Net Zero Oceanographic Capability

Ocean Observing Capability from Space

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1. Context and Purpose of this document

This document forms part of the Net Zero Oceanographic Capability report submitted to NERC in Q3 of 2021.

It summarises the findings of a dedicated activity to examine the contribution of spaceborne systems to deliver oceanographic observing capability.

The objectives of this activity are:

1. to examine spaceborne oceanographic observing capability available in 2020, identifying:
    - what ocean properties are currently measured from space.
    - who uses spaceborne ocean data and how are satellite data accessed.
    - how do spaceborne ocean observations relate to other ocean data.
2. to consider the evolution of spaceborne ocean observing in the 2020-2035 timeframe, including:
    - expected spaceborne observing capability in 2035.
    - trends and transformational technologies.
    - gap analysis and unknowns.
3. to identify the implications of satellite ocean observing capability on:
    - carbon emissions.
    - diversity and inclusion.

The report is structured to follow the logic outlined above.

The report concludes with a set of recommendations that identify gaps and opportunities to develop, consolidate and integrate spaceborne oceanographic capability as part of a coherent ocean observing system of global, coastal and polar seas.

2. Working assumptions

This activity focuses on satellite observations of physical and biogeochemical properties of the ocean globally and in coastal, shelf and polar seas. It does not consider spaceborne observations of human-related activities such as shipping, oil spills, fisheries monitoring, coastal management, etc.

The spaceborne observing capability considered in this report includes international, bilateral and national missions whose data are available free of cost for civilian purposes. Military and commercial missions are not considered.

3. Satellite Ocean Observing Capability: 2020 Baseline

This section reviews the satellite oceanography baseline capability in 2020, considering:

- what ocean properties are currently measured from space;
- who uses spaceborne ocean data and how are satellite data managed;
- how do spaceborne ocean observations relate to other ocean data.

3.1. Ocean properties measured from space in 2020

Spaceborne sensors provide measurements of many important ocean properties on many spatial and temporal resolutions and scales and levels of accuracy. Table 1 summarises the ocean properties that can be measured from space in 2020, with key characteristics of the spaceborne observations and some indicative missions. In this section, we begin by providing a short synopsis about the remote sensing method and applications for each satellite ocean observable.

3.1.1. Sea Surface Height or Sea Level

Sea Surface Height (SSH) or Sea Level (SL) is the height of the ocean surface above the reference ellipsoid. SSH is estimated with satellite altimeter radars that measure the range (distance) between the satellite and the ocean surface. SSH leads to global measurements of the ocean circulation by relating SSH differences (ocean slopes) to large-scale geostrophic currents using the geostrophic approximation and knowledge of the marine geoid. SSH also relates to sea level and storm surges, providing unique observations of sea level change on global, regional and coastal scales.

Satellite altimeter SSH has revolutionised our understanding of ocean processes and dynamics and forms an essential component of today’s ocean observing system. As an Essential Ocean Variable and an Essential Climate Variable, it requires high precision, accuracy and stability that put rigorous demands on the space segment. Key requirements for SSH are: to deliver sustained continuous global observations for climate research; to deliver near-real-time observations from 4 or more satellites in complementary orbits to observe the energetic ocean mesoscale (50-200km) for assimilation in operational ocean forecasting systems.

3.1.2. Sea Surface Temperature

Sea Surface Temperature (SST) is the water temperature close to the ocean surface. Satellite SST is obtained by sensing the natural emissivity of the ocean with infrared or microwave radiometer instruments. Infrared sensors produce high-accuracy high-resolution SST images that serve to map ocean mesoscale eddies and fronts, with levels of accuracy and precision that are compatible with climate research. IR SST data are however subject to large data losses due to clouds. IR SST relates to the temperature of the top few microns of the ocean (skin temperature) which can differ appreciably from the temperature sensed with others methods in the top few metres. Microwave radiometers produce SST images that are mostly unaffected by clouds, but spatial resolution and accuracy are poorer. Extensive efforts have been made to create blended SST products from infrared and microwave radiometer data. SST is the longest ocean dataset available from space, and together with SSH, one of the most important observations for modern oceanography. SST data are used extensively as model forcing and for assimilation in ocean, atmosphere and coupled models.

3.1.3. Ocean Chlorophyl concentration and inherent optical properties

Ocean Chlorophyl concentration (Chl-A), Suspended Particulate Matter (SPM) and other ocean water inherent optical properties (IOPs) can be derived from spectrally resolved water-leaving reflectances sensed by spectrometers operating in visible and near-infrared bands. Optical sensors produce high-resolution wide-swath images that serve to map the spatial extent and variability of water (river and sediment plumes) and land (morphological coastline changes). Optical sensors cannot observe through cloud cover and rely on suitable levels of natural light. This impacts their usefulness at high latitudes and polar regions outside summer months. Ocean colour provides key observations to understand the role of phytoplankton in marine systems, the global carbon cycle and the marine ecosystem response to climate change. Research continues to actively explore ways to extract information about other biogeochemical properties and waterborne substances. Increasingly, satellite optical data are assimilated in biogeochemical ocean models to provide wider assessments of marine ecosystem health. In coastal waters, optical data have direct applications to water quality monitoring and coastal management applications.

3.1.4. Ocean surface wind

Ocean surface wind (OSW) is the velocity of the air above the ocean surface, typically at a reference height of 10 metres. Satellite winds are measured using microwave instruments that sense wind-induced changes in ocean surface roughness (on scales of 1-50 cm). Microwave scatterometers measure wind speed and wind direction (i.e. Ocean Surface Vector Winds; OSVW) whilst microwave altimeters, radiometers and Synthetic Aperture Radars (SAR) only measure wind speed. Recent technical advances include GNSS reflectometry that uses bi-statically reflected satellite navigation signals (e.g. GPS, Galileo) to measure reflective properties of the Earth surface. Ocean winds are relevant to air-sea exchanges (momentum, heat, carbon, water) and are a key input through assimilation into operational systems for numerical weather forecasting, hurricane forecasting, storm surge forecasting, ocean wave forecasting and reanalyses.

3.1.5. Sea State

Sea State (SS) is the characterization of wind waves and swell in terms of integral parameters like wave height, period, direction or directional wave energy spectra. Waves generated by ocean surface stress evolve from wind waves to swell through nonlinear dynamical processes. Satellite altimeters measure Significant Wave Height (SWH) and wave period whilst SAR imagers estimate directional swell spectra from which integral parameters are derived (swell height, swell period, swell direction).

New empirical algorithms now also provide full wave parameters from SAR (e.g. SWH). Since 2018, the rotating altimeter, CFOSat, provides global estimates of the full directional wave spectrum. Sea state is relevant to ocean and climate science through waves' role in air-sea fluxes, global ocean circulation (e.g. dispersion of larvae, flotsam, plastic), vertical mixing and sea ice breakup. Ocean waves represent a major natural hazard for activities at sea (shipping, offshore industry, research and leisure cruises, instrument deployment and operations, etc.) and at the coast, where they are major contributors to coastal erosion, coastal and natural habitat loss, coastal flooding and sea level rise through wave setup, wave swash and wave runup.

3.1.6. Sea Surface Salinity

Sea Surface Salinity (SSS) is the concentration of salt in surface sea water. SSS is measured with satellite sensors through its influence of the sea water dielectric constant which changes surface emissivity at microwave frequencies around 0.5-1.5GHz (L-band). To retrieve SSS, the brightness temperature measured by L-band radiometers has to be corrected for SST and surface roughness (winds, sea state) effects, as well as many non-ocean phenomena (e.g. sun and moon glint, galactic noise, Radio Frequency Interference). Together with SST, SSS determines the density of sea surface waters, and therefore plays a key role in the global ocean circulation. SSS is also a marker of the balance between precipitation and evaporation, providing essential insight into air-sea exchanges, the global water cycle and climate.

3.1.7. Marine geoid and bathymetry

The geoid is the equipotential surface of the Earth's gravity field which, in the absence of wind and currents, would coincide with the ocean water surface. The geoid is an idealised irregular surface that relates to the distribution of mass within the Earth. Measuring the geoid globally has only become possible with the advent of satellite gravity missions like GRACE and GOCE in the early 2000s. In oceanography, the geoid is used extensively in combination with satellite altimeter sea surface height data to reconstruct absolute ocean geostrophic currents. Today's geoid models are limited by relatively coarse spatial resolution (100km at best) and the low confidence in coastal regions. Conversely, the GRACE mission revealed significant temporal changes in the gravity field which have since been related to redistribution of mass around the globe (including the redistribution of ocean waters and freshwater resources over land).

Bathymetry is the ocean depth relative to sea level, often now known as seafloor topography. In the open ocean, bathymetric features like underwater sea mounds have clearly detectable signatures in high-accuracy satellite altimeter sea surface height data. Notably, the improved accuracy and finer track separation of the Cryosat-2 satellite altimeter have led to global maps of deep ocean bathymetry with unprecedented levels of detail. The method is limited to deep waters though.

In shallow waters, bathymetry can also be estimated using optical images. The method is limited by water clarity which restricts its application to waters shallower than 30-50 metres. The improved resolution of modern spectrometer imagers (e.g.

Sentinel-2) can however produce regularly-updated free bathymetry maps with resolutions of the order of 20 metres. A wide range of satellite-derived bathymetry products are available via various commercial service providers.

3.1.8. Ocean currents

Ocean currents are the continuous directed movement of sea water generated by various forces like tides, pressure differences (geostrophy), wind stress, ocean waves, etc. Geostrophic currents can be derived from sea surface height gradients (SSH; see 3.1.1) measured by satellite altimetry, but only large and mesoscale features greater than 70 km (~20 km for delay Doppler altimeters) are resolved. SSH-derived currents do not include contributions from tides, wind (Ekman), near-inertial motions, waves (Stokes drift) and other ageostrophic motions. Despite these limitations, altimeter-derived currents are some of the most widely used satellite observations in ocean sciences.

Wind-driven ocean currents can be estimated using satellite wind stress data, notably from microwave scatterometers, with standard spatial resolutions around 25km. Doppler (phase) measurements from Synthetic Aperture Radars (SAR) and Along-track SAR Interferometric contain information about the total ocean surface displacement in the line-of-sight of the satellite sensors. Doppler data from high-resolution radar images (available at resolutions as fine as a few metres), can produce 2D maps of across-track Radial Surface Current Velocity with resolutions of order 1 km. The method has great potential for ocean circulation research, particularly in coastal regions, although difficult issues remain about how to correct the data for unwanted effects of ocean wind waves on microwave Doppler signals.

3.1.9. Sea Ice

Sea ice is frozen seawater that floats on the ocean surface. Since 1979, satellites have provided continuous, nearly complete record of sea ice extent and sea ice concentration using sensors that observe microwave radiation emitted by the ice surface. Unlike visible light, microwave emissions pass through clouds, giving year-round day-night capability, even during polar winters. Satellite altimeters and lidars measure sea ice elevation, freeboard and thickness over a mesh of narrow tracks. Advances in microwave altimetry (e.g. Cryosat-2, Sentinel-3) provide all-weather day-night capability that can detect sea ice features (e.g. leads) down to a few 100 metres, whilst lidars provide sub-decametre resolution (down to 7m for ICESat-2). Sea ice has a profound influence on climate, the global ocean circulation, weather and polar ecosystems. There are also considerable interests in real-time monitoring of sea ice conditions to assist shipping and offshore activities in ice-covered seas (Arctic).

3.2. Satellite ocean observing capability: users

Today, satellite ocean observations are generally free and open to all users regardless of nationality, status or intended use. This open data policy, spearheaded many years ago in the US by NASA and adopted more recently by the EU for the Copernicus Sentinel programme, has revolutionised the exploitation of satellite observations. As a result of this open data policy, the use of satellite data increased massively in recent years, and satellite data are now typically used multiple times, by multiple users, for multiple applications.

In this section, we outline some known uses of satellite ocean data by scientists, operational agencies and stakeholders in the private sector, noting that a complete review of this fast-evolving landscape is impossible, particularly in the context of such a short review. The last section details the main means of satellite ocean data access available today.

3.2.1. Science users

Satellite ocean observing capability provides essential information about many physical and biogeochemical components of the global ocean and its interactions with the atmosphere, the seafloor, with land and the cryosphere. Satellite ocean data are intrinsic constituents of modern oceanography, environmental and climate science, and are generally used in tandem with data from in situ sensors and numerical models.

Science applications of satellite ocean data are multifarious. Individual satellite images provide instantaneous wide-swath snapshots of ocean conditions (e.g. temperature, sea surface height,…) that serve to characterise the wider oceanographic context of in situ activities at sea (e.g. to guide mooring deployments or autonomous vehicle surveys). Instantaneous images provide also unique information about specific events, particularly in unexpected, extreme or remote conditions where other observations are difficult or absent (e.g. hurricanes, iceberg breakup, harmful alga bloom,…).

Satellite observations from multiple overpasses and multiple missions are combined to produce gridded or merged products that represent the most commonly used satellite data in science. Gridded satellite datasets document the state and variability of the ocean on global to local spatial scales, and hourly to multi-decadal temporal scales, and are used extensively to complement in situ observations and to validate numerical models (ocean, atmosphere, waves, biogeochemistry, climate).

3.2.2. Operational users

Satellite ocean observations are a critical capability for operational users through the data assimilation needs of their forecasting systems. This way, satellite ocean data are important for Numerical Weather Prediction (NWP) and natural hazard forecasting including hurricanes, extra-tropical storms, surges, floods, extreme sea states etc. Satellite ocean observations directly impact the quality of forecasts, leading all operational forecasting agencies (e.g. The Met Office, the NOAA

Hurricane Center, KNMI, Meteo France etc.) to use satellite ocean data as a major assimilation data feed. As a consequence, the data needs of operational agencies dominate the definition of requirements for satellite data latency (how soon data are available after acquisition) and for new satellite observations, products and missions. At the European level, ECMWF and Copernicus service providers like Copernicus Marine Service (CMEMS; https://marine.copernicus.eu) and the Copernicus Climate Change Service (C3S; https://climate.copernicus.eu) are dominant players in this field, providing easy free access to global satellite and model datasets in self-documented, easy-to-use, formats that have opened up the uptake of satellite and assimilation products by the wider scientific community.

3.2.3. Private sector users

Satellite ocean observing also attracts a large and growing body of stakeholders in the private sector. Private sector users tend to fall in one of three categories:

- Aerospace industries (so-called EO upstream sector), consisting of large multinational companies and SMEs that develop and build satellite sensors, instrument payloads, components and satellite platforms for large and small missions and (in some cases) deliver private satellite launch capability. These users' interest in satellite ocean data lies in the opportunities they offer for innovation, R&D and procurement of new capability through future missions. Examples in the UK include Airbus, Thales, Surrey Satellite Technology Ltd, Spire, etc.
- Commercial Earth Observation service providers (so-called EO downstream sector), consisting of large multinational companies and SMEs that offer EO services including project management, specialist consultancy, software development, bespoke satellite data products or value-added satellite-derived information products. These users' interests in satellite ocean data lie in the products and services they can develop and commercialise for paying customers. Examples in the UK include CGI, Telespazio UK, SciSys, 4EI, EarthI, Pixalytics, etc.
- Other private sector stakeholders, who use satellite ocean data directly or indirectly (e.g. as users of operational products or commercial EO services) to inform their business and decision-making. Examples include companies from the energy, transport, fisheries, water, offshore, wind and marine renewables sector (e.g. EDF Energy, E.ON, Shell) and the insurance, certification and quality assurance sector (e.g. Lloyds' Register, Bureau Veritas).

3.2.4. Government departments & public authorities

Satellite ocean observing capability is relevant to a number of government departments, both because it is part of their remit and because they are direct beneficiaries of the data.

BEIS are responsible for UK investments in Space and Earth Observation, working through various operators including the UK Space Agency (as UK representatives within ESA), Innovate UK, the Satellite Applications Catapult and the Met Office (as UK representatives within EUMETSAT). BEIS' interest lies in promoting innovation and opportunities for UK industry to support skilled jobs, economic growth and export.

Defra are responsible for the UK contribution to EU Copernicus, including the UK's ongoing commitment to the Sentinel satellite programme. Defra has direct interests in spaceborne Earth Observation by virtue of the role of satellites in delivering Defra's statutory monitoring obligations, for example through CEFAS (for water quality) or the Environment Agency (for flooding). The use of satellite ocean data by Defra remains low, however, and this represents one potential area of growth, notably for coastal change monitoring.

MOD have obvious interests in satellite ocean observing capability, notably to support the Navy and other military activities overseas. Little is known about MOD's use of satellite ocean data but there are indications of a desire by MOD for improved understanding and utilisation of the ocean observing capability offered by today's satellites. Improved uptake of marine EO data by MOD represents another area of strong potential growth.

3.3. Satellite ocean observing capability: data access

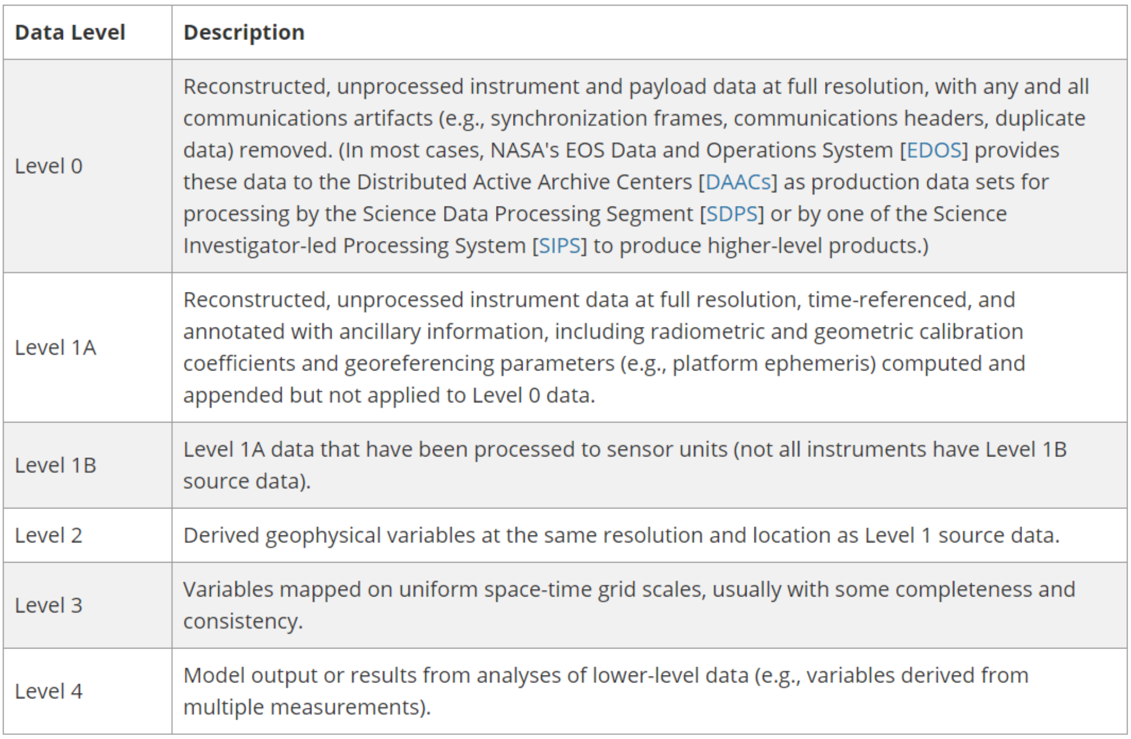
Satellite ocean observations are generally available freely and openly through various specialised online systems dedicated to disseminating data for different types of mission (science, operational), product levels (Level 0-4) and latency (Near Real Time/Non Time Critical). The product 'level' of the data refers to the degree of processing that has been applied, with exact definitions varying between agencies and satellite missions. As an example, Figure 1 shows the definitions used by the NASA Earth Observing System Data and Information System.

Satellite data products up to Level 2 are typically distributed by the space agencies responsible for ground processing (e.g. ESA, EUMETSAT) or dedicated EO archiving centres (e.g. PO.DAAC; https://podaac.jpl.nasa.gov). Satellite data used most typically for science are Non Time Critical (NTC) products. Those provide the highest-quality processing and delayed mode corrections and products are available typically within 30 days of acquisition. Near-Real-Time products are designed for time-critical applications (assimilation in forecasting systems, sea operations support, emergency interventions) whereby satellite data are available within a few hours of acquisitions

The European Space Agency provides access to data from ESA EO Missions, Third Party Missions, the Copernicus Space Component (CSC), as well as sample and auxiliary data from a number of missions and instruments (https://earth.esa.int). Likewise, NASA provides access to a wide range of satellite data through online repositories like https://earthdata.nasa.gov. Access mechanisms differ for different missions and range from interactive graphical user interfaces (GUIs), to secure ftp and on-demand cloud-based processing.

Data from operational missions tend to be promoted and serviced through operational data portals such as the EUMETSAT Ocean and Sea Ice Satellite Application Facilities (OSI-SAF) and the NOAA National Environmental Satellite, Data, and Information Service (NESDIS). Access to CSC Sentinel data is assured through the Copernicus Open Access Hub (https://sentinels.copernicus.eu) as well as mission specific online facilities like the EUMETSAT Copernicus Online Data Access for Sentinel-3 Ocean. For some missions, a selection of products are downloaded and archived by national data centres, like for example in the UK, the Centre for Environmental Data Analysis (CEDA; https://www.ceda.ac.uk) part of NERC's Environmental Data Service.

Beyond the original satellite observations, a multitude of satellite-based added-value products (Level 3 and above) are distributed also by organisations that produce them. This includes universities, research organisations, operational agencies and commercial companies, among others. Within Copernicus, the CMEMS and C3S offer notable access points to satellite ocean data, as well as in situ and model data, as well-documented standard products for all kinds of users and applications.



Data Level	Description
Level 0	Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e.g., synchronization frames, communications headers, duplicate data) removed. (In most cases, NASA's EOS Data and Operations System [EDOS] provides these data to the Distributed Active Archive Centers [DAACs] as production data sets for processing by the Science Data Processing Segment [SDPS] or by one of the Science Investigator-led Processing System [SIPS] to produce higher-level products.)
Level 1A	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e.g., platform ephemeris) computed and appended but not applied to Level 0 data.
Level 1B	Level 1A data that have been processed to sensor units (not all instruments have Level 1B source data).
Level 2	Derived geophysical variables at the same resolution and location as Level 1 source data.
Level 3	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency.
Level 4	Model output or results from analyses of lower-level data (e.g., variables derived from multiple measurements).

Figure 1: Product level definitions according to the NASA Earth Observing System Data and Information System (NASA, 2021)

3.3.1. Satellite data quality assurance

Quality assurance processes vary greatly for different satellite product levels and different data providers. For publicly owned missions, quality assurance is the responsibility of the space agency/operator (e.g. ESA) and Level 0 to Level 2 products are subject to strict quality assurance protocols against quantified mission requirements set before launch. For non-public satellites, no common quality assurance protocols are in place. Quality assurance of Level 3 and 4 products stays with the product originators and tend to be controlled via peer reviewed publication.

3.4. Relation with non-satellite ocean observations

Satellite and in situ ocean observations are strongly complementary and there are many reasons why combining satellite ocean data with non-satellite observations is beneficial. Satellites and in situ sensors measure the ocean with different spatial and temporal sampling, coverage, repeatability and levels of accuracy. Whilst many ocean properties cannot be measured with satellites, the availability of regular, global observations over many years and decades bring unique additional observing capability to in situ and modelling activities. Here, some of the motivations for combining satellite and non-satellite ocean data are outlined, noting those where better linkages could be advantageous.

3.4.1. Calibration/Validation of new satellite observations and products

In situ observations are essential to calibrate and validate measurements from recently launched satellites. Calibration is the process of quantitatively defining the system response to known, controlled signal inputs, and validation as the process of assessing by independent means the quality of the data provided (WMO, 1997). The same terminology and processes apply also to the calibration and validation of new geophysical products derived from new or existing satellites measurements (e.g. new ocean colour parameters).

Many types of in situ sensors and platforms are used to deliver the ground truth needed to evaluate the quality and reliability of satellite ocean data. Examples include the use of coastal tide gauges to validate altimeter sea level data; of moored buoys to validate satellite winds and sea state; of surface drifters and Argo to assess the quality of spaceborne salinity measurements. Increasingly, in situ data used for validation have to satisfy strict quality requirements to qualify as Fiducial Reference measurements (FRM) that can be used for validating spaceborne data.

Apart from a few notable exceptions (e.g. the Atlantic Meridional Transect programme onboard RSS James Clark Ross), observations from ships are used infrequently for satellite validation. Likewise, data from gliders and autonomous vehicles are not generally considered. This situation is likely due to the sporadic irregular sampling of these moving platforms, and lack of awareness in the Earth Observation community about the availability and means of accessing data from ships, gliders and other autonomous vehicles.

3.4.2. Supporting sea-going activities

Satellite ocean data are used routinely to optimise the positioning of ship surveys, and to support the deployment of moorings and of towed instruments. High-resolution ocean colour and sea surface temperature images are the most common observations used to guide sea-going operations, their wide swath and high-resolution being well suited to provide enhanced situational awareness. Those same satellite data are used also to support the navigation of glider fleets towards features of interest, or away from hazards in the ocean (e.g. icebergs, sea ice edge).

Other satellite observations are seldom used, probably through lack of awareness or logistical reasons (e.g. no knowledge or timely access to satellite data). For example, observations from high-resolution microwave radar imagers could represent valuable additional capability to support seagoing operations, particularly in adverse environmental conditions (poor/absent daylight, bad weather). Given the rapidly increasing number and diversity of satellite ocean missions, there are clear opportunities to using a wider range of satellite observations in support of seagoing activities.

3.4.3. Ocean and climate studies

The use of satellite ocean data in ocean and climate studies is a vast topic and it is not possible to cover this adequately in a short report. Instead, one example is given for illustrative purposes based on the RAPID observations of the Atlantic Meridional Overturning Circulation (AMOC) at 26°North.

The AMOC is a key component of both the Atlantic circulation and of the global climate system, being responsible for significant transports of heat, freshwater, carbon, and nutrients. Therefore, observing the AMOC is critical to both ocean and climate studies.

Initially, RAPID 26°N AMOC observations (starting in 2004) were based on in-water measurements from moorings, but even in the early stages, satellite winds were used to calculate the Ekman component of AMOC. More recently, the Ekman component has been obtained from re-analyses that incorporate satellite wind observations. Over time the approach to observing the AMOC has developed to include gliders and telemetry of data via satellite, and the exploration of satellite altimetry and gravimetry (ocean bottom pressure) to measure various components of AMOC currents. In terms of the heat and freshwater transports, Argo data have been incorporated into the calculations.

From the RAPID 26°N experience of observing the AMOC, it is clear that no one single observing approach – be it *in situ* (moorings, gliders, Argo) or satellite-based (altimetry, gravimetry, etc.) – can capture the full complexity of the AMOC flows in time and space. For example, at the western boundary at 26°N with its steep topography and strong currents, it is unlikely that gliders, Argo floats or altimetry will ever be able to provide the requisite measurements, and so a need for the use of moorings will remain. In contrast, at the eastern boundary, it is possible that the measurement system could be transitioned from moorings to a combination of glider and altimeter measurements.

However, it has to be borne in mind that when transitioning between measurements systems, they need to be overlapped to ensure that continuity and quality of measurements, especially of critical climate observations. This lesson has been learned with satellites, where dedicated tandem operations to allow overlapping missions are now customary. It is less common with regard to *in situ* observations, both with regard to more traditional approaches and newer autonomous ones. Overlapping observations will, in the short-term, incur higher costs (as two observing approaches are being run simultaneously) but this is absolutely critical if essential climate variables are being measured to ensure that the new approach is both continuous with the old one and produces data of a at least a similar or (hopefully) of a better quality.

This example serves to illustrate how ships, autonomous systems and satellites combine and contribute in different ways to the system needed today to observe the global ocean. Care must be taken therefore when migrating towards net zero carbon ocean observing capability to recognise that, whilst offering significant advantages in terms of sampling and operations, satellites and autonomous systems are not sufficient on their own to address every observing challenge.

4. Satellite Oceanographic Capability: 2020-2035 Horizon

This section reviews the evolution of satellite oceanographic capability in the 2020-2035 timeframe and beyond, considering:

- the expected spaceborne observing capability by 2035
- trends and transformational technologies
- gap analysis and unknowns

4.1. Approved spaceborne observing capability to 2035

4.1.1. Continuity of service for operational missions

Satellite ocean observations are now generally recognised as an essential component of the global operational observing system needed to support forecasting through assimilation. Observations such as SSH, SST, ocean colour, winds and sea state are now routinely ingested in near-real-time in most operational forecasting systems. The bulk to today's baseline capability is therefore expected to be maintained beyond 2035, mainly through established long-term operational programmes in Europe. Of those, the EUMETSAT METOP series and the EU Copernicus Space Component (Sentinels) are the two main programmatic routes that will ensure long-term continuity of service for satellite ocean capability (Table 2).

Other confirmed long-term commitments include numerous missions from China, India and Russia. However, access to data and metadata from these missions has historically been restricted and difficult, so these missions are not considered further.

4.1.2. Innovative science-driven ocean missions

Science-driven satellite programmes represent the other major route responsible for the development and launch of new missions. The Earth Explorer programme is ESA's most prestigious mechanism to select and develop science-driven missions. Earth Explorer missions have to address prominent scientific questions using innovative technology. Regular calls for mission ideas invite proposals from anyone in the scientific community. The scheme is popular but highly competitive, and the outcome is unpredictable. In 2019, ESA narrowly failed to select the Sea surface KInematics Multiscale monitoring (SKIM) candidate mission that proposed to measure total ocean surface currents globally for the first time. Since then, the Harmony mission was unexpectedly selected as the only candidate for Earth Explorer 10. If successful, Harmony will provide high-resolutions observations of surface currents and winds over extreme events and high-latitude storms.

Two approved missions that present significant interest to satellite ocean capability are the Surface Water and Ocean Topography (SWOT) mission and the Plankton, Aerosols, Cloud ocean Ecosystem (PACE) mission. SWOT is a highly innovative (and expensive) joint mission between space agencies in the US, France, Canada and the UK, with an expected launch in 2022. SWOT will be the first satellite to provide high-resolution two-dimensional images of sea surface height, that are expected to transform our understanding of ocean mesoscale dynamics. PACE is a NASA mission to advance observations of global ocean colour, biogeochemistry, aerosols and clouds and understand how the ocean and atmosphere exchange carbon dioxide. After being proposed for cancellation under the Trump administration in 2018, the mission was restored by Congress and is now under development with a launch scheduled for 2023.

4.1.3. New Space

Operational satellite programmes are characterised by long (decadal) development time and slow adoption of innovative technologies. Science-driven satellite programmes are prone to uncertainties (competitive selection process, unstable funding) and also characterised by development times in excess of 10 years. These long lead-in times and lack of flexibility has motivated the emergence of fast-track and disruptive space solutions that broadly fall under the umbrella of “New Space”.

New Space is a disruptive approach to space that relies on launches of numerous low-cost satellites in constellations. The approach has become viable thanks to the miniaturisations of sensors and the availability of low-cost commercial off-the-shelf components (COTS). The approach was pioneered by space companies whose business case depends on the availability of Earth Observation data. Examples relevant to ocean observing include Spire Global, Inc. and Capella Space, two multinational companies originally from the US, who fly constellations of multiple satellites in multiple orbital planes to deliver frequent observations of ocean, ice, land and vegetated surfaces using GNSS signals and X-band SAR systems (respectively).

4.2. Satellite ocean observing capability to 2035 and beyond

Most of the satellite ocean observing capability available today is set to continue to 2035 and beyond, courtesy of long-term European satellite programmes within Copernicus, Copernicus Next Generation and the Copernicus High Priority Candidate Missions (HPCM; Table 2). Whilst the technical specifications of these missions remain undefined at this stage, the driving principle of these operational programmes is the notion of guaranteed continuity of existing observing capability, with the potential for enhanced continuity that augments existing capability through technical improvements motivated by the documented needs of (operational) end-users.

In contrast, plans and prospects of science-driven, national and bilateral missions are unknown and unpredictable, given their exposure to random financial and political circumstances.

4.3. Gap Analysis

The ocean observing capability in the 2020-2035 timeframe features a number of recognised gaps listed below. We note that these gaps correspond to key drivers that will motivate proposals for new satellite ocean missions, some of which are likely to be approved and launched in the 2030-2040 horizon.

At time of writing, notable gaps in ocean observing capability include:

- Total ocean surface currents vectors, wind vectors and waves at 1-10km scales: this capability is critical to understanding small scale ocean surface dynamics and their contribution to horizontal and vertical ocean transports at air-sea-ice-land interfaces. Systematic observing of small-scale processes over all coastal, shelf and polar seas is the driving motivation of the SEASTAR mission proposal that was submitted by NOC to ESA Earth Explorer 11 in December 2020.
- Directional wave spectra: this capability is currently served by the SWIM instrument on the Chinese/French CFOSat mission. At this stage, there are no confirmed plans for a follow-on, despite strong interest by operational wave forecasting agencies.
- Gravity: this capability is currently delivered by GRACE-FO but there are no confirmed plans at present for a follow-on mission, despite strong interest in time-varying gravity to observe mass redistribution around the globe (applications to oceanography, hydrology and solid earth).
- High-resolution coastal ocean imaging: SAR and multispectral imagers already provide exceptional fine scale imaging capability with spatial resolutions below 10m (over small regions only due to current satellite-ground downlink capability limits). More progress is needed however to improve the spatial resolution of ocean colour and IR SST imagers (currently 300m-1km) for applications in coastal regions.
- Temporal sampling: the time interval between single mission overpasses can reach up to 5-10 days, making them inadequate to address the needs of near-real time applications. Extreme events and hazards (storm surges, hurricanes) call for frequent revisit (hourly) and all weather and day/night operating capabilities that may be best addressed by New Space solutions (e.g. constellations of small microwave SAR systems). Rapid temporal revisit is also relevant to observing needs linked to monitoring water quality, harmful blooms and river discharge, where near-real time and frequent revisit (hours) offers a practical solution to cloud obstruction. The technical solution to best address this need could consist of airborne or spaceborne geostationary systems, which are currently under investigations.

4.4. Trends and transformational technologies

Satellite ocean observing is currently undergoing very rapid transformations driven by a number of trends and technological advances that we outline briefly here.

- Operational imperatives and long-term continuity

  The growing duration of satellite data records and the need for independent global datasets to validate Earth system and climate models is driving global efforts towards building climate-quality records from satellite data. The original work to build consistent multi-mission satellite records of sea level and sea surface temperature is now inspiring similar efforts for other Essential Climate Variables like sea state and salinity, uncovering new phenomena and interactions within the climate system. The focus on climate introduces new constraints on satellite observing systems that have to ensure consistency across missions and technologies (e.g. using tandem phases as standard) and more rigorous assessments against independent fiducial reference data (usually from in situ sensors).

- New Space

  As already mentioned, New Space is a paradigm shift currently spreading through Earth Observation that relies on large constellations of low-cost small satellites or cubesats. Operated by commercial companies, the data is produced with short-lived instruments, without considerations for continuity, overlap or concerns about evolving technology. Emphasis is on producing large volumes of data for operational users who pay for the data to be ingested in assimilation systems. At this stage, little is known about the quality of the data or the long-term viability of the New Space business model.

- New data providers, changing landscapes

  This report has focused on satellite ocean capability provided by publicly funded space agencies in the western world (ESA, NASA, etc.) But Earth Observation is undergoing rapid transformation also through ambitious satellite programmes put forward by large countries like China, Russia, India but also Argentina, Brazil, Korea, Qatar, etc. Known unknown include questions over data access, data policy and quality assurance, as well as the likelihood of last-minute cancellations. Even so, it is clear that the satellite ocean observing landscape is likely to be influenced by the plans and activities of a much larger range of space data providers (and potentially, by the prospect of attacks on each-other’s orbiting space assets).

5. Environmental implications of satellite ocean observing

This section reviews current knowledge of the environmental implications of satellite oceanographic observing capability, notably with regards to net-zero carbon targets.

Within the scope of this study, the focus is on direct cost “at the point of use”, associated with delivering the observing capability. This analysis does not consider additional indirect costs linked, for example, to the manufacturing of the sensors and platforms, the extraction, refining and transportation of natural resources (e.g. metals, minerals, rare Earth ores), and the cost of satellite data handling and archiving.

In light of this, the main environmental implication of delivering satellite ocean observing capability is related to the carbon cost of the satellite launches.

5.1. Environmental implications of satellite launches

There is currently little verified information about the carbon cost of launching satellites of different classes into different orbits. Growing public awareness of the climate emergency and recent satellite launches by wealthy high-profile private individuals has led some in the media to put forward approximate estimates of carbon emissions per launch. Thus, according to one such source, the launch of the SpaceX Falcon 9 rocket (used to send astronauts to the International Space Station around 400km altitude) had a carbon cost equivalent of 5 return transatlantic flights. If proven correct, this carbon cost is relatively modest in the context of international air traffic. There are additional concerns however that today’s kerosene-fuelled rockets also transport large amounts of soot into the upper layers of the atmosphere, which could aggravate climate change and contribute to depleting the ozone layer.

The possibility of smaller satellites (e.g. cubesats) has contributed in part to a democratisation of satellite launches and a rapid acceleration in the number of satellites launched per year. Whilst the growth in satellite launches is strongly dominated by non-EO applications (e.g. communications, military, navigation), the trend for EO satellite launches also follows the general trend upwards. Nevertheless, it is worth noting that, as of December 2020, of the ~3300 satellites orbiting the Earth, less than 8% are public Earth Observation satellites, and of those, only a small fraction are responsible for delivering today’s ocean observing capability (~40 satellites overall including meteorological satellites).

Even so, these concerns over net-zero carbon, climate change and sustainability have stimulated space agencies responsible for satellite launch to investigate ways to reduce the carbon cost of future EO satellite launches. Thus, most agencies are actively exploring solutions that would allow future green satellite launches e.g. by launching rockets powered using sustainable fuels (e.g. from biomass). These developments in aerospace technology are likely to occur on similar scales as the expected greening of the aviation sector.

6. Implications of satellite ocean observing on Equality, Diversity and Inclusion across Oceanography

In its own right, satellite ocean observing shares the same issues of Equality, Diversity and Inclusion (EDI) that afflict the whole research sector, with marked under representation of BAME, LGBT and disabled communities. Satellite oceanography activities can however be carried out by any sufficiently skilled and motivated individual, and can fit within highly flexible work patterns and environments, provided individuals have access to appropriate computing infrastructure (internet connectivity with sufficient bandwidth, processing capability). Hence, with targeted effort, there is considerable potential for greater diversity and inclusion in this sector, without the barriers associated with oceanographic operations at sea.

Oceanographic operations at sea deliver ocean observing needs that cannot be satisfied with satellites. Ship-based operations rely on physical fitness and long periods away at sea to deliver observations such as full depth ocean profiling, physical samples collection (seawater, biology, biogeochemistry, sediments, etc.) and deploying/servicing moorings and monitoring stations for sustained long-term observations. In contrast, satellite oceanography work is mainly computer-based, and is amenable to people who, for whatever reason, cannot go to sea for extended periods. Satellite ocean observing thus makes it possible for a more diverse range of people to be involved in oceanographic research (as do Argo floats and autonomous vehicles).

7. Gaps, Opportunities and Recommendations

This section highlights some of the issues mentioned in earlier parts of the report that point to gaps in today's satellite ocean observing capability. In each case, we outline some of the opportunities arising from existing and future satellite ocean observing capability, together with recommendations for possible action.

7.1. Guided access to satellite ocean data and advice

Satellites provide a wealth of ocean observations that are relevant to users in environmental sciences, operational forecasting, government departments, public authorities and stakeholders in the private sector. Compared to other west world countries however, the UK tends to under-use its satellite ocean observing capability. Discussions with stakeholders from different communities frequently reveal low levels of knowledge and awareness in the UK of existing satellite ocean capability and its relevance to user needs.

This situation is not unexpected. The multiplicity of satellite missions, products and EO data portals presents a complex, ever-evolving landscape that non-experts can find difficult to navigate. Without knowledge about the benefits, drawbacks and relevance of different products and latest innovations, time-pressured users can easily use inappropriate satellite products (or give up), leading to disappointing or incorrect outcome that fuels further decline in satellite ocean data uptake.

The rapid progression of satellite ocean observing towards larger numbers of satellites and more diverse technologies, orbits and data providers presents significant opportunities to improve ocean observing capability. Nevertheless, the diversification of data sources, products, formats and quality standards will further complicate an already complex EO landscape for users. The UK expertise in satellite oceanography needed to provide the necessary knowledge and guidance to users already exists but is not widely publicised. Documenting existing satellite ocean capability could help users identify where to get independent expert advice and promote better and greater use of satellite assets by all categories of users.

7.1. Enhanced satellite support to sea-going activities

Satellite ocean data have previously been used in the UK to inform sea-going activities, for example to support glider deployment and piloting in near real time during MASSMO missions. However, satellite data products tend to be limited to ocean colour and sea surface temperature images. Whilst providing valuable wide-swath images to enhance situational awareness, these products are often impacted by cloud cover or low light conditions. Other types of satellite data could usefully be included to support sea-going operations, notably microwave radar imagers, that would provide additional high-resolution all-weather day-night capability that could prove particularly valuable in cloudy or low-light conditions at high latitudes.

Increasing the number and types of satellite products, including data also from smaller missions, would help to reduce the interval between satellite overpasses, to deliver more frequent and more up-to-date information for operations at sea.

Aside from supporting deployments and operations at sea, satellite data also bring opportunities to increase efficiency (ship transit, operational time) and safety for some expeditions. Closer integration between satellite oceanography experts and marine operators could give National Marine Facilities (NMF) access to satellite expertise during planning and execution to make better use of the unique spatial and near-real-time perspectives offered by today's satellite ocean capability. A trial that embeds satellite expertise within National Marine Facilities for up to 12 months could review and report on NMF data needs, opportunities and impact. Reviewing NMF data use, access and visualisation systems would reflect on what is available, what is possible and what steps are needed to progress towards better integrated systems to meet the needs of the oceanography research community. This could represent a pilot to design a truly integrated system able to access, integrate and visualise data from multiple satellite and in situ sensors and ocean models.

7.2. Unified satellite and in situ ocean data systems

Satellite ocean observations come in large volumes and a multitude of forms that reflect the large diversity of sampling, resolutions, uncertainties, formats, definitions, benchmarks and conventions of the original sources. Likewise, in situ data from ships, fixed platforms, drifters, floats and other autonomous vehicles present a vast assortment of standards, conventions, sampling and formats. This huge diversity on both sides represents a major practical obstacle to jointly explore and exploit ocean observations from different satellite and in situ sensors.

Recent developments in big data analytics, machine learning and cloud computing present opportunities to break these traditional barriers between satellite and in situ observations. New IT systems fronted by intuitive interactive interfaces could be developed for users to seamlessly interrogate databases of satellite and in situ data across the world. Such infrastructure could contribute to the UK effort towards data-only representations of the ocean and complement existing international initiatives to develop Digital Twins of the Ocean[1, 2, 3].

7.3. Rolling quality assurance for satellite and in situ data

The multitude of disruptive technologies arising from the New Space revolution brings with it many challenges for users interested in using the data. The diversity of programmatic routes used by New Space means these data streams will generally bypass the traditional quality-assessment frameworks that assure the quality and consistency of satellite data against established standards. Before these new data streams can legitimately be seen to contribute to satellite ocean observing capability, strict data quality assurance protocols should be set up and applied to evaluate these new data in the context of existing observations.

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[1] https://www.mercator-ocean.fr/en/digital-twin-ocean/

[2] https://www.esa.int/ESA_Multimedia/Images/2020/09/Digital_Twin_Earth

[3] https://www.sciencemag.org/news/2020/10/europe-building-digital-twin-earth-revolutionize-climate-forecasts

Traditionally, new satellite ocean data are evaluated using comparisons with observations from in situ sensors and other contemporary satellites. Data matchups, that assemble simultaneous collocated measurements from satellites and in situ sensors, are a keystone of these evaluations - the robustness of the quality assessments depending strongly on the sample size of the matchup database. With the increasing availability and diversity of satellite and in situ data, it would be beneficial to set up automated systems that routinely compile match-up datasets from various data sources for quality assurance purposes. Furthermore, assembling simultaneous collocated observations from three or more data sources would open up opportunities to compute error estimates independently for each data source based on advanced statistical estimation methods and data analytics. Such rolling match-up and evaluation protocols would bring wider benefits than satellite quality assurance alone, since the same system could also help to rapidly identify anomalous readings and operations in individual in situ sensors (e.g. in a fleet of gliders).

Ocean property		Sensing method	Spatial Resolution	Time resolution	Period	Indicative missions/instruments
Sea Surface Height, Sea Level		Altimetry	7km along-track, 80-315km at equator[4]	10-35 days[4]	1993-now	Topex, Jason-1/2/3, AltiKa, Cryosat-2, Sentinel-3 SRAL[5], HY-2A/B, Sentinel-6/MF
Sea Surface Temperature		Infrared radiometry	1km	1day or longer	1981-now	AVHRR, AATSR, Sentinel-3 SLSTR
		Microwave radiometry	25km	2-3 days	1978-2015	SMMR, TRMM TIM
Chlorophyl-A, Suspended Particulate Matter		Optical & NIR spectrometry	300m-1km	1day or longer	1997-now	SeaWIFS, MODIS, Sentinel-3 OLCI
Ocean Surface Winds		Scatterometry	25km	1day or longer	1991-now	ERS-1/2, QuikSCAT, METOP ASCAT
		Altimetry	Same as Sea Surface Height			
		Synthetic Aperture Radar	1km	6days or longer	1991-now	RADARSAT-1/2, Envisat ASAR, ALOS-2 PALSAR-2, TerraSAR-X, COSMO-SkyMed, NovaSAR, Sentinel-1
		GNSS reflectometry	25km	6hrs or longer	2014-now	TechDemoSat-1, CYGNSS, Spire
Sea State		Altimetry	Same as Sea Surface Height			
		Synthetic Aperture Radar	20km	Same as Ocean Surface Winds		
		Rotating altimetry		1day or longer	2018-now	CFOSat
Sea Surface Salinity		L-band radiometry	30-100 km	3days or longer	2009-now	SMOS, Aquarius, SMAP
Marine geoid, bathymetry		Gravimetry	300km	30days	2002-now	GRACE, GOCE[6], GRACE-FO
		Altimetry	Same as Sea Surface Height			
		Visible & NIR spectrometry	10-60m			Sentinel-2 MSI
Ocean currents		Altimetry	Same as Sea Surface Height			
		Synthetic Aperture Radar	Same as Ocean Surface Winds			
		Gravimetry	Same as Marine geoid			
Sea Ice	Extent, concentration	Microwave radiometry, Synthetic Aperture Radar, L-band radiometry, GNSS reflectometry	1-25km	Various	1979-now	See above
	Thickness	Altimetry	300m			Cryosat-2
		Lidar	Down to 7m			ICESat, ICESat-2

Table 1: Satellite Oceanographic observing capability: 2020 baseline (ESA, 2021; CEOS, 2021; WMO, 2021)

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[4] Except Cryosat-2 (7.5km; 369 days)

[5] All acronyms are defined in the glossary at the end of this report

[6] One-off 100km resolution geoid over the 3.5 years mission lifetime

Ocean property	Sensing method	Programmatic route	Mission/instrument	Nominal lifetime	Status
Sea Surface Height, Sea Level	Altimetry	CSC[7]	Sentinel-3C/D SRAL, Sentinel-6B	2023-2035, 2025-2031	Approved
		NASA/CNES/CSA/UKSA	SWOT	2022-2025	Approved
		Copernicus Next	Sentinel-3-NG Topo	2030-2040	Planned
		Copernicus HPCM[8]	Cristal		Planned
Sea Surface Temperature	Infrared radiometry	CSC	Sentinel-3C/D SLSTR		Approved
		Copernicus Next	Sentinel-3-NG Imaging	2030-2040	Planned
		Copernicus HPCM	CIMR		Planned
	Microwave radiometry	JAXA	GOSAT AMSR-3	2023-2030	Approved
Chlorophyl-A, Suspended Particulate Matter	Optical & NIR spectrometry	CSC	Sentinel-3C/D OLCI		Approved
		NASA	PACE	2023-2026	Approved
		Copernicus Next	Sentinel-3-NG Imaging	2030-2040	Planned
Ocean Surface Winds	Scatterometry	EUMETSAT METOP series	Metop-SG-B1/2/3	2024-2045	Approved
	Altimetry	Same as Sea Surface Height			Approved
	Synthetic Aperture Radar	CSC	Sentinel-1C/D		Approved
		Copernicus Next	Sentinel-1-NG	2030-2040	Planned
		ASI	COSMO-SkyMed 2nd Generation	2019-2028	Approved
	GNSS reflectometry	ESA SCOUT	HydroGNSS	2024-2027	Approved
Sea State	Altimetry	Same as Sea Surface Height			Approved
	Synthetic Aperture Radar	Same as Ocean Surface Winds			Approved
	Rotating altimetry	No follow-on at present			None
Sea Surface Salinity	L-band radiometry	Copernicus HPCM	CIMR		Planned
Marine geoid, bathymetry	Gravimetry	No follow-on at present			None
	Altimetry	Same as Sea Surface Height			Approved
	Visible & NIR spectrometry	CSC	Sentinel-2C/D MSI		Approved
		Copernicus Next	Sentinel-3-NG Imaging	2030-2040	Planned
		Copernicus HPCM	CHIME		Planned

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[7] Copernicus Space Component

[8] High Priority Candidate Mission

Ocean property		Sensing method	Programmatic route	Mission/instrument	Nominal lifetime	Status
Ocean currents		Altimetry	Same as Sea Surface Height			Approved
		Synthetic Aperture Radar	Same as Ocean Surface Winds			Approved
		ATI SAR	ESA Earth Explorer 10	HARMONY	2025-2028	Approved[9]
Sea Ice	Extent, concentration	Microwave radiometry Synthetic Aperture Radar L-band radiometry GNSS reflectometry	Various - see above			Various
	Thickness	Altimetry	Copernicus HPCM	CRISTAL		Planned
		Lidar	No follow-on at present			None

Table 2: Satellite Oceanographic observing capability to 2035 and beyond

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[9] Currently approved to enter Phase B

Glossary

AATSR	Advanced Along-Track Scanning Radiometer
ADEOS II	Advanced Earth Observing Satellite 2
AMSR	Advanced Microwave Scanning Radiometer
ASAR	Advanced Synthetic Aperture Radar
ASI	Agenzia Spaziale Italiana (Italian space agency)
ATI	Along-Track Interferometry
AVHRR	Advanced Very High Resolution Radiometer
C3S	Copernicus Climate Change Service
CEDA	Centre for Environmental Data Analysis
CEOS	Committee on Earth Observation Satellites
CHIME	Copernicus Hyperspectral Imaging Mission
CMEMS	Copernicus Marine Service
CNES	Centre National d'Etudes Spatiales (French space agency)
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter
CSA	Canadian Space Agency
CSC	Copernicus Space Component (i.e. Sentinels programme)
EO	Earth Observation (from satellites, in this context)
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HPCM	High Priority Candidate Missions
ICESat	Ice, Cloud and land Elevation Satellite
IR	Infrared (radiation)
JAXA	Japan Aerospace Exploration Agency
MSI	Multi-Spectral Instrument
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NIR	Near Infrared
PACE	Plankton, Aerosols, Cloud ocean Ecosystem

PO.DAAC	Physical Oceanography Distributed Active Archive Center
SLSTR	Sea and Land Surface Temperature Radiometer
SMAP	Soil Moisture Active Passive (mission)
SMOS	Soil Moisture and Ocean Salinity (mission)
SRAL	Synthetic aperture Radar Altimeter
SSH	Sea Surface Height
SST	Sea Surface Temperature
SSS	Sea Surface Salinity
SWOT	Surface Water and Ocean Topography (mission)
SMMR	Scanning Multichannel Microwave Radiometer
TRMM	Tropical Rainfall Measuring Mission
TMI	TRMM Microwave Imager
UKSA	UK Space Agency
WMO	World Meteorological Organisation

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