Chapter 2
Satellites and Operational Oceanography

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Abstract The chapter starts with an overview of satellite oceanography, its role and use for operational oceanography. Main principles of satellite oceanography techniques are then summarized. We then describe key techniques of radar altimetry, sea surface temperature, ocean colour satellite measurements. This includes measurement principles, data processing issues and the use of these data for operational oceanography. SAR, scatterometry, sea ice and sea surface salinity measurements are also briefly described. Main prospects are given in the conclusion.

2.1 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 to the development of global operational oceanography and its applications. The first ocean parameter to be globally monitored from space was the sea surface temperature on board meteorological satellites in the late 1970s. It is, however, the advent of satellite altimetry in the late 1980s that led the development of ocean data assimilation and global operational oceanography. In addition to providing all 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. GODAE demonstration was thus phased 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

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applications. An overview of satellite oceanography will be given here focusing on the most relevant issues for operational oceanography. The chapter is organized a follows. Section 2.2 provides 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. Main principles of satellite oceanography and general data processing issues are described in Sect. 2.3. We then detail key techniques of radar altimetry and gravimetry, sea surface temperature, ocean colour satellite measurements in Sects. 2.4, 2.5 and 2.6. This includes measurement principles, data processing issues and the use of these data for operational oceanography. SAR, scatterometry, sea ice and the new sea surface salinity measurements are briefly described in Sect. 2.7. Main prospects are given in the conclusion.

2.2 Role of Satellites for Operational Oceanography

2.2.1 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 a 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 (e.g. in the case of a parameter observed from space at high resolution).

This requires an adequate and sustained global ocean observing system. Climate and operational oceanography applications share the same backbone system (GOOS, GCOS, JCOMM). Operational oceanography has, however, specific requirements for high resolution measurements. Operational oceanography requirements have been presented in the GODAE strategic plan and in Le Traon et al. (2001). They have been refined and detailed in Clark and Wilson (2009) and Oke et al. (2009).

2.2.2 The Unique Contribution of Satellite Observations

Satellites provide long-term, continuous, global, high space and time resolution data for key ocean parameters: sea level and ocean circulation, sea surface temperature (SST), ocean colour, sea ice, waves and winds. These are the core variables observations 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 variability 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 demonstration is underway with the European Space Agency SMOS mission (and later on with the NASA/CONAE Aquarius mission).

2.2.3 Main Requirements

The main requirement for operational oceanography is to have a long-term, continuous and near real time access to the core operational satellite observations of sea level, SST, ocean colour, sea ice, wave and winds. For a given parameter, this generally requires several satellites flying simultaneously to get sufficient space and time resolution. The main requirements can be summarized as follows (e.g. Le Traon et al. 2006; Clark and Wilson 2009):

- In addition to meteorological satellites, a high precision (AATSR-class) SST satellite 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 is also useful for significant wave height measurements. A long-term series of a high accuracy altimeter system (Jason satellites) is needed to serve a reference for the other missions and for the monitoring of climate signals.
- Ocean colour is increasingly important, in particular, in coastal areas. At least two satellites are required.
- Two scatterometers are required to globally monitor at high spatial resolution the wind field.
- 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. Long-term continuity and transition from research to operational mode remains a major challenge (e.g. Clark and Wilson 2009).

Specific requirements for altimetry, SST and ocean colour are discussed in the following sections.

2.2.4 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. 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 includes the validation of altimeter velocity products with drifter data (e.g. 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). The comparison of in-situ and satellite data can also provide useful indication on the quality of in-situ data (e.g. Guinehut et al. 2008).

The comparison of in-situ and satellite data is also useful to check the consistency between the different data sets before they are assimilated in an ocean model (e.g. Guinehut et al. 2006).

In-situ data are also (and mainly) mandatory to complement satellite observations and to provide measurements of the ocean interior. Only the joint use of high resolution satellite data with precise (but sparse) in-situ observations of the ocean interior has the potential to provide a high resolution description and forecast of the ocean state.

2.2.5 Data Processing Issues

Satellite data processing includes different 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 these 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 also includes uncertainty estimates that are critical to an effective use of data in modelling and data assimilation systems. Links with data assimilation centers are needed, in particular, to organize feedback on the quality control performed at the level of data assimilation centers (e.g. comparing an observation with a model forecast), on the impact of data sets and data products in the assimilation systems and on 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 limitations of high level satellite products (e.g. gridded SST or sea level data sets) when using them.

2.2.6 Use of Satellite Data for Assimilation into Ocean Models

This is discussed at length in other chapters. Three important issues are emphasized here:

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 covariance should always be tested and checked as part of the data assimilation systems.
3. It is much better in theory and for advanced assimilation schemes 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 do 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 data high level processing (e.g. correcting biases or large scale errors, intercalibration) is often needed as it cannot be easily done within the assimilation systems.

2.3 Overview of Satellite Oceanography Techniques

2.3.1 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 after its reflection at the sea surface. In both cases, the propagation of the signal through the atmosphere, the emission from the atmosphere itself must be taken into account to isolate 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.

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

Satellite systems operate at different frequencies depending on the signal to be derived. Visible (400–700 nm) and infra-red (0.7–20 μm) frequencies are used for ocean colour and SST measurements. Passive (radiometry) microwave systems (1–30 cm) are used for SST 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°–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). Those are particularly important at microwave frequencies in the range 1–10 GHz which puts strong pressures on 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, O_3) and of water vapor means that only a limited number of windows exist in the visible, infra-red and microwave for ocean remote sensing. Even at these frequencies, the propagation effects through the atmosphere must be taken into account and corrected for. Propagation effects through the ionosphere must also be taken into account. 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 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 (that are much less sensitive to mispointing errors). Their footprint size is related to the pulse duration and is much smaller than for a beam limited sensor. Synthetic Aperture Radar uses the motion of the satellite to generate very long antenna (e.g. 20 km for ASAR) and thus to provide very high resolution measurements (up to a few meters).

2.3.2 Satellite Orbits and Measurement Characteristics

Orbits for ocean satellites are geostationary, polar or inclined orbits. 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 of a few km while it is of 1 km or less for polar orbiting satellites. Because a geostationary orbit must be in the same plane as the Earth's rotation, that is 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°).

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 700–800 km these satellites have an orbital period of approximately 90 min. These satellites usually operate in a sun-synchronous orbit. The satellite passes the equator and any given latitude at the same local solar time each day. Inclined orbits have an inclination between 0° (equatorial orbit) and 90° (polar orbit). They are used, in particular, to observe tropical regions (e.g. TMI on TRMM mission). 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.

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

2.3.3 Radiation Laws and Emissivity

2.3.3.1 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 Planck Law can be expressed through the following equation:

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

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

The Planck law gives a distribution that peaks at a certain wavelength; the peak shifts to shorter wavelengths for higher temperatures. The Wien displacement law and the Stefan-Boltzmann law are two other useful radiation laws that can be derived from the Planck law. The Wien law gives the wavelength of the peak of the radiation distribution ($\lambda_{max} = 3 \cdot 10^7/T$) while the Stefan-Boltzmann law gives the total energy E being emitted at all wavelengths by the blackbody ($E = \sigma \cdot T^4$). Thus, the Wien 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.

2.3.3.2 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 is comprised between 0 and 1. The emissivity generally depends on wavelength (λ) and polarization and has a directional dependence. e can be considered as a physical surface property and is a key quantity for ocean remote sensing. A blackbody absorbs all the energy it receives. A graybody absorbs only part of it 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 $1-\mathrm{e}$.

The brightness temperature (BT) is defined as $\mathrm{BT}=\mathrm{e}\cdot\mathrm{T}$ where T is the (physical) temperature. In the microwave band, it is proportional to the radiation L_{λ}.

2.3.3.3 Retrieval of Geophysical Parameters for Microwave Radiometers

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 (RTM), which computes the brightness temperatures that are measured by the satellite as a function of these variables. The RTM 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 RTM) brightness temperatures. Statistical or empirical inversions are also often used given uncertainties in RTMs. They use a regression formalism (e.g. parametric, neural network) to find the best relation between brightness temperatures and the geophysical parameter to be retrieved.

2.4 Altimetry

2.4.1 Overview

Satellite altimetry is the most essential observing system required for global operational oceanography. It provides global, real time, all-weather sea level measurements (SSH) with high space and time resolution. Sea level is directly related to ocean circulation through the geostrophic approximation (see Sect. 2.4.5). Sea level is also an integral of the ocean interior and is 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 (the "ocean weather") in models. Only altimetry can constrain the 4D mesoscale circulation in ocean models which is required for most operational oceanography applications.

2.4.2 Measurement Principles

An altimeter is active radar that sends a microwave pulse towards the ocean surface. 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 of a few centimeters for a distance of 800–1,300 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 vapor correction) and a tracking system for precise orbit determination (Laser, GPS, Doris) that provides the orbit altitude relative to a given earth ellipsoid.

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 and ENVISAT). The distance between tracks is inversely proportional to the repeat time period (e.g. about 315 km at the equator for TOPEX/Poseidon and 90 km for ERS/ENVISAT).

The main measurement for an altimeter radar is the sea surface height (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, the reader is referred to Chelton et al. (2001).

2.4.3 Geoid and Repeat-Track Analysis

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

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

N is the geoid, η the dynamic topography and ε are measurement errors. The quantity of interest for oceanographer is the dynamic topography (see next section).

Present geoids are not generally accurate enough to estimate globally the absolute dynamic topography η except at long wavelengths.

The variable part of the dynamic topography $\eta'(\eta - <\eta>)$ (or SLA for sea level anomaly) 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 $<\eta>$:

$$\mathrm{SLA(x,t) = SSH(x,t) - < SSH(x) >_t} = \eta\mathrm{(x,t)} - < \eta\mathrm{(x)} >_\mathrm{t} + \varepsilon'\mathrm{(x,t)}$$

To get the absolute signal, one has thus to use a climatology or to use existing geoids together with altimeter Mean Sea Surface (MSS) (or both). One can also rely on a model mean. Gravimetric missions (CHAMP, GRACE) are now providing much more accurate geoids, GOCE should almost "solve" the problem. Even with GOCE, however, repeat-track analysis will still be needed because of the small scales of geoid (below 50–100 km) will not be precisely known. GOCE will be used with an altimetric MSS to derive $<\eta>_t$ that can then be added to η'.

2.4.4 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 main operational oceanography and climate centers in Europe and worldwide. Main processing steps are product homogenization, data editing, orbit error correction, reduction of long wavelength errors, production of along track and maps of sea level anomalies. Major progress has been made in 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 a 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.

The mean dynamic topography (MDT) is an essential reference surface for altimetry. Added to the sea level anomalies, it provides the absolute sea level and ocean circulation (see previous section). After a preliminary MDT computed in 2003, a new MDT, called RIO-05, was computed in 2005. It is based on the combination of GRACE data, drifting buoy velocities, in-situ T,S profiles and altimeter measurements. The MDT was tested and is now used by several GODAE modelling and forecasting centers. It has a positive impact on the ocean analysis quality and forecast skill. An updated version was recently delivered (CNES-CLS09). Major improvement is expected soon with the use of data from the GOCE mission.

2.4.5 Sea Level Measurement Content

Satellite altimetry provides measurements of the dynamic topography η (i.e. sea level relative to the geoid). Assuming geostrophy and hydrostatic balance, one has:

$$\begin{cases} fv = \dfrac{1}{\rho_0}\dfrac{\partial P}{\partial x} & (2.1) \\ -fu = \dfrac{1}{\rho_0}\dfrac{\partial P}{\partial y} & (2.2) \end{cases} \qquad f = 2\Omega \sin\theta$$

$$\left\{ \frac{\partial p}{\partial z} = -\rho g \right. \tag{2.3}$$

with u, v zonal and meridional currents, P pressure and f the Coriolis parameter.

At the surface P=$\rho \cdot g \cdot \eta$ (η=sea surface topography relative to the geoid), thus there is a direct relationship between the dynamic topography and the surface (geostrophic) current:

$$\begin{cases} fv = g\dfrac{\partial \eta}{\partial x} \\ -fu = g\dfrac{\partial \eta}{\partial y} \end{cases} \tag{2.4}$$

Taking the derivative of (2.3), one gets the thermal wind equation. It means that density horizontal variations are associated with vertical shear (baroclinic motions):

$$f\frac{\partial v}{\partial z} = \frac{-g}{\rho_0}\frac{\partial \rho}{\partial x} \tag{2.5}$$

The integration of (2.5) from z_0 to z_1 yields:

$$v(z) = v(z_0) - \frac{g}{f}\int_{z_0}^{z_1} \frac{1}{\rho_0}\frac{\partial \rho'}{\partial x} dz \tag{2.6}$$

$$\text{or } v(z) = v(z_0) + \frac{g}{f}\frac{\partial \eta_s}{\partial x} \quad \text{with} \quad \eta_s(z_0, z_1) = -\int_{z_0}^{z_1} \frac{\rho'}{\rho_0} dz \tag{2.7}$$

η_s is the steric height. η_s is generally defined as η_s (bottom, surface).

At the surface, one has:

$$\begin{cases} v(z_0) + \dfrac{g}{f}\dfrac{\partial \eta_s}{\partial x} = \dfrac{g}{f}\dfrac{\partial \eta}{\partial x} \\ \text{with } v(z_0) = \dfrac{1}{f\rho_0}\dfrac{\partial P_{z0}}{\partial x} \end{cases} \Rightarrow \eta = \eta_s + \frac{P_{z0}}{\rho_0 g} \tag{2.8}$$

The dynamic topography (measured by altimetry) is thus the sum of a steric height term (integral of density anomalies which is generally referred to the baroclinic component) and a bottom pressure term (barotropic component). Sea level is thus more than a « surface » measurement. It corresponds to a signal over the full depth of the ocean and provides a strong constraint for inferring (together with in-situ measurements) the 4D ocean structure through data assimilation.

2.4.6 Operational Oceanography Requirements

Le Traon et al. (2006) have defined the main priorities for altimeter missions in the context of the European GMES (Global Monitoring for Environment and Security) Marine Core Service. Their Tables 2.1 and 2.2 give the requirements for different applications of altimetry and characteristics of altimeter missions.

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

1. Need to maintain a long time series of a high accuracy altimeter system (Jason series) to serve a reference mission and for climate applications. It requires one class A altimeter with an overlap between successive missions of at least 6 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. Recent studies (e.g. Pascual et al. 2006) show

Table 2.1 User requirements for different applications of altimetry

Application area	Accuracy[a] (cm)	Spatial resolution (km)	Revisit time (days)	Priority
1. Climate applications and reference mission	1	300–500	10–20	High
2. Ocean nowcasting/forecasting for mesoscale applications	3	50–100	7–15	High
3. Coastal/local	3	10	1	Low[b]

[a] For the given resolution
[b] Limited by feasibility

Table 2.2 Altimeter mission characteristics

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

that, at least three, but preferably four, altimeter missions are needed for monitoring the mesoscale circulation. This is particularly needed 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 an 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 SWOT mission) to better answer existing and future operational oceanography requirements for high to very high resolution (e.g. mesoscale/submesoscale and coastal dynamics). There is also a need to improve nadir altimetry technology (resolution, noise) and to develop smaller and cheaper instruments that could be embarked on a constellation of small satellites. The use of the Ka band (35 Ghz) allows, in particular, a major reduction in the size and weight of the altimeter. It will be tested for the first time with the CNES/ISRO SARAL satellite scheduled for launch in late 2011.

2.5 Sea Surface Temperature

2.5.1 Sea Surface Temperature Measurements and Operational Oceanography

Sea surface temperature (SST) is a key variable for 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 (heat fluxes, wind). It also characterizes the mesoscale variability of the upper ocean (eddies, 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 recently evidenced (e.g. Chelton 2005).

2.5.2 Measurement Principles

Infrared radiometers 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 black body). Atmospheric correction is based on 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 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 cloud. The first priority is thus 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. Consequences of poor cloud detection are low biases in SST climatic averages and "false hits" of cloud that can hide frontal and other dynamical structures. Geostationary infra-red 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 (19–37 GHz) are used to precisely estimate the attenuation due to oxygen, water vapor, 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 infra-red ones is that SST can be retrieved even through non-precipitating clouds, which is very beneficial in terms of geographical coverage.

2.5.3 SST Infra-Red and Microwave Sensors

Infra-red 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 a global coverage, with the important exception of cloudy areas. However, their accuracy (0.4–0.5 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. GOES and MSG series) are carrying radiometers with similar infrared window channels as the AVHRR instrument. Their horizontal resolution is coarser (3–5 km), but their great contribution comes from their high temporal sampling. Pre-operational demonstrators for advanced measurement of SST suitable for climate studies include the Along Track Scanning Radiometer ((A)ATSR) series of instruments that 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 of 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.

2.5.4 Key Developments in SST Data Processing

During the past ten years, a concerted effort to understand satellite and in situ SST observations has taken place leading to a revolution in 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 develop a set of dedicated products and services. There have been key developments in 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 in Donlon et al. (2009). Data processing issues are summarized in Le Traon et al. (2009).

A satellite measures the so-called skin temperature, i.e. at a depth from a few tens of microns (infra-red) up to a few mm only (microwave). Diurnal warming changes the SST over a layer of 1–10 m. 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 analyzed high resolution SST products have been produced, in particular, 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 in a screening and quality control of the retrieved observations from each single datasets and in 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 estimate and correction (relative to a chosen reference, currently AATSR). The gap free SST foundation field is finally computed from the merged set of selected observations using an objective analysis method. The guess is either climatology or a previous map.

2.5.5 Operational Oceanography Requirements

Table 2.3 from Le Traon et al. (2006) summarises weather, climate and operational oceanography requirements for sea surface temperature.

In order to meet the key requirements for SST no single sensor is adequate. To remedy this, GHRSST-PP has established an internationally accepted approach to blending SST data from different sources that complement each other (see previous section). 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 2.4 (from Le Traon et al. 2006).

Table 2.3 User requirements for SST provision

Application area	Temperature accuracy (K)	Spatial resolution (km)	Revisit time	Priority
1. Weather prediction	0.2–0.5	10–50	6–12 h	High
2. Climate monitoring	0.1	20–50	8 day	High
3. Ocean forecasting	0.2	1–10	6–12 h	High

Table 2.4 Minimum assemblage of missions required to meet the need for operational SST

SST mission type	Radiometer wavebands	Nadir resolution	Swath width	Coverage/revisit
A. Two polar orbiting meteorological satellites with infra-red radiometers. Generates the basic global coverage	3 thermal IR (3.7, 11, 12 μm), 1 near-IR, 1 Vis	~1 km	~2,500 km	Day and night global coverage by each satellite
B. Polar orbiting dual-view radiometer. SST accuracy approaching 0.1 K, 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)	~1,500 km	Earth coverage in 2 days
D. Infra-red 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 36,000 km altitude	Sample interval <30 min

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 and especially its dual-view methodology allow AATSR to deliver the highest achievable absolute accuracy of SST, robustly independent of factors such as stratospheric aerosols from major volcanic eruptions or tropospheric dust, which cause significant biases in other infra-red sensors. 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.

2.5.6 Conclusions

Satellite SST observations are essential observations for operational oceanography, weather and climate forecasting. SST data are systematically used for global and large scale observations for climate applications and to correct for large scale biases in ocean models (due to forcing field errors). Thanks to GHRSST, major improvements in data processing issues and use of different types of sensors have occurred. New high resolution products (from level 2 to level 4) are now available and used by ocean analysis and forecasting systems. High resolution SST data provide unvaluable information on mesoscale and submesocale phenomena. There is still a lot to do, however, to fully use the high resolution information content of SST observations in ocean models. This is an area of active research.

2.6 Ocean Colour

2.6.1 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 Chla in ocean models. Use of K and PAR (see below) 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.

Data products needed to support ocean analysis and forecasting models of open ocean biogeochemical processes are the concentration of chlorophyll-a (Chla), total suspended material (TSM), the optical diffuse attenuation coefficient (K) and the photosynthetically available radiation (PAR). 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.

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, monitoring of eutrophisation…. Use of ocean colour data in coastal seas is, however, more challenging as explained below.

2.6.2 Measurement 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 actually 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 black body in the infra-red) 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 which interact with the 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. More complex algorithms (e.g. neural network) and more frequencies are thus 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. This is an area of active research but first results are already promising.

An ocean colour satellite should have a minimum number of bands from 400–900 nm. 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 1,000 nm to improve correction over turbid water.

2.6.3 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 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 (Pottier et al. 2006; Mélin and Zibordi 2007; IOCCG 2007). 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.

2.6.4 Operational Oceanography Requirements

The needs and the broad classes of colour sensor are summarised in Tables 2.5 and 2.6 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

Table 2.5 User requirements for ocean colour data products

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	30	2–4	1–3 days
		K	5		
		PAR	5		
		Lw(λ)	5		
2. Ingestion in operational shelf sea and local models	Case 2	K	5	0.5–2	1 day desired, but 3–5 days useful
		PAR	5		
		Lw(λ)	5		
		Chlor	30		
		TSM	30		
		CDOM	30		
3. Data products used directly by marine managers in shelf seas	Case 2	K	5	0.25–1	1 day desired, but 3–5 days useful
		PAR	5		
		Lw(λ)	5		
		Chlor	30		
		TSM	30		
		CDOM	30		
4. Global ocean climate monitoring	Case 1	Chlor	10–30	5–10	8 day average
		K	5		
		PAR	5		
5. Coastal ocean climate monitoring	Case 2	Chlor	10–30	5	8 day average
		TSM	10–30		
		CDOM	10–30		
		PAR	5		
		K	5		
6. Coastal and estuarine water quality monitoring	Case 2	Lw(λ)	5	0.1–0.5	0.5–2 h

Table 2.6 Classes of ocean colour sensor

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

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 coloured dissolved organic material (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 2.5 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.

2.6.5 Conclusions

While ocean colour is now more and more used for operational applications (e.g. water quality), the development lags behind other remote sensing methods. This is because it is inherently difficult to retrieve ocean variables accurately and confidently. The potential of ocean colour measurements to calibrate or improve global, regional and coastal biogeochemical models is, however, considerable. The information content is very rich. This is a scientific and technical challenge. We are just beginning to use ocean colour products in ocean models. This is a challenging subject and it should be a high priority research topic for operational oceanography.

2.7 Other Techniques

2.7.1 Synthetic Aperture Radar

SAR is an active instrument that transmits/receives electromagnetic radiation. It operates at microwave (or radar) frequencies. Wavelengths are in the range of 2–30 cm corresponding to frequencies in the range of 15–1 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 oil spill. They also provide high resolution images of sea ice (see next section).

2.7.2 Sea Ice

Passive microwave (PM) data from the SSM/I instrument is the backbone of operational sea ice observations. Daily Arctic and Antarctic analysis of ice concentration are delivered in near real time from operational centers such as NCEP and the OSI SAF. These types of datasets are today assimilated in operational ocean model systems. Improved resolution and more detailed ice edge estimates are obtained by use of scatterometer data (e.g. QuickScat) and new PM data from AMSR-E. Ice drift information based on successive satellite passages from these instruments are also assimilated in ocean/ice models. High resolution sea ice information is derived from SAR data and images from optical and IR instruments. Operational services for offshore industry, shipping and safety in polar regions rely on regular iceberg detection and sea ice type, extent and deformation monitoring at a spatial resolution (~50–100 m) that is only feasible with spaceborne SAR.

Although ice coverage and ice motion is well observed there is still lack of regular information about the variation in ice volume. The ice thickness measurements from the advanced altimeter on Cryosat-II are thus very much welcomed (launched in April, 2010).

2.7.3 Satellite Winds

Scatterometers (e.g. Seawinds/Quickscat, ASCAT/MetOp) are radars operating at C or Ku bands. The main ocean parameters measured is the wind speed and direction. They also provide useful information on sea ice roughness. 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.

To enhance the spatial and temporal resolutions of surface wind, several attempts have been made to merge the remotely sensed data to the operational NWP wind analyses over the global oceans. More details about data and processing methods can be found in Bentamy et al. (2007).

2.7.4 A New Challenge: To 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): $BT = e \cdot SST = (1\text{-}R)\ SST$ where BT is brightness temperature an e sea surface emissivity. R (θ, SSS, SST, U…) is the reflexion coefficient (see Sect. 2.3). R depends on sea water permittivity and thus on sea surface salinity. Sensitivity is maximum at L-band. It is, however, 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 of brightness temperature 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 200 × 200 km and 10 days areas is achieved through averaging of individual measurements. The Aquarius satellite will be launched in 2011. It is a conventional L-band radiometer operating at 3 incident angles. Aquarius includes a L-band scatterometer to correct for sea surface roughness effects.

2.8 Concluding Remarks

The chapter provides only a very brief summary of ocean remote sensing measurement principles. More information can be found in Fu and Cazenave (2001), Robinson (2004) and Martin (2004) books.

Satellite data play a fundamental role for operational oceanography. They are mandatory to constrain ocean models through data assimilation and they provide directly useable data products for applications. Over the past 10 years, new and improved data sets and products needed by the modeling and data assimilation systems and for applications have been developed. Accuracy and timeliness of products have been improved. This has resulted in a larger and more systematic assimilation of satellite data into ocean models. Sampling and error characteristics, measurement content must be well understood, however, for a proper use in ocean models. In-situ data are also mandatory to calibrate, validate and complement satellite observations.

There are still a series of advances in satellite oceanography that are expected to impact operational oceanography and its applications:

- Continuous data processing improvements are needed so that data sets and products evolve according to requirements from modeling and data assimilation systems (including error characterization).

- New satellite missions for SSS (SMOS, Aquarius) and gravity (GOCE) and high resolution altimetry (SWOT) will likely have a major impact on operational oceanography.
- Better management of the huge amount of data coming from various instruments is needed. We need to exploit the data in an efficient way. New tools to search, process and visualize data from different sources are required.
- We are not fully exploiting the information content of satellite observations. Most observations are not yet sufficiently explored and used in ocean models. Synergy between observations (satellite, in-situ), models and new theories should be developed further. This is needed, in particular, to better exploit the high resolution information in satellite observations (e.g. Isern-Fontanet et al. 2006).

2.9 Useful URLs

This is a non exhaustive list of WWW sites where general information, data sets and products, softwares and toolboxes for satellite oceanography missions can be obtained.

Information on existing and future satellite missions:

CEOS WWW site: http://www.eohandbook.com/

Satellite altimetry:

http://www.aviso.oceanobs.com
http://topex-www.jpl.nasa.gov

Ocean colour:

http://www.ioccg.org
http://oceancolour.gsfc.nasa.gov
http://www.globcolour.info

Sea surface temperature:

http://www.ghrsst.org
http://www.remss.com

Multi-mission satellite data processing and distribution centers or facilities:

http://www.aviso.oceanobs.com/
http://podaac-www.jpl.nasa.gov/
http://www.myocean.eu.org/
http://cersat.ifremer.fr/
http://www.osi-saf.org/

Software and toolboxes:

- The European Space Agency has developed a series of toolboxes to facilitate the visualization and processing of satellite observations (ocean colour, SST, altimetry, SAR, gravimetry). http://earth.esa.int/resources/softwaretools

- SeaDAS is a NASA comprehensive image analysis package for the processing, display, analysis, and quality control of ocean colour data. http://oceancolour.gsfc.nasa.gov/seadas
- Supported by UNESCO, Bilko is a complete system for learning and teaching remote sensing. http://www.noc.soton.ac.uk/bilko

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