CNES PROPOSAL COVER SHEET

EUMETSAT/CNES Research Announcement CNES - DSP/OT/12-2118

Proposal No. ____________________

Title: Merging of satellite and in situ observations for the analysis of meso and submesoscale dynamics.

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Budget (for French Investigators only):

1st Year: 36.9 k€
2nd Year: 32.8 k€
3rd Year: 30.75 k€
4th Year: 26.65 k€
Total: 127.1 k€

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I. SUMMARY

Our proposal aims to improve our knowledge of the meso and submesoscale dynamics by merging altimetric data with various other satellite datasets (sea-surface temperature (SST) and salinity (SSS)) and/or in-situ observations. Three original techniques have been identified and are proposed in the present project:

- The three-dimensional (3D) structure of mesoscale eddies and their role in structuring the submesoscale dynamics and associated mixing.
- The development and test of a method to identify subsurface-intensified structures from satellite observations only (altimetry and SST).
- The improvement of the resolution of ocean fronts by combining large-scale tracer fields (SST, SSS) with lateral stirring computed from altimetric currents

These technique are based on specific methodologies, are independent and their development will constitute the three Work Packages (WPs) of the project. However, the combination of the different approaches will be studied too, with an aim to reconstruct the precise structure of oceanic eddies and understand the observed evolution.

Concerning the mesoscale dynamics, we will investigate the 3D structure of mesoscale eddies merging information from multi-sensor satellite data (altimetry and SST), and in-situ profiles acquired by Argo profiling floats. To this task, two different approaches will be used and combined: (*i*) in the WP1, we will apply an observational method that allows reconstructing the mean vertical thermohaline properties of mesoscale eddies in the region under study, combining multi-mission satellite altimetry products and Argo hydrographic profiles [*Chaigneau et al.*, 2011]; (*ii*) in the WP2, a new method will investigate the possibilities of using satellite altimetry and sea-surface temperature data only, to reconstruct the three-dimensional variations of the mesoscale dynamics. In particular, the comparison of surface circulations computed from geostrophy (from altimetry data) and surface quasi-geostrophy (from SST observations) theories will allow determining the signature of subsurface intensified structures. This open question is fundamental for anticipating future satellite altimetry missions such as SWOT that will acquire sea-surface height data having similar resolution as SST observations.

In terms of submesoscale dynamics, the WP1 will investigate the interaction between the mesoscale eddies detected by altimetry and (i) the submesoscale dynamical filaments and associated mixing determined from altimetry maps and Lagrangian advection diagnostics [e.g. *d´Ovidio et al.*, 2004]; (ii) the SST fronts automatically detected from MODIS images using a novel identification scheme [*Nieto et al.*, 2012]. The WP3 will be devoted to improve large-scale tracer SST and SSS fields, obtained from interpolated Argo in-situ data, by stirring and advecting these fields using altimetric-derived velocities. This method will also be used to improve the resolution of fronts in SSS fields observed from SMOS data. The WP3 will finally focus on the improvement of the resolution of the gridded altimetric geostrophic velocities used for the Lagrangian advection which in turn will help to improve the frontal structures in the upper ocean fields.

The proposed project will be performed preferentially in the North-East Atlantic and the Indian Ocean. These regions encompass a relatively high-number of available Argo floats needed for WP1-3, and enhanced-resolution altimetric products, that will be used in WP3, were recently

developed in these regions. This project will also focus in the NW Mediterranean Sea where airborne tests of the AirSWOT instrument will be carried out and new regional high resolution altimetric data set should be developed for this experiment (see TOSCA AirSWOT proposal). Although the techniques and methods developed in the frame of this project will be applied in these 3 contrasted regions, if robust and relevant, they will be easily applicable for other domains of interest.

II. EXPERIMENTAL OBJECTIVES

II.1. Scientific Context and General Objectives

The ocean, like the atmosphere, is a fundamentally turbulent system. Nearly 20 years of satellite altimetry measurements from numerous altimetric missions have shown that all of the world's oceans are full of mesoscale eddies and meanders [*Le Traon and Morrow*, 2001; *Chelton et al.*, 2007; 2011]. The ocean circulation is thus dominated by mesoscale variability mainly associated with ocean eddies or isolated vortices whose energy generally exceeds that of the mean flow by an order of magnitude or more. Most of the eddy energy is generated by instabilities of the mean flow [*Stammer and Wunsch*, 1999]. Eddies can feed energy and momentum back into the mean flow and help drive the deep ocean circulation [*Holland et al.*, 1982; *Morrow et al.*, 1994; *Lozier*, 1997]. They also transport heat, salt, carbon, and nutrients as they propagate in the ocean, and play a significant role in the global budgets of these tracers. Mesoscale processes also have a strong impact on the ecosystem [e.g. *Bakun et al.*, 2006], and on most operational oceanography applications (e.g., marine safety, pollution monitoring, offshore industry, fisheries, etc).

Mesoscale eddies are in particular associated with relatively strong dynamical perturbations of density and pressure on scales of 50-300 km, and can therefore be identified and tracked on satellite maps of sea surface height [*Chelton et al.*, 2007, 2011]. Although satellite altimetry has led to major advances in understanding the ocean dynamics at mesoscale, its three-dimensional observation remains problematic because of technological limitations of observing systems. Indeed, in-situ observations are restricted in both space and time, while satellite observations provide information only on surface ocean characteristics. Recent studies, based on the surface quasi-geostrophic theory, tested the feasibility to assess the vertical structure of oceanic mesoscale currents from surface information only [e.g. *Isern-Fontanet et al.*, 2008]. Although some subsurface patterns can be satisfactorily reproduced from these methods, they fail to correctly reproduce subsurface intensified mesoscale structures. **Thus, one of the objectives of this project is to investigate how such techniques can be improved to better infer the subsurface circulation from satellite surface observations only (WP2). To this task, we also propose to determine the mean three-dimensional structure of mesoscale eddies in several sites of the World Ocean, merging satellite information and in-situ data from ARGO floats (WP1).**

Superimposed to the mesoscale dynamics, high-resolution maps of sea surface temperature (SST) and sea-color reveal the presence of finer structures such as submesoscale filaments or fronts that separate water masses of distinct characteristics over short spatial scales of few kilometers. Associated with intense lateral and vertical velocities, sub-mesoscale processes are critical to the ocean / atmosphere exchanges, mixing between the surface and deep ocean, and exports between coastal and offshore areas [*Klein and Lapeyre*, 2009]. Furthermore, frontal structures are often the site of relatively high biological activity and play a crucial role in the distribution of pelagic species at different trophic levels [*Bakun*, 2006].

These sub-mesoscale dynamics have relatively small space and time scales (< 50-100 km; days) which are below the resolution of standard gridded altimetric products. Their space-time resolution has mainly been documented from high-resolution regional models, or high-resolution in-situ process studies [e.g. *Paci et al.*, 2005; *Legal et al.*, 2007]. However, a number of recent studies have applied the Finite-Size Lyupanov Exponents (FSLEs) technique to numerical model velocity fields or gridded altimetric current data [*Abraham and Bowen*, 2002; *d'Ovidio et al.*, 2004]. The FSLEs are able to predict regions of eddy mixing and transport barriers around strong jets. They provide Lagrangian contours following filament patterns, which result from the time variability of the geostrophic eddy field. Indeed in a turbulent field, the interaction between mesoscale eddies gives rise to regions of intense stretching and folding, with small-scale filaments ejected from vortex cores. Although mesoscale eddies are instrumental in the lateral stirring and advection of the open ocean, a thorough analysis of their role on structuring submesoscale features needs to be achieved. **We thus propose to quantify the distribution of submesoscale features and the associated mixing within and around mesoscale eddies (WP1). Finally, this project will also investigate the possibility to improve the resolution of ocean fronts by combining large-scale tracer fields (SST, SSS) with lateral stirring from altimetric currents (WP3).**

These issues will be addressed using an integrated approach combining various satellite datasets (satellite altimetry, SST and SSS) and in-situ hydrographic profiles acquired from ARGO floats and underway measurements. We will focus in 3 contrasted oceanic regions: the North-east Atlantic and Indian Ocean where new high-resolution altimetric products have been recently developed [*Dusurget et al., 2011*] and the density of ARGO profiles is high (Figure 1), and the western Mediterranean Sea where the AirSWOT program is planned. The main purpose of this project is to assess a better knowledge of the three-dimensional dynamics at mesoscale and its interaction with submesoscale structures in these 3 study regions. At the dawn of future wide-swath altimetric missions, this project will allow to estimate the feasibility of reconstructing the three-dimensional dynamics from high-resolution satellite surface data only.

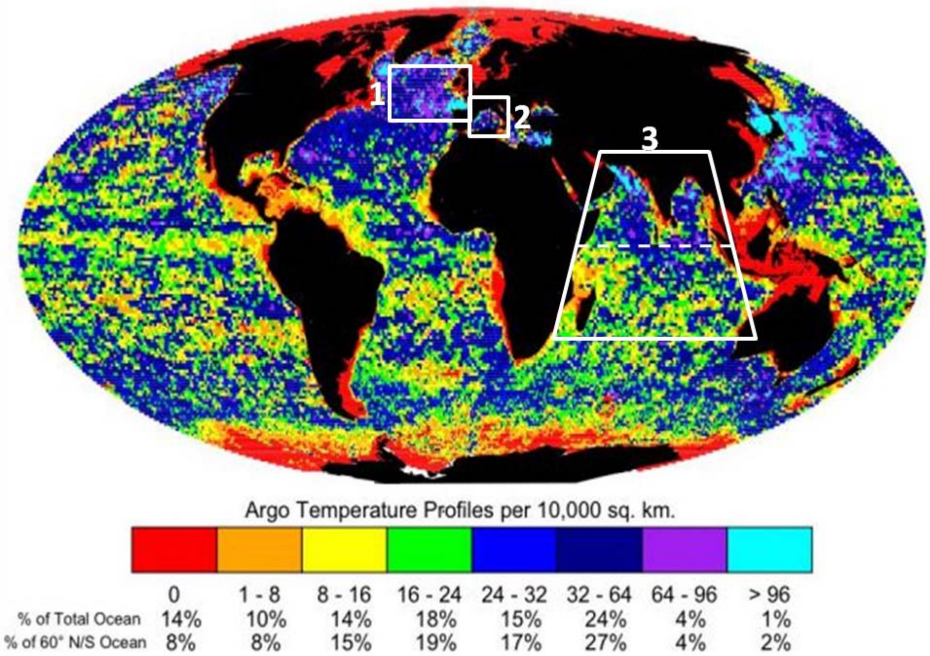


Figure 1. Number of temperature profiles ever taken by Argo floats. Percentages in the second row refer to the percentage of the total ocean area having that number of temperature profiles. Percentages in the third row refer to the percentage of the ocean area from 60°N to 60°S having that number of temperature profiles. (from http://wattsupwiththat.com/2012/02/06/where-in-the-world-is-argo/). The 3proposed study regions (1: North-east Atlantic; 2: Mediterranean Sea; 3: Indian Ocean) are delimited by white boxes.

II.2.WP1: 3- D structure of mesoscale eddies from satellite altimetry and Argo floats´ data, and their role on structuring submesoscale features.

A recent study conducted in the eastern South-Pacific showed the ability to combine satellite altimetry data and historical records of Argo float profiles (temperature and salinity) to reconstruct the mean three-dimensional (3-D) structure of mesoscale eddies [*Chaigneau et al.*, 2011]. Composite averages of Argo float profiles that surfaced into cyclonic and anticyclonic mesoscale eddies revealed key differences in their thermohaline vertical structure. For instance, the core of cyclonic eddies (CEs) was found to be centered at ~150 m depth within the thermocline, whereas the core of the anticyclonic eddies (AEs) was found at ~400 m depth impacting subthermocline layers (Figure 2). These main differences were attributed to the mechanisms involved in the eddy formation such as intrathermocline CEs (AEs, respectively) would be formed by instabilities of the surface (subsurface) current along the south-american coast. This study provided new insight into the potential impact of mesoscale eddies for the cross-shore transport of volume, heat and salt in the eastern South Pacific. Interestingly, numerical simulations revealed the presence of similar subsurface intensified eddies in both the Humboldt and California Upwelling Systems [*Colas et al.*, 2011; *Kurian et al.*, 2011].

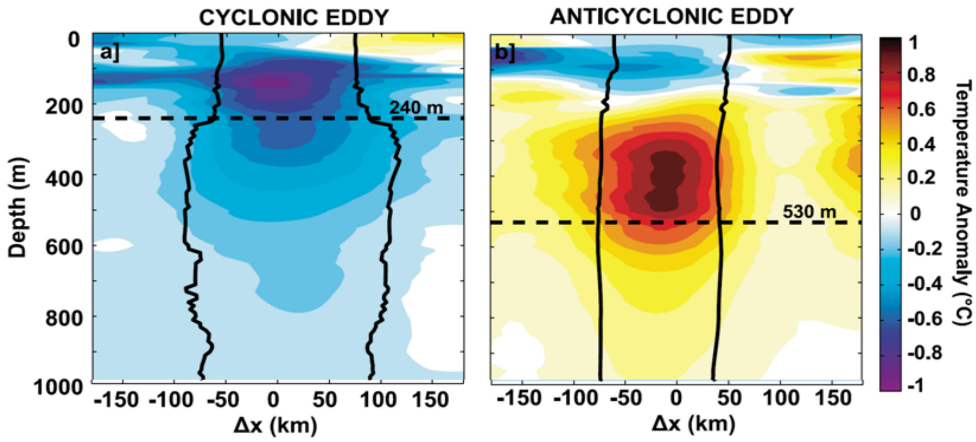


Figure 2. Vertical temperature section across the composite cyclonic (left) and anticyclonic (right) eddies reconstructed from altimetry data and ARGO profiles in the eastern South Pacific [from Chaigneau et al., 2011]. The cores of cyclonic and anticyclonic eddies are centered at different depths.

A similar approach was performed to investigate the vertical structure of anticyclonic eddies shed by the Agulhas retroflection [*Souza et al.*, 2011]. This study highlighted the central role of Agulhas rings in the heat transport and overturning circulation, being the main process responsible for the leakage of Indian Ocean waters to the Atlantic. **Based on the efficiency of such techniques to study the 3D shape of mesoscale eddies, the first specific objective of this WP is to perform similar analyses in other sites of the World Ocean (e.g. the North-East Atlantic, The Indian Ocean and the Mediterranean Sea). Using concomitant data from satellite altimetry (DUACS/AVISO product) and Argo floats, it will allow to depict the typical 3D structure of mesoscale eddies and to examine their potential impacts on the volume, heat and salt transports.** This study will also provide useful information and metrics needed for the reconstruction of subsurface mesoscale circulation from surface satellite data only (WP2).

As mentioned in Section II.1., observation of the mesoscale activity has been greatly enhanced by the advent of satellite altimetry, and the global multi-mission maps of altimetric sea level anomalies from DUACS/AVISO [*Dibarboure et al.*, 2011]. Although these gridded maps resolve only the larger mesoscales (150-200 km wavelength, time scales > 15 days), the temporal evolution of the velocity field inferred from these maps can be used to derive smaller-scale fronts and filaments, stirred around the larger eddies and created by the zones of convergence and divergence. **The second objective of this WP is to quantify the impact of mesoscale eddies on structuring submesoscale features and associated mixing. To this task, we will perform, within and around eddies, a composite analysis of the distribution of convergence lines, transport barriers and mixing estimated from Finite Size Lyapunov Exponents computed from satellite altimetry maps** (see example in Fig 3 for the eastern South-Pacific)**.**

Finally, submesoscale fronts are also widely observed in SST satellite data. **Thus, the third objective of this WP1 is to investigate how this submesoscale dynamics, directly observed from satellite sensors, are organized by the mesoscale dynamics detected from satellite altimetry maps.** The procedure will be rather similar to the one of the previous task, and will consist to (i) automatically detect mesoscale eddies on AVISO maps [*Chaigneau et al.*, 2009]; (ii) automatically detect submesoscale fronts from high-resolution SST satellite images [*Nieto et al.*, 2012]; (iii) combine both information to perform statistical analyses and determine the structuring of SST fronts within and around eddies. **This objective will also allow a better understanding of the relationship between dynamical fronts inferred from timeseries of SLA maps (FSLEs) and submesoscale fronts observed from a "passive" tracer (SST).** Note that the methods to be used (see Section III.1) are currently developed and applied in the eastern South Pacific (Fig. 3) but a deeper analysis needs to be performed and applied to other sites of the World Ocean.

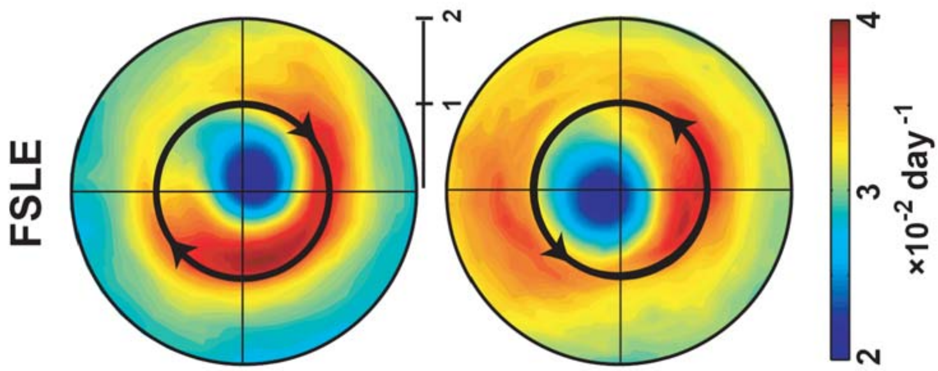


Figure 3. Mean distribution of FSLE values inside and around cyclonic (left) and anticyclonic (right) eddies in the eastern South Pacific. High values indicate areas of relatively intense mixing. The black thick line corresponds to the composite eddy edge.

II.3. WP2-Reconstruction of vertical mesoscale structures from satellite data only.

Except the GRACE satellites which measure ocean mass or ocean bottom pressure, satellite sensors measure only surface ocean properties (SSH, SST, Seas surface salinity, winds, chlorophyll, etc.). In-situ observations can provide observations of the 3D dynamics but remain sparse in space and time. Thus, a still open challenge in oceanography is to infer the subsurface circulation and properties from satellite observations only. This is particularly important for the assimilation of spatial observation into operational models. To this task, several approaches have been proposed in the last decade but, maybe except from ensemble approaches in regions where coherent structures are mainly subsurface, all assimilation techniques produce surface intensified structures from SSH (or SST) observations. Recently, *Isern-Fontanet et al* [2006] have proposed to use the surface quasi–geostrophic (SQG) theory to construct an estimate of the complete (3D) structure of oceanic currents and stratification from the observation of sea-surface density (or SST). This theory is based on two hypotheses: geostrophic equilibrium and no potential vorticity variations in deep layers. Although the geostrophic approximation is well verified for mesoscale eddies, the latter assumption (a constant potential vorticity along each isopycnic surfaces) is generally not verified, in particular for subsurface intensified structures (such as the composite anticyclonic eddy shown in Figure 2). The main drawback of the SQG theory is thus also to systematically assimilate the surface anomaly to a surface-intensified current and thus this approach fails to reproduce the structures having a subsurface intensified core [*Isern-Fontanet et al.*, 2008]. In summary, SST and SSH observations both contain information on the structure of oceanic eddies, that can lead to misinterpretations when used independently but whose combination could yield some insight on their structure.

The main objectives of this WP are first to evaluate the main limitations of the SQG theory (and evaluation of currents from SST observations alone) for different oceanic structures. We will then study the combination of SSH and SST observations to improve the reconstruction of the vertical variation of mesoscale eddies, in particular to identify subsurface intensified structures from surface ones (see section III.2 below). This study will particularly focus on mesoscale structures with increasing complexity:

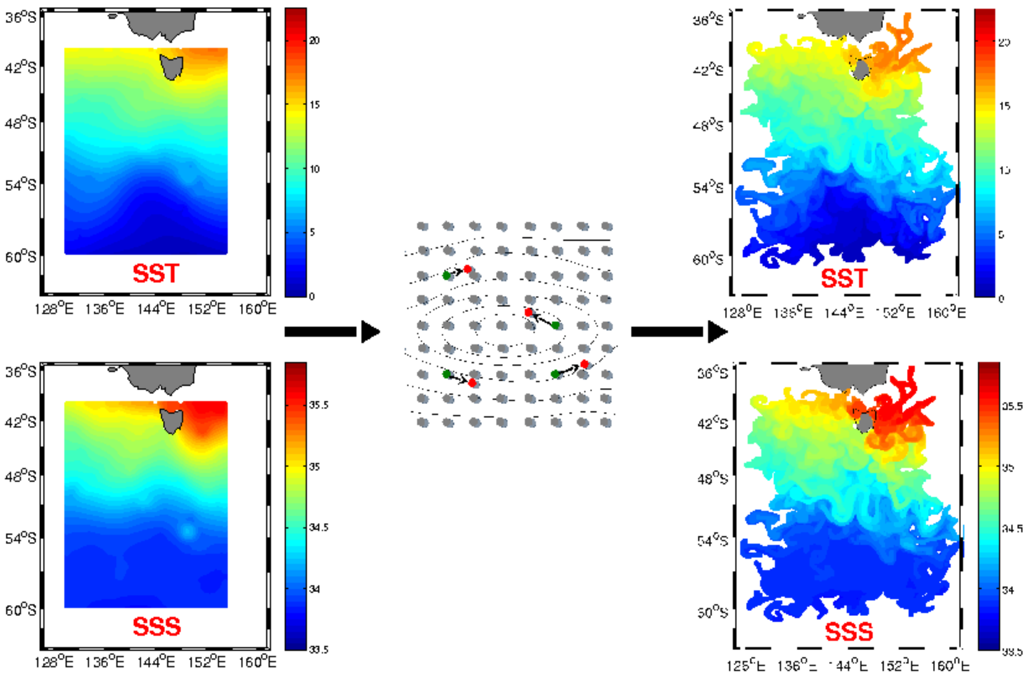
- Academic configurations will first be used, with axisymmetric vortices with a given shape, and the SQG model. Their SST and SSH signature will be studied and the reconstructed SQG dynamics will be compared to the reference. The error will be studied as a function of the vortex vertical structure (in particular the position and vertical extent of its core);
- More complex (3D) eddy structures will then be studied, retaining the SQG model. The evolution of coherent vortices and their interaction with surface geostrophic turbulence will be studied in this part, in particular subsurface coherent vortices whose surface signature (SST or SSH) is expected to be masked by the surface eddies;
- Tests with SST and SSH outputs from state of the art realistic ocean circulation models will then be made to evaluate and improve the methodology and build an indicator determining the position of the eddy core (surface or subsurface and possibly an estimate of its depth). The results will be compared to the full (3D) structure of the eddies identified in the realistic numerical model. The effect of wide swath altimetric observations versus present observations will be assessed;
- A process study will then be undertaken to infer the effect of the development of the winter mixed layer or the summer restratification of the surface layers -which could hide the (SST) signature of a vortex- on the previous method and indicator. To do so we will use a primitive equation model with a simple configuration : we will consider a single vortex but with different structures (surface and subsurface, cyclonic and anticyclonic) subject to different atmospheric fluxes and study its evolution (in particular its SST and SSH signature);
- The final step is to use realistic satellite observations (SSH and SST) obtained in a region where a vortex has been observed (and thoroughly documented) during a campaign at sea. Again both surface and subsurface eddies will be identified and tested. To do so, we have access to results from many past campaigns at sea, in particular in the Bay of Biscay (SEMANE, MOUTON, EPIGRAM programs).

As mentioned above, note that this work will be of particular importance in the framework of the preparation of the future wide swath SSH observation (SWOT mission) which will yield SSH and geostrophic surface current estimations with the same resolution as SST observations, allowing an easy combination of both dataset. This will be anticipated in the present WP2 by developing reconstruction algorithms for deep dynamical structure based on academic configurations or using results from numerical models.

II. 4. WP3: Improving the resolution of ocean fronts by combining large-scale tracer fields (SST, SSS) with lateral stirring from altimetric currents

As mentioned in Section II.2., the temporal evolution of the velocity field computed from DUACS/AVISO products can be used to derive smaller-scale fronts and filaments. The surface Lagrangian advection from these time-evolving altimetric geostrophic velocities has been shown to simulate quite successfully submesoscale processes, using the Finite-Size Lyapunov exponents - FSLE [*d'Ovidio et al.*, 2009], or by simply stirring a large-scale tracer field [*Despres et al.*, 2011].

We have applied this technique in the Southern Ocean region south of Tasmania, a domain marked by strong meso- to submesoscale features such as the fronts of the Antarctic Circumpolar Current (ACC). Starting with large scale surface tracer fields, obtained from interpolated Argo in-situ data, we then stirred these fields with altimetric velocities to obtain sharper frontal structures, which are better positioned and more intense than in the original fields (Figure 4, after *Dencausse and Morrow*, 2012). The fronts from the 'advected' fields were compared with high resolution in-situ or satellite data. We found a significant improvement after an optimal advection time of ~2-3 weeks, with enhanced signatures of the ACC fronts and a better spectral signature. The 2-3 week advection time was also consistent with the separation time derived from the FSLE analysis.



<u>Figure 4.</u> Schematic of the Lagrangian advection technique. The central figure shows particles placed on a dense regular grid (0.04°) which are advected horizontally using altimetric geostrophic velocities. The velocity fields along the particle trajectories are calculated every 3 hours from a linear interpolation of the weekly Aviso fields. Large scale tracer fields (e.g.SST and SSS on the left) are then interpolated at each initial particle

position. Tracer values are then carried by each particle onto their final position (right panel), to create an 'advected tracer field'. The advection time in this example is 19 days, from 1 January to 20 January 2007 (after Dencausse and Morrow, 2012)

The first objective of this WP3 is to extend this analysis to the global ocean. Previous analyses have been performed in the North Atlantic [*Despres et al.*, 2011] and the Southern Ocean [*Dencausse et al.*, 2012], where the frontal structure is intense and deeply penetrating. We intend to test the technique at other sites, in comparison with in-situ data in mid-latitude and tropical regions, where the surface frontal structure may be shallow, and even offset from deeper strong gradients detected by altimetry. Underway surface SST and SSS data from the ORE-SSS at LEGOS will be used to validate these tests.

The second objective of this WP3 is to improve the resolution of fronts in SSS fields, using SMOS and/or Aquarius satellite SSS data as the initial conditions and the Lagrangian advection from altimetry. We expect some improvement in the tropical to mid latitudes, if the surface SSS fronts are well correlated with the subsurface dynamical fronts. This will need to be investigated in detail.

The third objective will consider improving the resolution of the gridded altimetric geostrophic velocities, used for the Lagrangian advection. A number of improved resolution gridded products exist from regionally mapped altimeter data from 2000 onwards, when a minimum of 3 altimeter missions were in flight. These higher-resolution regional altimetry products are available for the Bay of Biscay [*Dussurget et al.*, 2011; CTOH product], in the Mediterranean Sea, around Madagascar, and around the Kerguelen Plateau (AVISO regional products). These regional products can resolve horizontal scales down to 50-100 km, but need to be analysed considering the larger error levels [*Dussurget et al.*, 2012]. We will compare the global and regionally mapped velocity fields, and their impact on the Lagrangian advection of the tracer fields, again in comparison to available high-resolution in-situ data.

In spring 2014, some airborne tests of the AirSWOT instrument will be carried out in the Northwest Mediterranean Sea. A new regional high resolution altimetric data set should be developed for this experiment (see TOSCA AirSWOT proposal). We intend to apply the Lagrangian advection technique to this region to identify the fronts using near-real time altimetry maps, in preparation for the AirSWOT experiment. The AirSWOT observations will also provide an unprecedented data set for intercomparisons with the predicted advected fronts.

Finally, the fourth specific objective concerns the improvement of frontal structures in the upper ocean fields. At present, upper ocean temperature and salinity fields are constructed from an optimal interpolation of available in-situ observations (mainly Argo floats), [eg*, Boyer et al.*, 2006; *Gaillard et al*, 2009] or the vertical projection of altimetry anomalies onto statistical modes [eg, *Guinehut et al.*, 2004]. Both of these methods are based on a static statistical approximation for the 3D projection of sparse or surface data. Early tests have shown that Lagrangian advection by altimetry of a sparse initial 3D tracer field can also improve the characteristics of subsurface fronts, in terms of their position and intensity over the upper 500 m [*Dencausse et al.*, 2012]. We intend to study this improvement by a more rigorous analysis with more case studies in the global ocean, and by using the higher-resolution regional altimetric data sets. The Lagrangian advected subsurface tracer fields will be compared to *i*) high resolution XBT or CTD sections across fronts and *ii*) the projections of surface altimetry data on vertical statistical modes (e.g. ARMOR3D - *Guinehut et al.*, 2004).

III. APPROACHES

III.1. Approach for WP1

Specific Objectives:

- Determine the 3D structure of mesoscale eddies in a given oceanic region
- Estimate their contribution to the volume, heat and salt transports.
- Determine the structuring of FSLEs and associated mixing by mesoscale eddies
- Determine the structuring of submesoscale SST fronts by eddies

Data to be used:

- Weekly SALTO/DUACS AVISO maps at 1/4° resolution (2000 →)
- Argo float profiles (2000→)
- FSLE maps distributed by CTOH (2000→)
- Daily (or weekly) SST maps from MODIS sensor at 4km×4km resolution (2002 →)

Methods:

- Identification and tracking of cyclonic and anticyclonic eddies (CEs and AEs, respectively) in SLA maps. First, to match the temporal resolution of the distinct datasets, SLA maps will be interpolated on a daily basis. Then, the proposed method to automatically detect mesoscale eddies in these SLA maps, is the one applied by *Chaigneau et al.* [2009] in the 4 major upwelling systems. The CE (AE) detection algorithm involves, first, searching for eddy centers associated with local SLA minima (maxima) in SLA maps. Then, for each possible CE (AE) center, the method searches for closed SLA contours using a dichotomy algorithm. The outer closed SLA contour, embedding only the considered center, corresponds to the eddy edge.

In a second stage, each vortex is tracked from the time of its appearance to its dissipation. Eddy tracking is performed by comparing each eddy at the current time *t* with those at time *t + dt* (*dt* = 1 week) within a radius of 150 km. A cost function CF of each eddy pair having the same polarity is evaluate and depends on the mismatch between their distances, vorticities, kinetic energies and radii [*Chaigneau et al.*, 2009]. In the cost function matrix so obtained, the minimum cost is found and the eddy at time *t + dt* is classified as a continuation of the one at time *t*. As eddies may disappear between consecutive maps, in particular if they pass into the gaps between satellite groundtracks, the same eddy is searched for 3 weeks after its disappearance.

- 3D structure of mesoscale eddies. The method to be used is the one developed by *Chaigneau et al.* [2011] in the eastern South Pacific. It first consists to classify Argo float profiles into 3 categories depending whether the floats surfaced outside an eddy or inside a CE or AE identified from daily SLA maps. In-situ profiles surfacing into CEs or AEs can be localized relative to their corresponding eddy centers identified as local maxima/minima in SLA. Then, assuming that all the CEs or AEs in the considered region exhibit similar 3-D structures, the spatial distribution of a given property (or anomaly) inside CEs and AEs can be investigated by a composite analysis using a coordinate system (Δx, Δy) in which each in-situ profile is located respectively to the corresponding eddy center ($\Delta x = \Delta y = 0$). The properties (temperature, salinity, density, geostrophic velocities) can then be objectively mapped on each vertical level, and the typical 3D structure of mesoscale eddies are reconstructed [see *Chaigneau et al.*, 2011; see also Fig.2].

- Volume, heat and salt transports associated to mesoscale eddies. With the knowledge of the 3D eddy structure and their temporal tracking, we can estimate the volume, heat and salt transport anomalies associated with mesoscale eddies. First, it consists to estimate the fraction of the water column that is effectively trapped by the eddies. It typically extends from the surface to the depth where the swirl velocity is weaker than the propagation speed [*Flierl*, 1981; *Chaigneau et al.*, 2011]. Then, annual mean "eddy" transports can be estimated by dividing the volume, heat or salt anomaly of one eddy by 1 year and taking into account the number of eddies per year [e.g., *Gordon and Haxby*, 1990; *van Ballegooyen et al.*, 1994; *Doglioli et al.*, 2007; *Chaigneau et al.*, 2011]. Using the eddy tracking algorithm and the mean 3D structure, such estimates will be performed in the distinct study regions.

- Structuring of FSLEs and associated mixing by mesoscale eddies. To this task the distribution of FSLEs will be extracted within and around each eddy detected in FSLE maps. The extraction will be done into different grid configurations considering either fixed spatial grid (e.g. 400km×400km around each identified eddy center) or normalized grid considering the eddy radii [e.g. *Rudeva and Gulev*, 2011; see also Figure 3]. Then, composite averages will be performed considering various eddy "categories" based on radius, amplitude or intensity classes. Using the temporal tracking of mesoscale eddies, similar analyses will be performed considering different stages of the CE and AE life-cycle (formation, development, maturation and decaying phases).

- Structuring of SST fronts by mesoscale eddies. First, SST fronts will be identified on daily (or weekly) maps using the methodology developed by *Nieto et al.* [2012]. SST maps are first segmented into moving windows and the distribution of SST values are analyzed in each of these windows. The algorithm makes the hypothesis that two populations of SST values are present corresponding of both water masses separated by the front. Criteria on the population differences and cohesion are used to determine the validity of the hypothesis. When the populations are statistically different, a front is identified [*Nieto et al.*, 2012]. An example of frontal detection in the eastern South Pacific is shown in Figure 5.
The compilation of the detected fronts will first allow determining the frontal occurrence (at annual and seasonal scales) in the regions under study. Then combining the submesoscale fronts detected from SST maps and mesoscale eddies detected from SLA maps, we aim to depict the typical distribution of frontal structures within and around CEs/AEs. To this task, a composite analysis, such as the one described previously, will be performed.

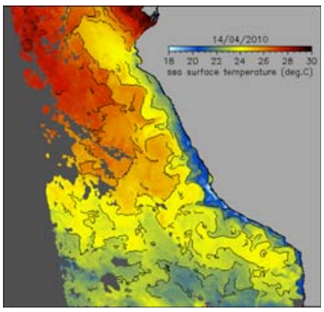


Figure 5. Example of frontal detection from a SST map in January 2010, in the eastern South Pacific.

III.2. Approach for WP2

Specific Objectives:

- Determine the nature of a mesoscale eddy (surface or subsurface intensified) from spatial SSH and SST observations;
- Evaluate the 3D structure of the vortex from SSH and SST observations;
- Study the evolution of a coherent (surface and subsurface) vortex when interacting with the surface geostrophic turbulence;
- Study the effect of atmospheric fluxes on the evolution of a vortex dynamics and its SST and SSH signature.

Data to be used:

- Weekly SALTO/DUACS AVISO maps at 1/4° resolution (2000 →);
- Daily SST maps from MODIS sensor at 4km×4km resolution (2002 →);
- Observations at sea, available from previous campaigns at sea;
- Results from numerical models.

Methods:

The general approach consists first to reconstruct the 3D structure of the circulation and stratification using the SQG theory and SST satellite data. The result corresponds to surface intensified structures (second hypothesis of the SQG theory: no internal potential vorticity structure). Second, the sea-surface height observed from satellite altimetry allows computing the "*true*" surface circulation by geostrophic approximation. This surface geostrophic circulation is related to both the surface density variations (SQG theory) and the vertical structure of potential vorticity. Thus, the difference between the observed surface geostrophic circulation and the one estimated from SST using the SQG theory represents the signature of the subsurface structure of the eddy. This residual in surface current can be used to estimate the vertical structure of potential vorticity and the 3D circulation (and stratification). In particular, it must be possible to identify subsurface eddies as we expect they are associated with opposite sign in SST-SQG and SSH-geostrophic circulation (see Figure 6).

Additional information is however needed to extrapolate vertically the distribution of the "interior" vortex signature. We aim at finding some methods to do so using combination of the previous information with results from WP1, where the typical vertical structure and the typology of surface and subsurface-intensified mesoscale eddies will be calculated in 3 contrasted oceanic regions. Given the nature of an eddy by WP2 (surface or subsurface and some information on the surface signature of the interior part of the eddy), we hope to be able to associate it to one class of vortex existing in an area, and use the mean profile associated with this class to describe it.

To evaluate the surface circulation from SST using the SQG theory a specific numerical model has to be developed. This consists in inverting the operator relating potential vorticity to density or the pressure field (which also represents the streamfunction in SQG theory). This will be done using the matlab toolboxes.

Realistic numerical results will also be used. They are based on existing and validated simulations performed at LEGOS in the areas of interest.

Finally, the process studies (interaction of coherent vortices with surface turbulence and influence of atmospheric fluxes on a vortex structure) will be performed using a primitive equation model in academic configurations.

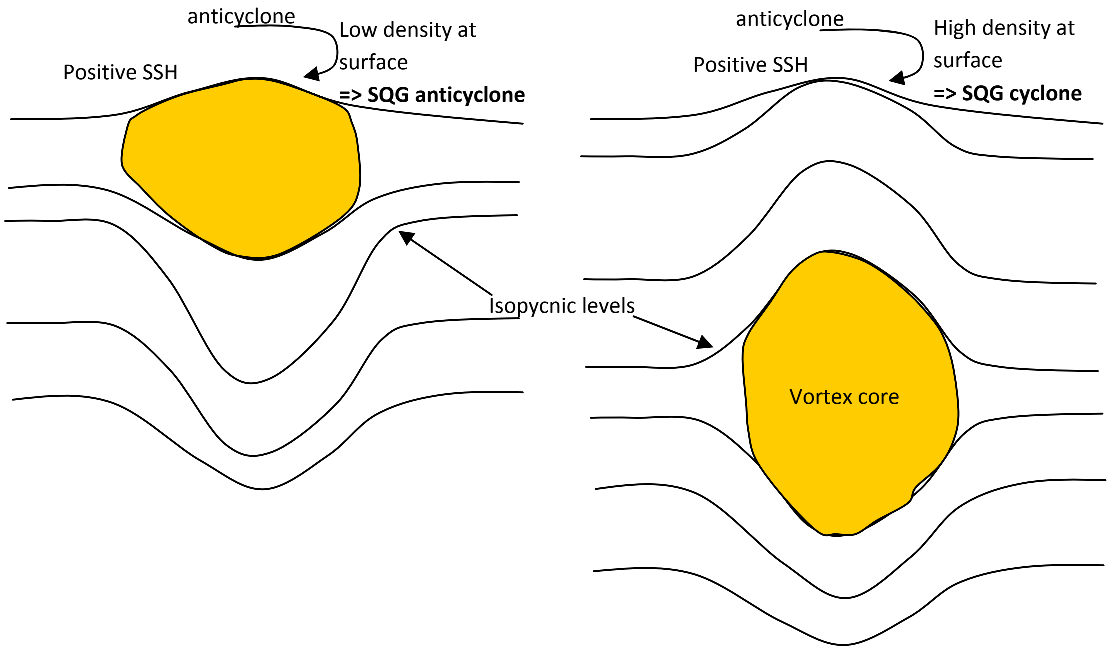


Figure 6: Schematic representation of surface and subsurface anticyclonic structures. In each case the vortex has an anticyclonic circulation at the surface and is associated with a positive SSH anomaly. However surface anticyclones are expected to be associated with an anticyclonic SQG signature, coherent with the altimetric signal, whereas the SQG signature is of opposite sign when the vortex is subsurface intensified.

III.2. Approach for WP3

Specific Objectives:

- Simulate submesoscale processes from large-scale tracer field using Lagrangian advection methods.
- Improve the resolution of fronts in SSS fields
- Improve the resolution of the gridded altimetric geostrophic velocities used for the Lagrangian advection.
- Improvement the frontal structures in the upper ocean fields

Data to be used:

- Weekly SALTO/DUACS AVISO maps at 1/4° resolution (2000 →)
- Argo float profiles (2000→)
- FSLE maps distributed by CTOH (2000→)
- Underway SSS data
- Regional higher-resolution altimetry products
- Argo floats
- SMOS and/or Aquarius SSS data

Methods:

Lagrangian advection technique

The velocity fields used for the Lagrangian advection will be derived from altimetric data, over the period from 2002 onwards, when at least 3 altimeter missions are available. The weekly global 1/4º gridded fields of surface geostrophic velocities calculated from sea surface height (SSH) fields will be used, as distributed by Aviso. The regional surface geostrophic velocity products are available from AVISO (for the Mediterranean Sea, around Madagascar and Kerguelen) and from the S.O. CTOH for the Bay of Biscay.

For the lagrangian advection, these weekly surface altimetric currents will be interpolated onto a finer space-time grid. We will then perform a Lagrangian advection, and each particle will be advected with its velocity and position computed every 3 hours (see illustration in Figure 4).

Tracer fields at the start time of an advection are interpolated onto the 0.04° particle grid. The Lagrangian trajectories of the particles are then computed and each particle trajectory then carries the initial tracer values along its pathway to its final position (see Figure 3). The advected tracer field is hence meant to simulate the tracer field on the final day of advection, as demonstrated by *d'Ovidio et al* [2009] and *Despres et al* [2011]. This advection is "passive", in that no tracer modifications are introduced during the advection period – such as those resulting from air-sea exchanges, or horizontal and vertical mixing. The method simply applies realistic lateral stirring of the initial tracer field. Tests may be carried out to include the effects of lateral diffusion or air-sea fluxes during the 2-3 week advection.

Tracer data for the Initial Fields

Different types of tracer fields will be used as the initial conditions for the advection. The large scale SSS and SST tracer fields are from an objective analysis of Argo float data (and GOSUD data from 2009 on) and temperature and salinity data from various in-situ measurements around the world [*Gaillard et al.*, 2009]. Products are mapped onto 3-D grids with ¼ degree horizontal spacing and between 59 and 152 vertical levels depending on the period. These initial tracer fields are available from the Coriolis website (http://www.coriolis.eu.org), where they are referred to as Global Ocean - Real Time In-situ Observations Objective Analysis.

References.

Abraham, E. R., and M. M. Bowen (2002), Chaotic stirring by a mesoscale surface-ocean flow, *Chaos*, 12, 373–381.

Bakun, A. (2006). Fronts and eddies as key structures in the habitat of marine fish larvae: opportunity, adaptive response and competitive advantage. *Scientia Marina 70* (2), 105–122.

Boyer, T.B.,, J.I. Antonov, H.E. Garcia, D.R. Johnson, R.A. Locarnini, A.V. Mishonov, M.T. Pitcher, O.K. Baranova, I.V. Smolyar, (2006). World Ocean Database 2005. S. Levitus, Ed., NOAA Atlas NESDIS 60, U.S. Government Printing Office, Washington, D.C., 190 pp.,

Chaigneau, A., M. Le Texier, G. Eldin, C. Grados and O. Pizarro (2011), Vertical structure of mesoscale eddies in the eastern South Pacific ocean: a composite analysis from altimetry and Argo profiling floats, *J. Geophys. Res.*, 116, C11025, doi:10.1029/2011JC007134.

Chaigneau, A., G. Eldin and B. Dewitte, (2009). Eddy activity in the four major upwelling systems from satellite altimetry (1992-2007), *Progress in Oceanography*, 83, 117-123.

Chelton, D. B., M. G. Schlax, R. M. Samelson, and R. A. de Szoeke (2007), Global observations of large oceanic eddies, *Geophys. Res. Lett.*, 34, L15606, doi:10.1029/2007GL030812.

Chelton, D. B., M. G. Schlax, and R. M. Samelson (2011), Global observations of nonlinear mesoscale eddies, *Prog. Oceanogr.*, 91, 167–216, doi:10.1016/j.pocean.2011.01.002.

Colas, F., J. C. McWilliams, X. Capet, and J. Kurian (2011), Heat balance and eddies in the Peru-Chile current system, *Clim. Dyn.*, doi:10.1007/s00382-011-1170-6

Dencausse, G. and R. Morrow (2012), Using lateral stirring from altimetric currents to induce finer structure in surface tracer fields, *J. Geophys. Res* (submitted).

Despres, A., G. Reverdin, F. D´Ovidio, (2011). Mechanisms and spatial variability of meso scale frontogenesis in the northwestern subpolar gyre. *Ocean Modelling* , 97–113

Dibarboure, G., Pujol, M.-I., Briol, F., Le Traon, P.-Y., Larnicol, G., Picot, N., Mertz, F., Ablain, M. (2011). Jason-2 in DUACS: updated system description, first tandem results and impact on processing and products. *Marine Geod*. 34, 214–241.

Doglioli, A. M., B. Blanke, S. Speich, and G. Lapeyre (2007), Tracking coherent structures in a regional ocean model with wavelet analysis: Application to Cape Basin eddies, J. Geophys. Res., 112, C05043, doi:10.1029/2006JC003952.

d'Ovidio, F., V. Fernandez, E. Hernandez-Garcıa, and C. Lopez (2004), Mixing structures in the Mediterranean Sea from Finite-Size Lyapunov Exponents, *Geophys. Res. Lett.*,p. 10.1029/2004GL020328.

d'Ovidio, F., J. Isern-Fontanet, C. López, E. García-Ladona, E. Hernández-García (2009). Comparison between Eulerian diagnostics and the finite-size Lyapunov exponent computed from altimetry in the Algerian Basin*", Deep Sea Res*. I, 56, 15-31.

Dussurget, R., Birol, F., Morrow, R., Demey, P. (2011). Fine resolution altimetry data for a regional application in the Bay of Biscay. *Marine Geod*. 34, 447–476.

Flierl, G. R. (1981), Particle motions in large-amplitude wave fields, Geophys. *Astrophys. Fluid Dyn*., 18, 39–74, doi:10.1080/03091928108208773.

Gaillard, F., E. Autret, V.Thierry, P. Galaup, C. Coatanoan, and T. Loubrieu , (2009). Quality control of large Argo data sets. JOAT, Vol. 26, No. 2. 337–351

Gordon, A. L., and W. F. Haxby (1990), Agulhas eddies invade the South Atlantic: Evidence from Geosat altimeter and shipboard conductivity temperature-depth survey, *J. Geophys. Res*., 95, 3117–3125, doi:10.1029/JC095iC03p03117.

Guinehut, S., P. Y. Le Traon, et al. (2004). "Combining Argo and remote-sensing data to estimate the ocean three-dimensional temperature fields - a first approach based on simulated observations." *Journal of Marine Systems* 46(1-4): 85-98.

Holland, W.R, P.E. Harrison and A.J. Semtner, (1982). Eddy resolving numerical models of large-scale ocean circulation*, in "Eddies in Marine Science" A.R. Robinson (ed), Springer-Verlag*, NY, pp 545-562.

Isern-Fontanet, I., B. Chapron, G. Lapeyre, and P. Klein, (2006). Potential use of microwave sea surface temperatures for the estimation of ocean currents. *Geophys. Res. Let*., L24608, doi:10.1029/2006GL027801.

Isern-Fontanet, J., G. Lapeyre, P. Klein, B. Chapron, et M. W. Hecht, (2008). Three-dimensional reconstruction of oceanic mesoscale currents from surface information. *J. Geophys. Res*., 113, C09005, doi :10.1029/2007JC004692.s.

Kurian, J., F. Colas, X. Capet, J. C. McWilliams, and D. B. Chelton (2011), Eddy properties in the California Current System*, J. Geophys. Res.*, 116, C08027, doi:10.1029/2010JC006895.

Klein and Lapeyre, (2009). The oceanic vertical pump induces by mesoscale and submesoscale turbulence.*Annual Review of Marine Science.*, 1, 351-375.

Le Traon, P.-Y. and R. A. Morrow, (2001). Ocean currents and mesoscale eddies. Satellite Altimetry and Earth Sciences. *A Handbook of Techniques and Applications, Academic Press* ed. L.-L. Fu and A. Cazenave, Eds., Academic Press, 171-215.

Lozier, M.S., (1997). Evidence of large-scale eddy-driven gyres in the North Atlantic, *Science,* 277, 361-364.

Morrow, R.A., R. Coleman, J.A Church, and D.B. Chelton, (1994). Surface eddy momentum flux and velocity variances in the Southern Ocean from Geosat altimetry. *J. Phys. Oceanogr*., 24, 2050-2071.

Nieto, K., H. Demarcq and S, McClatchie, (2012). Mesoscale frontal structures in the Canary Upwelling System: new front and filament detection algorithms applied to spatial and temporal patterns, accepted in Remote sensing of environment

Paci, A., G. Caniaux, M. Gavart, H. Giordani, M. Lévy, L. Prieur, and G. Reverdin (2005), A high-resolution simulation of the ocean during the POMME experiment: Simulation results and comparison with observations, *J. Geophys. Res*., 110, doi:10.1029/2004JC002712.

Rudeva, Irina, Sergey K. Gulev, (2011). Composite Analysis of North Atlantic Extratropical Cyclones in NCEP–NCAR Reanalysis Data. *Mon. Wea. Rev*., 139, 1419–1446.

Souza, J. M. A. C., C. de Boyer Montégut, C. Cabanes, and P. Klein (2011), Estimation of the Agulhas ring impacts on meridional heat fluxes and transport using ARGO floats and satellite data, *Geophys. Res. Lett.*, 38, L21602, doi:10.1029/2011GL049359.

Stammer, D. and C. Wunsch, (1999). Temporal changes in eddy energy of the oceans, *Deep Sea Res*., 46, 77-108.

IV. EXPERIMENTAL AND WORK PLAN

As mentioned in the previous section, the work to be undertaken involves an observational component (WP1 and WP3) and a conceptual/acdemic modelling component (WP2) that will be developed over the 4 year period 2013-2016.

The altimetric analysis (WP1-2-3) will be based on (i) gridded multi-satellite altimetric products from AVISO and (ii) newly developed regional products with higher-resolution currently available at LEGOS [*Dussurget et al.*, 2012].

Argo float profiles (WP1) are available from Coriolis data centre (www.coriolis.eu.org).

The Finite-Size Lypanov Exponents (FSLEs), calculated from the altimetric surface geostrophic currents, are made available by the CTOH at LEGOS (http://ctoh.legos.obs-mip.fr/products/submesoscale-filaments).

Fine-resolution (daily/weekly and 4×4km^2) SST data from MODIS sensor will be used in particular to extract frontal structures (WP1) and for surface conditions using SQG theory (WP2). Frontal extraction will be made with the collaboration of H. Demarcq (EME, Sète, France).
Satellite SSS from SMOS and/or Aquarius will also be used.
It is important to note that we expect to obtain funding for 2 PhD students: one to work on the eddy vertical structure (under the direction of Alexis Chaigneau), and the other on the reconstruction of subsurface circulation from altimetry and SST maps (under the direction of Yves Morel).

Tentative calendar for activities

2013-2014

During the first 2 years, we will mainly focus on the NW Mediterranean Sea to better describe the general meso and submesoscale characteristics in the region targeted by the AirSWOT program.

WP1.

- Apply the eddy detection and tracking algorithms in the Mediterranean Sea.
- Provide the general eddy characteristics (typical sizes, amplitudes, places of birth, modes of propagation, etc.)
- Extract and classify the Argo floats surfacing whether in CEs, AEs, or outside eddies.
- Reconstruct the mean 3D structure of mesoscale eddies in the NW Mediterranean
- Identify the fronts on SST maps and study their frequency of occurrence in the NW Mediterranean.
- Determine the mean occurrence frequency of SST fronts within and around eddies.
- Extract and perform the mean composite analysis of the FSLEs inside mesoscale eddies in the Mediterranean Sea.
- Analyze the FSLE and SST front distributions inside eddies depending on their size, amplitude, intensity.
- Investigate the evolution of the submesoscale structuring during the eddy life-cycle.

WP2.

- Develop a SQG inversion tool (first for 2D vortices, then for general 3D fields);
- Study the limits of the SQG approach and its dependence on the vertical structure of an eddy;
- Evaluate the information given by the combination of SSH and SST fields, in particular build an operator able to discriminate surface and subsurface eddies or even to give the position of the eddy core;
- Test the indicator on realistic numerical model outputs;
- Test the indicator on real satellite observations for chosen eddies observed at sea.

WP3.

- Apply the Lagrangian advection technique to improve the frontal structure of SSS fields using global data. Comparisons will be made with in-situ data. Underway surface SST and SSS data from the ORE-SSS at LEGOS will be used to validate these tests.
- End of 2013 : Apply the lagrangian technique in the NW Mediterranean, using a regional altimetric data product, to help prepare for the AirSWOT airborne campaign.
- Apply the Lagrangian advection technique to improve the frontal structure of SMOS or Aquarius surface salinity fields. Again, underway surface SST and SSS data from the ORE-SSS at LEGOS will be used to validate these tests.
- In late 2014, the AirSWOT observations should be processed, and will provide an unprecedented data set for intercomparisons with the predicted advected fronts from standard altimetry maps.

2015-2016

During the last two years, we aim to extend the previously developed methodology to the other targeted regions, mainly the NorthEast Atlantic and Indian Ocean.

WP1.

- Provide the mean eddy characteristics from satellite altimetry.
- Reconstruct the mean 3D structure of mesoscale eddies in the North-east Atlantic and Indian ocean
- Analyze the FSLE and SST front distributions inside eddies depending on their size, amplitude, intensity.
- Investigate the evolution of the submesoscale structuring during the eddy life-cycles.

WP2.

- Pursue the test of the indicator on realistic numerical or satellite results. Study the combination with results from WP1;
- Study the interaction of a coherent vortex with geostrophic surface turbulence and evaluate its SSH and SST signature;
- Study the effect of atmospheric fluxes on the evolution of a vortex dynamics and its surface signature. Evaluate the limits of the indicator.

WP3.

- Investigate the Lagrangian advection technique using higher-resolution regional altimetry products available for the Bay of Biscay (CTOH product), and around the Kerguelen Plateau (AVISO regional products). Compare the global and regionally mapped velocity fields, and their impact on the Lagrangian advection of the tracer fields, again in comparison to available high-resolution in-situ data sections.
- Investigate the Lagrangian advection technique on subsurface tracer fields in the upper 500 m of the ocean. Subsurface Lagrangian advection will also be compared to the static statistical projections based on surface altimetry data and vertical statistical modes (eg ARMOR3D).

V. ANTICIPATED RESULTS

This proposal should improve our understanding of the mesoscale and submesoscale dynamics in various key regions of the World Ocean. Their interactions will be studied as well as the feasibility of reconstruction of subsurface dynamics from satellite information only. From Lagrangian advection techniques this project should also improve the meso and submesoscale resolutions of currently available large-scale SST and SSS products.

Thus in this proposal we expect to better understand the meso and submeso scale dynamics using a variety of satellite data and in-situ vertical profiles. In the frame of this proposal, we expect to obtain the following results:

- Determine the typology of the eddy vertical structures by combining altimeter products and Argo float profiles. Since the feasibility of eddy reconstruction has been demonstrated and algorithms already developed in the frame of previous studies, a detailed atlas of the eddy characteristics will be produced for the targeted regions.
- Assess the structuring of submesoscale structures and associated mixing by the mesoscale eddies. The methodology has been partially developed and applied for the eastern South Pacific and we expect to provide maps of frontal occurrence and its repartition inside cyclonic/anticyclonic eddies.
- Be able to reconstruct the observed subsurface structures using satellite information only. We expect to be able to discriminate surface or subsurface intensified structures from SSH and SST data.
- Improve the resolution of the gridded altimetric geostrophic velocities used for the Lagrangian advection and improve the resolution of sea-surface salinity fronts from large-scale tracer field using Lagrangian advection methods.

VI. SIGNIFICANCE OF THE RESULTS

This proposal continues our on-going investigations of meso and submesoscale processes, and their interactions [*Chaigneau et al.*, 2008; 2009; 2011; *Morrow et al.*, 2008; 2010; 2011; Morel *et al.*, 2009; *Dussurget et al.*, 2011], but will be extended in distinct and dynamically important areas. In particular, we aim to quantify for the first time:

- The typical eddy vertical structures observed in the North-East Atlantic, the Mediterranean Sea and Indian Ocean.
- The role of the mesoscale eddies in structuring the near-surface submesoscale features (transport barriers and SST fronts).
- The possible reconstruction of observed subsurface structures from satellite information only.
- Improve the resolution of surface products (in particular SSS) using satellite altimetry products and Lagrangian advection schemes.

Investigation to better understand the meso and submesoscale dynamics (observed characteristics and interactions, potential reconstruction of subsurface intensified structures from altimetry data and improvement of rather large-scale SST and SSS products) is certainly of direct benefit to increase the value of NASA, CNES, NOAA and Eumetsat contributions to long and short-term climate variability studies. We propose the use of multi-missions satellite products (AVISO and refined regional products), SST and SSS products from MODIS and SMOS or Aquarius sensors, as well as in situ data from Argo float network and underway data from ORE-SSS in LEGOS. The combination of this variety of products and data for improved understanding of meso and submesoscale dynamics is the base of our proposal. Our planned activities, based in particular on the traditional 'nadir' altimetry data, shall be relevant and will provide the groundwork for testing and validating future altimetric missions, such as wide swath altimetry of the SWOT program. The choice of the Mediterranean Sea as one of the sites where our investigation will be applied should also benefit to the Air-SWOT experiment.

VII. MANAGEMENT AND COST PLANS

VII.1. Management plan

The present program is in direct continuation of the on-going researches of the proposing team. The PI Alexis Chaigneau will be responsible for the overall management and the coordination of this investigation. He will also oversee the WP1. Yves Morel will be in charge of the WP2, whereas Rosemary Morrow will be in charge of the WP3.
Note that in the frame of this proposal, 2 PhD fellowships have been proposed (at the "Direction Generale des Armées" and at the "École Doctorale SDU2E") for WP1 and WP2. Several Master students will also be involved in the 3 WPs of this proposal.

The proposed activities imply a few identified collaborations with:

- Hervé Demarcq (EME Research Unit , IRD, IFREMER& Univ. Montpellier II) for the frontal identification from SST data.
- Francesco d´Ovidio (LOCEAN/IPSL, Paris) for the validation of the Lagrangian advection and FSLEs computation.
- Dudley Chelton (COAS, Oregon State University) as an expert in mesoscale dynamics
- Thierry Delcroix (LEGOS, Toulouse) for the validation of surface salinity data from SMOS and the ORE-SSS.
- Florence Birol (LEGOS, Toulouse) for the altimetric analysis in the NW Mediterranean Sea
- Patrice Klein and Xavier Carton (LPO, Brest) for SQG dynamics analysis and the study of interaction of coherent vortices with surface geostrophic turbulence;
- Ronan Fablet (LABSTICC, Brest) as an expert in signal processing and mesoscale/submesoscale interaction.

VII.2. Cost plan

The salary costs for the identified permanent personnel are covered by the French institutions (CNRD, IRD, etc.). The LEGOS will provide most of the required data but only part of the computer facilities and support. However, a new computer/work station for each of the WPs will be required (data storage, processing and student training) as well as for H. Demarcq (EME Research Unit) for the frontal identification required in the WP1. Most of the data and products needed are already managed at LEGOS.
If the 2 PhD submitted fellowships are not funded this year, a PhD award will be required to CNES next year.
The travel expenses should cover participation to SWT meetings, a few identified conferences and visits to colleagues working in the identified fields of investigation (cf the management plan). Funding is also necessary for publications.

Materials

2 PCs in 2013 at LEGOS	6 kE in 2013
2 PCs in 2014 at LEGOS and EME	6 kE in 2014
Small computing and material expenses	2 kE/year
Publications (2-3 / year)	5 kE/year

Training

2*5 months per year for a master student.	2*2.5=5.0 kE/year

Travel

1 project reunion in Toulouse per year	3 kE/year
2 reunions in Sète per year for collaboration with Hervé Demarcq	2 kE/year
Participation in OSTST meetings :	
Europe : 2kE x 2 people (2014, 2016)	4 kE in 2014, 2016
USA : 4 kE x 2 people (2013, 2015)	8 kE in 2013, 2015
Participation at EGS or Ocean Sciences meetings (2 people)	5 kE per year

Management fees: 2.5% of the Total

Detailed Cost Schedule :

Year	2013	2014	2015	2016	Total
Materials	13 kE	13 kE	7 kE	7 kE	**40 kE**
Training	5 kE	5 kE	5 kE	5 kE	**20 kE**
Travel	18 kE	14 kE	18 kE	14 kE	**64 kE**
Management Fees	0.9 kE	0.8 kE	0.75 kE	0.65 kE	**3.1 kE**
Total	**36.9 kE**	**32.8 kE**	**30.75 kE**	**26.65 kE**	**127.1 kE**

VIII. BIBLIOGRAPHIC INFORMATION

VIII.1. Alexis Chaigneau

Dr Alexis Chaigneau graduated from the University Toulouse III received his PhD in Physical Oceanography in 2003. He spent 2 years in Chile (University of Concepción) as a postdoctoral research associate. Since 2005, he is research scientist for the "Institut de Recherche pour le Développement" (IRD). He has experience in mesoscale dynamics from analyses of remote sensing and in-situ data. He was Principal Investigator of the FLOPS program (deployment of 20 Argo floats in the eastern South-Pacific) and was also in charge of several glider experiments along the Peruvian coast. He was and is currently in charge of several Work packages of international projects (ANR-PCCC, ANR-PEPS, ANR-TOPINEME). He was research scientist at LOCEAN (Paris from 2005 to 2010) and is presently research scientist at LEGOS (since 2011). He also worked for 5 years in Peru (2005-2011) at the IMARPE (Peruvian Institute of the Sea) and was invited professor of the Universidad Peruana Cayetano Heredia. He is elected member of the scientific commission of the IRD.

SELECTED PUBLICATIONS (18 peer reviewed publications)

Bertrand A, **Chaigneau A**, Peraltilla S, Ledesma J, Graco M, et al. (2011) Oxygen: A Fundamental Property Regulating Pelagic Ecosystem Structure in the coastal Southeastern Tropical Pacific. PLoS ONE 6(12): e29558. doi:10.1371/journal.pone.0029558.

Chaigneau, A., M. Le Texier, G. Eldin, C. Grados and O. Pizarro (2011), Vertical structure of mesoscale eddies in the eastern South Pacific ocean: a composite analysis from altimetry and Argo profiling floats, *J. Geophys. Res.*, 116, C11025, doi:10.1029/2011JC007134.

Echevin, V., F. Colas, **A. Chaigneau**, and P. Penven (2011), Sensitivity of the Northern Humboldt Current System nearshore modeled circulation to initial and boundary conditions, J. Geophys. Res., 116, C07002, doi:10.1029/2010JC006684.

Cotté,C., F. d'Ovidio, **A. Chaigneau**, M. Lévy, I. Taupier-Letage, C. Guinet, 2011, Scale-dependent interactions of resident Mediterranean whales with marine dynamics. Limnology and Oceanography, 56 (1), 219-232.

Joo R., Bertrand S., **Chaigneau A.** and M. Niquen, 2011. Optimization of an artificial neural network for identifying fishing set positions from VMS data: An example from the Peruvian anchovy purse seine fishery. Ecol. Model. (222), 1048-1059.

Bertrand A, Ballón M, **Chaigneau A**, 2010. Acoustic Observation of Living Organisms Reveals the Upper Limit of the Oxygen Minimum Zone. PLoS ONE 5(4): e10330. doi:10.1371/journal.pone.0010330

R. Wood, C. S. Bretherton, C. R. Mechoso, R. A. Weller, B. Huebert, F. Straneo, B. A. Albrecht, H. Coe, G. Allen, G. Vaughan, P. Daum, C. Fairall, D. Chand, L. Gallardo Klenner, R. Garreaud, C. Grados Quispe, D. S. Covert, T. S. Bates, R. Krejci, L. M. Russell, S. de Szoeke, A. Brewer, S. E. Yuter, S. R. Springston, **A. Chaigneau**, T. Toniazzo, P. Minnis, R. Palikonda, S. J. Abel, W. O. J. Brown, S. Williams, J. Fochesatto, and J. Brioude, 2010. The VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx): goals, platforms, and field operations, Atmos. Chem. Phys. Discuss., 10, 1–53, doi:10.5194/acpd-10-1-2010

Chaigneau, A., G. Eldin and B. Dewitte, 2009. Eddy activity in the four major upwelling systems from satellite altimetry (1992-2007), Progress in Oceanography, *83,* 117-123.

Chaigneau, A., O. Pizarro and W. Rojas, 2008. Global climatology of near-inertial current characteristics from Lagrangian observations, Geophys. Res. Lett., 35, L13603, doi:10.1029/2008GL034060.

Chaigneau, A., A. Gizolme and C.Grados. 2008. Mesoscale eddies off Peru in altimeter records: identification algorithms and eddy spatio-temporal patterns. Progress in Oceanography,79, 106-119.

Chaigneau, A., R. Abarca del Rio and F. Colas. 2006. Lagrangian study of Panama Bight and surrounding regions, Journal of Geophysical Research, doi:10.1029/2006JC0035.

Chaigneau, A. and O. Pizarro. 2005. Surface circulation and fronts of the South Pacific Ocean, east of 120ºW, Geophysical Research Letters, 32, L08605, doi: 10.1029/2004GL022070.

Chaigneau, A. and O. Pizarro. 2005. Mean surface circulation and mesoscale turbulent flow characteristics in the eastern South Pacific, from satellite tracked drifters, Journal of Geophysical Research, 110, doi: 10.1029/2004JC002628.

Chaigneau, A. and O. Pizarro. 2005 Eddy characteristics in the eastern South Pacific, Journal of Geophysical Research, 110 (C6), doi: 10.1029/2004JC002815.

Chaigneau, A., R.A. Morrow and S. Rintoul, 2004. Seasonal and interannual evolution of the mixed layer in the Antarctic Zone south of Tasmania, Deep-Sea Research I, 51, 2047–2072.

Morrow, R. A., J.-R. Donguy, **A. Chaigneau** and S. Rintoul, 2004. Cold-core an.omalies at the subantarctic front,south of Tasmania. Deep-Sea Research I, 51 1417–1440.

Morrow, R., A. Brut and **A. Chaigneau,** 2003. Seasonal and interannual variations of the upper ocean energetics between Tasmania and Antarctica, Deep-Sea Research I, 50, 339–356.

Chaigneau, A., and R. Morrow, Surface temperature and salinity variations between Tasmania and Antarctica, 1993–1999, J. Geophys. Res., 107(0), doi:10.1029/2001JC000808, 2002.

VIII.2. Yves Morel

Position : research director (DR2) at CNRS/INSU

ACADEMIC DEGREES:

graduate of « Ecole Polytechnique »

graduate of « Ecole Nationale Supérieure des Techniques Avancées »

graduate of Paris VI University (master of science in oceanography)

Ph. D. from « Joseph Fourier University » (Thesis title : «The propagation of geophysical vortices. Application to Meddies »)

Habilitation to supervise researches

PRINCIPAL RESPONSABILIES - SCIENTIFIC and ADMINISTRATIVE :

Director of LEGOS.

Head of scientific projects. I have conducted important scientific projects at national level. I am currently the principal manager of the national project EPIGRAM. The goal of this project is to study the physical processes of the margin and the shelf in the English Channel and Bay of Biscay. It includes wave circulation coupling, ocean/atmosphere coupling associated with the development of the mixed layer. It is based on the development of numerical models and campaigns at sea.

I have conducted several campaigns at sea as a scientific director (more than 200 days at sea). These campaigns aimed at collecting data for specific process studies or to validate numerical models.

Member of scientific committees:

Scientific Instrument European Program « Hydralab / CORIOLIS Platform »

IFREMER scientific board

SELECTED PUBLICATIONS (38 peer reviewed publications)

Y. Morel, 1995. The influence of an upper thermocline current on intrathermocline eddies. J. Phys. Ocean., Vol. 267, pp. 23-51.

Y. Morel and J.C. McWilliams, 1997. Evolution of isolated interior vortices in the ocean. J. Phys. Ocean., Vol. 27, pp.727-748.

G.G. Sutyrin and **Y. Morel** , 1997. Intense vortex motion in a stratified fluid on the beta-plane. An analytical model and its validation. J. Fluid Mech., Vol. 336, pp.203-220.

J. Paillet, B. Le Cann, A. Serpette, **Y. Morel** and X. Carton , 1999. Real-time tracking of a galician Meddy. Geophys. Res. Let., 26, pp. 1877-1880.

C. Mauritzen, **Y. Morel** and J. Paillet , 2000. Mediterranean Water influence on the central waters of the North Atlantic. Deep-Sea Res., 48, p. 347-381.

Y. Morel and J. McWilliams, 2001. The effect of mixing on the stability of oceanic currents. J. Phys. Ocean., 31, p. 2280-2296.

F. Vandermeirsh, **Y. Morel** and G. Sutyrin, 2001. The net advective effect of a vertically sheared current on a coherent vortex. J. Phys. Ocean., 31, p.2210-2225.

X. Carton, L. Chérubin, J. Paillet, **Y. Morel**, A. Serpette and B. Le Cann, 2002. Meddy coupling with a deep cyclone in the Gulf of Cadiz. J. Mar. Syst. 32, pp. 13-42.

Paillet J., B. Le Cann, X. Carton, **Y. Morel** and A. Serpette, 2002. Northern Meddies. Part1 : Dynamics and evolution of a Galician Meddy. J. Phys. Ocean. 32, pp. 55-79.

Herbette S., **Y. Morel** and M. Arhan, 2005. Erosion of a surface vortex by a seamount on the beta-plane. J. Phys. Ocean., 35, pp. 2012-2030.

Chérubin L., **Y. Morel** and E. Chassignet, 2006. Loop Current ring shedding: the formation of cyclones and the effect of topography. J. Phys. Ocean., 36, pp.569-591.

Y. Morel, D. Darr and C. Taillandier, 2006. Possible sources driving the potential vorticity structure and long-wave instability of coastal upwelling and downwelling currents. J. Phys. Ocean., 36, No. 5, pp. 875–896.

Winter N., **Y. Morel** and G. Evensen, 2007. Efficiency of high order numerical schemes for momentum advection. J. Mar. Res., 67, pp. 31–46

Y. Morel, Rémy Baraille and Annick Pichon, 2008. Time splitting and linear stability of the slow part of the barotropic component. Ocean Mod., 23, PP. 73-81. doi: 10.1016/j.ocemod.2008.04.001

V. Mensah, M. Le Menn and **Y. Morel**, 2008. Thermal mass correction for the evaluation of salinity. J. of Atmospheric and Oceanic Technology-O, DOI: 10.1175/2008JTECHO612.1

Y. Morel and L. Thomas, 2009. Ekman drift and vortical structures. Ocean Mod., 27, PP. 185-197. doi:10.1016/j.ocemod.2009.01.002

C. Renaudie, R. Baraille, **Y. Morel**, G. Hello, H. Giordani, 2009. Adaptation of the vertical resolution in the mixed layer for HYCOM. Ocean Mod., 30, 178-189.

V. Rossi, **Y. Morel** and V. Garçon, 2010. Effect of the wind on the dynamics of the shelf : formation of a secondary upwelling along the continental margin. Ocean Mod., 31, 51 – 79

Meunier, V. Rossi, **Y. Morel**, X. Carton, 2010. Influence of bottom topography on an upwelling current : generation of long trapped filaments. Ocean Mod., 35, 277-303

C. Renaudie, R. Baraille, **Y. Morel**, G. Hello, H. Giordani, 2011. Observation and analysis of mixing in a tidal and wind-mixed coastal region. Ocean Mod., 37, 65 - 84.

A. Pichon, **Y. Morel**, R. Baraille, L. Quaresma, 2011. Observations and numerical simulations of internal tide in the Bay of Biscay. J. Mar. Sys., doi:10.1016/j.jmarsys.2011.07.003.

M. Le Hénaff, V. Kourafalou, **Y. Morel**, A. Srinivasan, 2011. Simulating the dynamics and intensification of cyclonic Loop Current Frontal Eddies in the Gulf of Mexico. J. Geophys. Res., 117, C02034, doi:10.1029/2011JC007279

A. Pasquet, T. Szekely, **Y. Morel**, R. Baraille, 2012. Production and dispersion of mixed waters in stratified coastal areas. Accepted in Cont. Shelf Res.

VIII.3. Rosemary Morrow

Nationality: French / Australian

Position : Physicien CNAP

ACADEMIC DEGREES:

Habilitation to supervise researches, May 2007. University Paul Sabatier, Toulouse III.
PhD in Physical Oceanography, 1993. University of Sydney, Australie.
Master of Science, 1987. Université de Sydney, Australie.
Bachelor of Science (Honours Class 1) in Marine Science, 1984. Université de Sydney, Australie.

PRINCIPAL RESPONSABILIES - SCIENTIFIC and ADMINISTRATIVE :

Head of French National Altimetric Observation Service: Centre de Topographie des Océans since 1997 ; section open ocean since 2004.
Scientifique programme leader : SURVOSTRAL (Southern Ocean) since 1997.
Scientifique programme leader : FLOSTRAL (Southern Indian Ocean) since 2001.
Member : Conseil Scientifique de l'Observatoire Midi-Pyrénées 1998-2001
Member : Comité International : « CLIVAR Southern Ocean Panel » 2002-2005.
Member : Commission National « "Océanographie Physique, Chimique et Biologique - OPCB » 2006-2008
Editor, « Ocean Dynamics », 2000-2009.
Editor, « Ocean Dynamics » Special Edition in memory of Christian Le Provost, 2005-2006.
Principal Investigateur: Topex/Poséïdon Extended Mission (1997-2002)
Principal Investigateur: Jason-1 Mission (2000-2008), Jason-2 mission (2008+)
Project Scientist CNES – Jason-1, Jason-2 and Jason-3, since 2009
Project Scientist CNES – Future Mission SWOT – oceanography component

SELECTEDPUBLICATIONS (44 peer reviewed publications)

Chaigneau A., **Morrow** R. and S. Rintoul, 2004. Seasonal and interannual evolution of the mixed layer in the Antarctic Zone, south of Tasmania. *Deep-Sea Research* I, 51, 2047-2072.

Dussurget, R. F. Birol, **R. Morrow**, P. Demey, 2011. Fine resolution altimetry data for a regional application in the Bay of Biscay. *Mar. Geodesy*, 34, 447-476.

Fang, F. and R. **Morrow**, Evolution and structure of Leeuwin Current eddies in 1995-2000. Deep Sea Res., *Deep Sea Res. II,* 50, 2245-2261, 2003.

Fieux M., R. Molcard and R. **Morrow** . Leeuwin Current and Eddies off Western Australia. *Deep Sea Res*. I, 52, 1617-1635, 2005.

Fu, L.L, D.B. Chelton, P.-Y. Le Traon, and R. **Morrow**, 2010. Eddy Dynamics from Satellite Altimetry, *Oceanography Magazine*, Volume 23, Number 4.

Hasson, A. ; A. Koch-Larrouy ; **R. Morrow** ; M. Juza ; T. Penduff, 2011. The Origin and Fate of Mode Water in the Southern Pacific Ocean, *Ocean Dynamics*, 62, 335-354. doi:10.1007/s10236-011-0507-3

Koch-Larrouy, A. R. **Morrow**, T. Penduff, M Juza (2009). Origin and mechanism of Sub Antarctic Mode Water formation and transformation in the Southern Indian Ocean, *Ocean Dynamics*, DOI 10.1007/s10236-010-0276-4.

Lambin, J., **R. Morrow**, L-L. Fu, J. K. Willis, H. Bonekamp, J. Lillibridge, J. Perbos, G.Zaouche, P. Vaze, W. Bannoura , F. Parisot , E. Thouvenot , S. Coutin-Faye, E. Lindstrom, M. Mignogno, 2010. The OSTM/Jason-2 Mission, *Mar. Geodesy*, 33, 4-25.

Morrow R. A, F. Birol, D. Griffin and J. Sudre, 2004. Divergent pathways of cyclonic and anti-cyclonic ocean eddies, *Geophys. Res. Lett*. 31, L24311, doi:10.1029/2004GL020974.

Morrow R., Donguy J.R., Chaigneau A. and S. Rintoul, 2004. Cold core anomalies at the Subantarctic Front, south of Tasmania. *Deep-Sea Research* I, 51, 1417-1440.

Morrow, R.A., F. Fang, M. Fieux and R. Molcard. "Anatomy of three warm-core Leeuwin Current eddies". *Deep Sea Res*.II, 50, 2229-2243, 2003.

Morrow, R., Valladeau, G., and Sallee, J. (2008). Observed subsurface signature of Southern Ocean decadal sea level rise. *Prog. Oceanogr.* Vol 77/4 pp 351-366

Morrow, R., M. L. Ward, A. M. Hogg, and S. Pasquet (2010), Eddy response to Southern Ocean climate modes, *J. Geophys. Res*., 115, C10030, doi:10.1029/2009JC005894.

Morrow, R.A. and P.-Y. Le Traon, 2011. Recent advances in observing mesoscale ocean dynamics with satellite altimetry. J. Adv. Space Res. (2011), doi:10.1016/j.asr.2011.09.033.

Sallee, J.B. N. Wienders, K. Speer and **R.A. Morrow**, 2006a. Formation of subantarctic mode water in the southeastern Indian Ocean, *Ocean Dynamics,* 56, 5-6, pp. 525-542.

Sallée, J.B. ; **Morrow**, R. and Speer, K, 2008. Southern Ocean fronts and their variability to climate modes, *J. Climate*, Vol. 21, 3020–3039.

Sallée, J.B; **Morrow**, R. ; Speer, K., 2008. Eddy heat diffusion and Subantarctic Mode Water formation, *Geophys. Res. Lett*, 35, L05607, doi:10.1029/2007GL032827

Sallée, J.B. ; **Morrow**, R. ; Speer, K. and Lumpkin, R. 2008.An estimate of Lagragian eddy statistics and diffusion in the mixed layer of the Southern Ocean, submitted to *J. Mar. Res*.,

Sudre, J. and **R. Morrow,** 2008. Global surface currents : a high-resolution product for investigating ocean dynamics. *Ocean Dynamics,* DOI 10.1007/s10236-008-0134-9.

Talley, L., R. Fine, R. Lumpkin, N. Maximenko, **R. Morrow**, 2010. Surface circulation and ventilation. In OceanObs09, Special Edition (in press).