CHAPTER 7

Satellites and Operational Oceanography

Pierre-Yves Le Traon[1,2]

[1]*Mercator Océan, Parc Technologique du Canal, Ramonville-Saint-Agne, France;* [2]*Ifremer, Plouzané, France*

The chapter starts with an overview of satellite oceanography, its role and use for operational oceanography. Main principles of satellite oceanography techniques are summarized. We then describe key techniques of radar altimetry, sea surface temperature, and ocean colour remote sensing. This includes measurement principles, data processing issues, and the use of data for operational oceanography. Synthetic aperture radar, scatterometry, sea ice and sea surface salinity measurements are also briefly described. Techniques used to assess the impact of present and future satellite observations for ocean analysis and forecasting are reviewed. We also discuss future requirements for satellite observations. Main prospects are given in the conclusion.

Introduction

There are very strong links between satellite oceanography and operational oceanography. The development of operational oceanography has been mainly driven by the development of satellite oceanography capabilities. The ability to observe the global ocean in near real-time at high space and time resolution is indeed a prerequisite for the development of global operational oceanography and its applications. The first ocean parameter to be globally monitored from space was sea surface temperature by meteorological satellites in the late 1970s. It was, however, the advent of satellite altimetry in the late 1980s that led to the development of ocean data assimilation and global operational oceanography. In addition to providing all kinds of weather observations, sea level from satellite altimetry is an integral of the ocean interior and provides a strong constraint on the 4D ocean state estimation. The satellite altimetry community was also keen to develop further the use of altimetry, and this required an integrated approach merging satellite and in situ observations with models. Thus, the GODAE demonstration was phased to coincide with the Jason-1 and ENVISAT altimeter missions (Smith and Lefebvre, 1997). Satellite oceanography is now a major component of operational oceanography. Data are usually assimilated in ocean models but they can also be used directly for applications.

An overview of satellite oceanography will be provided here, focusing on the most relevant issues for operational oceanography. The chapter is organized as follows. First is an overview of satellite oceanography, its role and use for operational oceanography. Main operational oceanography requirements are summarized. The complementary role of in situ observations is also emphasized. Next, main principles of satellite oceanography and general data processing issues are described. We then detail key techniques of radar altimetry, sea surface temperature, and ocean

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colour remote sensing. This includes measurement principles, data processing issues, and the use of these data for operational oceanography. Synthetic aperture radar (SAR), scatterometry, sea ice and sea surface salinity measurements are briefly described next followed by a review of tools used to quantify the impact of present and future satellite observations for ocean analysis and forecasting. Finally, future challenges and requirements for satellite observations are discussed. Main prospects are given in the chapter conclusion.

Role of Satellites in Operational Oceanography

The global ocean observing system and operational oceanography

Operational oceanography critically depends on the near real-time availability of high quality in situ and remote sensing data with sufficiently dense space and time sampling. The quantity, quality, and availability of data sets directly impact the quality of ocean analyses and forecasts and associated services. Observations are required to constrain ocean models through data assimilation and also to validate them. Products derived from the data themselves can also be directly used for applications.

This requires an adequate and sustained global ocean observing system. Climate and operational oceanography applications share the same backbone system (i.e., GOOS, GCOS, and JCOMM). Operational oceanography has, however, specific requirements for availability of high space and time resolution measurements and for near real-time measurements.

The unique contribution of satellite observation

Satellites provide long-term, continuous, global, high space and time resolution data for key ocean parameters: sea level and ocean circulation, sea surface temperature, ocean colour, sea ice, waves, and winds. These are the observational core variables required to constrain global, regional and coastal ocean monitoring and forecasting systems. They are also needed to validate them. Only satellite measurements can, in particular, provide observations at high space and time resolution to partly resolve the mesoscale and coastal variability. Satellite data can also be directly used for applications (e.g., SAR for sea ice and oil pollution monitoring, ocean colour for water quality monitoring). Sea surface salinity is a new and important parameter that could be operationally monitored from space; the feasibility has been demonstrated with the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission and the NASA/Comisión Nacional de Actividades Espaciales (CONAE) Aquarius mission.

Main requirements

Operational oceanography requirements have been presented in the GODAE strategic plan and by Le Traon et al. (2001). They have been further detailed in Clark and Wilson (2009), Drinkwater et al. (2010) and Le Traon (2011). Sea level, sea surface temperature (SST), surface geostrophic currents, ocean colour, sea surface salinity (SSS), waves, sea ice, and winds form the core operational satellite observations required for global, regional, and coastal ocean monitoring and forecasting systems. To deliver sustained, high resolution observations while meeting operational constraints such as near-real-time data distribution and redundancy in the event of satellite or instrument failure requires international cooperation and the development of virtual constellations as promoted by the Committee on Earth Observation Satellites (CEOS; e.g. Bonekamp et al., 2010).

Specific requirements for operational oceanography are as follows:

- In addition to meteorological satellites, a high precision (Advanced Along-Track Scanning Radiometer - AATSR-class) SST satellite mission, is needed to give the highest absolute SST accuracy. A microwave mission is also needed to provide an all-weather global coverage.
- At least three or four altimeters are required to observe the mesoscale circulation. This would also useful for significant wave height measurements. A long-term time series of a high accuracy altimeter system (Jason satellites) is needed to serve as a reference for the other missions and for the monitoring of climate signals.
- Ocean colour is increasingly more important, particularly in coastal areas. At least two satellites are required.
- Two scatterometers are required to globally monitor the wind field and sea ice at high spatial resolution.
- Two SAR satellites are required for waves, sea ice characteristics, and oil slick monitoring.

These minimum requirements have been only partly met over the past ten years (see Le Traon et al., 2015, for a recent review). Long-term continuity and transition from research to operational mode remains a major challenge.

Role of in situ data

Satellite observations need to be complemented by in situ observations. First, in situ data are needed to calibrate satellite observations. Most algorithms used to transform satellite observations (e.g., brightness temperatures) into geophysical quantities are partly based on in situ/satellite match up data bases. The in situ data are then used to validate satellite observations and to monitor the long-term stability of satellite observations. The stability of the different altimeter missions is, for example, commonly assessed by comparing the altimeter sea surface height measurements with those from tide gauges (Mitchum, 2000). Other examples include the validation of altimeter velocity products with drifter data (e.g., Bonjean and Lagerloef, 2002; Pascual et al., 2009), the systematic validation of satellite SST with in-situ SST from drifting buoys and the use of dedicated ship mounted radiometers to quantify the accuracy of satellite SST (Donlon et al, 2008). Comparison of in situ and satellite data can also provide indications of the quality of in situ data (e.g., Guinehut et al., 2009). The comparison of in situ and satellite data is also useful to check the consistency and information content between the different data sets (e.g., satellite sea level versus in situ dynamic height measurements) before they are assimilated in an ocean model (e.g., Guinehut et al., 2006).

Most importantly, in situ data are mandatory (and this is their main role) to complement satellite observations and to provide measurements of the ocean interior. Only the joint use of high resolution satellite data with precise (but sparsely available) in situ observations of the ocean interior has the potential to provide a high resolution description and forecast of the ocean state. The development of the Argo array of profiling floats and their integration with satellite altimetry and operational oceanography is an outstanding example of the value of an integrated ocean observing system (see discussion in Le Traon, 2013).

Data processing issues

Satellite data processing takes place in steps: level 0 and level 1 (from telemetry to calibrated sensor measurements), level 2 (from sensor measurements to geophysical variables), level 3 (space/time composites of level 2 data), and level 4 (merging of different sensors, data assimilation). Processing from level 0 to level 2 is generally carried out as part of the satellite ground segments.

Assembly of level 2 data from different sensors, intercalibration of level 2 products, and higher level data processing is usually done by specific data processing centers or thematic assembly centers. The role of data processing centers is to provide modelling and data assimilation centers with the real-time and delayed mode data sets required for validation and data assimilation. This includes uncertainty estimates, which are critical to an effective use of data in modelling and data assimilation systems. Links with ocean forecasting centers are needed, in particular, to organize feedback on: the quality control performed at the level of ocean forecasting centers (e.g., comparing an observation with a model forecast); the impact of data sets and data products in the assimilation systems; and new or future requirements.

High level data products (level 3 and 4) are also needed for applications (e.g., a merged altimeter surface current product for marine safety or offshore applications) and can be used to validate data assimilation systems (e.g., statistical versus dynamical interpolation) and complement products derived through modelling and data assimilation systems. It is important, however, to be fully aware of the limitations (e.g., mapping errors, limited effective space/time resolution) of high level satellite products (e.g., gridded sea surface temperature or sea level data sets) when using them.

Use of satellite data for assimilation into ocean models

The use of satellite data for assimilation into ocean models is discussed at length in other chapters of this book. Three important issues are emphasized in this chapter:

1. There can be large differences in data quality between real-time and delayed mode (reprocessed) data sets. Depending on applications, trade-offs between time delay and accuracy often need to be considered.
2. Error characterisation is mandatory for data assimilation, and a proper characterisation of error covariance can be quite complex for satellite observations. Data error variance (and covariance, but this is much more challenging) should always be tested and checked as part of the data assimilation systems.

In theory and for advanced assimilation schemes, it is much better to use raw data (level 2 or in some cases level 1 when the model can provide data needed for level 1 processing). The data error structure is generally more easily defined. The model and the assimilation scheme should also deliver a better high level processing (e.g., a model forecast should provide a better background than climatology or persistence). However, in practice this is not always true. Some high level data processing is often needed (e.g., correcting biases or large-scale errors, intercalibration of satellite missions) as it cannot be easily accomplished within complex data assimilation systems.

Overview of Satellite Oceanography Techniques

Passive/active techniques and choice of frequencies

There are two main types of satellite techniques to observe the ocean[1]. Passive techniques measure the natural radiation emitted from the sea or from reflected solar radiation. Active or radar techniques send a signal and measure the signal received from its reflection at the sea surface. In both cases, the propagation of the signal through the atmosphere and the emission from the atmosphere itself must be taken into account in order to extract the sea surface signal. The intensity and frequency distribution of the radiation that is emitted or reflected from the ocean surface allows the inference of its properties. The polarization of the radiation is also often used in microwave remote sensing.

Satellite systems operate at different frequencies depending on the signal to be derived. Visible (400 – 700 nm) and infrared (0.7 – 20 μm) frequencies are used for ocean colour and sea surface temperature measurements. Passive (radiometry) microwave systems (1 cm-30 cm) are used for sea surface temperature measurements in cloud situations, wind, sea ice and sea surface salinity retrievals. Radars operate in the microwave bands and provide measurements of sea surface height, wind speed and direction, wave spectra, sea ice cover, and types and surface roughness. Radar pulses are emitted obliquely (15 to 60°) (SAR, scatterometer) or vertically (altimetry).

The choice of frequencies is limited by other usages (e.g., radio, cellular phones, military and civilian radars, satellite communications). This is particularly important at microwave frequencies

[1] Gravimetry satellites (e.g. GRACE, GOCE), which measure the earth gravity field and its variations, are not included in these two categories.

in the range 1-10 GHz, which limits the frequencies used for earth remote sensing. The atmosphere also greatly affects the transmission of radiation between the ocean surface and the satellite sensors. The presence of fixed concentrations of atmospheric gases (e.g., O_2, CO_2, and O_3) and of water vapour means that only a limited number of windows exist in the visible, infrared and microwave for ocean remote sensing. Even at these frequencies, the propagation effects through the atmosphere (from the troposphere to the ionosphere) must be taken into account and corrected for. Clouds are a strong limitation of visible and infrared measurements.

There are also technological constraints for the choice of frequencies. The resolution of a given sensor is generally related to the ratio between the observed wavelength (λ) and the antenna diameter (D). For antenna diameters of a few meters, typical resolution at around 1 GHz (wavelength of 30 cm) is about 100 km, while at 30 GHz (wavelength of 1 cm) resolution is about 10 km. Radar altimeters use pulse limited techniques (which are much less sensitive to mispointing errors). Their footprint size is related to the pulse duration and is much smaller than that of a beam limited sensor. SAR uses the motion of the satellite to generate a very long antenna (e.g., 20 km for the ENVISAT Advanced Synthetic Aperture Radar (ASAR)) and thus to provide very high resolution measurements (up to a few meters).

Satellite orbits and measurement characteristics

Orbits for ocean satellites are geostationary, polar, or inclined. A geostationary orbit is one in which the satellite is always in the same position with respect to the rotating Earth. The satellite orbits at an elevation of approximately 36,000 km because that produces an orbital period equal to the period of rotation of the Earth. By orbiting at the same rate, in the same direction as Earth, the satellite appears stationary. Geostationary satellites provide a large field of view (up to 120°) at very high frequency, enabling coverage of weather events. Because of the high altitude, spatial resolution is on the order of a few kilometers, while it is 1 km or less for polar orbiting satellites. Because a geostationary orbit must be in the same plane as the Earth's rotation (i.e., the equatorial plane), it provides distorted images of the polar regions. Five or six geostationary meteorological satellites can provide a global coverage of the earth (for latitudes below 60°) (e.g., Martin, 2004).

Polar-orbiting satellites provide a more global view of Earth by passing from pole to pole, observing a different portion of the Earth with each orbit due to the Earth's own rotation. Orbiting at an altitude of 700 to 800 km, these satellites have an orbital period of approximately 90 minutes. They usually operate in a sun-synchronous orbit. At the same local solar time each day, the satellite passes the equator and any given latitude. Inclined orbits have an inclination between 0 degrees (equatorial orbit) and 90 degrees (polar orbit) and are used to observe tropical regions (e.g., Tropical Rainfall Measuring Mission (TRMM) Microwave Imager). High accuracy altimeter satellites such as TOPEX/Poseidon and Jason use higher altitude and non-synchronous orbits to reduce atmospheric drag and (mainly) to avoid aliasing of the main tidal signals.

The sampling pattern of a given satellite will be different depending on instrument types (along-track, imaging, or swath), frequencies, and antennas (see above). In addition, in the visible and infrared frequencies, cloud cover can strongly reduce the effective sampling.

Radiation laws and emissivity

Radiation from a blackbody

Planck's law describes the rate of energy emitted by a blackbody as a function of frequency or wavelength. A blackbody absorbs all the radiation it receives and emits radiation at a maximum rate for its given temperature. Planck's law gives the intensity of radiation L_λ emitted by unit surface area into a fixed direction (solid angle) from the blackbody as a function of wavelength (or frequency). The law can be expressed through the following equation:

$$L_\lambda = 2hc^2 / \lambda^5 \, [exp\ (hc/\lambda kT)\text{-}1]$$

where T is the temperature, c the speed of light (2.99 10^{-8} m s^{-1}), h the Planck's constant (6.63 x 10^{-34} J s), k the Boltzmann's constant (1.38 10^{-23} J °K^{-1}), and L_λ the spectral radiance per unit of wavelength and solid angle in W m^{-3} sr^{-1}.

Planck's law gives a distribution that peaks at a certain wavelength; the peak shifts to shorter wavelengths for higher temperatures. Wien's law gives the wavelength of the peak of the radiation distribution (λ_{max}= 3 10^7/T), while the Stefan-Boltzmann law gives the total energy E being emitted at all wavelengths by the blackbody (E = σ T^4). Thus, Wien's law explains the shift of the peak to shorter wavelengths as the temperature increases, while the Stefan-Boltzmann law explains the growth in the height of the curve as the temperature increases. Notice that this growth is very abrupt, since it varies as the fourth power of the temperature.

The Rayleigh-Jeans approximation (**$L\lambda=2kcT/\lambda^4$**) holds for wavelengths much greater than the wavelength of the peak in the black body radiation form. This approximation is valid over the microwave band.

Graybodies and emissivity

Most bodies radiate less efficiently than a blackbody. The emissivity e is defined as the ratio of graybody radiance to the blackbody. It has a non-dimensional unit and its value is comprised between 0 and 1. The emissivity (e) generally depends on wavelength **(λ)** and polarization and has a directional dependence; it can be considered as a physical surface property and is a key quantity for ocean remote sensing. A graybody absorbs only part of the energy it receives and the remaining part is reflected and/or transmitted. The absorptivity is equal to the emissivity, as a surface in equilibrium must absorb and emit energy at the same rate (Kirchoff's law). Similarly, the reflectivity is equal to 1 – e.

Retrieval of geophysical parameters for microwave radiometers

The brightness temperature (BT) is defined as BT = eT where T is the (physical) temperature. In the microwave band, it is proportional to the radiation L_λ. Brightness temperature is a measure of the intensity of emitted radiation. It is the physical temperature a blackbody would have to yield the same observed intensity of radiation emitted by a graybody.

The brightness temperature is an integrated measurement that includes all surface and atmosphere emitted power. Depending on frequency, it is more sensitive to a given parameter. Physical retrieval algorithms for geophysical parameters, such as the sea surface temperature, sea surface wind speed, sea ice or sea surface salinity are derived from a radiative transfer model, which computes the brightness temperatures that are measured by the satellite as a function of these variables. The radiative transfer model is based on a model for the sea surface emissivity and a model of microwave absorption in the Earth's atmosphere. The ocean sea surface emissivity (or reflectivity, see above) depends on the dielectric constant ε (which is a function of frequency, water temperature, and salinity), small-scale sea surface roughness, foam, as well as viewing geometry and polarization. The retrieval of a given parameter is possible through the inversion of a set of brightness temperatures measured at different frequencies and/or at different incidence angles. Inversion methods minimize the difference between measured and simulated (through a radiative transfer model) brightness temperatures. And given uncertainties in radiative transfer models, statistical or empirical inversions are also often used. These use a regression formalism (e.g., parametric, neural network) to find the best relation between brightness temperatures and the geophysical parameter to be retrieved.

Altimetry

Overview

Satellite altimetry is the most essential observing systems required for global operational oceanography (see Le Traon et al., 2017a for a recent review). It provides global, real-time, all-weather sea level measurements (sea surface height or SSH) with high space and time resolution. Sea level is directly related to ocean circulation through the geostrophic approximation. Sea level is also an integral of the ocean interior (density) and a strong constraint for inferring the 4D ocean circulation through data assimilation. Altimeters also measure significant wave height, which is essential for operational wave forecasting. High resolution from multiple altimeters is required to adequately represent ocean eddies and associated currents (aka the "ocean weather") in models. Only altimetry can constrain (through data assimilation) the 4D mesoscale circulation in ocean models that is required for most operational oceanography applications.

Measurements principles

An altimeter is active radar that sends a microwave pulse towards the ocean surface. A precise clock on board measures the return time of the pulse from which the distance or range (d) between the satellite and the sea surface is derived (d=t/2c). The range precision is within a few centimeters for a distance of 800 to 1300 km. The altimeter also measures the backscatter power related to surface roughness and wind and significant wave height.

An altimeter mission generally includes a bifrequency altimeter radar (usually in Ku and C or S Band) for ionospheric corrections, a microwave radiometer for water vapour correction, and a tracking system for precise orbit determination (Laser, GPS, Doris) that provides the orbit altitude relative to a given earth ellipsoid.

The main measurement for an altimeter radar is the SSH relative to a given earth ellipsoid. The SSH is derived as the difference between the orbit altitude and the range measurement. SSH precision depends on orbit and range errors. Altimeter range measurements are affected by a large number of errors (propagation effects in the troposphere and ionosphere, electromagnetic bias, errors due to inaccurate ocean and terrestrial tide models, inverse barometer effect, residual geoid errors). Some of these errors can be corrected with dedicated instrumentation (e.g. dual frequency altimeter, radiometer).

For a comprehensive description of altimeter measurement principles and measurement errors, the reader is referred to Chelton et al. (2001) and Escudier et al. (2017).

Geoid and repeat-track analysis

The altimeter missions provide along-track measurements every 7 km along repetitive tracks (e.g., every 10 days for the TOPEX/Poseidon and Jason series and 35 days for ERS, ENVISAT, and SARAL/Alti-Ka in its repeat-track phase). The distance between tracks is inversely proportional to the repeat time period (e.g., about 315 km at the equator for Jason and 90 km for ERS/ENVISAT/SARAL).

The sea surface height SSH(x,t) measured by altimetry can be described by:

$$SSH(x,t) = N(x) + \eta(x,t) + \varepsilon(x,t)$$

where N is the geoid, η the dynamic topography and ε are measurement errors. The quantity of interest for the oceanographer is the dynamic topography (see next subsection). Geoids are not accurate enough to estimate globally the absolute dynamic topography η at all wavelengths.

The variable part of the dynamic topography η' ($\eta - \langle \eta \rangle$) (or sea level anomaly, SLA) is, however, easily extracted using the so-called repeat track method. For a given track, η' is obtained by removing the mean profile over several cycles, which contains the geoid N and the mean dynamic topography $\langle \eta \rangle$:

$$SLA(x,t) = SSH(x,t) - \langle SSH(x) \rangle_t = \eta(x,t) - \langle \eta(x) \rangle_t + \varepsilon'(x,t)$$

To get the absolute signal, a climatology or existing geoids must be used together with altimeter Mean Sea Surface (MSS), or both. A model mean can also be relied upon. Gravimetric missions (GRACE, GOCE) are now providing much more accurate geoids. Even with GOCE, however, repeat-track analysis is still needed because the small scales of geoid (below 50 to 100 km) will not be precisely known. GOCE is used with an altimetric MSS to derive $\langle\eta\rangle_t$ that can then be added to η' (see next subsection).

High-level data processing issues and products

The SSALTO/DUACS system is the main multi-mission altimeter data center used today for operational oceanography. It aims to provide directly usable, high quality near real-time and delayed mode (for reanalyses and research users) altimeter products to the leading operational oceanography and climate centers in Europe and worldwide. The main processing steps are product homogenization, data editing, orbit error correction, reduction of long wavelength errors, production of along-track data, and maps of sea level anomalies. Major progress has been made with higher level processing issues such as orbit error reduction (e.g., Le Traon and Ogor, 1998), intercalibration, and merging of altimeter missions (e.g., Le Traon et al., 1998; Ducet et al., 2000; Pascual et al., 2006). The SSALTO/DUACS weekly production moved to daily production in 2007 to improve timeliness of data sets and products. A new real-time product was also developed for specific real-time mesoscale applications. A review of the SSALTO/DUACS processing is given in Dibarboure et al. (2011). Recent evolutions of the system are detailed on the DUACS website (https://duacs.cls.fr/)

Accurate knowledge of the marine geoid is a fundamental element for the full exploitation of altimetry for oceanographic applications and, in particular, for assimilation into operational ocean forecasting systems. SSH measured by an altimeter is the sea level above the ellipsoid, which is the sum of the Absolute Dynamic Topography (ADT or η) and the geoid height (N). The ADT is usually obtained by estimating a Mean Dynamic Topography (MDT or $\langle\eta\rangle$) and adding it to the altimetric SLAs (η'). The MDT is obtained, at spatial scales where the geoid is known with sufficient accuracy, as the difference between an altimeter Mean Sea Surface Height (MSSH=<SSH>) and a geoid model.

Thanks to the recent dedicated space gravity missions of GRACE and GOCE, the knowledge of the geoid at scales of around 100-150 km has greatly improved in the past years, so that the ocean MDT is now resolved at those scales with centimetre accuracy. However, the true ocean MDT over a given period (e.g., 10 – 20 years) contains scales shorter than 100-150 km, which are not resolved in geoid models based on remote sensing. To compute higher resolution MDT, space gravity data can be combined with altimetry and oceanographic in situ measurements such as hydrological profiles from the Argo array and velocity measurements from drifting buoys. This approach was used by Rio et al. (2014) to compute the CNES-CLS13 MDT, which is used in several global data assimilation systems.

Operational oceanography requirements

Le Traon et al. (2006) have defined the main priorities for altimeter missions in the context of the European Copernicus Marine Service. Tables 7.1 and 7.2 from this paper give the requirements for different applications of altimetry and characteristics of altimeter missions.

	Application area	Accuracy*	Spatial resolution	Revisit Time	Priority
1	Climate applications and reference mission	1 cm*	300-500 km	10-20 days	High
2	Ocean nowcasting/ forecasting for mesoscale applications	3 cm*	50-100 km	7-15 days	High
3	Coastal/local	3 cm*	10 km	1 day	Low**

Table 7.1: User requirements for different applications of altimetry (*for the given resolution; **limited by feasibility).

Class	Orbit	Mission characteristics	Revisit interval	Track separation at the Equator
A	Non-sun synchronous	High accuracy for climate applications and to reference other missions	10-20 days	150-300 km
B	Polar	Medium-class accuracy	20 - 35 days	80 - 150 km

Table 7.2: Altimeter mission characteristics.

The main operational oceanography requirements for satellite altimetry can be summarized as follows:

1. There is a strong need to maintain a long time series of a high accuracy altimeter system (e.g., the Jason series) to serve as a reference mission and for climate applications. It requires one class A altimeter with an overlap between successive missions of at least six months.
2. The main requirement for medium to high resolution altimetry would be to fly three class B altimeters in addition to the Jason series (class A). Most operational oceanography applications (e.g., marine security, pollution monitoring) require high resolution surface currents that cannot be adequately reproduced without a high resolution altimeter system. Studies (e.g., Pascual et al., 2006) have shown that at least three, but preferably four, altimeter missions are needed for monitoring the mesoscale circulation. This is particularly desirable for real-time nowcasting and forecasting. Pascual et al. (2009) showed that four altimeters in real time provide similar results as two altimeters in delayed mode. Such a scenario would also provide improved operational reliability. Moreover, it would enhance the spatial and temporal sampling for monitoring and forecasting significant wave height.

In parallel, there is a need to develop and test innovative instrumentation (e.g., wide swath altimetry with the NASA/CNES SWOT mission) to better answer existing and future operational oceanography requirements for high to very high spatio/temporal resolution (e.g., mesoscale/submesoscale and coastal dynamics). There is also a need to improve nadir altimetry technology (e.g., increase resolution, reduce noise) and to develop smaller and cheaper instruments that could be embarked on a constellation of small satellites. For instance, the use of the Ka band (35 Ghz) allows for a major reduction in the size and weight of the altimeter and improved performances (Verron et al., 2018). The new generation of nadir altimeters provide enhanced capability thanks to a SAR mode (also known as Delay-Doppler processing mode) that allows reducing significantly the measurement noise level compared to conventional pulse-limited altimeters (Dibarboure et al., 2014; Boy et al., 2017). Noise level for 1 Hz sampling (about 7 km) is thus about 1 cm RMS for SAR altimeters compared to about 3 cm RMS for conventional pulse limited altimeters. More information is given in Chapter 8 (Morrow et al.).

Sea Surface Temperature

Sea surface temperature measurements and operational oceanography

Sea surface temperature (SST) is a key variable in operational oceanography and for assimilation into ocean dynamical models. SST is strongly related to air-sea interaction processes and provides a means to correct for errors in forcing fields such as heat fluxes and wind. It also characterizes the mesoscale variability of the upper ocean, resolving eddies and frontal structures, at very high resolution (a few km). SST data are often directly used for operational oceanography applications. They provide useful indices (e.g., climate changes, upwelling, thresholds). SST data can also be used to derive high resolution velocity fields (e.g., Bowen et al., 2002). Accurate, stable, well-resolved maps of SST are essential for climate monitoring and climate change detection. They are also central for numerical weather prediction, for which the role of high resolution SST measurements has been clearly evidenced (e.g., Chelton, 2005).

Measurements principles

Infrared radiometers (IR) operate at wavebands around 3.7, 10.5 and 11.5 μm where the atmosphere is almost transparent. The brightness temperature measured from infrared radiometers differs from the actual temperature of the observed surface because of non-unit emissivity and the effect of the atmosphere. Emissivity at IR frequencies is between 0.98 and 0.99 (close to a blackbody). Atmospheric correction is based on a multispectral approach, when the differences between brightness temperatures measured at different wavelengths are used to estimate the contribution of the atmosphere to the signal. At 10 μm, the solar irradiance reaching the top of the atmosphere is about 1/300 of the sea surface emittance. At 3.7 μm, the incoming solar irradiance is on the same order as the surface emittance. As a result, this wavelength can be used during nighttime only. Different algorithms are thus used for nighttime and daytime.

There is no IR way of measuring SST below clouds. Thus, the first priority is to detect cloud through a variety of methods. For cloud detection, the thermal and near-infrared waveband thresholds are used, as well as different spatial coherency tests. Poor cloud detection biases the SST low in climatic averages, and “false hits” of cloud can hide frontal and other dynamical structures. Geostationary infrared sensors can see whenever the cloud breaks.

Microwave sensors operate at several frequencies. Retrieval of SST is done at 7 and/or 11 GHz. Higher frequency channels (19 to 37 GHz) are used to precisely estimate the attenuation due to oxygen, water vapour, and clouds. The polarization ratio (horizontal versus vertical) of the measurements is used to correct for sea surface roughness effects. The great advantage of microwave measurements compared to infrared measurements is that SST can be retrieved even through non-precipitating clouds, which is very beneficial in terms of geographical coverage.

SST infrared and microwave sensors

Infrared radiometers, such as the Advanced Very High Resolution Radiometer (AVHRR), on board operational meteorological polar orbiting satellites offer a good horizontal resolution (1 km) and potentially global coverage, with the important exception of cloudy areas. However, their accuracy (0.4 to 0.5°K derived from the difference between collocated satellite and buoy measurements) is limited by the radiometric quality of the AVHRR instrument and the correction of atmospheric effects. Geostationary satellites (e.g., the GOES and MSG series) are carrying radiometers with infrared window channels similar to the ones on the AVHRR instrument. Their horizontal resolution is coarser (3-5 km), but their high temporal resolution sampling provides an advantage. Advanced measurements of SST suitable for climate studies include the Along Track Scanning Radiometer (ATSR) series of instruments, which have improved on-board calibration and make use of dual views at nadir and 55° incidence angle. The along track scanning measurement provides an improved atmospheric correction leading to an accuracy better than 0.2°K (O’Carroll et al, 2008). The main drawback of these instruments is their limited coverage due to a much narrower swath than the AVHRR instruments. Several microwave radiometers have also been developed and flown over the last 10 years (e.g., AMSR, TMI). The horizontal resolution of these products is around 25 km and their accuracy around 0.6 – 0.7°K.

Key developments in SST data processing

During the past ten years, there has been a concerted effort to understand satellite and in situ SST observations, revolutionizing the way we approach the provision of SST data to the user community. GODAE, recognizing the importance of high resolution SST data sets for ocean forecasting, initiated the GODAE High Resolution SST Pilot Project (GHRSST-PP) to capitalize on these developments and create a set of dedicated products and services. There have also been key advances in the data processing of SST data sets over the last 10 years. As a result, new or improved products are now available. A full description of the GHRSST-PP is provided by Donlon et al. (2009). Data processing issues are summarized by Le Traon et al. (2009).

A satellite measures the so-called skin temperature, i.e., from a few tens of microns (infra-red) up to only a few mm (microwave). Diurnal warming changes the SST over a layer of 1 to 10 meters. The effect can be particularly large in regions of low wind speed and high solar radiation. GHRSST has defined the foundation SST as the temperature of the water column free of diurnal temperature variability. A key issue in SST data processing is to correct satellite SST measurements for skin and diurnal warming effects to provide precise estimations of the foundation SST. Night and day SST data from different satellites can then be merged through an optimal interpolation or a data assimilation system.

Several new high resolution SST products have been produced specifically in the framework of GHRSST-PP. These high resolution data sets are estimated by optimal interpolation methods merging SST satellite measurements from both infrared and microwave sensors. The pre-processing consists mainly of screening and quality control of the retrieved observations from each single data set and then constructing a coherent merged multi-sensor set of the most relevant and accurate observations (level 3). The merging of these observations requires a method for bias estimation and correction (relative to a chosen reference, currently AATSR). Finally, the gap-free SST foundation field is computed from the merged set of selected observations using an objective analysis method. The guess is either climatology or a previous map.

Operational oceanography requirements

Table 7.3 from Le Traon et al. (2006) summarises weather, climate, and operational oceanography requirements for SST. No single sensor is adequate meets the key requirements for SST. To remedy this, GHRSST-PP has established an internationally accepted approach to blending SST data from different sources that complement each other (refer to previous subsection). For this to work effectively, there must be an assemblage of four distinct types of satellite SST missions in place at any time, as defined in Table 7.4 (from Le Traon et al., 2006).

	Application area	Temperature accuracy [K]	Spatial resolution [km]	Revisit Time	Priority
1	Weather prediction	0.2 – 0.5	10 – 50	6 – 12 hrs	High
2	Climate monitoring	0.1	20 – 50	8 d	High
3	Ocean forecasting	0.2	1 – 10	6 – 12 hrs	High

Table 7.3: User requirements for SST provision.

The priority expressed by the international SST community, through GHRSST, is to continue to provide a type B (ATSR class) sensor. Its on-board calibration system, especially its dual-view methodology, allow AATSR to deliver the highest achievable absolute accuracy of SST, robustly independent of factors that cause significant biases in other infrared sensors such as stratospheric aerosols from major volcanic eruptions or tropospheric dust. Because its absolute calibration (for dual view) is better than 0.2 K it is used for bias correction of the other data sources before assimilation into models or analyses. A type C sensor (microwave) is also required beyond AMSR-E on Aqua.

Ocean Colour

Ocean colour measurements and operational oceanography

Over the last decade, the applications of satellite-derived ocean colour data have made important contributions to biogeochemistry, physical oceanography, ecosystem assessment, fisheries oceanography, and coastal management (IOCCG, 2008). Ocean colour measurements provide a global monitoring of chlorophyll (phytoplankton biomass) and associated primary production. They can be used to calibrate and validate biogeochemical, carbon, and ecosystem models. Progress towards assimilation of ocean colour data is less mature than for SST or SSH, but there are already convincing examples of assimilation of chlorophyll-a (Chla) in ocean models.

Data products needed to support ocean analysis and forecasting models of open ocean biogeochemical processes include the concentration of chlorophyll-a (Chla), total suspended material (TSM), the optical diffuse attenuation coefficient (*K*), and the photosynthetically available radiation (PAR). Use of *K* and PAR is needed to define the in-water light field that drives photosynthesis in ocean ecosystem models and that is required to model and forecast the ocean surface temperature. Ocean colour is a tracer of dynamical processes (mesoscale and submesoscale) and this is of great value for model validation. It also plays a role in air-sea CO_2 exchange monitoring.

	SST mission type	Radiometer wavebands	Nadir resolution	Swath width	Coverage / revisit
A	Two polar orbiting meteorological satellites with infrared radiometers. Generates the basic global coverage	3 thermal IR (3.7, 11, 12 μm) 1 near-IR, 1 Vis	~1 km	~2500 km	Day and night global coverage by each satellite
B	Polar orbiting dual-view radiometer. SST accuracy approaching 0.1K, used as reference standard for other types.	3 thermal IR (3.7, 11, 12 μm) 1 near-IR, 1 vis, each with dual view	~1 km	~500 km	Earth coverage in ~4 days
C	Polar orbiting microwave radiometer optimised for SST retrieval. Coarse resolution coverage of cloudy regions	Requires channels at ~7 and ~11 GHz	~50 km (25 km pixels)	~1500 km	Earth coverage in 2 days
D	Infrared radiometers on geostationary platforms. Spaced around the Earth	3 thermal IR (3.7, 11, 12 μm) 1 near-IR, 1 Vis	2 - 4 km	Earth disk from 36000 km altitude	Sample interval < 30 min

Table 7.4: Minimum assemblage of missions required to meet the need for operational SST.

At regional and coastal scales, there are many applications that require ocean colour measurements: monitoring of water quality, measurement of suspended sediment, sediment transport models, measurement of dissolved organic material, validation of regional/coastal ecosystem models (and assimilation), detection of plankton and harmful algal blooms, and monitoring of eutrophication. Use of ocean colour data in coastal seas is, however, more challenging as explained below.

Measurements principles

The sunlight is not merely reflected from the sea surface. The colour of water surface results from sunlight that has entered the ocean, been selectively absorbed, scattered and reflected by phytoplankton and other suspended material in the upper layers, and then backscattered through the surface. The subsurface reflectance $R(\lambda)$ (ratio of subsurface upwelled or water-leaving radiance on incident irradiance) that is the ocean signal measured by a satellite is proportional to $b(\lambda)/[a(\lambda)+b(\lambda)]$ or $b(\lambda)/a(\lambda)$ where $b(\lambda)$ is the backscattering and $a(\lambda)$ the absorption of the different water constituents.

Sunlight backscattered by the atmosphere (aerosols and molecular/Rayleigh scattering) contributes to more than 80% of the radiance measured by a satellite sensor at visible wavelengths. Atmospheric correction is calculated from additional measurements in the red and near-infrared spectral bands. Ocean water reflects very little radiation at these longer wavelengths (the ocean is close to a blackbody in the infrared) and the radiance measured is thus due almost entirely to scattering by the atmosphere.

Unlike observations in the infrared or microwave frequencies for which emission is from the sea surface only, ocean colour signals in the blue-green can come from depths as great as 50 m.

Sources of ocean colour variations include:

- Phytoplankton and its pigments
- Dissolved organic material
    - Coloured Dissolved Organic Material (CDOM or yellow matter) is derived from decaying vegetable matter (land) and phytoplankton degraded by grazing or photolysis.
- Suspended particulate matter (SPM)
    - The organic particulates (detritus) consist of phytoplankton and zooplankton cell fragments and zooplankton fecal pellets.
    - The inorganic particulates consist of sand and dust created by erosion of land-based rocks and soils (from river runoff, deposition of wind-blown dust, wave or current suspension of bottom sediments).

Colour can tell us about relative and absolute concentrations of those water constituents that interact with light. Hence we measure chlorophyll, yellow substance, and sediment load. It is difficult to distinguish independently varying water constituents:

- Case 1 waters are where the phytoplankton population dominates the optical properties (typically open sea). Only one component modulates the radiance spectrum backscattered from the water (phytoplankton pigment). Concentration range is 0.03 – 30 mg m^{-3}. Water in the near IR is nearly black for blue water. Atmospheric correction that is based on IR frequency measurements is thus relatively simple. Using green/blue ratio algorithms for chlorophyll, of the form Chla = A(R550/R490), provides an accuracy for Chla of ~ ±30% in open ocean.
- Case 2 waters are where other factors (CDOM, SPM) are also present. There are multiple independent components in water, which have an influence on the backscattered radiance spectrum. The retrieval procedure has to deal with these multiple components, even if only one should be determined. At high total suspended matter concentrations, problems also occur with atmospheric correction. Therefore, more complex algorithms (e.g., neural network) and more frequencies are required. Although this remains a challenging task, much progress has been made over the past five years. Useful estimations of Chla and SPM can thus be obtained in the coastal zone (e.g., Gohin et al., 2005).

Ocean colour can also provide information on phytoplankton functional types as changes in phytoplankton composition can lead to changes in absorption and backscattering coefficients (IOCCG, 2014). This is an area of active research with important implications for the assimilation of ocean colour data in ocean models.

An ocean colour satellite should have a minimum number of bands from 400-900nm. The role of the various bands is:

- 413 nm - Discrimination of CDOM in open sea blue water.
- 443, 490, 510, 560 nm - Chlorophyll retrieval from blue-green ratio algorithms.
- 560, 620, 665 nm and others - Potential to retrieve water content in turbid Case 2 waters using new red-green algorithms.
- 665, 681, 709 nm and others - Use of fluorescence peak for chlorophyll retrieval.
- 779, 870 nm for atmospheric correction plus another above 1000 nm to improve correction over turbid water.

Processing issues

The processing transforms the level 1 data, normalized radiances observed by the ocean colour radiometer, into geophysical properties corrected from atmospheric effects. Level 2 products include water leaving radiances at different wavelengths, chlorophyll-a concentration of the surface water (usually with case 1 and case 2 algorithms), total suspended matter (TSM), coloured dissolved and detrital organic materials (CDOM), diffuse attenuation coefficient (K) and photosynthetically available radiation (PAR).

Merging of several ocean colour satellites is needed to improve the daily ocean coverage. This requires combining data from individual sensors with different viewing geometries, resolution, and radiometric characteristics (e.g. IOCCG 2007; Le Traon et al., 2015). The availability of merged datasets allows the users to exploit a unique, quality-consistent, time series of ocean colour observations, without being concerned with the performance of individual instruments.

Category	Category of use	Optical class of water	Minimum set of satellite-derived variables needed	Accuracy [%]	Spatial resolution [km]	Revisit Time
1	Assimilation into operational open ocean models	Case 1	Chlor K PAR Lw(λ)	30% 5% 5% 5%	2 - 4	1 – 3 days
2	Ingestion in operational shelf sea & local models	Case 2	K - PAR Lw(λ) Chlor TSM CDOM	5% 5% 5% 30% 30% 30%	0.5 - 2	1 day desired, but 3-5 days useful
3	Data products used directly by marine managers in shelf seas	Case 2	K PAR Lw(λ) Chlor TSM CDOM	5% 5% 5% 30% 30% 30%	0.25 - 1	1 day desired, but 3-5 days useful
4	Global ocean climate monitoring	Case 1	Chlor K PAR	10 – 30% 5% 5%	5 - 10	8 d average
5	Coastal ocean climate monitoring	Case 2	Chlor TSM CDOM K PAR K	10 – 30% 10 – 30% 10 – 30% 5% 5%	5	8 day average
6	Coastal and estuarine water quality monitoring	Case 2	Lw(λ)	5%	0.1 - 0.5	0.5 – 2 hrs

Table 7.5: User requirements for ocean colour data products

Operational oceanography requirements

The needs and the broad classes of colour sensor are summarised in Tables 7.5 and 7.6 from Le Traon et al. (2006). They distinguish categories of use between the needs of the open ocean forecasting models, the finer scale shelf sea and local models, and those operational end users who analyse the data directly rather than through assimilation into a model system. There is a variety of additional products desired in coastal waters depending on the local water character. These include the CDOM and the discrimination of different functional groups of phytoplankton.

Some operational users prefer to use directly the atmospherically corrected water leaving radiance, $L_w(\lambda)$ (defined over the spectrum of given wavebands), applying their own approach for deriving water quality information or for confronting a model. Climate applications (categories 4 and 5) are envisaged to be derived from the operational categories 1 and 2, respectively, trading spatial and temporal resolution for improved accuracy. Category 6 is included in Table 7.5 to represent those users needing to monitor estuarine processes in fine spatial detail and to resolve the variations within the tidal cycle. This is a much more demanding category than the others.

A Class A simple SeaWiFS-like instrument with a resolution of 1 km and a set of 5 or 6 wavebands would be adequate for user Categories 1 and 4, to monitor global chlorophyll for assimilation into open ocean ecosystem models and for monitoring global primary production. It would fail to meet the main requirement to monitor water quality in coastal and shelf seas represented by user categories 2 and 3. These require a Class B imaging spectrometer sensor.

In order to satisfy the ocean colour measurement requirements for operational oceanography, the minimum requirement is for one Class B sensor and at least one other sensor (Class A, B or C). The Class C sensor corresponds to an imaging spectrometer on a geostationary platform. As well as uniquely serving the user Category 6 by resolving variability within the tidal cycle, it also serves other user categories in cloudy conditions by exploiting any available cloud windows that occur during the day.

Class	Orbit	Sensor type	Revisit Time	Spatial resolution	Priority
A	Polar	SeaWiFS type multispectral scanner, 5-8 Vis-NIR wavebands	3 days	1 km	High
B	Polar	Imaging spectrometer (MERIS/MODIS type)	3 days	0.25 – 1 km	High
C	Geostationary	Radiometer or spectrometer - feasibility to be determined	30 min	100 m – 2 km	Medium

Table 7.6: Classes of ocean colour sensor

Other Techniques

Synthetic aperture radar

SAR is an active instrument that transmits and receives electromagnetic radiation. It operates at microwave (or radar) frequencies. Wavelengths are in the range of 2 cm to 30 cm corresponding to frequencies in the range of 15 GHz – 1 GHz. It works in the presence of clouds, day and night. Synthetic aperture principle is to generate a very long antenna through the motion of the platform. For ASAR, the length of the synthetic antenna is approximately 20 km. This leads to very high resolution.

The surface roughness is the source for the backscatter of the SAR signal. The signal that arrives at the antenna is registered both in amplitude and phase. Although the SAR sees only the Bragg waves ($\lambda_B = \lambda/2 \sin \theta$, where θ is the incidence angle, λ the radar wavelength and λ_B the resonant Bragg wavelength), these waves are modulated by a large number of upper ocean and atmospheric boundary layer phenomena. This is the reason why SAR images express wave field, wind field, currents, fronts, internal waves, and spilled oil. They also provide high resolution images of sea ice (see next sub section).

Sea ice

Low resolution passive microwave sensors (Special Sensor Microwave/Imager (SSM/I) series of the US Defense Meteorological Satellite Program) have provided essential sea ice extent and concentration data from 1979 to present. These data can be extended and combined with scatterometer data. Moreover, sea ice drift estimates from scatterometers and radiometers are widely used for model validations and contribute importantly to the long-term sea ice monitoring. Sea ice thickness observations are needed to enable accurate estimations of the total sea ice volume. Great expectations were given to the CryoSat-2 launched in April 2010 with an altimeter designed for sea ice freeboard measurements. Thanks to the careful inter-comparison to the ICESAT laser altimeter mission data the retrieval accuracy has been reliably assessed (e.g. Laxon et al., 2013). Thickness of thin sea ice (<30 cm) for the Arctic freeze-up period can also be derived from the SMOS mission, which make these data highly complementary to the Cryosat-2 estimates of the thicker sea ice. From 2016, the Sentinel-1 A/B satellites have delivered high resolution (better than 30 m) SAR data in wide swath mode and simultaneous co- and cross-polarisation. This allows estimations of sea ice drift with a daily temporal resolution. Studies are now focusing on sea ice thickness, drift, and deformation analysis combining satellite data (like SMOS, CryoSat-2) with new data from the Sentinel-1 SAR missions.

Winds and waves

Scatterometers (e.g., Seawinds/QuikSCAT, ASCAT/MetOp) are radars operating at C or Ku bands. The main ocean parameters measured are the wind speed and direction. They also provide useful information on sea ice roughness. The principle is based on the resonant Bragg scattering. For a smooth surface, oblique viewing of the surface with active radar yields virtually no return. When wind increases, so does surface roughness and the reflected signals towards the satellite sensor. The wind direction can be derived because of the azimuthal dependence of the reflected signal with respect to the wind direction.

Over the past five years, there have been significant advances to develop and make accessible a harmonized set of altimeter and SAR wave products. These have been invaluable for numerical wave modelling and for applications. In particular, multiple altimeter missions have continued to provide precise significant wave height observations with a global coverage, which are essential to calibrate and validate numerical wave models and improve their forecasting skills through data assimilation. The sequence of ESA SAR C- and X-band instruments continuously operated on the ERS-1, ERS-2, ENVISAT RADARSAT, and TerraSAR-X satellites from 1991–2015 has also had a valuable impact on ocean wave observation and modelling, especially with regards to adequate determination of the swell attenuation over large distances. The future CFOSAT mission (to be launched in 2018) is expected to provide significant advances for winds and waves monitoring from space.

A new challenge: estimate sea surface salinity from space

At L-band (1.4 GHz), brightness temperature (BT) is mainly affected by ocean surface emission (atmosphere is almost transparent):

$$BT = e\ SST = (1\text{-}R)\ SST$$

where BT is brightness temperature and *e* is the sea surface emissivity. R (θ, SSS, SST, U…) is the reflection coefficient (see section 3.3). R depends on sea water permittivity and thus on sea surface salinity. Sensitivity is maximum at L-band, however it is very low (0.2 - 0.8 °K/psu) and increases with sea surface temperature.

The SMOS satellite was launched in November 2009. It is an L-band radiometer that measures BT at different incidence angles (0-60°). SMOS is a synthetic aperture radiometer which provides a high spatial resolution (~40 km, precision 1 PSU). SSS accuracy of 0.1-0.2 PSU over 10-day 200 km x 200 km areas is achieved through averaging of individual measurements. The Aquarius satellite was launched in 2010. It is a conventional L-band radiometer operating at three incident angles. Aquarius includes an L-band scatterometer to correct for sea surface roughness effects. These missions provide global SSS at spatial resolution varying from 50 km (SMOS) to 100 km (Aquarius) on weekly to monthly time scales. Many scientific studies have revealed the high potential of these new data sets (see Lagerloef et al., 2014 and Reul et al., 2014 for a review). Efforts to demonstrate the impact of satellite SSS data assimilation for ocean analysis and forecasting is an ongoing activity (see chapter by T. Lee). Measurement errors remain an issue, but more work should be carried out in the coming years thanks to improved data sets and products.

Assessing the Impact of Satellite Observations in GOV models

GOV (GODAE OceanView) systems have been used to investigate the impact of satellite data within their data assimilation and forecasting framework in a number of global and regional studies summarized in Oke et al. (2015a) and Oke et al. (2015b). This is also the focus of the GOV OSEval (Observing System Evaluation) Task Team. Most of these studies demonstrate the impact of the satellite data in the context of the other observing systems using Observing System Experiments (OSEs) whereby an experiment is run assimilating all available data, and a parallel run of the system is carried out assimilating all the data except for the data type to be investigated. The difference between the two runs shows the impact of the withheld data in the context of all the other data, and the two runs can be assessed by comparing the outputs with assimilated and independent data. Le Traon et al. (2017) provided a review on the use of OSEs to assess the impact of the altimeter constellation on GOV systems. A complementary approach for estimating the influence of the observations on the analysis is the computation of the so-called "degrees of freedom for signal" (DFS), which represents the equivalent number of independent observations that constrain the model analysis at the observation point (Cardinali et al., 2004). DFS quantifies the influence of observations on analyses without having to run dedicated experiments withholding some data.

Impact of future observations can be assessed using OSSEs (Observing System Simulation Experiments). OSSEs typically use two different model runs (from two different models or from the same model with different resolution, parametrization, or forcing). One model is used to perform a "truth" run and it is treated as if it is the real ocean. The truth run is sampled in a manner that mimics either an existing or future observing system, yielding synthetic observations. A measurement error (and often a representativity error) is then added to the synthetic observations that are then assimilated into the second model. The model performance is evaluated by comparing it against the truth run. OSSEs need a careful design so that results are representative of the actual ocean. Calibration of OSSEs with OSEs (i.e., verifying that, for an existing observing system, an OSSE yields the same result as an OSE) should be systematically applied. For example, Mercator Ocean has performed first OSSEs of SWOT observations using a 1/12° regional model of the Iberian Biscay region that includes tidal forcing (Benkiran et al., 2017). The truth run was derived from a 1/36° model run over the same region. SWOT errors were derived using the JPL SWOT Simulator. This first study quantified the highly significant improvement of SWOT data with respect to existing conventional nadir altimeters to constrain ocean models.

Future Satellite Requirements

Challenges for the next decade

A complete overview of the evolution (past, present, future) of the satellite ocean mission details is maintained within the CEOS Earth Observation handbook (http://www.eohandbook.com/) and/or the World Meteorological Organization's Observing Systems Capability Analysis and Review (OSCAR) tool (http://www. wmo-sat.info/oscar/).

The satellite-based data record lengths now exceed 25 years (altimetry, SAR, scatterometry) and 35 years (radiometry). In the 2020-2030 timeframe, sustained satellite observations will be common for almost all the variables addressed in the previous section, except for the sea surface salinity. Altogether, this ensures that operational oceanography will be supplied with a rich amount of highly important satellite observations. In addition to securing continuity in the observations, the retrieval accuracies have also gradually improved thanks to advancing sensor technology and retrieval algorithm performances.

Still, many key ocean phenomena are undersampled and require much higher space and time resolution. Model resolutions are regularly increasing, but our observation capabilities are not. Coastal regions, which are of paramount importance for operational oceanography, are characterized by small spatial and temporal scales. There is also growing evidence that we need to better observe the submesoscale ocean dynamics. Hence, a major challenge for satellite oceanography is to address the ongoing need for improved resolution. This challenge is partly addressed through the development of virtual constellations, but it also requires developing new observing capabilities (e.g., swath altimetry with SWOT, geostationary ocean colour missions). New satellite observing capabilities (e.g., for surface currents) also need to be developed (e.g., SKIM, see Ardhuin et al., 2017). Fusing of different types of observations to extract better information is another complementary approach.

Future requirements: The Copernicus Marin Service perspective

The Copernicus Marine Environment Monitoring Service (CMEMS) is one of the six pillar services of the Copernicus program (see Le Traon et al., 2017 and chapter by Drevillon et al.). CMEMS includes most of the European contributions to GOV. It provides regular and systematic reference information on the physical state, variability, and dynamics of the ocean, ice, and marine ecosystems for the global ocean and the European regional seas. Copernicus Marine Service perspectives with respect to the long-term evolution of satellite observing systems are given hereafter.

First, continuity of the present Copernicus satellite observing system should be guaranteed as this is mandatory for maintaining the CMEMS service. This is particularly relevant to the Sentinel 6 altimeter reference mission (follow-on of Jason-3) and the two satellite constellation of Sentinel 3 (altimetry, sea surface temperature, and ocean colour) and Sentinel 1 (SAR).

In the post 2025 time period, Copernicus Marine Service model resolutions will be increased by a factor of at least 3 (e.g. global 1/36°, regional 1/108°) compared to the present and more advanced data assimilation methods will be available. The objective will be to describe at fine scale the upper ocean dynamics to improve our capabilities to describe and forecast the ocean currents and provide better boundary conditions for very high resolution coastal models (up to a few hundred meters). This is essential for key applications such as maritime safety, maritime transport, search and rescue, fish egg and larvae drift modelling, riverine influence in the coastal environments, pollution monitoring, and offshore operations. When moving to higher resolution, it will be necessary to constrain CMEMS models with new observations. The most important satellite-based observation is SSH from altimetry. As explained in previous sections, the SSH is an integral of the ocean interior properties and is a strong constraint for inferring the 4D ocean circulation through data assimilation. Multiple nadir altimeters (at least 4 altimeters) are required to adequately represent ocean eddies and associated currents in models. Much higher space/time resolution (e.g., 50 km / 5 days) will be needed in the post-2025 time period. This can be achieved through a combination of swath altimetry (to be demonstrated during the SWOT mission to be launched in 2021) with nadir SAR altimetry.

Monitoring the ecosystems in European seas is also a fundamental need, both for European policies (Marine Strategy) to monitor the health of the seas and coastal waters and to support sustainable fishery and aquaculture industries. Specifically, much more frequent observations of the highly variable biological parameters of the European regional seas are urgently needed. This is required to monitor the ocean ecosystem functioning at the diurnal scale and to monitor rapidly evolving phenomena (e.g. river outflows, phytoplankton and harmful algae blooms, sub-mesoscale features) and to constrain coupled biological-physical 3D models in regional seas and coastal zones. An ocean colour geostationary satellite would provide unique capabilities to provide such a monitoring. It should be complemented with new in situ biogeochemical observations (e.g., BGC Argo, Gliders, FerryBoxes). The development of hyperspectral sensor capabilities would also be relevant to

CMEMS (e.g., to improve the quality of Ocean Colour products in coastal zones and to differentiate between the types of phytoplankton in the ocean) (e.g., the NASA PACE and ASI PRISMA missions).

Sustainable passive microwave SST and sea ice observations are also very important in the global ocean and in polar regions. Such observations are available in all weather conditions, while infrared SST observations are available in cloud-free conditions only. Passive microwave SST and sea ice are a crucial contribution to weather forecasting and CMEMS ocean and analysis and forecasting models. CMEMS also requires specific observations for polar regions. In addition to passive microwave observations, one of the most important short term priorities is the continuation (including a few enhancements such as additional use of Ka band, more optimized orbit configuration, real-time capabilities) of the Cryosat-2 mission to monitor sea ice thickness, continental ice shelves elevation changes and contribute to the observation of the ocean surface topography in ice free regions.

Other requirements (e.g., surface current, SSS, wave, improved geoid, wind) should also be considered. Today, they do not have today the same (due to maturity of satellite technology or foreseen impact on the service). Surface current and SSS are two very important variables required for CMEMS. The potential impact is high but this requires developments or improvements in satellite technology. Thus, research and development should be done to further advance our capabilities to observe SSS from space building on SMOS achievements. There is also a strong need to test new mission concepts allowing the direct measure of surface currents at high resolution and to develop capabilities to fully use these observations to constrain ocean analysis and forecasting systems. Meanwhile, use of imaging SAR-based range Doppler retrievals (S1) should be reinforced.

Waves are observed today through altimeter (S3, S6) and SAR (S1) missions. New satellite concepts (CFOSAT) will soon allow for a better retrieval of directional wave spectra. This could lead to an improved design of future Sentinel missions. Finally, new gravity missions could be required to improve the geoid at small scales (and derived mean dynamic topography) and to monitor large-scale mass changes in the ocean. However, the main priority at present is to further develop the exploitation of GOCE data and to derive new mean dynamic topographies from the merging of GOCE, altimetry, and in situ observations. The Ocean Surface Vector Wind (OSVW) measurements through scatterometers are also important to improve NWP forcing fields. Europe, through the Eumetsat MetOP series, provides a unique contribution to the international CEOS OSVW virtual constellation. This should be pursued and coordination of the CEOS OSVW should be reinforced to optimize the existing and future scatterometer constellation.

Concluding Remarks

The chapter provides a brief introduction to ocean remote sensing measurement principles and the use of satellite observations for operational oceanography. The different techniques will be detailed further in the other chapters. More information can also be found in Fu and Cazenave (2001), Robinson (2004), Martin (2004), Emery and Camps (2017), and Stammer and Cazenave (2017).

Satellite data plays a fundamental role for operational oceanography. There have been important achievements over the past 10 years to ensure real-time availability of high quality satellite data and to develop the use of satellite observations for operational oceanography. Multiple mission high resolution altimeter products are now readily available. There have been many improvements (timeliness, new products) and major efforts were undertaken to include new missions in the operational data stream in a very limited time. New MDTs from GRACE and GOCE have a major impact on data assimilation systems and further improvements are expected. Thanks to GHRSST, major improvements in SST data processing techniques and use of different types of sensors have occurred. The use of ocean colour data in operational oceanography has become a reality and there has been continuous progress in data access, data processing, and data assembly systems. SMOS and Aquarius have demonstrated the feasibility and utility of measuring SSS from space. The ocean community and GOV now need to fully invest in the critical assessment and application of the data.

In situ data are mandatory to calibrate and validate and to complement satellite observations. Although the consolidation of the Argo in situ observing system and its integration with satellite altimetry and operational oceanography (e.g., Le Traon, 2013) was an outstanding advancement, the evolution of the in situ observing system remains a strong concern. The potential of satellite observations is not and will not be fully realized without a sustained in situ observing system.

Improvements in models and data assimilation techniques have resulted in a better use of satellite observing capabilities. However, the information content of satellite observations is not being fully exploited. Use of new theoretical frameworks to better exploit high resolution information from satellite data is required and further improvements in data assimilation schemes are needed to better take into account observations (e.g., towards L1B and L2 assimilation, correlated errors, biases, representativity errors). The potential of ocean colour data to calibrate or improve biogeochemical models is considerable. But this is a complex issue and, as such, development lags behind other remote sensing techniques. This is a challenging and high priority research topic for operational oceanography.

There is a need to develop further OSE/OSSE activities (GOV Task Team). This is essential to define needs, quantify impacts, and to improve data assimilation systems.

Finally, new satellite missions such as high resolution altimetry (SWOT) missions will likely have a major impact on operational oceanography. There is also great potential for satellite missions to improve the monitoring of waves and winds (e.g., CFOSAT, see Hauser et al., 2016) or for directly measuring surface currents from space (e.g., SKIM, see Ardhuin et al., 2017).

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