RESEARCH SATELLITE MISSIONS

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ABSTRACT

Satellites view the world oceans in days to weeks, and can repeat such measurements for many years. Among the Essential Climate Variables (ECVs), those that can be measured from space are sea surface temperature, height, vector winds, colour, sea state and sea ice. In addition, there are emerging ECVs: ocean mass and sea surface salinity.

Our Recommendations can be summarized as follows:

- Sea Surface Temperature–Continue the high resolution infrared record, and the all-weather microwave record. Research: obtain better blended products with improved, well characterized accuracy.
- Sea surface height–continue the climate record of the Jason-series, and the operational use of the high inclination altimeters. Make these sustained, systematic observations useful for both applications and research. Use CryoSat for improved resolution, and approve the Surface Water Ocean Topography (SWOT) mission for launch no later than 2016. Research: improve the accuracy for climate record.
- Ocean Vector Winds–Continue the climate record obtained by the European Space Agency's Advanced Scatterometer (ASCAT). Replace QuikSCAT (Quick Scatterometer) as soon as possible. Develop sustained, systematic observations to follow on QuikSCAT. Research: a constellation, with improved spatial resolution and sensitivity.
- Ocean Colour– Continue the data record, fly climate-quality, well calibrated instruments. Research: improved analyses enabled by sensitive, well-characterized instruments. Derive new parameters, for example distinguish between plankton species, using existing and planned instruments with increased spectral band coverage, such the European Medium Resolution Imaging Spectrometer (MERIS) and the planned US Hyperspectral Infrared Imager (HyspIRI).
- Sea State– Improve coverage. Derive new quantities.
- Sea Ice– Continue the climate record of sea ice coverage. Research: improved resolution. Add sea ice thickness and dynamics.

  For all of the above, the concept of constellations must be followed: voluntary coordination of the observing systems from different countries to improve accuracy, resolution and overall coverage for any one parameter.
- Sea Surface Salinity – An emerging ECV. Research: use the Soil Moisture and Ocean Salinity (SMOS) mission, launched in November 2009, and the future Aquarius/SAC-D mission to begin a climate record.
- Ocean mass - An emerging ECV. Continue to improve the accuracy of the first 6 years of this climate record of total ocean mass, and time changes of ocean bottom pressure from the Gravity Recovery and Climate Experiment (GRACE) mission. Ensure continuity of this new

measurement. Improve the time-averaged geoid using GOCE, aided by GRACE, CHAMP, and historical laser-tracked geodetic satellites.

The previous decade saw these ECVs be used primarily on their own. We fully expect interdisciplinary use of two or more ECVs to become the norm in the next decade.

1. INTRODUCTION AND BACKGROUND

Satellites have revolutionized our ability to observe the world's oceans, covering them globally, with time intervals as short as one day, and repeating those global observations for years, sometimes a decade and longer for a single satellite. The past decade has seen satellite observations of the ocean take root, mature. Sustaining this progress, and enhancing the capabilities of current and future satellites (deriving additional variables, enhancing resolution, accuracy or both) are the key to the next decade. Since a series of satellites are needed to make a long time series, and different sensors measure the same variable with different advantages (e.g., microwave or infrared measurements of sea surface temperature), one must view these observations not by the technology but by the variable being observed. The community has already agreed to a set of Essential Climate Variables (ECVs) for the ocean, included in the Global Climate Observing System (GCOS). Among the ECVs, those that satellites have already demonstrated an ability to measure with the required accuracy are: ***sea surface temperature, height, vector winds, colour, sea state (waveheight and directional properties), and sea ice (extent, thickness, other properties)***. In addition, there are emerging ECVs. Ocean ***mass*** and the marine geoid are variables recently (since 2003) added to those that can be measured from space, at least over large spatial scales. ***Sea surface salinity*** is the latest addition and its measurement will be demonstrated shortly. This Plenary paper reviews the current state of these observations, their future prospects, and makes a few recommendations.

This Plenary paper benefits from much more detailed White Papers, specializing in each of these ECVs, which are cited in the respective sections below.

Satellites are expensive to design, build and launch, hence the time from mission concept to launch is measured in years. This characteristic can leave data gaps in time, with negative consequences for the essential intercalibration between successive satellites that is critical to producing consistent time series suitable for climate research (especially decadal variability, Fig. 1). This is less of a problem for operational satellites, such as the Defense Meteorological Satellite Program (DMSP, which carry the SSM/I (Special Sensor Microwave Image) instrument), or the NOAA-n (National Oceanic and Atmospheric Administration) series (which carry the AVHRR (Advanced Very High Resolution Radiometer)) than for research satellites such as the Jason-1 and 2 (Ocean Surface Topography Mission) whose successor is still in the planning stages. A consequence of these delays is potential gaps in the time series from satellites, a problem depicted in Fig. 1.

Although not discussed below, none of these satellite sensors exist without their accompanying in-situ data. In situ sensors are used for calibration, for example the buoys whose temperature data calibrate satellite multichannel infrared sensors for sea surface temperature. In situ sensors are used for validation, for example, the set of tide gages and the dedicated stations used to detect subtle drifts in radar altimeter data. In situ sensors are used to provide complementary data not available from satellite sensors, for example, the directional wave buoys that yield time series of wind wave height and their directions over broad frequency bands, or the Argo (Array for Real-time Geostrophic Oceanography) floats that provide vertical profiles of temperature and salinity.

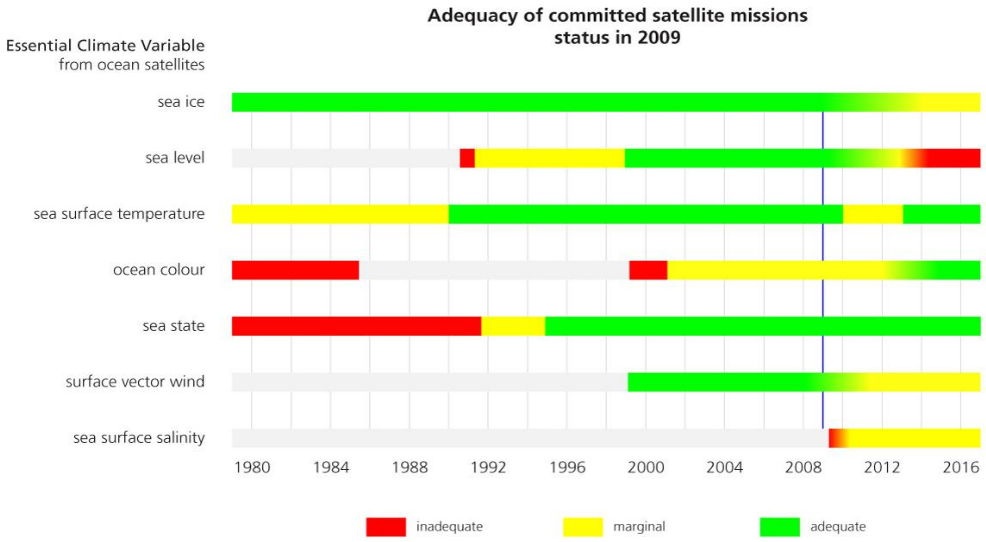

Figure 1. A conceptual view of the adequacy of research satellite observations of the ECVs.

2. CLIMATE VARIABLES

In this section we briefly review past achievements and the next decade's needs for each ECV and emerging ECVs.

2.1 Sea Surface Temperature

The past decade: SST (Sea Surface Temperature) has been measured from satellites continuously since 1978 (Advanced Very High Resolution Radiometer, AVHRR, infrared) and 1997 (Tropical Rainfall Mapping Mission Microwave Imager, TMI, microwave). The past decade saw increases in resolution, accuracy, and number of instruments in space, in particular today's Advanced Along-Track Scanning Radiometer (AATSR) and Moderate Resolution Imaging Spectroradiometer (MODIS) (infrared) and Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR/E) (microwave). Microwave has the advantage of continuous coverage, mostly unobstructed by clouds, but a relatively coarse spatial resolution (~12-25 km) and difficulty near coastlines, while infrared has the advantage of spatial resolution (1 km and shorter), but unable to observe in the presence of cloud cover (Fig. 2 shows the strengths and weaknesses of each, and the advantages of a blended product).

These data have been used in research, e.g. [1], and operationally for fisheries, hurricane forecast (http://www.nhc.noaa.gov/modelsummary.shtml), and more. The past decade saw a large effort (GHRSST (Global High Resolution Sea Surface Temperature), then the GODAE (Global Ocean Data Assimilation Experiment) High-Resolution Sea Surface

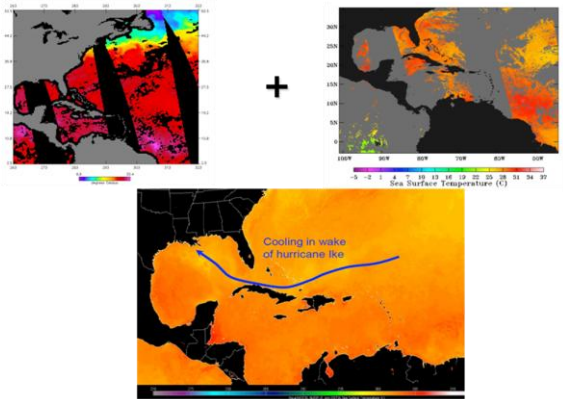

Figure 2: A combination of data from microwave instruments (upper left), which 'see' through clouds, and IR (Infrared) instruments (upper right) with their high resolution, is necessary to map SST properly. The lower panel is a combination of high resolution MODIS with AMSR-E data, in this case identifying the cooling in the wake of hurricane Ike.

Temperature Pilot Project, now called the Group for High Resolution SST) to bring together research and operational user communities, IR and microwave experts, to homogenize products, blend the best qualities of microwave and IR products, and more.

The next decade. Recommendations: SST is very useful in operational applications, among them initialization of atmospheric models and guiding fisheries, hence it will continue to be measured from space by many agencies, albeit for applications. The main danger is that the focus on applications only will discard microwave instrumentation and the accuracy, procedures and validation data needed for research applications.

The Community White Paper [2] has a comprehensive set of recommendations for the SST observing system. Urgent attention to continuity of satellite microwave data is needed, as well as to the generation of accurate climate data records (CDRs).

2.2 Sea Surface Height

The past decade: While radar altimetric measurements of the ocean started in 1974, with Skylab, followed by Geos-3 and Seasat, ***precision*** *radar* ***altimetry*** started in 1992 with TOPEX/Poseidon, then Jason-1, and the Ocean Surface Topography Mission (OSTM/Jason-2), which were designed for oceanographic research rather than operational needs. The orbit was selected to minimize tidal aliasing, the instruments measured most quantities needed to correct the travel time measurement (dual frequency altimetry to correct for ionospheric path delay; 3 frequency radiometer to retrieve the water vapor content of the atmosphere and associated wet path delay). These missions, while very accurate, leave large gaps between their nadir groundtracks, hence they were very nicely complemented by European Resources Satellite (ERS)-1 and -2, ENVISAT (Environmental Satellite) and, Geosat Follow On (GFO) designed for operational applications. During the past decade, the set (TOPEX/Poseidon, Jason-1 and -2, ENVISAT, GFO) have provided unprecedented observations of the ocean surface topography at scales larger than about 200 km and made significant advances in our understanding of global ocean circulation and sea level change. Among the many achievements of precision altimetry, one may cite [3], who combined altimeter observations with historical tide gauge data to reconstruct a 100-year record of global sea level rise, and show that sea level rise has accelerated in the past decades. Altimetry, surface drifters, and GRACE (the Gravity Recovery and Climate Experiment satellite) data yielded the absolute ocean topography averaged over 1993-2002, and revealed zonally oriented striations, zonal jet-like patterns [4], and the ubiquity and motion of large scale eddies [5]. See http://sealevel.jpl.nasa.gov for a comprehensive, impressive bibliography of altimetry-derived results. Current measurements of sea surface height encounter special problems near coastlines, but have proven very useful even there [6].

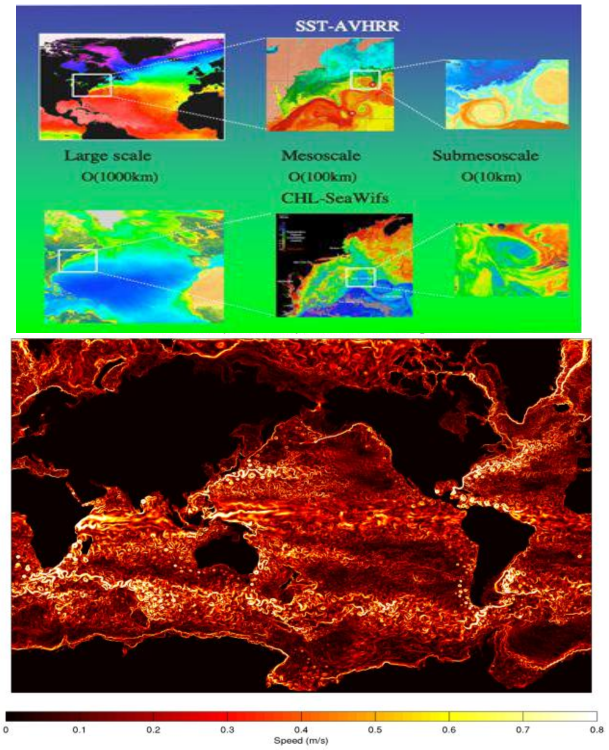

Fig 3: SST and Ocean Color data (upper panel) reveal submesoscale features, with horizontal scales of a few km. Numerical models (lower panel) show the ubiquity of mesoscale processes. The SWOT mission is designed to measure the SSH (Sea Surface Height) signature of mesoscale and submesoscale processes.

The next decade. Recommendations:

(i) The first need for the next decade is not to lose ground. Satellites of the Jason series, with their accuracy and minimal tidal aliasing can serve as a reference to high inclination satellites, such as the AltiKa instrument aboard the SARAL satellite, a joint mission of the French and Indian space agencies (Centre National d'Études Spatiales, CNES, and Indian Space Research Organization, ISRO), and the radar altimeter aboard Sentinel-3 (European Space Agency, ESA), China's HY-2 and U.S's Geosat Follow On GFO-2. A single traditional radar altimeter samples every 2-10 km alongtrack and leaves 200-300 km between tracks; a set of 2-3 such altimeters flying simultaneously barely resolves the mesoscale. A combination of these with current technology is needed to observe the mesoscale. This brings up the concept of an altimeter constellation [7], given the need to coordinate among many space agencies of several countries to optimize the overall sampling. Furthermore, it is necessary to balance the need to use altimetry for climate research with the need to use it for operational applications, such as hurricane and wave forecasting. Fortunately, Jason-3 was approved in both the budgets of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the U.S. National Oceanic and Atmospheric Administration (NOAA).

(ii) The second need is to take advantage of more advanced technologies, given that nadir altimetry today is essentially the same technology used over the past 30 years, while we now have more advanced technologies at hand. The first of these is the Delay Doppler altimeter, which processes the alongtrack returns in a manner similar to an alongtrack Synthetic Aperture Radar (SAR). This approach promises an order of magnitude increased resolution alongtrack (300m), and lower noise. SIRAL (SAR Interferometric Radar Altimeter), an instrument combining Synthetic Aperture Radar (SAR) and interferometer modes, which will be carried aboard the CryoSat mission, an endeavour of the European Space Agency (ESA), with launch planned in early 2010 (http://www.esa.int/esaMI/Cryosat/index.html).

iii) In the past few years, the importance of the submesoscale became apparent: [8] show a cascade of energy from the mesoscale to the submesoscale, whereby the ocean spectra remains “red” down to wavelengths of order 1 km, rather than what current altimeters resolve alongtrack, with noise dominating at wavelengths of ~ 100km. The submesoscales include fronts and filaments (Fig. 3) most effective in the vertical transport of ocean properties between the upper layers of the ocean and the deep ocean, and they account for about 50% of the total vertical transport. This vertical transport is crucial to understand and model the oceans' uptake of atmospheric CO_2. The shortcomings in observing the submesoscale can also be addressed in two steps. First, with SIRAL's 300m along-track resolution, even though leaving large gaps between tracks. The next step is a truly wide-swath, high resolution, 2-dimensional interferometric instrument, such as the one planned to fly aboard a mission named Surface Water / Ocean Topography (SWOT, Fig. 4), which is being designed jointly by the US and French space agencies, NASA (the National Aeronautics and Space Administration in the US) and CNES (Centre National d'Études Spatiales in France), and is scheduled for launch in 2016. An OceanObs 2009 White Paper focuses on this instrument and mission [9].

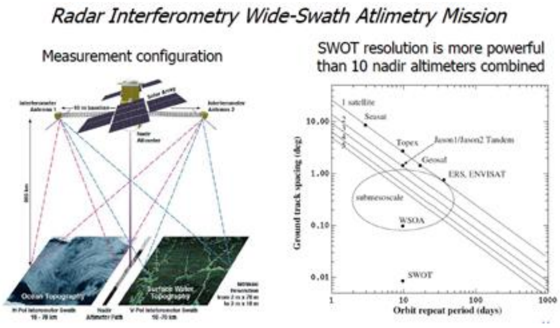

Figure 4: The Surface Water-Ocean Topography (SWOT) mission will use a Ka-band SAR interferometric system with 2 swaths, 60 km each, to yield a spatial resolution of ~ 1km and 2 cm vertical accuracy. The inclination and repeat cycles under consideration (all submonthly) trade off land and ocean requirements, sample higher latitudes that Jason, while minimizing tidal aliasing.

Perhaps another way to summarize the recommendations is that what is urgently needed is confirmation of future missions –both for operations and research (Jason-series, Sentinel-series, and SWOT) given the delays from confirmation to actual launch.

GPS-Reflectometry is a technique to measure sea surface topography with sufficient promise to warrant further study [10].

2.3 Ocean vector Winds

The past decade: The wind stress vector at the surface of the ocean has been measured with active sensors called scatterometers since 1978 (Seasat, Ku band, NASA). The measurement was continued throughout the 1990s with scatterometers aboard the ERS-1 and ERS-2 satellites (C band, ESA, the European Space Agency), briefly by NSCAT (NASA Scatterometer) on the ADEOS (Advanced Earth Observation Satellite) satellite (Ku band, 1996, NASA and JAXA, the Japan Aerospace Exploration Agency), from 1999 to date by SEAWINDS on QuikSCAT (Quick Scatterometer) (Ku band, NASA), the ASCAT instrument (C band) on the METOP (Meteorological Operational Satellite) series since 2006 (EUMETSAT), and an instrument similar to SEAWINDS on Oceansat 2 (ISRO, India Space Research Organisation is the Indian space agency). Rain contaminates the signal, more so for Ku band; QuikSCAT can get to within 15 km of land, ASCAT within 30 km. In all cases, the scatterometer measures ripples at the sea surface, in equilibrium with the wind stress. An 'equivalent neutral wind' conversion is performed in order to compare the data with the relatively large database of near surface winds. Wind speed but not direction has been measured with passive microwave radiometers (SSM/I, TMI, AMSR-E (Advanced Microwave Scanning Radiometer - Earth Observing System)) and all radar altimeters. However, it is possible to measure wind vectors with passive radiometers if they can sense polarizon: the polarimetric passive Windsat, launched in 2003 has proved the ability to measure direction also. Scatterometer winds have been used extensively in scientific research (e.g., [11] and [12]) as well as in operational applications [13]. Detailed descriptions, with many applications, and extensive references can be found in [14].

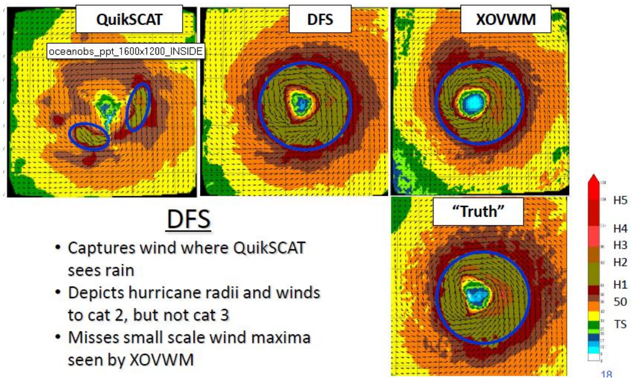

Figure 5. The proposed Dual Frequency Scatterometer would combine the frequencies of the US (K band) and ESA (C band) scatterometers. In addition to combining the best features of both, it will help solve any biases between these two solutions. The figure shows simulated retrievals for the 2005 hurricane Katrina (Rodriguez et al, 2009, pers. comm.)

The next decade. Recommendations:

METOP/ASCAT is a planned series, targeted at operational applications. QuikSCAT has failed to deliver vector wind measurements since late November 2009, after over a decade of flawless operation. The loss of QuikSCAT results in an 80 to 90% loss in detected hurricane force winds from extratropical cyclones. To date, there is no other capability that matches QuikSCAT's consistency in retrievable wind speed range, coverage of extreme (>30ms-1) winds, and sampling 90% of the ice-free oceans daily [13]. Data from non-US, non-European instruments have not yet been analyzed so as to determine their accuracy. There are *plans* for a dual frequency scatterometer (DFS, C and K band, NASA/NOAA/JAXA), *and* a post EUMETSAT Polar System (EPS), however at this point none of those have a go-ahead. This guarantees a gap in accurate Ku band Scatterometry

The DFS concept (Fig. 5) will solve a lingering bias between C and K band retrievals, unimportant for operational applications, but very important for scientific research, and would give the advantages of both in measurements of high wind in rainy conditions.

Scatterometry will suffer a decline of capability unless data from new satellites become available, calibrated and validated. Improved spatial/temporal resolution and sensitivity is needed. (e.g. DFS on -W2, Post-EPS). This need is urgent, given the loss of QuikSCAT. A comprehensive set of recommendations regarding ocean vector winds can be found in [14].

2.4 Ocean Color

The past decade: The past decade witnessed an abundance of satellite instruments measuring Ocean Color Radiances (OCR), from which it is possible to derive phytoplankton chlorophyll-a (a measure of phytoplankton biomass), coloured dissolved organic matter, particulate carbon, suspended sediment and the diffuse attenuation coefficient (an indicator of water transparency). Among these are SEAWIFS and MODIS on Aqua (NASA, USA); MERIS on ENVISAT (ESA); OCM on Oceansat 1 and 2 (ISRO , India), POLDER-3 (POLarization and Directionality of the Earth's Reflectances) (CNES, France), OSMI (Ocean Scanning Multispectral Imager) (KARI (Korea Aerospace Research Institute), Korea), and instruments with a regional focus, such as HY-1A and 1B (China). It also saw the formation of the Ocean Color Radiances Virtual Constellation, an effort to "ensure a long-term, sustained record of calibrated satellite ocean colour radiances (OCR) at key wavelength bands to determine the impact of ocean climate signals and climate change on ocean ecosystem and biogeochemical parameters" [15]. The key effort, as also seen in SST, SSH and the other ECVs, is the need to produce well inter-calibrated measurements from multiple satellites, a constellation, so as to yield a time series that reflects changes in the oceans, not in the instruments. OCR data have been used in scientific research [16], [17] and Fig. 6, and practical applications, such as fisheries ([18]; http://www.ioccg.org/).

Dynamic Green Ocean Models (DGOM) are an important class of users of these data. DGOMs explicitly represent various types of plankton. Among other data, DGOMs need ocean color for their evaluation. Derived products such as chlorophyll distribution can be used to examine whether the modeled total phytoplankton concentration is realistic. DGOMs also produce total primary production, also a derived product from ocean color. As with all other remote sensors, in-situ data are necessary to provide both variables not detected from space, and the vertical profile of many variables. A comprehensive review of DGOMs and their data needs can be found in [19].

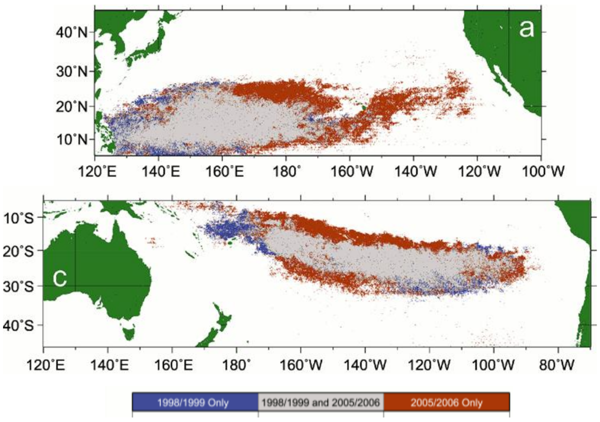

Figure 6: Low chlorophyll region change between 1998 and 2006. A decade of SeaWIFS data shows expansion of low chlorophyll regions [17]

The next decade. Recommendations: Several missions with instruments able to measure ocean 'color' have been approved but not launched yet, such as OLCI (Ocean-Land Colour Instrument) on Sentinel 3A (ESA), VIIRS on NPP (National Polar-orbiting Operational Environmental Satellite System Preparatory Project) and NPOESS (NASA, USA), and instruments on GCOM-C (Global Change Observation Mission - Carbon cycle) (JAXA, Japan). HyspIRY (NASA, USA) HY-2 (China). Other missions have not yet been approved, such as the Aerosol-Cloud-Ecology (ACE, NASA). It is important that these assets be placed in orbit, and the data be made widely available. Acceleration of research missions (e.g. ACE) is needed. Continue the record, and fly climate-quality instruments. The OCR-VC's main objectives are 1) to ensure OCR measurement continuity; 2) to provide high quality, well calibrated data; 3) data harmonization; 4) to facilitate timely and easy access to data; 5) Capacity building and Outreach. Research: improved analyses enabled by sensitive, well-characterized instruments, reference [14] has the necessary details. Again, in-situ data are crucial [18].

2.5 Sea State

The past decade: Satellite radar altimeters have provided significant wave height continuously for over two decades (Seasat, Geosat and Geosat Follow On, ERS-1 and -2, TOPEX/Poseidon, Jason-1 and 2, ENVISAT). It is also possible to obtain an approximate wave age (sea or swell), since the altimeter also measures a radar cross section, a proxy for local wind speed. While significant wave height is an important quantity (see Fig. 7 for an example), numerical wave models, whether used for physical studies or forecasting, require much more detailed information: for each frequency band, the energy in that band, and the next four moments of the probability density function of direction, namely the standard deviation (spread, second moment), skewness (third moment) and kurtosis (the fourth moment) [20] and [21], thus a minimum of five variables per frequency band. While the best way to obtain this information is from in-situ platforms, their spatial coverage is hardly global. From space, only Synthetic Aperture Radar (SAR) yields directional information. The Canadian RadarSat-1 and -2, European ERS-1 and -2, Japanese ALOS/PALSAR (Advanced Land Observation Satellite/Phased Array type L-band Synthetic Aperture Radar), German Terrasar-X, and the European ENVISAT ASAR have all flown, or are still in operation, providing sea state information with 25m resolutions over long strips about 100km wide, or 100m resolution over 500km wide area strips [21]. QuikSCAT (Ku band) and ASCAT (C band, with half the spatial coverage) have provided marine surface wind vectors with which to force wave models.

The next decade. Recommendations: Nadir radar altimeters of the ENVISAT series, Jason-3, and new entrants such as the French AltiKa aboard an ISRO satellite (India), HY-2A (China), GFO-2 (USA), Sentinel 3, will continue to provide significant wave height. The simultaneous existence of several such instruments is necessary to improve space-time resolution. SARs are essential in order to provide wave direction and wavelength information. Replacement of the QuikSCAT Ku-band scatterometer is essential due to its coverage and accuracy in order to provide the forcing needed by wave models.

2.6 Sea Ice

The past decade:

Sea-ice extent has been measured from passive microwave instruments since 1979 (Scanning Multichannel Microwave Radiometer, SMMR), then the series of SSM/I instruments aboard the Defense Meteorological Satellite Program (DMSP) satellites since 1987. In the last decade, scatterometers [22] Synthetic Aperture Radar (SAR, [23]) have been added to the tool set that detects and measures the extent of sea ice (the area of ocean covered with at least 15% ice,). The ice salinity and roughness are characteristic for different ice ages and ice types, which can be used as proxies for ice thickness categories [23] and [24]. New ice can be mapped by

combinations of scatterometer and radiometer data [25] and [26] and the thickness of thin ice can be retrieved from passive microwave data ([28] and Fig. 8. SAR data are useful for mapping ice deformation and ridged ice [29] and [30] and Fig. 9. Ice drift (displacement vectors) can also be obtained from passive radiometry [31]

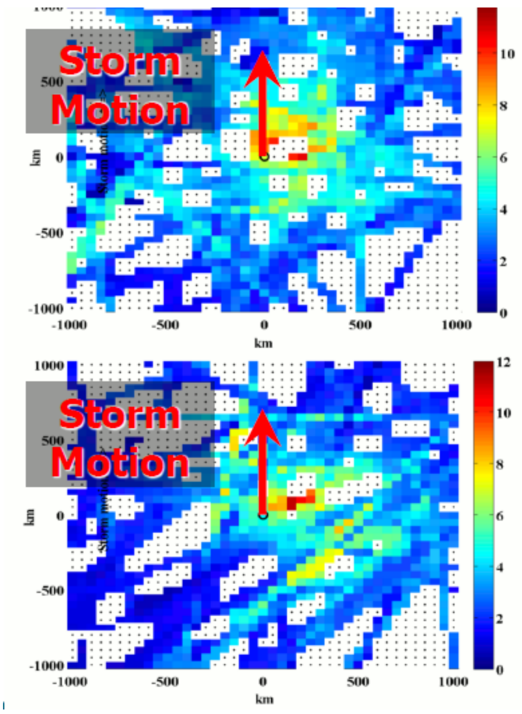

Figure 7. Altimeters provide surface waveheight information even around tropical cyclones. The figure shows significant waveheight relative to the direction of motion of the cyclone. Notice intensification in right-front quadrant. (Callahan and Oslund, 2009, pers comm.).

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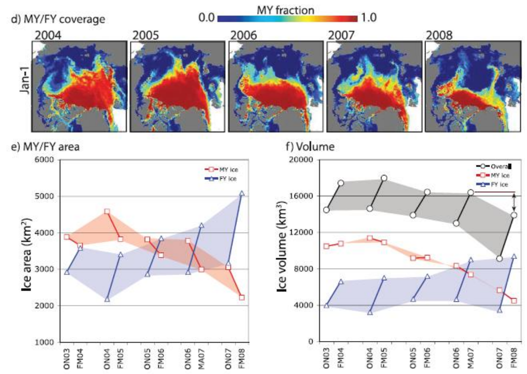

Figure 8 Changes in the Arctic ocean sea ice coverage (d. top), area (lower left, e) and volume (lower right, f), distinguishing between first year (FY) and multiyear (MY) components. MY ice is the fraction of sea ice that survives the warm season [32]

Among the important research findings of sea ice extent detection has been the monotonic decrease in Arctic summer minimum sea ice extent from 1978 to date (http://nsidc.org/data/seaice_index/). Other important properties of sea ice can be observed from space. Ice freeboard has been measured with nadir radar altimeters [33] as well as laser altimeters [34], [35], and ice thickness derived from the freeboard (for thin ice, passive microwave can derive the thickness). Different ice ages and types also differ in the surface roughness and salinity, which form proxies for ice thickness categories. Reference [25]. Ice 'drift' (surface velocity) has been measured from SAR, passive microwave radiometry and visible channels in AVHRR by cross-correlating two images separated by relatively short times [31]. Examples of important research findings using these data can be found in [33], [27] and [22] among others. Reference [36] is devoted to sea ice; the interested reader is directed there for a deeper understating and further details.

The next decade. Recommendations:

The next decade will witness the launch of CRYOSAT 2 (radar, alongtrack interferometry) and ICESAT 2 (laser), both of which will yield high alongtrack resolution, for ice topography and freeboard determination. Additional SAR instruments are at different stages of planning to be placed in space: Sentinel-1, PALSAR, and TerraSAR-X.

Because some will be at C or X band, and others at the much longer wavelength L band.

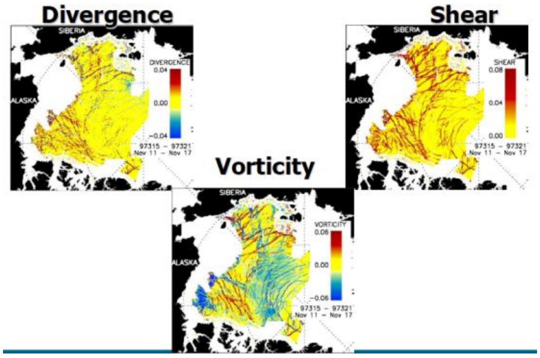

Figure 9: High resolution Synthetic Aperture Radar reveals deformations and flow in sea ice [30.]

3. EMERGING CLIMATE VARIABLES

The variables described in this section were not listed as ECV, in large part because they could not be measured before with the required accuracy, a weakness that has now been overcome. We offer them as emerging climate variables, and fully expect they will become as essential as those listed in Sect. 2.

3.1 Sea Surface Salinity

The past decade:

A remarkable demonstration exists of a measurement of sea surface salinity (SSS) from space, over the Amazon plume, using the AMSR-E microwave sensor [37], a sensor not designed for such a measurement. Until now, sea surface salinity has not been measured from space with sensors optimized for measurements. The importance of salinity is well known from decades of in-situ data: the meridional overturning circulation, ocean fronts, the marine component of the overall Earth hydrologic cycle, all have salinity as a critical component (Fig. 10).

The first mission dedicated to SSS measurements over the ocean is the Soil Moisture and Ocean Salinity (SMOS) mission, developed by ESA in cooperation with the space agencies of France and Spain, launched November 2, 2009, which is now undergoing commissioning.

The next decade. Recommendations.

SMOS will be followed by the NASA-CONAE (CONAE, Comision Nacional de Actividades Espaciales, is the space agency of Argentina) Aquarius/SAC-D mission to be launched in late 2010. SMOS was designed to observe both soil moisture over the land and SSS over the oceans. The Aquarius instrument has been optimized to measure SSS. Both SMOS and Aquarius intend to provide 150-200 km spatial resolution globally, and accuracy of approximately 0.2 psu or better on monthly averages, but there are technical differences between them, for example, the Aquarius instrument has a collocated scatterometer to measure the wind-caused roughness of the sea surface. In addition, in-situ campaigns to complement these spacecraft are planned.

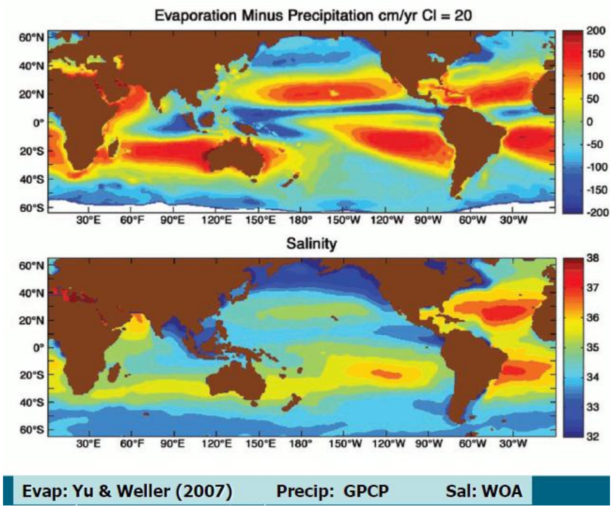

Figure 10: Water Cycle. Similarities and differences between climatological evaporation minus precipitation (top) and climatological surface salinity (from the World Ocean Atlas. Monthly surface salinity data from the SMOS and the Aquarius/SAC-D missions will shed light on the global freshwater budget.

Since this is the first time SSS will be measured in earnest from space, both SMOS and Aquarius are explorer-type missions, not part of a series. Given the delay between planning new missions and actual launch, this is a good time to start planning for future measurements of SSS from space [38]

3.2 Ocean mass / bottom pressure

The past decade:

Ocean mass was measured directly from space for the first time in the last decade using a satellite pair that actually measures gravity acceleration. Averaged over the global oceans we call the quantity 'ocean mass', when viewed over a relatively small patch of ocean this is ocean bottom pressure. Bottom pressure recorders and pressure inverted eco sounders (PIES) have measured bottom pressure over 1-3 year time spans at widely scattered locations in the ocean. The difference between sea surface height from satellite radar altimetry and the dynamic height measured from hydrography or Argo floats has yielded ocean mass averaged over the global oceans. However, the GRACE mission, for the first time, has measured time-varying gravity fields that can be interpreted as the spatial distribution of ocean bottom pressure and the globally-averaged ocean mass monthly without interruption from January 2003 to the present time (from August 2002 if one accepts lower accuracy).

GRACE yields bottom pressure averaged over areas approximately 700-1000 km in diameter. The data compare favourably against bottom pressure recorder data at mid to high latitudes [39], [40] and [41] and Fig. 11. The seasonal spatial distribution of ocean bottom pressure compares well with the difference between altimetric sea surface height and climatological dynamic topography from hydrographic data [42]. At low latitudes, the signal to noise ratio is poor [43]. Displacements of the 'solid' Earth, such as the drift due to Glacial Isostatic Adjustment [44] must be corrected with independent models of the process, or the changes in gravity in the proximity of large mass displacements due to earthquakes must be excluded from oceanographic analysis.

GRACE data have been applied to separate the globally averaged halo- and thermosteric sea level rise from the component due to mass addition [45], [46] and [47], to study oscillations in the N. Pacific [48], response of the Antarctic Circumpolar Current to wind changes [49] and [50], and to study low frequency exchanges of seawater between ocean basins [51].

GRACE is at the stage radar altimetry was in the mid 1990s. Algorithms keep improving, the error in the data are being pushed down: a release 05 of the data is imminent.

The next decade. Recommendations.

A GRACE follow-on mission, with improved technology, has been recommended in the Decadal Survey of the United States National Research Council in time 'tier 3', that means no launch until late in the decade of the 2010s, perhaps in the early 2020s. Support for such a mission comes primarily for its demonstrated ability to measure ice mass loss over Greenland and Antarctica [52], over smaller glaciers, and over land. However, a launch in the late 2010s or the following decade will leave a huge gap in the time series. A gap-filler mission has been proposed, using the same technology as GRACE, to fly at an earlier time.

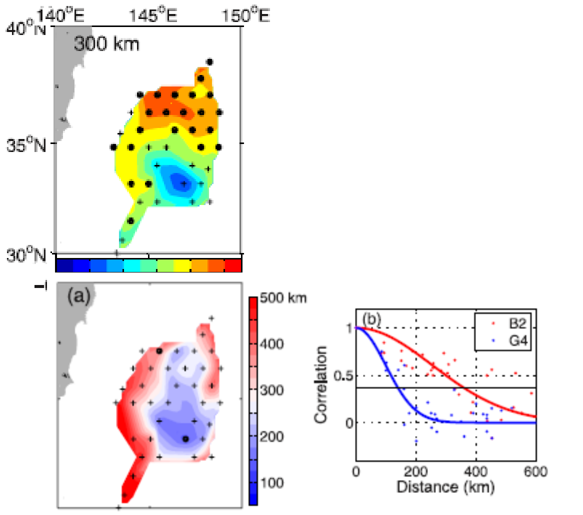

Figure 11. Top, Correlation between GRACE 'bottom pressure' and PIES (pressure inverted eco sounder instrument) at KESS (Kuroshio Extension System Study) location [41]. Bottom left: correlation distance among KESS PIES; bottom right: sample correlation function for two PIES locations, typical of the long and short correlation distances.

We recommend an early approval of such a mission, and subsequent build and launch, in order to minimize the now-inevitable data gap.

4. CONCLUDING REMARKS.

Satellite measurements of sea surface temperature, height, color and vector winds have become essential tools in oceanographic research and many practical applications. The expected improvements in each of these variables over the next decade will increase their usefulness. The last two decades have witnessed satellite sensors fulfill their promise. We fully expect the new satellite measurements to be initiated in this decade to become as useful as their predecessors.

It is essential to continue the capabilities already developed as a global backbone for the next decade's operations and research.

Even though any one satellite provides global coverage, depending on the swath width such coverage may take days to weeks to be obtained. Today we have ocean-viewing satellites from the U.S., Europe, China and India. It is important that such satellite sensors be considered a constellation of intercalibrated sensors. It is also essential that their data be freely and widely available as has traditionally been the case with data from U.S. satellites. Such constellations would then constitute an integrated observing system.

We discussed each ECV in isolation. It is clear that synergies among them exist. For example, in the wake of a hurricane, upwelling brings up nutrients leading to cold, productive waters; such process requires measurements of winds to pinpoint the storm's strength, ocean color instruments to see the increased plankton, and sea surface temperature to understand the upwelling. We expect numerical models that include ocean physics and biochemistry to integrate these data. A future challenge is indeed the integration of the various ECVs to observe the Earth System.

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