

# Ocean Remote Sensing: Challenges for the future

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*Abstract-* Challenges facing ocean remote sensing are unlimited as the variety of sea surface dynamics and meteorological conditions across the globe and their range of spatial and time scales. Ultimate goals are to be able to make accurate estimates of selected key sets of geophysical variables, with the intention of either making predictions across time and spatial boundaries, or advancing fundamental knowledge through development of empirical relationships and/or theoretical models. Improvements are constantly being sought in both our understanding of the geophysical processes themselves, the sensor physics and the electromagnetic and microwave properties of the surface and its associated air-sea interface, as well as the sampling capabilities to ensure proper monitoring using the vast number of specialized technologies that can be selected to concentrate on one or a few of the physical processes for accurate measurements. The increasing quality, quantity and duration of these ocean observations are then critically important for practical applications as well as to assess local or global climate changes, both from natural and man-made influences.

## I. INTRODUCTION

Global Earth Observation systems have certainly a unique capability and have already demonstrated significant applications on our current way to understand and manage the Earth's environment. Thanks to improved in situ networks, spatial and temporal coverage of satellite remote sensing, and numerical simulations, operational oceanography is emerging to address major concerns (global monitoring, disaster management support, climate change issues, etc). To ensure that its effect will be pervasive, in science, in industry, in the improvements of health and social welfare, questions, challenges, focus and investigations have already been shifted towards a more efficient management of the processing chain – from the sensor to the user. In particular, these efforts include consistent combined analysis and retrospective analysis using the different satellite observations within improved dynamical frameworks. Currently, there are indeed pressing needs to further explore how to build robust representations of ocean climate indices and predictors by using improved numerical simulations, observations and statistical techniques. A main challenge is then to clearly assess the strengths and weaknesses of the different available observations to provide meaningful basis for predicting the

intensity, the frequency and the tendency of particular events and anomalies.

For instance, pathways and mechanisms of oceanic heat, fresh water and biogeochemical transports are critical issues in the comprehension of the present climate, its variability, and its stability. As well, the air-sea exchanges under extreme environmental conditions are of key interests to determine the oceanic responses to localized events. Energy inputs in the region of intense storm tracks are thought to represent the main kinetic energy sources necessary to maintain the deep ocean stratified and to strengthen ocean stirring processes. Consequently, satellite-derived improved measurements of ocean surface wind characteristics (magnitude, direction), sea surface temperature and sea surface elevation are essential global products. Scatterometers, radiometers and altimeters can be stated as revolutionary developments in the study and view of the global ocean. For instance, thanks to the relatively long time series of these measurements obtained from different platforms since the beginning of the nineties, dedicated analysis are now possible to characterize the variability in these satellite-derived surface fields. More specifically, the link between changes in the mean fields with changes in storms distribution characteristics can be more closely investigated and assessed. As recently revealed [1], enhanced cyclone density are generally well collocated with negative sea-level pressure anomalies further associated with large scale sea surface temperature anomalies. One key question is then to better assess the quality of the satellite derived wind estimates under extreme conditions.

Furthermore, global ocean measurements inevitably involve a certain tradeoff between spatial resolution and temporal resolution, and also to force compromises in mission designs. Numerous geophysical processes and various oceanic phenomena with short spatial scales are generally systematically revealed using higher resolution instruments, such as imaging radars and high resolution optical instruments. These processes are generally not fully resolved by the current lower resolution instruments to challenge our ability to better understand and highlight the role of the smaller scale phenomena to control the upper ocean dynamics. The need to improve satellite spatial resolution becomes obvious when considering coastal applications and monitoring. But, these

new available high resolution measurements usually directly question our ability to better understand and model the revealed features in terms of both ocean processes and sensor physics.

Ocean geophysical monitoring certainly demands skills in making continuous observations and real-time interpretations that never seem fully adequate. The wide range of spatial scales (from millimeters to kilometers) may certainly not be matched, even using the broad spectrum of sensor technologies that have the optimum capabilities based on their electromagnetic frequency, polarization, incidence angle, coherence, Doppler characteristics and spatial/time resolution. Another crucial fact is that we are daily facing a stream of data pouring from space. Today, we are all familiar with the words “Mega” or “Giga”. But already, we are now talking “Terabytes” or “Petabytes” of data to download, analyze, understand, transform in an accessible way. Oceanographers and end-users can thus often be deluged with data, and the gap between data collection and analysis will grow in absence of dedicated tools and/or fully assessed theoretical dynamical framework to help the interpretation. Fifteen to twenty-five years long time series of satellite-retrieved parameters such as sea surface temperature, waves, sea surface height, surface wind vectors, sea-ice extension, etc.. are now available and provide an ever-growing massive archive that still has to be fully explored. The increasing resolution of the sensors, the upcoming shift from exploratory satellite mission to a fully operational and sustained mission, the raise of new space agencies (China, India) all contribute to dramatically increase the amount of data to be stored and explored. This emphasizes the need to better understand the sensor physics and capabilities, the need to propose combined uses of the different instruments, as well as the needs for innovative and very efficient data-mining methodologies.

At the same time, as the cost of new satellites and/or sensors is an increasing factor to consider for new spatial programs, there is a need to assert these new devices through modelling and simulations. These simulations must be end-to-end, i.e. include the sensors overall characteristics (antennas, radar or other device parameters, acquisition process) as well as very knowledge of the physics giving rise to the phenomena we are observing. First this will allow a better understanding of all interactions between observing means (very often electromagnetic waves) and the ocean surface. Then this will demonstrate the need for interoperability between sub-elements of the simulation (see [2] in this conference). This will also foster development of new and innovative ideas before physically building the devices. For instance combination of fully polarimetric SAR in combination with altimeters could be tested beforehand. Finally, last but not least, the extraordinary huge amount of data coming from the observations must be processed in a reasonable time and above all stored in practical fashion, meaning that very efficient compression/retrieval schemes must be achieved.

The following section will present the need to combine physical data for a better geophysical understanding of the Ocean processes. Then we will show why we need better resolution, not only from a spatial point of view, but in time as well for reaching coverage good enough for the marine community. Finally we will present some new surface measurements accessible from space, namely the salinity.

## II. COMBINED PHYSICAL PARAMETERS

Available over the last 15 to 20 years, satellite data can be combined with in situ measurements to provide invaluable and essential sources of information for looking at changes over a wide range of spatial scales at seasonal and multi-annual time scales, and to emphasize the role of extremes during these last 15 years. Available global observations from space now include sea surface temperature, sea surface wind, ocean surface topography, information related to sea state, oceanic precipitations and primary production, as well as sea ice extents. Combined use and blending of these passed and actual deployed sensor programs (satellite-based or other platforms) are already underway to provide daily merged sea surface temperature products [3], daily merged surface wind products [4], as well as combined altimeter sea surface topography products [5]. For these higher level products (Level 3 and Level 4 products) statistical techniques are used to map different types of dataset in a coordinated sense, to apply the necessary corrections between the different sensor-derived estimates. Considering sea surface temperature satellite measurements, all these observations can be either redundant (over clear areas for instance) with possible important discrepancies between each other (instrument biases, sensor physics), or can exhibit partial/large gaps (over cloudy or rainy areas). Therefore, the identification and follow-up of any feature or event becomes very challenging since a single and consistent sensor can hardly be used.

Thanks to global observations, extreme weather events such as tropical cyclones or explosive mid-latitude storms and polar lows can now be more commonly reported and analyzed. Satellite-measurements are critical for short term forecasting, but also offer means to better question the role of extreme conditions for the state of ocean at local and global scales and effects on ocean circulation and ocean heat transport. As demonstrated by radiometers onboard the DMSP satellite series, WindSat and TRMM, as well as by scatterometers onboard the ERS, ADEOS, QuikScat and METOP satellites, unprecedented synoptic observations of surface wind and atmospheric water content are now possible and are revealing the storm structures with impressive detail (see Fig. 1). However, satellite estimates do not really provide direct measurements of geophysical parameters and can suffer from limitations linked to the sensors characteristics.

As examples, scatterometer measurements are strongly affected by rain at Ku-band, and even at C-band, and the radiometers resolution is too coarse to delineate the fine scale

structures associated with extreme conditions. Each observing system can certainly offer specific information, but questions still remain for retrieving local environmental extreme wind conditions. Finer resolution can certainly help and today, Envisat and Radarsat C-band Synthetic Aperture Radars (SAR) are commonly used to complement the extreme observations by providing this finer resolution. Interestingly, while certainly limited by its relatively coarse across-track sampling, the actual altimeter (Jason-like) dual frequency radar cross section measurements have been demonstrated to provide very valuable information. Altimeter signals can be processed using specialized algorithms to retrieve the surface wind speed and significant wave height, along with the rain rate in extreme weather events [6]. Quite surprisingly, winds up to 50 m/s have been estimated in hurricanes for the first time using altimetry, to open new perspectives for estimation of extreme event intensity.

Combined with scatterometer and radiometer measurements, the altimeter measurements can thus further provide valuable information to describe the sea state structures in the wake, near the center, and ahead of the storm, to be related to the intensity of the surface winds and sea states. Of special importance is the storm surge propagating faster than the storm over long distances. As well, direct

consequences of intense winds, swells are surface waves that outrun their generating wind, and radiate across ocean basins. As wavelength and celerity also scale with wind speed, the longest swells become the fingerprints of the most powerful ocean storms. Swells can be very persistent with energy e-folding scales exceeding 30,000 km. Using such a property, recent works have then demonstrated that it is possible to combine satellite measurements, e.g. the altimeter significant wave height measurements and the Envisat ASAR Wave Mode measurements, to reconstitute the history of the longer swell waves propagating over thousand of kilometers and to track them back to the source (Fig. 2). The longer the waves, the faster they escape, and a co-located match-filter space-time analysis can be used to evaluate the source intensity. This can help to propose a more consistent view of the storm intensity/wave field using the different satellite sensors to overcome the individual sensor intrinsic limitations to retrieve very high surface winds under extreme conditions. Such a combined consistent analysis can be essential to issue more precise rules for storm intensity estimation. Today, the analysis of remotely generated swell systems can further build on available numerous co-located in situ buoy measurements and all available satellite measurements.

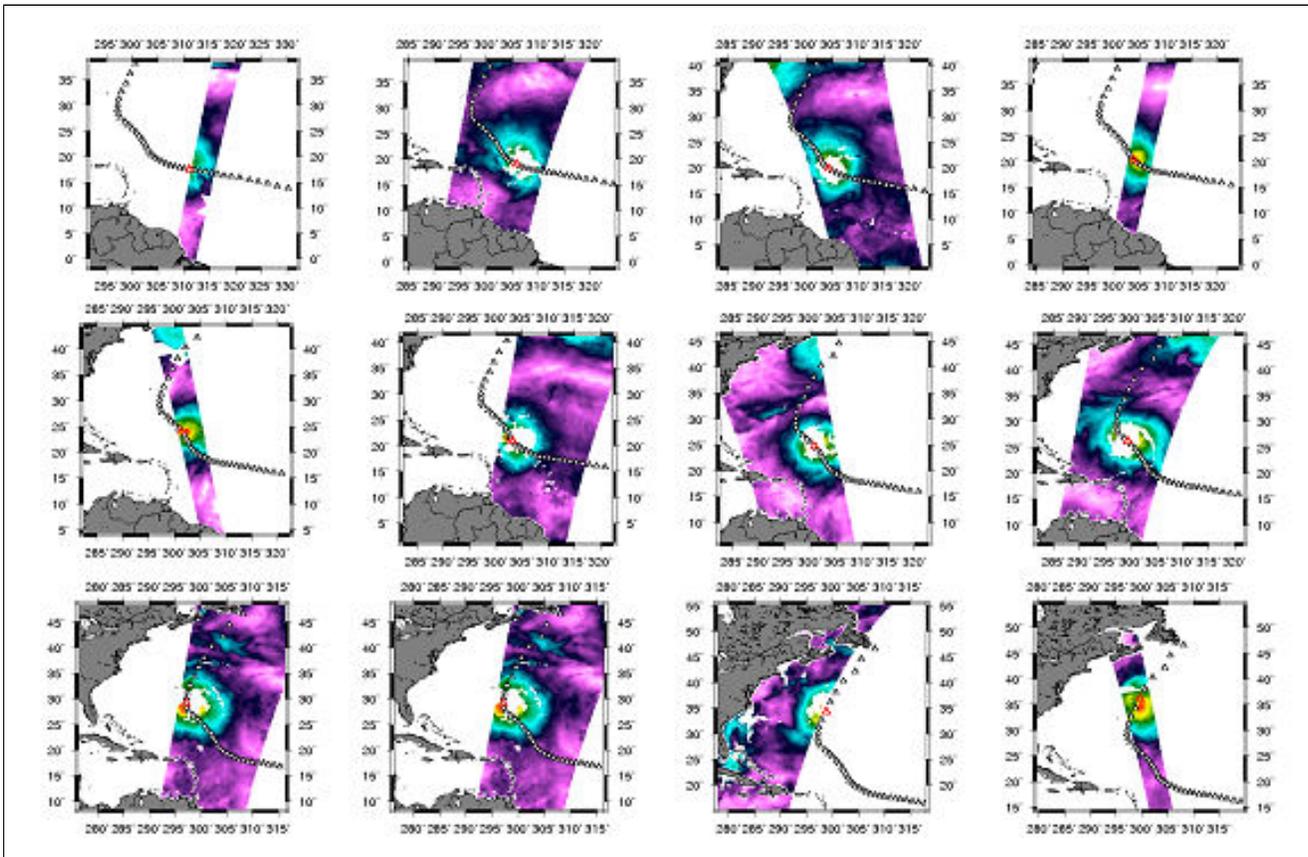


Figure 1. Hurricane Gert [1999] as an example of spatio-temporal event of interest monitored by different satellite scatterometer observations: hurricane tracks in a series of ocean surface wind estimation illustrating partial view effects as well as partial occlusions due to the acquisition process. For instance, the central area of the hurricane is sometimes occluded (represented in white) due to heavy rain effects. The large (1600km, ku-band) swath is from the Quiksat satellite, while the narrower one (500 km, C-band) is from the ERS2 satellite.

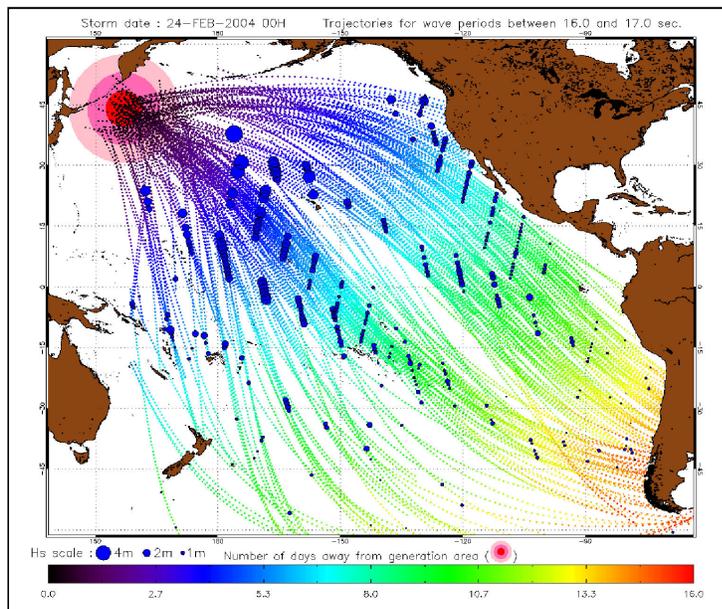


Figure 2. Measurement derived great-circle trajectories for swell systems with periods between 16 s and 17 s. The selective space-time match-filter is built according to the selected group velocity and estimated swell propagation directions from ENVISAT SAR measurements at locations indicated by blue circles. Size of the circles is related to the computed significant wave height. Trajectories are color-coded as a function of the propagation time since the swell generation at the source locates with the red circle. Accordingly, altimeter, scatterometer measurements (not shown) can then be easily co-located, and in situ buoy measurement selected.

### III. HIGHER RESOLUTION

A basic tool for measuring the oceanographic topography is the radar altimeter. Satellite altimetry is a very mature satellite remote sensing technique with an extensive body of literature describing previous and current instrumentation and the scientific results from the different altimeters that have flown in space. Yet, the ocean's mesoscale and submesoscale energy is difficult to map with conventional radar altimeters because of the narrow illuminated swath, regardless of the orbital configuration. To resolve mesoscale eddies adequately requires observations with the finest possible space-time resolution. Multiple satellites bearing identical high-class altimeters (TOPEX, JASON, ERS, or ENVISAT) could map the mesoscale ocean features if their orbits were all accurately known. However, funding multiple payload launches is not necessary likely. Another solution would be to develop altimeters with multiple-beam illumination patterns [7].

At present, the imaging radars, better known as Synthetic Aperture Radars (SARs) are really the best way to obtain this increased resolution. Following such a concept, interferometric techniques are emerging technologies to provide radar line-of-sight sea surface motion information at very high spatial resolution. Furthermore, improved polarization capabilities are also developed to help the radar image contrast analysis. Thus, the extremely large quantity of very good observations and the recent year progress in technology will certainly challenge our ability to quantitatively interpret these data, but will also allow new

developments using these high spatial and temporal resolution measurements. Furthermore, there is now the opportunity to combine all types of measurements (*in situ*, coastal or air/space-borne). For instance, on top of the usual SST and reflectance images indicative of surface and sub-surface dynamics, we can now observe related signatures of roughness variations from the imaging radars delineating numerous convergence and divergence zones in the upper layers of the ocean. As often obtained, very small features, such as frontal zones or spiraling eddies, at the 10 to 5 km scales are usually manifested in Sea Surface Temperature (SST) maps and/or Chlorophyll concentration fields, which are observable under favorable cloud conditions with infra-red radiometers and optical instrument at typical resolutions of 1 km. These small oceanic features are usually associated with surface current gradients which will then manifest in sea surface roughness variation measurements. Oceanic processes are thus often detected with imaging radars, which have typical resolutions of 100 m. Fig. 3, 4 and 5 are examples of such observations and derived results.

To help interpret such a wealth of surface information, it has been recently put forward a new dynamical framework which leads to anticipate that, under favorable environmental conditions, ocean dynamics in the upper layers of the ocean is mostly driven by the distribution of surface density anomalies [8]. This would then further imply that the 3D dynamics of the ocean could be recovered from high resolution SST measurements. This information combined with vertical velocities has never been fully exploited. This rich

information about the turbulence of the ocean dynamics and such a variety of observed phenomena may still seem to be difficult to handle, especially at very high resolution. Nevertheless, specific processing and extraction of main characteristics will certainly allow a better understanding of the physical and biological upper ocean processes and, therefore, will lead to quantitative analysis of the observed different phenomena. Indeed one must take into account the research advances, with an easier access to data and the improved possibility to compare with reference measurements (in situ, HF radar measurements near coastal areas). For coastal applications, the structure of surface currents is generally very complex, dominated by the local bathymetry, tidal cycles, wind and sea state conditions. Imaging instruments are then certainly more ideally suited for these observations. Conventional along-track interferometry techniques can provide a measure of the instantaneous sea surface scatterer velocity by measuring the phase difference between two return signals from the same surface patch, separated by a very short time interval. Direct instantaneous frequency determination from the phase history analysis of single antenna returns is less conventional, but can also be used to evaluate the mean velocity of scatterers on the ocean surface. Both techniques have demonstrated the feasibility to infer near shore current velocities along the radar line-of-sight direction. These techniques have the potential to meet very high spatial resolution requisites, but have the disadvantage that only one component of the two-component surface current is mapped. Fig. 6 still shows a good example of coastal surface currents measured and modeled. From this example, the radar inferred surface motions clearly reveal the amplitude (3 m/s) and spatial extension (some hundreds of meters) of coastal currents in the west tip of Brittany, which are mostly dominated by tidal motions [9]. Additional numerical simulations of this area (not shown) reveal that currents can be as high as 5 m/s.

Combined with all other potential sources of very high resolution information, expected new results should help to

better determine and quantify absolute surface current, surface current deformation including divergence, shear and rotation, surface drift estimation of practical importance for marine operations, oil dispersion and pollution transport.

#### IV. NEW MEASUREMENTS: SEA SURFACE SALINITY

Measurement of ocean surface salinity dynamics from space poses numerous engineering and scientific challenges that push the boundaries of ocean remote sensing capabilities. The principles of measuring sea surface salinity (SSS) from space are somehow well established. They involve precise determination of the dielectric characteristics of seawater through low-noise passive microwave (MW) radiometer measurement of the ocean's brightness temperature (TB), optimally performed at a low frequency near 1.4 GHz (L-band). There are numerous stringent error budget considerations carried within both the design and development of the L-band sensor hardware and within the salinity estimation methods for the future systems being developed at ESA (soil moisture and ocean salinity (SMOS)) and NASA (the Aquarius ESSP mission).

Sea surface salinity from space clearly presents new challenges because science requirements impose the need for resolution of the order of 0.1 psu (practical salinity units). This requirement means that competing terms carried in the ocean TB measurements, foremost being sea surface temperature (SST) and ocean surface roughness, must be accounted for in a new and more robust manner. More specifically, it is necessary to develop consistent electromagnetic/geophysical inversion scheme for the expected surface roughness and foam emissivity signatures at L-band. Models must also be capable to correct for Sun glint and galactic radiation scattered towards the future SMOS/MIRAS sensor. In that context, proper definition and use of the auxiliary data processing for SMOS, including the key SST, sea state and wind fields, is mandatory and certainly very challenging for the remote sensing salinity retrieval.

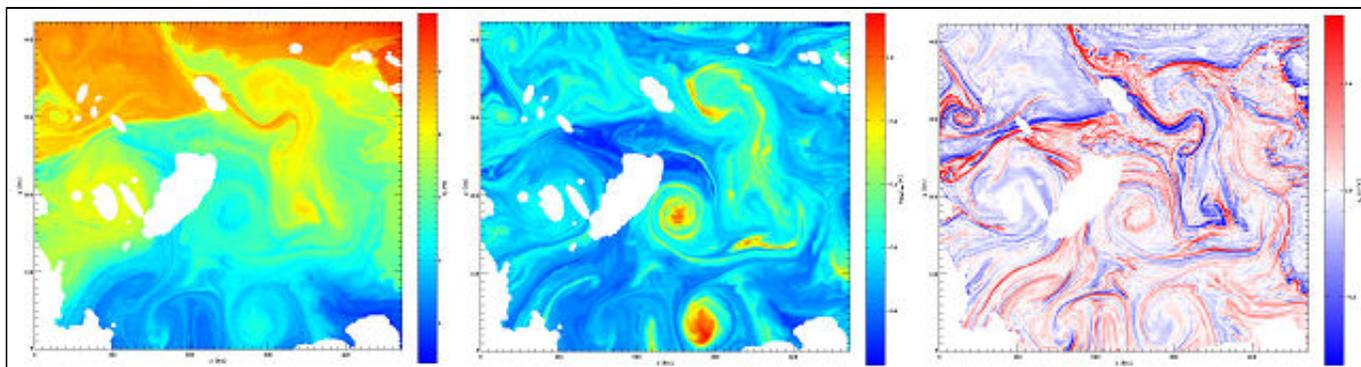


Figure 3: From left to right, instantaneous Sea Surface Temperature (SST) and Chlorophyll concentration maps, with high-pass filtering of the SST map.

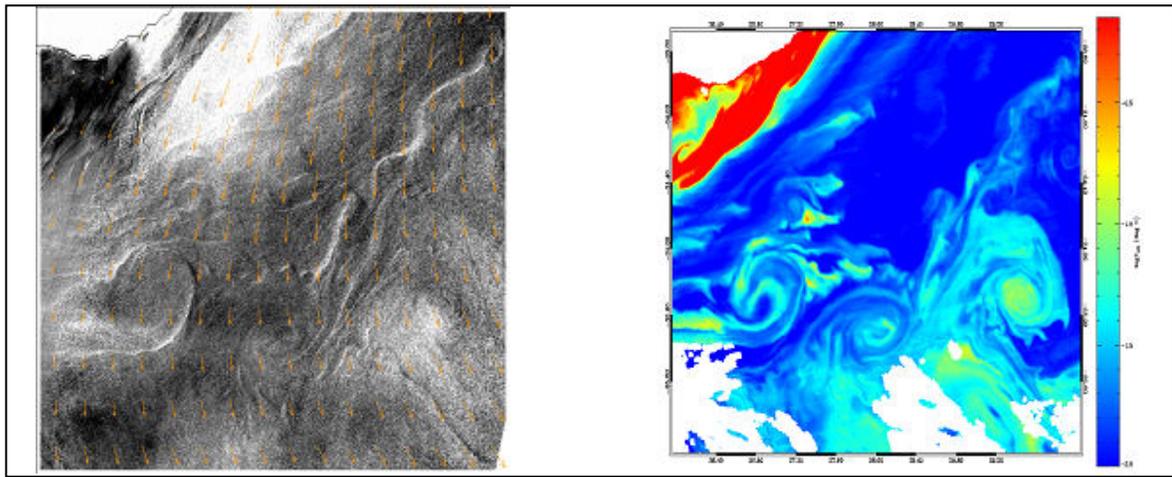


Figure 4. Left: SAR image and wind intensity superimposed. Right: Simultaneous (less than 6 hours) chlorophyll concentration image. The intensity variation zones are associated with the convergence and divergence zones. The color image presents also these zones associated with vertical speed variations in the mixing layer.

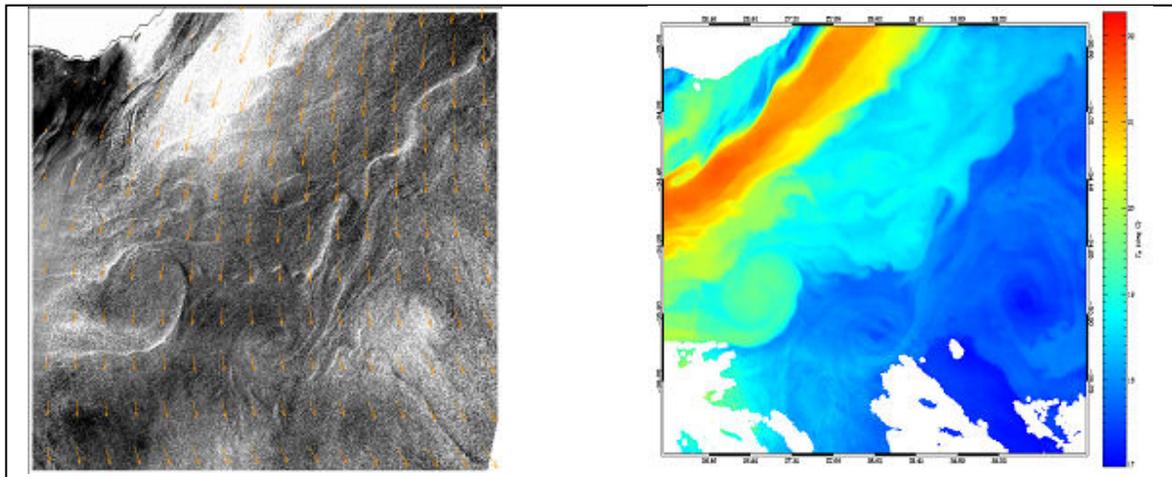


Figure 5. Left: SAR image and wind intensity superimposed. Right: Simultaneous (less than 6 hours) temperature reflectance image. The strong radar intensity variations are associated with temperature frontal zones.

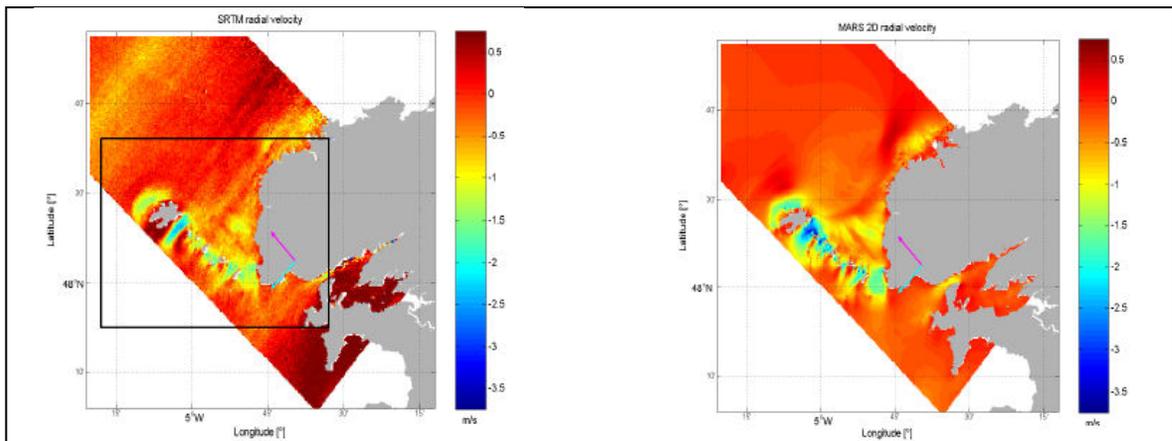


Figure 6. Radial current velocities measured using the Shuttle Radar Topography Mission data (left) and simultaneous radial velocities obtained from numerical simulations (right) of the circulation on the continental shelf in the west tip of Brittany.

## V. CONCLUSIONS

Interactions between electromagnetic waves and the ocean water-surface are governed by a variety of physical and chemical parameters such as temperature and salinity, as well as, among others, the sea surface roughness geometry and velocity, foam coverage, and foam thickness, level of upper ocean turbulence and associated surface currents, ocean spray and gas exchanges, ... An area of unfilled promise in ocean surface remote sensing is thus the development of consistent inversion of sea surface characteristics via the ever-increasing complement of microwave and optical techniques. To date, most retrieval algorithms, operationally implemented to infer geophysical parameters, can be termed empirical. These so-called geophysical model functions (GMF) are derived according to extensive comparisons between in situ and /or model outputs with co-located satellite measurements.

Moreover, during the past few years there have been considerable interests and achieved efforts in more precisely understanding the mechanisms by which surface expressions of oceanic and atmospheric phenomena are detected by remote sensing instruments. Such necessary investigations certainly stem largely from the potential of these measurements to provide invaluable synoptic information at improved temporal and spatial resolution. Satellite remote sensing techniques always present difficulties but are unique to better decipher the complex interplay between crucial parameters controlling the air-sea interaction and biological processes, to cover both

near-real monitoring needs and climate large-scale studies. Besides new measurements, future challenges will thus certainly be dedicated to better combine the different types of measurements (active, passive, optical, Doppler) to infer multi-sensor geophysical products, but will also be focused on improved data management and mining techniques to fully ensure the use of all available sources of information.

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