White paper on

Mesoscale / sub-mesoscale dynamics in the upper ocean

March 18, 2015

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1 – Low-frequency ocean variability

Several decades of research on low-frequency (sub-inertial[1]) ocean variability have brought scientific understanding to a point where **new, high-resolution global observations of upper ocean motions are required** to make progress in two critical areas: (1) mesoscale[2] variability and the associated lateral exchange processes ("eddy fluxes") and (2) sub-mesoscale variability and the associated upper-ocean vertical exchange processes ("vertical exchange"). Recent research, mostly from high resolution numerical simulations in large domains, suggests that mesoscale and sub-mesoscale variability and the associated exchange processes are not independent, but rather may be coupled in subtle but important ways, including a variety of potential mechanisms for the nonlinear transfer of energy between different scales. This mesoscale and sub-mesoscale variability and the associated eddy fluxes and vertical exchange play essential roles in ocean circulation dynamics and physical-biological coupling. However these roles still need to be better understood. Future improvements in our ability to model and predict accurately the ocean's role in the Earth's climate system and the functioning and evolution of global ocean ecosystems will depend importantly on new advances in understanding these fundamental physical oceanographic processes.

The distinction between mesoscale and sub-mesoscale sub-inertial variability may be made on the basis of dynamical considerations or of **an a priori choice of horizontal scale**. In this white paper, we adopt the latter approach, and define sub-inertial motions with horizontal wavelengths greater than 50 km to be the ocean "mesoscale" and those less than that to be the "sub-mesoscale." For reference, the wavelength resolutions of existing along-track and mapped altimeter observations are, respectively, about 70 km and 200 km x 200 km. The transition to the dynamical sub-mesoscale, where the latter involves unbalanced or extended balanced dynamics including gradient wind and frontogenesis, may occur at different scales than the 50 km wavelength that is taken here as an operational definition of sub-mesoscale.

Great progress has been made in the last two decades in characterizing and analyzing the larger mesoscale ocean field, using conventional nadir altimetry. However, our understanding of mesoscale dynamics remains fundamentally incomplete, and the associated practical problem of understanding and predicting lateral eddy fluxes of heat and material properties remains unsolved. Many numerical simulations indicate that these fluxes are an essential link in the ocean's large-scale circulation and therefore an essential influence on the ocean's role in the Earth's climate system. Developing an understanding of

[1] Sub-inertial motions are defined here as those with intrinsic frequency less than the local Coriolis frequency.
[2] The "ocean scales" in this paper refer to a statistical definition based on the wavelength of the spectral energy of these motions. This differs from the diameter of individual structures, often referred to as "feature scales", which can be shown to be about a factor-of-2 smaller than the wavelength scales (D.Chelton, pers. comm.). For example, a 50 km scale in spectral wavelength is associated with a feature scale of approximately 25 km.

these processes that can serve as the basis for reliably predicting their response to a changing ocean state and their evolution in the Earth's changing climate is one of the important current challenges in physical oceanographic research.

New insights into the dynamics controlling vertical exchange in the upper ocean have come **from high-resolution numerical simulations** in large domains conducted over the past decade (see section 3). These simulations suggest that vertical exchange in the upper ocean occurs principally at wavelength scales smaller than 100 km, and that motions at these scales may have a large impact on physical-biological coupling and on the lateral dispersion of natural and anthropogenic tracers. In addition, they have shown that sub-mesoscale motions may have a strong impact on mesoscale variability. More precisely, these recent simulations suggest **the existence of a much richer variety of dynamical regimes,** and associated spectral energy transfer mechanisms and pathways, **than has been apparent before**, through which sub-mesoscale motions may be coupled to mesoscale motions. The sub-mesoscale regime is of additional interest for the larger-scale dynamics, because it can support, both, an upscale and a downscale transfer of energy, which may be an essential component of the overall ocean-circulation energy balance. These results imply that a complete understanding of mesoscale variability and the associated eddy fluxes also will not be possible without a simultaneous understanding of sub-mesoscale dynamics. **Although conventional nadir altimeters** have revealed unexpected mesoscale turbulent properties of the oceans (Morrow & Le Traon, 2012, ASR), they only capture the larger mesoscale dynamics. As such, they cannot quantify the smaller meso and sub-mesoscale fields, let alone be used to address the more subtle problem of identifying the different energy pathways involving sub-mesoscales and their coupling to the mesoscales.

These major advances point to the need for repeated global observations at finer space and time scales than are presently resolved by conventional altimeters. The wide-swath SWOT altimeter will map the sea-surface height (SSH) field with a spatial resolution more than ten times higher than can be achieved from conventional altimeters, and with an order of magnitude lower noise due to their interferometric SAR technique, that will allow unprecedented observations in the 15-100 km range of wavelength scales (see Fu & Ferrari, 2008, EOS and the SWOT Science Requirements document (April 2014: https://swot.jpl.nasa.gov/science/). **This emphasizes the strong potential of the SWOT mission to advance understanding of mesoscale and sub-mesoscale dynamics and to identify the rich variety of energy pathways revealed by modelling studies over the last ten years. Such observations may confirm or complement results from numerical studies, but may also lead to surprising and startling discoveries that were not predicted.**

This white paper mainly addresses some of the potential general science questions that can be addressed from the SSH **signals** that can be observed with SWOT. Even though the measurement errors of SWOT will be smaller than with conventional altimeters, the SWOT Project estimates that the measurement errors will be equivalent to the ocean signal at scales (spectral wavelengths) of 15 km on a global average, and the errors will mask the ocean signal at smaller scales. These **measurement errors vary regionally and seasonally**, as the surface wind-wave conditions change, which should affect the observability of the **dynamical regimes** involving sub-mesoscales (that **also vary regionally and seasonally**). Recent estimates based on altimetric wave conditions and SWOT estimated noise levels indicate that ocean features that are smaller than 15 km may be resolvable in summer (under low wind and wave conditions) but the resolution may be limited to larger scales of 20-30 km in winter when the higher wind-wave conditions add more measurement noise (Dufau et al., 2014). SWOT will make these fine resolution observations within two 50 km wide swaths separated by a 20 km nadir gap. A conventional nadir-looking altimeter will also be onboard SWOT for making SSH measurement along the center of the nadir gap. The SWOT measurement errors are smallest in the center of each swath, and increase towards the nadir and outer extremities of each swath. Finally, the swaths will overlap locally in a complicated pattern. Although there is a 21 day exactly repeating cycle for the nominal mission, there is also a 10-day subcycle, so that, locally, measurements occur at intervals ranging from a few to 10 days, depending on the latitude. During the calibration phase, the mission will also fly in a 1-day repeat orbit with science data available for around 60 days. This will allow a better resolution of the fast temporal evolution of the sub-mesoscale processes, although only in limited regions where the fast-sampling phase ground tracks repeat.

As such, SWOT will allow the observation and characterization of fine-scale SSH structures with improved 2D spatial resolution across the swath, resolving mesoscale and sub-mesoscale spectral wavelengths down to 15 km. Due to the global coverage of the swaths, the temporal resolution is lower, around 10-20 days, which does not allow monitoring of the movement of the smaller, more quickly evolving sub-mesoscale structures as they pass between the swath observations. The expected improvements in the scientific understanding of small mesoscale and sub-mesoscale processes on wavelength scales ranging from 15-100 km are summarized in the following sections.

2 - An improved observation of mesoscale ocean dynamics: eddies, turbulence, and lateral fluxes

The new 2-dimensional information that SWOT will provide at mesoscale wavelength scales smaller than the present capability of about 200 km offered by conventional mapped altimeter data[3] promises exciting and important new advances in our understanding of ocean circulation and its role in the climate system. In turbulent flows of any type, most of the turbulent transport is generally accomplished by the largest eddy structures (Tennekes and Lumley, 1973). Lateral turbulent fluxes of heat and material properties in the ocean are therefore almost certainly dominated by mesoscale eddy structures. In order to understand these fluxes, it is necessary to understand the growth and decay processes of the associated eddy structures that can significantly depend on sub-mesoscale dynamics (see section 3). It is by and during these growth and decay stages that the character and amplitude of the eddy transport are determined.

Advances in characterizing mesoscale ocean variability based on two decades of nadir altimetry have included global along-track wavenumber spectra of sea-surface height (Stammer, 1997; Xu and Fu, 2012; Fu and Ubelmann, 2014), a global analysis of coherent eddy structures with lifetimes from weeks to years (Chelton et al., 2011), and a quasi-universal empirical wavenumber-frequency spectrum model for sea-surface height and related geostrophic variables (Wortham and Wunsch, 2014). A number of recent dynamical analyses based on the nadir altimetry data offer intriguing suggestions regarding the nonlinear processes supporting the observed variability, including evidence for upscale spectral energy transfer (Scott and Wang, 2005, Scott and Arbic, 2007) and effective stochasticity in eddy growth and decay processes (Samelson et al 2014), but the magnitude (and sign) of the inferred spectral energy fluxes strongly depend on the resolution of the sea surface height (SSH) field used for the inference (Arbic et al., 2013) as further discussed in section 3. Basic questions remain regarding even the processes that may be involved in the statistical equilibration of the mesoscale eddy field and its role in turbulent transport: for example, bottom friction (Arbic and Flierl, 2004), air-sea interaction (Gaube et al., 2015; Jin et al, 2009), or others.

[3] Along-track data are available at a higher wavelength resolution of about 70 km, but the one-dimensional description provided by along-track data is insufficient for analysis of mesoscale dynamics.

In that context, the SWOT mission will provide exciting new opportunities to study directly the global mesoscale eddy field and the dynamics controlling the evolution of eddy structures, which is essential for an understanding of mesoscale eddy transports and fluxes. The global two-dimensional sea-surface height fields with 15-km spatial resolution that will be provided by the SWOT swath measurements will resolve the full range of energy-containing spatial scales of the mesoscale eddy field, providing an unprecedented view of mesoscale dynamics and promising fundamental progress on these challenging problems.

The role and importance of vertical velocities are discussed extensively in Section 3, in the sub-mesoscale context, as recent model simulations indicate that vertical motion is an order of magnitude or more stronger at sub-mesoscales than at mesoscales. However, vertical motion is nonetheless still quite strong at mesoscales (meters per day). Mesoscale time scales are likely longer than sub-mesoscale timescales, and consequently the integrated Lagrangian vertical motion associated with some mesoscale vertical velocities may be more important than a direct comparison of instantaneous mesoscale and sub-mesoscale vertical velocities would imply. SWOT measurements will provide important new information on mesoscale vertical velocities, especially those arising from air-sea coupling (e.g., Gaube et al., 2015).

3. Identification of the energy pathways involving sub-mesoscales

At sub-mesoscales**,** mechanisms associated with energy pathways – that concerns the transformation of potential energy (PE) into kinetic energy (KE) and the spectral energy transfers between motions of different horizontal scales – can be viewed in terms of the vertical velocity field (Lapeyre & Klein,2006, JPO; Thomas et al., 2008, OM; Capet et al.,2008, JPO; Klein et al.,2008, JPO; Tulloch & Smith,2009,JAS; Ferrari, 2012, Science; McWilliams et al.,2012,GRL, Mensa et al.(2013, OM), Gula et al. (2014, JPO)). This vertical velocity field, usually associated with instability or frontogenesis, allows the transformation of PE into KE at sub-mesoscales (Samelson, 1993, JGR; Samelson and Chapman, 1995, JGR; Haines & Marshall, 1998,JPO; Boccaletti et al., 2007, JPO). One part of this energy is subsequently transferred to larger scales through an inverse KE cascade (e.g., Charney, 1971); the other part is directly transferred downscale and ultimately lost to dissipation (e.g., Capet et al.,2008,JPO; Klein et al.,2008,JPO; Skyllingstad and Samelson, 2012,JPO). **Inclusion of these sub-mesoscale dynamics** in numerical simulations can alter the **total eddy KE by as much as a factor of two** (Sasaki et al., 2014, NC; Qiu et el., 2014, JPO) and significantly enhance **the lateral dispersion of passive tracers** (Haza et al, 2012,JPO). Many of these model results are consistent with analyses of the limited relevant observations that are presently available [Ferrari and Rudnick (2000,JPO), Le Traon et al. (2008, JPO), Zhai et al. (2008,GRL); Lumpkin & Elipot (2010, JP0), Kim et al. (2011, JGR), Xu & Fu (2011, 2012, JPO), Shcherbina et al. (2013, GRL), Callis & Ferrari (2014, JPO), Poje et al., 2014, PNAS]. In addition, sub-mesoscale variability has been shown to **affect physical-biological interactions and, consequently, ocean biodiversity** (Levy et al., 2012, GRL; Levy et al, 2014, GRL).

High resolution SSH should allow us to assess the component of the **ocean dynamics** that is in geostrophic balance, over a range of scales that includes the mesoscales and a large part of the sub-mesoscales. As mentioned above, ocean dynamics involving sub-mesoscales are characterized by several **energy pathways, *or dynamical regimes,*** in the world oceans. Several regimes have been identified so far (see Lapeyre 2009, JPO and Tulloch et al 2011, JPO). Characteristics of the most important ones are described below.

One is the classical "interior regime" where mesoscale eddies are sustained by baroclinic instability in the ocean interior, occurring at scales close to the first Rossby radius of deformation. This regime is associated with an important conversion of PE into KE at mesoscales. Some idealized simulations have been devoted to this specific regime. Their results (X. Capet, A. Ponte, pers. comm.) indicate that sub-mesocales are weakly energetic, which leads to a k^{-3} velocity spectral slope (Ponte & Klein, 2013, OD). The second regime is the "surface regime" driven by baroclinic instability close to the surface (or Charney instability, 1947,JM). This regime involves a significant vertical velocity field in both the mesoscale and sub-mesoscale ranges and a conversion of PE into KE over this large range of scales. It is characterized by a k^{-2} velocity spectrum slope near the surface (Capet et al. 2008, JPO; Klein et al.2008, JPO). Its nonlinear equilibrium properties are close to Surface Quasi-Geostrophic (SQG) turbulence (Blumen, 1978,JAS), which has led to the SQG paradigm (Lapeyre & Klein, JPO'06).

Lapeyre (2009, JPO) and Tulloch et al. (2011, JPO) have examined the relative importance of these two regimes in the global ocean. Tulloch et al. (2011, JPO), using in-situ data, point to a dominance of the « interior regime » in the energetic eastward currents such as the Gulf Stream and the Kuroshio Current. In other regions, the co-existence of both the « surface regime» and the « interior regime» may explain the dynamics of the mesoscale eddy field. Qiu et al. (2008, JPO) argued that the seasonality of mesoscale production in the Subtropical Countercurrent in the North Pacific Ocean results from a « surface regime » that is activated only in winter.

Recently Mensa et al. (2013,JPO) described a third dynamical regime in the subtropical gyre of the North Atlantic Ocean. It is related to a strong production of sub-mesoscales in winter due to Mixed-Layer Instabilities (MLIs) (see recent studies of Boccaletti et al., 2007,JPO; Fox-Kemper et al.,2008, JPO). This wintertime « MLI regime » is associated with significant vertical velocities at sub-mesoscales and a conversion of PE into KE that is largest at these scales (Mensa et al., 2013,JPO; Capet et al., 2008,GRL; Sasaki et al., 2014, NC). Its nonlinear equilibrium is characterized by a k^{-2} velocity spectral slope in winter (see preceding studies and Gula et al.,2014, JPO). This regime seems to overcome the impact of the « surface regime » in the Subtropical Countercurrent (Qiu et al., 2014, JPO) and the « interior regime » in the Kuroshio (Sasaki et al., 2014, NC). Results display an increase of the total sub-mesoscale and mesoscale KE by a factor two in these regions (Qiu et al., 2014, JPO; Sasaki et al., 2014, NC) and a seasonal KE variation well in agreement with the observations of Zhai et al. (2008, GRL). A recent analysis of satellite and in-situ observations (in particular those obtained during the LatMix experiment, Shcherbina et al., 2013, GRL) by Callies & Ferrari (in revision) appears to confirm this energetic MLI regime in winter involving a velocity spectrum with a k^{-2} slope whereas a k^{-3} slope is observed in summer. These results are consistent with Xu & Fu (2012, JPO) who found an average $k^{-2.5}$ slope in the energetic western boundary currents when the velocity spectra are averaged over many years.

SWOT will provide unique global observations which should allow us to characterize these different regimes in different regions and seasons. But before testing the observability of these regimes, **a more detailed investigation of the regional and seasonal variability of the sub-mesoscale dynamics and its impact on larger scales** is still needed. In particular in the eastern part of oceanic basins, the tropics, the ACC, … where the question of the dominant dynamical regimes is still open…. **These studies could be addressed using HR global numerical simulations and reanalysis of existing observations. Observability of these regimes can be tested with the sampling and error fields provided by the SWOT simulator.**

Another question concerns the impact of ageostrophic motions, i.e. motions that depart from the geostrophic balance. These motions, usually weak at mesoscale, can be significant at sub-mesoscales. In particular, they can involve very large vertical velocities of ten and possibly hundreds meters per day at scales smaller than 20 km. They can explain the magnitude of the direct KE cascade through which KE is transferred to dissipation scales (Capet et al.,2008, JPO; Klein et al.,2008, JPO; …). As such they impact on the part of the

KE that feeds larger scales and the part that cascades to smaller scales and is ultimately dissipated. These energy cascades associated with the ageostrophic motions need to be further investigated in different regions of the global ocean and in different seasons. Another form of ageostrophic dynamics in need of further investigation is diabatic ML dynamics, that also affect sub-mesoscale motions (Ponte et al., 2013, JPO ; Gula et al., 2014, JPO). Since sub-mesoscale fronts in winter are often associated with negative Ertel potential vorticity (Sasaki et al., 2014, NC), mechanisms such as symmetric ageostrophic instability can occur. These may affect how the sub-mesoscales impact on larger scales, as well as the level of KE that is dissipated (see Thomas, 2012, JFM ; Thomas et al., 2013, DSR).

Although these various ageostrophic motions cannot be directly investigated from SWOT observations of SSH, the **question of their dynamics and their impact on ocean variability needs to be addressed from modeling studies. What range of spatial scales is involved? How do these ageostrophic motions affect the direct and inverse KE cascades and therefore the SSH scales that will be observed by SWOT? What are their impacts on the lateral fluxes and vertical buoyancy fluxes?** Studies using HR primitive equation and non-hydrostatic models, as well as the analysis of in-situ observations (such as LatMix), may help us to answer these questions.

A more specific question concerns the interactions between internal waves and the meso/sub-mesoscale dynamics and how they impact on SSH. (see also Danioux et al., 2011, JPO, 2012, JFM ; Whitt & Thomas, 2013, JPO, 2015, JPO ; …). Using in-situ data, Callies and Ferrari (2014, JPO) found that the velocity spectrum is affected by internal waves for scales smaller than 20 km in the Western North Altantic Ocean, but that can reach scales of 100 km in Eastern North Pacific Ocean. This questions the pertinence of previous idealized studies (Klein et al, 2009, GRL), indicating negligible impact of these waves on SSH. These studies have to be revisited for a large range of situations involving different regions at different seasons. The relevance of this question applies especially to the eastern part of oceanic basins where internal tide KE is comparable to that of geostrophic motions (Richman et al.,2012, JGR). As a result, internal tides potentially lead to incoherent signatures on SSH (Ponte et al, 2015 GRL), making their removal from the SWOT SSH observations somewhat difficult. Since one of the main objectives of the SWOT oceanography mission is to examine non-tidal signals, **a high priority should be to better understand this impact of internal waves on SSH. Again numerical models may help to answer this question.**

4. Synergistic extensions: Estimating the potential vorticity (PV) field in the ocean over a large scale range using satellite data in combination with the ARGO dataset.

The SWOT mission will provide 2D SSH at a spatial resolution ten times higher than that of conventional altimeters but with a low temporal resolution: 10 to 20 days. However, the sub-mesoscale and smaller range of mesoscale variability from 15-100 km can be expected to evolve rapidly in time. SWOT will therefore only be able to provide "snapshots" of this small-scale variability within the swaths, assuming that the spatial resolution of the measurements is sufficient to resolve the small-scale features. To investigate the temporal evolution of the surface (geostrophic) velocity field, it will be necessary to extrapolate the SWOT data temporally in the gaps between each swath observation. Simple averaging will involve smoothing which will suppress much of the sub-mesoscale variability that is of interest. More sophisticated schemes, based on what we know on meso/sub-meoscale dynamics, may need to be developed. Indeed, the potential of SWOT may be significantly increased if the new observations on 15-100 km wavelength scales are analyzed using new robust dynamical frameworks related to mesoscale/sub-mesoscale turbulence. Developing these

dynamical or statistical extrapolation/interpolation techniques is a major challenge. Appropriate studies should be undertaken in the next few years, prior to the SWOT launch, to meet this challenge. These studies will rely on existing and developing high resolution OGCMs and the SWOT simulator to test the results with realistic errors.
One way to extend the SWOT spatial and temporal coverage is to combine the SWOT 2D SSH observations with other satellite observations available during the SWOT mission period. These could include alongtrack SSH from conventional and SAR altimeters: e.g;, Jason-CS, Sentinel-3; Sentinel-1 2D SAR images; AVHRR-AMSR SST, etc. These satellite data will have space and time scales quite different from SWOT, and can provide complementary SSH and SST coverage. In addition, the ARGO float dataset covering all the oceans, provide daily datasets of T and S vertical profiles from the surface down to 2000m. Although these data have a low spatial (300 km) and temporal (10 day) resolution, they should allow us to specify the larger-scale vertical structure and link the surface and the interior dynamics.

A question is : can all of these heterogeneous global datasets be used to **recover the ocean dynamics**? In other words, how should we exploit the synergy from these datasets ?

A classical answer would be to use statistical interpolation tools to estimate SSH or SST fields on a regular grid. This approach, used for conventional altimetry today, allows us to recover the mesoscale fields but, as pointed out before, will smooth out the most interesting dynamical information about smaller scales provided by the alongtrack or swath datasets. Assimilation techniques could be another answer. But the existing models and assimilation schemes should be tested to see whether they are appropriate for such a high spatial resolution and rapidly varying dynamics. Furthermore the computational cost may be much too high.

Recent studies have attempted to develop new directions to exploit the synergy from the use of the different satellite datasets. Pujol et al. (2012, JTECH) showed that merging SWOT with a constellation of several altimeters would partially compensate for the swath time sampling limitations. Results from Isern et al. (2006,GRL), Buckingham et al. (2014, JGR) and Autret (2014, PhD) emphasized the benefits of using satellite microwave radiometer SST measurements combined with altimeter data to derive mesoscale surface ocean currents using the SQG formulism. Ubelmann et al. (2014, JTech) developed a very simple dynamical interpolation method to retrieve SSH between two SSH fields separated by temporal gaps of up to 20 days. This method, based on potential vorticity properties (PV being the cornerstone of ocean and atmosphere dynamics), was able to retrieve gridded maps with wavelengths smaller than 150 km. Work should continue to include more physics in these reconstructions, and in particular more terms in the PV equation.

Further studies exploiting this synergy should be strongly encouraged in order to retrieve dynamical surface information at the highest temporal and spatial resolution possible, in particular within the observation gaps.

These future satellite observations should allow us to retrieve the ocean dynamics at mesoscale wavelengths smaller than the present capability. This opens a new possibility, to try and diagnose the 3D dynamics in the ocean interior. Certain approaches are being developed which rely on the properties of the different dynamical regimes described in section 3, and are based on characterizing the potential vorticity field. This can **allow us to estimate the 3D balanced ocean dynamics (including the W-field)**. New dynamical frameworks have been developed within this context in recent years. Studies based on these theoretical frameworks include those of Lapeyre & Klein (2006, JPO), LaCasce & Mahadevan (2006, JMR), Klein et al. (2009, GRL), Smith & Vanneste (2012, JPO), Wang et al. (2013, JPO), Ponte & Klein (2013, JPO), Berti & Lapeyre (2014, OM); Xiao & Smith (in prep.), Flierl et al. (in prep.).

The first step is to estimate surface PV at the highest possible resolution from satellite observations, either from high resolution SWOT SSH or SST as a proxy for surface density. The next step is to relate **surface PV to interior PV. This can be done through a structure function which is depth dependent** (see Wang et al., 2013; Ponte & Klein, 2013; Xia et al., in prep.)**.** Such a structure function could be **estimated from the ARGO dataset**. The relevance and depth scale of this structure function (usually no more than 800m) depend on the existence of critical layers at depth, which could be diagnosed in all oceanic regions using the ARGO dataset.

The third step is based on other PV properties. PV is conserved along a lagrangian trajectory and experiences a direct cascade. This means that lagrangian techniques can allow us to recover smaller scale structures at the surface and at depth. These techniques have proved to be very efficient: lagrangian statistics based on the temporal evolution of gridded altimetry maps allow us to reconstruct ocean features with finer scales, including dynamical transport barriers aligned with the larger fronts (D'Ovidio et al., 2009, LeHahn et al.,2007,JGR) as well as finer-scale tracer fields (Despres et al., 2011; Dencausse et al., 2013).

Preliminary results based on these PV properties are very encouraging in mid latitude regions. They should be further developped and tested in different regions and conditions, using high resolution OGCMs as a testbed. These developments represent a major challenge that deserves to be addressed within the context of SWOT.

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