Remote Sensing of the Changing Oceans

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Chapter 2
Climate Data Issues from an Oceanographic Remote Sensing Perspective

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Abstract In this chapter we review several climatologically important variables with a history of observation from spaceborne platforms. These include sea surface temperature and wind vectors, altimetric estimates of sea surface height, energy and water vapor fluxes at the sea surface, precipitation over the ocean, and ocean color. We then discuss possible improvements in sampling for climate and climate change definition. Issues of consistency of different data sources, archiving and distribution of these types of data are discussed. The practical prospect of immediate international coordination through the concept of virtual constellations is discussed and applauded.

Keywords Oceanographic satellite sensors · Scatterometers · Altimeters · Microwave radiometers · Infrared and ocean color sensors · Winds · Sea surface temperature · Air-sea fluxes · International cooperation for climate quality data · Sampling · Consistency · Archiving and distribution

1 Introduction and Motivation

This book chapter is a background paper for future action. It follows on a workshop held during the Pan Ocean Remote Sensing Conference 2008 in Guangzhou, China entitled: "International Coordination and Planning for Enhanced Climate Monitoring and Data Stewardship". The interest in this subject by many remote sensing scientists has grown from observing how often we have missed optimizing the application of our satellite data sets for lack of communication and coordination. While intergovernmental coordination has been taken up by the

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Committee on Earth Observation Satellites (CEOS), the Global Earth Observing System of Systems (GEOSS), Ocean Observations Panel for Climate (OOPC) and Global Climate Observing System (GCOS), the benefit and awareness still have to come down to the level of scientific investigations (e.g. See GEOSS, 2010; OOPC, 2010).

In the 20th and 21st century we have created climate changes that may cause serious problems for humankind. We consider changes in the atmosphere, the ocean and the cryosphere intimately related, so they cannot be separated when discussing changes to the complex Earth system. That high energy use by a burgeoning population and increased affluence in many places is causing a warming climate system is now well proven according to the International Panel on Climate Change (IPCC) report 2007 (Solomon et al., 2007). This report states:

> Warming of the climate system is unequivocal.
>
> Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.

What are the manifestations of the climate and oceanographic changes in global and regional effects? This was the theme of the PORSEC 2008 conference. This article addresses the status of satellite observations on an international scale with emphasis on oceanographically important measurements. The subject is far too vast to review in this chapter, so it is our intention to focus on some mature and relevant climate/oceanographic variables observed from space and discuss some satellite missions and data management projects where cooperation may give major dividends in the near term.

Satellite scientists have a grave responsibility to get the facts straight and be able to inform the leaders around the world about trends in climatic variables and uncertainties in our knowledge. We also need to understand where the changes may lead to serious hazards due to enhanced storm intensity and frequency, sea-level rise, modified monsoons, drought, flooding and more.

Part of this responsibility is to work together to accelerate our accomplishments in finding the facts. This article will promote ideas for coordinated sampling of important data with satellite constellations, consistent and uniform calibrations and algorithms, long-term archiving of these data and efficient and convenient distribution for research and applications.

We begin by reviewing the status of satellite remote sensing of certain oceanographic and climatically important variables in Sect. 2. Section 3 discusses some results obtained based on these observations aiming to demonstrate their significance and contribution to understanding the changing Earth system. Section 4 discusses four aspects of data collection, sampling, calibration, archiving and distribution. These must be well done for adequate collection and use of the valuable and expensive satellite data in aiding understanding of our global climate, the oceans and what the records tell us about changes. The fifth section is a summary and charge for action.

2 Parameters of Focus

This section discusses the successes and desirable improvements for measurement of a select number of variables: surface wind speed and momentum flux over the ocean, sea surface temperature (SST), precipitation, air-sea energy fluxes including turbulent fluxes and radiative fluxes, sea surface height measurements and ocean color.

2.1 Winds Over the Oceans

Instruments to infer the surface winds over the oceans from space have been in use for nearly 2 decades by the time this book is printed and were famously illustrated by several of the microwave instruments on the SEASAT satellite, launched in 1978 and operated for 3 months (e.g. Katsaros and Brown, 1991). This satellite carried the well-established visible and infrared sensors, as well as experimental instruments such as a microwave radiometer, a scatterometer, i.e. a radar system that measures the roughness of the sea from which wind vectors can be inferred. It also carried an altimeter, a range-measuring radar, which determines the height of the ocean relative to the satellite, from which currents and oceanic heat content can be derived. The shape of the signal also provides information on sea state. The Synthetic Aperture Radar, SAR, on SEASAT provided high-resolution views of the sea surface measuring waves, surface roughness (later converted to wind speed) and ice cover. It allowed detection of oceanic fronts, slicks and ships.

These microwave instruments represented relatively new technologies and were mounted together on a polar orbiting satellite platform for the first time. All the microwave instruments depend on variations in the surface roughness in order to provide surface wind information. (Full discussion of these issues and others in this section can be obtained from the text by Robinson, 2004).The signals can be used to derive wind speed and in the case of the scatterometer also wind direction (e.g. Jones et al., 1982). The SEASAT Ku-band scatterometer data allowed scientists to learn how to interpret radar returns from 3 stick antennae, in terms of wind speed and direction basically by inverting an empirical model relating measured scatterometer backscatter coefficients and the surface wind speed and direction. The model calibration is mainly based on the use of in-situ and/or numerical model data collocated in space and time with scatterometer measurements (Bentamy et al., 1999; Stoffelen, 1999; Wentz et al., 2001). Since 1991 there have been several scatterometers in space, two from the European Space Agency, ESA, on the European Remote Sensing satellites 1 and 2, ERS 1/2, launched in 1991 and 1995, respectively. These scatterometers see well through clouds. The C-band scatterometers are relatively insensitive to the small ocean waves at low wind speeds, while the Ku-band instruments are more adversely impacted by clouds and precipitation, but respond better to the small waves or roughness elements at low wind speeds. (See the chapter by Bentamy et al. in this book). A Japanese – U.S. collaboration led to the launch of Ku-band scatterometers, NSCAT (NASA scatterometer) on the Advanced Earth Observing Satellite ADEOS in 1996. Unfortunately, ADEOS had an early demise, which lead to the fast launch in 1999 of QuikSCAT, a satellite carrying the Seawinds scatterometer. This was a copy of the instrument designed for ADEOS II, which was launched in 2002. The Seawinds on QuikSCAT was very successful (e.g. Ebuchi et al., 2002; Katsaros et al., 2001). It collected data for a full 10 year period allowing many new analysis techniques and algorithms to be tested. For example, Long (2004) achieved higher spatial resolution by sophisticated processing of the original data. When ADEOS II was flying, there was a period of a tandem sampling by two identical scatterometers (Liu et al., 2008).

The Seawinds scatterometer has a continuous 1,800 km wide swath, including the nadir region, which has proven very important. One such instrument views the global ocean once every 12 h at 50 degrees latitude, but less frequently in the tropics. The sampling with several scatterometers is further discussed in Sect. 4.

Since October 2007, the new Advanced Scatterometer, ASCAT, onboard METOP-A, launched by EUMETSAT, is collecting data for an operational agency. (EUMETSAT is the European organization for meteorological satellites for weather, climate and environmental applications). It provides valuable surface wind information with high space and temporal resolutions over the global ocean using two C-band beams, each side of nadir. Figure 2.1 illustrates ASCAT wind retrievals and how it and QuikScat sampling enhance the coverage when analyzed together.

Alternative sources of wind speed observations are microwave radiometers and Synthetic Aperture Radar (SAR). SAR cannot be used to obtain wind directions, except indirectly through patterns in the images, such as windstreaks; however, the consensus is that these directions are much less accurate and robust than scatterometer directions. The outstanding advantage is that SAR can retrieve very close to the coast, which is not the case with the current generation of scatterometers and radiometers. The additional great disadvantage is that access to SAR data is highly restrictive and costly. Microwave radiometers typically obtain only wind speed, although an attempt has been made to use multiple looks at the same footprint to derive direction also from the Stokes parameters of the emitted signal (using several look-angles and multiple polarization combinations). Such an instrument was launched as a pilot project (WindSat) in January 2003 (Smith et al., 2006). The hope was that polarimetric microwave radiometers could serve the surface wind sensing need at low cost over the ocean and replace the need for scatterometers, but consensus seems to be at this juncture that a passive instrument has too many limitations (Bourassa et al., 2010). The polarimetric radiometers suffer too much from rain-induced interference, and are poor for the low to moderate wind speeds found over 50% of the Earth's water surface.

An active system works better through rain, and has better directional information which is very important for many applications, not least of which is storm analysis. The scatterometer is clearly the instrument of choice for oceanic surface wind and momentum information, except in the very near coastal regions where SAR would be useful if the data were made available. A review of the scatterometer calibrations and the impact of variations in retrievals upon air-sea flux estimates are provided in the chapter by Bentamy et al. in this book.

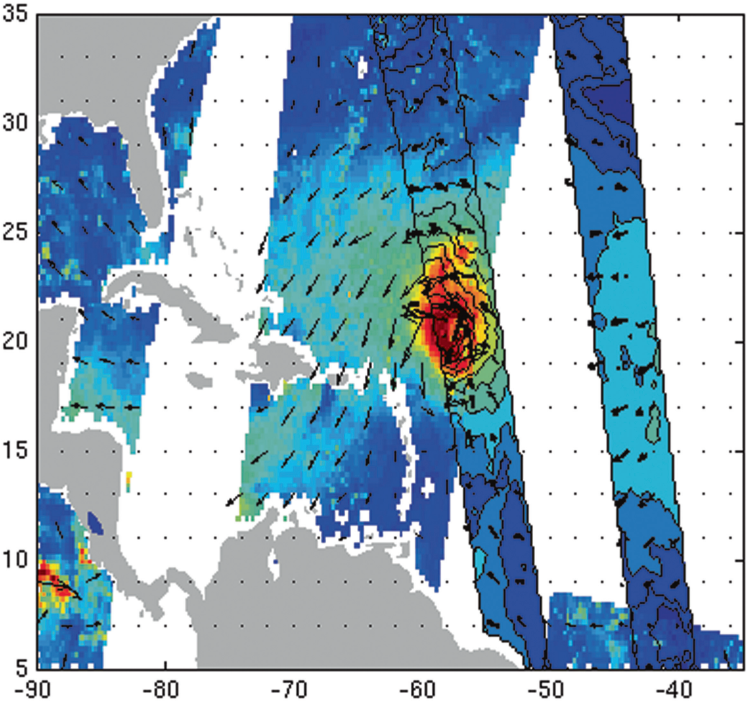

Fig. 2.1 ASCAT and QuikSCAT wind observations of hurricane Bill on August 19, 2009. The time separation between the two scatterometer measurements is about 2 h and 30 min

Winds are the most rapidly changing ocean surface variables. On average, QuikSCAT observed the ocean surface twice a day. However, locations near the poles are observed four to six times a day, and large areas around 20° are missed every fourth day. Several studies over the years have shown that diurnal variability of surface winds is very important for coupling the ocean's mixed layer to the atmosphere. Ocean-Sat-2 carrying a scatterometer was launched on September 23, 2009 by India's space agency and Hy-2 is an expected 2010 launch by China's space agency. A constellation of inter-calibrated scatterometers is highly desirable to determine the diurnal cycle in surface wind. The sampling with several scatterometers is further discussed in Sect. 4.1.

2.2 Sea Surface Temperature

This parameter often used singly to define changes in the climate has the longest history of measurements from space and has become so well established through the long-lived NOAA program of two satellites in morning and early afternoon polar orbits that it is almost taken for granted. Two satellite imagers with wide swaths (2,000 km) cover the whole Earth each day sensing in the atmospheric window regions of the infrared, 3.5–4.0 and 8–12 μm. In the latter window products are nowadays limited to 10–11 μm to avoid the central ozone line inside the 8–12 μm "window". Standard products have used empirical fits to surface observations by buoys or ships to correct for biases mostly caused by atmospheric variability not sensed by standard sensor suites. Microwave observations of SST through clouds were reported by Wentz et al. (2000) for the first time since SEASAT, but they were not available globally and routinely, since they were derived from the radiometer on the Tropical Rainfall Measuring Mission, TRMM. Since June 2002 microwave measurements of SST by the Advanced Microwave Scanning Radiometers, AMSRs, on NASA's Earth Observation satellites in polar orbits have given valuable information on the SST below the heavily clouded regions of the Earth, which were eliminated in the purely IR- method (Reynolds et al., 2007). The increased sampling has allowed shorter times for averaging, now daily, and substantially improved the mean values. However, the statistics changed drastically, so that two products are produced now in order to avoid an unphysical jump in the data when the microwave SST's became available. The article by Smith et al. (2008) reviews this new product of NOAA's and complexities that have arisen due to two sensors that effectively measure different depths near the sea surface – of the order of – 0.2 mm for IR and 2 cm for microwaves. Zhang et al. (2009) review the total system for operational sea surface temperature production.

The diurnal variation of sea surface temperature, especially the formation of a warm layer in low latitudes when the wind is weak, has lead to new concerns related to absolute "accuracy" and the need to define exactly what of many definitions of SST is desired for the climate record. The ubiquitous "cool" film is a thin layer, produced by an upward heat loss from the topmost layer at the interface (even when the net heat flux may result in heating of the ocean due to strong insolation). The shortwave radiation is absorbed over a depth of many 10 s of meters due to penetration by the sunlight and may be distributed over the whole thermocline due to turbulent mixing of the upper ocean in moderate to strong winds (e.g. Saunders, 1967; Katsaros, 1980; Schluessel et al., 1990; Gentemann et al., 2009). Even with strong turbulent mixing there remains a thin "cool film" of the order of a few millimeters near the interface. The infrared radiation measured by infrared remote sensing emanates from that micro-layer, while buoys, ships and the microwave sensors correspond to the temperature at a greater depth in the water, where there may remain a gradient of temperature, so that not even these sensors agree on a SST value. The concept of SST is therefore somewhat ill-defined. An international group was formed to consider these issues (Poulter et al., 2007); currently it is known as the Group for High Resolution SST, GHRSTT, (Donlon et al., 2009 – GHRSST is pronounced "GRIST" for convenience). It is an on-going project defined as follows:

> *"GHRSST has four main tasks that are relevant to the development of the SST observing system: (1) Improved SST data assembly/delivery (2) Testing of SST data sources (3) Perform inter-comparison of SST products (4) Develop applications and data assimilation of SST to demonstrate the benefit of the improved observing system. GHRSST has successfully demonstrated that the requirements of the Global Ocean Data Assimilation Experiment, GODAE can be met and has been instrumental in defining the shape and form of the modern-era SST measurement system and user service over the last 10 years" – (Donlon et al., 2010).*

A difficulty for climate studies that remains is that this long record, 1985–2009 cannot be fully consistent. Overlapping data from the different sources and methods of processing are therefore invaluable for inter-calibrations.

For the future, agreements exist between The European Organization for the Exploitation of Meteorological Satellites, EUMETSAT, and NOAA that they share responsibility for operational polar orbiting satellites. The Initial Joint Polar System (IJPS) has the arrangement that EUMETSAT operates its polar-orbiting Meteorological Operational, METOP, satellite series in the morning orbit, and NOAA will continue to guarantee its satellites in the afternoon orbit. These agreements are likely to be extended for NOAA's new series of satellites under the National Polar-Orbiting Operational Environmental Satellite System, NPOESS.

The success of the NOAA satellite program for measuring SST (and visible data for cloud information) and the extensive use by fishermen and others for 3 decades is an encouraging example of exceptional success, and one may add, exemplary leadership in generously sharing these data by the USA. The widespread use of SST information has resulted in joint planning for the future. The IR-SST's have been made available to anyone via direct read-out, the so-called APT (Automatic Picture Transmission) since the late 1970s, but these data were, of course, not qualified and fully calibrated. A so-called *Pathfinder* project has continued re-analysis of the high resolution NOAA data, adding refinements to algorithms and known corrections. The long-time global record dating from 1981 is available from http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/. These new Version 5.0 data are being developed at University of Miami at the Rosenstiel School of Marine and Atmospheric Sciences and the National Ocean Data Center (NODC) and distributed in partnership with the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC). In this 4 km Pathfinder project, the entire time series has been reprocessed at the 4 km Global Area Coverage (GAC) level, the highest resolution possible globally up through about 2006 and interim data for 2007 through near present have also been generated.

In addition to the IR sensors measuring in the window region of the spectrum on the NOAA polar orbiting satellites, such sensors were also mounted on the geostationary satellites since the early 1980s and could observe at 4 km resolution. They are mostly used for cloud/weather observations, but can provide SST as well, because frequent observations ameliorate the cloud interference, which is so serious for polar orbiting instruments. Multiple views of the same area as the clouds pass by may allow retrieving the SST between the clouds (e.g. Legeckis and Zhu, 1997). However, global sampling via geostationary satellites requires coordination between 6 such systems, and the footprints of these satellite observations do not reach to the poles.

2.3 *Precipitation and Evaporation*

These two variables, precipitation and evaporation are possibly the most difficult of the variables to measure globally by any means – satellite measurements are the only ones that could provide global coverage, but sampling of precipitation is a major problem due to its intermittent nature. Most records are based on indirect estimates using the cloud brightness or cloud top temperature as indicators of deep and raining systems (e.g. Adler et al., 2003).

Direct measurements of precipitation over oceans are almost non-existent, and even attempts to put rain gauges on ships and buoys have had little success due to flow distortion by the ship's structure. Buoys also have issues with contamination by sea spray, so today satellite estimates of precipitation are typically calibrated against coastal radar estimates of precipitation, which in turn are calibrated against ground based rain-gauge networks (Adler et al., 2003). In spite of these difficulties we do now have precipitation estimates based on inferences from the temperature and patterns of cold cloud tops and from microwave radiometer measurements of the cloud water particles and large particle scattering (These are airborne precipitation particles, which may or may not coincide with precipitation impacting on the sea surface.) A method for estimating the ground precipitation combining various methods called CMORPH (which stands for CPC Morphing technique, where CPC is Climate Prediction Center), has been developed for routine use (Joyce et al., 2004). It is flexible, because it can combine various measurements and their algorithms by "morphing" them together.

A dramatic step forward in rain measurements from space was provided by the Tropical Rainfall Measuring Mission, TRMM (Simpson et al., 1988; Kummerow et al., 2000) which carried a narrow-swath rain radar and the TRMM Microwave Radiometer, TMI. A nice example of using the one spaceborne rain radar to date with algorithms calibrated by coastal radars is found in the climatological study of rainfall in tropical cyclones by Lonfat et al. (2004). This subject has come a long way thanks to TRMM, which points the way to better planned systems described in Sect. 4. Stephens and Kummerow (2007) discuss the improvements in estimates that are possible when clouds and precipitation are analyzed in concert.

For the Earth's general hydrologic balance and for changes in the ocean we need to know the net fresh water flux, evaporation minus precipitation, E-P. Reasonably good estimates of evaporation over the ocean using satellite data have been available since a method was proposed by Liu (1984). It uses the bulk air-sea flux models and wind speed, SST and estimates of atmospheric near surface humidity based on the column integrated water vapor content obtained from microwave radiometers. Over the past 25 years this method has been used, somewhat modified (e.g. Schultz et al., 1993, 1997) and incorporated with other air-sea energy flux estimates, as discussed in Sect. 2.4).

2.4 Air Sea Energy Fluxes

The fluxes of energy across the air-sea interface, as turbulent fluxes of latent and sensible heat in the atmospheric boundary layer, and short and long wave radiative fluxes have sometimes been the focus of discussion about accuracy required of climate quality data. A value of 10 W m^{-2} on an annual time scale was established as the needed accuracy in net air-sea transfer of energy by a committee in the early 1980s and has been the number suggested many times since; more recently in a chapter of the 2007 report of the Intergovernmental Panel on Climate Change, IPCC, (Bindoff et al., 2007). Finer accuracy is required in Polar Regions (Bourassa et al., 2010). These fluxes depend on many of the variables obtainable from space, so this accuracy requirement puts a heavy burden on the satellite observations over the global oceans. We are not today meeting this accuracy – or one could claim that we don't even know if we could do it, since high quality net flux is not regularly derived. What we have is mostly one or two terms in the heat budget obtained by a certain group and/or technique over a limited period of time, or we have long-term records, whose consistency is not well proven and the accuracy is known to be less than this ideal.

Another consideration is that the fluxes are derived quantities – not directly measured, so an error in their values is due to a compound effect of many variables and physical parameterizations (e.g. Fairall et al., 2010, OCEANOBS09 and references therein.) Nonetheless, many products exist today and are the consequence of diligent efforts over the past 3 decades or more. The earliest method to derive evaporation rate and latent heat flux from satellite data was the study by Liu (1984), who used the bulk aerodynamic formulas discussed by Fairall op cit. and data from the Scanning Multichannel Microwave Radiometer, SMMR (flown both on Seasat and on Nimbus) to estimate near surface atmospheric humidity. SST and surface wind speed are also required and available from satellites already in 1984 as described in Sects. 2.1 and 2.2. Further work to develop the satellite method for latent heat flux, emphasizing the concentration of humidity in the atmospheric boundary layer, were presented by (Schultz et al., 1993, 1997). The reader is referred to the work by the group at IFREMER for evaporative heat flux based mostly on satellite input data (Bentamy et al., 2003 and a chapter in this book). Alternatively, there are products (e.g. Yu et al., 2008), where numerical model, in situ observations, and satellite data are merged. Sensible heat flux has often been tied to the evaporative flux, because the near surface air-temperature, T_a, has remained a difficult variable to obtain from space and not obtained very satisfactorily from numerical models (Kubota and Shikauchi, 1995). New efforts to improve estimates of T_a and near-surface humidity using multi-sensory microwave observations have been reported (Jackson et al., 2006, and work continues on improvements Gary Wick personal communication, 2009). Strong air- sea temperature contrasts over the warm ocean currents during cold air outbreaks remain difficult to assess, and may remain so for some time.

Radiative transfer models have taken observations at the top of the atmosphere, TOA, and inferred the surface irradiances for shortwave irradiance at the air-sea interface (e.g. Gautier et al., 1980; Pinker and Lazlo, 1992). The International Satellite Cloud Climatology Project, ISCCP, is a basis for much of the estimation of surface solar irradiance (Rossow and Duenas, 2004). The variable atmospheric transmission due to aerosols, which are not adequately measured in the long-term record still imply large uncertainty (e.g. Slingo et al., 2006). For the downwelling longwave radiation, use of cloud information and the microwave data on liquid water content shows promise (e.g. Schmetz, 1991; Brisson et al., 2001). Outgoing longwave radiation from the ocean simply requires the black body formula with a value for the surface emissivity of the full infrared spectrum, which however also requires information on the sea state. Community efforts to inter-compare the satellite products are underway within the SEAFLUX program (Curry et al., 2004).

2.5 Altimetry

Satellite altimeters are designed to deliver relatively long revisit (10 days and more) and global views of sea surface height. The concept is well established since early missions GEOS-3 and SEASAT that date back to the 1970s. The launch of the TOPEX/Poseidon in 1992 provided the greatest impetus for satellite altimetry research in the 20th century. Its launch was followed by the Jason-1 (2001) and Jason-2 (2008). The European space Agency, ESA, satellites were launched in 1991, 1995, 2002 (ERS-1, ERS-2, ENVISAT) and the US Navy launched a series of Geosat satellites (1985 and 1998). Whilst some of these missions are still in active orbit and expected to continue operation for the foreseeable future, new missions are planned to be launched by space agencies over the next few years, e.g., CryoSat-2, AltiKa, Sentinel-3, HY-2, including new experimental concepts such as SWOT (Fu et al., 2010). Satellite altimetry is recognized as an essential component of the Global Earth Observation System of Systems. To date satellite altimetry has focused on the open ocean (Fu and Cazenave 2001), but recently the coastal ocean has emerged as an important domain for these data (see the chapter by Vignudelli et al. in this book). Only through a synergy from various altimeters can a thorough and complete characterization of mesoscale circulation be obtained (Cipollini et al., 2010). A valuable application has been the incorporation of altimetric data to estimate the depth of the warm water available as a heat source for hurricane intensification in the Caribbean (Goni et al., 2003; Goni et al., 2009) and western Pacific ocean (Lin et al., 2008).

An uninterrupted flow of altimeter data has been accumulating, contributing to the ability to address scientific and societal challenges in the ocean. However, in some cases the various missions were designed without continuity in mind, with different observing strategies usually driven by their particular objectives of accuracy, spatial resolution and temporal revisit requirements. For example, the T/P and Jason series main objective was to generate the best estimates of sea level over time to serve climate monitoring, but these data can be also used to better understand the ocean circulation. As a result, data from the various satellite altimeters were processed independently. Nevertheless, the missions have common foundations concerning retrievals, orbits, geophysical corrections, data calibration and exploitation.

Assimilation of altimeter data into operational oceanographic models and the increased precision (of the order of 1 cm in sea surface height), makes this technology ready for operational use. EUMETSAT and NOAA have already established cooperation agreements with regard to altimetry (see Sect. 4).

2.6 Ocean Color

Ocean color optical sensors on satellites continue to provide significant data on surface chlorophyll concentrations. Value of the satellite data increases as users gain experience and a larger number of years are covered. Observations from space are quite different from measurements made from research ships, so the interpretation has taken some time to develop. A confounding problem is that chemical and biological elements both contribute to variations in color. Instruments with more spectral bands can help to address this issue in some cases. Also, newer instruments can detect spectral signatures which provide useful additional information, but are not yet widely applied.

The ocean color science developed from the 4-band Coastal Zone Color Scanner, the CZCS, on the Nimbus 7 satellite, launched by NASA in 1978. This provided ocean-color bands at blue, blue-green, green and red wavelengths, sufficient for estimates of chlorophyll and water brightness using a simple atmospheric correction. After a data gap of 10 years, the short-lived Japanese OCTS and the US SeaWiFS were launched. SeaWiFS, which has only recently stopped providing data (August 2009) has 8 spectral bands, adding a UV band aimed at separating CDOM from chlorophyll, and near infrared bands to improve atmospheric correction. The simple and well-calibrated design of SeaWiFS has allowed it to collect more than 10 years of "Climate Quality" global ocean color data, "Climate Quality" referring to its ability to address the question, "How is global primary productivity changing under the long-term impact of increasing carbon dioxide in the atmosphere?"

SeaWiFS was followed by NASA's 36-band MODerate-resolution Imaging Spectroradiometer, MODIS, launched on both the Terra satellite (1999) and the Aqua satellite (2002). MODIS has 9 spectral bands giving water color information at 1 km spatial resolution, and also includes two bands with 250 m, and five bands with 500 m spatial resolution for "sharpening" images, three bands for atmospheric water vapor and 17 thermal bands for atmospheric and sea surface temperature. MODIS ocean color bands include two, at 665 and 673 nm, designed to measure chlorophyll fluorescence. MODIS also provides bands in the short-wave infrared which give improved data in silty water.

The European Space Agency launched the 15-band MEdium Resolution Imaging Spectrometer, MERIS, in 2002. This has 11 water color bands at 300 m spatial resolution, but with much of the data available only at the reduced resolution of 1,200 m, computed by on-board averaging of 4 by 4 pixels. The additional two bands on MERIS, compared to MODIS, are at 620 nm and 709 nm. The 620 nm band is in a relatively wide gap in MODIS coverage. The 709 band provides an improved baseline for fluorescence measurements and also detects a peak in water-leaving radiance due to intense surface blooms and floating vegetation. The radiance of this peak can be computed as MCI, the Maximum Chlorophyll Index. There are numerous sensors for the ocean color, past, present and future as seen in Fig. 2.2, but additional consideration should be given to planning as discussed below.

Satellite ocean color remote sensing today seems to aim mostly at a single product: surface chlorophyll concentration. Standard web pages, such as NASA's "ocean

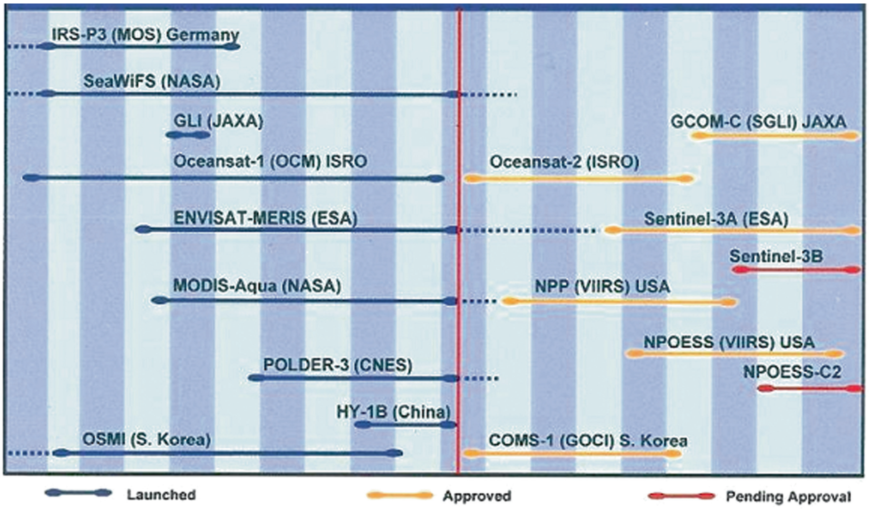

Fig. 2.2 Ocean color sensors from many agencies, table from IOCCG (2008)

color" site (http://oceancolor.gsfc.nasa.gov) guide users mostly to this, but also provide normalized water-leaving radiance, useful for detecting bright blooms.

The new sensors have the ability to distinguish a wider range of targets, but have moved away from the stability and simplicity of SeaWiFS. Given the need for monitoring of long-term changes in surface chlorophyll and hence in primary productivity, there is a feeling that, expressed in verse:

We've needed one more SeaWiFS for many, many years,

Instead we bought two MODIS's, a MERIS and a VIIRS.

VIIRS was designed as the replacement sensor for the more basic AVHRR imager, but because of program cut-backs it is now the effective replacement for SeaWiFS and MODIS. There have been many delays and compromises in its design. It lacks spectral bands provided by MODIS and MERIS and will not have the stability provided by SeaWiFS. This lack was the subject of a recent briefing note by Siegel, Yoder and McClain, "Thoughts about the Future of Satellite Ocean Color Observations" (October, 2008), which concluded "It appears likely that the ocean biology and biogeochemistry communities will face a multi-year gap in our climate data records." In view of the importance of these data, international pressure is needed to address this shortcoming.

For understanding the ocean carbon cycle, there is also a requirement for estimating concentration of Particulate Organic Carbon (POC) in the ocean. This represents the assemblage of living particles (bacteria, phyto- and zooplankton) and non-living material (detritus, fecal pellets, aggregates) that contribute to the biological pump (transfer of carbon from the upper layers to the deeper ocean by biological processes). POC sinks from surface waters to deeper layers, removing carbon from the surface layer and supplying food to mesopelagic and benthic organisms. Despite its importance, POC concentrations and its variability over basin or global scales have been poorly assessed. (IOCCG, 2008).

As well as the gaps in instrument capability, there are also gaps in algorithm development. Both MODIS and MERIS provide information on the chlorophyll fluorescence signal at 685 nm, but there are few regularly available products providing this to users. MERIS has a band at 709 nm which is useful for detection of intense blooms and floating vegetation (Gower et al., 2008), but again there is no standard product based on this.

SeaWiFS, MODIS and MERIS all have bands near 410 nm designed to detect Colored Dissolved Organic Material (CDOM). Quantitative measurements are at present hampered by lack of a robust capability for aerosol characterization and hence estimation of aerosol radiance contribution to the measured signal at 410 nm. This is another potential capability of ocean color satellites that needs development.

Separation of different species of phytoplankton has long been a goal of satellite remote sensing. One species group, coccolithophores, are easy to recognize by the bright, bluish-white color, caused by the many microscopic coccoliths shed during a bloom. Surface chlorophyll concentrations are often too low to be used for detection of these blooms. Other species are much harder to separate. There are special cases, for example where cyanobacteria bloom regularly in the Baltic Sea in July, and where *Tricodesmium* blooms regularly in the Red Sea and other tropical and sub-tropical waters. In other cases, successes are claimed in more conservative separation into "phytoplankton functional groups" (Nair et al., 2008) or into blooms of "large" and "small" cells (Sathyendranath et al., 2004).

3 The Value of Coordinated Data Sets

The parameters discussed in Sect. 2 are part and parcel of our definition of climate. The classic definitions of land climates by Köppen and later Köppen-Geiger are based on surface air temperature and precipitation patterns and dates back more than 100 years. A modern review by Peel et al. (2007 and see references therein) discuss the problem of fitting all of the Earth's land types into these categories. These two variables are very basic to oceanic climates as well. The variables we have included here are not exclusive, but include those oceanographic ones measured by satellites which are important and which already have a good record. Air temperature over the sea, is NOT among them, however, as noted above in discussion of air-sea fluxes. It is likely that we will have to rely on better atmospheric numerical model analyses and use of blending techniques to get global estimates of air temperature above the sea surface and proper atmospheric stability functions for evaluating the turbulent heat fluxes. No fully adequate estimation technique has been found that can be used for all latitudes and seasons.

The White Paper by Donlon et al. (2010) and the GHRSST reports present numerous recommendations for international cooperation and further work for this variable. SST is the foundation of estimates of surface winds from scatterometers, air-sea heat fluxes (latent and sensible heat fluxes) and outgoing longwave radiation. Climate studies depend heavily on time series of Sea Surface Temperature evaluations. Precipitation climatologies exist and have benefitted from TRMM radar data, which provides a great example for how a high quality measurement can validate a large body of supporting data (see, for example, the tropical cyclone rain estimates by Lonfat et al. (2004) mentioned in Sect. 2.3).

Derivation of sea surface elevation and the energy content of the upper ocean has become quite mature science and the satellite altimeter sensors are at least semi-operational since the beginning of the 21st century (Wilson et al., 2010). For a comprehensive view of the Earth, its oceans and climate we need at least all of the variables listed in Sect. 2 and chemical and biological measurements and many in-situ data as well. The approximately 3000 ARGO drifting buoys, which cycle in the top layers of the ocean, provide the supporting information to the satellite measurements for more fully describing the state of the upper ocean, and meeting the requirements of the Global Ocean Data Assimilation experiment, GODAE (Guinehut et al., 2009).

Better evaluation of aerosols will be crucial for understanding any changes in the radiation balance at the sea surface. To provide these data for analysis we must coordinate the sampling and management from today onward and not allow missed opportunities to occur. For many measurements we have been in research and learning phase, but from 2010 onward we have enough experience to know what is needed and have the organizations to help coordinate the work internationally.

Here we have not dealt with land, the upper atmosphere or the Polar Regions, which in themselves deserve the same attention to give us a comprehensive view of the climate on the Earth. Ocean color does not have a complete and consistent series of sensors in space as noted in Sect. 2.6, but it is emerging as an important measure of the status of the ocean's health, It is not a measure of climate in the classical sense of Köppen definitions related to atmospheric weather patterns, but it has great importance for understanding the changes that are occurring in the oceans and especially in coastal regions due to the evolution of other variables.

4 The Issues of Concern for an adequate Climate Data Record in the future

Our workshop focused on 4 main issues and they will now be discussed in turn:

4.1 Sampling

Many of the instruments to obtain high resolution and high accuracy data, and all of the microwave instruments to date, have been mounted on polar orbiting satellites or satellites in other low Earth orbits, both because of power concerns at launch and for obtaining high resolution observations. (Visible and IR data can now be obtained from geostationary satellites at 40,000 km at resolutions of the order of kilometers, but that was not so in the early days, and boosting the large antennas needed for microwave sensors to geostationary heights have not been attempted yet.) To sample the global ocean from geostationary heights require 6 satellites, each observing a 60 degree sector. We currently have this system in place, mostly motivated by weather observations, but they have contributed valuable data for climate research as well. A good example is the contributions to the International Satellite Cloud Climatology Project, ISCCP.

Sampling of the global ocean by any microwave instrument more than once per day still requires multiple polar orbiting satellites for good coverage. Possible constellations and overlap between instruments abound and some activities are under way. A concept of *virtual constellations* has emerged through the Council of Earth Observation Satellites (See CEOS, 2008), which refers to post-facto arrangements rather than major planned and coordinated satellite launches, although international coordination is gaining ground. The aim is to ensure continuous time-series and when possible fill the gaps that risk occurring in these series due to political and economic pressures, if only one nation's agency is solely responsible. The virtual constellation concept is 'in support of the Group on Earth Observations (GEO, http://earthobservations.org), objectives and as a component of the Global Earth Observation System of Systems (GEOSS).

> *A Constellations is a coordinated set of space and/or ground segment capabilities from different partners that focuses on observing a particular parameter or set of parameters of the Earth system. The CEOS Constellation for Ocean Surface Topography (OST) goal is to implement a sustained systematic capability to observe the surface topography of global oceans from the basin scale to the mesoscale (=100 km). The surface topography from satellite altimeters and the upper-ocean density field from Argo profiling floats (which currently number around 3000) are oceanic analogues to the surface pressure from barometers and the density field from atmospheric profilers. Observations of these two fundamental state variables are necessary for understanding the dynamics of the oceans, assessing their role in climate and developing an operational forecast capability. (Wilson et al., 2010*)

A multi-mission, accurate and consistent altimetry data base would give a more complete picture of the ocean surface than would be possible with a single satellite. It also would help to meet the needs of the Intergovernmental Panel on Climate Change to rely on high quality altimeter climate data records. This calls for re-visiting and rigorously reprocessing of the original records, including application of homogeneous algorithms, inter-calibration (during tandem and overlapped periods) with the adoption of internationally accepted standards.

The series of satellite altimeters have been operated in de facto constellation, although in the absence of agreements between the various space agencies. However, the issue might become even more challenging in future since more missions are being planned (Fig. 2.3), with broader sensor variety, different data rates, increasing complexity, etc. The use of several satellite altimeters coordinated in a "virtual constellation" would optimize resources in operation and exploitation and would address possible emerging data gaps (Wilson et al., 2010).

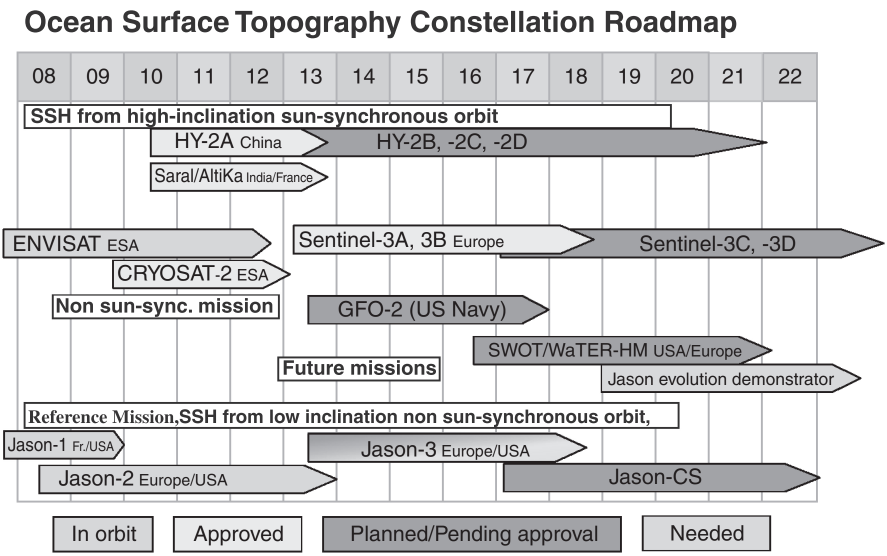

Fig. 2.3 Ocean Surface Topography Missions constituting a virtual constellation

The CEOS Constellation for Ocean Surface Vector Wind (OSVW) will collect observations of vector winds over the global ice-free oceans from multiple satellites and distribute them within sufficiently short time interval to make them useful for forecasting, but also provide the appropriate products for retrospective analysis and research. With India's and China's scatterometers in addition to METOP and Seawinds or a follow on, we could have 4 scatterometers in space simultaneously. Figure 2.4 by Liu et al. (2008) provides a graphic illustration of the optimal spatial coverage and mean re-visit times for various combinations of swaths from these 4 scatterometers, if orbits are ideally timed.

The three constellations formally agreed upon by CEOS are the topographic constellation quoted above, and one for precipitation and ocean color, respectively.

The proposed precipitation constellation has grown out-of the usefulness of the TRMM radar to tie other precipitation estimates together, working mainly with a calibration function for climate issues. As TRMM aged, a follow-on mission was proposed, the Global Precipitation Measuring mission (GPM); the Japanese Aerospace and Exploration Agency, JAXA and NASA playing important roles with others included. It will have a central major satellite carrying a rain-radar, and would be accompanied by numerous, small satellites providing frequent coverage of the globe with wide-swath scanning microwave radiometers (Fig. 2.5 is an illustration of the GPM concept compared to the TRMM constellation.) A US National Research Council Report describes the GPM mission with focus on NOAA's role (Committee on the Future of Rainfall Measuring Missions, 2007).

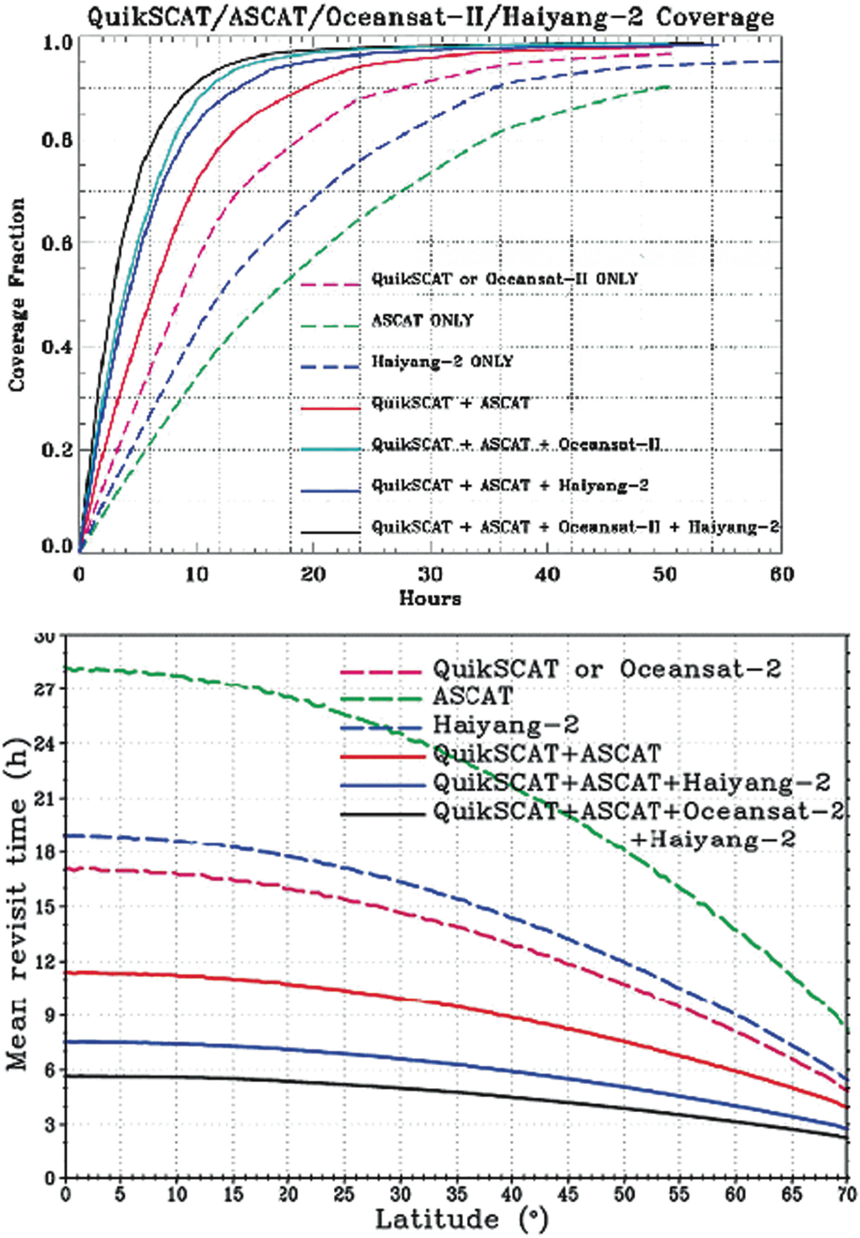

Fig. 2.4 Top panel: Calculated spatial coverage as a fraction of the Earth's surface by combinations of current and future scatterometers; Bottom panel: Revisit times for a position on the Earth as a function of how many scatterometers are contributing data

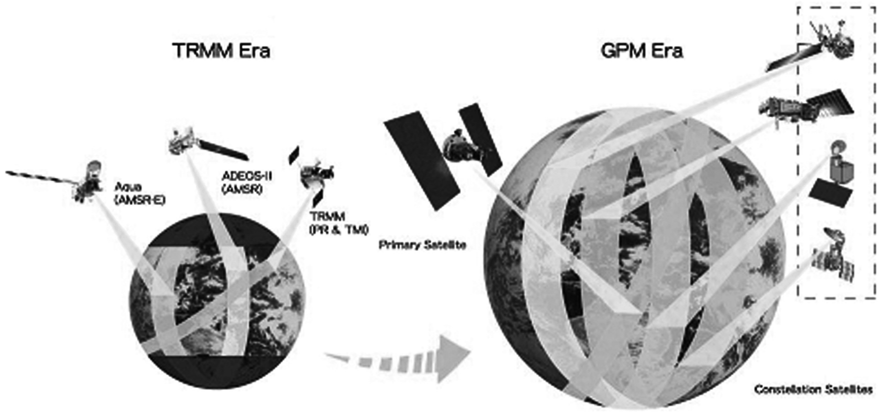

Fig. 2.5 Artist's rendition of the constellation visualized for the Global Precipitation Measuring mission with the very successful TRMM mission, which has already proven the concept

The Virtual Constellation for ocean color is being implemented (see Fig. 2.2). Its objective is to provide calibrated radiances at key wavelength bands. Cross-calibration is an important aspect of a constellation and is currently being used by several ocean color instruments. One can hope that the valuable record from SeaWifs will encourage many nations to contribute an instrument. A possible scenario can be found in the latest report from the International Ocean Colour Coordinating Group, IOCCG, (IOCCG, 2008, and www.ioccg.org)

Similar proposals for virtual constellations exist for atmospheric composition and land surface imaging, but are not yet implemented. The scatterometer constellation also requires further coordination.

The emerging space programs in India and China have many of the established important climatic parameters in their portfolios, so it is fervently hoped that they will soon be front and center in these virtual constellations with their data. Innovation in sampling techniques of individual instruments and new choice of frequencies or combinations of more than one microwave frequency are likely to develop from these interactions and the all important calibration of any sensor benefits tremendously by access to data from other instruments in the constellation, team meetings and discussions. The USA /NASA soon learned how valuable input from many users could be for improving data and products, so the concept of instrument teams was developed more than 3 decades ago. Currently many other space agencies, notably ESA and JAXA, follow this method of enlarging the user groups.

4.2 Consistency

We include in the concept of consistency both accuracy, which refers to the absolute value of a variable and the concept of understandable and systematic errors. The uncertainty due to random errors in an individual measurement is not very problematic for climate records, since the averaging done to obtain climatic long-term time-series will tend to eliminate them in the final product. Systematic errors leading to biases are more serious, because they can imply a climatic trend, which may instead be due to varying transmission properties of the atmosphere or degradation of the satellite sensor. A typical example is the biases in sea surface temperature that were discovered for the tropical Atlantic ocean. They were found to be caused by the aerosol clouds emanating from the Saharan desert in seasonal dust storms. Similar effects occur over the Indian Ocean and were well identified after the eruption of the Pinatubo volcano. When the physics is understood and we have available supportive data about the radiative effects of the aerosol in the atmosphere, we can correct for these effects. The difficulty is that the bias errors are often not fully understood from the beginning and lead to unfounded speculation about regional climate changes.

Due to the intense concern about climate change and the important role of SST in identifying a warming climate signal, much has been learned about the atmospheric aerosol and its effects on satellite data. In addition to effects on the interpretation of infrared signals for SST, the radiative transfer models that derive sea surface short wave irradiance from measurements of solar irradiance above the atmosphere, so called Top of the Atmosphere, TOA, values, must also include the aerosol effect (e.g. King et al., 1999). Only approximate methods have been used to date due to limited input data on the aerosol. Older data sets will have only approximate aerosol corrections, since direct measurements of the aerosol's presence were not obtained with older instruments of limited spectral resolution.

Early satellite instruments were not always calibrated for absolute values. For example visible radiation was post-calibrated using the reflection of the Earth's surface in the White Sands desert of New Mexico (e.g. Catherine Gautier, personal communication, 1980s). Such development often required field programs to determine the exact reflectivity of the sands in several spectral bands. Many other satellite instruments have been calibrated post-launch with in situ measurements. The corner reflectors used to test satellite radars is another example. The jungles of the Amazon in Brazil have been used as a black body substitute for calibrations and consistency checks on microwave radiometers in space.

Buoy and ship data provide the standard inter-comparison data sets for many of the satellite sensors. Two programs have been instituted to ensure research quality ship observations: the Global Ocean Surface Underway Data (GOSUD) and the Shipboard Automated Meteorological and Oceanographic System (SAMOS). The SAMOS initiative is working to improve access to calibrated, quality-controlled, surface marine meteorological data collected by automated instrumentation on research vessels (primarily) and select merchant ships, while GOSUD focuses on the collection, quality evaluation, and distribution of near surface ocean parameters (salinity and sea temperature) from vessels. The importance of ongoing quality control was illustrated by the discovery of a bias in the ERS-2 scatterometer surface wind vectors compared to the winds from ERS-1and subsequent scatterometers. This was found and corrected by comparison with collocated buoy winds.

A most valuable approach for obtaining a consistent climate data record is to plan for overlap between a new satellite instrument in a series and the previous one by arranging orbits such that this can happen in the beginning of a satellite mission. Inter-comparisons of this sort are invaluable. The continuous calibration of all the members of the constellation in the GPM rain-radar program, as illustrated in Fig. 4.3 is a case in point. For altimeters the practice has been to have crossing orbits for some time, where the cross-over points clearly and rapidly show any differences. Coordination of these efforts has been led by the Group on Earth Observations.

The intergovernmental Group on Earth Observations (GEO) is a voluntary partnership of governments and international organizations, providing a framework within which to develop new projects and coordinate Earth observation strategies and investments. As of June 2009, GEO's Members include 79 Governments and the European Commission. In addition, 56 intergovernmental, international, and regional organizations with a mandate in Earth observation or related issues have been recognized as Participating Organizations. GEO Members and Participating Organizations are working towards the realization of a coordinated, comprehensive, sustained Earth observation system of systems called the Global Earth Observation System of Systems (GEOSS). The aim is to enable societal benefits of Earth observations, including advances in scientific understanding in the nine Societal Benefit Areas (Disasters, Health, Energy, Climate, Water, Weather, Ecosystems, Agriculture, and Biodiversity).

4.3 Archiving and Distribution

These two topics, archiving and distribution, are closely connected. They depend on institutions that are well established and have solid financial support. Today, much of the archiving is distributed with links between operators and certain groups working on establishing good meta-data records. These give important information *about* the data so that researchers can make informed decisions about whether and how the data are relevant to their work. This subject is developing as more long-term records become established. We did not as a group expect to propose any changes, but we note here some sites that can be helpful. Several of them have so-called Help-Desks that allow the person seeking information on accessing the center's data to have direct contact with helpful and knowledgeable persons. This is a crucial service.

Currently, there are many efforts to work out differences between sensors in consecutively launched space-borne instruments. This has lead to formation of groups to ensure that the resulting Earth System Data Records (ESDRs) and especially Climate Data Records (CDRs), are consistent in terms of calibration of the instruments and data products. The latter aspect involves comparison of methods and algorithms for evaluation of the raw data. A new NASA sponsored program: Making Earth System data records for Use in Research Environments (MEaSUREs), has several active projects. The program focuses on finding consensus for algorithms, best practices and evaluation of errors and limitations of the data (Martha Maiden and other sponsors of a session at the 2009 Annual Meeting of the American Geophysical Union, personal communication, 2009). This effort ought to include all national agencies investing in spaceborne geophysical measurements.

The Committee on Earth Observation Science (CEOS) consists of members of most (or all) space agencies, and the forum has had successes such as the *Virtual Constellation* concept discussed in Sect. 4.1). However, many important variables have not received this attention with full international cooperation yet. A large obstacle is the considerable costs and man-power required for the re-processing to correct a time-series when improvements have been identified and agreed upon. The data records maintained at *Institut Francais de Recherche et de L'Exploitation de la Mer, IFREMER*, based on the ERS1/2 since the beginning in 1991 have been reprocessed several times as algorithms were improved and bias errors were discovered. NASA has an on-going program of re-analysis, which is illustrated best by the Pathfinder program.

The US has the National Climate Data Center, which maintains and distributes all manner of climate-related data. Emphasis on a web-based meta-data system, from which the data sources can be found, even though they may be distributed in different centers, is a good and practical idea. Furthermore, the U.S. maintains several Distributed Active Archiving Center's, DAACs, of which the one for Physical Oceanography, the PO.DAAC, is of most interest here: http://podaac.jpl.nasa.gov. A continuous and well supported system of centers for climate data around the world is to be encouraged. We must, however, find ways to support these efforts, without allowing them to entrain all resources from the climate research enterprise, especially as the data sets proliferate and algorithms may multiply. Judicious coordination that does not stifle innovation and valuable discovery of problems with the data and yet does not neglect good maintenance and stewardship of already collected data, is the goal. The maintenance issue may seem mundane, but is actually both a complex and demanding undertaking. An obvious requirement is clear and effective communication between the data/computer specialists and the scientists and other users. The optimal functioning of the system is in everyone's interest, but it is wise to bear in mind the different mind-sets of the many communities that need to work together for the goal of a complete, easy to use and understandable climate data record, which is within reach of anyone who needs to or wishes to know. A good English word for this goal is "transparency", like a beautiful window into the facts.

5 Possible Future Developments

The changing climate of the Earth and the serious consequences for mankind and other living creatures on the planet makes it important that scientists arrive at a reasonable way to work together to constantly improve the climate data records.

To face the challenges of climate change, decisions must be based on reliable Earth observation data. On one side there is the need of reprocessing existing archives and on the other to ensure continuity of crucial data sets. Through the Global Monitoring for Environment and Security (GMES) initiative (major details at www.gmes.info) Europe is developing its own system to monitor the state and evolution of Earth's atmosphere, land, sea and ice. The GMES infrastructure builds on a dedicated constellation of satellites, called the Sentinels, expected to be operational during the 2013–2023 time frame.

Satellite remote sensing is a natural focus for international efforts, since every satellite launch requires major national organizations behind them, so that the infrastructure for cooperation and collaboration already exists. Many new satellite missions are already international cooperative ventures with at least two countries involved; for instance the soon-to-be launched Aquarius with Argentina and the US collaborating. Above we mentioned the EUMETSAT and NOAA collaboration for operational polar orbiting satellites, and the geostationary placement of the 6 satellites also has required coordinated planning for many years. The nations that have more recently become mature satellite data collectors, e.g. India and China now have a great opportunity to contribute in significant ways to the improvement in sampling, which is so crucial for climate records.

We would like to charge all like-minded readers to join us in fostering this spirit of a truly global community of Earth scientists, who work for a comprehensive network of climate observations that give credence to statements made to governments regarding the most important issue of our time – the changing climate regimes on this planet.

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