The Effect of the North Equatorial Counter Current on the Generation and Propagation of Internal Solitary Waves near the Amazon River shelf as observed in SAR imagery

José Carlos B. da Silva, Jorge M. Magalhaes [1,3]
Maarten C. Buijsman[2]
Carlos A.E. Garcia, Paulo H. Calil [3]
João Antonio Lorenzzetti, Carina Macedo[4]
Carlos Lentini[5]
Fernando Pelon Miranda[6]
Carlos Henrique Beisl[7]

[1] Universidade do Porto – Faculdade de Ciências, DGAOT
Rua do Campo Alegre, 687 - 4169-007 – Porto, Portugal
{jdasilva, jorge.magalhaes}@fc.up.pt
[2]University of Southern Mississippi, Department of Marine Science
1020 Balch Blvd, Stennis Space Center, MS, USA
maarten.buijsman@usm.edu
[3] Universidade Federal do Rio Grande - FURG
Av Itália km 8 - Campos Carreiros - RS, Brazil
dfsgar@furg.br
[4] Instituto Nacional de Pesquisas Espaciais - INPE
Caixa Postal 515 - 12227-010 - São José dos Campos - SP, Brasil
{loren, crmacedo}@dsr.inpe.br
[5]Instituto de Fisica - Depto. Fisica da Terra e do Meio Ambiente
GOAT - Grupo de Oceanografia Tropical - Universidade Federal da Bahia - UFBA
Travessa Barao de Jeremoabo, Campus Ondina
Salvador - Bahia - Brazil
[6]Petrobras – CENPES – Ilha do Fundão, Q-7
Rio de Janeiro - RJ, Brazil
fmiranda@petrobras.com.br
[7]LABSAR - COPPE/UFRJ
Cid. Universitária - Centro de Tecnologia - Bloco I-114
Av. Athos da Silveira Ramos, 149
Rio de Janeiro – RJ, Brazil

Abstract. The Brazilian continental shelf break in the tropical Atlantic Ocean off the Amazon River mouth is amongst the most energetic regions in the world for generation of internal tides (Baines, 1982). Since the early 1980s there have been *in situ* observations of Internal Solitary Waves (ISWs) near the North Equatorial Counter Current (NECC) off the Brazilian continental shelf, where localized surface velocity pulses of up to 2 m/s have been documented (e.g. Brandt et al., 2002). Despite these early efforts, the region remained largely unexplored until recently. Here we present a first account of the coherence crest-lengths, propagation characteristics and seasonal variability of ISWs on and off the shelf, based on Synthetic Aperture Radar (SAR) images. Available ENVISAT ASAR scenes (29 in total), and additional ERS-1/2 SAR, TerraSAR-X and RADARSAT images of the region of the tropical Atlantic Ocean comprising the geographic coordinates [40°- 50° W, 0°- 8° N] have been examined. The SAR image analysis revealed the following main results: 1) The ISW signatures, whose coherence crest-lengths can exceed 200 km, are first detected near the southern edge of the countercurrent and intensify on the northern edge of the NECC; 2) In October, there is a strong refraction/ advection of ISWs towards the east, as they enter the influence of the NECC (in between 4° and 5° N); 3) Some on-shelf regions are prone to intense ISW signatures in the SAR, which are believed to be associated with intricate bottom-topography.

Keywords: remote sensing, Synthetic Aperture Radar, Internal Solitary Waves, Amazon Shelf, Tropical Atlantic Ocean, resonance, transcritical regime.

1. Introduction

Since the early 1980s there have been several observations of Internal Solitary Waves (ISWs) near the North Equatorial Counter Current (NECC) off the Brazilian continental shelf in the tropical Atlantic Ocean. These are large-amplitude interfacial waves of solitary character, with localized surface velocity pulses of up to 2 m/s which produce signatures detectable in Synthetic Aperture Radar (SAR) images. It has been argued that these waves strongly differ from those typically observed for trains of tidally generated ISWs (Brandt et al., 2002), who claimed that different mechanisms are possibly involved in their generation and/or evolution. A peculiarity of these waves is their pulse like character, since only one or two solitary waves are usually observed to develop within the space scales associated to the mode-1 internal tide propagation (with wavelengths of approximately 100-140 km). Another distinct feature is that the waves were found more than 500 km away from the nearest significant topographic variations (the Brazilian shelf break) (see Brandt et al., 2002). The full two dimensional (2D) horizontal structure of the ISWs in question was not well known until now, neither their seasonal and interannual variability in a region of the ocean highly affected by currents and planetary Rossby waves (Hormann et al., 2011). Here we present a first account of the coherence lengths, propagation characteristics and temporal variability of ISWs crossing the NECC off the South American coast.

We investigate the influence of the NECC and its seasonal variability on the ISW spatial structure and propagation directions. It is argued that the northward thermocline shoaling along the propagation path of internal tides (generated at the South American continental slope) is capable of boosting ISW growth in October, by increasing the relative importance of the waves' nonlinearity parameter in relation to other parameters that influence the steepening and break-up of the internal tide. Furthermore, the nature of the ISW generation that occurs on the shelf is investigated through examination of the criticality of the flow over bottom-topography**.**

2. Methodology

All available ENVISAT ASAR scenes (29 in total) of the region of the tropical Atlantic Ocean comprising the geographic coordinates [40°- 48° W, 0°- 8° N] have been examined. Figure 1 presents a composite map constructed by plotting the locations of the (leading) ISWs found on two typical images of different seasons: May 2009 (in blue) and October 2011 (in red), in relation to the bathymetry of the region. The meridional section labelled S (located at longitude 44.5° W, from 3.5° to 8° N) represents a cross section that is oriented approximately perpendicular to the main axis of the NECC current. Graphics in Figure 2a and 2b were obtained from climatology of the study region for the months of May and October, respectively. The climatology was performed over 32 (1980/01 – 2011/12) years of monthly means for: potential temperature; salinity; zonal velocity (u-current) and meridional velocity (v-current) provided from NOAA/OAR/ESRL PSD, Boulder, Colorado (http://www.esrl.noaa.gov/psd/data/gridded/data.godas.html).

The data is provided at 1/3x1/3 degrees for all latitudes at 40 vertical levels comprehending 5 m to 4478 m of depth for the whole globe. From there, some derived quantities such as squared Brunt–Väisälä frequency (N^2) and sea state equations were based on the UNESCO algorithms available at (http://woodshole.er.usgs.gov/operations/sea-mat/).

3. Results

Internal Waves at two distinct spatial scales will be analysed: 1) Large scale ISWs whose coherence crest lengths can exceed 200 km, which are long-lived features, mainly propagate offshore

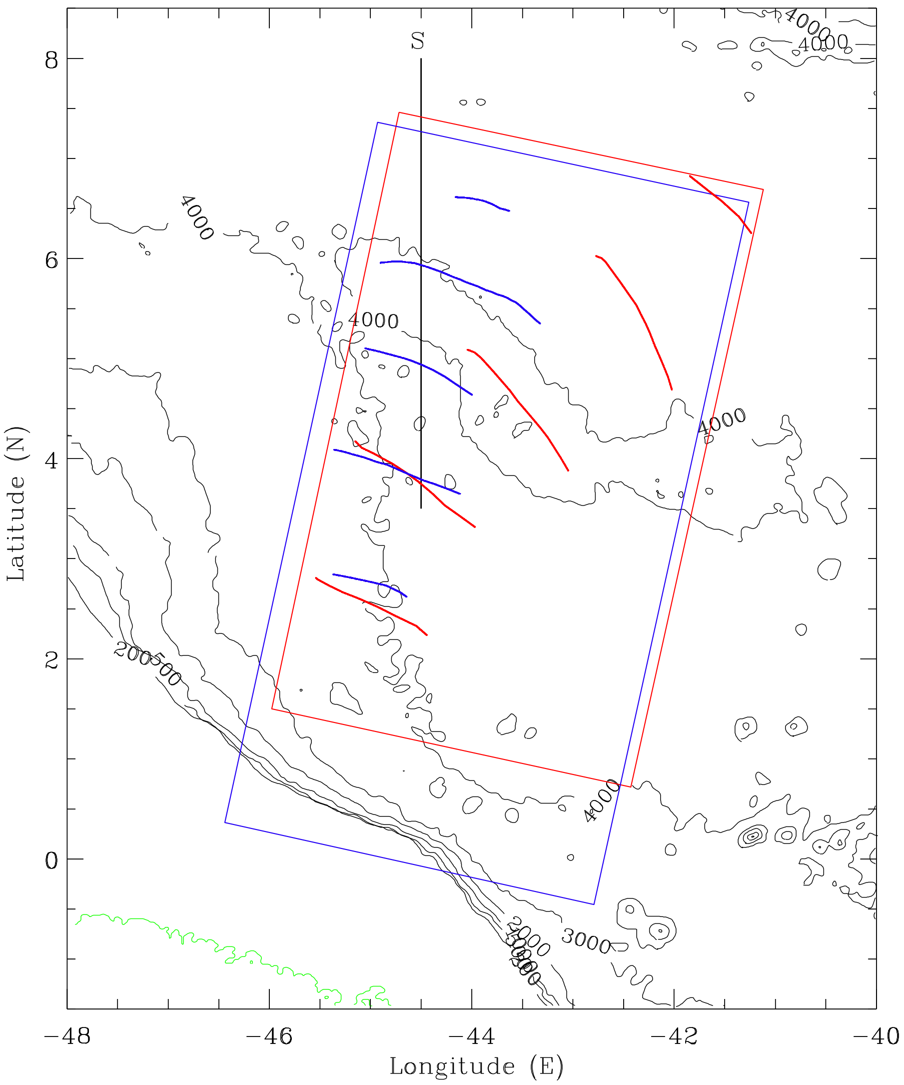

Figure 1. Composite map of ISW observations based on two ENVISAT ASAR images (those of 11 May 2009 and 3 October 2011). The meridional transect "S" represents a cross section that is used to plot climatic parameters presented in Figures 2a and 2b. The blue lines represent ISWs observed in May and the red lines ISWs measured in October.

into the deep ocean and are thought to have tidal origin; and 2) Smaller scale ISWs which are generated over the shelf and might be relatively short-lived.

3.1 Large scale ISWs off the shelf

Figure 2 clearly shows a significant seasonal variability of the near-surface thermocline structure and of the zonal currents. The average climatology for May (Fig. 2a, top panel) shows a thermocline depth (maximum vertical temperature gradients) at approximately 130 meters below the surface that is nearly constant along section "S". In contrast, the average climatology for October (Fig. 2b, top panel) reveals a thermocline depth that varies from some 150 m south of the NECC to less than 100 m north of the NECC (also in agreement with Ivanov et al., 1990). In other words, the thermocline shoals towards the north along section "S" (see also Fig. 1 for location of section "S") in October, but is horizontal in May. The current vertical structure is also markedly different for May and October. While in October the NECC clearly shows up as a maximum in the near-surface velocity (Fig. 2b, bottom panel) flowing eastwards (positive average velocities reach 0.5 m/s) located approximately at 50 m depth between 4.5° and 5° N, in May the current relaxes, and there is even a small westward component that is noticeable in the near-surface (see Fig. 2a, bottom panel).

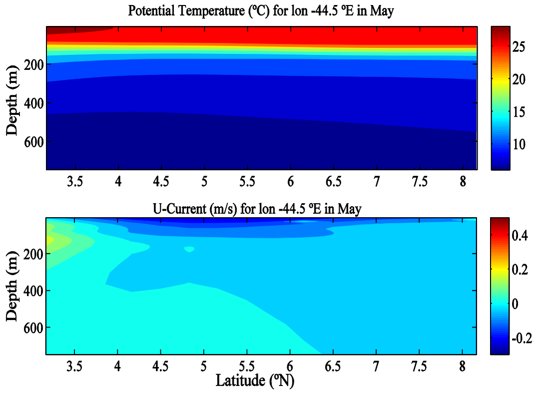

Figure 2a. Potential temperature (top) and eastward current (bottom) for May climatic mean corresponding to label “S” in Figure 1.

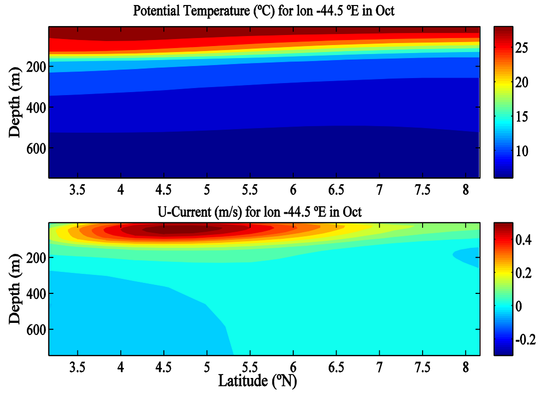

Figure 2b. Potential temperature (top) and eastward current (bottom) for October climatic mean corresponding to label “S” in Figure 1.

The SAR image analysis revealed three main results for these large scale ISWs: 1) The ISWs signatures, whose coherence crest lengths can exceed 200 km, are first detected near the southern edge of the NECC and intensify on the northern edge of the NECC (see map in Fig.1); 2) In October, there is a strong refraction/ advection of ISWs towards the east, as they enter the influence of the NECC (in between 4° and 5° N); 3) The average propagation speed of ISWs is estimated as 3.7 m/s in October and only 2.3 m/s in May, based on the SAR. Note that the eastward flowing NECC near the surface may reach 1.6 m/s (see e.g. Brandt et al., 2002) (significantly more than the climatic mean in Fig. 2b), which partly explains the faster propagation of ISWs observed in October; 4) There is a more extensive penetration of the waves into the north Atlantic in October.

A recent study about ISWs generated at the Luzon Strait of the South China Sea (SCS) (see Buijsman et al., 2010) addressed the influence of thermocline shoaling and a transverse current (Kuroshio) on the ISWs growth. Numerical modelling showed that a thermocline shoaling along the ISWs propagation direction increases the relative importance of the waves’ nonlinearity parameter in relation to other parameters that influence the steepening and break-up of the internal tide (Buijsman et al, 2010). This enhances the evolution of (interfacial) internal tides of first mode into ISWs (the nonlinearity parameter is given by e.g., $\alpha = A/h$, where A is the vertical amplitude of the internal tidal wave and h is the depth of the waveguide, which proxy can be taken as the depth of the thermocline). Here we suggest that the northward thermocline shoaling (Fig. 2, top panel) along the propagation path of internal tides (possibly generated at the South American continental slope) is capable of boosting ISW growth in October, similarly to the case of the SCS (see Buijsman et al., 2010). The ISW propagation pathway that is observed in October is strongly affected by the NECC current, introducing a significant eastward component in the waves’ trajectory. In future we plan to investigate the effect of the NECC current in ISW growth at interannual time scales. Note that the width of the NECC current (along section “S”) is close to the characteristic wavelength of long internal tides of the first mode. This fact may also have an influence on wave growth across the NECC, which can be tested with modelling as in Buijsman et al. (2010). We plan to investigate the influence of NECC and its seasonal and interannual variability on ISW strength and direction. This will be done by comparing the amplitudes of SAR backscatter profiles from archived imagery with the temporal and spatial variability of the NECC (and associated hydrographic parameters) in the study region.

A possible factor for the more extensive penetration of the internal waves into the north Atlantic in October (in comparison with May observations) is that the thermocline at this time of year may sustain any generated interfacial waves better than the thermocline in May. The rate at which wave energy would leak from the thermocline into the deeper ocean (causing dissipation of the waves on the thermocline) has been termed "radiation damping" and investigated theoretically (see Akylas et al., 2007). Given that the upper layer depth (h) is larger in May (see Figs. 2a and 2b), then the parameter μ in Akylas et al. (2007) will also be larger in May, with more rapid dissipation of the waves being expected (see Akylas et al., 2010, equations 2.3 and 2.18). Another reason may obviously be the faster propagation of the waves in October, which would certainly drive them farther away into the north Atlantic at that time of year (for a similar lifetime as the May waves).

3.2 Small scale ISWs on the shelf

The Amazon shelf is forced mainly by tides, wind stress and the North Brazilian Current (NBC). Cross-shelf current speeds of up to 2 m/s are associated to quasi-resonant tidal oscillations, especially of the semidiurnal type. On the Amazon shelf the mean flow is northwestward for both the Amazon river plume and the underlying shelf water. The Amazon river water can be found on the inner shelf, usually inshore of the 15 m isobath or in a thin near-surface layer about 5-10 m inshore of the 30 m isobath.

Although hydrographic regimes and main current variability are reasonably well understood for this region, the existence of internal waves of the solitary types (i.e. ISWs), have not been reported to our knowledge. This is quite surprising since the Amazon shelf has been classified as the third largest hotspot for internal tides in the Ocean by Baines (1982). Figure 1 shows an ENVISAT ASAR image dated 14 February 2007 acquired at 01:30 UTC (Universal Time Coordinates) which reveals the existence of intense ISWs on the shelf in the form of packets (or trains) of waves concentrated in a region of the mid-shelf (depth is about 70-80 m there). The location of this hotspot seems associated to intricate bottom features, as suggested and confirmed by other similar SAR images of the region (not shown). This fact points to the existence of some steep underwater banks or complicated canyon topography that is not evident in global bathymetry maps (see text below).

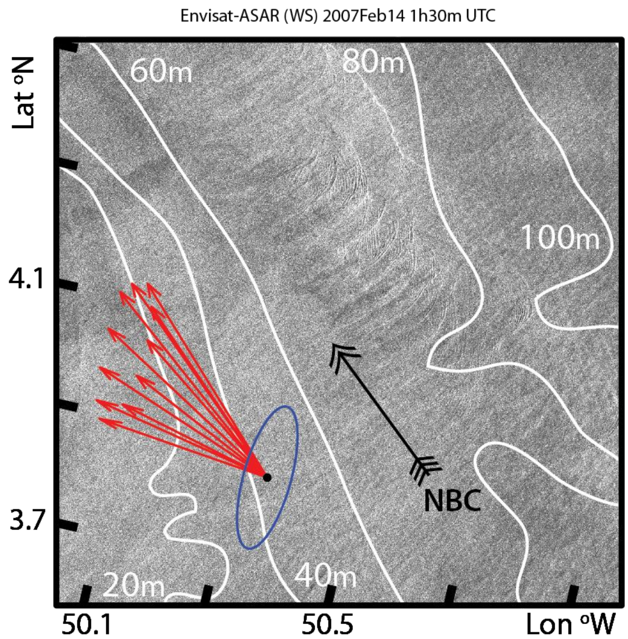

Figure 3. ENVISAT ASAR image in IM mode of the Amazon shelf off the Brazilian state of Amapá. The image was acquired on 14 February 2007 at 01:30 UTC and reveals surface signatures on intense ISWs whose propagation direction opposes the North Brazilian Current (see text for details). Overlaid isobaths are those of the 20, 40, 60, 80 and 100 meters.

Predominance of strong currents on the shelf suggests that those internal waves observed in the SAR may be generated in the critical, or transcritical, regime (see e.g. da Silva and Helfrich, 2008), i.e. when the densimetric Froude number slightly exceeds unity (Fr ≥ 1). The transcritical regime can be defined as a bandwidth of forcing speeds, relative to the limiting long-wave phase speed of the system, where finite-amplitude, upstream propagating internal wave disturbances are possible. Solutions to the Kortweg-*de Vries* equation for upstream propagating solitons, or ISWs, have been found (see e.g. Redekopp and You, 1995) provided the amplitude forcing is sufficiently large and positive to overcome downstream-advective effects (see Redekopp and You, 1995). The amplitude forcing is usually prescribed in the form of a bottom topographic step (see e.g. Grimshaw and Smyth, 1986), or it can also be in the form of a lateral constriction to the fluid (e.g. Clarke and Grimshaw, 1994). Given the bathymetry of the localized region where ISWs were observed in the SAR, whose detail is shown in Figure 4, it is likely that underwater bottom banks are the cause of topographic forcing. We next thus evaluate the criticality of the flow in the region of those ISWs.

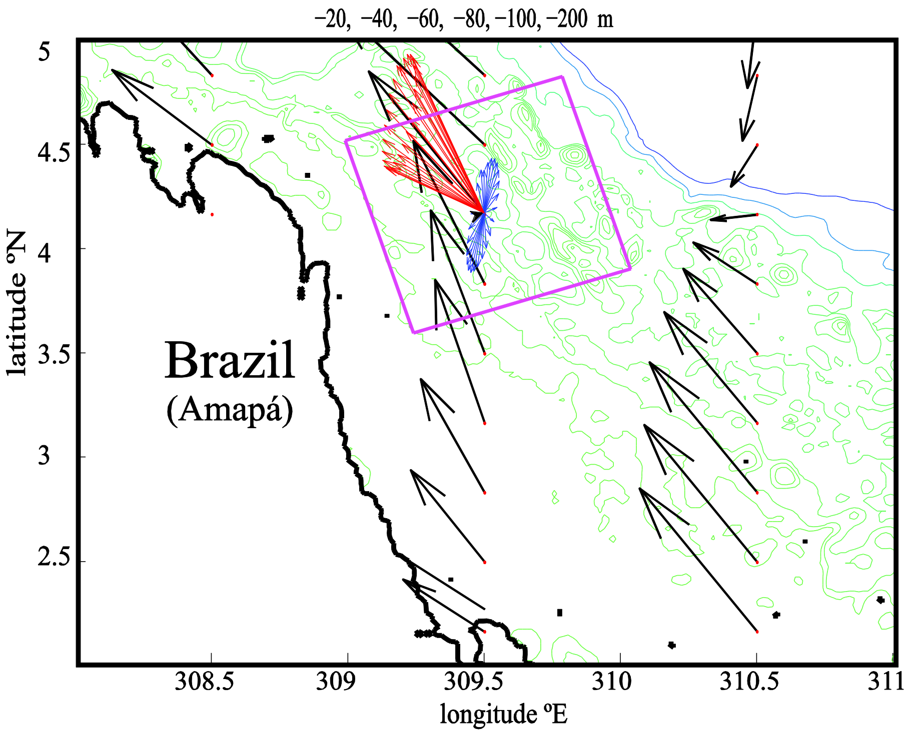

Figure 4. Map of the study region showing bottom contours. The rectangle in magenta represents the area covered by the SAR image in Figure 3. Black arrows represent the February climatology steady currents of the NBC, and the blue elipse and vectors inside represent the semidiurnal tidal currents. Red vectors represent the composed NBC and tidal currents (see text for details).

A densimetric Froude number was calculated based on an average stratification vertical profile for the study region and the combined steady NBC and tidal currents. The Froude number was calculated as follows:

$$F_r = \frac{\vec{U}.\vec{n}}{c},$$

where ***U*** is the vector of the velocity of the barotropic tidal current added to the steady current, ***n*** is the unit vector normal to the wave fronts detected in the SAR, and c is the phase speed of the first mode obtained from a standard boundary value problem (see e.g. Smyth et al., 2010). We note that the flow is indeed supercritical during part of the tidal cycle, thus passing through the transcritical band. Therefore, it is suggested that the observed ISWs in the SAR are generated through resonance when the flow is nearly critical and capable to extract energy from the flow that feeds ISW generation. We believe the forcing mechanism is somewhat connected with the intricate bottom features of the region.

4. Conclusions

In this paper we provide a first-hand account of the horizontal spatial structure of ISW trains on and off the Amazon shelf, revealed with SAR images. The crest length coherence, wavelengths, and extent of penetration of the waves into the North Atlantic are revealed for the first time. There exists a seasonal variability in those ISWs which propagate into deep water. In October, there is a strong refraction of ISWs towards the east, as they enter the influence of the NECC (in between 4° and 5° N), while in May this refraction is reduced or inexistent. The generation mechanism of the ISW trains observed in the SAR is consistent with the disintegration of the internal tide whose origin is likely to be the shelf break. The reason for the extensive penetration of ISWs into the Tropical North Atlantic needs further investigation.

ISWs have been found to propagate in the upstream along- shelf direction, according to the limited number of SAR images that have been analyzed. They are consistent with resonant generation, i.e. when the flow (tide superposed on steady NBC) passes through a transcritical band, and are likely associated to intricate bottom topography along the shelf. In future we plan to further investigate and confirm the criticality of the flow as well as the seasonality of those on shelf internal waves.

References

Akylas, T.R.; Grimshaw, R.H.J.; Clarke, S.R.; Tabaei, A. Reflecting tidal wave beams and local generation of solitary waves in the ocean thermocline. **J. Fluid Mech.**, 593, 297 – 313, doi:10.1017/S0022112007008786, 2007.

Brandt, P.; Rubino, A.; Fisher, J. Large-Amplitude Internal Solitary Waves in the North Equatorial Countercurrent. **Journal of Physical Oceanography**, American Meteorological Society, Boston MA, p. 1567-1573, 2002.

Buijsman, M.C.; McWilliams, J.C.; Jackson, C.R. East-west asymmetry in nonlinear internal waves from Luzon Strait. **Journal of Geophysical Research – Oceans**, American Geophysical Union, Vol. 115, C10057, doi:10.1029/2009JC006004, 2010.

Clarke, S. R.; Grimshaw, R. H. J. Resonantly generated internal waves in a contraction**, J. Fluid Mech.**, 274, 139–161, 1994.

da Silva, J. C. B.; Helfrich, K. R. Synthetic Aperture Radar observations of resonantly generated internal solitary waves at Race Point Channel (Cape Cod), **J. Geophys. Res.**, 113, C11016, doi:10.1029/2008JC005004, 2008.

Grimshaw, R.H.J.; Smyth, N. Resonant flow of a stratified fluid over topography. **J. Fluid Mech.**, 169, 429 – 464, 1986.

Hormann, V.; Lumpkin, R.; Greg Foltz. On the interannual North Equatorial CounterCurrent variability, In: PIRATA-16/TACE/TAV Joint Meeting, March 2011.

Ivanov, V.A.; Ivanov, L.I.; Lisichenok, A.D. Redistribution of energy of the internal tidal wave in the North Equatorial Countercurrent region. **Sov. J. Phys. Oceanogr.**, Vol. 1, No. 5, pp. 383-386, 1990.

Redekopp, L.G.; You, Z. Passage through resonance for the forced Korteweg-de Vries equation. **Physical Review Letters**, vol. 74, number 26, 5158-5161, 1995.

Smyth, W.D.; Moum, J.N.; Nash, J.D. . Narrowband, high-frequency oscillations at the equator. Part II: properties of shear instabilities. **J. Phys. Oceanogr**.doi:10.1175/2010JPO4451.1, 2010.

Acknowledgements

José da Silva gratefully acknowledge CNPq (*Conselho Nacional de Desenvolvimento Científico e Tecnológico*) and *Ministério da Ciência, Tecnologia e Inovação* through *Programa Ciência Sem Fronteiras* for a PVE (*Pesquisador Visitante Especial*) Grant (400720/2013-2). Jorge Magalhães and JdS are grateful to the Federal University of Rio Grande (FURG) and *Instituto de Oceanografia* there (LEOC) for kind hospitality during a sabbatical leave. Jorge Magalhães would also like to acknowledge a FCT grant reference SFRH / BPD / 84420 / 2012.