint IOC/WMO Integrated Global Ocean Station System (originated in 1969), when I was a student in the 1970s. A host of historic IOC and WMO programmes were involved, including the WMO- ICSU Global Atmospheric Research Programme

(GARP). Then, in the 1990s, IOC and WMO became co-sponsors of the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS) and the World Climate Research Programme (WCRP). More recently, IOC has been contributing to the ocean dimensions of the annual WMO Statements on the State of Global Climate and to the WMO-facilitated report "United in Science." Both Organizations also provide scientific guidance to the continuing critical negotiations under the United Nations Framework Convention on Climate Change (UNFCCC).

From a governance point of view, the closest connection between oceanography and meteorology was achieved with the establishment of the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). During the 20 years of JCOMM (1999–2019), the meteorological and oceanographic communities truly worked together, adjusting practices where necessary and delivering as one. This work goes on. The JCOMM in situ Observations Programme Support Centre (JCOMMOPS) continues today as a joint venture called OceanOPS. IOC-affiliated experts are already working in the new WMO constituent body structures established by the WMO Governance Reform.

The work of the newly established WMO/IOC Joint Collaborative Board (JCB) is rapidly acquiring momentum. In my interview in the 2015 in the WMO Bulletin, Volume 64(2), I referred to the "strong complementarity of IOC and WMO [that] calls for developing joint strategies and plans." Now, six years later, the JCB is indeed discussing, for the first time, a Joint Collaborative Strategy of two our organizations.

WMO is an observer to many IOC programmes, including the tsunami warning and mitigation system. Many National Meteorological Hydrological Services (NMHSs) of WMO Members contribute to tsunami monitoring and warning. The IOC International Oceanographic Data and information Exchange programme (IODE) cooperates with the WMO Information System (WIS).

Looking into the future

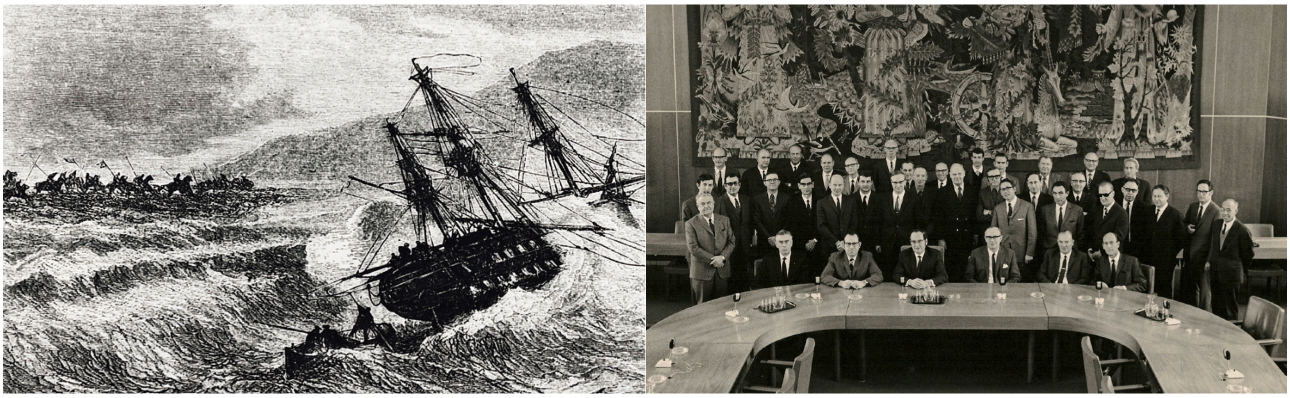
WMO, "the UN voice on weather, climate and water," is at present rapidly strengthening its ocean dimension,

The Establishment of the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology, a personal history by Peter Dexter, *was published in 2020 in celebration of the WMO 70th and IOC 60th Anniversaries*

including investing in observations of the physical state of the ocean and striving to facilitate ocean data exchange for meteorological and climate applications.

IOC is also going through a period of critical re-evaluation and solidifying its position as the home of ocean science in the UN system. IOC serves as custodian agency for two SDG 14 ("Ocean SDG") indicators. It coordinates the UN Decade of Ocean Science for Sustainable Development (2021 – 2030). Two of the Decade expected societal outcomes, namely the "safe and predicted ocean," are of particular relevance to WMO.

As we move forward, strengthening our collaboration, we need to reflect more comprehensively and accurately on the role of the ocean in atmospheric processes to harness the immense opportunities.



Sketch of ship foundering, Black Sea, Crimean War (left), and Joint WMO-IOC IGOSS/MAOA[1] Meeting, 1972 (right).

The joint IOC/WMO work on ocean observations and data input for short-range predictions for high-impact weather, including tropical and extratropical cyclones, which depend on the state of the ocean, will bring further breakthroughs. By exploiting sources of predictability associated with the ocean, we will be able to increase the skill of climate projections and predictions for a range of valuable time scales.

There is an urgent need to address as a multi-partnership the sustainability of the coastal zones, which involves a number of oceanographic, meteorological, hydrological, ecological, economic and social issues.

This short analysis cannot mention all aspects of our current cooperation nor the even more numerous future possibilities for working together. However, I hope it illustrates the paradigm that in the modern world, true leadership is manifested through partnership.

1 The Joint IOC Working Commitee for Integrated Global Ocean Services System and the WMO Executive Panel for Meteorological Aspects of Ocean Affairs

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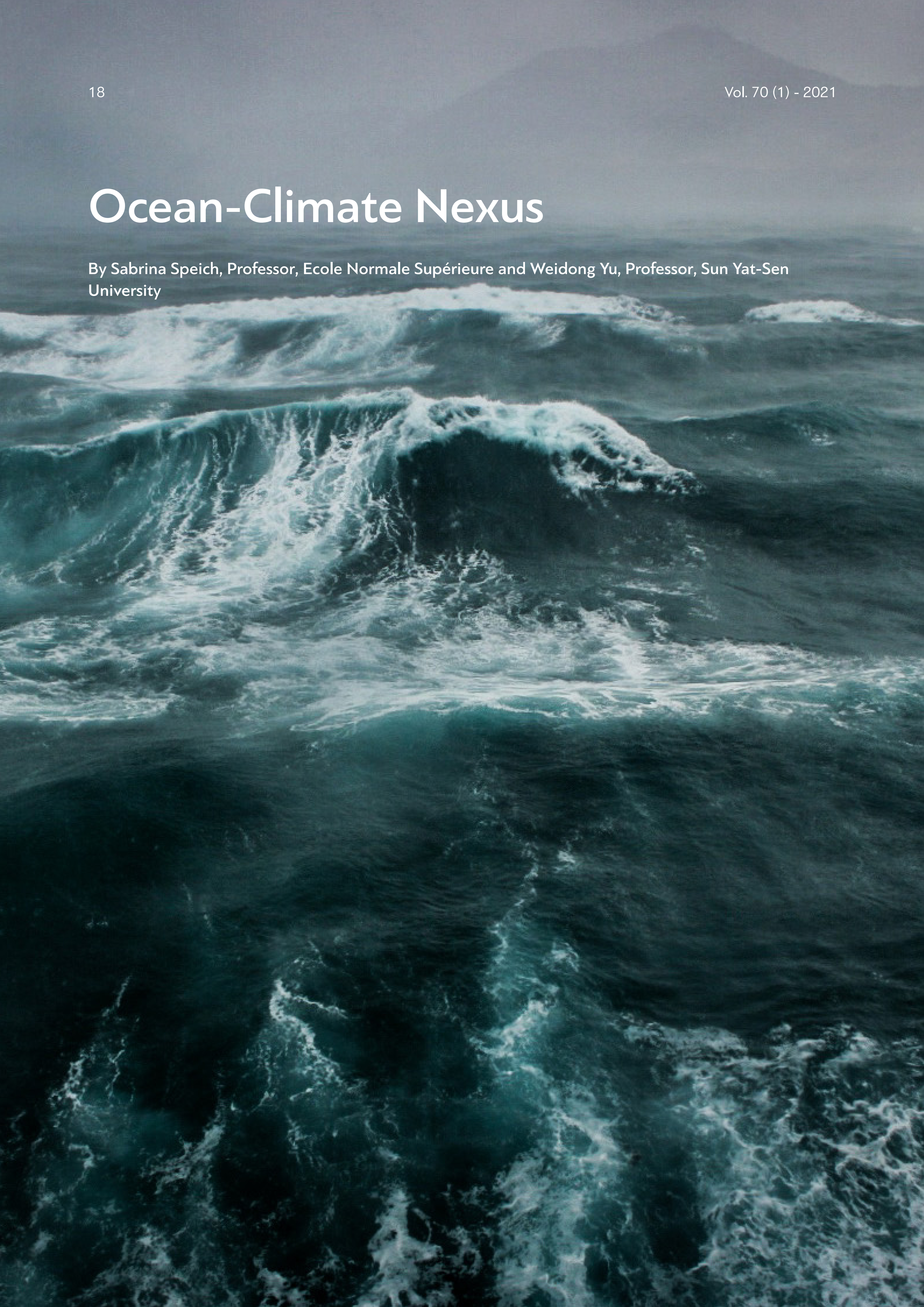
Ocean-Climate Nexus

By Sabrina Speich, Professor, Ecole Normale Supérieure and Weidong Yu, Professor, Sun Yat-Sen University



The ocean is a thin layer of saltwater that envelopes 71% of the Earth and contains 96% of its water. It contains the most varied biodiversity on the planet and is responsible for around 50% of gross primary production. It also acts as the Earth's thermostat, absorbing and transforming a significant portion of the radiation from the sun that reaches the Earth's surface. It provides water vapour to and exchanges heat with the atmosphere, shaping the Earth's weather and climate and its variability over a range of time scales, from hours to millennia. It mitigates climate change by absorbing almost all the excess heat (89%: Von Schuckmann et al., 2020) and a quarter of the CO_2 (Friedlingstein et al., 2020) produced by human activities.

The ocean receives heat from the sun electromagnetic radiation, mainly in the tropical regions. There is a constant back and forth exchange of water, energy and carbon between the ocean surface and the atmosphere at all latitudes where it is not ice-covered. The ocean is not static and ocean currents redistribute the excess heat received in the tropics towards higher latitudes, and towards the deep ocean. This transport is stronger at high latitudes – in polar regions – where surface waters become denser and sink, mainly due to high heat losses. The time scale of the transport and redistributions is highly variable, from season or year in tropical regions to a decade in the surface layers, and several hundred years, even thousands of years in the deep layers.

The global transport of heat, fresh water and carbon through the ocean is not only comparable in size to that of the atmosphere, but the ocean is the main reservoir of these properties for the atmosphere. The continuous ocean-atmosphere exchange of these properties and their storage in the ocean makes the ocean a key regulator of weather and climate at every time scale (from minutes to millennia: e.g., Smith et al., 2012; Doblas-Reyes et al., 2013; Kirtman et al., 2013; Meehl et al., 2014), extending the predictability of the Earth system at these scales. Seasonal and decadal prediction systems rely principally on accurately forecasting the fast dynamic and slow ocean modes of variability and their role in modulating the atmosphere (Kirtman et al., 2013). In order to ensure skilful – useful – predictions, models must be initialized with the ocean observations.

Timely and sustained ocean observations, both satellite and in situ, are crucial for the development of skilful predictions that meet societal expectations and needs (Smith et al., 2012). Much of the information underlying such predictions comes from globally-coordinated ocean basin scale observing systems. Major international weather and climate forecasting groups, including the European Centre for Medium-Range Weather Forecasts (ECMWF), the U.S. National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) and WMO, have requirements for ocean information to enable a resilient and sustainable blue economy. In addition, there is growing public recognition of the critical importance of information on current and future ocean conditions to meet diverse user needs. These include better observation and forecasting of waves, currents, sea level, water quality and the abundance of living marine resources as well as improved marine, weather and climate prediction services.

**References are available online*

The Role of the Ocean in a Changing Climate

By Hans-Otto Pörtner, Alfred-Wegener-Institute, Bremerhaven; Co-Chair Working Group II, Intergovernmental Panel on Climate Change (IPCC)[1]

All life on Earth depends directly or indirectly on the ocean and cryosphere (cryosphere is the term for the portion of the Earth where water is frozen). The ocean and cryosphere support unique habitats, and are interconnected with other components of the Earth system through the global exchange of water, energy and carbon. The projected responses of the ocean and cryosphere to human-induced greenhouse gas emissions and global warming include climate feedbacks, changes over decades to millennia that cannot be avoided, thresholds of abrupt change and irreversibility. Given these projections, governments requested in 2016 that the Intergovernmental Panel on Climate Change (IPCC) prepare a special report on the ocean and cryosphere in a changing climate.

The role of the IPCC

The IPCC is the United Nations body for assessing the science related to climate change. It was established in 1988 by the WMO and the United Nations Environment Programme (UNEP), and endorsed later that year by the UN General Assembly. The IPCC Secretariat is hosted by the WMO in Geneva, with the Secretary of the IPCC appointed and funded by the WMO and the Deputy Secretary appointed and funded by UNEP.

The IPCC prepares comprehensive assessments of the state of the scientific knowledge of climate change and associated ecological, social and economic impacts, and potential response strategies. The IPCC was awarded the Nobel Peace Prize in 2007 jointly with Albert Gore "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change."

Since its inception, the IPCC has produced five Assessment Reports (ARs) and is now working on the Sixth. IPCC reports contributed to the creation of the United Nations Framework Convention on Climate Change (UNFCCC), which is responsible for the annual climate negotiations. The Fifth Assessment Report (AR5) provided scientific input to the UNFCCC negotiations leading to the Paris Agreement in 2015. In addition, the IPCC has produced methodology reports and special reports as well as technical papers in response to requests from UNFCCC, governments and international organizations.

Each IPCC report draws on the expertise of hundreds of authors from all over the world, with many more experts contributing to the reports through comments at the formal review stages. The Summary for Policymakers is finalized in an IPCC approval session with government representatives and authors working on the text to ensure it is consistent with the full assessment. IPCC reports draw authority from this endorsement by policymakers and the scientific community.

Ocean and cryosphere in a changing climate

The IPCC agreed in 2016 to prepare the requested special report on the ocean and cryosphere as part of its AR6 work programme. The resulting IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) was released in September 2019. More than 100 authors from 36 countries assessed the latest scientific literature for the report, referencing about 7 000 scientific publications and considering

1 Disclaimer: The author contributed to this article in his personal capacity. The views and opinions expressed in this article are the author's own and do not represent those of the IPCC.

over 31 000 review comments from experts and governments.

This was a benchmark contribution to global understanding of the ocean, weather and climate, and focused attention at the “Blue” Conference of the Parties (COP25) to the UNFCCC in Madrid, Spain, in December 2019. SROCC highlighted the need to prioritize strongly coordinated action to reduce risks from changes in the ocean. It also underlined the benefits of combining scientific and local or indigenous knowledge to develop suitable options to manage climate change risks and enhance resilience.

The ocean has absorbed more than 90% of the excess heat in the climate system. By 2100, the ocean will have absorbed two to four times more heat than it has in the last 50 years if global warming is limited to 2°C, and up to four to seven times more if emissions are higher. In warmer ocean waters, the mixing between water layers is reduced, and with it the supply of oxygen and nutrients for marine life. In addition, the ocean has absorbed between 20% to 30% of human-induced carbon dioxide emissions over the past 40 years, causing ocean acidification. Ocean warming, oxygen loss and acidification and changes in nutrient supplies are already affecting the distribution and abundance of marine life in coastal areas, in the open ocean and on the ocean floor.

There is overwhelming scientific evidence that this will result in significant consequences for ecosystems, society and economies. Ocean warming and changes in ocean chemistry are already disrupting the ocean food web, with impacts on marine ecosystems and the people that depend on them. Communities that depend highly on seafood may face risks in the future to nutritional health and food security.

Sea level has risen by around 15 cm during the 20th century. Sea level rise is due to meltwater from glaciers, to the expansion of warming sea water and to growing meltwater inputs from ice sheets in Greenland and Antarctica. The increasing contribution from these ice sheets is accelerating the rate of sea level rise, currently at 3.6 mm/year.

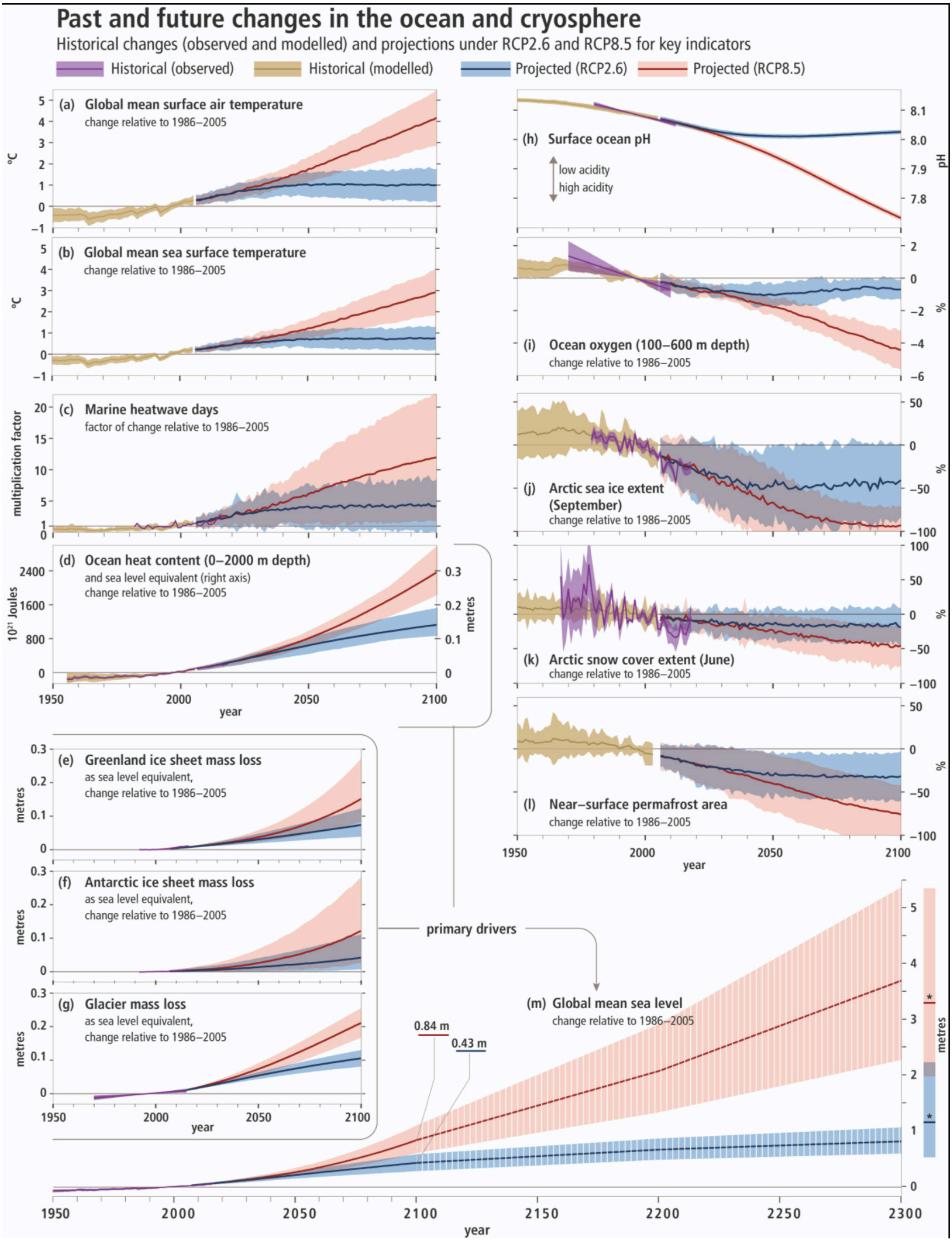
Sea level will continue to rise for the next centuries. Projections show that sea level rise can reach around 30 cm to 60 cm by 2100 even if greenhouse gas emissions are sharply reduced and global warming is limited to well below 2°C. However, if greenhouse gas emissions continue unabated, the increase will be between 60 cm to 110 cm by 2100 and reach much beyond over centuries. Sea level rise is not globally uniform but varies regionally – processes not driven by recent climate change can exacerbate sea level rise regionally.

Sea level rise and more intense storm events will also increase the frequency of extreme sea level events that occur during high tides with increasing risks for many low-lying coastal cities and small islands. In addition, increases in the intensity of tropical cyclone winds and rainfall are exacerbating extreme sea level events and coastal hazards such as storm surge. Without major investments in adaptation, low-lying regions will be exposed to an increased flood risk and some, including island nations, will likely become uninhabitable given the climate-related ocean and cryosphere changes. When this will occur is difficult to assess in many regions. A lower rate and degree of ocean and cryosphere change would provide greater scope for adaptation opportunities.

Another type of extreme event, marine heatwaves (periods of extremely warm near-sea surface temperature that persist for days to months and can extend up to thousands of kilometres) have become more frequent and intense since the early 1980s. Under future anthropogenic warming, marine heatwaves are projected to further increase in duration, intensity, frequency and spatial extent. Projections show that frequencies of marine heatwaves will be 20 times higher at 2° C warming in comparison to pre-industrial levels. Impacts of average and extreme warming include mass mortalities of coastal species and large-scale bleaching of coral reefs as well as shifting fish stocks with reduced fisheries results.

Knowledge and action

The SROCC assessment reveals the benefits of ambitious mitigation and effective adaptation for sustainable development and, conversely, the escalating costs and risks of delayed action. Knowledge and action can make a difference. The ocean on



Observed and modelled historical changes in the ocean and cryosphere since 1950, and projected future changes under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios. For full caption see Figure SPM.1.

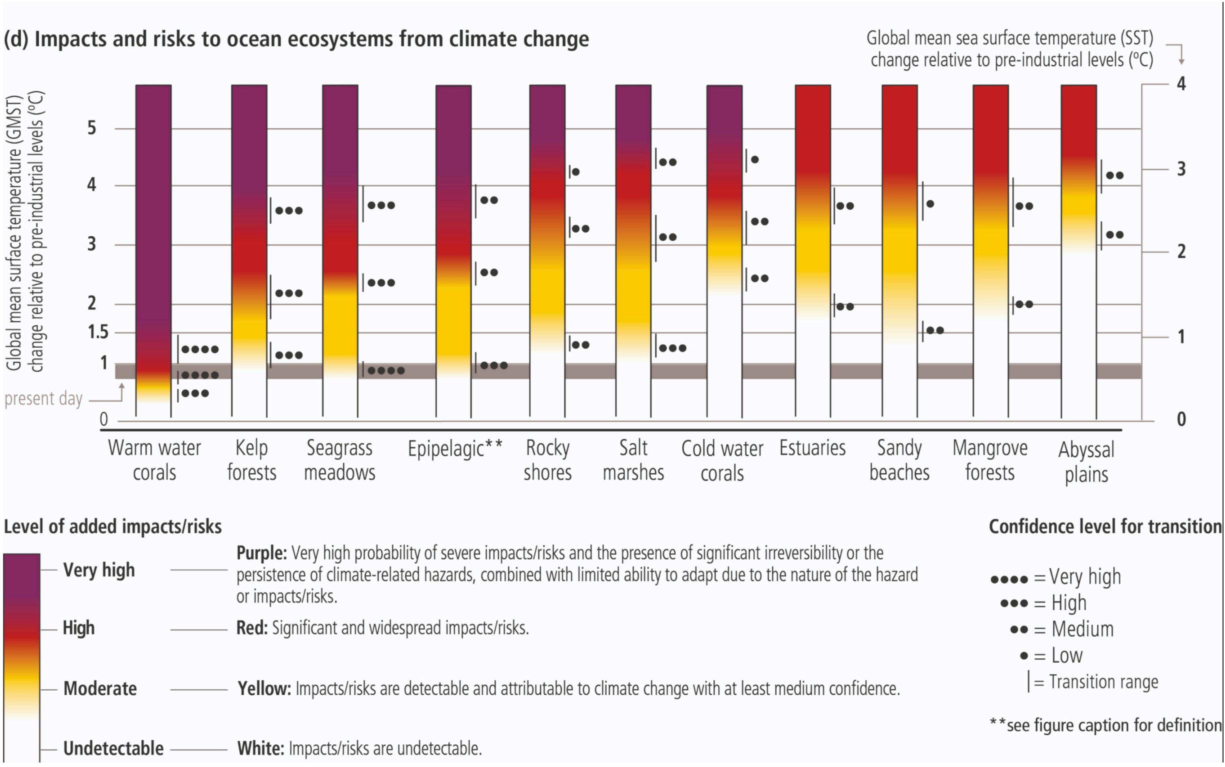


Figure 2: Assessment of risks for coastal and open ocean ecosystems based on observed and projected climate impacts on ecosystem structure, functioning and biodiversity. Impacts and risks are shown in relation to changes in Global Mean Surface Temperature (GMST) relative to pre-industrial level. Since assessments of risks and impacts are based on global mean Sea Surface Temperature (SST), the corresponding SST levels are shown. For full caption see Figure SPM.3d.

which we all depend can be supported by parallel actions: strong reduction of greenhouse gas emissions accompanied by integrated responses, including the restoration of degraded coastal ocean habitats and a careful management of ocean resources.

Promotion of climate literacy and drawing on local, indigenous and scientific knowledge systems enables public awareness, understanding and social learning about locality-specific risk and response potential. Sustained long-term monitoring, sharing of data, information and knowledge and improved context-specific forecasts – including early warning systems to predict more extreme El Niño/La Niña events, tropical cyclones and marine heatwaves – help to manage negative impacts from ocean changes.

The IPCC forthcoming Sixth Assessment Report will provide the latest knowledge of the ocean in Working Group I (Physical Science Basis of Climate Change) and Working Group II (Impacts, Adaptation and Vulnerability).

References available online

Global Climate Indicators: Ocean heat content, acidification, deoxygenation and blue carbon

By Kirsten Isensee[1], Katherina Schoo[1], John Kennedy[2], Karina von Schuckmann[3], Omar Baddour[4], Maxx Dilley[4]

WMO has published annual State of the Global Climate reports since 1993. In 2020, it published a five-year climate report for 2015 to 2019 incorporating data and analyses from the State of the Global Climate across this period. The initial purpose of the annual report was to inform Members on climate trends, extreme events and impacts. In 2016, the purpose was expanded to include summaries on key climate indicators to inform delegates in Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC). The summaries cover the atmosphere, land, ocean and cryosphere, synthesizing the past year's most recent data analysis. There are four ocean related climate indicators: ocean heat content, sea level, sea ice and ocean acidification.

This article highlights the heat content summary from the State of the Global Climate 2020, ocean acidification, deoxygenation and blue carbon, covered in the WMO State of the Global Climate 2018, 2019 and 2020.

Ocean Heat Content

Ocean heat content measurements back in the 1940s relied mostly on shipboard techniques, which constrained the availability of subsurface temperature observations at global scale and at depth (Abraham *et al.*, 2013). Global-scale estimates of ocean heat content are thus often limited to the period from 1960 onwards, and to a vertical integration from the surface down to a depth of 700 metres (m). With the deployment of the Argo network of autonomous profiling floats, which reached target coverage in 2006, it is now possible to routinely measure ocean heat content changes down to a depth of 2000 m (Roemmich *et al.*, 2019) (Figure 1).

The summary on ocean heat content, provided by Mercator Ocean, France, states that the increasing emission of greenhouse gases is causing a positive radiative imbalance at the top of the atmosphere – called the Earth Energy Imbalance (EEI) – which is driving global warming through an accumulation of heat energy in the Earth system (Hansen *et al.*, 2011; Rhein *et al.*, 2013; von Schuckmann *et al.*, 2016). The EEI is the portion of the forcing that the Earth's climate system has not yet responded to (James Hansen *et al.*, 2005), and is an indicator of the global warming that will occur without further change in forcing (Hansen *et al.*, 2017). Ocean heat content is a measure for this heat accumulation in the Earth system from a positive EEI, the majority (~90%) is stored in the global ocean, it is thus a critical indicator for the changing climate.

Consequently, ocean warming is having wide-reaching impacts on the Earth climate system. For example, ocean heat content increase contributes to more than 30% of observed global mean sea-level rise through the thermal expansion of sea water (WCRP, 2018). Ocean warming is altering ocean currents (Yang *et al.*, 2016; Voosen, 2020; Yang *et al.*, 2020, Hoegh-Guldberg *et al.*, 2018) and indirectly altering storm tracks (Hoegh-Guldberg *et al.*, 2018; Trenberth

1 Intergovernmental Oceanographic Commission of UNESCO Secretariat

2 Met Office Hadley Centre, UK

3 Mercator Ocean international, France

4 WMO Secretariat

et al., 2018;Yang *et al*., 2016).The implications of ocean warming are widespread across Earth's cryosphere too, as floating ice shelves become thinner and ice sheets retreat (e.g. Serreze and Barry, 2011, Shi *et al*. 2018, Polyakov *et al*., 2017; Straneo *et al*., 2019; Shepherd *et al*., 2018). Ocean warming increases ocean stratification (Li *et al*., 2020) and, together with ocean acidification and deoxygenation, can lead to dramatic changes in ecosystem assemblages and biodiversity, to population extinction and to coral bleaching (e.g. Gattuso *et al*., 2015, Molinos *et al*., 2016, Ramirez *et al*., 2017).

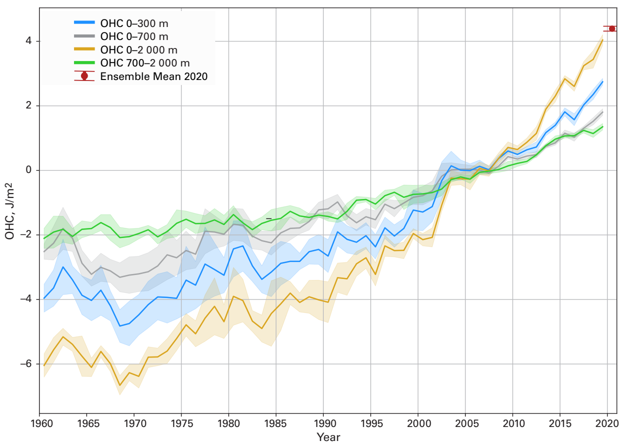


Figure 1: 1960–2019 ensemble mean time series and ensemble standard deviation (2-sigma, shaded) of global ocean heat content anomalies relative to the 2005–2017 climatology for the 0 to 300 m (grey), 0 to 700 m (blue), 0 to 2000 m (yellow) and 700 to 2000 m depth layer (green). The ensemble mean is an outcome of a concerted international effort, and all products used are referenced in the legend of Fig. 2. The trends derived from the time series are given in Table 1. Note that values are given for the ocean surface area between 60°S–60°N, and limited to the 300 m bathymetry of each product, respectively.

Source: Updated from von Schuckmann et al. (2020). The ensemble mean OHC (0-2000 m) anomaly (relative to the 1993-2020 climatology) has been added as a red point, together with its ensemble spread, and is based on CMEMS (CORA), Cheng et al., 2017 and Ishii et al., 2017 products.

Ocean Acidification

The IOC-UNESCO, supported by the Global Ocean Acidification Observing Network (GOA-ON), has provided a summary on ocean acidification for the annual State of the Global Climate since 2017.

Over the past decade, the oceans absorbed around 23% of annual anthropogenic CO_2 emissions (Friedlingstein *et al*. 2020). Absorbed CO_2 reacts with seawater and changes the pH of the ocean. This process is known as ocean acidification. Changes in pH are linked to shifts in ocean carbonate chemistry that can affect the ability of marine organisms, such as molluscs and reef-building corals, to build and maintain shells and skeletal material. This makes it particularly important to fully characterize changes in ocean carbonate chemistry. Observations in the open ocean over the last 30 years have shown a clear trend of decreasing pH (Figure 2). There has been a decrease in the surface ocean pH of 0.1 units since the start of the industrial revolution (1750) with a decline of 0.017-0.027 pH units per decade since late 1980s (IPCC 4AR and SROCC). Trends in coastal locations, however, are less clear due to the highly dynamic coastal environment, where a great many influences such as temperature changes, freshwater run-off, nutrient influx, biological activity and large ocean oscillations affect CO_2 levels. In order to characterize the variability of ocean acidification, and to identify the drivers and impacts, a high temporal and spatial resolution of observations is crucial.

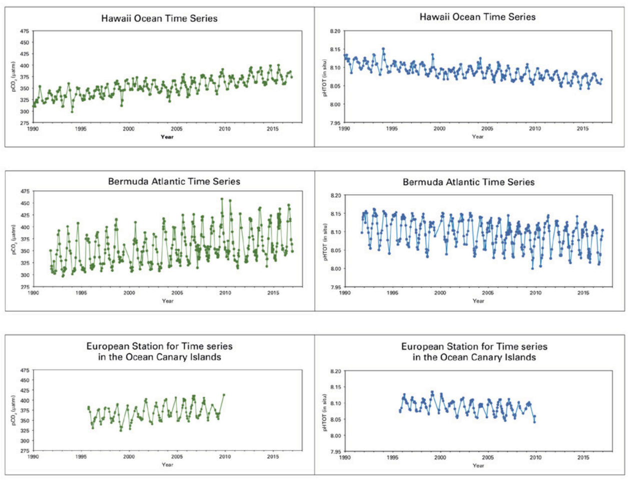


Figure 2: pCO_2 and pH records from three long-term ocean observation stations. Top: Hawaii Ocean Time-Series (HOTS) in the Pacific Ocean; Middle: Bermuda Atlantic Time Series (BATS); Bottom: European Station for Time-Series in the Ocean Canary Islands (ESTOC) in the Atlantic Ocean. Credit: Richard Feely (NOAA- PMEL) and Marine Lebrec (IAEA OA-ICC), IOC-UNESCO, GOA-ON.

In line with previous reports and projections, the State of the Global Climate 2020 report states that ocean acidification is ongoing and that global pH

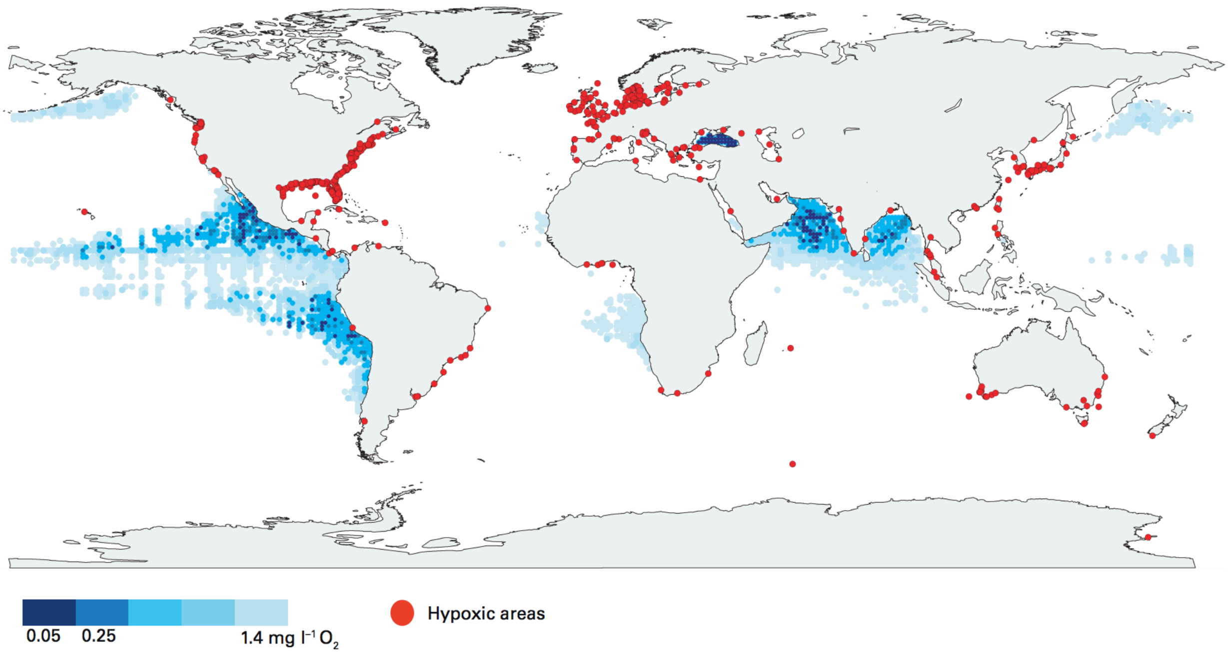


Figure 3: Oxygen Minimum Zones (blue) and areas with coastal hypoxia (red; dissolved oxygen concentrations <2 mg/L) in the ocean. Coastal hypoxic sites mapped here are those in which anthropogenic nutrients are a major cause of oxygen decline (data from Diaz and Rosenberg, 2008 and Diaz, unpublished. Figure adapted after Isensee et al., 2015, Breitburg et al. 2018, GO2NE 2018).

levels continue to decrease. More recently established sites for observations in New Zealand show similar patterns, while filling important data gaps in ocean acidification monitoring in the southern hemisphere. Availability of operational data is currently limited, but it is expected that the newly introduced Methodology for the Sustainable Development Goal (SDG) Indicator 14.3.1 ("Average marine acidity (pH) measured at agreed suite of representative sampling stations") will lead to an expansion in the observation of ocean acidification on a global scale.

Deoxygenation of open ocean and coastal waters

The IOC-UNESCO Global Ocean Oxygen Network (GO_2NE) coordinates the annual report's summary on deoxygenation, with a focus on understanding its multiple aspects and impacts.

Both observations and numerical models indicate that oxygen is declining in the modern open and coastal oceans, including estuaries and semi-enclosed seas. Since the middle of the last century, there has been an estimated 1% to 2 % decrease (i.e. 2.4-4.8 Pmol or 77-145 billion tons) in the global ocean oxygen inventory (Bopp *et al.*, 2013; Schmidtko *et al.*, 2017). In the coastal zone, many hundreds of sites are known to have experienced oxygen concentrations that impair biological processes or are lethal for many organisms. Regions with historically low oxygen concentrations are expanding, and new regions are now exhibiting low oxygen conditions. While the relative importance of the various mechanisms responsible for the loss of the global ocean oxygen content is not precisely known, global warming is expected to contribute to this decrease directly because the solubility of oxygen decreases in warmer waters, and indirectly through changes in ocean dynamics that reduce ocean ventilation, which is the introduction of oxygen to the ocean interior. Model simulations for the end of this century project a decrease of oxygen in the open ocean under both high and low emission scenarios (Figure 3).

In coastal areas, increased river export of nitrogen and phosphorus since the 1950s has resulted in eutrophication of water bodies worldwide. Eutrophication, leading to higher primary production and decomposition of this material increases oxygen consumption and, when combined with low ventilation, leads to the occurrence of oxygen deficiencies in subsurface waters. Climate change is expected to further amplify deoxygenation in coastal areas influenced by anthropogenic nutrient discharges, decreasing oxygen solubility, reducing ventilation by strengthening and extending periods of seasonal stratification of the water column, and in some cases where precipitation is projected to increase, by increasing nutrient delivery.

The volume of anoxic regions of the ocean's oxygen minimum zones has expanded since 1960 (Schmidtko *et al.*, 2017), altering biogeochemical pathways by allowing processes that consume fixed nitrogen and releasing phosphate, iron, hydrogen sulfide (H_2S) and, possibly, nitrous oxide (N_2O). The relatively limited inventory of essential elements, like nitrogen and phosphorus, means such alterations are capable of perturbing the equilibrium of the chemical composition of the ocean. We do not know to how positive feedback loops (e.g. remobilization of phosphorus and iron from sediment particles) may speed up the run away from equilibrium.

Deoxygenation affects many aspects of the ecosystem services provided by the ocean and coastal waters. For example, deoxygenation impacts biodiversity and food webs, and can reduce growth, reproduction and survival of marine organisms. Low-oxygen-related changes in spatial distributions of harvested species may force people to change their fishing locations and practices and can reduce the profitability of fisheries. Deoxygenation can also increase the difficulty of providing sound advice on fishery management.

Coastal blue carbon

The IOC-UNESCO together with the Blue Carbon Initiative (co-organized by Conservation International, IOC-UNESCO and IUCN) supports scientists, coastal managers and governments in measuring carbon stocks in coastal and marine ecosystems. Together they contribute on the blue carbon indicator to the annual report.

In climate mitigation, coastal blue carbon (also known as "coastal wetland blue carbon"; Howard *et al.* 2017) is defined as the carbon stored in mangroves, tidal salt marshes and seagrass meadows within the soil, the living biomass above ground (leaves, branches, stems), the living biomass below ground (roots and rhizomes) and the non-living biomass (litter and dead wood). When protected or restored, coastal blue carbon ecosystems act as carbon sinks (Figure 4a). They are found on every continent except Antarctica and cover approximately 49 million hectares (Mha).

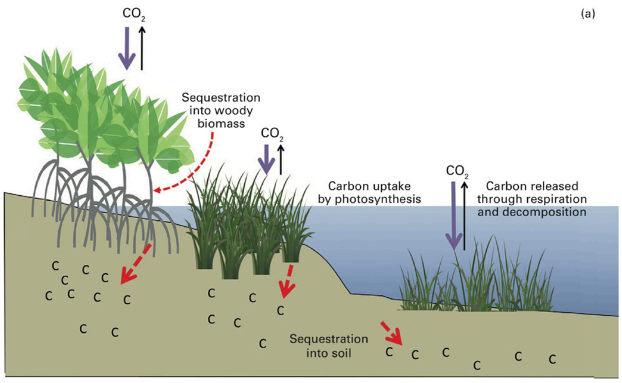


Figure 4 (a): In intact coastal wetlands (from left to right: mangroves, tidal marshes, and seagrasses), carbon is taken up via photosynthesis (purple arrows) where it gets sequestered long-term into woody biomass and soil (red dashed arrows) or exhaled (black arrows).

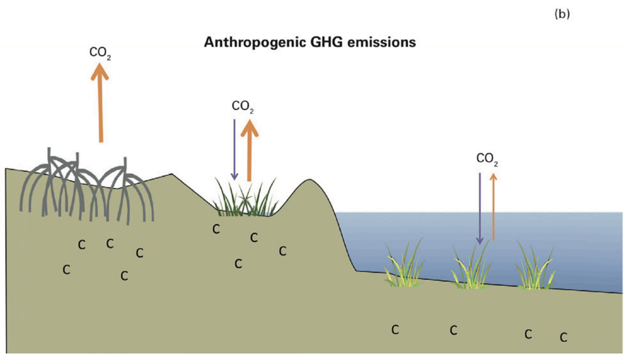


Figure 4 (b): When soil is drained from degraded coastal wetlands, the carbon stored in the soils is consumed by microorganisms that release CO_2 as a metabolic waste product when they exhale. This happens at an increased rate when soils are drained and more oxygen is available, which leads to greater CO_2 emissions. The degradation, drainage and conversion of coastal blue carbon ecosystems from human activity (i.e. deforestation and drainage, impounded wetlands for agriculture, dredging) results in a reduction in CO_2 uptake due to the loss of vegetation (purple arrows) and the release of globally important greenhouse gas emissions (orange arrows).

Currently, for a blue carbon ecosystem to be recognized for its climate mitigation value within international and national policy frameworks, it is required to meet the following criteria:

1. Quantity of carbon removed and stored or prevention of emissions of carbon by the ecosystem is of sufficient scale to influence climate

2. Major stocks and flows of greenhouse gases can be quantified

3. Evidence exists of anthropogenic drivers impacting carbon storage or emissions

4. Management of the ecosystem that results in increased or maintained sequestration or emissions reductions is possible and practicable

5. Management of the ecosystem is possible without causing social or environmental harm.

However, the ecosystem services provided by mangroves, tidal marshes and seagrasses are not limited to carbon storage and sequestration. They also support improved coastal water quality, provide habitats for economically important and iconic species, and protect coasts against floods and storms. Recent estimates revealed that mangroves are worth at least US$1.6 billion each year in ecosystem services.

Despite their importance for ocean health and human wellbeing, mangroves, tidal marshes and seagrasses are being lost at a rate of up to 3% per year. When degraded or destroyed, these ecosystems emit the carbon they have stored for centuries into the ocean and atmosphere and become sources of greenhouse gases (Figure 4b).

The Intergovernmental Panel on Climate Change (IPCC) estimates that as much as a billion tons of CO_2 being released annually from degraded coastal blue carbon ecosystems – mangroves, tidal marshes and seagrasses – which is equivalent to 19% of emissions from tropical deforestation globally (IPCC 2006).

References are available online

Climate and Ocean research: The World Climate Research Programme (WCRP)

By Michael Sparrow, WMO Secretariat

Ocean issues are gaining visibility due to various organizational and political developments at the international level. These include:

- The growing Blue Economy
- The Sendai Framework for Disaster Risk Reduction, which motivates the development of multi-hazard impact-based services for decision-making support
- An increasing awareness of the importance of the ocean for understanding, predicting and responding to climate variability and change and sustainable development, as highlighted by publications such as the Intergovernmental Panel on Climate Change's (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate
- The United Nations Ocean Conferences, Sustainable Development Goals and Decade of Ocean Science for Sustainable Development (2021-2030). An opportunity to drive innovation, advance ocean science.

International ocean research is largely coordinated through the International Oceanographic Commission (IOC) of UNESCO, International Science Council (ISC) and WMO and their partnerships. WMO has significant interests in the development and delivery of ocean information to underpin the breadth of research, applications and services delivered by its Members, thus the Organization is involved in a range of ocean activities. The World Climate Research Programme, co-sponsored by WMO, IOC-UNESCO and International Science Council (ISC), offers a prime example of this coordination and partnership in climate research.

IOC ocean science efforts are organized under a collection of activities. In addition to WCRP, these are coordinated through a number of small projects and teams on themes such as ocean carbon and acidification, nutrients, eutrophication and deoxygenation, climate science (WCRP), climate change and ecosystem impacts, and marine plastics. The IOC, in partnership with WMO and other UN agencies, led the development of the UN Decade of Ocean Science for Sustainable Development, which has the potential to strengthen the international ocean research effort. The Joint WMO-IOC Collaborative Board (JCB), coordinates joint ocean related activities between the two Organizations.

ISC connects its two UN partners to a very broad global scientific constituency not usually directly connected to intergovernmental agencies. For example, there is the International Union of Geophysics and Geodesy that includes the International Association of Physical Sciences of the Ocean, which convenes regular international scientific conferences and fora. There is also the Scientific Committee on Oceanic Research (SCOR) that focuses on promoting international cooperation in planning and conducting oceanographic research and solving methodological and conceptual problems that hinder research. SCOR includes capacity building in a number of its research programmes and working groups, mainly targeting the development of observational methodologies and best practices. A recently signed cooperation agreement between ISC's Future Earth and WCRP will more closely link their science activities, particularly in what is often referred to as 'Actionable Science."

WMO climate-ocean research activities are coordinated through the WCRP. One of the core WCRP projects is the Climate and Ocean: Variability, Predictability and Change (CLIVAR), which launched in 1995. The WCRP "Grand Challenges" includes the Regional Sea Level Rise and Coastal Impacts and Near Term Prediction (www.wcrp-climate.org/grand-challenges/grand-challenges-overview). It also has a number of new "Lighthouse" activities that cover different aspects of the climate system, of which the ocean component is critical. One example is My Climate Risk, which aims to develop a new framework for assessing and explaining regional climate risk to deliver climate information that is meaningful at the local scale, and which will include regional sea level aspects (www.wcrp-climate.org/wcrp-ip-la).

Climate and Ocean – Variability, Predictability and Change

CLIVAR focuses on international scientific research coordination in the ocean. CLIVAR's mission is to understand the dynamics, the interaction and the predictability of the coupled ocean-atmosphere system. To this end it facilitates observations, analysis and predictions of changes in the Earth's climate system, enabling better understanding of climate variability and dynamics, predictability, and change, to the benefit of society and the environment in which we live. It aims to improve:

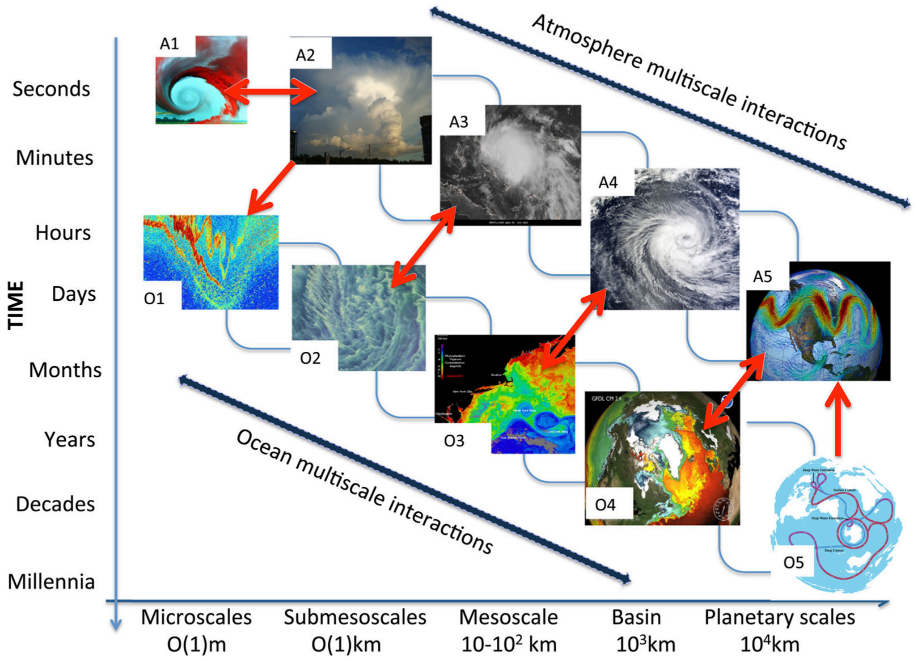
- Ocean system models
- Ocean-observing systems
- Ocean data, synthesis and information systems
- Knowledge transfer and stakeholder feedback
- Education, capacity building and outreach.

CLIVAR builds on the success of the Tropical Ocean Global Atmosphere (TOGA) project and the World Ocean Circulation Experiment (WOCE), both advanced the scientific understanding of ocean circulation and atmosphere-ocean interactions.

CLIVAR research has provided fundamental knowledge about the drivers of variability and predictability in the coupled climate system with emphasis on the ocean, the key subsystem that regulates the Earth climate. For instance, CLIVAR initiatives have been instrumental in the development of El Niño Southern Oscillation (ENSO) seasonal prediction systems and pioneered decadal predictions. The development of coupled models as part of CLIVAR contributed significantly – through the development of coupled climate modelling capabilities and of climate model intercomparison projects – to understanding the response of the climate system to anthropogenic increases in radiatively active gases and changes in aerosols.

CLIVAR – through the advancement of climate observing systems, process studies and coupled climate models – has greatly advanced our understanding of the processes driving ocean circulation and its role in the coupled climate system. We now have unique, new observing, modelling and reanalysis capabilities that support scientific investigations into ocean dynamics and variability and this is due in large part to CLIVAR. In addition, CLIVAR embraces and often formally endorses many new activities and projects that develop outside its framework but that demonstrate clear relevance to its goals and objectives. CLIVAR organizes topical scientific workshops aimed at communication, collaboration education, and furthering the careers of young scientists. WCRP, through CLIVAR, makes fundamental contributions to the knowledge and understanding of the climate system and which underpin the provision of operational climate services.

The CLIVAR legacy includes the implementation and development of multinational and multi-platform observing networks in all ocean basins, the development of climate models with realistic ocean components and the development of ocean reanalyses. These bridge observations and modelling through data assimilation. In-situ elements of established observing systems include global deployment of surface drifters and profiling Argo floats, ocean gliders, arrays of moorings in both tropical and extra-tropical locations, full-depth sampling of the water column from ships of the repeat hydrography program, etc. Since the late 1970s, satellite observations of the ocean have become a crucial part of the global observing system. CLIVAR works closely with the Global Climate Observing System (GCOS) and Global Ocean Observing System (GOOS), using the "Framework for Ocean Observing"



Science Directions in a Post COP21 World of Transient Climate Change: Enabling Regional to Local Predictions in Support of Reliable Climate Information

Stammer, D., Bracco, A., Braconnot, P., Brasseur, G. P., Griffies, S. M., & Hawkins, E. (2018). Science directions in a post COP21 world of transient climate change: Enabling regional to local predictions in support of reliable climate information. Earth's Future, 6, 1498–1507. https://doi.org/10.1029/2018EF000979

to guide its implementation of an integrated and sustained ocean observing system.

As WCRP moves into a new strategic planning and implementation phase, CLIVAR's new objective is to describe, understand and model the dynamics of the coupled climate system, emphasizing ocean-atmosphere interactions and identifying the processes responsible for climate variability, change and predictability on subseasonal-to-seasonal, interannual, decadal and centennial time scales. In detail, CLIVAR will critically contribute to the new WCRP strategy by covering the following topics:

- Understanding the ocean's role in climate variability, change, and transient sensitivity
- Understanding the ocean's role in shaping the hydrological cycle and distribution of precipitation at global and regional scales
- Understanding the drivers of regional climate phenomena that provide predictability on different time scales
- Provision of coordinated observations, analyses and predictions of variability and change in the Earth's climate system
- Detection, attribution and quantification of climate variability and change
- Development and evaluation of climate simulations and predictive capabilities.

To this end, CLIVAR coordinates the international research in climate and ocean science, facilitating cooperation amongst national and multinational efforts, thereby enabling global climate research beyond the regional and institutional capabilities of any individual nation. It facilitates observations, analysis, predictions and projections of variability and changes in the Earth's climate system, enabling better understanding of climate variability and dynamics, predictability, and change, to the benefit of society and the environment in which we live. Through its Panels, Research Foci, workshops, summer schools and conferences, CLIVAR continues to bring together researchers from all over the world (see e.g. Stammer et al., 2018). In doing so, CLIVAR develops a strong, multidisciplinary international community of scientists at all stages of their career to coordinate the efforts required to measure, simulate and understand coupled ocean-atmosphere dynamics, and to identify processes responsible for climate variability, change and predictability.

The development of reliable regional climate change information that can be provided on time scales from seasonal to centuries and beyond, to the benefit of humanity and life on Earth, is central to future climate science strategies. CLIVAR through its work contributes directly to reaching those goals. It is anticipated that in a 5- to 10-year timeframe much progress will be achieved in expanding theoretical process understanding, in improving climate models through better representation of important climate processes in numerical models and in improving regional climate predictions and associated climate information on time scales from seasonal to decadal. This will build firmly on efforts required to improve and sustain the Global Climate Observing System (GCOS).

CLIVAR, like many WCRP activities, relies on national support, provided through annual voluntary contributions and crucially on the hosting of International Project Offices. CLIVAR has two such offices: The International CLIVAR Global Project Office, hosted by the Ministry of Natural Resources First Institute of Oceanography in Qingdao, China, and the International CLIVAR Monsoon Project Office, hosted by the Indian Institute of Tropical Meteorology in Pune, India.

Regional Sea-level Change and Coastal Impacts

Recognizing that coastal sea level rise is among the most severe societal consequences of anthropogenic climate change, WCRP formed a Grand Science Challenge on Regional Sea-level Change and Coastal Impacts.

Contemporary global mean sea level rise will continue over many centuries as a consequence of anthropogenic climate warming, with the detailed pace and final amount of rise depending substantially on future greenhouse gas emissions.

Over the coming decades, regional sea level changes and variability will significantly deviate from global mean values. The detailed sea level change along coastlines can therefore potentially be far more substantial than the global mean rise and will depend on many processes involving the ocean, the atmosphere, the geosphere and the cryosphere. Societal concerns about sea level rise originate from the potential impact of regional and coastal sea level change and associated changes in extremes on coastlines around the world, including potential shoreline recession, loss of coastal infrastructure, natural resources and biodiversity, and in the worst case, displacement of communities and migration of environmental refugees.

Local sea level rise and extreme events can have significant impacts on coastal zones. On subsiding coasts, the impacts of resulting sea level rise are already demonstrable in some coastal cities and deltas. It is very likely that a large fraction of the world's coasts will be affected by climate-induced sea level rise. Detailed impacts, however, will vary strongly from region to region and coast to coast. They cannot be easily generalized, as changing mean and extreme coastal water levels depend on a combination of near shore and offshore processes, related to climatic but also non-climatic anthropogenic factors. These include natural land movement arising from tectonics, volcanism or compaction; land subsidence due to anthropogenic extraction of underground resources; and changes in coastal morphology resulting from sediment transport induced by natural and/or anthropogenic factors.

The overarching goal of the Sea Level Grand Challenge has been to:

- establish a quantitative understanding of the natural and anthropogenic mechanisms of regional to local sea level variability
- to promote advances in observing systems required for an integrated sea level monitoring
- to foster the development of sea level predictions and projections that are of increasing benefit for coastal zone management.

A roadmap to sustained observations of the Indian Ocean for 2020-2030 https://doi.org/10.36071/clivar.rp.4.2019

Over its lifetime, the Grand Challenge has addressed the following imperatives, led by six parallel, but interconnected, working groups:

1. An integrated approach to historic sea level estimates (paleo time scale)
2. Quantifying the contribution of land ice to near-future sea level rise
3. Contemporary regional sea level variability and change
4. Predictability of regional sea level
5. Sea level science for coastal zone management
6. Global sea level change

A key tenet of this activity is that is not only led by scientists. The four co-chairs of this activity, are from the user community and scientists who work closely with a range of stakeholders (policy makers, coastal engineers etc.). The connection to services has been a thread throughout the Grand Challenge's lifetime, working closely with IOC and with the Global Framework for Climate Services (GFCS) as appropriate. Connections to the UN Ocean Decade are being made.

The Grand Challenge will come to an end at a final conference planned in July 2022 in Singapore. However, the activities of the Grand Challenge will continue both within CLIVAR and within the new Lighthouse activities.

Focus on the polar Oceans

In terms of weather and climate, what happens in the polar regions does not stay at the poles. Rapid changes in the polar regions are fundamentally impacting weather and climate patterns around the world.

These regions are historically difficult to observe and understand due to the hostile conditions for making observations, and complex interactions between the ocean, ice and atmosphere. The regions are also challenging to model as, in addition to the above, compromises need to be made in terms of model projections at the poles.

Polar regions represent an important testbed for developing and improving the seamless Earth System approach. The WMO World Weather Research Program (WWRP) Polar Prediction Project has moved forward in advancing coupled assimilation methods in an operational framework. At the same time, the WWRP and WCRP communities are exploiting the Year of Polar Prediction field campaign for modeling improvements. A consolidation phase is under development that could provide key research questions for future Earth System projects.

The Year of Polar Prediction (YOPP) itself built on the earlier legacy of the International Polar Year 2007-2008 (IPY), co-sponsored by WMO and the ISC. The IPY encouraged greater interactions between the disciplines, the engagement of social sciences and indigenous peoples as well as the next generation of scientists. Many of the polar observational networks and groups set up during the IPY are still active. A YOPP Data Portal (yopp.met.no) is currently under development.

The Global Cryosphere Watch (GCW) was established to provide continuity in the focus on polar regions, within the framework of WMO. While the WMO Polar Space Task Group and the Association of Early Career Polar Scientists provide cryosphere focused coordination between space agencies.

WCRP has a number of polar-ocean related activities, usually lead by CLIVAR and its sister Core Project CliC (Climate and Cryosphere) and often in partnership with other polar-focused organizations. For example, the CLIVAR/CliC/SCAR (Scientific Committee on Antarctic Research) Southern Ocean Region Panel which aims to serve as a forum for the discussion and communication of scientific advances in the understanding of climate variability and change in the Southern Ocean and to advise CLIVAR, CliC, and SCAR on progress, achievements, new opportunities and impediments in internationally-coordinated Southern Ocean research. WCRP, through this Southern Ocean Region Panel has submitted, with SCAR and others, including from the private sector, a proposal for a Southern Ocean Regional Decade Programme to the UN Decade to “improve the understanding of the Southern Ocean and its role in the Global Ocean”. It will engage various stakeholders – scientists, policy makers, industry and non-governmental organizations – to develop and facilitate research priorities and actions for the Southern Ocean taking environmental, economic and social dimensions into account. A relatively new CLIVAR/CliC Northern Oceans Panel serves a similar role in the Arctic region.

National Meteorological and Hydrological Services

In terms of the role of ocean-climate research in meeting the needs of NMHSs, the science produced by WCRP scientists is crucial in a number of areas, including:

- Supporting the co-design (by science and operations) of improved seasonal to decadal predictions

- Supporting the underlying research required to improve our understanding of the processes involved in providing improved skill in forecasts over a range of timescales

- Improving the understanding of the dynamics, the interaction and the predictability of the coupled ocean-atmosphere system for a range of time scales, including modes of variability (such as ENSO) and abrupt changes to the system (including extremes)

- Understanding how low frequency variations of ocean mean state impact on sub-seasonal variability, and on sub-seasonal extreme events, such as ocean heat waves that result in coral bleaching

- Understanding the role of the ocean in the planetary energy balance.

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Learning from the past to understand the future: historical records of change in the ocean

By Rob Allan[1], Kevin Wood[2], Eric Freeman[3], Clive Wilkinson[4], Axel Andersson[5], Andrew Lorrey[6], Philip Brohan[7], Martin Stendel [8], John Kennedy[7]

To better anticipate future weather and climate impacts on the Earth system and society, there is an ever-increasing demand for longer and higher resolution terrestrial and marine databases of the weather. The construction of these baseline climate data resources requires a massive effort to recover and translate handwritten records to digital format, and then quality control, integrate and serve huge amounts of historical weather data to a new generation of modelling and retrospective analysis (reanalysis) systems running on the world's most powerful computers.

Over the last decade there has been growing recognition of the importance of historical marine weather data to fill major gaps in existing data coverage. Marine data, covering the 70% of the Earth that is ocean, are a critical (and for most of history only) means to quantify the various roles that the global ocean play in climate regulation over time, and hence provide the best means to foresee the future trajectory of the climate and its likely impact on every aspect of life. Indeed, the urgent need to anticipate future climate, combined with increasingly capable models and data-driven reanalysis systems, has transformed the value of historical weather data to climate science.

The main source of historical marine data are weather anecdotes, remarks and observations recorded in logbooks and diaries written aboard ships that sailed local seas or crossed the oceans of the world for centuries. Standardized tabulations of non-instrumental information and measurements of marine weather appeared at the beginning of the sixteenth century, while more systematic observations using high-quality meteorological instruments commenced in the mid- to late eighteenth century. The first efforts to establish international coordination and standardization in marine meteorology arose with the Brussels Maritime Conference (1853). It is from this period that naval and merchant ships of many nations began to systematically collect and record weather and sea-surface observations by the millions. Today these records provide the data needed to drive state-of-the art models and reanalyses.

COADS to ICOADS

In the marine data rescue field, a major effort was initiated in the 1980s to produce the most complete collection of surface marine weather observations. The Comprehensive Ocean Atmosphere Data Set (COADS) was the outcome of those efforts and included newly available repositories of digitized marine weather observations from multiple sources, typically produced and stored on punch cards at that time. Following increased international support and contributions to the dataset's development over the years, the project

1 Atmospheric Circulation Reconstructions over the Earth (ACRE) Manager, Met Office Hadley Centre, United Kingdom
2 University of Washington, Cooperative Institute for Climate, Ocean & Ecosystem Studies, and NOAA Pacific Marine Environmental Laboratory, U.S.
3 University of Maryland, Cooperative Institute for Satellite Earth System Studies, and NOAA National Centers for Environmental Information, U.S.
4 ACRE OCEANS/CSW Associates-Data Services, U.K.
5 Deutscher Wetterdienst, Germany
6 National Institute of Water and Atmospheric Research, New Zealand
7 Met Office Hadley Centre, U.K.
8 Danish Meteorological Institute, Denmark

was renamed to the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) in 2002 to better reflect the important contributions made by international partners and global data managers.

Over its existence, ICOADS has also achieved recognition as the major repository and access point for historical marine weather observations recovered from digitization efforts, small and large. This includes historical weather data recovered and digitized by the CDMP (Climate Database Modernization Program: 2000-2011), CLIWOC (Climatological Database for the World's Oceans 1750-1850: 2001-2003), RECLAIM (RECovery of Logbooks And International Marine data: 2004->), International Atmospheric Circulation Reconstructions over the Earth (ACRE), 2007->) initiative (Allan et al., 2016) and the CoRRaL (UK Colonial Registers and Royal Navy Logbooks: 2008-2009) projects.

The most current version of ICOADS is Release 3: ICOADS R3.0 (covering 1662-2014) (Freeman et al., 2017), with monthly near-real-time extensions from 2015-present. Figure 1, from the latter publication, provides a comparison of years 1800 to 2014 between ICOADS Releases R2.5 and R3.0, showing the gains made from the numerous data recovery efforts. The significance of these rescue efforts is shown, in both volume and temporal coverage, and are critical to further expanding this major collection and providing public access to more ocean data. As ICOADS looks to modernize and expand its collections in the near future for a new dataset release, historical data rescue and digitization efforts will be vital in providing new sources of data for the dataset, further enabling better scientific understanding of historical environmental conditions over the global oceans.

Since the release of ICOADS R3.0, concerted efforts have been made to expand the recovery, imaging and digitization of historical global marine weather data. Much has been undertaken by a mix of ongoing and new data rescue projects and citizen science activities under Deutscher Wetterdienst (DWD, German Weather Service), National Oceanic and Atmospheric Administration (NOAA) and the University of Washington working with the U.S. National Archives, and the efforts of the Global Surface Air Temperature (GloSAT), (2019->) project, or linked to the international ACRE initiative, and its ACRE Oceans chapter (e.g. the EU Copernicus C3S Data Rescue Service [DRS] and the UK Newton Fund projects of ACRE China under CSSP China, ACRE/C3S DRS/WCSSP South Africa, ACRE/C3S DRS Argentina and ACRE/C3S DRS Antarctica). These initiatives have included new, interlinked marine citizen science data rescue foci under Old Weather (2013->), Weather Detective (2014-2017) and Southern Weather Discovery (2018->). The Danish National Archives has also identified a collection of more than 7000 archive boxes of ship-based weather data dating from 1650 onward that are suitable for digital imaging and transcription. All the marine data digitized by the above will be provided to ICOADS and the new EU Copernicus Global Land and Marine Observations Dataset (GLAMOD) (Thorne et al., 2017).

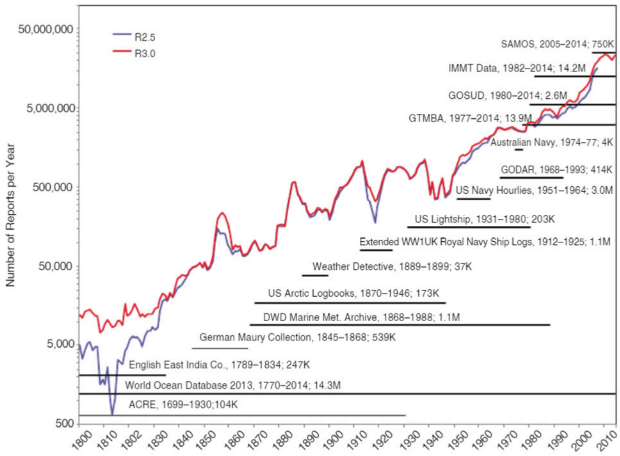


Figure 1: Major historical digitized and external archive marine data sources add to ICOADSv3, from 1800-2014. Horizontal black lines show the time range of the original marine data sources. The annual numbers of reports are plotted as curves (logarithmic scales on the vertical axis), blue for the previous ICOADS R2.5, and red for ICOADS R3.0. Marine data coverage prior to 1800 is sparse, and that following 2007 continues to grow annually. Source: Freeman et al. (2017).

ACRE Oceans

The great bulk of the data rescued (imaged/scanned and catalogued) by ACRE Oceans was achieved through the efforts of just two individuals, focusing on three different archives in the United Kingdom –The Met Office (UKMO), Hydrographic Office (UKHO) and National Archives (TNA) – and working with a number of other repositories around the world (Argentina, Australia, Chile, New Zealand, Scandinavia, South Africa and U.S.). Some of these historical marine data have since been digitized using both traditional keying and citizen science initiatives. In 2019, ACRE Oceans scanned 2.6 million, and had digitized 1.5 million, historical marine observations. For just the Antarctic and the Southern Ocean regions, the following tabulation provides a comprehensive picture of the imaging/scanning and digitization that has been undertaken. It should be noted, that much of the rescued data were recovered from just a few archives and much more has been uncovered but not imaged. There are a number of other archives around the world that could potentially hold such data but have not yet been visited.

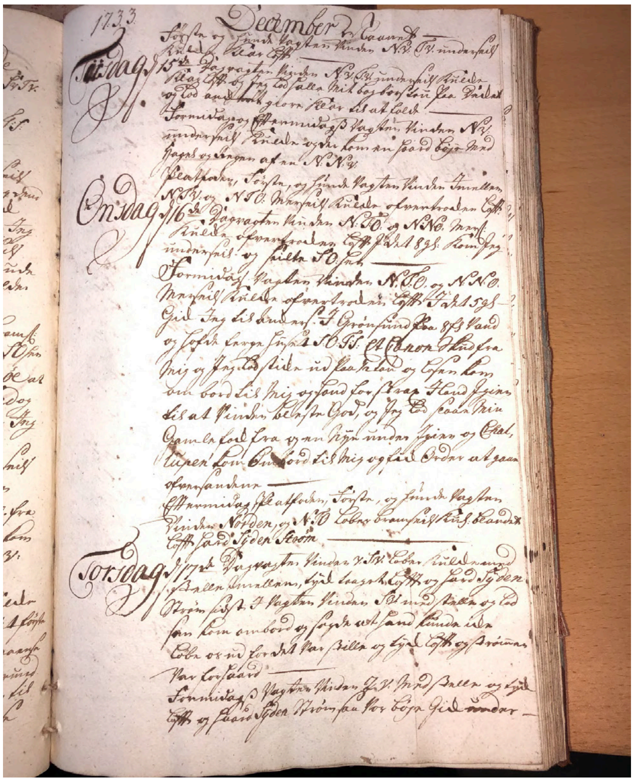
It is important to recognize that historical marine data are not only found in naval and merchant shipping logbooks. There are meteorological and oceanographic data in marine surveying and hydrographic documents (e.g. Remark Books), material connected with the regulation of whaling and fisheries, marine cable laying, transportation of mail (packet ships), yachts, vessels carrying convicts and settlers and many other types of documents other than ship logbooks. The bulk of this material still needs to be addressed – imaged/scanned and/or digitized, catalogued and archived.

It is also worth mentioning that new archives, and new types of documentation are always coming to light – for instance at the UKHO, ACRE Oceans found workbooks used to compile observations of meridian distances to establish the longitude of places, also had twice daily pressure and air temperature. These had been overlooked before because the observations were obscured by all the other figures around them.

Deutscher Wetterdienst

DWD holds in its Seewetteramt (Hamburg Marine Meteorological Office) an archive of several collections of original historical worldwide weather records from ships and also German coastal and overseas land stations. The archive originates from the Deutsche Seewarte (German Marine Observatory), a predecessor of DWD that existed from 1868 to 1945 in Hamburg. With a stock of more than 37 000 meteorological ship logbooks, it is one of the world's largest archives of this kind.

The historical archive of ship logbooks consists of several logbook collections starting in 1828. The first observations are from regular nautical logbooks. All other collections consist of standardized meteorological logbooks that were introduced by Maury (1840 to 1860). Starting in 1868, the German Marine Observatory provided their own meteorological journals to German merchant ships. The weather observations from these logbooks were used to produce charts of weather, winds and currents. Based on this climatological knowledge and the experience of the sailors, the German Marine Observatory compiled sailing instructions for merchant ships in return for their voluntary observations – a system that is still in existence with the International Voluntary Observing Ship (VOS) Scheme.



Monday, 14 December 1733. At the marker it says that there was wind from the west with a strength of bramsejls kuling (i.e. topgallant sail).

The overall number of marine observations in the historical archive of the Seewarte is estimated to be at least 23 million observations, and likely to be considerably more. Efforts to digitize the logbooks

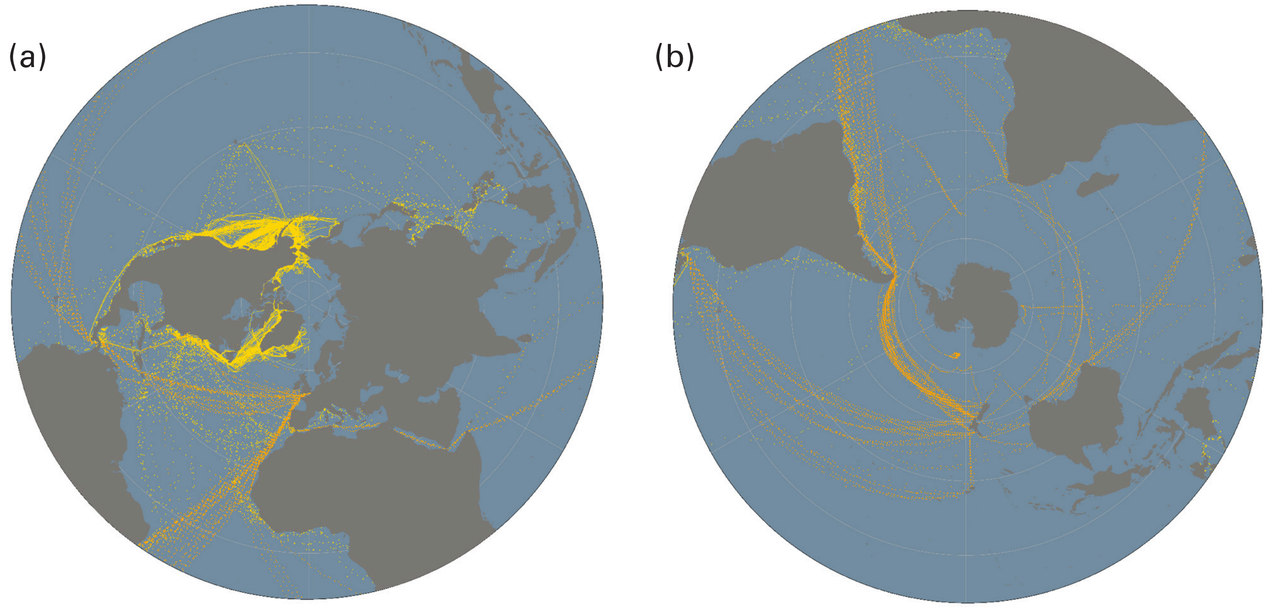


Figure 2: Ships' positions where new-to-science marine-meteorological and sea-ice observations have been recovered from historical records (a. Northern Hemisphere, b. Southern Hemisphere). Data extracted via the Old Weather citizen-science project from U.S. federal sources, primarily Navy and Coast Guard vessels are shown in yellow. Positions in orange are data extracted from logbooks by the Southern Weather Discovery (SWD) citizen-science project run by the New Zealand National Institute of Water and Atmospheric Research (NIWA). Approximately 1-2% of ~130K images with maritime weather observations that have been supplied to NIWA have been keyed through SWD, which is expected to accelerate in coming years to improve Southern Hemisphere spatiotemporal coverage.

started in the early 1940s and millions of observations were transferred to punch cards at that time. Since then, the digitization effort has been continued at DWD in several phases. Until now, about 15 million observations have been digitized and added to a digital data base.

A sophisticated workflow has been established to digitize the contents of the ship journals, consisting of several steps: gathering all metadata for a specific logbook, optical scanning of the logbooks and finally transcription (keying) of the contents. All digitized data from each step are stored in a database system. Finally, quality-controlled data are included in the DWD's marine meteorological archive as well as ICOADS.

Digitization efforts, not only at DWD, have been ongoing for decades in different projects, most of which have been detailed in this piece. Consequently, the different data archive contents are fragmented, e.g. some logbooks were only partly digitized, or the database entries originate from different digitization periods. For other datasets, the links to the respective metadata records has been lost over time. In the course of data exchange programmes, some data has been duplicated in several archives.

Hence, a further challenge, in parallel with the integration of newly digitized data, is the consolidation and homogenization of the existing data archives. A priority for DWD in this context is the assignment of missing ship IDs to each observation. This will allow for identifying data gaps and applying a better-quality control on entire ship voyages leading to a significantly improved quality of the existing data collections.

The efforts to digitize DWD's historical archives contents are ongoing. Apart from meteorological ship logbooks, several archives of land stations are currently being digitized, quality controlled and submitted to international databases (more information on DWD data rescue activities are available here).

The DWD digitization effort still relies mostly on keying the observations by hand. A variety of old German handwriting and unusual data sheet layouts are a persistent challenge for automatic text recognition systems. Future machine-based transcription may significantly speed up the transcription. However, the (meta)data management of the rescued data, as well as the handling and scanning of the old and fragile documents still require a lot of careful work to create high quality modern data sets originating from these valuable historic data sources.

NOAA/University of Washington/U.S. National Archives

NOAA and the University of Washington (Cooperative Institute for Climate, Ocean & Ecosystem Studies) have been collaborating with the U.S. National Archives since 2011. During this period, the project has produced high-resolution digital images of 4 618 volumes of federal ship logbooks, dating between 1844 and 1955. These are all publicly available worldwide on the National Archives Catalog. These assets have so far produced about 1.5 million new-to-science hourly weather records via the Old Weather citizen-science project. As shown in figure 2a, more than 600 000 weather and sea-ice observations pertaining to the Arctic have been further enhanced by painstaking reconstruction of ship tracks to hourly resolution using the 'dead reckoning' and pilot information contained in the logbooks (i.e. data on the ship's course and distance run, bearings and ranges from known landmarks).

The process of creating digital surrogates, transcribing and quality-controlling weather data from them, and passing these data into ICOADS and the International Surface Pressure Databank (ISPD) is ongoing. Sea-ice data recovered by Old Weather have been used for validation of a model-based reconstruction of Arctic sea-ice volume over the last century (Schweiger et. al 2019, Wood et. al 2019), and transcribed weather data are also available for machine learning research on handwriting recognition (HCR).

The enormous potential for data rescue is illustrated by the size of the U.S. collection that remains largely unutilized. Beginning in 1847, the logbooks of the U.S. Navy, Coast Guard/Revenue Cutter Service and Coast Survey contain 24-hourly weather records per day, and include 7–10 variables per hour, although not all variables were uniformly acquired in fact until after the U.S. Civil War (1861–1865). There are roughly 22 700 logbooks in the National Archives that date between 1801 and 1941. Until 1915, most volumes contain about one year's worth of observations, and then from 1915–1941 logbooks were generally bound in monthly volumes. Conservatively estimating that only half of these logbooks contain all 24-hourly observations that would amount to 75 500 000 weather records to be recovered. There are undoubtedly tens of millions more unrecovered weather records from the World War II era and after.

The United States Steamer "Powhatan" in a cyclone of Hatteras – From a sketch by G.T. Douglass, U.S.N. – [See Page 374.] in Harper's Weekly, May 12, 1877.

Danish Meteorological Institute/National Archives of Denmark

The National Archives of Denmark contain huge collections of logbooks. Starting as early as the mid-seventeenth century, it has been possible to identify more than 7 000 archive boxes, filling more than 700 metres of shelves with logbooks and other maritime data. Only a very small part of this data has been digitized to date.

Data has been made available by many seafaring nations recently, but the Danish data, apart from its sheer age, is special in two respects:

1. There were regular ship connections between Denmark and the other parts of the Realm of Denmark. This enables us to obtain a wealth of information about wind, weather, temperature

and ice extent en route to Greenland and Iceland and back.

2. The Øresund duty was a tax that every ship passing through the Øresund between Denmark and today's Sweden (Danish at the time) had to pay. In certain years, this duty made up about a third of the Danish national budget. Therefore, the king decreed that ships would not pass without paying their duties, and ships were installed at several places along the sound and at the Great Belt to enforce this. The logbooks of these ships are interesting because they have a high temporal resolution and go back to the seventeenth century.

The National Archives and the Danish Meteorological Institute are setting up a project, named ROPEWALK (Rescuing Old data with People's Efforts: Weather and climate Archives from LogbooK records), to digitize this enormous amount of data. Machine-learning techniques will be used as much as possible, then the remaining data will be digitized by volunteers as has been the case in other comparable projects. The digitized data will be quality-checked and made available to the scientific community.

National Institute of Water and Atmospheric Research

The National Institute of Water and Atmospheric Research (NIWA) in New Zealand have been conducting meteorological data rescue as a contribution to ACRE (via ACRE Pacific and ACRE Antarctica) since 2009. They also have been passing data to the ISPD through that channel. During the past decade, their focus has primarily been on recovery of southwest Pacific and Southern Hemisphere high latitude meteorological observations spanning the period 1800–1950.

NIWA hold millions of observations dating back to the mid-1850s, and ongoing efforts are creating digital surrogates and a metadata catalogue to verify physical document holdings and keyed data held in digital archives. Several other high-value historic meteorological documents have been located in New Zealand (Lorrey and Chappell, 2016), which have been used to reconstruct synoptic weather patterns and have been compared to marine observations rescued by other scientific organizations.

In recent years, NIWA has driven the Southern Weather Discovery (SWD) citizen science platform hosted on Zooniverse (southernweatherdiscovery.org), recovering ~250 000 Southern Hemisphere marine weather observations, promoting meteorological data rescue and completing experimentation on replicated data keying (Fig. 2b). They are also actively collaborating with Microsoft on an Artificial Intelligence (AI) for Earth project that is comparing manually transcribed observations and those completed by automatic means.

Challenges and actions

The principal challenges faced by the marine data rescue community fall largely into two categories: access to historical records and conversion from manuscript to digital format.

In the first category, ship logbooks, which tend to have the largest quantities of high-quality marine weather data, are often 100 or more years old and considered documents of national significance. The state archives that typically have responsibility for the care and preservation of these sometimes-fragile documents are understandably cautious about handling. However, it is not uncommon to encounter other barriers, such as monetization of access (beyond the cost of the imaging itself), or other embargoes on access that effectively limit uses at the scale necessary for data rescue.

In the second category, conversion to an actionable digital format is also a significant bottleneck. At present, this step relies on manual transcription, either via double-blind keying or citizen-science (crowdsourcing). These approaches are quite worthwhile if targeting particular regions or time periods with sparse data, such as the Arctic or Southern Ocean, or a discrete research question. However, a large-scale conversion of the vast quantities of unused marine weather data that are known to exist will require an efficient AI/machine-learning solution.

Finally, digitized records must be as complete as possible with detailed metadata (where possible). This is especially important when dealing with data biases, which depend on knowledge about parameters such as solar radiation, wind speed and direction, humidity and air temperature. For metadata, information like where thermometers are stored or sheltered, locations of screens, observing platforms and details of other instrumentation can all be important. For sea surface temperatures, there is rarely information about instrumentation for engine room measurements or what type of ocean sampling bucket was used, and often little about how measurements were made (Kent and Kennedy, 2021). Documentation of methods, such as can sometimes be found in marine observer handbooks and etc, are also important. In conjunction with the above is the need to reprocess legacy data so that as much can be obtained from them as possible, but also to assess what is complete and what is not. All of these efforts would benefit immeasurably from access to more sustainable funding sources.

Actions which are beginning to address the above needs include:

- In the U.S., NOAA has recently elevated both citizen-science and machine auto-transcription development with targeted funding opportunities for small business and via the NOAA High Performance Computing and Communications Program's Information Technology Incubator.

- Private philanthropy has been increasingly engaged in supporting climate science in areas where funding has traditionally been challenging

- The coming together of EU Copernicus, WMO, ACRE, DWD, UK Newton Fund, NOAA, NIWA and similar initiatives and funding streams, which are all increasingly working in conjunction with the National Weather Services, to rebuild and enhance fundamental data infrastructure to meet the needs of high-performance reanalysis and emerging AI applications in this domain.

Once in digital format, the technology exists to assimilate every marine weather observation collected by every ship, every day, for the past two centuries. What is learnt about the long-term state and future of the Earth System from such a comprehensive reanalysis may prove to be of the utmost importance in the future.

References are available online

Ocean Observations Programmes to Monitor Climate and Address Societal Needs: The Role of the OOPC

By Sabrina Speich, Professor, Ecole Normale Supérieure; Co-chair OOPC and Weidong Yu, Professor, Sun Yat-Sen University; Co-chair OOPC

The ocean absorbs, transports, redistributes and stores heat in such a way that it acts as a regulator of climate. More than three billion people rely on the ocean for their livelihoods. The ocean also provides a wealth of socio-economic, environmental and cultural benefits to all mankind. Understanding the ocean is key to harnessing and sustaining those benefits, while at the same time preserving its health.

But the ocean is vast. While many nations have ocean monitoring programmes in place, these are often limited to the area within their respective Exclusive Economic Zones (EEZs). Large expeditions and experimental campaigns into remote ocean basins have collected invaluable data that have changed our understanding, not only of the ocean, but of the whole Earth; however, they have not provided a comprehensive picture of all its surface. Satellites changed this to a great extent, but only for the upper layers of the ocean. Whilst humanity has mapped the surface of Mars extensively using a range of orbiting space probes, only 20% of the seafloor has been mapped.[1] Even after decades of oceanographic campaigns, experimental platforms and satellites – as well as other technological headways like the revolution of autonomous sensors – the picture is not complete, we have obtained snapshots, not a comprehensive view.

The design of an observing system to monitor the ocean in all its width and depth in a sustainable, continuous way, is fundamental challenge that requires a global approach. In 1996, the Ocean Observations Physics and Climate (OOPC) panel was formed under three United Nations programmes – the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS) and the World Climate Research Programme (WCRP) – to address this challenge.[2] Established in 1991, 1992 and 1993 respectively, these three programmes have the same co-sponsors: WMO, the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), and the International Scientific Council (ISC)[3].

The OOPC was given three goals:

1. Foster the development and agreement of an international plan for sustained global ocean observations in support of the goals of its co-sponsors

2. Suggest mechanisms for the evaluation and evolution of the agreed plan

3. Liaise between all entities involved in global ocean observations.

These goals have evolved with time and the initial focus on physical variables has expanded. This article will describe the achievements and progress of OOPC over the last 25 years.

1 The mapping the entire ocean seabed is the very ambitious goal of the Nippon Foundation-GEBCO (General Bathymetric Chart of the Oceans) Seabed 2030 Project.

2 The OOPC superseded the Ocean Observing System Development Panel (OOSD, 1990–1994), which had been charged with the design of an ocean observation system for climate.

3 GOOS and GCOS have an additional sponsor: the United Nations Environment Programme (UNEP).

Late nineties: Conceiving the pieces

The initial focus of OOPC was the open ocean, while other GOOS panels and groups were in charge of the enclosed and shelf seas and near-shore coastal seas. In its first years, OOPC produced a number of reviews prompted by the arrival of new technologies and observing capabilities. Two fine examples are the Global Sea Level Observing System (GLOSS) in view of new satellite capability and the Ship-of-Opportunity Program (SOOP). The panel was also involved in forming the Global Ocean Data Assimilation Experiment (GODAE, 1997), which placed new demands on the ocean observing system, and in developing the concept for the very successful and still operational Argo program[4].

OOPC's early work culminated in the First International Conference on the Ocean Observing System for Climate, held in San Rafael, France, in October 1999 (OceanObs'99). OceanObs'99 cemented the foundations of what we now know as the sustained ocean observing system for climate. From OceanObs'99, there emerged a consensus within the ocean observing communities to undertake an internationally coordinated sustained global ocean observing effort for ocean physical and carbon variables with respect to climate applications.

2000–2009: Establishing the networks

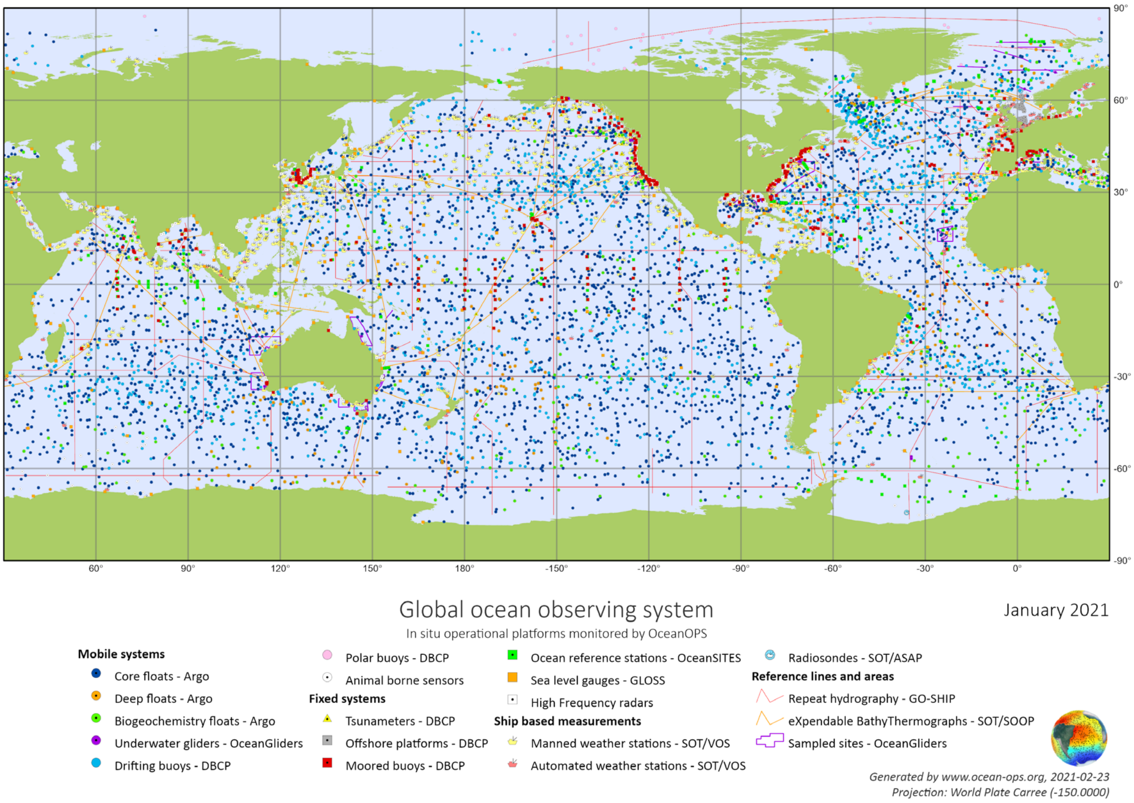
During the 2000s, OOPC worked with various partners to support the establishment of several sustained observing networks, building on the OceanObs'99 recommendations. These include the establishment of the OceanSITES moored time-series initiative in 1999, and development of the International Argo array of profiling floats in 2000. OOPC's involvement was critical to brokering data agreements and incorporating these new networks into existing programmes, such as the SOOP and the global eXpendable BathyThermograph (XBT) network, and in connecting to the growing number of satellite missions. In 2001, OOPC conducted a review of the Tropical Moored Buoy Array. During this period, OOPC partnered with WCRP in the Climate and Ocean: Variability, Predictability and Change (CLIVAR) project and collaborated with other WCRP panels, ensuring both the development of a sustained ocean observing system and providing input to regional and basin process-studies. Building on its input to the establishment of GODAE, OOPC's indirect sponsorship was vital to bringing climate change considerations into the plan for the development in 2002 of what is now the Group for High Resolution Sea Surface Temperature (GHRSST) project.

The second International Conference on the Ocean Observing System for Climate (OceanObs'09) was held in Venice, Italy, in September 2009, with OOPC as one of its leaders. OceanObs'09 recognized the utility of ocean observations beyond climate and the need to expand beyond physical variables to include biogeochemical and ecosystem variables within the ocean observing system. Thus, a key recommendation from OceanObs'09 was for international integration and coordination of interdisciplinary ocean observations. To this end, there was strong engagement with the various ocean communities involved in ocean observations and with end-users. The OceanObs'09 sponsors also commissioned a Task Team to respond to this challenge, leading to the release in 2012 of A Framework for Ocean Observing (FOO) (Lindstrom et al., 2012; Tanhua et al., 2019).

2010-2019: Beyond physical variables and towards societal needs

The FOO applied a systems approach to sustained global ocean observing. It used Essential Ocean Variables (EOVs) as the common focus and defined the system based on requirements, observations, and data and information as the key components. Notably, it incorporated both coastal and open ocean observations. The assessment of feasibility, capacity and impact for each of the three system components was based on readiness levels, that is to say concept, pilot and maturity. The FOO provides guidelines for evolving the observing system in the service of a broad range of applications and users. To support expansion of the ocean observing system, GOOS expanded to include three disciplinary panels: OOPC became the physics and climate panel, International Ocean Carbon Coordination Project (IOCCP) provided oversight of ocean biogeochemistry, and a new biology and ecosystems Panel (BioEco) was formed. OOPC retains

4 https://argo.ucsd.edu/



State of the networks that integrate Global Ocean Observing System (GOOS) monitored by the WMO/IOC-UNESCO in situ Observations Programme Support Centre (OceanOPS) as well as other networks such as GLOSS and Argo

the dual roles of ocean panel of GCOS and physics panel of GOOS. Delivery to GCOS requires OOPC to work across all components of GOOS, coordinating ocean input and interacting with its sibling Terrestrial (TOPC) and Atmosphere (AOPC) GCOS panels.

The OceanObs'19 conference sought to further align science, technology and human capacity in ocean observing to address growing and urgent societal needs. It emphasized the importance of ocean observations as the key source of information on natural hazards – from harmful algae and bacteria blooms, tsunamis, storm surges, marine heatwaves and storms to other extreme weather events – ecosystem health and biodiversity, ocean pollution, and sea level change. It highlighted the need for observations to support ecosystem-based management, marine and weather forecasting, climate predictions and projection, marine safety and navigation, decision support for climate adaptation, deep-ocean exploration, and seafloor mapping, among many other areas. The need to integrate ocean observation and research agendas to meet societal needs is becoming more important than ever (Visbeck, 2018).

After 2020: The future of ocean observations and coordination efforts

In this article we have described the history and some successes of OOPC, with its multiple responsibilities towards GCOS, GOOS and WCRP. Given the increasing complexity of the mix of observing platforms and sensor technologies, and the ever-expanding users, and their differing and sometimes divergent requirements, OOPC faces new challenges. To address these challenges, the questions that OOPC will need to consider are (Sloyan *et al.*, 2019):

- How do we evolve the observing system to meet a broader range of applications, ranging from extreme events (e.g., cyclones, storms, marine heatwaves, and coastal inundation forecasting) to climate monitoring and supporting ecosystem services?

Ocean Basin Observing Systems: some successes

Looking back into the early 1980s, one of the most successful GOOS stories started with the initial implementation of the Tropical Atmosphere Ocean (TAO) array, led by the U.S. National Oceanic and Atmospheric Administration (NOAA), in the tropical central to the eastern Pacific Ocean. It was later extended to the west with the introduction of TRITON array, contributed from Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The ten-year period from 1985 to 1994 witnessed the development of TAO-TRITON array covering the entire tropical Pacific Ocean, which represented an immense contribution to build up one basin scale ocean observing system to address the scientific and social requirements, that is the monitoring, understanding and predicting of El Niño and its global impacts. The initiative was triggered by the surprising super El Niño in 1982/82, which demonstrated that nature is always far more complex than it appears. The success of El Niño observation, theory, prediction and services is regarded as one of the most important advances in ocean and climate science in the 20th century. The Tropical Pacific Observing System 2020 project (TPOS 2020), aims to evolve the 30-year-old TAO-TRITON into a more sustainable and fit-to-purpose observing system.

The Indian Ocean basin tells another story. There, the ocean observation system started early in 21sth century, lagging behind its Pacific neighbour. The Indian Ocean Observing System (IndOOS) was proposed and discussed at OceanObs'99 in San Rafael, France. The CLIVAR-GOOS Indian Ocean Panel was then established to plan and develop IndOOS. IndOOS was fast tracked through international cooperation, with contributions from Australia, China, India, Indonesia, Japan, South Africa and the U.S. in valuable ship time and/or instrument investment. The recent IndOOS decadal review produced a revised version of the plan to be implemented from 2021.

- What actions do we need to take to keep exercising the system through reviews; engaging users, innovation, broadening participation?
- How do we continually evaluate and innovate the observing system to ensure it performs as an integrated system?
- How do we maintain the interest and momentum for sustaining observations, when much of the funding is on short term cycles?[5]

In January the UN Decade of Ocean Science for Sustainable Development 2021-2030 was launched. It offers a once-in-a-life-time opportunity to seek solutions to improve the knowledge of the ocean and transform its status according to the Sustainable Development Goals (SDGs). The focus of the Decade is on science and several directions for research and development have been put forward. However, theoretical knowledge is not sufficient. It is necessary to identify who must do what and to stimulate a move from scientific knowledge to actionable solutions. In seeking to answer the questions above, OOPC will continue to support GOOS, GCOS and WCRP in connection with the ocean observing community and other stakeholders to engage in transformational programs in the framework of the Decade, to advance a fit-for-purpose ocean integrated observing system to serve society across all requirements.

5 Unlike satellite observations (which rely on public funding, as well as funding from the industry) and marine meteorological observations (integrated in the operational, sustained observation programs carried out by the National Meteorological and Hydrological Services), in situ ocean observations are mostly funded by research projects of a limited duration (the longest commitment is typically 5 years), with serious risks for the continuity of the time series.

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Global Cryosphere Watch – sea-ice information for science and operations

By Petra Heil[1], Penelope Wagner[2], Nick Hughes[3], Thomas Lavergne[4] and Rodica Nitu[5]

Sea ice is a key indicator of climate change. While changes in sea ice affect the access to polar oceans and surrounding seas and their resources, and are an important factor for ensuring the safety of navigation in the high latitudes. Furthermore, changing sea-ice cover impacts ocean circulation and weather patterns, locally and in the mid and low latitudes.

The WMO Global Cryosphere Watch (GCW) provides a focused approach to addressing the needs of Members and their partners for observing the cryosphere as a key component of the Earth system. Through the GCW, cryospheric data can be accessed and used to meet information needs. Value-added analyses and indicators can build on the in situ, space-based and airborne observations and models of the cryosphere, available in the GCW, to develop products and services.

Sea ice is a high priority activity of GCW, with a particular focus on fostering consistency of sea-ice observations across polar regions and on sustaining access to well understood sea-ice data and satellite products – critical inputs to numerical weather predictions, climate monitoring and operational services. These GCW sea-ice activities are coordinated with the other ocean relevant activities of the WMO Technical Commissions. In 2020, GCW became one of the joint stewards of the Ocean Observations Panel for Physics and Climate (OOPC)[6], monitoring the Essential Ocean Variable (EOV) and Essential Climate Variable (ECV) for sea ice.

Observing sea ice is not trivial due to scale, remote access, extreme operating conditions, high associated costs. Data acquisitions and subsequent assessments are often fragmented between research, academic and operational entities. Furthermore, various issues related to sea-ice observations, data standardization and use are not fully resolved. However, demand for near real-time and increased spatial resolution information on sea-ice concentration, thickness, pressure, stage of development, presence of icebergs and other parameters is increasing, driven by forecasting and decisions for navigation, search and rescue, and climate and ecosystem services in polar regions.

GCW coordinates three priority activities related to sea ice:

1. the harmonization and standardization of sea-ice observations and reporting protocols

2. the consistent definition and dissemination of observing requirements across operational and scientific applications

3. facilitation of the characterization of satellite sea-ice derived products and how their use supports specific applications.

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1 Research Scientist, Australian Antarctic Division and University of Tasmania (Australia)

2 Research Scientist, Norwegian Meteorological Institute, Norway

3 Head of Norwegian Ice Service, Norwegian Meteorological Institute, Norway

4 Research Scientist, Norwegian Meteorological Institute, Norway

5 WMO Secretariat

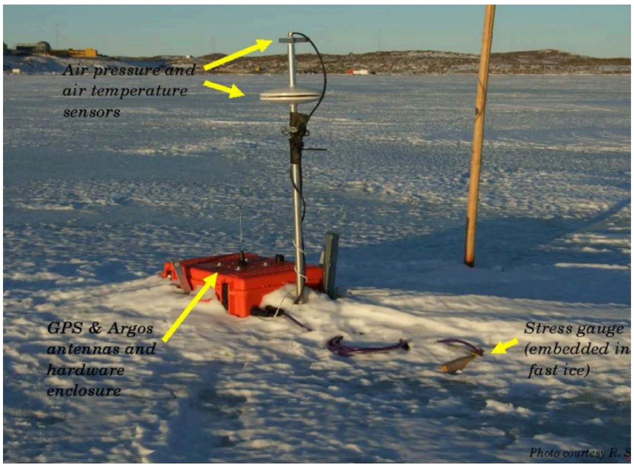
6 The OOPC is co-sponsored by the WMO/IOC-UNESCO/ ISC/UNEP Global Climate Observing System (GCOS), the IOC-UNESCO Global Ocean Observing System (GOOS), and the WMO/IOC-UNESCO/ OSC World Climate Research Programme (WCRP).

In situ sea-ice and snow sampling – together with coordinated oceanographic, atmospheric and biogeochemical observations – provide key information and anchorage points for deriving products from remotely-sensed data and to calibrate and validate numerical simulations. (Photo: P. Heil)

GCW works in close collaboration with the WMO Polar Space Task Group on the third priority. All three align with activities planned within the framework of the UN Decade of Ocean Science for Sustainable Development.

GCW facilitates. These include programmes under the Global Ocean Observing System (GOOS), those operated by Sea Ice Services, and long-standing research programmes such as Antarctic Sea Ice Processes & Climate (ASPeCt), IceWatch, Antarctic Fast Ice Network (AFIN), the International Arctic Buoys Programme (IABP) and International Programme for Antarctic Buoys (IPAB). ASPeCt is the expert group on multi-disciplinary Antarctic sea-ice zone research within the Scientific Committee for Antarctic Research (SCAR) Physical Sciences program, coordinating ship-based data collection in the Southern Ocean, data calibration and building an observational record. Building on the research Data Network Arctic Shipborne Sea Ice Standardization Tool (ASSIST) developed under the Climate and Cryosphere Project (CliC) of the World Climate Research Programme (WCRP), IceWatch has been adopted by the Norwegian Meteorological Institute, to collate and archive sea-ice observations from the Northern Hemisphere. Finally, AFIN is the Antarctic Fast Ice Network concerned with the acquisition of near-coastal ocean-sea ice-atmosphere observations.

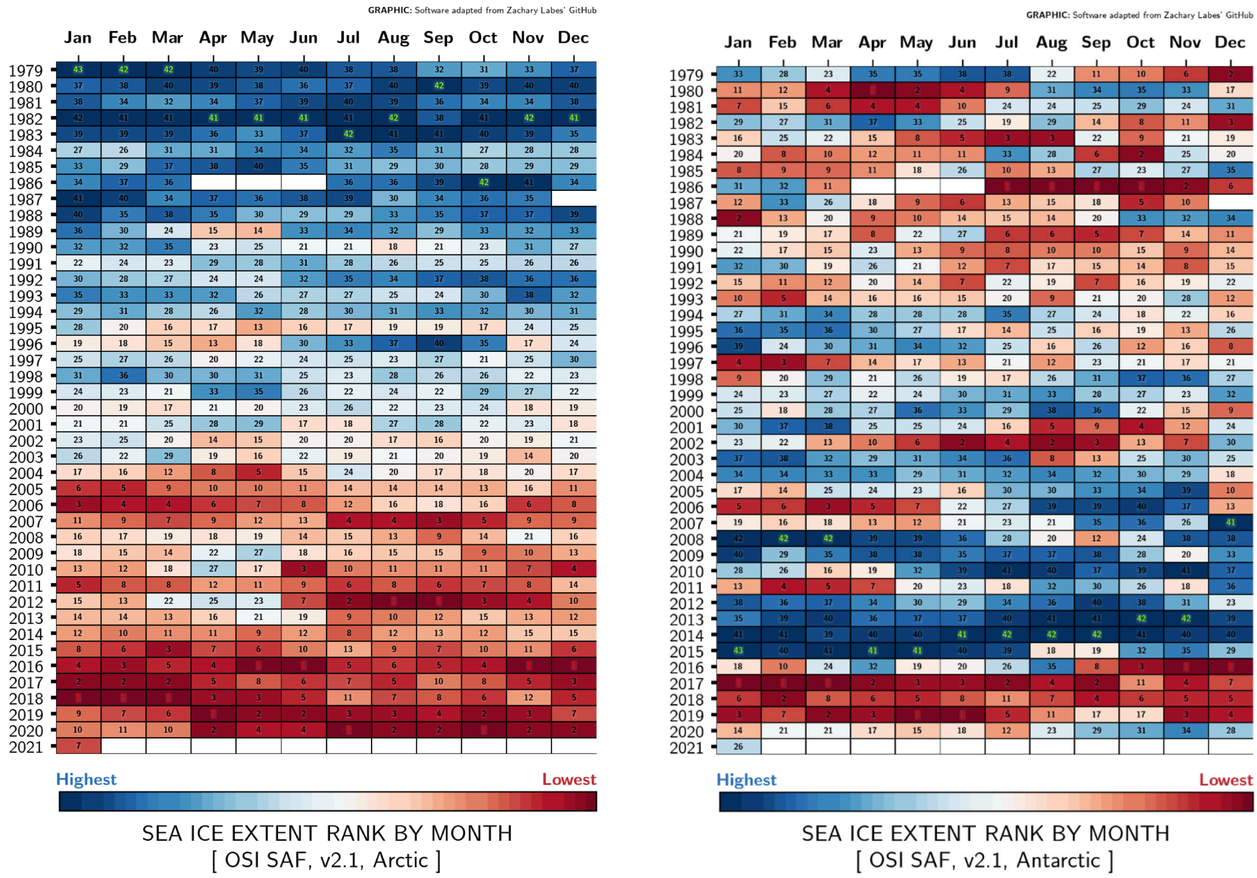
Expendable remotely-operating instrumentation on, in and below the sea ice, as pictured here, provide crucial information on the state of the sea ice and its snow cover and how it evolves and moves in response to atmospheric and oceanic forcing. (Photo: P. Heil)



In situ instrumentation provides high-spatial and temporal resolution data on a range of sea-ice properties crucial to understand the processes driving sea-ice evolution and linking changes in sea-ice properties to discrete forcing. (Photo: R. Steele)

Standardized observing and reporting protocols are necessary to overcome the scarcity and fragmentation of sea-ice data for both, the Arctic and the Antarctic, and to provide normed and well characterized input for the development and validation of numerical models and remote sensing data products. This is possible through collaboration with other programmes, which

The consolidation of sea-ice observing requirements is a GCW priority in the context of balancing the needs for weather and climate monitoring with the demand for near real-time (< 24 hours) higher spatial resolution (hundreds of metres) data. The consolidated requirements would need to reflect the needs of applications for sea-ice operational



The steady decline of the Arctic (a) and Antarctic (b) sea-ice extent in the 40+ years of satellite data records. Image shows ranks (1: lowest, 43: highest) of monthly mean sea-ice extent for the Arctic and Antarctic, respectively. Rows/ columns represent years/months and colours go from blue (highest) to red (lowest). (Based on EUMETSAT OSI SAF data with R&D input from ESA CCI (courtesy T Lavergne (Norway)).

monitoring activities, for search-and-rescue and for understanding and addressing the dramatic effects of climate change on polar ecosystems, which also relates to food security, including for indigenous populations.

In parallel, well-documented observing requirements support the evolution of observing systems for polar regions, where there is a significant reliance on satellite observations. Satellite mission objectives and their implementation rely on input from user communities to prioritize investments, for instance, when satellites near their expected end-of-life and must be replaced. One example is the Call for Support, signed by over 600 scientists from more than 30 countries, to fill the anticipated gap in the polar radar-altimetry capabilities. This and other potential gaps, if materialized in practice, would introduce decisive breaks in the long-term records of sea-ice (and ice-sheet) thickness change at an extremely critical time when the continuity of climate monitoring is essential for monitoring progress under the Paris Agreement of the United Nations Framework Convention on Climate Change. This underlines the importance of WMO's role in supporting the identification of user needs and critical gaps to inform decisions on satellite mission priorities, from forecasting weather and ocean conditions and monitoring ocean, ice and waves conditions for safety of navigation in the polar regions to the continuity of climate records.

Consistency of observing products available from diverse space missions, and their alignment with user needs, are critical. In this regard and in consultation with the international community, GCW has initiated an intercomparison of satellite products on sea-ice thickness and snow depth on sea ice. Ice thickness provides an integrated measure of changes in the energy budget, while snow on sea ice adds a key insulating layer. The latter, where sufficiently thick such as in the Antarctic, may contribute to sea-ice volume through snow-ice formation.. These parameters are critical for forecasting and navigation in polar waters as sea-ice thickness limits the use of vessels of certain ice classes, and the gluing effect of snow cover reduces icebreaking effectiveness. While a wide array of retrieval methods is available for estimating sea-ice thickness from a range of satellite observations, estimating the snow thickness on sea ice remains a challenge (IPCC, SROCC, 2019). The intercomparison is expected to provide recommendations on future space missions for addressing acknowledged gaps. GCW will provide the scientific steering of the project.

The 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate documented the need for a coordinated and holistic approach to observing and investigating changes in sea ice. It noted the remaining "critical gaps in knowledge concerning interactions between the atmosphere and specific elements of the polar ocean and cryosphere." Then went on to state that these gaps "... limit the understanding of ongoing and future trajectories of the polar regions and their climate systems". GCW is well positioned to encourage and effectively coordinate projects to fill these gaps and to foster consequent data analysis and publication of data and results.

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From JCOMMOPS to OceanOPS: supporting oceanography and marine meteorology in-situ observations

By Mathieu Belbéoch and Emanuela Rusciano, WMO-IOC OceanOPS

Eighty-six countries are involved in ocean observations with about 10 000 in situ ocean observing platforms and 170 satellites continuously monitoring the global ocean and atmosphere. The analyses, forecasts and products based on ocean observations are the bedrock of decisions across a swath of socio-economic sectors, especially in marine transportation, coastal communities, climate, agriculture and ocean health. Society's need for ocean information is increasing. In response, the Global Ocean Observing System (GOOS) is gaining in complexity, scope and coverage. Strong coordination is required within and amongst communities of observers from around the world to ensure delivery and cost efficiency from observations through to data management systems and information services.

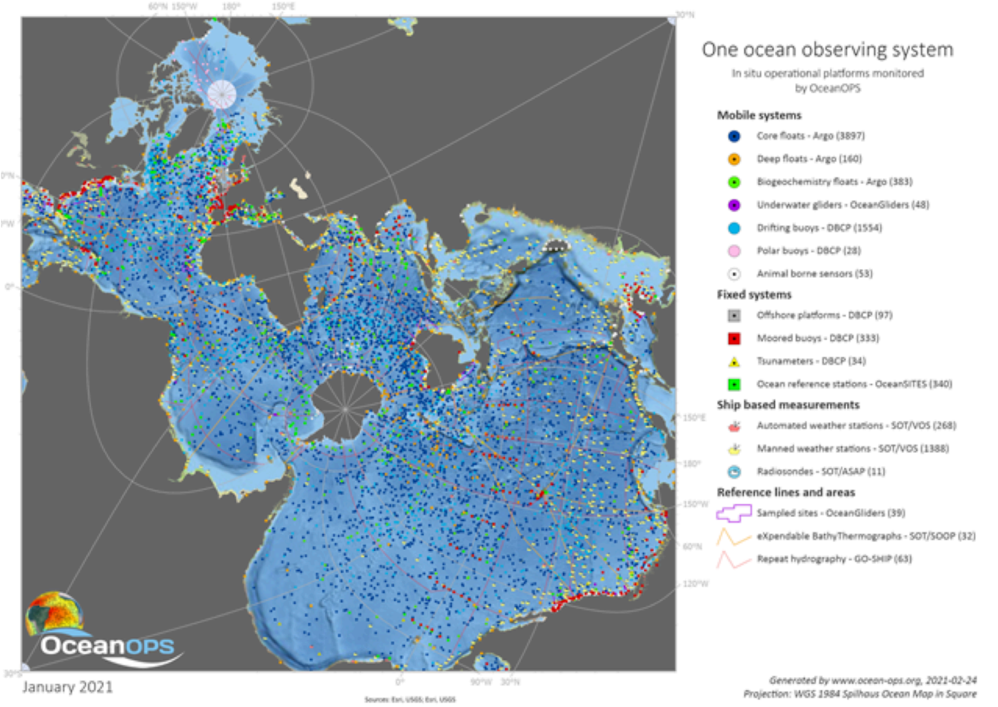
In 1999, the World Meteorological Congress and the IOC/UNESCO Assembly adopted identical resolutions to establish the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). In turn, the first JCOMM session in 2001 established the Observing Platform Support Centre, known as JCOMMOPS.

Initially, JCOMMOPS built on the coordination facilities provided by the Data Buoy Cooperation Panel since the 1980s and the Ship Observations Team. It later also encompassed the revolutionary Argo profiling float programme, a key outcome of the OceanObs'09 conference. Synergy was realized between these three global marine observational programmes, which assists those in charge of implementing National observing components, through an integrated and international approach.

From 2001 to 2015, JCOMMOPS Centre was located in Toulouse (France), hosted by the CLS company, to interact closely with users of the Argos telecommunication system. There, it benefitted both from an operational infrastructure and access to a large raw data hub. The Centre operated initially with two technical coordinators then it grew gradually to support more sustained ocean observing systems, including the OceanSITES, GO-SHIP, OceanGliders, GLOSS and some emerging networks of the JCOMM/GOOS Observations Coordination Group (OCG) such as the animal-based measurements (AniBOS).

The Centre developed a number of innovative services for real-time monitoring of the global networks' performance and to assist implementers on a day-to-day basis, including in their operations at sea. The small JCOMMOPS team pioneered the web and Geographic Information System (GIS) technologies to track the ocean observing networks and offer a useful toolbox to scientists, program managers and to the GOOS/JCOMM governance.

The team opportunistically chartered a 20-metre sailing ship, Lady Amber, to assist Argo and Data Buoy Cooperation Panel (DBCP) implementers in filling gaps in the global arrays and demonstrate that low cost and low footprint solutions could find their place amongst the fleet of merchant and research vessels. The vessel did an equivalent of two circumnavigations, in the South Atlantic and Indian Ocean, seeding close to hundred instruments. This success story led to the establishment of a ship coordinator at JCOMMOPS to support the Ship Observations Team (SOT) and the Global Ocean Ship-based Hydrographic



One ocean observing system

Investigations Program (GO-SHIP) and to act on all cross networks ship issues, including with civil society, non-governmental organizations (NGOs), sailing explorers and races.

In 2015, the Centre and staff moved to Brest (France), within the Institut Français de Recherche pour l'Exploitation de la Mer (Ifremer), to be closer to implementers in a worldwide ocean pole and with strong support from regional authorities. Its information system remained in Toulouse in the operational CLS cloud, with a 5-staff team in the Brest office. After years of preparation, a full revamp of the original information system and web-based applications was undertaken in 2015. It integrated the monitoring dashboard for GOOS and provided network specific tools and indicators, all fueled by a growing diversity of metadata and real-time pulses from the platforms.

Ocean Observing System Report Card

The annual publication since 2017 of the Ocean Observing System Report Card is a major achievement for the Observations Coordination Group and the Network experts. The publication communicates on the societal values of the observing system and encourage international collaboration, new partners, Members and Member States to join the challenge of building an integrated, sustained, innovative, globally implemented observing system that meets the growing demand for ocean services and science. It also helps the networks to raise their standards to meet integrated goals.

OceanOPS

In 2018, an external review of JCOMMOPS was conducted by the Observations Coordination Group to help the Centre and its stakeholders to better capitalize on its uniqueness and strengths and to identify issues, opportunities and challenges. The Review provided a tabulation of both strategic and operational actions for consideration and underlined the need for a five-year strategic plan that responds to key drivers and engages the JCOMMOPS stakeholder base. Therefore, JCOMMOPS started gathering perspectives and recommendations from stakeholders in 2019 in order to develop the strategic plan. The WMO Governance Reform, which was ongoing at the time, raised the ocean agenda and injected momentum into the JCOMMOPS process. In 2020, the five-year strategic plan was released. The WMO Governance Reform having disbanded JCOMM to create the Joint WMO-IOC Collaborative Board, the opportunity was taken to rebrand JCOMMOPS into OceanOPS.

OceanOPS supports efficient observing system operations to ensure the transmission and timely exchange of high-quality metadata, and assists with the provision of free and unrestricted data delivery to all users. The OceanOPS strategy is based on key goals, including: monitoring for the improvement of the global observing system performance, leading metadata standardization and integration, supporting and enhancing its operations, enabling new data streams and networks, and shaping the OceanOPS infrastructure for the future.

OceanOPS will develop tools and metrics to analyze the observing networks and system trends and report back to stakeholders to encourage performance improvement and cost efficiency. A core activity will be the harmonization of metadata for each observing network, individually and across the ocean observing system collectively. This will vastly increase data usability and global monitoring capacity. OceanOPS will maintain network specific services critical to ocean observing systems implementation, such as the IOC-UNESCO warning and notification system for floats approaching Coastal States waters. OceanOPS also has responsibility for allocating unique WMO identifiers to all met-ocean platforms and for providing integrated ocean metadata to the WMO OSCAR system. The WMO Governance Reform placed OceanOPS within the larger Earth System monitoring approach to develop synergies with cryosphere and hydrology.

OceanOPS believes there is a great potential to develop collaboration with third parties – civil society and the private sector – to contribute to the GOOS. The recent Vendée Globe Race offers a great example: ten skippers deployed autonomous instruments and carried out met-ocean observations during the race (see page…). OceanOPS has proposed a project for UN Decade of Ocean Science for Sustainable Development to frame these contributions and find solutions to distribute these datasets. Pilot projects are underway to develop an international data exchange service for non-institutional data, including with the WIS 2.0.

Challenges ahead

Over the past 20 years, OceanOPS has provided essential services, monitoring, coordinating and integrating ocean data and metadata. Based on its historical experience at the heart of the observing systems, OceanOPS has also identified a number of challenges that GOOS will have to overcome to build a globally integrated, sustainable and fully implemented observing system. Some are geographical: the opportunities to deploy autonomous instruments in the southern ocean are rare and the large majority of funding countries are in the North. While others are political: it is difficult to gain access to coastal states' waters to complete the implementation of the GOOS. GOOS needs to reduce its fragmentation through an integrated and dimensioned design and an efficient governance. An unprecedented communication effort is needed to demonstrate its societal value to Member States to boost their support.

OceanOPS represents a core element of GOOS, essential to delivery, efficiency, insight and management of the observing system enterprise. It will work to address these challenges with the larger GOOS community.

Vendée Globe Race Skippers go global with ocean observing!

By Emanuela Rusciano[1], Mathieu Belbéoch[1], Emma Heslop[2] and Albert Fischer[2]

A new era of sailing for science is beginning with the support of International Monohull Open Class Association (IMOCA) skippers during the Vendée Globe to the Global Ocean Observing System. Their participation is taking place within the framework of the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), and under the leadership of OceanOPS.

It was not enough to race to circumnavigate the world's ocean, braving equipment failure and stormy conditions, the fearless Vendée Globe skippers needed an extra challenge. So, they took on the task of making vital ocean observations, witnessing to their engagement for the ocean!

"The Vendée Globe is a race that I would like to win, but this additional challenge will allow us to find solutions to climate change," explained Boris Herrmann, Team Malizia/IMOCA skipper during the race. "We cannot stress enough the importance of the oceans, without them there would be no life on earth. As major players in our climate system, they store over 90% of the excess heat from radiative forcing and absorb about a quarter of the human-produced CO_2 emitted annually. This is why we are continuing our ocean research mission to protect this incredible wilderness."

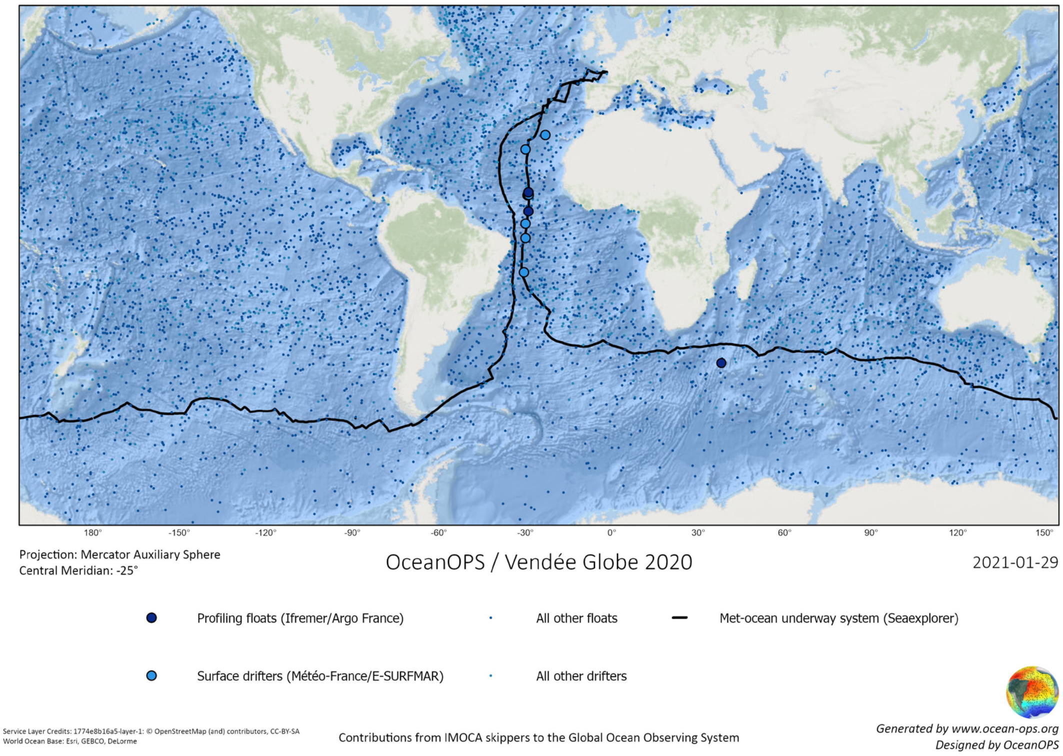
Despite the extra weight and responsibility for observing equipment, this link-up between the Global Ocean Observing System (GOOS) and 10 of the IMOCA skippers in the Vendée Globe race has been wildly successful. These observations are from some of the least visited regions of our global ocean, this is what makes the race so exciting and the data so valuable.

"I deployed a profiler float when I was leaving the Pot-au-Noir, a shipping route which is usually sparsely navigated," said Louis Burton, Bureau Vallée 2/IMOCA skipper. "The float weighed 20 kg and keeping extra weight to a minimum is crucial for the race, but it was worthwhile. It was my choice. The future of the planet is in serious danger.

Thanks to OceanOPS – the joint IOC-UNESCO/WMO centre supporting GOOS, which coordinates and monitors the sustained in situ components of the global ocean observing system – seven meteorological buoys and three profiling floats, operated respectively by Météo-France and Argo France, were deployed by the IMOCA skippers at agreed positions in the Atlantic Ocean. Four skippers also carried onboard equipment to measure essential ocean variables – such as sea surface salinity, temperature, CO_2, atmospheric pressure – and measuring the microplastics pollution at sea. The data collected during the Vendée Globe were shared in real-time in an international open-source database.

"The Ocean is our playground and our working environment," noted Kojiro Shiraish, DMG Mori/IMOCA skipper. "Over the years, I have seen the ocean changing in various ways. As a child, in my home town of Kamakura the ocean was polluted with heavy oil. We would go for a swim and sometimes come back with lots of heavy oil all over our body. This was such a serious problem that the Japanese government had to work very hard to make the ocean clean. Since then, the ocean in Japan has become very clean but there is now a bigger problem. A problem that we cannot see directly because it is so small.

1 WMO-IOC OceanOPS
2 IOC-UNESCO/GOOS



Yachts participating in round-the-world races often traverse under sampled areas. During their journey, they can gather high-value datasets, including meteorological (e.g. air pressure, wind) and oceanographic parameters (e.g. salinity, pCO_2), that add value to near real-time forecasting applications. After quality control, these datasets flow into archives, like the Surface Ocean CO_2 Atlas (SOCAT), for climate applications. The yachts also deploy autonomous instruments, like drifters and floats, in regions with very limited shipping. Here: Seaexplorer Yacht Club de Monaco in the 2020 Vendée Globe Race.

This problem is called micro-plastic. Just looking at the water, we feel that the water is very clean but in fact it could be polluted. The problem is very serious and we need to find better solutions to counter this. The ocean is the lungs of the planet earth. We need to treat it better to be able to live a better life."

Alexia Barrier, the 4myplanet/IMOCA skipper who deployed an Argo float near the Kerguelen Islands, related, "We are several Vendée Globe sailors to have boats equipped with sensors and to collect oceanic data that transmit daily to scientists. Considering the number of days we spend on the water and the remote places we travel through on a round-the-world trip, we provide a legitimate source of information."

Alexia, Boris and Luis are also involved in educational programs to make children concerned about the oceans. Ahead the race, Emanuela Rusciano, physical oceanographer and coordinator of science and communication at OceanOPS, addressed three classrooms in Brest and Plouzané, France, in special session on ocean observations. Students were familiarized with an Argo float and learned how it helps scientists to study global warming and collect data inaccessible to satellites, right down to the ocean's depths. After the instrument's deployment, educators and students will follow the trajectory of the float, which they signed, and access resources about the data acquired from the Adopt-a-Float program portal.

© Boris Herrmann / Seaexplorer – Yacht Club de Monaco

The Voluntary Observing Ships Scheme*

The Joint WMO-IOC Voluntary Observing Ships (VOS) scheme is an important component of the global observing system, providing meteorological and oceanographic data essential to operational meteorology, maritime safety services and a range of marine climatological applications. Ocean observation data is also of critical importance to global climate studies.

The VOS scheme is regulated by the Joint WMO-IOC Ship Observation Team (SOT) and supported by Port Meteorological Officers (PMO), which acquires data to support research, climate forecasting, numerical weather prediction and maritime safety services amongst other applications.

Today the overall registered VOS fleet is over 4 000. In 2020 navigation was disrupted by COVID-19 restrictions, nonetheless about 2 800 identified stations submitted more than 2.5 million observations. The OceanOPS platform reports that there are around 1 600 operational stations in a month.

* Zhichao Wang, Martin Kramp and Champika Gallage (WMO Secretariat)

The deployment of ocean observing instruments at sea is fundamental for the continuous measurement of oceanographic and atmospheric parameters of the ocean. Observations are crucial for delivering marine weather and ocean services to support safety of life and property at sea, maritime commerce and the well-being of coastal communities. Observations also provides insights into the global weather and climate system and the impacts of long-term climate change, as well as information on the increasing stress on the ocean from human activities.

“Observations from racing yachts, especially those acquired in remote areas of the ocean, are going to be vital for gaining a more complete knowledge of the ocean and the atmosphere above it, and for a more effective prediction of how the ocean may change in coming years”, said Albert Fischer Director, GOOS Project Office at IOC-UNESCO.

“For 10 years now,” continued Alexia, “I have been pledging for ocean sustainability and protection, and I have been trying to help scientists to better understand the ocean. I have realized that, due to the long period I spent at sea in very remote oceanic areas where only a few ships go, I can be really useful for ocean study and preservation. The oceanographic data I have acquired during this Vendée Globe are very rare and precious for the scientists.”

“The global ocean observing system is under growing pressure to meet the demand for weather and ocean services and forecast products, multi-hazard early warning systems, and climate and ocean health applications,” stated WMO Director of Infrastructure Anthony Rea. “In the current global COVID-19 pandemic, several ocean observing systems and ocean monitoring operations have been impacted. WMO therefore extends its appreciation and congratulations to the Vendée Globe skippers for their valuable contribution to weather and ocean observations.”

Martin Kramp, the Ship Coordinator at OceanOPS, complemented the Vendée Globe skippers for their important contribution to weather forecasting and understanding the health of the ocean. He explained, “These instruments help us in areas where we have little means to gather met-ocean data. Observations, such as the atmospheric pressure data acquired by the drifting buoys and transmitted in real-time to the operational centres, help to improve weather forecasting and protect safety of lives at sea, while

@IMOCA, modified by OceanOPS

the high-quality temperature data from profiling floats will enable scientists, throughout the world, to significantly improve the estimates of ocean heat storage."

Long Jiang, the Technical Coordinator at OceanOps for the Data Buoy Cooperation Panel added: "The deployment of barometer-equipped surface drifters are critical for numerical weather predictions as atmospheric pressure can't be measured directly from satellites."

In the future, "We would like the carrying of weather and sea water instrumentation to be part of the IMOCA class rules for ocean races, so that every skipper, whether racing for the podium or not, takes part to the observation and preservation of the ocean", added Mr Kramp.

"As a skipper, I am very aware of the importance of protecting the environment, particularly the oceans. In my opinion, France has a particular responsibility because it governs the second largest maritime space in the world, this includes the maritime areas of its overseas departments and territories. The sustainable development initiatives of the IMOCA Class made it possible to take ownership of targeted actions and become a real ambassador of the program," said Manu Cousin, Groupe SETIN/IMOCA skipper.

© *Manuel Cousin / Groupe SETIN*

The scientific initiative carried out during the Vendée Globe supports a GOOS made up of thousands of buoys, profiling floats, underwater robots, ship-based sensors and marine mammals equipped with oceanographic sensors. All these instruments are already supplying scientists and marine and weather forecasters with essential data about the conditions at sea for climate studies, weather forecasts and early warnings, and ocean health monitoring.

These new cooperation and collaboration with sailors are key to help scientists filling in geographical gaps in the GOOS and to support the safety of people and the future of our planet.

“About 2 000 autonomous instruments (such as profiling floats and drifting buoys) must be deployed every year to sustain the GOOS. We are calling today, through a specific UN Ocean Decade project, on civil society to support the GOOS implementation. We want to unlock the potential of citizens, non-governmental organizations, the private sector and world class sailors and mariners, some of our best ocean ambassadors,” said Mathieu Belbéoch, OceanOPS Lead.

The UN Ocean Decade offers a unique opportunity to change the way we care about the ocean and effectively support ocean science and oceanography for its protection and sustainable development. The Decade is a chance for all of us to contribute actively towards putting in place a more sustainable and complete ocean observing system that delivers timely data and information accessible to all users on the state of the ocean across all basins.

The involvement of the IMOCA skippers in this scientific project is part of a partnership that was signed in January 2020 between UNESCO and IMOCA to support ocean science and protect the ocean. For two years, the two organizations will carry out various joint projects including met-ocean observations.

The Vendée Globe/IMOCA scientific project contributes to growing global awareness in the racing community of the necessity to act to preserve the ocean. It results from the work that has been carried out over several years by the OceanOPS to team with “sailing ships of opportunity” to gather meteorological data and deploy oceanographic instruments at sea. This project follows similar initiatives by sailors coordinated by OceanOPS in the Volvo Ocean Race (and this will still be the case on The Ocean Race 2022-2023), the Barcelona World Race, the Clipper Race, the Rallies organized by Jimmy Cornell and the recent IMOCA-organized Arctique-Les Sables D’Olonne Race.

“Our skippers benefit from a unique experience. They navigate in the most isolated places on the globe and are the first to witnesses the impact of human activity on the oceans. The IMOCA Class is aware of the urgent need to protect and preserve our seas, which makes the partnership with OceanOPS and UNESCO's IOC even more valuable. In the next IMOCA cycle (2021-2024), we want to go further in involving more teams in the scientific contribution process”, said Antoine Mermod IMOCA Director.

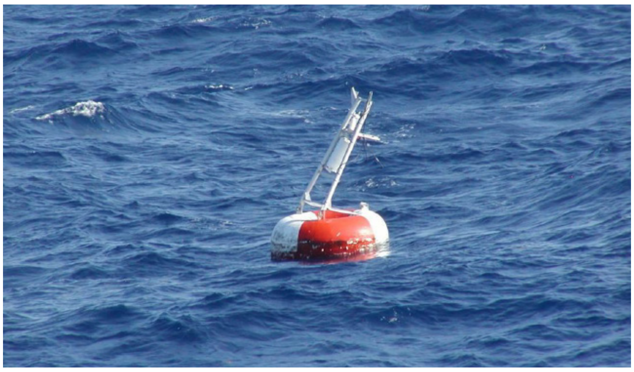
“On behalf of the ocean observing community, I wish to congratulate and thank all IMOCA skippers for their commitment to the ocean protection and their invaluable contribution to weather and ocean observations”, said Mr Belbéoch.

For further information on how to participate in the UN Ocean Decade observation project, please contact Emanuela Rusciano, erusciano@ocean-ops.org

Protecting Buoys for our Safety

By Champika Gallage and Sarah Grimes, WMO Secretariat

Ocean data buoys (moored and drifting) collect in situ oceanographic and meteorological data that are critical to a wide user community of government, academic, military, public health, emergency response stakeholders, marine transportation, tourism and fisheries industries. These observations are used in multiple applications, including to strengthen the quality and accuracy of severe and routine weather forecasting, improved coastal ocean circulation models, environmental and ecosystem monitoring and research, and tsunami warning capability. Monitoring ocean health can only be done through long-term multi-disciplinary observations, many of which are sourced from data buoys that are uniquely suited for this task. Failure to maintain a sustainable network of data buoys puts the health of our ocean and estuaries at risk.



Damaged TAO buoy, with the superstructure tilting at an angle. Source: B. Burnett, NDBC, 2009 (DBCP-25)

Data buoy vandalism refers to the intentional interference with, damage to, or theft of observing platforms attributable to human action. Data buoy vandalism has been a troublesome problem for many buoy operators around the world. In addition to the significant financial impact on buoy programs and operations, vandalism disrupts vital data collection and reporting by moored and drifting buoys, placing lives, property and economies in peril.

Data buoys are deployed in every ocean, and international cooperation is implemented via the Data Buoy Cooperation Panel (DBCP), which operates under the WMO-IOC Governance. DBCP has taken the lead in reducing and mitigating buoy vandalism. A 3-pronged approach has been used to address data buoy vandalism:

- regulatory policy and enforcement
- engineering and technical modifications to buoy systems to enhance situational awareness and impede third party interference
- the development and distribution of outreach and education materials on the value of ocean data buoys and the impacts of vandalism.

For a detailed overview of data buoy vandalism impacts and responses, see Ocean Data Buoy Vandalism- Incidence, Impact and Responses (DBCP Technical Document No. 41).

DBCP has published the "Outreach Strategy to Reduce Damage to Ocean Data Buoys from Vandalism" to guide development of outreach and educational resources to raise public awareness of the critical value of the services provided by ocean observation networks and warning systems, and of the related disaster risk-reduction benefits. It will help promote education and outreach, especially to recreational, artisanal and commercial fishers. It will also broaden support of community stakeholders and enable proactive engagement at regional and local scales through the development of new partnerships to share lessons learned and generate new ideas for addressing vandalism issues.

Many years of buoy vandalism information tracking has identified fishing activities as the primary cause of damage to data buoys (moored). Buoys act as fish aggregating devices (FADs), which fishing vessels exploit in pursuit of fish. This increases the incidence of direct contact between the buoys and fishing vessels. There are also rare incidences of damage from

Ocean Buoy awareness video released for World Ocean Day 2020 – public outreach to encourage people not to touch buoys.

unintentional impacts such as inadvertent collision with a buoy. Drifting buoys are vandalized by picking them up from the ocean and, in some cases, when these are beached.

Buoy vandalism has been a problem since the establishment of ocean observing networks in the late 1980s. Incidences of data buoy vandalism are apparent in both ocean and coastal networks. The issue has garnered international attention because many moored buoy platforms – in the tropical Pacific, eastern tropical Indian Ocean and equatorial Atlantic Ocean – are internationally supported and provide data to the international community. Further, these networks are located outside Exclusive Economic Zones (EEZs) on the high seas. This means the response to vandalism events requires both national and international efforts.

Numerous local, national and international efforts have been made to educate and inform people, in particular the fishing community, about the negative consequences of data buoy losses for research; weather, climate and ocean forecasting; and tsunami warnings. These observing losses have direct impact on loss of human life and property. So far, the efforts have had limited success – they have drawn awareness to the impacts of data buoy vandalism but have not stemmed the continued loss of buoys. This global issue needs assistance and engagement at all levels – regional, national and local.

WMO released a public awareness cartoon on buoy vandalism for World Ocean Day in 2020. The video informs the public, especially in coastal small islands, about the value of buoys for understanding weather and climate and even for tsunami warning and has a straightforward message not to touch buoys. The cartoon is pitched to a broad audience and can be rolled out across social media for the public, schools and other community settings. Currently available in English, Fijian, French and Hindi to reach Pacific Island communities, the WMO intends to translate it into other languages for other regions around the world. The Fiji Meteorological Service has also provided print and DVD to remote islands where Internet connection is unreliable or unavailable.

Ocean Prediction - modelling for the future

By Fraser Davidson[1], Andrew Robertson[2], Frédéric Vitart[2], Anthony Rea[3], Michel Jean[4], Andreas Schiller[5], Thomas J. Cuff[6], Sarah Grimes[3], Eunha Lim[3], Estelle de Coning[3], Peiliang Shi[3]

The ocean is the Earth's largest ecosystem. It plays a major role in regulating the weather and climate of the planet. In addition, the ocean moderates global warming through CO_2 absorption and its massive heat capacity.

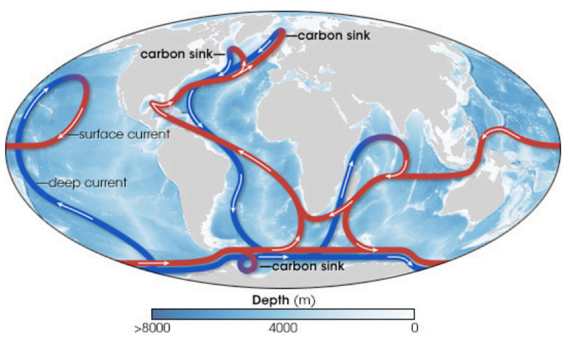


Figure 1: The ocean's surface layer (0-40 metres) absorbs atmospheric carbon that gets transported to the deep ocean in specific areas near the poles (noted by Carbon sink) where the mixed layer and deep ocean interface. (Map by Robert Simmon, NASA adapted from the IPCC 2001 and Rahmstorf 2002).

The United Nations indicates that 40% of the world's population – nearly 2.4 billion people – live within 100 km of coasts and estimates the size of coastal economies to be between US$ 3–6 trillion a year[7]. Coastal areas host essential infrastructure such as ports, harbors, desalination plants, power plants, aquaculture pens, etc. The ocean provides food, enables trade and has a strong role in many indigenous cultures. Knowledge of its physical characteristics and of the biological life it contains contributes to tourism, fisheries, maritime transportation, renewable and non-renewable energy extraction, and much more. The ocean itself can be a source of minerals and medical ingredients.

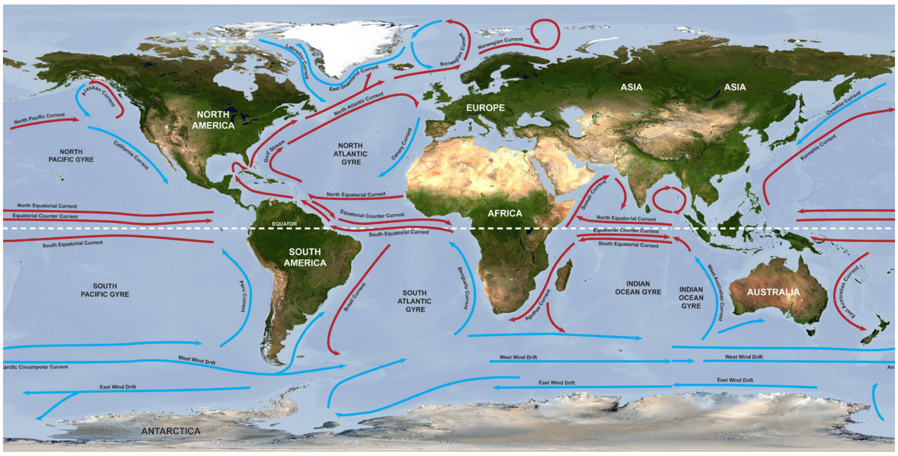
Thus, the importance of marine and coastal safety and ocean resilience cannot be underestimated. Climate information is essential to guide future coastal development and to adapt existing infrastructure to mitigate the impacts of hazardous marine and ocean weather. Impact-based early warnings for natural hazards and climate prediction and projections help coastal communities and businesses to avoid risks and increase resilience.

The ocean itself is an essential Earth System component in climate change projections. Understanding the ocean is fundamental to understanding the planet and the changes that are being wrought upon it by human activity. Today the ocean ecosystem and physical characteristics are being impacted by human actions, and the repercussions will be felt by all. There can be no delay in furthering knowledge and comprehension of the ocean, its interaction with the atmosphere and the impact of humanity on the ocean.

History

Historically, the exploration and exploitation of the ocean has gone hand in hand with the growth in knowledge about it, and the atmosphere above it. It was at the initiative of the oceanographer, meteorologist and astronomer Matthew Maury,

1 Co-Chair, OceanPredict Science Team
2 Co-chairs of the WWRP/WCRP S2S project
3 WMO Secretariat
4 President, Commission for Observation, Infrastructure and Information Systems (INFCOM)
5 CSIRO Oceans and Atmosphere
6 Director, Office of Observations, National Weather Service, NOAA; Chair, WMO Standing Committee on Marine Meteorology and Oceanographic Services
7 https://www.un.org/sustainabledevelopment/wp-content/uploads/2017/05/Ocean-fact-sheet-package.pdf



Surface drifts and currents of the oceans (Source: NOAA)

then a lieutenant in the U.S. Navy, that the First International Meteorological Conference was held in Brussels in 1853 to achieve a uniform system of meteorological observations at sea. The Conference paved the way for the creation some 20 years later of the International Meteorological Organization, the predecessor of WMO.

The same Matthew Maury was one of the first to publish met-ocean contributions in a book entitled "The Physical Geography of the Sea and its Meteorology" (Maury 1864). His marine environmental perspectives on winds and currents led, amongst others, to a decrease in transit times across the world's ocean, resulting in economic and safety benefits. Indeed, his pioneering work laid the foundation for modern marine meteorology. Today, there is still an urgent need for oceanographers to continue Maury's quest and to share their knowledge with those far and near with all who benefit from or are impacted by the ocean.

Operational oceanography

Operational oceanography can be described as the provision of routine oceanographic information needed for decision-making purposes. The core components of operational oceanographic systems are a multi-platform observation network, a data management system, a data assimilative prediction system and a dissemination/accessibility system. These are interdependent, necessitating communication and exchange between them, and together provide the mechanism through which a clear picture of ocean conditions, in the past, present and future, can be seen.

As is the case with the atmosphere, ocean prediction spans multiple time scales, from hours to days up to monthly and seasonal predictions.

The advances in ocean observations and prediction systems over the last 20 years have made operational oceanography infrastructure critical to a wide range of marine activities. Predictions –ranging in timescales from the immediate, to support safety and for tactical decisions, through to seasonal and longer timeframes, to inform planning and resilience activities – all require operational oceanography.

Differences in ocean and atmosphere

Air and water have extremely different properties that are exemplified by comparing the atmosphere and the ocean. The weight of the top 10 m of the ocean is equivalent to the weight of the entire atmosphere above it. The heat capacity of the top 2.5 m of the ocean is equivalent to that of the entire atmosphere above it. Additionally, the top 2.5 cm of the ocean contains the same amount of water as the entire atmosphere above it. While both atmosphere and ocean are governed by the same equations of motion, their circulation characteristics, scales of motion and properties are markedly different. The interaction between these two domains is also one of the fundamental processes driving weather and climate on Earth.

From a WMO perspective, ocean and atmospheric prediction are intrinsically linked through physical processes that are increasingly taken into consideration by modellers in both domains. At time scales of less than a few days, the interaction between the ocean and atmosphere has a big influence on weather in certain locations, such as near coasts that experience ocean upwelling, particularly when upwelling is linked to sudden changes in ice cover. At time scales beyond a few days, the ocean-atmosphere interaction contributes to weather forecasts over all locations and its importance increases with greater lead times. At seasonal and climate prediction scales, the coupling of ocean and atmosphere in the prediction systems is crucial.

Weather forecasting, such as for tropical cyclone formation and intensity, and longer-term predictions, such as for seasonal precipitation, are reliant on temperature and current observations in the ocean (Weller *et al* 2019).

Status of Ocean Prediction

To understand the status of ocean prediction, one must first get an overview of the current state of ocean prediction systems and the international network that unites them to get an outlook on future improvement of the science behind ocean prediction, the prediction system capacity and the potential for further integration of ocean systems into seamless Earth System models. The maturing of oceanographic observations, forecast systems and research, the core ocean forecasting disciplines of data assimilation, ocean modelling, forecast verification and observing system evaluation is now enabling new research and operational areas to flourish.

A key to any prediction system is the real-time availability of observations from surface and from space-based platforms. The important differences between the atmosphere and the ocean become very apparent here. From a remote sensing satellite perspective, the ocean is less transparent and therefore less measurable at depth than the atmosphere. Satellite-based information, therefore, is in large part only available for the very surface of the ocean. However, satellite-based altimeters that measure sea surface height are an oceanographic remote sensing strength. Ocean height is representative of the depth integrated processes between ocean surface and bottom, and satellite altimetry enables the definition of large-scale ocean eddies in real time in the prediction systems. Additionally, altimetry enables tracking of long-term changes in ocean depth, such as sea level rise.

The Tropical Pacific Observing System (TPOS), which measures long-term changes in ocean-atmosphere heat exchange, was designed in the 1980s to improve the scientific understanding of the El Niño–Southern Oscillation (ENSO) phenomenon in order to better predict ENSO events. It has since provided vital data contributing to improved ENSO forecasts for decisions about agriculture, for example (Hansen *et al*., 1998; Chiodi and Harrison, 2017). Ocean observing systems have been developed for the Atlantic (PIRATA) and Indian Ocean (RAMA) following the TPOS model. TPOS is also adapting to meet the observational, experimental and operational needs of today and the future.

Data Assimilation – Data assimilation schemes vary among ocean forecasting groups. The primary objective is to minimize the misfit of model results with the observations while respecting the rules of physics. Observations assimilated in ocean forecast systems now include altimetry, ocean colour, surface velocities, sea ice and data from emerging platforms such as ocean gliders. Many systems now employ multi-model approaches or ensemble modelling techniques. A key upcoming change in data assimilation will be the arrival of the Surface Water and Ocean Topography (SWOT) altimeter, which will provide a true two-dimensional picture of the ocean surface topography with roughly 2 km resolution, rather than along satellite track measurements, where the tracks are interspaced by 200 km and separated over time.

Short term prediction – Short term ocean predictions encompass timescales from the next few hours to ten days or more and are often referred to as forecasts. There has been significant progress in ocean forecasting in recent years (Bell *et al*. 2015, Davidson *et al* 2019). Improvements of forecasting systems have included increased resolution (horizontal and vertical), inclusion of tides, sea ice drift and thickness, ecosystem approaches, improvement to mixing biases and extending regional mode areas [e.g., polar regions and progress of coupled modeling (wave coupling, sea ice, hurricane models, etc.)].

Short-to-medium-term coupled ice–ocean–wave–atmosphere prediction is being used to improve weather forecasts on the timescale of three days to two weeks. This will enable safer at-sea and coastal operations through improved prediction of extreme weather and climate events such as tropical cyclones. Increased activities in the high latitudes are also driving the further development of operational ice and ocean prediction.

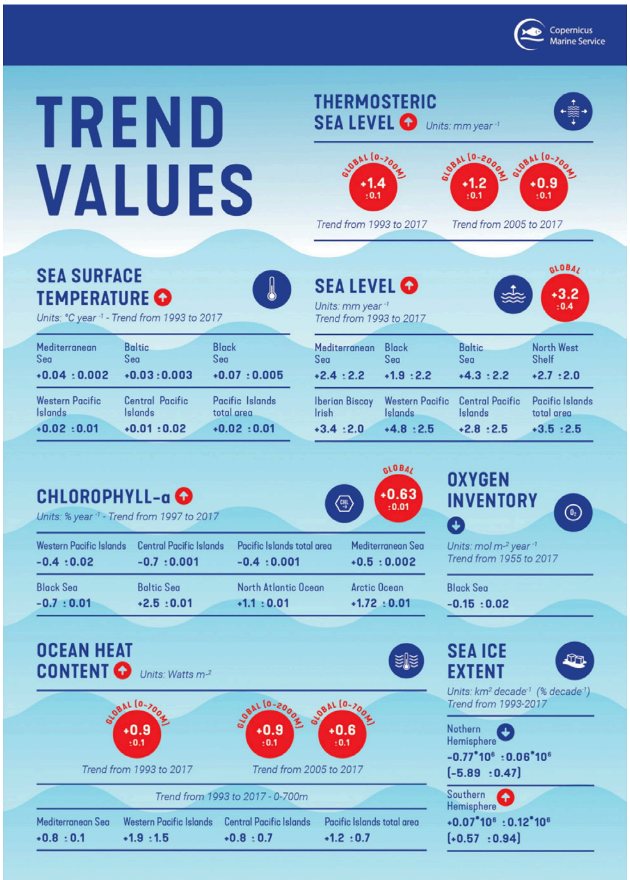
Sub-seasonal to Seasonal prediction – Unlike large-scale atmospheric events which evolve on daily time scales, large scale ocean events typically evolve on weekly to monthly time scales and include marine heat waves and variations in sea level that can cause fair-weather flooding and exacerbate the flood risks of tropical and extratropical storms.

Sub-seasonal to seasonal prediction, with a forecast range longer than two weeks but less than a season, is now routinely performed using coupled ocean-atmosphere models. At lead times longer than two weeks, coupling of the atmosphere to the ocean contributes, for example, to predictability of monsoon variations and the Madden Julian Oscillation (e.g., Woolnough *et al.*, 2007). In addition, satellite observations suggest that midlatitude ocean mesoscale eddy–induced sea surface temperatures can influence the atmospheric planetary boundary layer, which may drive predictability of winter storm-tracks on sub-seasonal to seasonal timescales (Saravanan and Chang, 2019).

Sub-seasonal prediction of regional variations in sea surface temperature and near-surface currents is also of direct interest for a wide range of activities and enterprises including management of fisheries, offshore mining activities and ocean transportation.

Coastal Prediction – Along coasts, decision-makers looking after increasingly populated and urbanized coastal areas are benefiting from coastal operational oceanography. This is because operational oceanography is increasingly able to provide accurate information on phenomena such as coastal river plumes from sediments and nutrients, predicting the occurrence and evolution of harmful algae blooms, and coastal erosion.

Sea ice – Sea ice is also considered to be part of the coupled ocean system. Due to its insulating and reflective properties, sea ice regulates exchanges between the atmosphere and ocean. At the sub-seasonal to seasonal timescale, prediction systems increasingly account for sea ice, either to improve the forecasts themselves, or to provide dedicated sea-ice forecasts. Sub-seasonal prediction of sea ice has wide potential applications as well (for example ship routing) but these have not yet been fully harnessed (Chevallier *et al*. 2019).



An example of a one-page state of the ocean summary from ocean reanalysis systems of the European Union's Copernicus Marine Service (source: Annual Ocean State Report (von Schuckmann et al 2019)

Climate reanalyses and ocean reporting – In parallel with efforts by the climate community to generate "reanalyses" of past conditions, the state of the ocean analysis aims to recreate ocean conditions over the last 30 years at global and regional scales. Three-dimensional analyses of the past and present ocean state at global-to-coastal scales are being developed based on the same modelling and

Prediction

assimilation infrastructure used for ocean forecasting. This follows the approach of atmospheric reanalyses using available historical observations to generate physically-consistent data cubes. The annual Ocean State Report (von Schuckmann *et al* 2019) of the European Union's Copernicus Marine Service is a premier example of careful analysis of a year's worth of analysis data against a historical context. A summary graph provides large scale trends of the main ocean variables in various regions of the globe.

Communication and verification –The communication and dissemination of information to downstream users has improved. Nowadays, the dissemination of outputs from forecasting systems is akin to the approaches taken by WMO in the distribution of numerical weather prediction products. Most ocean forecasting systems are also now investing in verification, monitoring and validation efforts to be able to show the value of their products to their users.

Strengthening ocean predictions through partnerships

The United Nations Decade of Ocean Science for Sustainable Development provides an opportunity to further galvanize operational oceanography. The Decade brings momentum for international and national ocean communities to come together to extend the network and science essential for the generation of comprehensive ocean information. A key goal of the Decade is a predicted ocean where society has the capacity to understand current and future ocean conditions.

WMO and Intergovernmental Oceanographic Commission (IOC) of UNESCO have long recognized the value and need for ocean forecasting services and have worked together towards enablement and understanding of the full value chain on ocean prediction. In recent years, the Global Ocean Observing System (GOOS)[8] has emphasized this focus on ocean prediction to deliver relevant services for societal benefit. The international ocean forecasting community is collaborating across OceanPredict, GOOS, WMO, IOC, the Committee on Earth Observation Satellites (CEOS), and the Blue Planet initiative of the intergovernmental Group on Earth Observations (GEO). These partnerships reinforce the sharing of ideas and bring together the oceanographic and atmospheric science and modelling communities. Partnerships within national settings are also advancing ocean predictions for societal benefit. Examples from the Australian, Canadian and U.S. governments show the success of collaboration between meteorological and oceanographic institutions.

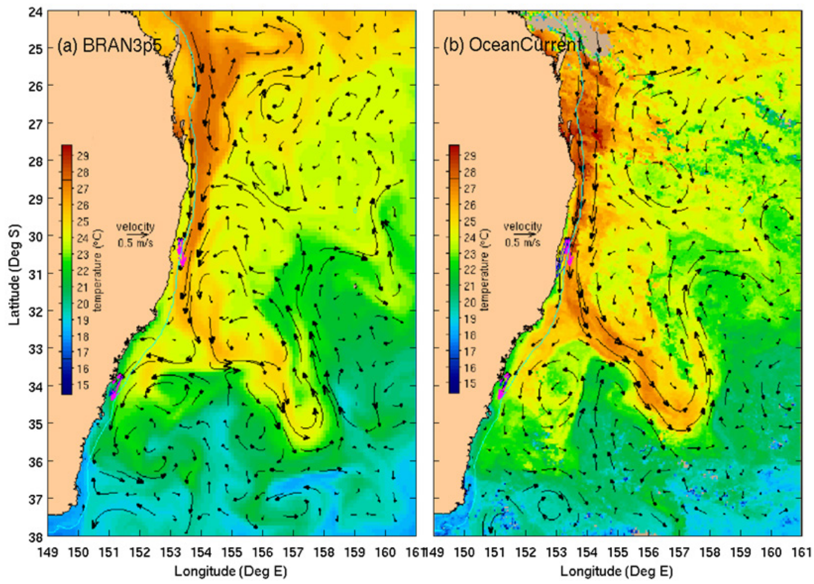
Bluelink Ocean Forecasting Australia

Bluelink is a partnership between the Australian Bureau of Meteorology (BOM), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Department of Defence with collaborating partners that include the Integrated Marine Observing System, the Defence Science and Technology Group, National Computational Infrastructure, and the university sector.

The operational Bluelink ocean forecast system is used to transform physical oceanographic observations into coherent analyses and predictions. These analyses and predictions form the basis for information services about the marine environment and its ecosystem and can provide boundary data for weather predictions. Bluelink information services are available to marine industries – commercial fishing, aquaculture, shipping, oil and gas, renewable energy – government agencies – search and rescue, defence, coastal management, environmental protection – and other stakeholders – recreation, water sports, artisanal and sport fishing – who depend on timely and accurate information about the marine environment.

At its core, Bluelink consists of three inter-connected component systems at global, regional and near-shore (littoral zone) scales. The key scientific objective is to deliver reliable, operational ocean forecasts and reanalyses of the ocean mesoscale (global system), sub-mesoscale (regional system) and nearshore circulation (littoral zone system) at timescales from days to weeks. Beyond the traditional short-term forecasting of physical ocean properties (temperature, salinity, surface height, currents,

8 Co-sponsored by IOC, WMO, United Nations Environment Programme (UNEP) and International Science Council (ISC)



Typical example of (a) Bluelink reanalysis fields and (b) observed fields for the Tasman Sea. Colour shows SST, arrows show surface velocity. (This comparison is adapted from: www.marine.csiro.au/ofam1/bran1/br3p5_EAC_tv12/20120111.html.)

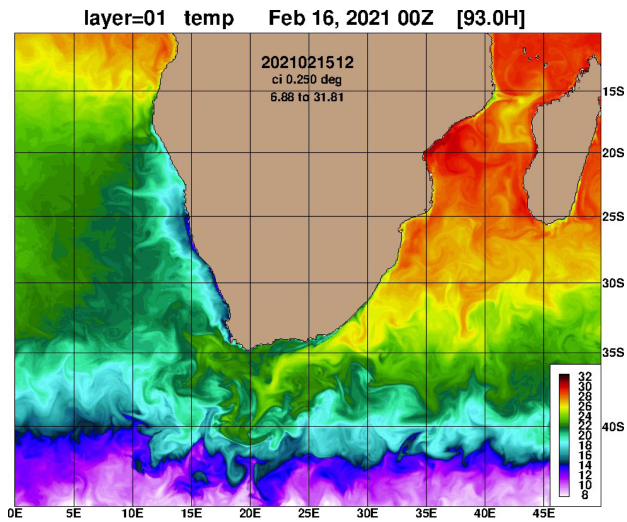
waves), marine activities such as water quality and habitat management as well as climate monitoring increasingly rely on operational oceanographic data and products.

US Partnership in Ocean Modelling for an Earth System

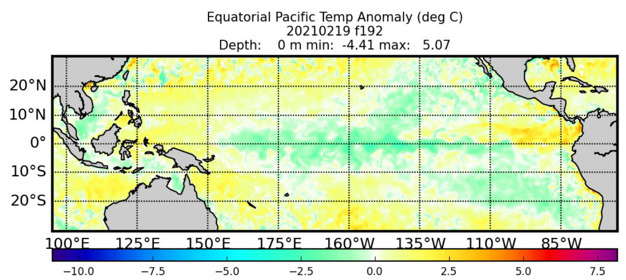
Within the U.S., the National Oceanic and Atmospheric Administration (NOAA) and the Department of the Navy have partnered for well over a decade to develop and implement operational ocean predictions. The output of these models provides the basis for a variety of met-ocean forecasting services to support safe maritime operations, including tropical cyclone predictions, search and rescue, response to marine environmental emergencies, such as oil spills, and operations near the marginal sea-ice zone.

The U.S. Navy began running global ocean circulation models in 1999 (Rhodes *et al*. 2002). The present version of the Navy Global Ocean Forecast System (GOFS), operational in 2020, couples the Hybrid Coordinate Ocean Model with the Community Ice Code Sea Ice (CICE) model. In 2021, the Navy will operate a 1/25 degree GOFS with CICE and tides.

NOAA implemented its global Real-Time Ocean Forecasting System (RTOFS) in 2011. Initially based on the U.S. Navy's development of GOFS, NOAA also incorporated the Navy Coastal Ocean Data Assimilation System (NCODA) into RTOFS. RTOFS Version 2.0, implemented in December 2020, incorporated an upgraded NOAA Ocean Data Assimilation (DA) system, RTOFS-DA.



GOFS forecast sea surface temperature, Day 7-1/2 (Source: U.S. Naval Research Laboratory)



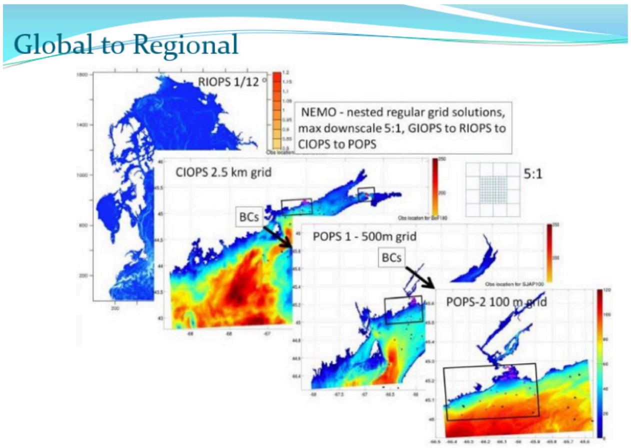
Global RTOFS forecast sea surface temperature anomaly, Day 8 (Source: NOAA)

In 2017, as part of the Hurricane Forecast Improvement Project, NOAA implemented a new regional scale coupled ocean-weather model. The Hurricanes in a Multi-scale Ocean coupled Non-hydrostatic (HMON) model provides forecasters with intensity and track guidance from 0 to 5 days to support the official warning and forecast products from the National Hurricane Center/ Regional Specialized Meteorological Centre (RSMC) Miami. Like HMON, the operational Hurricane Weather Research and Forecast model also uses coupled ocean states prescribed using initial and boundary conditions from RTOFS.

Efforts such as these, representing just a subset of the U.S. operational ocean modelling efforts, are shaping the development of fully-coupled Earth system prediction capability. As part of a national effort codified in legislation as the Weather Research and Forecasting Innovation Act of 2017, NOAA is collaborating across the nation's weather enterprise – government agencies, academia and the private sector – to improve its numerical weather prediction. NOAA will accomplish this through an Earth Prediction Innovation Center (EPIC), engaging the enterprise to accelerate scientific research and modelling contributions into the Unified Forecast System (UFS). As a community-based Earth system data assimilation and prediction system, the UFS will, over the next five years, lead to full Earth systems coupling – ocean, atmosphere, land, sea ice and the biosphere – for weather and climate applications. EPIC will facilitate this broad collaboration with a cloud development environment, code repository, observations and tools, and community support and engagement.

Canadian Partnership in Atmosphere-Ocean-Ice Monitoring, Coupled Prediction and Ocean Services

The Canadian Operational Network of Coupled Environmental PredicTion Systems (CONCEPTS) is a collaboration between three Federal Departments: Fisheries and Oceans Canada (DFO), Environment and Climate Change Canada (E3C) and the Department of National Defence (DND). The network works to develop and implement computer models that support ocean-ice forecasting advancements. The aim is to take advantage of breakthroughs in ocean modeling and new real-time global oceanographic observation systems to produce oceanographic forecast products and improve seasonal to inter-annual climate forecasts. This core network is leveraging multiple collaborations with academic institutions, the private sector and institutions abroad such as Mercator Ocean International.



An example of the prediction systems cascading approach used to generate products and services at high spatial and temporal resolution, for the Bay of Fundy, Canada. (Paquin et al 2019)

In order to facilitate collaboration across government departments and with external CONCEPTS partners, a three thrust strategy was implemented in 2009:

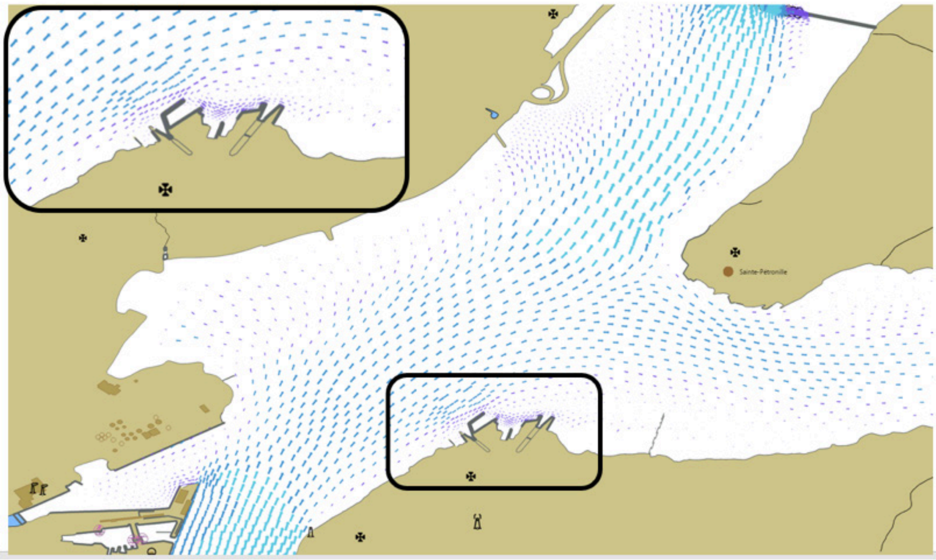
1. the collection and dissemination of measurements of physical properties of marine environments for assimilation in models to improve forecasts from environmental (weather, ice, wave and ocean) prediction systems in Canada

2. the development of coupled environmental prediction systems to improve analyses and forecasts from environmental (weather, ice, wave and ocean) prediction systems in Canada

3. the availability of CONCEPTS products and services for end users including:

   (a) providing feedback to monitoring and prediction systems for continuous improvements

   (b) enabling collaboration within and outside of CONCEPTS through the development and



An example of product for E-Navigation application generated by a high resolution estuarian river 2D prediction system run by the Canadian Meteorology and Environmental Prediction Center H2D2 (Matte et al 2017)

provision of discovery, visualization and accessibility systems of observation and model output.

The current suite of coupled atmosphere-ocean-ice prediction systems comprise:

1. Global Ice Ocean Prediction System (GIOPS) running at ¼ degree resolution[9]

2. Regional Ice Ocean Prediction System (RIOPS) running at 1/12 degree resolution over the North Pacific, the Arctic and the North Atlantic[10] [11]

3. Coastal Ice Ocean Prediction System (CIOPS) running at 1/36 degree over the Northwest Atlantic and the Northeast Pacific[12]

4. Great Lakes Water Cycle Prediction System (atmosphere, ocean, ice, hydrology) running at 2 km horizontal resolution

5. Hydrodynamic modelling over the St. Lawrence River from Montréal to Québec city

The cascading approach being used opens the door to products and services at multiple spatial and temporal scales. Planning work is currently underway to couple those with biogeochemical modeling systems. The overarching System of Systems feeds the information required to enable electronic navigation approaches.

S2S Project

To bridge the gap between medium-range weather forecasts and seasonal forecasts, the WMO World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP)[13] launched the Sub-seasonal to Seasonal prediction project (S2S). The main goal of the project is to improve forecast skill and understanding of the sub-seasonal to seasonal timescale, and to promote the uptake of S2S predictions by operational centres and exploitation by the applications communities (www.s2sprediction.net). The first phase of the S2S ran from 2013 to 2017 and the second phase started in 2018 and will end in 2023. One research focus of Phase 2 is the sub-seasonal to seasonal predictability and prediction of ocean and sea-ice. S2S works in coordination with the Working

9 G. Smith et al., QJRMS, Volume142, Issue695, January 2016 Part B, Pages 659-671

10 JF Lemieux et al., 2016, QJRMS, Volume142, Issue695, January 2016 Part B, Pages 632-643

11 Smith, G.C., Liu,Y., Benkiram, M., Chikhar, K., Surcel Colan, D.,Testut, C.E., Dupont, F., Lei, J., Roy, F., Lemieux, J.F., and Davidson, F., 2020. The Regional Ice Ocean Prediction System v2: a pan Canadian ocean analysis system. Geoscientific Model development Discussions, pp1-49.

12 Paper in preparation

13 Co-sponsored by WMO, IOC and ISC

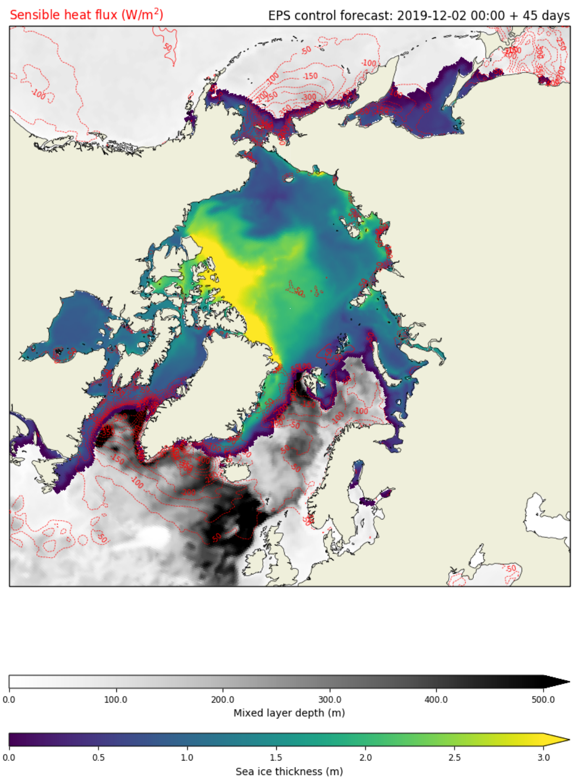
Groups on Subseasonal to Interdecadal Prediction (WGSIP), on Data Assimilation and Observation Systems (DAOS), and on Predictability, Dynamics, Ensemble Forecasting (PDEF) to promote improved sub-seasonal predictions though better initialization of the ocean/sea-ice state and depiction of key ocean and sea-ice processes that provide predictability at sub-seasonal timescales.

A major achievement of the first phase of S2S was the establishment in 2015 of the S2S database containing near real-time sub-seasonal forecasts (up to 60 days) and re-forecasts (sometimes known as hindcasts) from 11 operational centres. Most of the S2S models are coupled ocean/sea-ice/atmosphere models, and the list of parameters available from the S2S database has always included sea-surface temperature and sea-ice cover.

Since January 2020, nine new ocean and sea-ice parameters have been added to the S2S database, consisting of 20° C isotherm depth, mixed-layer thickness, salinity and potential temperature in the top 300 m, surface currents, salinity, sea-surface height and sea-ice thickness. The availability of this extensive set of ocean and sea-ice variables substantially increases the power of the database for S2S coupled system research and to address key science questions. Currently, the new variables are available from four models – European Centre for Medium-Range Weather Forecasts (ECMWF), E3C, Chinese Meteorological Administration (CMA) and Météo-France – three weeks behind real-time forecasts (from January 2020) and the corresponding re-forecasts, which are produced in near real-time. In the coming year, the new variables will become available from an expanded set of S2S models.

As an example of what is already being done, Zampieri *et al*. (2018) evaluated the forecast skill of several models from the S2S database and found that some of them displayed significant skill in predicting sea-ice cover up to a month in advance. This important result suggests that state-of-the-art sub-seasonal to seasonal forecasts could be potentially useful for applications such as ship routing in Arctic regions. The availability of the new ocean variables should trigger new research studies on the predictability of high-impact ocean weather, such as heatwaves, which will provide insights on the possible use of these sub-seasonal forecasts for applications such as fishery. The image below provides an example of a possible use for this ocean data in ocean weather maps. In this example, sea-level anomalies relative to the climate are issued for a forecast lead time of 3 to 4 weeks.

The addition of the new parameters will also make the S2S database more apt to lead to a better understanding of air-ice-ocean interactions at the sea-ice margin, as illustrated in below. It will also help diagnose the evolution of ocean drift with forecast lead time in the S2S forecasts.



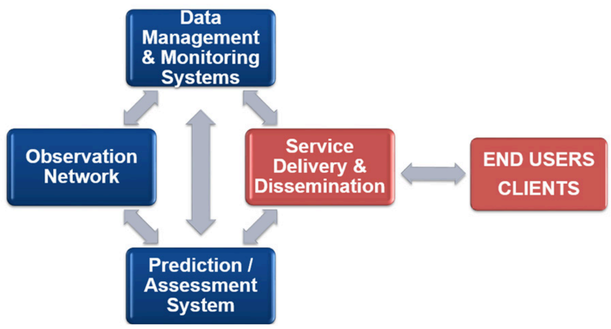
Sea-ice thickness, mixed layer depth, and sensible heat fluxes over the ocean from the ECMWF extended-range control forecast starting on 2 December 2019 and verified on 16 January 2020 (45-day lead time).

In order to coordinate these activities, S2S Phase 2 includes an ocean subproject, which will develop a protocol for coordinated case studies that can be conducted by centres doing S2S prediction of specific ocean extreme events and air-sea interactions, for example the onset of ENSO. Examples could include a predictability study of a prominent coral bleaching event in 2017, and the intra-seasonal air-sea interaction at the onset of the 2015/2016 El Niño event.

Organization of international ocean prediction

Recent literature[14,15] has documented the strength of the value cycle approach (Day, 1999) in the research to operations to services technology transfer. In particular, Ruti *et al*. (2020) provide a description of this cycle in the current meteorological context and as a key component to enable the Earth Systems approach. This value chain links the production and delivery of these services to user decisions and to the outcomes and values resulting from those decisions. User feedback is then fed back to Research and Operations in order to further improve services. Similar thinking is taking place in other disciplines.

The image below (adapted from Schiller *et al* 2019) depicts the marine value chain. There are two key international initiatives which support ocean predictions: OceanPredict and GOOS. For over two decades, OceanPredict and its predecessors have been focused on research and operational implementation of ocean forecasting systems. GOOS has provided ocean observations for initializing and validating ocean predictions, driven by the collaboration between the WMO and IOC.



14 WMO, 2015: Valuing weather and climate: Economic assessment of meteorological and hydrological services. WMO-1153, 308 pp.

15 Ruti et al., Advancing Research for Seamless Earth System Prediction, Bull. Amer. Met. Soc. 2020, DOI: https://doi.org/10.1175/BAMS-D-17-0302.1

OceanPredict

In the late 1990s, the international Global Ocean Data Assimilation Experiment (GODAE) was launched to (i) demonstrate the feasibility and utility of ocean monitoring and forecasting on the daily-to-weekly timescale and (ii) contribute to building a global operational oceanography infrastructure (Smith and Lefebvre, 1997; Schiller *et al*., 2018). Building on its success, GODAE OceanView was established in 2009 (Bell *et al*., 2009) to define, monitor and promote actions aimed at coordinating and integrating research associated with multi-scale and multi-disciplinary ocean analysis and forecasting systems.

In 2019, GODAE OceanView became OceanPredict which continues to expand its activities with an added emphasis on ocean prediction as part of the broader network of international initiatives linked to operational oceanography. OceanPredict is thus developing close partnerships with international entities including the WMO, the IOC, GOOS and GEO Blue Planet.

OceanPredict is supported by 14 countries. However scientific and technical participants from any country are welcome in OceanPredict and its task teams. Participants from 41 countries attended the OceanPredict19 symposium (Vinaychandran *et al* 2020), including scientists from operational prediction centres, government agencies, academia and private consortiums/companies.

Most OceanPredict groups are integrally linked to or are a part of numerical weather and environmental prediction centres such as NOAA, E3C, MétéoFrance and the Japan Meteorological Agency to name a few. In fact, seven of the nine WMO World Meteorological Centres (WMC's) are members of OceanPredict. Additionally, all of the prediction centres have academic collaborators that support some of their research. OceanPredict coordinates research and development activities in ocean data assimilation, ocean system evaluation, marine ecosystem prediction, coastal ocean prediction, atmosphere ocean coupled prediction systems, and intercomparisons and validations of ocean prediction systems.

Collaboration on these themes includes academic researchers, researchers from operational prediction agencies, and development teams that support development, operations and dissemination at prediction agencies. Through international workshops, under the leadership of a dedicated Science Team, OceanPredict brings the various communities together to advance the science and applications of ocean prediction. Leading experts from the WMO community are keynote speakers, and some workshops are joint events with WMO partners such as ECMWF. The OceanPredict Science Team has three core objectives:

- assessments of forecast system and component performance combined with component improvements
- initiatives aiming to exploit the forecasting systems for greater societal benefit
- evaluations of the dependence of the forecasting systems and societal benefits on the components of the observation system.

Outlook

As ocean forecast models progress, it will become increasingly important to define and project what type of events will be predictable by ocean prediction systems and by coupled atmosphere ocean prediction systems with useful accuracy and confidence intervals.

An aspect to keep in mind is the ability of systems and users to consume prediction products. A good example of this is E-navigation to support maritime safety, where new file standards and methodologies will enable ship bridge-embedded or hand-held navigation systems to fully exploit numerical output from ocean and atmospheric prediction systems in real time. This will enable advanced route planning software, but also enable numerical engineering models (digital twins) of a ship, translating environmental prediction information into ship impact information. It is important to note that for most at-sea activities, the user wants complete and coherent marine environmental information and predictions, which could include variables like wind, waves, ice conditions, atmospheric temperature, atmospheric pressure, water level, water temperature and water salinity.

Links to meteorology and WMO

In moving forward, the link between operational oceanography and operational meteorology needs to strengthen. More specifically, the full value chain in operational oceanography will require both international and national frameworks to deliver overall end user value. There is already significant interaction with oceanography groups in the WMO community, such as evidenced by the emerging use of the WMO Information System (WIS) for ocean observations. In moving forward, while most weather prediction centres include ocean prediction in their activities, it will be important to strengthen the ocean-weather relationship from observations through to prediction and end use.

Leveraging WMO Systems in the future of Ocean Prediction

The WMO has well-developed frameworks covering the full value chain for meteorological services that evolves to meet demands while enabling new work and information flows across the whole Earth System value chain. Three of these frameworks are discussed in this section with respect to the ocean prediction value chain.

WIGOS

The **WMO Integrated Global Observing System (WIGOS)** provides an overarching framework for integrating the various sources of observations that contribute to WMO application areas. WMO Rolling Review of Requirements (RRR) compares observational user requirements with observing systems capabilities to determine how the design of WIGOS needs to evolve. Together with impact studies for the identification of observational gaps, the RRR is used to prioritize the evolution of the global observing systems and to recommend key actions to WMO Members and other significant programmes to address gaps.

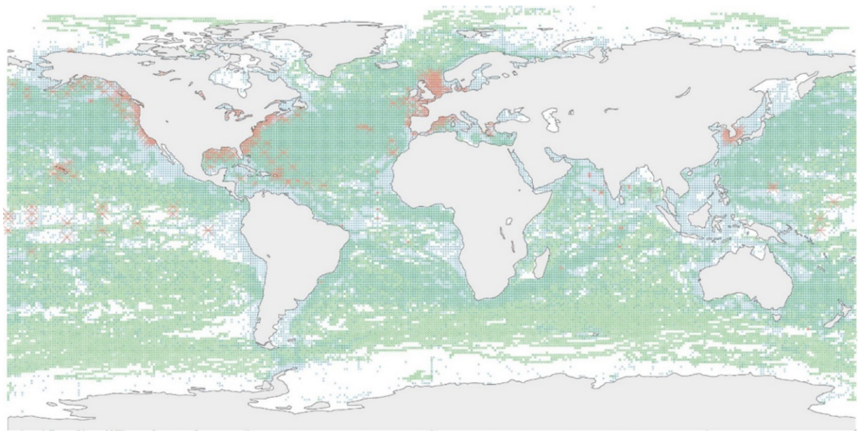


Figure 4: Data coverage by the three major components of the Global Observing System (GOS) (i.e., ships, drifting buoys, and moored buoys) based on information received by Météo-France through the GTS in 2018 (see legend for symbol details). (from Front. Mar. Sci., 30 August 2019 | https://doi.org/10.3389/fmars.2019.00419)

The WIGOS framework provides a systematic approach that can enable ocean prediction groups to implement systematic evaluations of observed impacts against forecasts in order to appraise performance across the whole ocean prediction value chain. In particular, implementation of a Rolling Review Process on the Ocean Forecast side would better connect the full oceanographic value chain, and ensure that investment in ocean observations provide the best value for money with respect to better ocean prediction information services.

WIS

The **WMO Information System (WIS)** join NMHSs and regions together for data exchange, management and processing. At present most ocean observations used in near real-time prediction systems are transmitted via the WMO Global Telecommunications System (GTS) (See figure below for coverage of GTS transmitted observations in 2018).

GTS has also proven to be an effective channel for Tsunami Warnings by delivering messages with a delay that is, in most cases, less than two minutes. WMO is evolving WIS/GTS to use new technologies for data exchange, and WIS 2.0 will provide better means to subscribe to data streams and effective ways to deliver warning messages.

In the future, enabling ocean data on the WIS will have many dividends. WIS provides the global infrastructure for the exchange of data and information between all NMHSs and incorporates the long-established GTS for the delivery of real-time observational data (and increasingly those metadata needed to make best use of the real-time data) needed for their operational requirements. While the GTS remains the standard method of global data exchange between NMHSs and fulfills their operational requirements and applications, the academic community and the public have a clear need for a more streamlined and consolidated data management architecture, which should provide access to data and metadata in a common format.

GDPFS

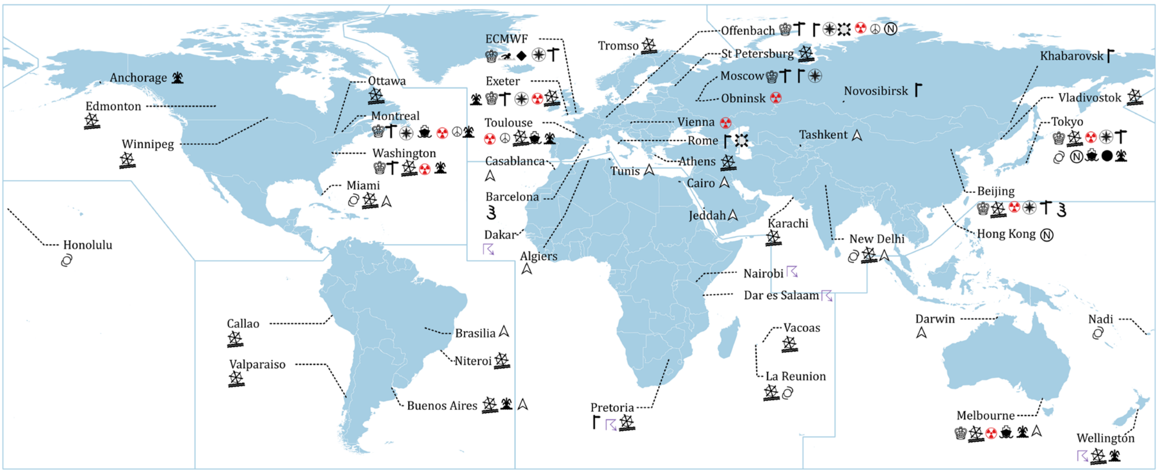
The **WMO Global Data-Processing and Forecasting System (GDPFS)** enables all NMHSs to make use of advances in numerical weather prediction (NWP) by providing a framework for sharing data related to operational meteorology, hydrology, oceanography and climatology. The GDPFS is a cascading process that brings the NWP strength of WMO's global centres (WMCs) down to regional centres (RSMCs) then to NMHSs in a coordinated way. RSMCs enable the delivery of harmonized services, including for marine and ocean matters. More than 40 RSMCs have responsibility to support ocean related services including for marine meteorology, ocean wave prediction, severe weather and tropical cyclones.

As previously mentioned, seven of the nine designated WMCs have ocean prediction systems encompassed

WMO Designated Global Data-processing and Forecasting System Centres

- Nowcasting and Weather Forecasting (upto 30 days)

Updated on 19 August 2019



Legend

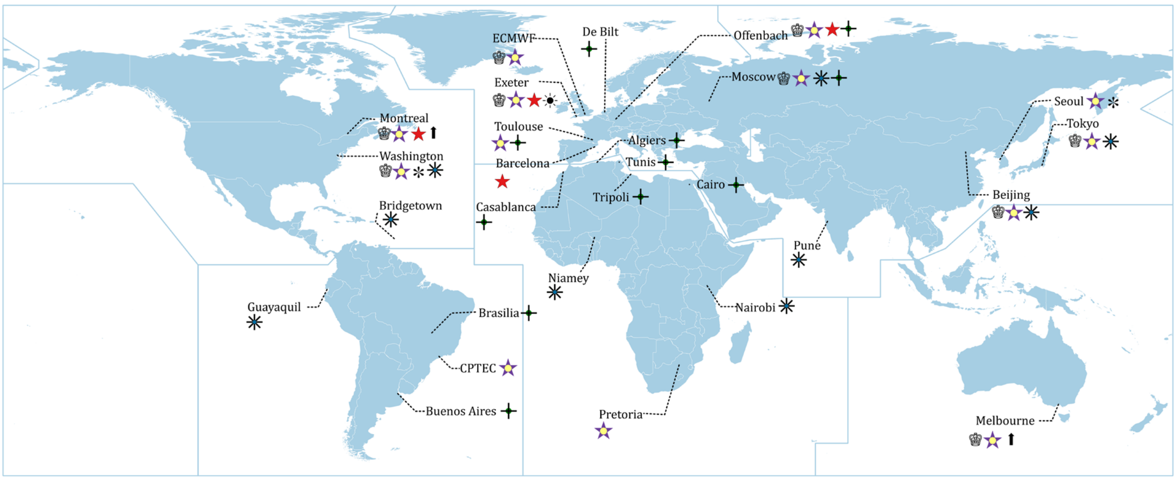
- World Meteorological Centres (WMCs)* (9)
- RSMCs Geographic Specialization (12)
- RSMCs(NRT***) Lead Centre for Coordination of Wave Forecast (1)
- RSMCs(NRT***) Lead Centre for Coordination of EPS Verification (1)
- RSMCs(NRT***) Lead Centre for Coordination of DNV (1)
- RSMCs Numerical Ocean Wave Prediction (4)
- RSMCs Tropical Cyclone Forecasting (6)
- RSMCs Severe Weather Forecasting (5)
- RSMCs Marine Meteorological Services (24)
- RSMCs Nuclear Emergency Response** (10)
- RSMCs Non-Nuclear Emergency Response** (3)
- RSMCs Sand and Duststorm Forecasts (2)
- RSMCs Nowcasting (3)
- RSMCs Limited Area Ensemble NWP (2)
- RSMCs Global Ensemble NWP (7)
- RSMCs Limited Area Deterministic NWP (6)
- RSMCs Global Deterministic NWP (8)
- ICAO designated Volcanic Ash Advisory Centres (9)

* World Meteorological Centres are also Global Producing Centres for a) Deterministic Numerical Weather Prediction, b) Ensemble Numerical Weather Prediction, and c) Long-Range Forecasts.
** RSMC for nuclear and non-nuclear emergency response have Atmospheric Transport and Dispersion Modelling (ATDM) capabilities.
*** NRT stands for Non-Real-Time
DESIGNATIONS USED
The depiction and use of boundaries, geographic names and related data shown on maps and included in lists, tables, documents, and databases on this web site are not warranted to be error free nor do they necessarily imply official endorsement or acceptance by the WMO.

WMO Designated Global Data-processing and Forecasting System Centres

- Long-range and Climate Forecasting (over 30 days)

Updated on 04 July 2019



Legend

- World Meteorological Centres (WMCs)* (9)
- RSMCs(NRT**) Lead Centre for coordination of ADCP*** (1)
- RSMCs(NRT**) Lead Centre for coordination of LRFMME**** (2)
- RSMCs(NRT**) Lead Centre for coordination of LRF verification (2)
- RCC - Networks Regional Climate Prediction and Monitoring NODEs (11)
- RCCs Regional Climate Prediction and Monitoring (9)
- GPC for ADCP*** (4)
- GPC for Long-Range Forecasting (13)

* World Meteorological Centres are also Global Producing Centres for a) Deterministic Numerical Weather Prediction, b) Ensemble Numerical Weather Prediction, and c) Long-Range Forecasts.
**NRT stands for Non-Real-Time
***ADCP stands for Annual to Decadal Climate Prediction
****LRFMME stands for Long-Range Forecast Multi-Model Ensemble

DESIGNATIONS USED
The depiction and use of boundaries, geographic names and related data shown on maps and included in lists, tables, documents, and databases on this web site are not warranted to be error free nor do they necessarily imply official endorsement or acceptance by the WMO.

The GDPFS centres responsible for weather forecasting up to 30 days (upper) and for long-range and climate forecasting (lower).

in the OceanPredict initiative that run in coupled or uncoupled prediction modes as part of their day-to-day operations. Encompassing ocean prediction systems within such a framework has many advantages, including integration of scientific advances in ocean predictions and applying new observation systems (ie. SWOT) into operational ocean/environmental prediction systems.

Such weather/ocean collaboration is already underway, as evidenced by an upcoming ECMWF and OceanPredict meeting on data assimilation in May 2021. This collaboration needs to flourish. It is anticipated that, under the UN Decade of Ocean Science for Sustainable Development, a framework can be put in place for the full operational oceanographic value chain, akin to that of the GDPFS. By the end of the Decade, a fully integrated value chain for Marine Environmental Prediction (Operational Oceanography and Meteorology) is envisaged, however, an open question remains: how should its ocean component be built? The options are to build a full ocean value chain framework first or to build ocean components into the existing elements of the meteorological value chain put together by the WMO.

In moving forward, the link between operational oceanography and operational meteorology needs to strengthen. More specifically, the full value chain in operational oceanography will require both international and national frameworks to deliver overall end user value. There is already significant interaction with oceanography groups in the WMO, such as evidenced by the use of GTS for ocean observations. In moving forward, while most weather prediction centres include ocean prediction in their activities, it will be important to strengthen the ocean weather relationship from observations through to prediction and end use products and services.

Partnerships for the future

The vision of the WMO, as stated in the WMO Strategic Operational Plan 2020-2023, is "to see a world where all nations, especially the most vulnerable, are more resilient to the socioeconomic consequences of extreme weather, climate, water and other environmental events and underpin their sustainable development through the best possible services, whether over land, at sea or in the air." To achieve this, WMO is embracing an Earth System approach that will enable access to and use of numerical analysis and Earth System prediction products at all temporal and spatial scales from the WMO Seamless GDPFS.

In order to continuously improve products and services, all the key components of the Earth System need to be integrated into seamless data assimilation and prediction systems, leveraging WIGOS, WIS 2.0 and the WMO Seamless GDPFS. Within the WMO community the WMO Reform has provided the framework to achieve the integration of disciplines required to achieve this goal. It also provides mechanisms to better partner with key relevant national and international organizations, academic institutions and the private sector. One single entity cannot achieve this by itself, and resource pressures are such that replication of existing infrastructure will not be possible. In addition, the required high-performance computing, storage and telecommunication will likely exceed what individual Nations can afford.

Public, academic and private partnerships are therefore essential. Leveraging existing global, regional and national infrastructure will allow all communities to benefit from the information available to feed their decision-making systems. WMO and its partners firmly believe that together we will achieve the grand challenges facing humanity today – as underlined in the United Nations Sustainable Development Goals – and we will be better prepared to find solutions for those to come in the future.

References available online

Products and services for a changing ocean

By Thomas J. Cuff[1], Val Swail[2], Sarah Grimes[3], Christine Bassett[4], Johan Stander[3], Ian Lisk[5], Cyrille Honore[3], Wilfran Moufouma Okia[3], Patrick Parrish[3] and Zhichao Wang[3]

Coastal communities regularly make make life-saving decisions in the face of extreme weather, coastal inundation and rising sea levels. Scientists predict that all of these threats will increase due to climate change. Mariners rely on forecasts and warnings of impending high waves, high winds and sea ice, and they use information on surface currents and winds to increase the efficiency of ocean transit – thereby helping to reduce pollution and greenhouse gas emissions. Coastal communities require meteorological and oceanographic (met-ocean) information to plan for and respond to marine emergencies. It is, therefore, evident that short-term weather forecasts, environmental met-ocean products and services, and seasonal, sub-seasonal and long-term climate predictions are essential for national, environmental and economic security and for the safety of life and property at sea and in coastal communities. WMO and National Meteorological and Hydrological Services (NMHSs) have worked together to develop the capabilities, technologies and capacity to deliver tailored services in each of these areas and for all of these stakeholders.

Maritime interests worldwide depend on timely, accurate and relevant oceanographic and marine meteorological analyses, forecasts and services, tailored to the needs of individual and community decision-making. Such services require a globally-connected and distributed effort, with strong collaboration between the oceanographic, marine meteorological and Earth science communities. Satellite applications, output from ocean and numerical weather and climate prediction models, forecasting systems and expert knowledge and experience – down to the local level – are essentials in the marine services value chain. A comprehensive understanding of the needs of users and stakeholders – shipping and other maritime industries, tourism and coastal communities – and how they interface with the range of marine products and services being provided, is also necessary.

To meet the many challenges related to climate change and mitigate the impacts of human activity on the Earth system, the weather, ocean and climate communities must harmonize their efforts. Close cooperation within these communities enables innovation and the quick identification of solutions to the many challenges that coastal communities and marine ecosystems face today.

Coastal Services and Disaster Risk Reduction

Coastal hazards – including weather-related events, such as violent storms, extreme waves, swell, storm surge, increased river discharge, and geophysical related events, such as tsunamis – cause significant human and environmental damage, killing thousands and displacing hundreds of thousands every year. Some one billion people worldwide live on low-lying land that is less than 10 metres (m) above high tide levels, and about a quarter of those live on land below the 1 m level (Kulp and Strauss, 2019). The need for

1 Chair, WMO Standing Committee for Marine Meteorological and Oceanographic Services and Director, Office of Observations, National Weather Service, (US) National Oceanic and Atmospheric Administration (NOAA)
2 Emeritus Associate, Environment and Climate Change Canada
3 WMO Secretariat
4 Knauss Fellow, Office of Observations, NOAA
5 President, WMO Commission for Weather, Climate, Water and Related Environmental Services & Applications, and Head, Hazard Partnerships, The Met Office (UK)

MS Expedition, Errera Channel, Antarctica. As climate change creates more opportunities for tourism in the high latitudes, so does the corresponding threat of a marine environmental emergency (Source: V. Grimes, 16 November 2018).

timely, reliable multi-hazard early warning systems (MHEWS) to enable those people to move to safety as hazards approach cannot be underestimated.

Tropical cyclones are particularly threatening to coastal communities (see *Whirling World – Tropical Cyclones and the Ocean* on page 95). However, it is flooding, rather than wind, that is the primary killer when these extreme events occur. The combination of rapidly rising storm surge and freshwater flooding resulting from the heavy rains can produce severe coastal inundation. Three of the four coastal inundation events with the highest fatalities in the past 50 years have been due to storm surge. Most notable is the estimated 300 000 to 500 000 deaths due to Tropical Cyclone Bhola in Bangladesh in 1970 (Cerveny *et al*, 2017). Though coastal inundation is often associated with tropical cyclones, it may also occur with extratropical storms, including in ice-covered waters that can cause severe damage to coastal infrastructure.

WMO is implementing coastal MHEWS in communities at risk. The WMO Coastal Inundation Forecasting Demonstration Project (CIFDP), established in 2009 (Swail et al. 2019), integrated met-ocean observations, such as sea level, ocean waves, wind, pressure and precipitation with hydrological information such as river stage and discharge. In 2019, the 18th World Meteorological Congress agreed to sustain the effort as the Coastal Inundation Forecasting Initiative (CIFI) and with specific requests from Members to include tsunamis. The CIFI, along with other initiatives such as the WMO Storm Surge Watch Scheme and the Intergovernmental Oceanographic Commission (IOC)

Services in Oceanographic and Meteorological Communities

It is important to note the differing perceptions of a "service" in the meteorological and oceanographic communities. Oceanographers tend to view a "service" as the provision of information and model output data to support a range of user-specific applications and systems, whether these are operationally supported or not. As a result, there is a rapid uptake of new science and innovation in the oceanographic community.

The meteorological community regards a "service" as also including the operationally-supported delivery of a user-defined product or data service. Therefore, meteorological services are more structured, aligned with quality management principles as promoted by WMO for many years.

of UNESCO coordinated global tsunami early warning system will help countries to build greater capacity to provide early warnings for coastal inundation, contributing to an integrated MHEWS in support of national disaster risk reduction and management strategies and activities. WMO has been supporting this in recent years through partnership with the International Network for MHEWS (IN-MHEWS) and joint coordination of the Global MHEWS Conference. (See *Oceanic Science for Services in Small-Island Developing States* on page 101 and *Multi-Hazard Early Warning Systems: The Coastal Inundation Forecasting Initiative* on page 105)

Maritime Safety Services

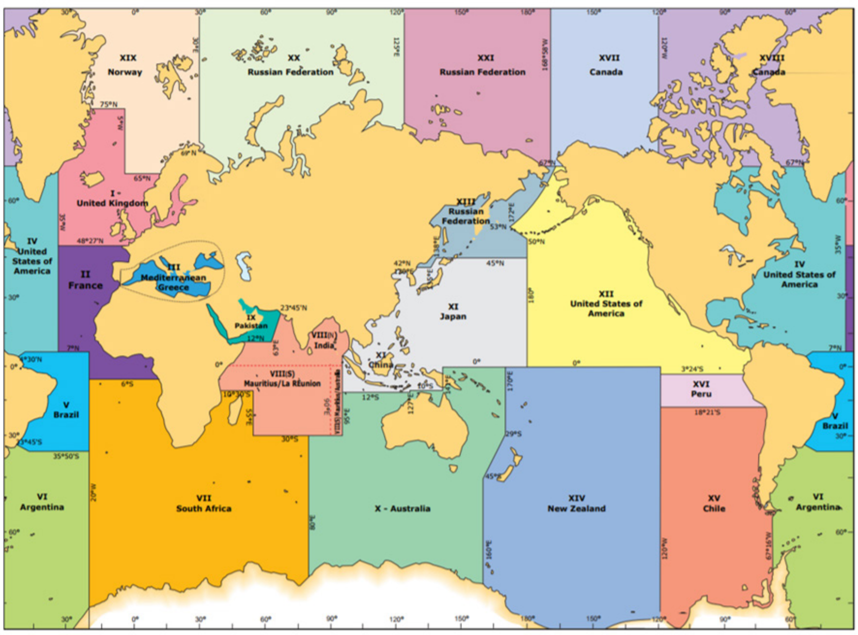
The global economy relies on the safe and efficient movement of goods and passengers between ports and on commercial activities that take place on the open ocean and near coastlines. Traveling safely at sea requires information regarding natural hazards. Maritime safety services refer to activities undertaken to enhance safe ocean transit and the conduct of other activities at sea and near coasts, whether the hazards relate to navigation or to weather.

The International Maritime Organization (IMO) is the agency that maintains the UN International Convention for the Safety of Life at Sea (SOLAS), and through

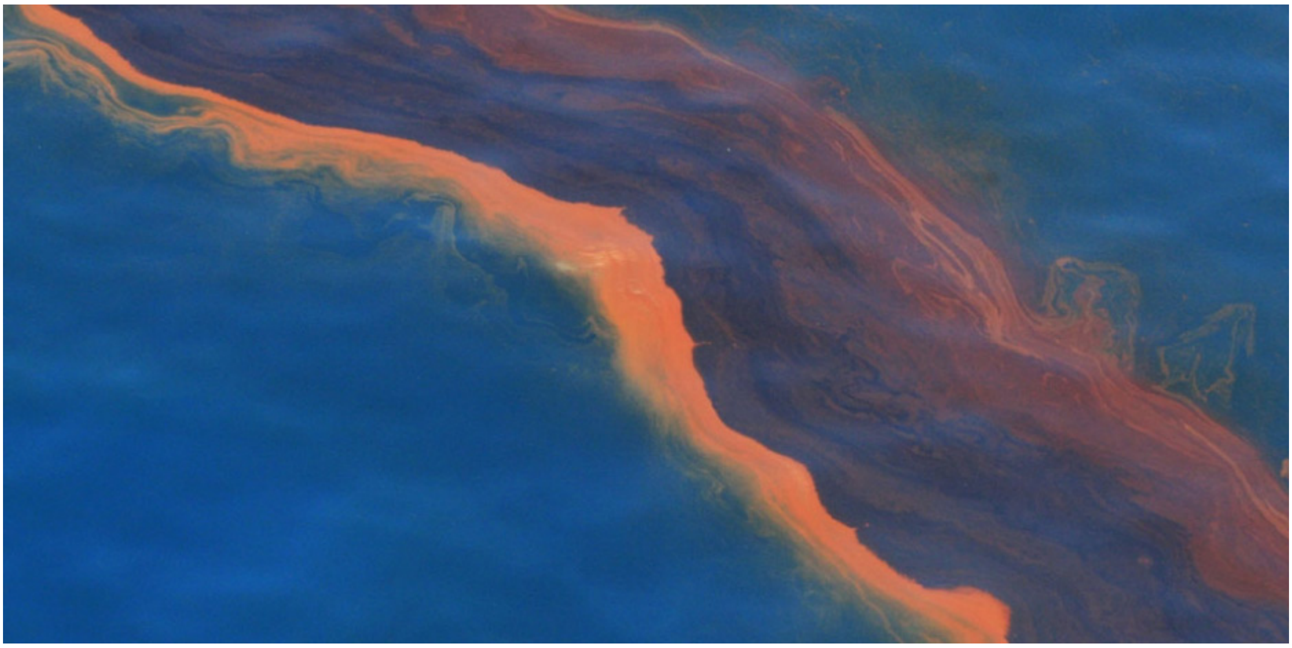
International initiatives supported by marine and ocean services

The marine and ocean services provided by WMO Members contribute, amongst others, to the following international initiatives:

- International Maritime Organization's (IMO) Safety of Life at Sea (SOLAS); Prevention of Pollution from Ships (MARPOL); and International Code for Ships Operating in Polar Waters (Polar Code)
- UN Framework for Climate Change Convention (UNFCCC), including the Paris Climate Change Agreement
- Sendai Framework for Disaster Risk Reduction (DRR)
- Small Island Developing States (SIDS) Accelerated Modalities of Action (SAMOA) Pathway
- UN Sustainable Development Goals (SDGs)
- UN Decade of Ocean Science for Sustainable Development.



METAREA Map (Source: WMO No. 558)



Oil visible on the surface of the Gulf of Mexico near the Deepwater Horizon oil spill on 12 May 2010 (Source: NOAA).

this they are responsible for ensuring minimum safety standards for life and ships at sea. The WMO mandate for SOLAS is to ensure Members provide relevant met-ocean maritime safety information daily for decision-making by seaborne vessels. WMO supports NHMSs in their role as the authoritative agencies for marine meteorological safety information and services.

The WMO also supports the IMO's Global Maritime Distress and Safety System (GMDSS) through the Worldwide Metocean Information and Warning Service (WWMIWS), which coordinates the ocean through 21 defined areas, called METAREAs. NMHSs provide weather-related Maritime Safety Information (MSI) through the WWMIWS in the form of marine warning and forecast products, transmitting them via the WMO Marine Broadcast System. METAREA Coordinators are assigned by their governments to coordinate the provision of MSI for each area. They work closely with their counterpart NAVAREA Coordinators, who provide the navigational MSI through the Worldwide Navigational Warning Service (WWNWS) of the International Hydrographic Organization (IHO). This partnership between WMO, IHO and IMO, as well as the interaction between METAREA and NAVAREA coordinators with their respective national agencies, is crucial to the safety of life and property at sea.

Polar regions

Transiting near sea ice presents unique navigational challenges. The WMO works to coordinate standards, terminology, exchange formats and other guidance material for sea-ice and iceberg products and services. This supports navigation, coastal and offshore activities in sea-ice and iceberg conditions by monitoring sea-ice coverage in both hemispheres. In partnership with the International Ice Charting Working Group (IICWG), WMO experts provide technical advice to national Arctic and Antarctic ice forecasting centres. Through its expert network, WMO also works to support the efforts of national ice services to provide products and services in compliance with the IMO's recently implemented Polar Code (2017).

WMO participates in the Protection of the Arctic Marine Environment (PAME) Shipping Best Practice Forum coordinated by the Arctic Council, of which it is an Observer. The Forum supports effective and practical implementation of the IMO Polar Code (2017) by publicizing information relevant to all involved

Harmful algal bloom on 11 July 2019, Lake Erie, North American Great Lakes. (Source: NOAA)

in safe and environmentally sound Arctic shipping. The WMO Polar Shipping page, initiated in 2020 and directly linked to the PAME Polar Portal, acts as a single entry point for public access to practical polar information relevant to shipping and polar operators. The bi-annual WMO Arctic Consensus Statement on the Seasonal Climate Outlook and regional climate summary produced through the Arctic Climate Forums also informs shipping communities of the sea-ice outlook during polar summer and winter seasons (see *Skating on Thinning Ice: Challenges in the Changing Arctic* on page 86).

Marine Emergency Response

As maritime activities and operations increase, so has the need for operational services that deliver forecasts and hazard/risk mapping for marine environmental emergencies such as oil and chemical spills. WMO recognizes the need to support countries in Search and Rescue (SAR) efforts and Marine Environmental Emergency Response (MEER). SAR efforts track life and property at sea, while MEER is crucial for tracking and containing the path of environmental pollutants, such as oil and chemical spills at sea. Specialized centres for marine emergency management enhance technical capabilities, exchange diagnostic and forecast data, and provide coordination for services and information to meet requirements as defined by the International Atomic Energy Agency (IAEA) and IMO. WMO's effort in this area is implemented through the Global Data-Processing and Forecasting System (GDPFS), which downscales forecasts from the global, to regional to national and local level. The added value of local knowledge and expertise in the final GDPFS step contributes to key SAR and MEER decision-making (see *Oil spill management and salvage in the Indian Ocean* on page 109).

Marine Climate Services

Marine climate services support a wide range of ocean activities – such as the design and operation of offshore and coastal facilities like drilling platforms and nuclear plants – marine transportation, fishery and regulatory activities for coastal states to ensure safety of lives and the environment. These services are also essential for establishing risk and vulnerability as a pillar of impact-based forecasting. Climate services provide the baseline for climate change detection and attribution for most marine variables, including waves, sea level, sea surface temperature, salinity, sea ice and icebergs.

Wind-generated waves play a major role in coastal sea-level dynamics and shoreline change. Future changes to deepwater wave climate (height, frequency and direction) will likely affect approximately 50% of the world's coastlines, and could drive significant changes in coastal oceanic processes and hazards (Morim et al., 2019). These issues are being addressed through the WMO-supported Coordinated Ocean Wave Climate Project (COWCLIP), the focus of which is being expanded to include global storm surge climatology.

As coastal and maritime communities continue to face unprecedented challenges in response to global environmental change, there is an increasing need to better understand local, regional, and global changes in natural phenomena. Further research is needed into how climate change will impact the intensity and frequency of the El Niño Southern Oscillation (ENSO), the occurrence of marine heatwaves, especially in tropical and polar regions, the intensity and frequency of harmful algal blooms (HABs), and waves and storm surge in polar regions that were previously protected by sea-ice cover. The WMO is working to improve the provision of marine climate services that help coastal and maritime communities to better prepare for sub-seasonal and seasonal events and to develop long-range forecast products and services to address emerging threats.

Accurate climate forecasts are of utmost importance for food security, especially for fisheries. The international coordination of the collection and processing of marine and ocean data – and the preparation and delivery to users of marine and ocean climate products and services – is priority for WMO. Operational oceanographic services are providing ocean re-analyses that will ensure the availability of global data sets for fishery management decision support systems, especially related to the impacts of weather and climate change on fishery resources. In 2012, WMO and IOC of UNESCO recognized the need to provide climate services for oceanic fishery and aquaculture industries, for sub-seasonal, seasonal and long-range forecast products and services, which might also lead to enhanced observations and data transmission by fishery vessels. Liaison between meteorological services, oceanographic institutions and regional fisheries management bodies is important for establishing the requirements for marine weather and climate information. WMO will continue this work in collaboration with the co-sponsored (IOC/WMO/UNEP/ISC) Global Ocean Observing Systems (GOOS), which coordinates observations, modelling and analysis of marine and ocean variables to support research, assessments and operational ocean services worldwide.

In addition, WMO supports climate services for fisheries through Regional Climate Centres (RCCs), for example in Western South America, where ENSO has a big influence on fish populations (see *Monitoring ENSO and creating ocean and climate services - the role of CIIFEN* on page 88). RCCs operate across various geographical areas where climate variability and change are pronounced and where forecasts are crucial to support seasonal planning in local communities. For Arctic regions especially, where the ocean is a critical driver in the seasonal patterns, the Arctic Regional Climate Centre Network has been established and the associated Arctic Climate Outlook Forum meets twice annually bringing together providers and users of climate information across the Arctic region to agree on the coming fall and spring seasonal outlooks – with clear predictions of sea ice extent. All of this contributes to the Climate Service Information System, the operational backbone of the Global Framework for Climate Services.

Capacity Development and Marine Competencies

The WMO places great emphasis on building the capacity of marine services in coastal states through strong development and training programs, and in cooperation with partners such as the IMO, IHO and IOC. The Organization also strengthens public awareness and preparedness for hazards in coastal communities. This is exemplified by the 2019 WMO video on coastal inundation for the Pacific Islands, which includes education on both weather-related

Coastal flooding awareness cartoon helping to inform the public on what to do, and what not to do, in the event of a flood early warning (Source: WMO, 2019)

inundation and tsunamis and preparedness with actions to be taken.

From the late 1990s to 2015, WMO offered training workshops to NMHSs staff on Storm Surge and Wave Forecasting. The Guide to Wave Analysis and Forecasting (WMO No. 702) and the Guide to Storm Surge Forecasting (WMO No. 1076) provided content for those workshops.

WMO meets annually within a broader Joint WMO-IMO-IOC-IHO-IALA[6]-IMPA[7] Capacity Development Panel, to discuss common training, awareness and capacity development synergies and needs, while ensuring open collaboration among partners. In addition to public awareness, through innovations in technology and a commitment to improving public weather services, WMO is bolstering the capability of meteorological services to provide better early warnings and forecasts, and to understand their customer needs for impact-based forecasting.

There are significant gaps in all regions of the world when it comes marine service delivery. To address this issue, WMO has designed a unique course to help meteorological services to self-assess their marine capabilities. The Spanish-speaking staff of NMHSs in South America were the first to participate in the April to June 2020 (3-month) online session that was supported by the Spanish Meteorological Agency (AEMET) and ended in June 2020. Ms. Alicia Cejas, METAREA Coordinator for Argentina noted that the WMO course "has been useful to focus on several service delivery aspects, the main one being to reach all users, because we will never give quality service without knowing the needs of our users". The course will be expanded globally over the next four years. The course will also partly contribute to the endorsed Marine Weather Competency Framework for implementation in WMO Members.

The road ahead

As we gain a better understanding of the needs and challenges facing users and stakeholders in coastal areas and the marine community, the WMO will continue to work with partners to strengthen the capacity of Members to provide operational weather, ocean and climate forecasts, while promoting a safe, productive and healthy ocean. Several reports, most recently the WMO State of Climate Services 2020, have highlighted the need to strengthen the capacity of Members to provide authoritative early warnings

6 International Association of Marine Aids to Navigation and Lighthouse Authorities

7 International Maritime Pilots' Association (IMPA)

for marine and terrestrial areas. Integrated multi-hazard early warning systems are a key component of climate change adaptation and of informed disaster risk reduction and management activities. The WMO Global Multi-Hazard Alert System (GMAS) framework, currently under development, will better support preparedness and response decisions for maritime and coastal communities while facilitating capacity development.

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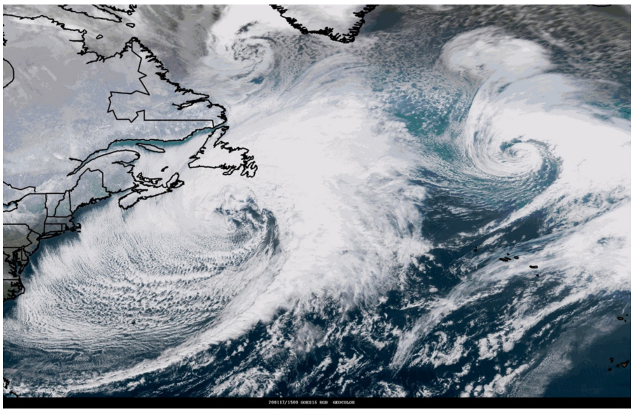
Extreme Maritime Weather: Improving Safety of Life at Sea

By Joseph Sienkiewicz[1] and Thomas J. Cuff[2]

Incidents in recent years have highlighted the hazards of extreme weather at sea, emphasizing the need for action to better protect life and property aboard vessels. Hurricane force winds and phenomenal waves, in particular, endanger sea-going vessels regardless of size. Ships operating in high latitudes also face the threat of freezing spray, in addition to the more well-known hazards created by icebergs and sea ice. Despite the availability of high-resolution satellite imagery, increasingly skilful numerical weather prediction models and improved forecasting services, in the twenty-first century vessels continue to be lost at sea.

The loss of the *SS El Faro* near the Bahama Islands, with all 33 souls aboard, during Hurricane *Joaquin* in 2015 was particularly notable. The follow-on investigation exposed problems with the decision processes aboard the ship, particularly the proper use of hurricane predictions and the criticality of timely information in rapidly evolving weather. In 2019, the tug *Bourbon Rhode* perished in Hurricane *Lorenzo* in the Atlantic Ocean, losing 11 of its crew of 14. In 2020, Typhoon *Maysak* claimed the *Gulf Livestock 1* in the East China Sea, with just 2 of 43 crew members surviving; nearly 6 000 live cattle were lost.

Extratropical cyclones at sea can be just as dangerous as the extreme winds and waves generated by hurricanes. These systems traverse the mid and high latitudes and are often larger in size and with a faster forward motion than tropical cyclones, causing conditions at sea to rapidly change. In the North Pacific and Atlantic Oceans, hurricane force winds associated with extratropical cyclones occur more often than hurricanes. In February 2016, the cruise ship *Anthem of the Seas*, en route from New York to Port Canaveral, Florida, experienced extreme winds well-above 100 knots and waves up to 15 metres high in an explosively intensifying winter storm off the southeastern U.S. coast. Unable to overcome the rapidly changing conditions, the vessel was drawn into the storm, suffering a partial loss of propulsion and requiring repairs upon return to port.



GOES-16 geo-colour imagery of 3 intense extratropical cyclones in the north Atlantic Ocean on 17 January 2020. The western most cyclone, south of Newfoundland, generated a broad area of hurricane force winds. The cyclones west of Greenland and in the eastern Atlantic both generated storm force winds. (Source: NOAA)

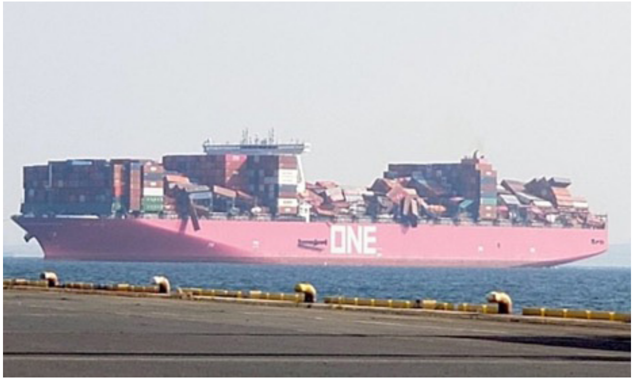
More recently, in March 2019, cruise ship *Viking Sky* lost propulsion power in rough seas off the rocky Norwegian coast, dragging both anchors for a time. Fortunately, the anchors held nearshore, allowing the evacuation of approximately 460 of its passengers via helicopter prior to being towed to port. Initial findings indicated that the diesel generators shutdown from a loss of lubricating oil suction due, in part, to the vessel's pitching and rolling in heavy seas.

There was a series of fatal ship losses in the South China Sea during December 2020. Near the end of December 2020, the fishing vessel *Yong Yu Sing #18*, operating in the open waters of the North Pacific, was lost about 530 nautical miles northeast of Midway Island, in a very strong storm of hurricane force intensity. While the vessel survived the storm and was located, its crew of 10 appeared to have abandoned ship; none were found.

1 NOAA National Weather Service (NWS), Ocean Prediction Center

2 NOAA National Weather Service; Office of Observations; Chair, WMO Standing Committee-Marine Meteorological and Oceanographic Services (SC-MMO); Member, WMO-IOC Joint Collaborative Board (JCB)

There was a marked increase in container loss and damage in late 2020, particularly, over the North Pacific Ocean. Most noteworthy, the *ONE Apus* en route from Yantian, China, to Long Beach, U.S., in late November was well south of a large storm of hurricane force strength yet still experienced phenomenal container loss and damage. Over 1 800 containers were lost overboard, with others damaged, far exceeding any previous documented container loss without losing the ship itself.



Damage to the container ship ONE Apus, 8 December 2020 (Source: Twitter/@nobuya0827)

While many losses at sea can be attributed to extreme winds and waves, ice accretion on the superstructure and masts of vessels operating in the high latitudes can destabilize them, causing them to capsize. Freezing spray and the subsequent ice accretion may have been a significant factor in the sinking of the both the *Scandies Rose* off Alaska with five lives lost in late December 2019, and the Russian trawler *Onega* in the Barents Sea with seventeen lives lost in December 2020.

Extreme maritime weather continues to contribute to the loss of cargo, vessels, and crews. However, investigations reveal a number of causative factors in addition to the weather. Under the Safety of Life at Sea (SOLAS) Convention, the WMO and IMO have collectively worked to reduce the vulnerability of the maritime community in the event of hazardous or extreme maritime weather. Despite this, there continues to be an unacceptable loss of life and property at sea. In view of this, and recognizing the growing demand for marine services that communicate impact-based forecasts for better decision-making, in October 2019 the WMO and IMO jointly held the first International Symposium on "Extreme Maritime Weather: Towards Safety of Life at Sea and a Sustainable Blue Economy" at IMO Headquarters in London. Over 200 participants from over 40 different countries attended, representing private and public sectors, including government ministers and ambassadors. Representatives from the WMO, IMO, IOC, marine weather service providers, and various sectors of the maritime industry explored how to improve the value chain from the collection of marine weather and ocean observations through to forecasting and the dissemination of marine forecasts and services to users and stakeholders.

Working together, the WMO and IMO seek a wide range of societal benefits, including:

- a reduction in the loss of life and property at sea and along coastlines,
- improved operational efficiency and reduced emissions through optimal ship voyage routing,
- environmental monitoring and forecasting to aid coastal management, and
- more effective environmental emergency response efforts.

The next WMO/IMO International Symposium will be hosted by Indonesia, hopefully in 2022.

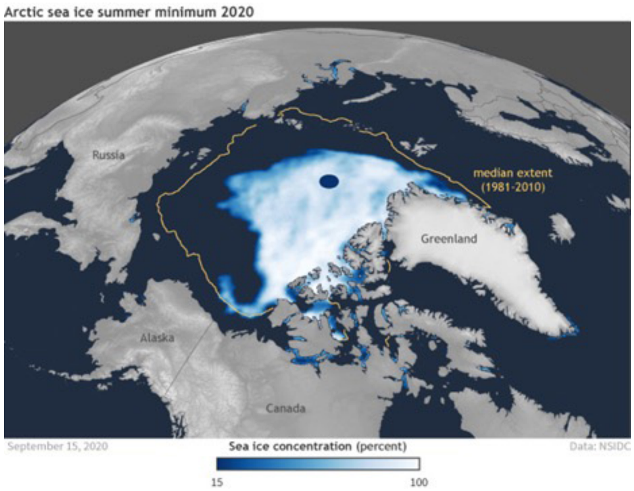
Skating on Thinning Ice: Challenges in the Changing Arctic

By Thomas J. Cuff[1], Keld Qvistgaard[2], John Parker[3] and Christine Bassett[4]

Readers of the Bulletin are keenly aware of climate change and its impact on everyday life; however, they may not know that, in the immediate future, it is the highly sensitive polar regions that may be the most impacted. This is particularly true of the Arctic. The gradual warming of the Arctic Ocean and its surrounding seas is a direct outcome of the significant warming of land masses in the high latitudes, especially during the Eurasian summer season. This warming has steadily thinned sea ice formed over centuries. Although the entire basin freezes during the winter, the diminished sea-ice coverage during the summer season results in a relatively large extent of thinner winter ice over the Arctic. This relatively thin "first year ice" melts quickly, allowing the Arctic Ocean to absorb more of the sun's heat. This, in turn, gradually thins the thicker "multi-year ice" which, over several summer seasons, eventually melts and further erodes the summer ice pack.

Although conditions do vary somewhat from year to year, minimum Arctic sea-ice extent in the Arctic, which typically occurs in mid-September each year, has shown a general decline since satellite records began in the late 1970s. According to the U.S. National Snow and Ice Data Center, the past 14 summer seasons, from 2007–2020, represent the lowest 14 years of minimum ice extent. The minimum Arctic sea-ice extent in 2020 was the second lowest on record.

The diminishing summertime Arctic sea-ice extent is having profound effects on the region. While there is some inter-annual variability in coverage, the general trend towards an overall decrease in summer sea ice is increasing the length of a safe Arctic Ocean shipping season. Routing ships through the Arctic during the summer season has the potential to save substantial costs and reduce fuel consumption for shipping goods between northern Europe and Asia, although significant variability in geographic coverage from year to year creates uncertainty in the start dates and length of each shipping season. However, more ship transits also increases the likelihood of maritime incidents and the associated potential for adverse ecological impacts in the culturally and environmentally sensitive Arctic. Hence, maritime authorities in the region must continue to increase their capacity to respond to marine environmental emergencies.



Arctic sea-ice concentration (%), 15 September 2020 (Source: U.S. National Snow and Ice Data Center)

The decrease in summer sea-ice extent has also increased the threat of storm surge in the region. With more open water and shorter seasons with ice coverage, more of the Arctic coastline is susceptible to damage from high winds and waves. The impacts to the shoreline in some areas have been startling. The U.S. Geological Survey has documented erosion rates along the north coast of Alaska of as much as 18 metres per year. Along the west coast of Alaska, towns are increasingly threatened by inundation.

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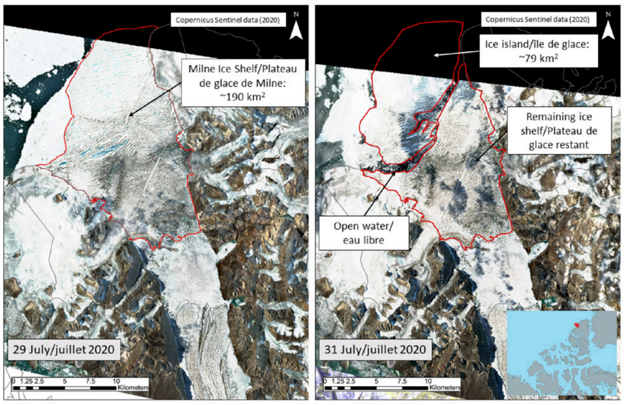
1 NOAA National Weather Service; Office of Observations; Chair, WMO Standing Committee-Marine Meteorological and Oceanographic Services (SC-MMO); Member, WMO-IOC Joint Collaborative Board (JCB)

2 Danish Meteorological Institute (DMI); and Member, SC-MMO

3 Environment and Climate Change, Canada (ECCC); and Vice-Chair, SC-MMO

4 Knauss Fellow, Office of Observations, National Weather Service, NOAA

Another demonstration of a changing landscape in the Arctic was the dramatic break-up of the Milne Ice Shelf on Ellesmere Island, Canada, in July 2020. It was considered the last of Canada's ice shelves. Its break-up created large ice islands that are now adrift in the Arctic Ocean and reduced the ice shelf extent by almost half. This was attributed to above normal temperatures, sustained offshore winds and open water in front of the ice shelf.



Tweet by ECCC Canadian Ice Service regarding Milne Ice Shelf collapse (2 August 2020)

Changes in the extent and thickness of sea ice present an emerging social and economic threat to coastal communities in the Arctic. The reduction of multi-year ice leaves much of the Arctic vulnerable to an increase in the frequency, duration and intensity of marine heatwaves. The timing and duration of these events hold enormous implications for the timing of nutrient delivery and primary productivity, as well the reproductive success of culturally, economically and ecologically important species. Impacts include community and geographic shifts in key marine species such as copepods, krill, pollock and salmon; the closure of numerous commercially important fisheries; and earlier arrival of marine species at higher latitudes. Moreover, these events led to increased harmful algal blooms (HABs) further north and mass stranding of marine mammals and seabirds.

Sea ice analysis and services are provided worldwide to mariners and other users through a series of national and regional services. The Baltic Sea Ice Services (Denmark, Estonia, Finland, Germany, Latvia, Lithuania, the Netherlands, Norway, Poland, Russia and Sweden), the European Ice Services (Denmark, Finland, Iceland, Norway and Sweden), the North American Ice Service (Canada, U.S.) and the EU's Copernicus Marine Environment Monitoring Service (CMEMS) are a few examples. Operational sea-ice and iceberg services are coordinated globally through the International Ice Charting Working Group (IICWG), an independently chartered entity representing 15 of the world's operational national ice services in both hemispheres.

During the first WMO-IMO International Symposium on Extreme Maritime Weather (2019), participants identified several key recommendations in support of safe Polar navigation, including:

- Better monitoring of climate change to provide long-range services
- Incorporating and standardizing ice charts into shipboard Electronic Chart Display and Information System (ECDIS)
- Establishing standards for ice forecasters and analysts
- Improving iceberg models to predict location drift and deterioration
- Improving training to close the gap between met-ocean information providers and users.

Sea ice surrounding the Southern tip of Greenland, Cape Farewell (Source: K. Qvistgaard, 10 April 2010)

Monitoring ENSO and creating ocean and climate services - the role of CIIFEN

By Felipe Costa do Carmo and Juan José Nieto, Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN)/Regional Climate Centre for Western South America (RCC-WSA)

The intense 1997/1998 El Niño had serious impacts on many countries around the world, including those in the western region of South America. In the coastal region of Peru and Ecuador increases in precipitation led to severe flooding and significant economic losses, mainly in fishing and agriculture sectors (CAF, 2000). After this event, the United Nations General Assembly proposed for the creation of the Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN), which would ally WMO, the United Nations Office for Disaster Risk Reduction (UNDRR) and the Government of Ecuador, and later the government of Spain joined through the Agency of Meteorology of Spain (AEMET). Thereafter evaluation missions and a series of regional meetings preceded the launch CIIFEN in 2003 in Guayaquil, Ecuador.

In 2015, CIIFEN became the designated WMO Regional Climate Centre (RCC) for Western South America (RCC-WSA) at the request of the National Meteorological and Hydrological Services (NMHSs) of Bolivia, Chile, Colombia, Ecuador, Peru and Venezuela. This designation opened opportunities to improve regional climate and oceanic products and services while strengthening the regional platform and horizontal cooperation among the region's institutions.

CIIFEN began to host annual Regional Climate Outlook Forums (RCOFs) for western South America. The forecast is produced by each NMHS of the RCC-WSA, compiled by CIIFEN and distributed to a wide range of users from many sectors.

El Niño Southern Oscillation (ENSO) monitoring and its impacts

The 2015/2016 El Niño event was declared one of the three strongest recorded since 1950, on par with the 1982/1983 and 1997/1998 El Niño events (WMO, 2016) (Image 2). The impacts were felt around the globe – an estimated 60 million people were affected by El Niño-related drought, floods and extreme heat and cold. In consequence, the forced migration of populations, after the collapses of their livelihoods and damages to basic infrastructure, was attributed to the El Niño (FAO, 2016; OCHA, 2016; UNDRR, 2016).

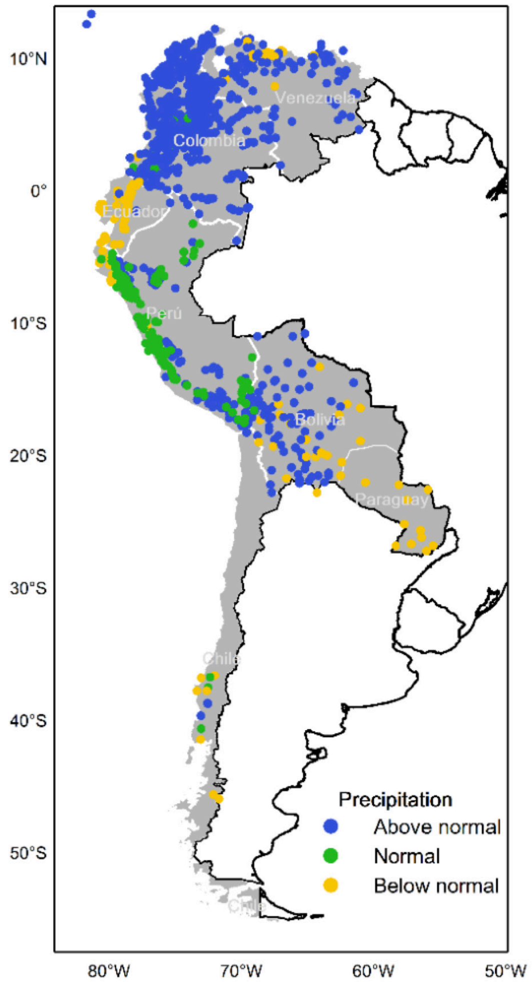
Flooding in Ecuador caused by extreme precipitation during El NIño 2015/2016 (Credit: Diario El Telégrafo)

CIIFEN carries out operational analysis of ENSO conditions. Its monthly bulletins contain detailed information on monitoring and evolution of the most important oceanic and atmospheric variables to declare an early warning. Bulletins that compile and summarize the information produced by Global Producing Centres (GPCs) are shared with subscribers through e-mail and social media.

Scientific value and benefits of ocean and climate services

Monitoring and forecasting climate and oceanic conditions, as well as the updating ENSO perspectives is the beginning of the process, the information must then be communicated in an assertive, timely manner using language that is accessible to the end users. Tailored end-user services also need to be developed. Ocean and climate services are especially important for fisheries and agriculture in western South America, where food security and national economies depend to a large extent on these sectors.

CIIFEN has been involved in various projects and initiatives to evaluate how ocean and atmospheric



Seasonal precipitation forecast for December 2020 – February 2021, made by the National Meteorological and Hydrological Services of the countries of western South America (Bolivia, Chile, Colombia, Ecuador, Peru and Venezuela) and Paraguay. This information is sent to CIIFEN every month for the production of the regional bulletin.

variables influence agricultural productivity. The most recent, sought to understand the relationship between the ocean and climate with the productivity of cocoa plants in Ecuador. It included analysis of how the El Niño/La Niña events have affected productivity in past harvests. Such research will improve Early Warning Systems and the use of climate and ocean information in agricultural planning and decision-making.

Gaps and further steps

Science is advancing in leaps and bounds, especially in the area of climate and oceanography. The development of satellites has made it possible to obtain a quantity of data and information that was unimaginable in previous decades. However, inter-institutional exchange and coordination must be strengthened in order to integrate climate and ocean information into government and development sector planning. For this, it is essential to have the information that addresses end user needs, translated into terms and language understood by the end-user.

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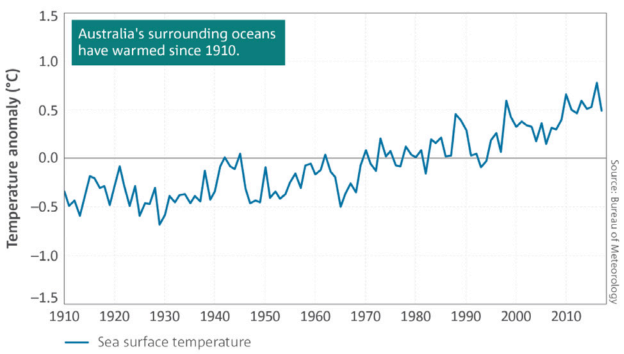
Services

Predicting extreme ocean temperatures on timescales useful for marine management

By Claire Spillman[1] and Alistair Hobday[2]

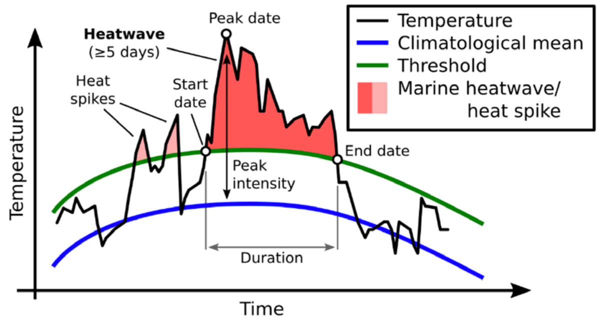
Ocean temperature extremes, such as marine heatwaves, can have a major impact on marine ecosystem health and the productivity of fisheries and aquaculture.

The oceans around Australia have warmed substantially since 1910, when compared to average ocean temperatures for 1961–1990. Warming is particularly pronounced in south-east and south-west waters – across the Pacific and Indian Oceans. Climate projections indicate that this warming trend is set to continue in coming decades, together with an increase in frequency, duration and intensity of marine heatwaves. What will this mean for marine habitats?



Annual sea surface temperature anomalies in the Australian region, referenced to the 1961–1990 standard averaging period. State of the Climate: www.bom.gov.au/state-of-the-climate/oceans.shtml

Marine heatwaves are typically defined as a period of five or more days in which ocean temperatures are above the 90th percentile, that is in the top 10%, of recorded figures for that region at that time of year. These severe ocean events have increased in frequency, duration and intensity over the past 100 years, with impacts on species and habitats reported around the world. These extremes offer a view of ocean conditions that may be the usual in the future.



Marine heatwave definition as per Hobday et al 2016 (Source: www.marineheatwaves.org/all-about-mhws.html)

Forecasts for marine industries and managers

Warmer oceans can have significant impacts on marine ecosystems such as mass coral bleaching, increasing disease risks for coral and fish, and changing the growth rates, distribution and migration patterns of fish. Extreme events such as marine heatwaves, combined with a warming baseline, have the potential to seriously impact marine ecosystems and the fishery industry in the coming decades.

How can marine managers better cope with these extreme ocean heat events and their impacts?

Advance warning of an impending marine heatwave can provide an early window for the implementation of management strategies to minimize impacts. The Australian Bureau of Meteorology (BOM) produces operational seasonal forecasts of sea surface temperature (SST) and thermal stress up to six months into the future for Australian waters (www.bom.gov.au/oceanography/oceantemp/sst-outlook-map.shtml). BOM, in collaboration with the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO), has worked together with many marine industries and agencies around the country to develop useful forecast products to help stakeholders manage their climate risk.

1 Bureau of Meteorology, Australia

2 Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

Seasonal forecasts of ocean temperature several months into the future can support operational decision-making, and help inform questions such as:

- Where do we survey this summer in the marine park?
- Will our fish stocks be further south this year?
- Do we need extra staff to manage fish farm operations this summer?
- Should we harvest from our aquaculture business to avoid a heatwave?

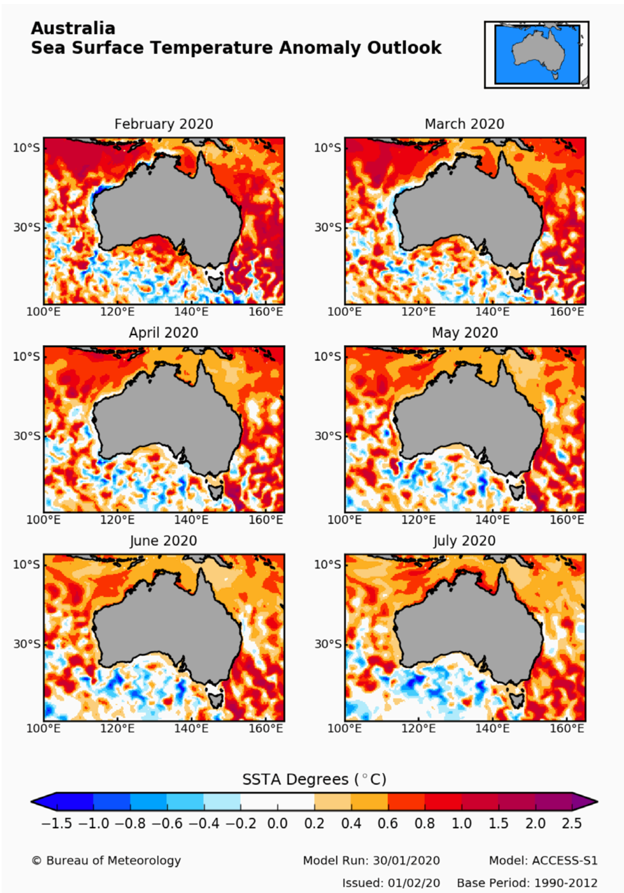
Forecast usefulness depends on the management decision timeline and the critical environmental period affecting the decision, together with forecast accuracy at that time. BOM and CSIRO have spent over 10 years working together with marine stakeholders to improve forecast delivery and use. They have developed seasonal forecast tools in Australia that are used by coral reef managers, fishers and fishery management authorities, and aquaculture businesses.

Predicting coral bleaching risk

The Great Barrier Reef Marine Park Authority has been using BOM's seasonal ocean temperature forecast tools since 2009 to help support the management of the Reef. Seasonal ocean temperature forecasts indicate how much warmer or cooler than usual surface oceans are around the Reef over the coming six months. Accumulated thermal stress forecasts also predict how long temperatures will exceed the normal summer temperatures. High ocean temperatures are the primary cause of mass coral bleaching, a stress response of corals whereby they expel their tiny symbiotic algae (zooxanthellae), exposing their white skeleton. Mass coral bleaching events occurred on the Reef in 1998, 2002, 2016, 2017 and 2020.

The Great Barrier Reef is larger than Italy and presents a huge management task. Reef managers use forecast information to determine the risk of mass bleaching occurring in the coming summer. Managers can then target regions of the Reef and relocate resources for monitoring of bleaching. It is important to understand how bleaching events evolve over time and advance warning of conditions that promote bleaching allows surveys to occur before, during and after an event to gauge the full impact on Reef health. Forecasts are also used to brief the government, tourist operators and the general public.

Surveying bleached coral in the Great Barrier Reef. (Credit: P Marshall, Commonwealth of Australia Great Barrier Reef Marine Park Authority)



Seasonal ocean outlook of sea surface temperature anomalies (difference from normal) for Australian waters for February-July 2020 issued on 1 February 2020.

Predicting marine heatwaves

There is growing interest in the prediction of ocean extremes such as marine heatwaves. A new BOM/CSIRO research project is investigating the seasonal prediction of marine heatwaves several months into the future. This unique research will develop new seasonal marine heatwave forecast products for Australian waters.

These forecasts will provide information regarding location, severity, duration and likelihood of future marine heatwaves, all important considerations for proactive operational responses and management of the impacts of these extreme events.

Looking to the future

Warming ocean temperatures due to climate change are likely to increase both the frequency and severity of heat related impacts on marine resources in the future. Skillful prediction of these extreme ocean events can assist governments, industries and communities to respond and adapt to the growing impact of marine heatwaves in a changing climate.

From Us to Us - Enhancing maritime weather and coastal services in Indonesia and beyond

By Dwikorita Karnawati[1], Guswanto, Nelly Florida Riama, Eko Prasetyo, Anni Arumsari Fitriany, Andri Ramdhani, Bayu Edo Pratama, Suci Dewi Anugrah[2]

Indonesia has over 17 000 islands and one of the longest coastlines in the world. It is heavily reliant on marine industry, food and transportation for a sustainable economy and livelihoods. The safety and security of people at sea and along its coastlines is preeminently important for Agency for Meteorology, Climatology and Geophysics of the Republic of Indonesia (BMKG).

Indonesia is the epicentre of multi-scale interactions in the atmosphere and ocean that have a profound impact on the state of the Pacific and Indian oceans as well as on air-sea thermal exchanges, modulating climate variability over a wide range of time scales.

Maritime Weather Observation and Services

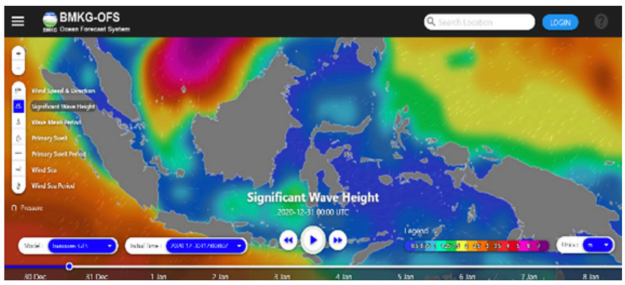
From 2020–2025, the BMKG Strengthening of Marine Meteorology Systems Project (MMS) will enhance and modernize ocean and meteorological observations, adding both fixed (coastal buoy, marine AWS, HF Radar) and mobile (vessel AWS, surface drifter, floats, and glider) stations. These observations will be assimilated into a high resolution coupled ocean-atmospheric model.

The BMKG Ocean Forecast System (OFS) provides a 10-day forecast on wind, waves, swell, currents, temperature, salinity, water level, trajectory and coastal inundation for the safety of maritime activities in Indonesia. These services support sustainable development across various sectors, including shipping, fisheries, mining, energy, tourism, industry, search and rescue, small island area resources and research.

In addition, BMKG established the Fisherman Weather Field-School to work closely with the traditional fishery and aquaculture sectors to increase their understanding and use of weather and climate information. Various communication methods are used to reach a broad public audience, including social media.

BMKG Fisherman Weather Field-School works closely with the traditional fishery and aquaculture sectors to increase their understanding and use of weather and climate information (Lempasing Fishing Port, Bandar Lampung, 11 March 2021)

Furthermore, BMKG is formulating marine impact-based information for the marine transportation sector (see maritim.bmkg.go.id/inawis) and a trajectory model to support Search and Rescue (SAR) activities and environmental emergency services to trace and mitigate the spread of oil spill.



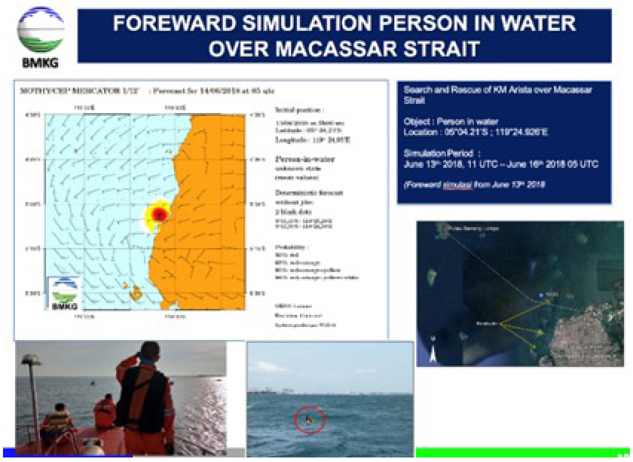
BMKG – Ocean Forecast System

BMKG has shared its developments in maritime weather services with the small-island developing states in WMO Regional Association V (South-West Pacific) (RA V). For example, OFS has been implemented in the Solomon Islands since 2017 with support from United Nations Economic and Social

1 Meteorology, Climatology and Geophysical Agency (BMKG) of the Republic of Indonesia; Permanent Representative to the WMO

2 Meteorology, Climatology and Geophysical Agency (BMKG) of the Republic of Indonesia

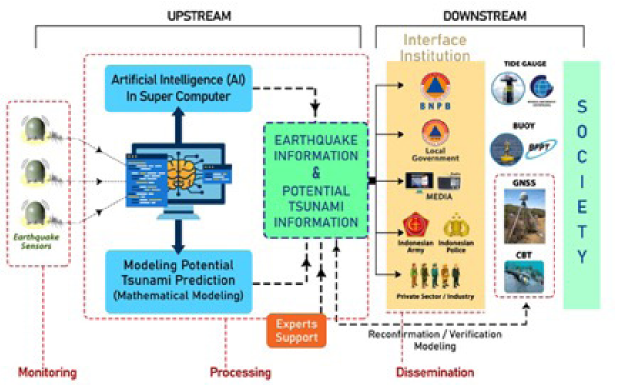
Commission for Asia and the Pacific (UNESCAP) and WMO guidance. In addition, the BMKG hosted WMO Regional Training Centre provided basic virtual training on impact-based forecast, including for maritime weather services, to 34 participants from RA V.



BMKG and Search and Rescue (SAR) activities

Coastal Hazard Management

The Indonesia Coastal Inundation Forecast System (INA-CIFS) is being developed as part of OFS to provide coastal flood early warning services using coastal inundation modelling. The pilot projects for the system were implemented in Jakarta and Semarang.



The end-to-end of the Tsunami Early Warning System (InaTEWS)

Its location at the juncture of four active tectonic plates leaves Indonesia prone to earthquakes and tsunamis. BMKG has a central role in the operation of the Indonesian Tsunami Early Warning System (InaTEWS) and as the Tsunami Service Provider for 28 countries along the Indian Ocean rim.

To strengthen the tsunami monitoring and early warning, 411 sensors are integrated to the Internet of Things (IoT) system and Artificial Intelligent (AI) that supports 18 000 tsunami scenarios. A cable-based tsunami-meter, buoys and tsunami radar will soon enhance the network's capacity to detect near-field and non-tectonic tsunamis. Social media and mobile applications extend the reach of BMKG's warning and alerts for all such events.

Through education at the Earthquake Field School, BMKG strengthens community resilience in vulnerable coastal areas. The program promotes the integration of local knowledge into the natural warning approach for near-field tsunami, and trains participants to evacuate immediately to the safe tsunami zone whenever they feel the shaking of a quake longer than the time it takes to count to ten.

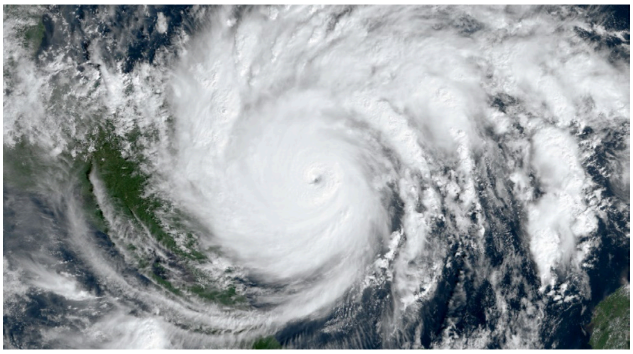
BMKG is also an active member of the Intergovernmental Oceanographic Commission (IOC) of UNESCO, especially in its role as the tsunami service provider for the Indian Ocean Region and as the host of the Indian Ocean Tsunami Information Center.

Whirling World – Tropical Cyclones and the Ocean

By Anne-Claire Fontan[1], Taoyong Peng[1], Xiao Zhou[1], Sarah Grimes[1], Estelle de Coning[1], Zhuo Wang[2], Nanette Lomarda[1], Champika Gallage[1], Cyrille Honoré[1], Jürg Luterbacher[1], Anthony Rea[1], Johan Stander[1]

Over the past 50 years, 1 945 disasters have been attributed to tropical cyclones, which killed 779 324 people and caused US$ 1.4 trillion in economic losses – an average of 43 deaths and US$ 78 million in damages every day. In terms of weather, climate and water-related disasters, tropical cyclones represent 17% of disasters, 38% of deaths, and 38% of economic losses. – WMO Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970-2019) to be published in 2021

Tropical cyclone! Typhoon! Hurricane! Whichever word is used -depending on your region - the image is the same: violent winds that can destroy coastal communities, and torrential downpours that can trigger landslides and flash floods. The impacts are devastating at sea and at landfall, as the combination of waves, storm surge and rainfall can result in catastrophic coastal inundation that takes a heavy toll on life and property.



Hurricane Iota at peak intensity approaching Nicaragua on 16 November 2020, 1500 UTC (Source: NOAA, GOES-16).

The death and destruction caused by tropical cyclones led to global calls for action at the United Nations in the 1970s that laid the foundation for the creation of the WMO Tropical Cyclone Programme (TCP) 40 years ago. Its aim was to help set-up regionally and nationally coordinated early warning systems to reduce the loss of life and damage from these extreme weather events. The collaboration now in place with national, regional and global stakeholders remains key to the success of activities that help to reduce the losses associated with tropical cyclones.

1 WMO Secretariat

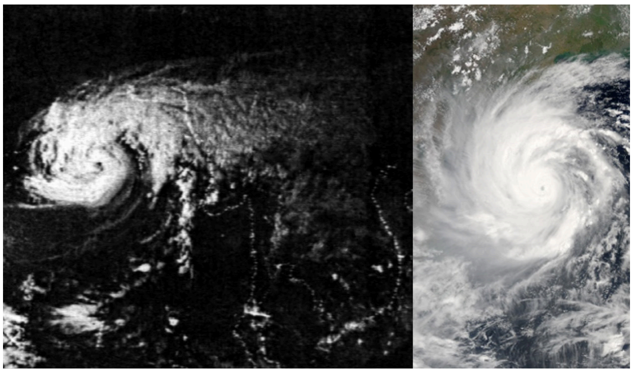
2 University of Illinois; Chair, Tropical Meteorology Research Working Group

Damage and devastation caused by storm surge after Super Typhoon Haiyan hit central Philippines 10 November 2013. (Credit: Marcel Crozet/ILO 2013)

Ocean observations for tropical cyclones

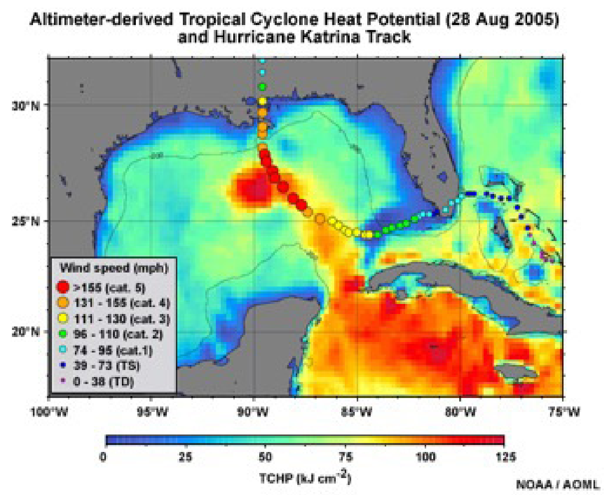
Tropical cyclone is the generic term for the rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters and decays and dissipates as it moves over cooler waters or land. Formation (cyclogenesis) and intensification depends strongly on ocean temperatures, exceeding 26° Celsius (C) within the top 60 metres. Ocean observations – satellite and in situ – are, therefore, essential for early forecast and warnings for tropical cyclones.

International cooperation has led to real-time and global tropical cyclone monitoring through rapid-scanning geostationary satellites. From the first polar orbiting meteorological satellite in 1960 to the geostationary operational satellites in 2021, the evolution of satellite capability brought enormous change to tropical cyclone monitoring and analysis over the ocean. Today – thanks to international data exchange from surface-, airborne, and space-based platforms, along with improvements in modelling and advances in computation – the five-day track forecast is as accurate as was the two-day forecast in the 1960s.



(Left) cyclone over the Bay of Bengal, 11 November 1970 (Source: NOAA); (Right) Super Cyclonic Storm Amphan over the Bay of Bengal on 18 May 2020. (Source: NASA)

Polar orbiting satellites allow observations such as the extent of hurricane and storm force winds at sea, sea surface temperature and features and, recently, satellite-derived coastal bathymetry – depth and contours of underwater terrain. Coastal bathymetry data improves the accuracy of storm surge estimation.



Altimeter-derived Tropical Cyclone heat potential for 28 August 2005 and Hurricane Katrina track (Source: COMET, Microwave Remote Sensing, 2nd Edition)

The network of offshore *in situ* observations provides a better understanding of air-sea interaction, as such it is essential for the tropical cyclone forecasting. The WMO/IOC-UNESCO Voluntary Observing Ship (VOS) network deploys expendable bathythermographs (XBTs), Argo floats and drifting buoys to sample ocean temperature. Additionally, VOS and moored and drifting buoys may also provide wind, wave, sea surface temperature and atmospheric pressure measurements. Atmospheric pressure at sea level is also a crucial observation as it is directly associated with the intensity of a cyclone.

Coordination of forecasting and warning services

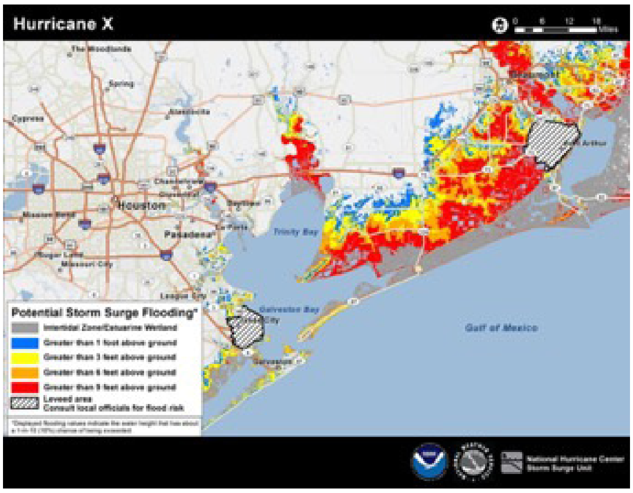
WMO plays an important role in supporting countries to improve their tropical cyclone forecast and warning services through well-coordinated regional and national centres. The TCP encompasses five regional bodies, with their respective Tropical Cyclone Regional Specialized Meteorological Centres (TC RSMCs[3]) and National Meteorological and Hydrological Services (NMHSs).

Today, RSMCs are leading the development of forecasting products and services with sector and location-specific impacts to support national responses for disaster risk reduction with more certainty than before. These are being developed for tropical cyclone forecasting, marine meteorology, ocean wave prediction, severe weather forecasting. TC RSMCs provide forecasting guidance on tropical cyclone track and intensity, together with information on other marine related hazards, for national authoritative forecast and warning services. Recent developments include products depicting location specific potential for storm surge inundation. Since 2008, all TC RSMCs have implemented storm surge forecasting models and capabilities through the WMO Storm Surge Watch System.

Forecasting information over the oceans regarding hazards associated with tropical cyclones is provided to maritime interests via the Global Maritime Distress and Safety System (GMDSS).

3 TC RSMC is an RSMC which conducts Tropical Cyclone forecasting, including marine-related hazards.

The 1st WMO International Workshop on Tropical Cyclone, held 25 November – 5 December 1985 in Bangkok, Thailand (Source: Thailand Meteorological Department)



Map of potential storm surge flooding (Source: TC RSMC Miami, NOAA)

researchers, including storm surge experts. In addition, the WMO World Weather Research Programme has coordinated field experiments to better understand the intensity, structure, motion and precipitation processes of tropical cyclones. Experts have also worked on tropical cyclone climate change assessment. On the short time scale, the ocean-related topics for research are off-shore sudden changes of track and intensity, extremely heavy rainfall outside the periphery of the tropical cyclone, storm surge forecasting, and coastal flooding around landfall period. On the sub-seasonal and longer time scales, ocean conditions provide important sources of predictability, with research focused on better understanding and predicting tropical cyclone activity.

Capacity Development

WMO coordinates training for NMHSs on all tropical cyclone-related hazards, including regional workshops on storm surge and wave forecasting. Tropical cyclone forecasters also have their own website (severeweather.wmo.int/TCFW/), and the Global Guide to Tropical Cyclone Forecasting (WMO-No. 1194), which contains a collection of state-of-art sciences and technologies and best practices for their use.

WMO Research Efforts

WMO research efforts include the WMO Tropical Meteorological Research Working Group's series of International Workshops on Tropical Cyclones every four years. This brings together forecasters and

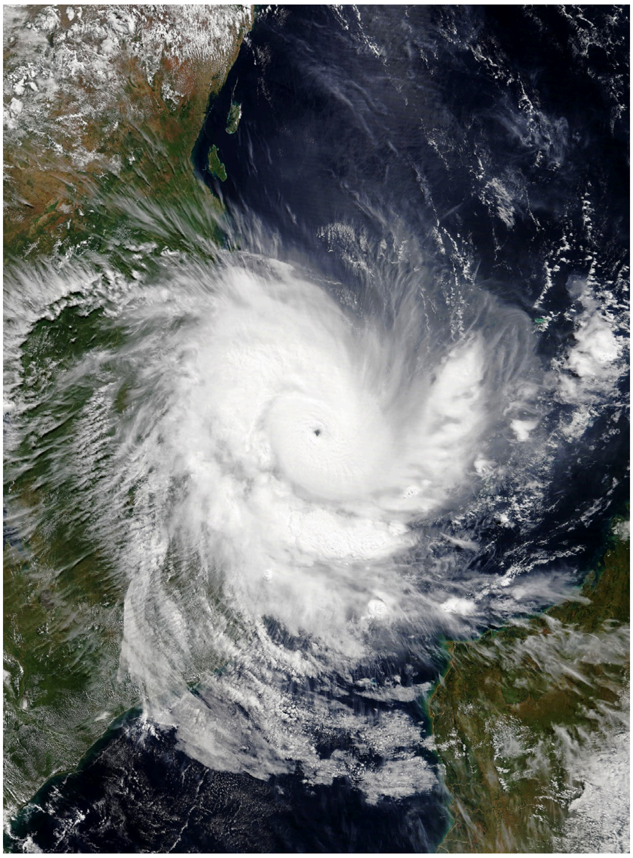
Looking forward

WMO recognizes the need for better tropical cyclone forecasts as well as the need to work with partners to better prepare people for risks. Hundreds of millions of people around the world are affected and damages amount to billions of dollars annually. WMO is accelerating research-to-operations, monitoring of the ocean and the sharing of data to deliver impact-based forecasting and warning services for tropical cyclones. Better knowledge and tools, and the inclusion of partners in the social sciences will help to effectively translate early warnings into early actions that save lives.

Multi-Hazard Early Warning System (MHEWS), a tool for Effective Ocean Prediction and Services

By Agnes Kijazi[1], Wilbert Muruke[2], Mohamed Ngwali[3], Wilberforce Kikwasi[4], Mathew Ndaki[5]

With its long and open coastline of over 30 000 km, Africa is vulnerable to natural hazards originating from the Atlantic Ocean to the west, Mediterranean Sea to the North, and Red Sea and Indian Ocean to the East. The risks include tropical cyclones, coastal inundation (including from tsunamis), strong winds and rising sea levels due to climate change. The United Republic of Tanzania is on the South Western Indian Ocean (SWIO), a region vulnerable to tropical cyclones.



Tropical Cyclone Kenneth approaching Mozambique at peak intensity on 25 April 2019 (NASA)

The Tanzania Meteorological Authority (TMA) has a Multi-Hazard Early Warning System (MHEWS) with Standard Operating Procedures (SOP) that activate when a weather warning is issued on land or at sea. The SOP takes onboard all key actors in the National Early Warning System (NEWS), composed of the Disaster Management Office (DMO) in the Prime Minister's Office as the overall coordinator of disaster management in the country, TMA, the Media and the stakeholder communities – that is ocean users when the hazard is at sea or threatens coasts.

TMA is responsible for issuing weather-related warnings for both land and sea. The information is passed on to all stakeholders through various channels, including TMA website, newspapers, television, radios and social media. When a hazard leads to a disaster, TMA communicates the warning to DMO. DMO decisions depend on MHEWS information provided. The aim is to facilitate effective communication and appropriate action in timely manner.

Tropical Cyclone *Kenneth*

The development of Tropical Cyclone *Kenneth* north of Madagascar was tracked by satellite and TMA's Numerical Weather Prediction (NWP) system from 20 April 2019. On 21 April, TMA issued early warning information to the public on the development of the depression. TMA received updated alerts from the Tropical Cyclone Regional Specialized Meteorological Centre (TC RSMC) Meteo-France La-Reunion. When the increasingly strong cyclone started moving toward the coast of Tanzania and Mozambique, TMA communicated the MHEWS information to the National Disaster Management Office (DMO). On 25 April, Kenneth reached its peak with a central pressure of 934 hectopascals (hPa) and wind speed of 230 kilometres per hour (km/h) with gusts to 305 km/h – the most severe and damaging tropical cyclone ever to hit the region. On that day, it made landfall over north east of Mozambique, influencing the weather

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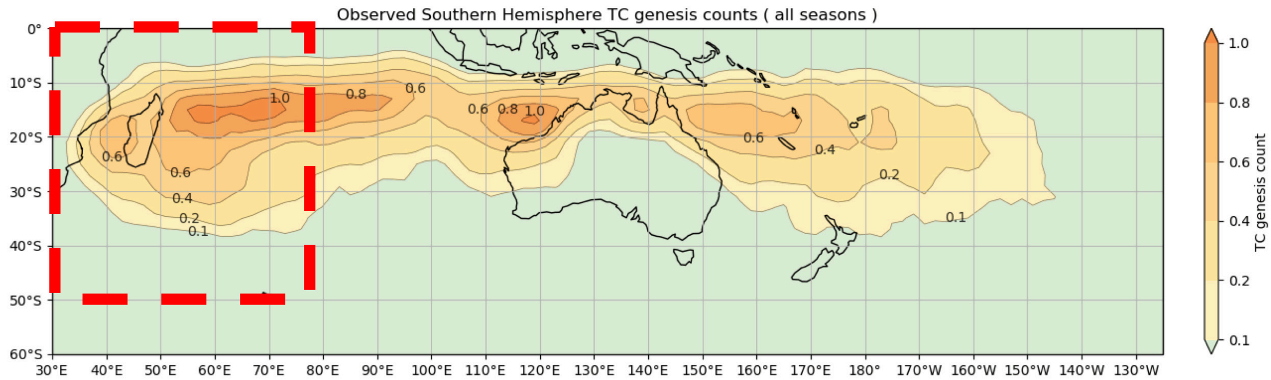
1 Director General of the Tanzania Meteorological Authority (TMA); Permanent Representative of the United Republic Tanzania to the WMO and the Third Vice-President of WMO

2 Manager, International Cooperation, TMA

3 Director, TMA-Zanzibar Office

4 Head of Marine Meteorological Services Office, TMA

5 Meteorologist, TMA



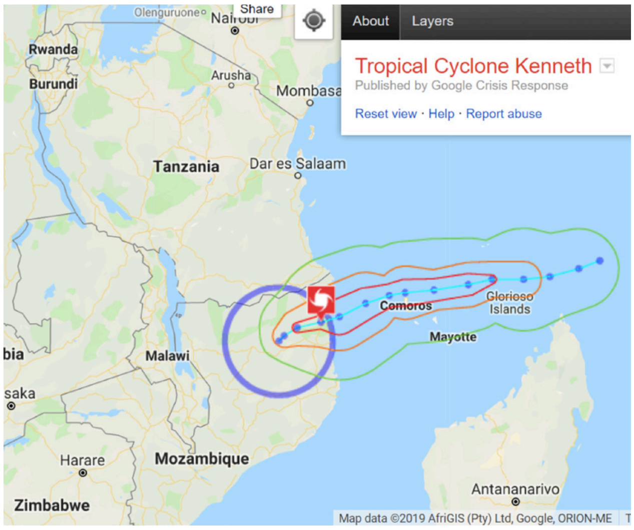
Area of tropical cyclone formation over SWIO in the southern hemisphere (adopted from Australian Bureau of Meteorology (bmo.gov.au/climate/map).

systems in Tanzania, especially over the southern coast. The cyclone dissipated thereafter.

Dr. Agnes Kijazi, Director General, Tanzania Meteorological Authority (TMA) and Third Vice-President of WMO, with Col. Jimmy Matamwe, Director, Disaster Management Office (DMO)-Prime Minister's Office (PMO), and Mr Bashiri Taratibu, Assistant Director, DMO, jointly issuing a warning cancellation to the public on 26th April 2019.

As the cyclone intensified and approached the coast, TMA continued to provide warnings, conducting frequent press conferences as per the SOPs, while the DMO coordinated disaster responders, providing them with evacuation sites and other facilities. On 26 April, the Director General of TMA and the Director of National Disaster Management Office jointly issued a cancellation of the state of emergency through a press conference.

MHEWS and SOPs were effective in predicting, monitoring, communicating and coordinating the response to the tropical cyclone. Everyone played their role, including the Media who updated the public continuously with information from TMA. Thus, communities were evacuated to safe places in a timely manner.



Severe Tropical Cyclone Kenneth made a landfall over Northeastern parts of Mozambique.

Challenges

Ocean prediction and services in Africa, and specifically in Tanzania, face several major challenges:

- The inadequacy of the observation and monitoring infrastructure (e.g. automatic weather stations along the cost and water buoys)
- Limited human capacity in marine observation and forecasting

- Limited computational capacity and technology in data processing, packaging and dissemination; and

- Limited awareness by the communities.

Conclusion and recommendations

The MHEWS SOPs are an effective tool in connecting ocean prediction and services to users and emergency responders. They are most effective, however, when they are customized to individual stakeholders, to ensure each to take the appropriate actions when at risk. Activities have to be developed for individual SOPs for diverse stakeholders.

Institutional capacity building is of paramount important in African NMHSs to ensure effective early warning for marine hazards, which scientists predict will intensify due to climate change.

International cooperation needs to be enhanced to ensure sustainability and support the capacity of NMHSs to deliver multi-hazard early warning for effective management of marine related disasters ranging from cyclone induced coastal inundation to tsunamis.

Oceanic Science for Services in Small-Island Developing States

By Arlene Laing[1], Ofa Fa'anunu[2] and David Farrell[3]

The United Nations Decade of Ocean Science for Sustainable Development, 2021–2030, promises benefits to all nations but especially to the Small-Island Developing States (SIDS) of the Caribbean and the Pacific, whose development is tied to their ability to use their marine resources. The extent and resources of the Exclusive Economic Zones (EEZ) of SIDS are significantly larger than their corresponding land areas. However, the full benefits of those resources are not being used by SIDS due to inadequate knowledge of the characteristics of the marine environment, the opportunities and the hazards. Paramount among the latter are severe tropical cyclones, sea-level rise, coastal inundation and erosion and, in recent years, the influx of Sargassum in the Caribbean. All of those are exacerbated by climate variability and climate change and threaten the vulnerable economies of SIDS.

Caribbean

The tourism sector is the primary economic driver of most Caribbean SIDS. The "science for sustainable development" value chain must bring tangible benefits to the marine, and related economic sectors such as tourism, to benefit the Caribbean.

Successful harnessing of science to deliver value requires:

- accurate and timely observations
- research that improves understanding, prediction capability and aids in the development of better services
- capacity development and training in marine meteorology and service delivery
- regional cooperation among meteorological, oceanic and coastal environmental agencies
- understanding of the needs of users whose livelihoods depend on a safe, clean, well-predicted and sustainable ocean.

West Coast of Trinidad and Gulf of Paria, with oil and gas industry vessels. (Source: Arlene Laing, 22 August 2018)

In addition to search and rescue operations, the services of the National Meteorological and Hydrological Services (NMHSs) are also valuable to the oil and gas industry. This was illustrated recently by the near failure of a vessel containing approximately 1.3 million barrels of crude oil in the Gulf of Paria (the body of water between Trinidad and Venezuela, Image 1). The fate of the cargo and its local and regional socio-economic impacts were echoed at all levels of Government within the Caribbean Community (CARICOM) and highlighted the vital role of marine forecasting services.

To achieve the goal of a safe, clean and well-predicted ocean, the NMHSs of Caribbean States and Territories are being supported by the Caribbean Meteorological Organization (CMO), which has been working with the WMO to improve marine meteorology competencies and service delivery. The Caribbean Institute for

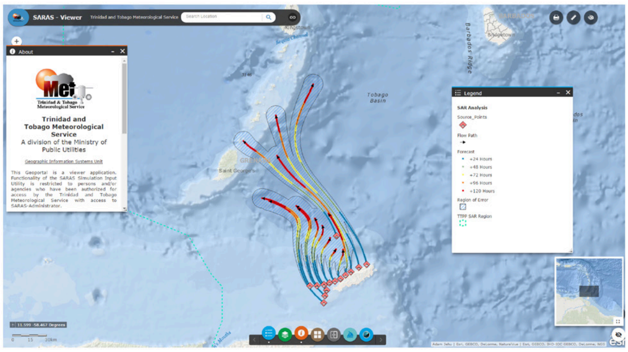
1 Permanent Representative of the British Caribbean Territories to the WMO

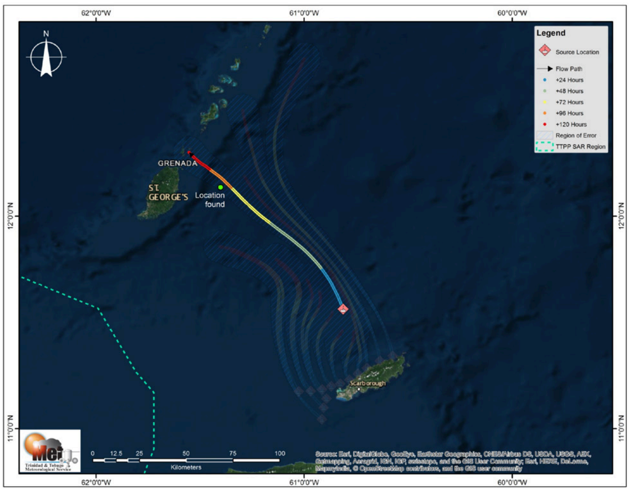
2 President of WMO Regional Association V (South-West Pacific), Permanent Representative of Tonga to the WMO. Director of Meteorology and Coast Watch Services, Tonga Meteorological Services

3 Hydrological Adviser of the British Caribbean Territories to the WMO

Meteorology and Hydrology (CIMH) and has taken the lead on training and technical support and has embarked on the establishment of a Marine Forecast Support Centre that will support:

- capacity development to deliver improved regional and national marine forecasts
- regional and international partnerships to support marine observations and science to better manage marine resources and marine early warning systems
- regional and international scientific collaborations to advance marine science research and research capacity across the region.

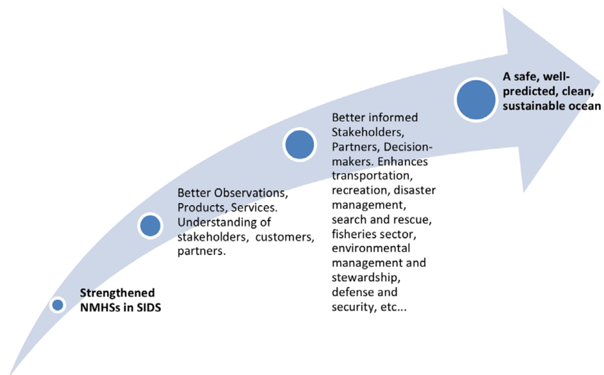




Example from the Trinidad and Tobago Meteorological Service of Search and Rescue Analysis System (SARAS), which predicted drift scenarios (upper) to identify the search region for a fishing vessel with a lone fisherman during 4-7 September 2016. The prediction model was based on hindcast numerical weather prediction models, archived satellite imagery, Doppler radar data, and revised using reanalysis ocean currents every 12 hours; (lower) the successful scenario illustrating the location found. (Source: Trinidad and Tobago Meteorological Services)

CIMH was a key participant in the 2020 EUREC4A field campaign, which supported extensive marine data collection east of the Caribbean island chain extending from Barbados to Suriname. The campaign is expected to lead to major advances in understanding of the marine environment. The Marine Forecast Support Centre will integrate CIMH's regional Wavewatch-3 daily significant wave-heights 7-day forecasts, and its evolving regional Hybrid Coordinate Ocean Model (HYCOM) and observation platform. In 2019, with sponsorship of the Cooperation of African, Caribbean and Pacific (ACP) States and the European Union (EU), via the Caribbean Development Bank (CDB), CIMH delivered a 3-week regional marine forecasting workshop to over 20 persons: members of its staff, of NMHSs and other stakeholders. Since the workshop, several NMHSs have begun the process of implementing their own forecast models to improve their marine forecasts.

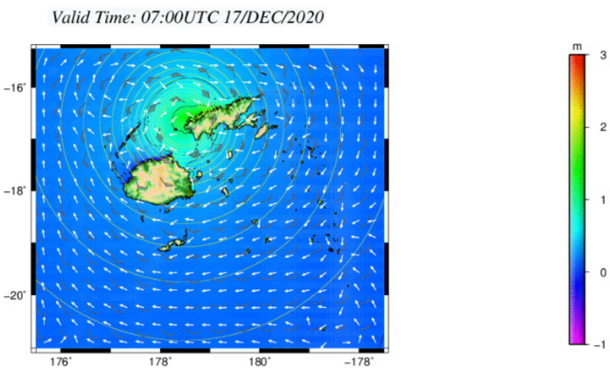
In terms of marine service delivery, the CMO Headquarters Unit has been coordinating with the Regional Maritime Adviser of the IMO, the Association of Caribbean States and other regional stakeholders to connect with maritime customers in the Caribbean and to better understand their needs. Those activities have aided the WMO in the development of training for user-oriented services. The strengthening of NMHSs in SIDS, through improvements along the science-to-services value chain, enhances decision-making and stakeholder performance in a variety of maritime and coastal sectors.



The marine services value chain for SIDS.

Pacific Islands

Often referred to as Large Ocean Island States, the 22 Pacific SIDS are scattered across the planet's largest ocean with vast ocean EEZs. They are reliant on the marine economy for survival. Ocean information is the basis of sound decision-making for sectors such as fisheries, tourism, transportation and basic safety services at the coast and at sea. This is especially true during weather and climate extremes that are often ocean related, for example coastal hazards, high waves, storms including tropical cyclones and rising sea levels. Climate change has exacerbated these threats and brought the additional threat of sea level rise. Furthermore, the threat of geologically induced hazards such as tsunamis pose a great risk. Meteorological services are key to the provision of early warnings at sea and along the coast for these island economies. This importance was recognized in 2015 by the Pacific Meteorological Council (PMC) with the establishment of a dedicated Pacific Islands Marine and Ocean Services Panel (PIMOS). The Panel offers technical advice to the PMC on marine and ocean services matters for the region.



Storm Surge Model product of Tropical Cyclone Yasa in December 2020 that allowed the Fiji Meteorological Service to provide warnings to coastal communities of the Fiji Islands. (Source: Fiji Meteorological Service)

Following recommendations from the 5th Pacific Meteorological Council (PMC-5) in Samoa in 2019, innovative tools are being deployed to strengthen high resolution ocean forecasts (wave inundation, for example) across the Pacific. These tools will complement systems currently operating or in development in Fiji, Kiribati, Republic of the Marshall Islands, Samoa, Tonga and Tuvalu. In addition, the WMO Coastal Inundation Forecasting Demonstration Sub-Project in Fiji, which was completed in 2019, successfully implemented a Coastal Inundation System at the Fiji Meteorological Service with funding from Korea Meteorological Administration (KMA). Similar coastal inundation forecasting projects are underway in Kiribati and Tuvalu, funded by the Climate Risk and Early Warning Systems (CREWS) initiative. The WMO Regional Association V (South-West Pacific) Tropical Cyclone Committee has also established a dedicated group of experts to support the development of coastal inundation and storm surge early warnings across the region.

Small Outboard Motor (OBM) boats that are used daily to cross between islands in Tonga. The small OBM boats are a common mode of transport throughout the Pacific. (Source: O. Fa'anunu, 2019)

In parallel, the Pacific NMHSs are actively participating in international discussions such as the Global Multi-Hazard Early Warning Conference (MHEWS), jointly organized by the WMO along with other international partners such as United Nations Office for Disaster Risk Reduction (UNDRR) and UNESCO. Related to this, the Pacific Islands are involved in the International Network on Multi-Hazard Early Warning Systems (IN-MHEWS) and the development of the Global Multi-Hazard Alert System (GMAS). Efforts are underway to strengthen both coastal MHEWS and impact-based forecasting in the Pacific Islands.

Climate variability and tidal change impacts are keenly felt in the Pacific Islands. To help the islands prepare for, adapt to and mitigate impacts from these challenges, the Australian Bureau of Meteorology established the Climate and Oceans Support Program in the Pacific (COSPac). Consultation across the islands is helping the Program to build tools that can forecast and report on climate, tides and the ocean. Examples include monthly ocean outlooks and a variety of forecast and information on sea surface temperature, sea level, chlorophyll mapping, waves, king tides and coral bleaching alerts to improve the understanding of impacts in coastal zone fisheries, businesses and communities. Seven NMHS in the region are now delivering these services and an eighth will join them by the end of 2021. The COSPac season climate outlooks are useful to communities likely to be impacted by climate variability events such as the El Niño Southern Oscillation (ENSO). COSPac is also supporting the long term and sustained monitoring of tides, which is helping to build a long-term record of sea level data across the islands.

The Pacific Ocean Portal developed under the COSPPac project to support the NMHSs to develop ocean products for their sectors.

To further build resilience and strengthen early warning systems, a coordinated regional effort is in progress in the Pacific to create a wave buoy network for early warning and inundation detection that will capitalize on historical regional cooperation between countries. State-of-the-art baseline data have been and are being collected through a series of projects and several studies that will contribute to increased ocean hazard-related risk knowledge are underway.

The WMO-IOC Data Buoy Cooperation Panel (DBCP) is planning a next-phase Pacific Islands Ocean Data Access and Applications Workshop in 2021. The WMO Marine Services Course, currently planned for 2020-2021, will complement these capacity development efforts, enabling NMHSs to self-assess their capacity and to share their experiences with other NMHSs. The results will be used to tailor a specific training to address the needs identified by the participating NMHSs. It will also support the implementation of marine weather competency training.

Tsunami early warning is also of critical importance in the Pacific Islands, where many of the meteorological services work closely with National Disaster Management Agencies to coordinate early warnings. A project funded by the Japanese Government through JICA (Japan International Cooperation Agency) is setting-up a Nationwide Early Warning System for Tsunami in Tonga, installing 88 tsunami sirens and over 500 community radios. The Pacific Resilience Program, funded by the World Bank, is upgrading the Tonga Maritime Radio for the same purpose.

Regional efforts in marine meteorology and oceanography are assisted by the Secretariat of the Pacific Community (SPC) and the Secretariat of the Pacific Regional Environment Programme (SPREP). They play an active role in developing oceanographic capacity in NMHSs and supporting the NMHSs to coordinate better with the marine sector, including the supervision of a PhD student since 2019. SPC is on the Global Ocean Observing System (GOOS) Steering Committee, and part of the Ocean Observations Coordination Group, jointly coordinated by WMO and the IOC.

The NMHSs of the Pacific Islands region are excited to get involved the UN Decade of Ocean Science for Sustainable Development and to seize the opportunities it offers to strengthen collaboration with other institutions and partners across the region. The NMHSs will benefit from the efforts to coordinate the identification of gaps on ocean data and science that are paramount for ocean, weather and climate services.

Multi-Hazard Early Warning Systems: The Coastal Inundation Forecasting Initiative

By Val Swail, Emeritus Associate, Environment and Climate Change Canada

The Coastal Inundation Forecasting Demonstration Project (CIFDP) and its subprojects aimed to improve safety from flooding in communities at risk, a fundamental priority of WMO. CIFDP was unique in facilitating the design and development of a comprehensive alert and warning system for coastal flooding caused by multiple sources.

Four separate and disparate CIFDP subprojects were undertaken, in Bangladesh, the Caribbean, Fiji and Indonesia (see WMO Bulletin 68(2), Early Warnings for Coastal Inundations). Each had a different set of forcing mechanisms which, coupled with the varying degrees of capacity and emergency management structure within the country, made them unique. Their successful implementation showed that integrated coastal inundation forecasting and warnings can be improved and coordinated by National Meteorological and Hydrological Services (NMHSs). In the following paragraphs, we describe the general considerations required to undertake a coastal inundation forecasting (CIF) early warning system, with some illustrative examples from the most recently completed project, Fiji[1].

What to predict? Fiji experiences tropical storms that bring heavy rains and river flooding along with large storm surges and high seas and damaging inundation due to long period swells from extratropical storms in the southern ocean off New Zealand. When other factors – such as the tide and sea surface height anomaly and a fringing reef along the south coast – are taken into account, the forecast problems for a coastal inundation system in Fiji are very complex, requiring innovative modelling approaches and impact-based products. This is further complicated by the need for timely forecasts and warnings, usually with more limited capacities associated with Small Islands Developing States (SIDS).

1 This project was made possible through donor funds from the Korea Meteorological Administration (KMA)

It is very rare that the required accuracy of bathymetry and topography information is available, particularly in SIDS and Least Developed Counties (LDCs). Necessary meteorological and oceanographic information – waves, water level, river levels and flow – is also usually inadequate. As part of the Fiji project, improvements were made through detailed surveys to the bathymetry and topography information on the coral coast, vital for mapping coastal inundation (note that in the Caribbean subproject topography enhancements were achieved through the use of the TANDEM-X satellite, which provided data equivalent to the gold-standard LiDAR surveys). Wave measurements from buoys deployed on the Coral Coast as part of the CIFDP provide early warning of damaging swells coming from the south; they also provide vital information for the validation of the forecast systems. New water level measurements also provide valuable information for coastal flooding. Unfortunately, these buoys are often subject to damage, either by accident or through vandalism. A new WMO video (available here) was developed to raise awareness in local communities by highlighting the value of this critical ocean infrastructure for their own safety and livelihoods.

Forecasts and warnings are not useful unless they reach the "last mile", i.e. the general population. In addition to radio and TV broadcasts, the Internet and social media are used extensively in Fiji for warning dissemination. Social media were widely used for warnings about TC Harold; the total reach of Facebook peaked to 172 864 according to Fiji Meteorological Service (FMS). Twitter had 6 404 impressions, and Instagram warnings were also issued.

Capacity development for FMS operations covered all the components of the forecast system and life cycle management of the new measurement systems for waves, ocean and river levels. Institutional end users, such as the disaster managers, were also trained to use the new forecast products. In addition, public awareness of coastal inundation was addressed by the development of a WMO video (available here) on the dangers and actions to be taken when fleeing or if caught in rising waters.

Coral Coast, Fiji is one of the well-known tourist areas, where beachside resorts are located. The tourist beaches are prone to coastal inundation from long range swell from the southern ocean – the top image shows the event in 2011, and the second image shows the same umbrella, damaged after the event (Source: SPC)

In April 2020, Severe Tropical Cyclone Harold carved a path through several Pacific Islands. As the storm approached, FMS issued its first ever wave and storm surge warnings during a cyclone, enabled by a new coastal inundation forecasting system of the CIFDP Fiji-subproject. Mr. Misaeli Funaki, Director of the FMS, reported that "the new coastal inundation forecasting system enabled the accurate recording of wave and storm surge magnitude, and sound numerical model guidance for storm surge and waves. This led to timely forecasts and formed the basis of successful evacuation warnings to vulnerable communities during Tropical Cyclone Harold (more than 2 000 people were evacuated), which minimized fatalities from such a devastating and life-threatening storm." The Fijian National Disaster Management Office estimated that some 3 400 homes were impacted, and that damage was above FJ$ 10 million.

Tsunamis

Tsunamis are dangerous coastal threats. While infrequent, they have the potential to produce catastrophic impacts on coastal communities in a matter of minutes to hours. Tsunamis are not under the WMO mandate, however, many WMO Members have made their NMHSs responsible for issuing tsunami warnings. Thus, in this area, WMO collaborates closely with IOC, which leads a focused global tsunami warning and mitigation system. The WMO provides dissemination of tsunami warnings via the Global Telecommunications System (GTS) as well as transmission of data from some tide gauges via meteorological satellites.

While tsunamis have a different forcing mechanism and different predictive models, there are common requirements that are the same as for coastal inundation forecasting, including the need for better bathymetry and topography and for timely forecast dissemination 24/7 in a matter of minutes to hours. Many countries with vulnerable coastal communities also have operational tsunami warning systems. However, there are opportunities to leverage the successful international tsunami efforts in collaboration with the CIF-EWS; especially for community warning and the "last mile".

South Atlantic Ocean Prediction and Services

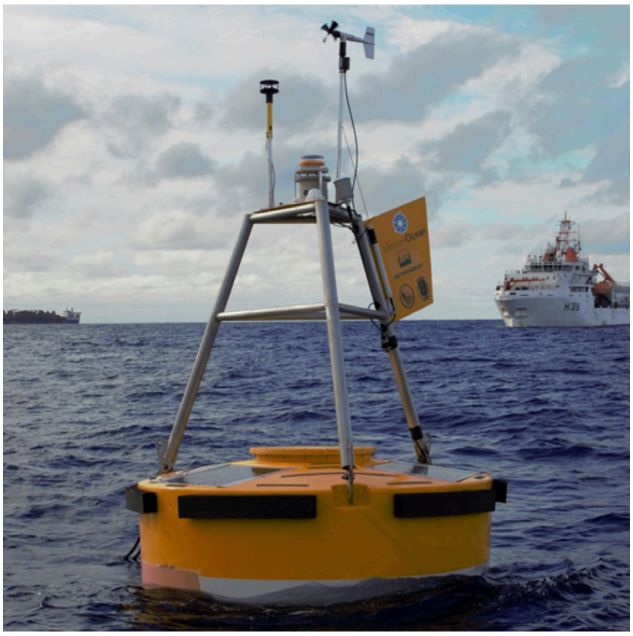
By Daniel Peixoto de Carvalho, Commander, Brazilian Navy

Marine weather warnings and forecasts are life-saving tools for mariners and populations that live by the sea. This is especially true in Brazil, where half the population lives within 200 kilometres (km) of coastline, and one-third of the population dwell in coastal cities. In addition, the Santos and Campos' oceanic basins in Southeast Brazil hold 92% of the second largest national oil reserve in South America. There are 54 oil rigs and Floating Production, Storage and Offloading units, which are ship-like oil rigs in the basins. Thus, the Atlantic Ocean plays a vital role in daily lives and the economy of Brazil. The Serviço Meteorológico Marinho (SMM, Marine Meteorological Service) must be weather-ready at all times.

SMM issues official weather warnings and forecasts for the coast and high seas over a maritime area of 12,047,648 km2. If it were a country, it would be the second largest in the world. Met-ocean observations are critical to forecasting over such an extensive area of responsibility. Weather analysis starts by comparing issued forecasts to the current weather. Numerical weather prediction models assimilate such observations to bring nature into their calculations. Therefore, forecasters cannot calibrate results in poorly observed areas.

On the east coast of South America, low-pressure centres develop from Northern Argentina to Southern Brazil very frequently and are associated with cold fronts that push extratropical cyclones offshore. However, the greater danger comes with less frequent tropical and subtropical storms. They develop once or twice a year on average and can take the population by surprise. Advance warning for such events come from SMM weather buoys and voluntary observing ships that provide *in situ* marine observations to complement satellite data.

On 27 March 2004, tropical cyclone Catarina developed off the coast of Santa Catarina state in Southern Brazil and made landfall between Passo de Torres and Balneário Gaivota. It was Brazil's first-ever tropical cyclone. It claimed the lives of 11 people, 20 cities declared disaster conditions and damages amounted to some US$ 40 million (Carvalho 2018). In 2011, SMM issued an official list of cyclone names. It has since named ten subtropical cyclones (Subtropical Storm Oquira was the most recent in December 2020) and one tropical storm, Iba, in March 2019.



Brazilian Navy Research Vessel Vital de Oliveira deployed two met-ocean buoys at Santos oil basin in early December 2020 (Credit: ENS Queiroz Machado)

However, operational forecasting is only a part of the story. Met-ocean observations are also fundamental to support scientific research. Brazilian researchers run such projects with support from universities and the private sector and also contribute to the Global Ocean Observing Systems (GOOS). The Executive Committee (EC) of GOOS-Brazil convenes representatives from different public administration areas – transportation, agriculture, fisheries, environment, science, technology and defense – and operates 10 Navy research vessels. Brazil offers a unique model of integration as the Centro de Hidrografia da Marinha (CHM) (Navy Hydrographic Centre) manages EC GOOS-Brazil and SMM. CHM also issues official nautical charts and navigational warnings. This integration at the national level creates opportunities at all levels as there is coordination on understanding stakeholder needs and knowledge of all available resources and assets, from ships, ship schedules, available seats, instruments and equipment to professional specializations. This global view is paramount to identify solutions and to develop win-win relationships between diverse stakeholders.

The integration of ocean services under CHM suggests a way forward for regional cooperation. Met-ocean observations in a single country are insufficient for operational forecasting and scientific research. Two key actions are needed to improve regional collaboration:

1. All Members should be aware of all ongoing national projects to collect data. A good start would be to update websites with information on active projects, detailing the standard procedures for collect data and providing regular, reliable outputs.

2. A unique secured Internet address could display the specifications of all available ships and their schedules, instruments, equipment, seat availability and the ship routes. A designated national authority could be empowered to gather and share this information.

The underlying goal is for Members to better know each other. Countries are usually aware of national capabilities and challenges but often do not look to their neighbors to complement them and fill the gaps. Coordination at the regional level would undoubtedly achieve this. The timing is right as the world looks forward to the UN Decade of Ocean Science for Sustainable Development having started in January 2021.

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Oil spill management and salvage in the Indian Ocean

By Pierre Daniel, Meteo-France and Renganaden Virasami, Mauritius Meteorological Service

Accidents happen. And once they happen, time is of the essence when it comes to rescuing victims, salvaging damaged goods and property and the subsequent clean-up. This is especially true at sea where there can be treacherous and changing conditions. Marine weather forecasts and predictions, crucial for such efforts, can involve a range of national, regional and international entities. That was the case on 25 July 2020, when the bulk carrier *Wakashio* ran aground on a coral reef near the Pointe d'Esny, in southern Mauritius in the Indian Ocean.

The Wakashio wreck at the south of Mauritius, 21 August 2020 (©Cedre)

The vessel, with some 20 crew, contained 3 800 tons of fuel oil (VLSFO), 200 tons of marine diesel and 90 tons of lubricant, but no leaks were observed when the wreck occurred. Nonetheless, danger was imminent and an emergency response protocol was put into action. Meteorological service played a critical role.

The Mauritius Meteorological Service (MMS), within minutes of learning of the wreck, provided all authorities concerned with information on the state of the sea at the time of wreck and 3-day weather forecasts for the wreck area, which included wind and wave parameters. The Mauritian authorities activated the national anti-pollution plan and alerted neighbouring countries, including France (Reunion Island). A first oil drift calculation, made with the MOTHY drift model of Météo-France, showed that a leak could reach the Mauritian coast very quickly, however, the risks for Reunion Island seemed limited. MMS continued to report twice daily to relevant authorities with 3-day forecasts for sea-state, wind and wave. Wave observations from the waverider buoy off Blue Bay (a couple of km from the wreck) were closely monitored and regularly communicated to all parties concerned.

Then, a few days after the shipwreck, the Mauritian Coast Guard detected small oil leaks in the lagoon and deployed preventative anti-pollution booms around the *Wakashio*. Despite considerable resources, it was impossible to refloat the vessel.

A mangrove impacted by pollution at Anse Fauvelle, Mauritius (©Cedre)

The critical role of marine weather and ocean forecasting

On 6 August, the situation deteriorated: the vessel was leaking and an oil slick was observed on the sea surface. MMS increased their reporting frequency to 3 times daily of 5-day forecasts of weather at sea, wind and wave. The 5-day forecasts were based mainly on the U.S. National Oceanographic and Atmospheric Administration's (NOAA) Wavewatch III and real-time observation of the wave and wind at sea from the MMS station at Blue Bay to develop accurate forecasts of local sea conditions. The Director of MMS provided daily marine weather briefings to the National Crisis Committee (NCC), as well as twice weekly briefings to the National Crisis Management Committee, chaired by the Prime Minister. The marine forecasts informed all decisions taken to manage the oil spill and manage the wreck.

First storage location for recovered waste which was stored in barrels (©Cedre)

The Commander of the Southern Indian Ocean Maritime Zone requested the assistance of Météo-France and alerted the Drift Committee, led by Cedre[1], including experts from Météo-France, the Service Hydrographique et Océanographique de la Marine (Shom) and the Institut français de recherche pour l'exploitation de la mer (Ifremer)[2]. Drift predictions of the extent of the pollution in the lagoon were made by Météo-France to estimate the risks to the coasts of Reunion Island. Outside the lagoon, ocean current forecasts from the Copernicus Marine Service were used.

Most of the fuel oil was pumped out of the wreck on 12 August and the clean-up of the coasts began with many local volunteers.

On the 15 August, the *Wakashio* broke in two during a towing attempt. The drift forecasts then included drifts of ship debris. On the 17th, the front part of the vessel was towed out to sea, while the Mauritian authorities considered where to sink it. Météo-France made drift forecasts for several geographical positions to determine which locations may have a pollution risk for Reunion Island. The place of immersion was shifted northwards following this analysis.

The bow sank on the 24 August. The stern is still on site. No pollution has affected the coasts of Reunion Island. The pollution that has affected Mauritius is estimated at between 600 and 1 000 tons. The MMS continue their daily 5-day outlooks for the NCC and NCMC. All weather and sea data for the event are being archived for further analysis and studies.

1 Centre of Documentation, Research, and Experimentation on Accidental Water Pollution

2 French Research Institute for Exploitation of the Sea (French: Institut français de recherche pour l'exploitation de la mer)

2021 United Nations Decade
of Ocean Science
2030 for Sustainable Development

This special Ocean themed WMO Bulletin is officially registered as a contribution to the United Nations Decade of Ocean Science for Sustainable Development.

WMO wishes to acknowledge the following individuals for their assistance with the editing of this special "Ocean" themed Bulletin:

- Ian Lisk, President, WMO Commission for Weather, Climate, Water and Related Environmental Services & Applications, and Head, Hazard Partnerships, The Met Office (UK)
- Thomas J. Cuff, Chair, WMO Standing Committee on Marine Meteorology and Oceanographic Service, and Director, Office of Observations, National Weather Service, U.S, National Oceanic and Atmospheric Administration
- Val Swail, Emeritus Associate, Environment and Climate Change Canada
- Jonathan Lynn, Head, Communications and Media, Intergovernmental Panel on Climate Change

World Meteorological Organization

7 bis, avenue de la Paix - Case postale 2300 - CH-1211 Geneva 2 - Switzerland
Tel.: +41 (0) 22 730 81 11 - Fax: +41 (0) 22 730 81 81
Email: wmo@wmo.int - Website: www.public.wmo.int

ISSN 0042-9767