Internal tides and mesoscale interactions in a tropical area: insights from model, in situ data, and SWOT

L. Gourdeau[1], S. Cravatte[1] and F. Marin[1]
[1]LEGOS, Université de Toulouse, CNES, CNRS, IRD, UPS, Toulouse, France

1. Introduction and objectives

In preparation for the future SWOT mission, significant efforts focused on estimating the signature of internal tides over the global ocean from altimetry and models (Shriver et al., 2014; Ray and Zaron, 2016; Zhao et al., 2016). A lot of work has been done in recent years to document and disentangle the signature of submesoscale features and internal tides on SSH (Qiu et al., 2018; Torres et al., 2018). This transition scale falls at 40-100 km in the interior subtropics, and exceeds 200 km in the tropical ocean. Such a spatial scale is large enough to expect strong interactions between internal tides, currents and meso/submesoscale eddies that are a source of the incoherence of internal tides. Whereas coherent tides (with fixed phase and amplitude) are possibly predictable, incoherent tides are much more problematic to detect and predict, and may compromise the ability of future wide-swath altimetric missions to observe submesoscale circulation. Better understanding how internal tides become incoherent and sign in SSH is thus a critical issue.
The internal tide signal in the tropics was at the origin of the discrepancy between SSH wavenumber spectra estimated from altimetry and models with mesoscale slope of k^{-2} in altimetry against k^{-4} in models (Fig. 1 ; Tchilibou et al., 2018) and SSH wavenumber altimetric spectra exhibit in the tropics a clear peak of variability that is commonly attributed to the baroclinic M2 tide of mode 1 (Fig. 1, Dufau et al., 2016).
To document how the characteristics of internal tides depend on background conditions such as stratification, and mesoscale activity, Tchilibou et al. (2020) show that for the Solomon Sea in the South West pacific La Niña conditions, with a high level of mesoscale activity, favor the appearance of incoherent internal tides while El Niño conditions, with enhanced near-surface stratification, favor higher modes and is more characterized by small scale coherent tide-induced sea surface heights.

Our project is motivated by the SWOT SSH observability of the meso/submesoscale range (15-100 km wavelength) in a tropical region where internal tides and mesoscale eddies have similar amplitude and are supposed to strongly interact. Such region must be close to the critical latitude separating non-linear dynamics of the mid-latitudes from linear dynamics of the equatorial band (~25°NS, Theiss, 2004; Klocker et al., 2016). The choice of the region is the area South of New Caledonia (SNC).

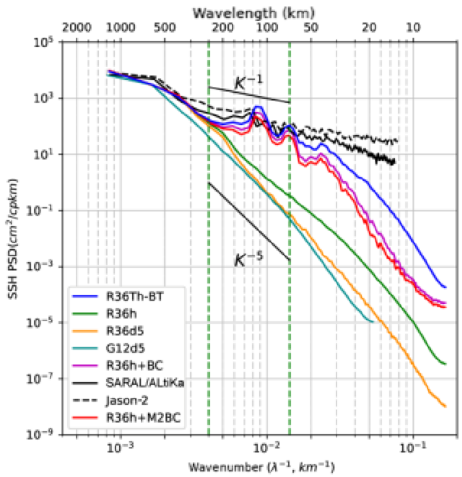

Figure 1: Meridional SSH wavenumber spectra along 3- 13°S averaged over 163-165°E for hourly outputs of a regional model with explicit tides. Once the barotropic signal has been removed, the full spectrum is in blue. Once the incoherent internal tides have been removed, the spectrum is in purple. Considering the coherent M2 internal tide only, the spectrum is in red. Once the full internal tide signal has been removed, the spectrum is in green. Once internal waves and internal tides have been filtered, the spectrum is in yellow. The spectrum in cyan is for 5-day averaged outputs of a lower resolution global model. (from Tchilibou et al., 2018)

The mean circulation around New Caledonia, its variability at seasonal and intraseasonal timescales, the EKE and large mesoscale eddies properties have been well studied and documented in recent papers (Kessler and Cravatte, 2013; Cravatte et al., 2015; Qiu and Chen, 2004; Qiu et al., 2009; Keppler et al., 2018). Mesoscale eddies detected by altimetry are long-lived and ubiquitous in this region. They propagate westward, and although a great number of them are generated in the region, some also propagate from the eastern basin. They tend to have mean amplitudes of around 9 cm in SSH, mean radii of about 100 km, and large EKE (200 cm^2s^{-2}) (Fig. 2).

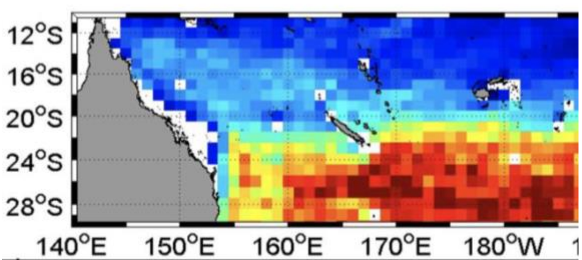

Figure 2 : Mean eddy life time on 1°x1° boxes from gridded AVISO altimetric maps and eddy detection method.
Source: Keppler et al. (2018)

To investigate fine scale/high frequency motions of interest for SWOT, available high-resolution *in situ* observations (Shipboard Acoustic Doppler Current Profilers (SADCP), ThermoSalinoGraph (TSG), glider transects) have been revisited (Sérazin et al., 2020). From structure functions, figure 3 exemplifies the ability of SADCP data to document the governing ocean dynamics for 3-100 km spatial scales, as a function of depth. South and East of New Caledonia, surface layers are dominated by rotational motions for scales larger than 10 km, and the slope of the structure function close to 1 for scales larger than 20 km is characteristic of SQG dynamics. This gives evidence of a surface-intensified regime where motions are dominated by vortices within the mesoscale to submesoscale range, involving frontogenesis and mixed layer instabilities.

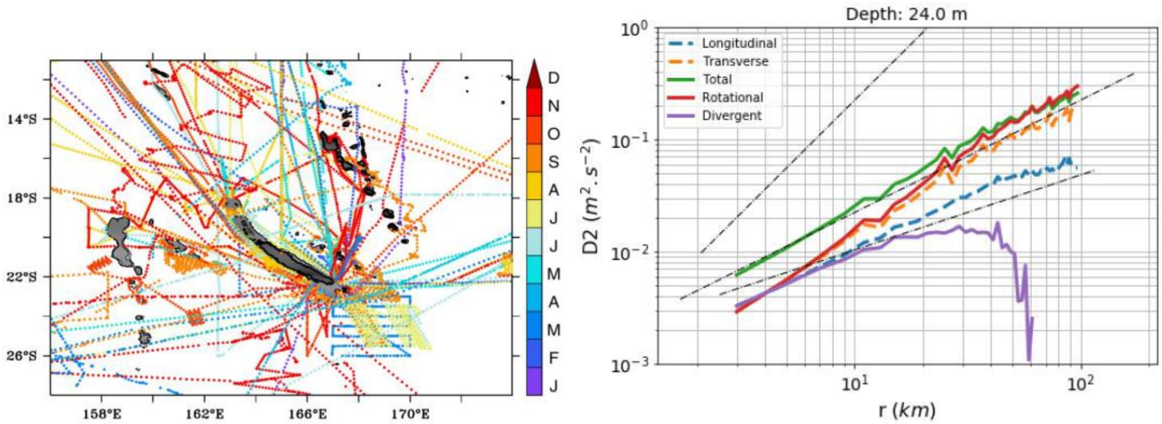

Figure 3: a) Sampling of SADCP data around New Caledonia. b) Mean velocity structure functions (SFs) computed on each segment in the Vauban channel (located between New Caledonia and Loyalty Islands) at the surface are plotted in the range 3-100 km. Longitudinal (dashed blue curve) and transverse (dashed orange curve) structure functions are used to compute the total SFs (green curve) as well as the associated rotational (red) and divergent (purple) SFs. Classic power laws (r^2,r, $r^{2/3}$) are plotted for reference. From Sérazin et al. (2020).

The South West Pacific with its numerous archipelagoes, seamounts and islands is moreover a strategic place for the generation of internal tides, especially South of New Caledonia (Fig. 5a, Niwa and Hibiwa, 2011; Lavergne, 2019). Our knowledge of the exact generation sites is however still fragmentary but a preliminary study based on the FES2014 barotropic tide model provides a first estimation of the conversion rate of barotropic to baroclinic energy for the M2 component (Fig. 3a). It confirms the signature of coherent M2 baroclinic tides in altimetry, propagating from a generation site at the southern tip of New Caledonia (Fig. 3b, Ray and Zaron, 2016). Internal tides have also been observed in the region by cruises and glider transects, and reveal pycnocline displacements as large as 100 meters (J. Lefevre, personal communication; G. Sérazin, 2020)

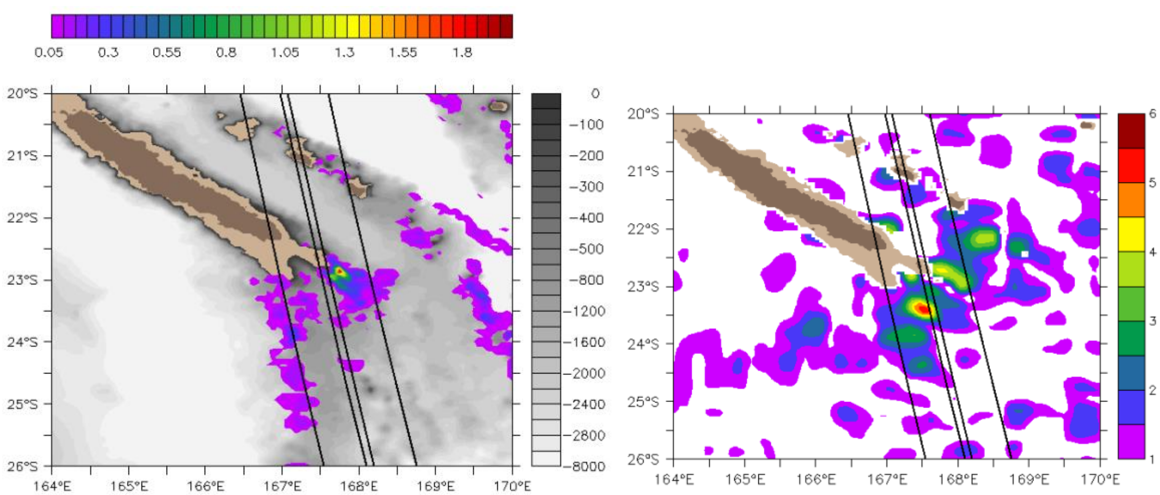

Figure 4: a)) Theoretical barotropic to baroclinic energy conversion estimated from FES2014 in the South of New Caledonia (in Wm^{-2}). b) SSH signature of M2 internal tides from altimetry (unit: cm; source:Ray and Zaron, 2016).

Based on the considerations developed above, our project aims to document the internal tides, their interactions with the mesoscale eddy field, and their observability by SWOT in the South New Caledonia region.

The questions to be addressed are:

- What are the parts of internal tides generated locally and remotely?
- What tidal energy is associated with high-mode internal tides?
- How coherent are the predicted internal tides?
- What are the mechanisms responsible for the coherence loss of the internal tides?
- How is the mesoscale field perturbed by internal tides?
- To what extent can we predict the propagation of internal tides through a mesoscale eddy field?
- What are the vertical structures of the internal tides, and what are their signatures in SSH?
- What is our capacity to disentangle the signals associated with balanced and unbalanced motions?

Additional questions related to the project include:

- How do fine scale dynamics impact biogeochemistry?
- What is the impact of internal tides dissipation on mixing, and cooling of the surface ocean?

Do the internal tides and breaking waves impact the temperature, SSH and local circulation of the New Caledonia lagoon?

2. Approach

During the first 6 months after launch, SWOT will be in a fast sampling phase on a one-day repeat orbit, and a SWOT swath will cross the region South of New Caledonia (Fig. 4). This represents a unique opportunity to test the observability of the satellite measurements for such high frequency motions. We propose an *in situ* experiment during this fast sampling phase of SWOT to document the 3D structures of meso/submesoscale and internal tides that will be observed at the surface by SWOT. The New Caledonia site with the IRD center at Noumea is an appropriate basis for an *in situ* experiment:

The strength of the present project is to improve our understanding of the internal tide signal, its interaction with the mesoscale field, and SWOT observability from the concerted efforts of numerical modelling, field measurements, and satellite remote sensing.
Also, the in situ experiment will be an opportunity for biogeochemists to analyze the impact of fine-scale features on the distribution of biogeochemical variables and ecosystems, such as nitrogen fixation.
In addition, we take advantage that the SWOT swath in New Caledonia includes a lagoon to extend the purpose of the project to explore the potential of SWOT high-resolution data to observe the interaction between the open ocean and the lagoon.

The project is divided in 4 complementary workpackages:
WP1: Modelling
WP2a: In situ experiment
WP2b: Extension of the cruise to synergetic objectives (biogeochemistry)
WP3: SWOT observability
WP4: HR SWOT data at the interface between open-ocean, reefs and lagoon

The WP1 modelling task is the starting point of the project to firstly understand the physics at work and their SSH signature, and secondly to refine the design of the in situ experiment. A 1/60° resolution regional model simulations forced with realistic atmospheric forcing and explicit tides will be performed. The 1/60° resolution in the New Caledonia zoom is chosen

to be high enough to effectively resolve scales as low as 5-6 km, smaller than the 15 km effective resolution of SWOT. Before that, the analysis of the 1/12° global Mercator model will provide first evidence of the ability of the model to simulate the internal tide fields in the region.
The WP2 in situ experiment task is the core of the project. In interaction with WP1, the design of the cruise, and particularly the choice of the location for intensive measurements will be adjusted. Four cruises are planned in the context of this project. Two short cruises are necessary to deploy and recover moorings. Two longer 2-week cruises are proposed during the SWOT fast sampling phase (i.e. in the first months of 2022) and will be dedicated respectively to repeated en-route measurements along a propagation ray of internal tides and to hydrological fixed stations during which repetitive CTD and micro-turbulence casts will be carried out.
The WP3 SWOT observability task is crucial to make the link between the in situ measurements and the SWOT mission. If a first modelling approach is expected, most of this task is dependent on the delivery of the SWOT data in the months following the fast sampling phase. Because this is a new generation of altimetric data, we anticipate that several data processing will be needed before an accurate dataset can be made available. We will invest in this preliminary task.
The WP4 on HR SWOT capabilities in a lagoon environment will investigate the usability of SWOT altimetry in the lagoon. The processes responsible for producing an observable sea level signal include wave setup, infragravity waves and wind driven surge. The processes will be either modeled or directly measured. Then, an analysis of the HR SWOT products will be conducted to compare with the observed and/or modeled processes.

3. Anticipated results

This project is part of the cal/val SWOT plans discussed at the last ST-SWOT meeting besides the main cal/val site planned in the California Current System motivated by spectral requirements. This project will contribute with others to the 2D validation and use of SWOT SSH measurements in different dynamical regions. The originality of the present project for SWOT is the focus on the interactions between internal tides and eddies in an area at the limit between the non-linear dynamics of the mid-latitudes and the linear dynamics of the tropics. The results obtained will help to improve our understanding of the interactions between mesoscale eddies and internal waves, and to characterize the signature of the internal waves in SSH. They will also provide new insights on the internal waves dissipation, and on their impact on mixing, SST and air-sea coupling.
The project takes advantage of the IRD center in Nouméa where the R/V Alis is based to propose an in situ experiment just off the lagoon in the open ocean during the SWOT fast sampling phase. We propose relatively low cost cruises that will be dedicated not only to fine-scale dynamical processes but also to studying the impacts of fine-scale structures on biogeochemistry.

This project contributes to the “Adopt a crossover” CLIVAR project (P.I. F. D’Ovidio) whose objective is to federate the fine scale (1-100 km) international community around the SWOT project.

References

Cravatte, S., Kestenare, E., Eldin, G., Ganachaud, A., Lefèvre, J., Marin, F., et al. (2015). Regional circulation around New Caledonia from two decades of observations. Journal of Marine Systems, 148, 249–271. https://doi.org/10.1016/j.jmarsys.2015.03.004

De Lavergne C., S. Falahat, G. Madec, F. Roquet, J. Nycander, C. Vic, 2019, Toward global maps of internal tide energy sinks, Ocean Modelling, 137, 52–75, https://doi.org/10.1016/j.ocemod.2019.03.010

Dufau, C., M. Orsztynowicz, G. Dibarboure, R. Morrow, and P.-Y. Le Traon (2016), Mesoscale resolution capability of altimetry: Present and future, J. Geophys. Res. Oceans, 121, 4910–4927, doi:10.1002/2015JC010904.

Keppler, L., Cravatte, S., Chaigneau, A., Pegliasco, C., Gourdeau, L., & Singh, A. (2018). Observed characteristics and vertical structure of mesoscale eddies in the southwest tropical Pacific. Journal of Geophysical Research: Oceans, 123. https://doi.org/10.1002/2017JC013712

Kessler, W. S., and Cravatte, S. (2013). Mean circulation of the Coral Sea. Journal of Geophysical Research: Oceans, 118, 6385–6410. https://doi.org/10.1002/2013JC009117

Qiu, B., Chen, S., & Kessler, W. S. (2009). Source of the 70-day mesoscale eddy variability in the Coral Sea and the North Fiji Basin. Journal of Physical Oceanography, 39(2), 404–420. https://doi.org/10.1175/2008JPO3988.1

Qiu, B., & Chen, S. M. (2004). Seasonal modulations in the eddy field of the South Pacific Ocean. Journal of Physical Oceanography, 34(7), 1515–1527. https://doi.org/10.1175/1520-0485(2004)034<1515:SMITEF>2.0.CO;2

Qiu, B., Chen, S., Klein, P., Wang, J., Torres, H., Fu, L. L., & Menemenlis, D. (2018). Seasonality in transition scale from balanced to unbalanced motions in the world ocean. Journal of Physical Oceanography, 48(3), 591–605. https://doi.org/10.1175/JPO-D-17-0169.1

Niwa, Y., Hibiya, T., 2011. Estimation of baroclinic tide energy available for deep ocean mixing based on three-dimensional global numerical simulations. J. Oceanogr. 67, 493–502.

Ray, R. D., & Zaron, E. (2016). M2 internal tides and their observed wavenumber spectra from satellite altimetry. Journal of Physical Oceanography, 46(1), 3–22. https://doi.org/10.1175/JPO-D-15-0065.1

Shriver, J. F., J. G. Richman, and B. K. Arbic (2014), How stationary are the internal tides in a high-resolution global ocean circulation model?, J. Geophys. Res. Oceans, 119, 2769–2787, doi:10.1002/2013JC009423.

Sérazin G., F. Marin, L. Gourdeau, S. Cravatte, R. Morrow, M.L. Dabat, Scale-dependent analysis of in situ observations in the mesoscale to submesoscale range around New Caledonia, in revision in Ocean Sci, https://doi.org/10.5194/os-2019-124

Tchilibou, M., Gourdeau, L., Morrow, R., Serazin, G., Djath, B., and Lyard, F., 2018, Spectral signatures of the tropical Pacific dynamics from model and altimetry: a focus on the meso-/submesoscale range, Ocean Sci., 14, 1283-1301, https://doi.org/10.5194/os-14-1283-2018.

Tchilibou M., L. Gourdeau, F. Lyard, R. Morrow, A. Koch Larrouy, D. Allain, B. Djath, 2020. Internal tides in the Solomon Sea in contrasted ENSO conditions, Ocean Sci., 16, 615–635, https://doi.org/10.5194/os-16-615-2020.

Theiss, J. (2004), Equatorward energy cascade, critical latitude, and the predominance of cyclonic vortices in geostrophic turbulence, J. Phys. Oceanogr., 34, 1663– 1678.

Torres, H. S., Klein, P., Menemenlis, D., Qiu, B., Su, Z., Wang, J., et al. (2018). Partitioning ocean motions into balanced motions and internal gravity waves: A modeling study in anticipation of future space missions. Journal of Geophysical Research: Oceans, 123. https://doi.org/10.1029/2018JC014438

Zhao, Z. (2018). The global mode-2 M2 internal tide. Journal of Geophysical Research: Oceans, 123, 7725–7746. https://doi.org/10.1029/2018JC014475