Flow structures over mesophotic coral ecosystems in the eastern Gulf of Mexico

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Abstract

Simultaneous time series of current velocity profiles are used to characterize flow structures over intermediate-depth coral ecosystems in the eastern Gulf of Mexico. Understanding of temporal variability and spatial coherence in flow is necessary to establish connectivity among these ecosystems. Time series were collected at Pulley Ridge (the westernmost site), Northern Dry Tortugas, and Southern Dry Tortugas. Overlapping data spanned the period from March 22, 2013 to June 20, 2015. The strongest currents were approximately 1 m s^{-1} southeastward at Pulley Ridge. Subtidal velocities from the three sites were decomposed into real-vector, concatenated empirical orthogonal functions (EOFs). Results from EOFs indicated that Mode 1, which explained 63% of the subtidal variations, was roughly in the same direction at each of the three sites. Mode 1 directionality indicated potential interconnectivity between Pulley Ridge and Southern Dry Tortugas, and between Northern Dry Tortugas and Pulley Ridge. Mode 1 also suggested limited to no connectivity between the two Dry Tortugas sites as the flows over the two sites were parallel. Mode 2 explained close to 24% of the variability and showed incoherence among the three sites. Wavelet analysis of EOF coefficients indicated dominance of >1 week variability in this region. Flow variability may be associated with wind forcing and Loop Current variability as confirmed by satellite altimetry. Wind forcing caused part of the intra-monthly (<1 month) periodicity in flows. Sea level in the area of the Loop Current, as derived from EOF application on altimetry data during the period of velocity measurements, was related to Mode 1 of the currents at sub-monthly (>1 month) periods. The relationship was more robust, but inverse, when comparing sea level off the northwestern coast of Cuba to the Mode 1 of the currents. These results characterize physical connectivity among South Florida coral ecosystems and have biophysical implications for coral fish populations.

1. Introduction

Mesophotic coral reefs develop at intermediate light levels (30-100 m deep, Kahng et al., 2010) and are also referred to as ‘twilight’ reef ecosystems (Brokovich et al., 2008). In contrast to shallow water reefs, mesophotic reefs are typically insulated from the influence of wave action (Lesser et al., 2009) and from high temperature stress (e.g. Hoegh-Guldberg et al., 2007). Still unknown is the potential role of these mesophotic reefs in counteracting massive bleaching on shallow water reefs. A crucial topic that should allow evaluating such role of mesophotic reefs and manage their protection is understanding the connectivity of populations between healthy and degraded ecosystems. Physical connectivity among reef sites can be established through the study of regional current velocity structures. In the Gulf of Mexico, the regional circulation is dominated by the Loop Current – Florida Current system, part of the Gulf Stream western boundary current.

This study aims at providing basic information on flow structures at the Pulley Ridge and Dry Tortugas regions, near the southern edge of the West Florida Shelf at the eastern Gulf of Mexico. Its specific objective is to determine the influence on such flow structures of local wind stresses and of regional circulation patterns, such as the Loop Current variability. This study relies on a unique data set of currents from a mooring array at 3 sites in the study area. This is the first time that long-term (almost 3 years) current velocity profiles have been collected at any mesophotic reef, including the Pulley Ridge and Dry Tortugas. The dataset has already been used to discuss physical and biophysical connectivity around the eastern Gulf of Mexico and the Florida Keys (Kourafalou et al., 2018). The data validated numerical simulations that illustrated the influence of the Loop Current - Florida Current system on local dynamics of the Pulley Ridge and Dry Tortugas reefs. Withdrawal of the Loop Current - Florida Current system from the continental shelf break may favor onshore flows that can carry open-sea waters over the coral reefs. Simulations also showed that only the area over the Northern Dry Tortugas, located farther from the shelf break (Fig. 1), was influenced by the wind. The formation of local cyclonic eddies near the Dry Tortugas can also promote or hinder physical connectivity between these reefs (Kourafalou et al., 2018). Biophysical simulations (Vaz et al., 2016), based on the same hydrodynamic simulations as Kourafalou et al. (2018), indicated mesophotic-shallow connections, with larvae spawned at Pulley Ridge reaching the Florida Keys settlement grounds. The findings of these studies suggest that a combination of regional circulation, wind-induced shelf circulation and eddies associated with the Loop Current – Florida Current system control the connectivity between these mesophotic coral reefs and also impact the circulation at shallower reefs downstream in the Florida Keys. Other factors related to wave shoaling, such as wave-induced currents and wave breaking, might play a role on the local circulation regime (e.g., Sous et al. 2017). Wave-shoaling influence will be appreciable in coastal regions and narrow passages between islands (e.g. Florida Keys). The study area is characterized by open and relatively deep coral reef regions where wind waves remain deep.

Model findings (Kourafalou et al., 2018; Vaz et al., 2016) motivated further verification of connectivity patterns through Empirical Orthogonal Function (EOF) analysis of the moored observations. This analysis illustrated the dominant spatial structures displayed by the flow and described how such spatial structures varied over time. The ultimate project goal is to use a unique data set covering complex circulation patterns around mesophotic reef ecosystems to understand the physical connectivity mechanisms, thus helping managers develop reliable strategies to protect these economically relevant, but environmentally fragile, resources. In addition, the results presented here provide unique information for the understanding of physical connectivity in mesophotic reefs, in tropical and subtropical systems, and in the eastern Gulf of Mexico in particular.

2. Study Area

The mesophotic reefs of the Pulley Ridge region, including Dry Tortugas, are located on the continental shelf of the eastern Gulf of Mexico, west of Florida Keys, between 83ºW and 84ºW, and between 25.4ºN and 25.75ºN (Fig. 1). The reefs are near semicircular shoals between 1 and 15 km in diameter, and between 1 and 10 km from the shelf break, where the Loop Current - Florida Current system evolves in the Straits of Florida. The reefs are scattered over a sloping shelf that increases from 20 to 70 m depth over ~90 km.

The region is forced by tides, heat fluxes and momentum fluxes, including the Loop Current - Florida Current system (Gordon, 1967; Johns et al., 2002) and mesoscale cyclonic eddies (Sponaugle et al., 2005; Kourafalou and Kang, 2012; Kourafalou et al., 2018). At Pulley Ridge, on the basis of nearly 3 years of measurements obtained in this study, the amplitude of the O1 (33.4% of sea level variability) tidal constituent is 0.11 m while the K1 (31.3% of sea level variability) is also 0.11 m. The amplitude for M2 (20.6% sea level variability) is 0.09 m and for S2 (4.6% sea level variability) is 0.04 m. These 4 constituents explain close to 90% of the sea level variability according to the data collected. Other relevant tidal harmonics, contributing >1% of the water level variability, are P1, Q1 (both diurnal), SSA (semiannual), and SA (annual). The ratio of diurnal to semidiurnal amplitudes is 1.7, which indicates a regime of mixed tides with diurnal dominance. Maximum tidal ranges are typically 0.6 m but can reach 0.7 m when the synodic (14.77 days) and declinational (13.66 days) fortnights coincide, while minimum ranges are between 0.1 and 0.15 m. Despite its microtidal regime, tidal variations are prevalent in the currents observed. The inertial period at the latitude of the study (24ºN) is close to 30 h. The study area represents a zone of confluence of the Loop Current -Florida Current system at the shelf break with mixed tidal currents on the west Florida shelf.

Momentum fluxes are related to southward wind stress from October to March and northward from April to September (e.g. Boicourt et al., 1998; Zavala-Hidalgo et al., 2014). Heat fluxes follow the expected annual cycle of heat gain from April to September and heat loss from October to March with perturbations from advective fluxes related to the Loop Current (Etter, 1983). Freshwater influence is appreciable in Florida Bay from May to October (Lee et al., 2006; 2008; Stabenau and Kotun, 2012) but remains shoreward from the Pulley Ridge region. Additional forcing from the Loop Current -Florida Current system depends on incompletely understood processes in the Yucatan channel (Weisberg and Liu, 2017). This current system can provide physical connectivity between the Northern Gulf of Mexico and the Florida Keys (Chang and Oey, 2013; Schiller and Kourafalou, 2014; Le Hénaff and Kourafalou, 2016; Androulidakis et al., 2019), and between the Caribbean reefs and the Florida Keys (Sheinbaum et al., 2002). The study area represents a zone of confluence of wind-driven currents and mixed semidiurnal tidal currents on the shelf, and the Loop Current - Florida Current system at the shelf break.

3. Data collection and analysis

3.1 Data collection

Three bottom-mounted Teledyne RD Instruments Workhorse acoustic Doppler current profilers (ADCPs) were deployed at Pulley Ridge, Southern Dry Tortugas and Northern Dry Tortugas (Fig. 1) concurrently for 27 months. Deployments sought to document the overall temporal and spatial variability of flows at the mesophotic Florida reefs. The three ADCPs were mounted on trawl-resistant frames. A 307.2 kHz ADCP was deployed at Pulley Ridge (24º 42.00380'N, 083º 40.46700'W) in a depth of 66.5 meters, and was the westernmost site. This instrument recorded hourly ensembles of 70 pings with a vertical resolution (bin size) of 4 m from August 16, 2012 to June 20, 2015. A 614.4 kHz ADCP was moored at a depth of 54.3 m at Northern Dry Tortugas (24º 46.45050'N, 083º 05.66814'W) from August 15, 2012 to June 23, 2015. Profiles were recorded in ensembles of 120 pings every hour, also with a 4 m bin size. The mooring at Southern Dry Tortugas (24º 28.54390'N, 083º 09.21180'W) had a 307.2 kHz ADCP at a depth of 66.3 m. Velocity profiles were recorded hourly at 70 pings per ensemble, in 4-m bins, between March 22, 2013 and June 24, 2015.

The ADCP locations were chosen to capture flow structures within the mesophotic coral reef area of Southeast Florida. The site at Pulley Ridge was chosen within the Habitat Area of Particular Concern, to avoid trawling and to minimize possible local bathymetric effects. The Dry Tortugas sites were also chosen to reduce shadowing effects from nearby shoals (e.g., Riley's Hump to the south, Sherwood Forest to the north). Mooring locations had to be outside of the Dry Tortugas preserve areas (if only by a few meters) to minimize permitting challenges.

Wind velocity data and Gulf of Mexico Loop Current position were used to try to explain some of the variability observed in the current profiles at the 3 sites. Wind velocity data were obtained from Vaca Key, Florida station (VCAF1; 24.711º N, 81.107º W) of the National Data Buoy Center of the National Oceanic and Atmospheric Administration in the United States. It is the closest station to the mooring sites with complete data sets. It is also representative of the wind conditions over the southern Western Florida shelf as shown by wind comparisons between different locations over the Pulley Ridge and Tortugas areas (Kourafalou et al., 2018; Androulidakis et al., 2018). Wind speed and direction were obtained at hourly intervals that overlapped the common observational period of the three moorings from March 2013 to July 2015.

Loop Current information was derived from satellite sea surface height anomalies (SSHAs) every 5 days in the Gulf of Mexico on a grid with a spatial resolution of 1/6º (Zlotnicki et al., 2016). Data were retrieved for the period March 2013 to August 2015. Five possible indices were explored to represent the Loop Current. The first index was described with the temporal variability (or coefficients) of the first three EOF of SSHA data, averaged over a horizontal box. This box was selected on the Loop Current position in EOF Mode 1. The three empirical modes, together, explained close to half of the variability of SSHAs (see Section 3.2). The second and third indices for the Loop Current were derived from the average SSHA values in a) the same box selected from the EOFs (second index), and b) a box NW of Cuba, where EOF Mode 1 had a trough (third index). The fourth index was the same index used by Kourafalou et al. (2018), based on the 17 cm sea surface height contour (Leben, 2005). The fifth index was represented by daily values of the Florida Current transport. Values were obtained from a submarine cable, between Florida and Bahamas at the northern Straits of Florida (see Acknowledgments) and were filtered with a Lanczos filter centered at 30 days to eliminate intra-monthly variations.

3.2. Data Analysis

Concatenated, real-vector EOFs (Kaihatu et al., 1998) were calculated for all station data together, to describe the dominant vertical structure (or modes) of currents at the 3 sites and to establish the temporal variability of the dominant modes. Estimates were made on the velocity vectors $\vec{v}(z, t)$, where z is depth and t is time, after tidal and inertial variations were filtered with a Lanczos window (e.g. Thomson and Emery, 2014) centered at 34 h. Velocity vectors $\vec{v}$ were concatenated with the two horizontal velocity components (u, v) at the 3 sites. The concatenated matrix $\boldsymbol{V}$, with the velocity components of the 3 sites, had 70 rows associated with every u and v times series. In essence, the EOF analysis consists of solving the eigenvalue problem associated with the covariance matrix of $\boldsymbol{V}$. The eigenvectors obtained from the eigenvalue problem represent the prevailing velocity profiles. The eigenvalues represent the variance explained by each EOF Mode and the coefficients of the eigenvectors depict the temporal evolution of the current profiles. The EOF analysis synthesized the data collected by the ADCPs and provided information on the dominant structure of the velocity profiles, as well as their temporal variability.

Continuous wavelet transforms (e.g., Torrence and Compo, 1998) converted the temporal variability of EOF modes 1 and 2 of the flow into time-varying spectra, by using a 4th order Morlet wavelet. Wavelet transforms represent here the changes over time of the dominant periods of subinertial variability at each sampling site. Wavelet transforms for EOF Mode 1 of subtidal currents were compared then to the transform of the Loop Current index and to the transform of each component of the wind. The comparison was made through a normalized cross-wavelet, or wavelet coherence. Wavelet coherence between pairs of variables allowed determination of instances when flow variability was consistent with the Loop Current - Florida Current system or with wind. Each of the analyses outlined above is presented next as performed on the measured time series.

4. Results

This section presents the low-pass filtered velocity components to compare qualitatively the variability at the 3 sites. Subsequent results obtained from the EOF analyses put such a qualitative comparison into statistical context. The spatial structure of modes 1 and 2 is then placed in the regional perspective. Nearly depth-independent flows represent these 2 modes, which together explain 87% of the variability throughout the 27 months of measurements. Ensuing portrayal of wavelet power spectra of the time series of current velocity EOF modes 1 and 2 illustrates instances of most energetic flow and their typical period of variability. EOF

Mode 1 of subtidal currents is then compared qualitatively to a Loop Current index and to the wind velocity components. The qualitative relationships are then explored statistically with the wavelet transform of EOF 1 being compared to that of the Loop Current index and of the wind velocity components.

4.1 Low-pass filtered velocities

Flows at Pulley Ridge were predominantly southeastward (Fig. 2), consistent with the direction of the Loop Current transport from the Gulf of Mexico toward the Florida Current genesis. The zonal component of subtidal velocity at Pulley Ridge (PR in Fig. 2) was predominantly positive (eastward), while the meridional component was mainly negative (southward). There were periods at Pulley Ridge with direction reversals, such as March to July 2014 and October 2014, with negative zonal component and positive meridional component. The subtidal flow speed at this location showed a tendency to decrease throughout the period of observations. There were pulses of up to 1 m s^{-1} from March 2013 to November 2013 that were related to the Loop Current proximity to Pulley Ridge (Kourafalou et al., 2018). Flows at Southern Dry Tortugas (SD in Fig. 2) were similar to those at Pulley Ridge only at a few instances such as between March and July 2014 and in early May 2015. In general, Southern Dry Tortugas current distribution was more similar to Northern Dry Tortugas (ND in Fig. 2) than to Pulley Ridge, most notably in the meridional (north) component and during 2013 and early 2014. This cursory inspection of the low-pass filtered velocities leaves unanswered questions on how the flow structure was related from station to station. Analysis with the EOFs sheds light onto the interrelationship among sites and their response to distinct forcings.

4.2 EOF Analysis

Results from EOFs indicated that subtidal unidirectional flow, as portrayed by modes 1 and 2 together, explained 87% of the variance. Eigenvectors provided the horizontal and vertical structure of the flow fields (Fig. 3). Mode 1 showed that the flow direction at the 3 sites ranges inside the same quadrant, even within 30º. At each location, the flow veered clockwise with depth <20º but maintained the same general direction. The structure of Mode 1, which explained 63% of the variance of the flow may suggest interconnectivity among all sites, except where the flow was nearly parallel (between Southern and Northern Dry Tortuga). Connectivity from Southern Dry Tortugas to Pulley Ridge may have occurred when Mode 1 coefficients were negative. The same could be said about connectivity from Northern Dry Tortugas to Pulley Ridge. In fact, a reconstruction of Mode 1 showed very similar flow at the 3 sites after December 2013 (Fig. 4a). At the beginning of the time series, Mode 1 was similar at Pulley Ridge and Southern Dry Tortugas, although weaker at the latter. In general, Mode 1 flows were strongest at Pulley Ridge (both components). Eigenvectors of Mode 1 reveal a stronger connectivity between the two reefs near the shelf-break (subject to oceanic current influence) than connectivity of either shelf-break site with a location on the shelf interior. The site on the shelf is primarily influenced by shelf currents.

Eigenvectors for Mode 2 showed flows with the same sign in the zonal component at Northern and Southern Dry Tortugas (Fig. 3). The flow structure appeared divergent for positive instances of the EOF coefficients but illustrated possible connections from Southern Dry Tortugas to Pulley Ridge and from Northern Dry Tortugas to Pulley Ridge with negative EOF coefficients. At the 3 sites, Mode 2 showed very little veering with depth, i.e., smaller (<15°) direction change than Mode 1. However, Mode 2 eigenvectors at the Dry Tortugas sites had larger vertical shears, i.e., larger differences in surface minus bottom speeds, than Mode 1 eigenvectors. The reconstructed Mode 2 (Fig. 4b) illustrated these concepts by displaying practically no resemblance among sites. Southern Dry Tortugas exhibited the strongest flows associated with this mode. The variability related to modes 1 and 2 was explored in detail with wavelet transforms.

4.3 Wavelet Transforms of EOF Subtidal Flows

The wavelet transform of the time series of Mode 1 coefficients for the subtidal flow (Fig. 5a) showed monthly to seasonal variability (Fig. 5b). This is illustrated by the spectral energy of Mode 1 being statistically significant at the 95% level (inside the thick contour of Fig. 5b) and persistent throughout the observation period. The most energetic variability occurred at periods of around 40, 90, and 120 days (Fig. 5b). Tidal fortnightly (13.6 and 14.7 days), as well as tidal monthly (27.6 and 29.5 days), periodicities were influential in the Mode 1 signal. Synoptic variability of 10 days was sporadic and of lesser energy than the variability with periods greater than one fortnight. Synoptic variability was greatest in 2013 and decreased toward 2015, as indicated by the downward sloping contour of 95% statistical significance (Fig. 5b). For Mode 2 (Fig. 6a), the wavelet power spectrum showed similar variability as Mode 1 in terms of dominant periodicities. There were persistent energetic variations at periods >120 days (Fig. 6b). Prominent periodicities also occurred at around 40 days in the autumn of 2014 and at near 60 days in late-summer of 2013 and 2014. As with Mode 1, synoptic variability of Mode 2 decreased from 2013 to 2015. Modes 1 and 2 of subtidal flows showed their greatest variability (largest wavelet spectral amplitude) at periods greater than 1 month.

4.4 Loop Current - Florida Current System

The data set of sea surface height anomalies (SSHA) was also analyzed with EOFs to try to identify an effective Loop Current index. In turn, the index could serve to link the variability to the currents in the Pulley Ridge area. Results of the EOF analysis on the SSHA for the same observational ADCP period (27 months) are shown in Fig. 7. Eigenvectors are portrayed in maps of sea surface height in the Gulf of Mexico. Mode 1 describes a sea-surface bulge in the gulf's central part, flanked by two depressions to the east and west. This spatial structure is related to the positive coefficients of Mode 1 that occurred after February 2014 (Fig. 7). During the first year of measurements, the subtidal currents exceeded 0.5 m s^{-1} at the Pulley Ridge region as they flowed southeastward (Figs. 2 and 4a). Prior to February 2014, Mode 1 coefficients were negative (Fig. 7) so the bulges on the Mode 1 map had opposite signs. Mode 1 explained only ~21% of the variability of sea levels in the region so, by itself, it is not representative of an index for Loop Current activity. Mode 2 explained almost as much variability as Mode 1 (~18%), while its horizontal structure shows a short-amplitude Loop Current meandering around northwestern Cuba (Fig. 7). Mode 2 also showed a sea level bulge toward the northern gulf, south of the Mississippi Delta. The coefficients of Mode 2 displayed a clear annual cycle with peaks in October and troughs in March-April. Mode 3 and Mode 4 displayed more bulges and troughs than modes 1 and 2. Their temporal variability maintained their sign for longer periods than the other two modes. Despite the signal deconstruction, it is challenging to derive a Loop Current index that relates to the flow variability at the Pulley Ridge region.

Alternative indicators were explored further with the AVISO SSHA data. Sea level at the typical Loop Current location (average in the northwestern square of maps on Fig. 7) could be used as a proxy for Loop Current activity. This signal (Fig. 8a) was similar to an index implemented in Kourafalou et al. (2018), which was based on water temperature fields. Both Loop Current indicators had similar variability in 2014 and 2015 (Fig. 8a) but diverged in 2013. The index based on water level had long-term variations that emulated, at least qualitatively, Mode 1 subtidal currents at Pulley Ridge (Fig. 8a).

Another indicator of Loop Current activity was sought with AVISO sea level values just to the northwest (NW) of Cuba. An index was determined from mean values in the southeastern square of maps of Figure 7, a usual area of Florida Current evolution. It could also be regarded as a ‘young’ Loop Current position. This water level signal off NW Cuba, still inside the Gulf of Mexico, had remarkably similar variations to the normalized Florida Current transport (Fig. 8b). Variations at shorter periods were disparate, relative to Mode 1 of subtidal currents.

Qualitatively, the Florida Current and the sea level off NW Cuba had an inverse relationship to Mode 1 subtidal current variations at the Pulley Ridge region (Fig. 8b). The qualitative relationships between currents at Pulley Ridge and Dry Tortugas (Mode 1) and remote forcing indicate that, for the most part, when the Loop Current bulges up in the inner Gulf of Mexico, sea levels drop off NW Cuba. Ultimately, this relationship could be the linkage between ‘young’ and ‘extended’ phases of the Loop Current, which should be explored in the future. Most evident is the result that subtidal currents in the Pulley Ridge-Dry Tortugas region (Mode 1) respond inversely to water levels off northern Cuba, a precursor to the Florida Current. Mode 1 of subtidal currents is compared to wind velocity components next.

4.5 Wind Forcing

Another potential driver of the subtidal variability in the flow around Pulley Ridge-Dry Tortugas is wind. The wind components can be compared qualitatively to EOF modes 1 and 2 of the subtidal flows (Fig. 9a). The eastward wind component was mostly negative throughout the period of measurements, consistent with the influence of the Trade Winds, which blow westward (Fig. 9b). There were sporadic eastward wind events, being most persistent in the period from December 2013 to February 2014. These persistent eastward winds also had a southward component associated with typical winter northwesterlies in the northern and eastern Gulf of Mexico. The northward wind component displayed near-semiannual variations with southward wind appearing mainly in the fall and winter (Fig. 9b). During the summer, this component was positive but weaker than in the rest of the year as winds were dominated by the Trades influence. Qualitatively, winds show no discernible relationship with modes 1 or 2 of subtidal currents (Fig. 9). In periods longer than one month, subtidal flows and winds overall seem to be disconnected. At intra-monthly scales, there may be occasional relationship that requires further scrutiny. The relationships between subtidal flows and Loop Current, as well as the linkage between subtidal currents and wind forcing, are explored in the Discussion with wavelet coherence analysis.

5. Discussion

Subtidal flow variability in the Pulley Ridge area was related to Loop Current structure and to wind forcing at different temporal scales, in agreement with numerical model results (Kuorafalou et al., 2018). Quantitative linkages are explored in time, throughout the observation period, and as a function of frequency (or period) of variability via comparison of the continuous wavelet transform of each variable. Although the subtidal flow variability is highly heterogeneous in space and time (Figs. 3 to 8), wavelet coherence analysis identified portions of the record when variables were related and at what periods of variability. Figures 3 to 8 suggest that there was no persistent response of the flow at Pulley Ridge to forcing from Loop Current or wind. However, there were periods of clear Loop Current influence when approaching the Pulley Ridge area, as in several months at the end of 2013. Some generalities could be drawn from the wavelet coherence analyses described next.

Values of wavelet coherence between Loop Current index (black line in Fig. 8a) and Mode 1 of subtidal current wavelets (Fig. 10a) were statistically insignificant most of the time. Only at the beginning of the observation period there was a direct relationship between the two, at fluctuations near one month. Other significant values appeared intermittently at periods between 20 and 60 days (Fig. 10a). These are the portions on the diagram that are encircled by a black contour and that show vectors. However, these apparent relationships had changing phases (arrows changing directions) that made no physical sense (Grinsted et al., 2004).

In contrast to the Loop Current index-Mode 1 relationship, the wavelet coherence between water level off NW Cuba (Fig. 8b) and Mode 1 subtidal currents at Pulley Ridge (Fig. 10b) had ~5-month fluctuations that were strongly coherent throughout the observation period. The coherence between these fluctuations appear as a red band limited by a black contour, centered at around 150 days (Fig. 10b). Because the arrows in that band are pointing roughly to the left, Mode 1 and water level off NW Cuba were in near antiphase at those periodicities. Antiphase between the variables indicated that decreases in water level off NW Cuba were associated with increases of southeastward flows at the Pulley Ridge-Dry Tortugas Region. A similar response with significant coherence (>95% confidence limit) occurred in fluctuations with periods of ~2 months, centered at ~64 days, after mid-2014. The first few months of the records were also coherent at 60 to 90 days (Fig. 10b) albeit falling outside the cone of influence (Torrence and Compo, 1998), meaning that the relationship was tentative at that time. Thus, part of the variability of currents in Pulley Ridge-Dry Tortugas could be related to remote forcing related to the Loop Current - Florida Current system, as a ~5-month fluctuation appeared at both records throughout the period of observations. An enhanced version of a Loop Current index is needed to improve the exploration of the relationship between Loop Current and currents at Pulley Ridge. Because it is challenging to constrain the Loop Current in terms of its position, of the value of its surface topography, of its water temperature or of its flow conditions, future efforts shall attempt to determine linkages with flows near the Yucatan channel. Sea levels off NW Cuba, which are dominated by a 'young' phase of the Loop Current may provide a promising index of such linkage. The next step was to investigate wind forcing.

The coherence of wavelet power spectra between the two components of wind velocity and subtidal currents Mode 1 (Fig. 11) displayed sporadic linkages at periods <1 month. The zonal component of the wind (Fig. 11a) was coherent with subtidal currents practically throughout the period of observations, albeit at different intra-monthly periodicities. However, autumn and winter displayed the most significant coherence between these two variables. For example, coherence squared between these two variables was statistically significant in late 2013 and early 2014 at periods between 8 and 20 days. Similar response was recorded in late 2014 and early 2015. The phase lag between eastward wind and subtidal currents was 180° (arrows pointing leftward). This antiphase indicated that westward winds caused eastward currents at intra-monthly periodicities. Moreover, most of 2014 exhibited significant coherence at periods between 2 and 6 months.

The meridional component of wind (Fig. 11b) had less persistent periods with statistically significant coherence than the east component throughout the observation span. Variations <1 month were also most prevalent in winter and autumn, when southward winds were strongest. However, phases were inconsistent from one coherent period to another. Only two periods, one in early 2014 and one in the autumn of 2014 (Fig. 11b), were consistent in their 90° phase lags. This indicated a quadrature relationship between northward winds and currents in which maximum currents were reached at the end of a northward pulse. Although eastward winds seem to have been more influential than northward winds in the subtidal flow records, it was evident that intra-monthly variations of wind influenced the flow at those periods.

It was also apparent that subtidal currents over the southern West Florida Shelf result from an interaction between remote (Loop Current) and local (wind) forcing that is more complex than the description presented here. The analyses carried out with the subtidal flow considered only EOF Mode 1, which explained 63% of the observed variability. This Mode described depth-independent flows moving in roughly the same direction at the 3 sites sampled. Therefore, the analyses disregarded part of the variability that is more heterogeneous. The spatial structure of the flow in the area is likely to describe eddies and recirculations, which were not well defined in the records and not discussed. However, these eddies were evident in Kourafalou et al. (2018), when combining mooring data with model simulations and satellite observations. Three moored records of current velocities, alone, were insufficient to decipher such complexity. A study solely based on *in situ* observations will require a much denser coverage of measurements that resolve shelf, shelf-slope exchange, and remote processes.

6. Conclusion

Current velocity profiles were recorded for ~2.5 years at 3 sites on the southern West Florida Shelf. Records documented shelf flows in a gulf with mesophotic corals greatly influenced by a looping western boundary current. Results described the complexity of the flows at the transition zone between a western boundary current (regional branches of the Gulf Stream) and the shelf. Analyses of the velocity profiles found that most of the variability was represented by nearly depth-independent flows moving approximately in the same direction at the 3 sites sampled (EOF Mode 1). These flows were likely driven by remote forcing via the Loop Current in extended (gulf interior) and retracted (near NW Cuba) phases at sub-monthly periodicities (>1 month) and by local forcing (winds) at intra-monthly periodicities (<1 month). Flow variability related to more complex spatial structures is likely linked to the nuanced morphologic changes in the area where the Florida Current interacts with shelf currents. Flows moving in the same direction at the three sites sampled (EOF Mode 1) indicated more robust connectivity between Pulley Ridge and Southern Dry Tortugas than between Northern Dry Tortugas and either of the other two sites. This reveals that connectivity was stronger between the two reefs near the shelf-break (subject to oceanic current influence) than with a location on the shelf interior, which was influenced primarily by shelf currents.

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References

Androulidakis, Y., Kourafalou, V., Özgökmen, T., Garcia‐Pineda, O., Lund, B., Le Hénaff, M., Hu, C., Haus, B.K., Novelli, G., Guigand, C. and Kang, H. (2018) Influence of river‐induced fronts on hydrocarbon transport: A multiplatform observational study. Journal of Geophysical Research: Oceans, 123(5), pp.3259-3285.

Boicourt W. C., W. J. Wiseman Jr., Valle-A. Levinson and L. P. Atkinson (1998) Continental shelf of the southeastern United States and the Gulf of Mexico: In the shadow of the western boundary current. In: The sea, vol. 11 (A. R. Robinson and K. H. Brink, Eds.). John Wiley, Hoboken, N. J., pp. 135-182.

Brokovich E, Einbinder S, Shashar N, Kiflawi M, Kark S (2008) Descending to the twilight-zone: changes in coral reef fish assemblages along a depth gradient down to 65 m. Mar Ecol Prog Ser 371:253–262.

Chang, Y.-L., & Oey, L.-Y. (2013). Loop Current growth and eddy shedding using models and observations: Numerical process experiments and satellite altimetry data. J. Phys. Oceanogr., 43, 669–689. https://doi.org/10.1175/JPO-D-12-0139.1

Etter P.C. (1983) Heat and freshwater budgets in the Gulf of Mexico. J. Phys. Oceanogr., 3, 2058-2069.

Grinsted, A., J.C. Moore, S. Jevrejeva (2004) Application of the cross-wavelet transform and wavelet coherence to geophysical time series. Nonl. Proc. Geophys 11, 561-566.

Gordon, A (1967) Circulation of the Caribbean Sea. Journal of Geophysical Research 72 (24): 6207–6223.

Hoegh-Guldberg, H., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, *et al.* (2007) Coral reefs under rapid climate change and ocean acidification, Science, 318, 1737–1742.

Johns, W., T. Townsend, D. Fratantoni, W. Wilson (2002) On the Atlantic Inflow to the Caribbean Sea. Deep-Sea Research Part I: Oceanographic Research Papers 49 (2): 211–243.

Kahng, S.E., Garcia-Sais, J.R., Spalding, H.L. et al. (2010) Community ecology of mesophotic coral reef ecosystems. Coral Reefs 29, 255–275. https://doi.org/10.1007/s00338-010-0593-6

Kaihatu, J.M., R.A. Hanadler, G.O. Marmorino, L.K. Shay (1998) Empirical orthogonal function analysis of ocean surface currents using complex and real-vector methods. Journal of Atmospheric and Ocean Tedchnology. 15, 927-941.

Kourafalou V., Androulidakis, Y.S., Kang, H., Smith, R.H., Valle-Levinson, A. (2018) Physical connectivity between Pulley Ridge and Dry Tortugas coral reefs under the influence of the Loop Current/Florida Current system. Progress in Oceanography, 165, 75-99.

Leben, R.R. (2005). Altimeter-derived loop current metrics. Circulation in the Gulf of Mexico: Observations and Models. In: Sturges, W., Lugo-Fernandez, A. (Eds.), American Geophysical Union, pp. 181–201.

Lee, T.N., E. Johns, N. Melo, R.H. Smith, P. Ortner, and D. Smith (2006) On Florida Bay hypersalinity and water exchange. Bulletin of Marine Science 79(2):301–327.

Lee, T.N., N. Melo, E. Johns, C. Kelble, R.H. Smith, and P. Ortner (2008) On water renewal and salinity variability in the northeast subregion of Florida Bay. Bulletin of Marine Science 82(1):83–105.

Lesser, M.P., M. Slattery, J.J. Leichter (2009) Ecology of mesophotic coral reefs. J. Exper Mar Biol Ecol 375:1-8.

Sheinbaum, J. J., Candela, A., Badan, & J. Ochoa (2002) Flow structure and transport in the Yucatan channel. Geophysical Research Letters, 29(3), 1040. https://doi.org/10.1029/2001GL013990

Sous, D., Chevalier, C., Devenon, J.L., Blanchot, J. and Pagano, M. (2017) Circulation patterns in a channel reef-lagoon system, Ouano lagoon, New Caledonia. Estuarine, Coastal and Shelf Science, 196, 315-330.

Sponaugle, S., T.N. Lee, V.H. Kourafalou and D. Pinkard (2005). Florida Current frontal eddies and the settlement of coral reef fishes. *Limnology and Oceanography,* 50: 1033-1048.

Stabenau, E., and K. Kotun (2012) Salinity and Hydrology of Florida Bay: Status and Trends 1990–2009. National Park Service, Everglades National Park, South Florida Natural Resources Center, Homestead, FL. Status and Trends Report. SFNRC Technical Series 2012:1. 39 pp

Thomson, R.E. and W. Emery (2014) Data Analysis Methods in Physical Oceanography, 3rd Edition. Elsevier Science, 728 pp.

Torrence, C. and G.P. Compo (1998) A practical guide to wavelet analysis. Bull. Amer. Meteo. Soc., 79(1), 61-78.

Vaz, A.C., Paris, C.B., Olascoaga, M.J., Kourafalou, V.H., Kang, H. and Reed, J.K. (2016) The perfect storm: match-mismatch of bio-physical events drives larval reef fish connectivity between Pulley Ridge mesophotic reef and the Florida Keys. Continental Shelf Research, 125, pp.136-146.

Weisberg, R.H. and Y. Liu (2017) On the Loop Current penetration into the Gulf of Mexico, J. Geophys Res, Oceans, 122,12, 9679-9694, https://doi.org/10.1002/2017JC013330.

Zavala-Hidalgo, J., R. Romero-Centeno, A. Mateos-Jasso, S.L. Morey, B. Martinez-Lopez (2014) The response of the Gulf of Mexico to wind and heat flux forcing: what has been learned in recent years? Atmosfera, 27(3), 317-334.

Zlotnicki, Victor; Qu, Zheng; Willis, Joshua. 2016. JPL MEaSUREs Gridded Sea Surface Height Anomalies Version 1609. Ver. 1609. PO.DAAC, CA, USA. Dataset accessed [2018-12-05] at http://dx.doi.org/10.5067/SLREF-CDRV1.

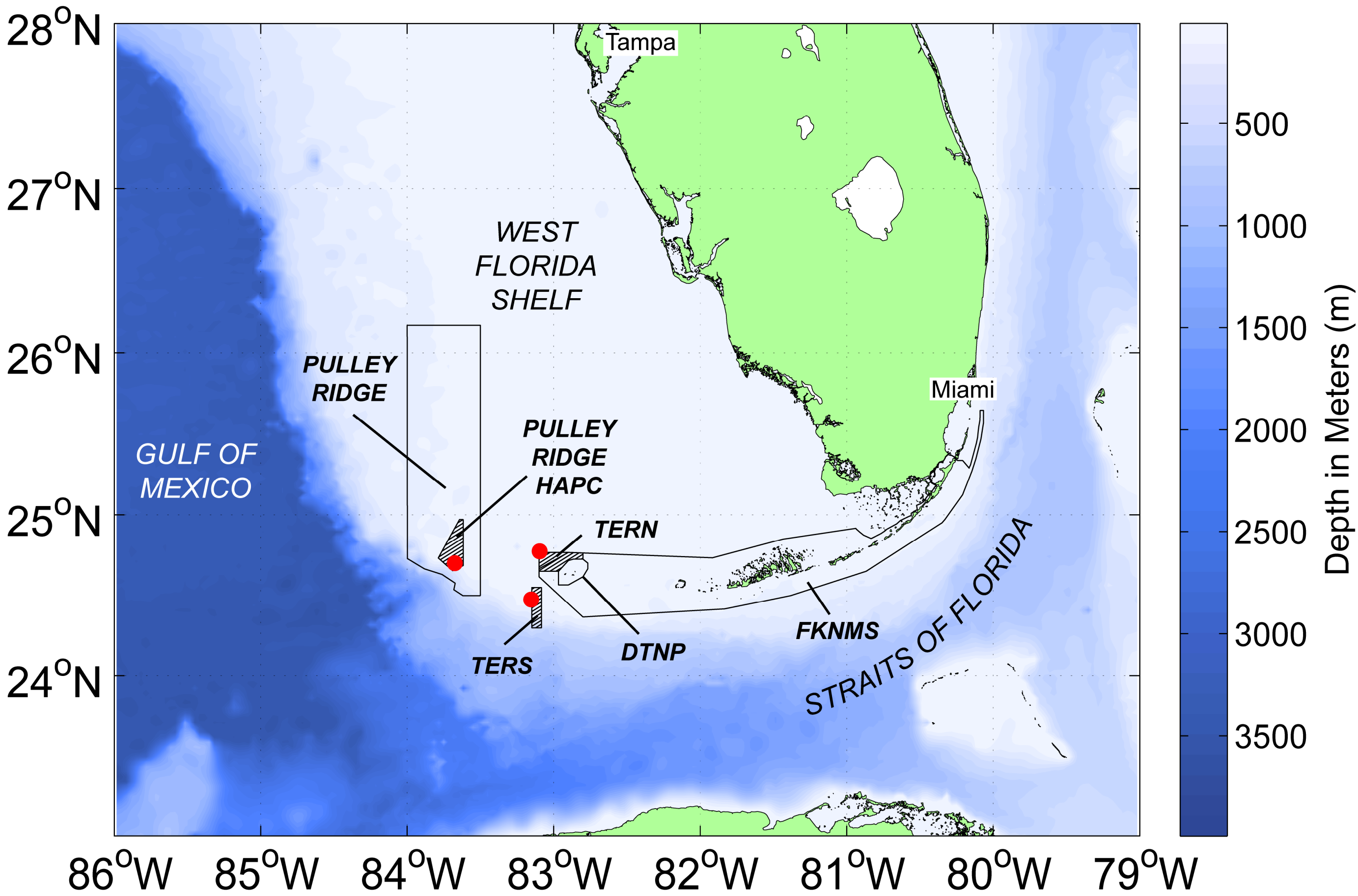


Figure 1. Study area in the eastern Gulf of Mexico, including the West Florida Shelf and Straits of Florida. Red markers represent moored ADCP locations at Pulley Ridge (Habitat Area of Particular Concern, HAPC), in the Northern Dry Tortugas (near Tortugas Ecological Reserve North, TERN), and in the Southern Dry Tortugas (near the Tortugas Ecological Reserve South, TERS). The boundaries of the Dry Tortugas National Park (DTNP) and the Florida Keys National Marine Sanctuary (FKNMS) are also shown for reference.

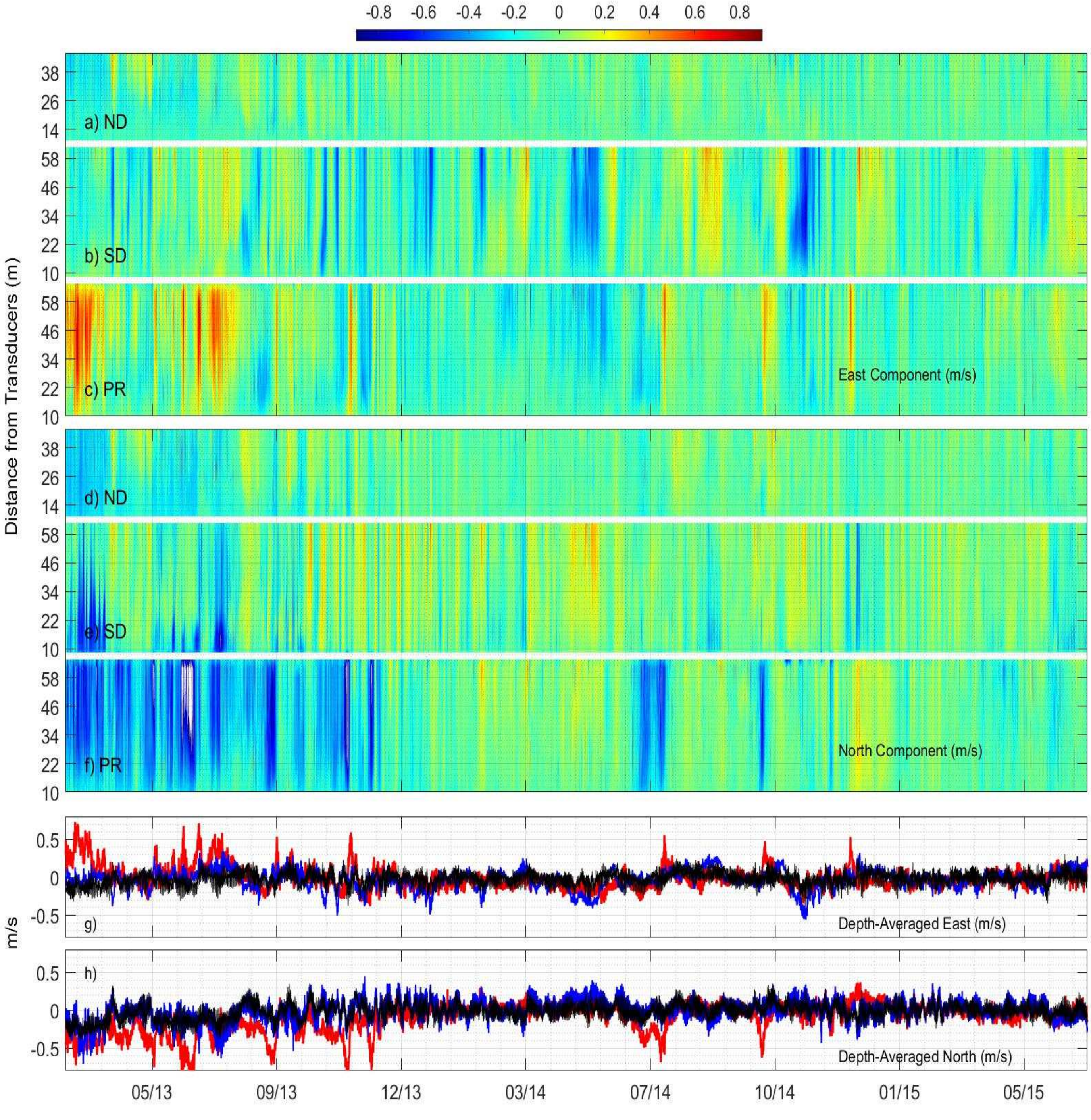


Figure 2. Low-pass filtered flow components (m s^{-1}) at the 3 sites during 27 months. a), b) and c) show the east component of the flow; d), e) and f) show the north component. PR is Pulley Ridge, SD is Southern Dry Tortugas, and ND is Northern Dry Tortugas. The vertical axis displays the approximate upward distance from the bottom at each one of the three sites. Positive

values (red) represent eastward and northward flow components. Panels g) and h) display the corresponding depth-averaged values for PR in red, SD in blue and ND in black.

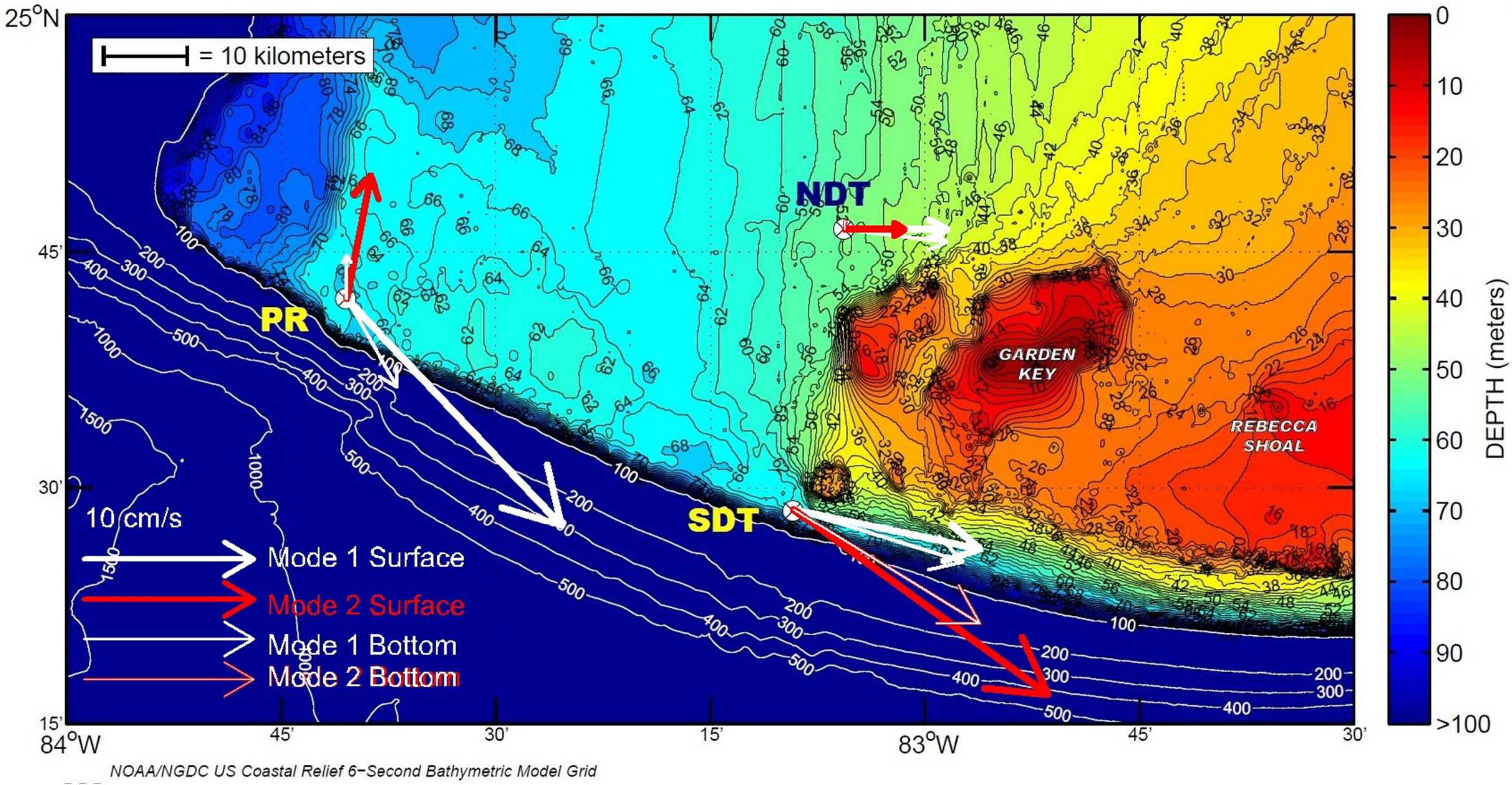


Figure 3. Vector EOF Modes 1 and 2 at surface and bottom. Pulley Ridge (PR), Northern Dry Tortugas (NDT), Southern Dry Tortugas (SDT). Mode 1 explained 63.1% of the variability, while Mode 2 explained 23.9%.

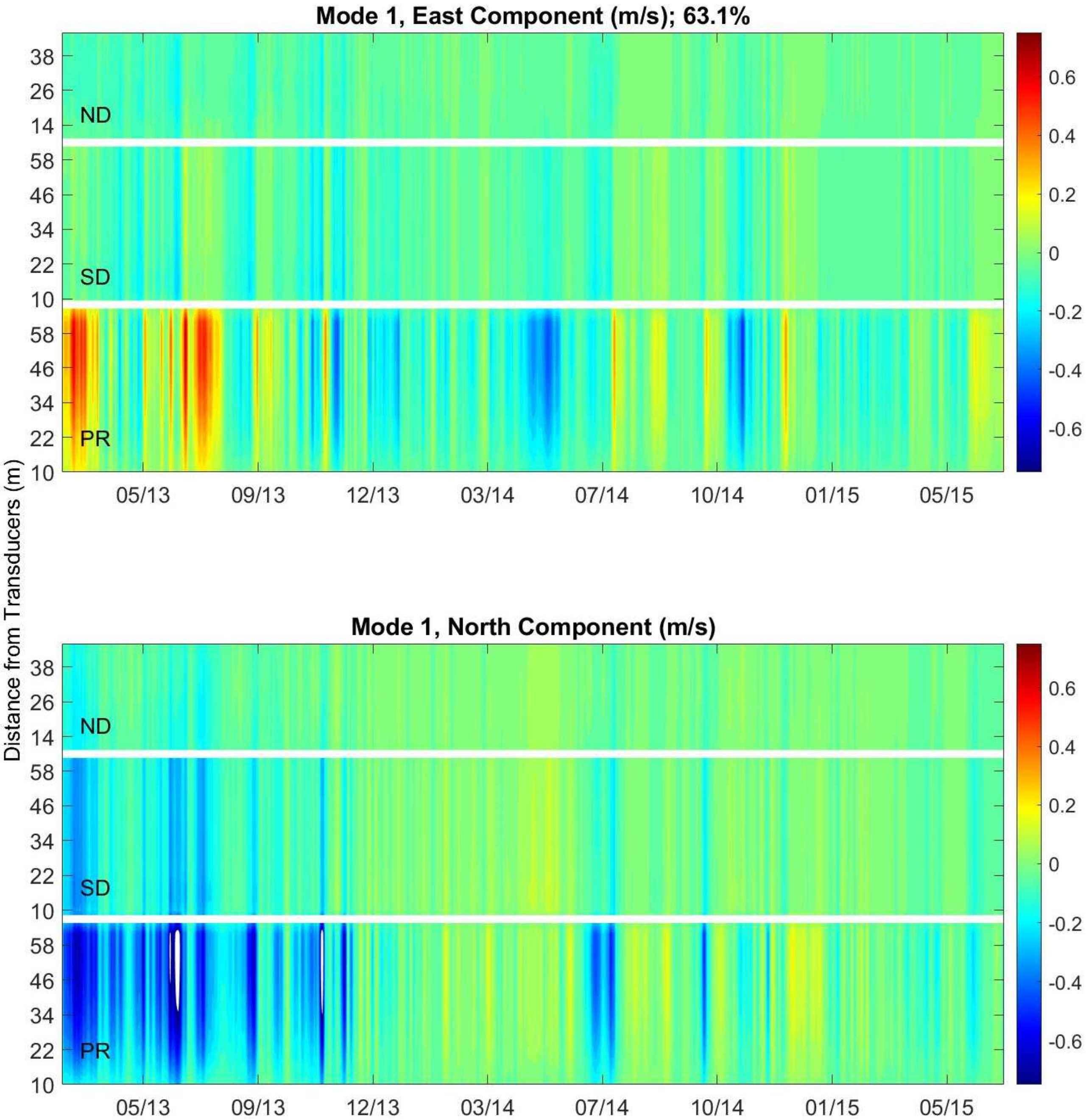


Figure 4a. Reconstructed EOF Mode 1. PR – Pulley Ridge; SD – Southern Dry Tortugas; ND – Northern Dry Tortugas. Explanation of figure is the same as Figure 2.

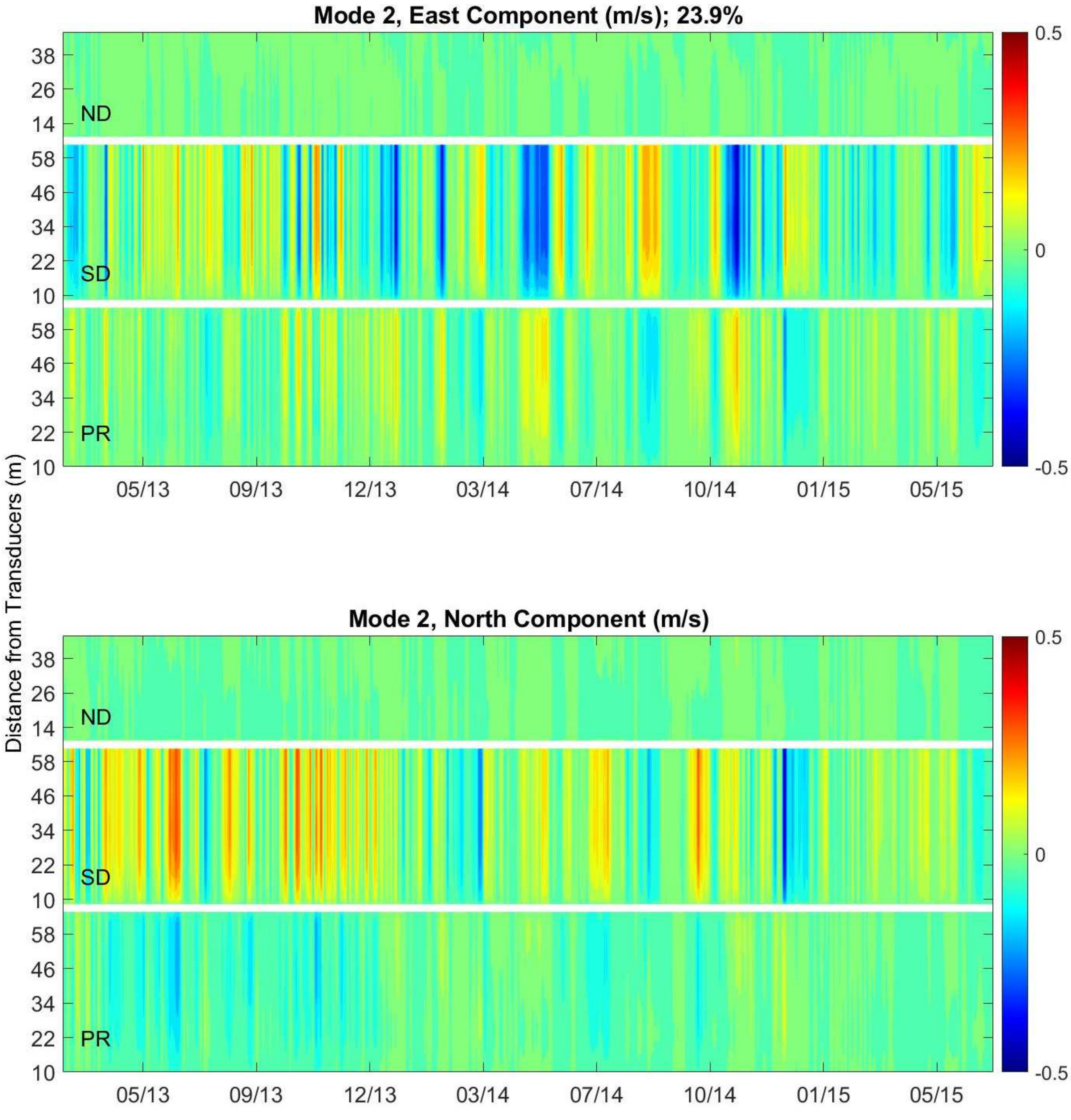


Figure 4b. Same as Figure 4a, but reconstructed EOF Mode 2.

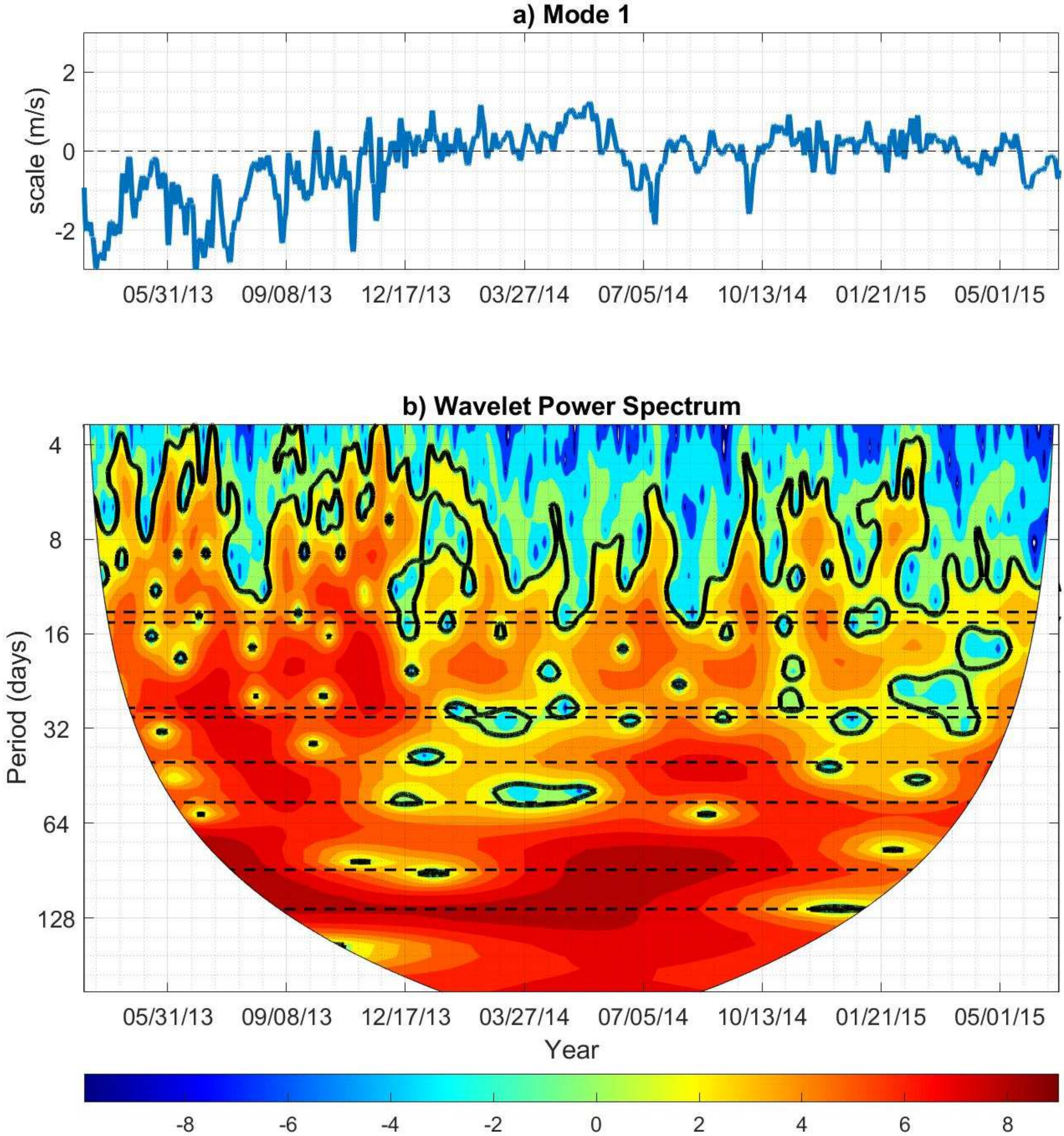


Figure 5. a) Scales or coefficients of Mode 1 shown in Figure 4a. b) Wavelet power spectrum (Morlet 4 wavelet) of EOF Mode 1 for subtidal currents. The 95% significance level is shown as a black contour. Horizontal dashed lines indicate periods, in days, of 13.7, 14.8, 27.6, 29.5, 41, 55, 90, and 120.

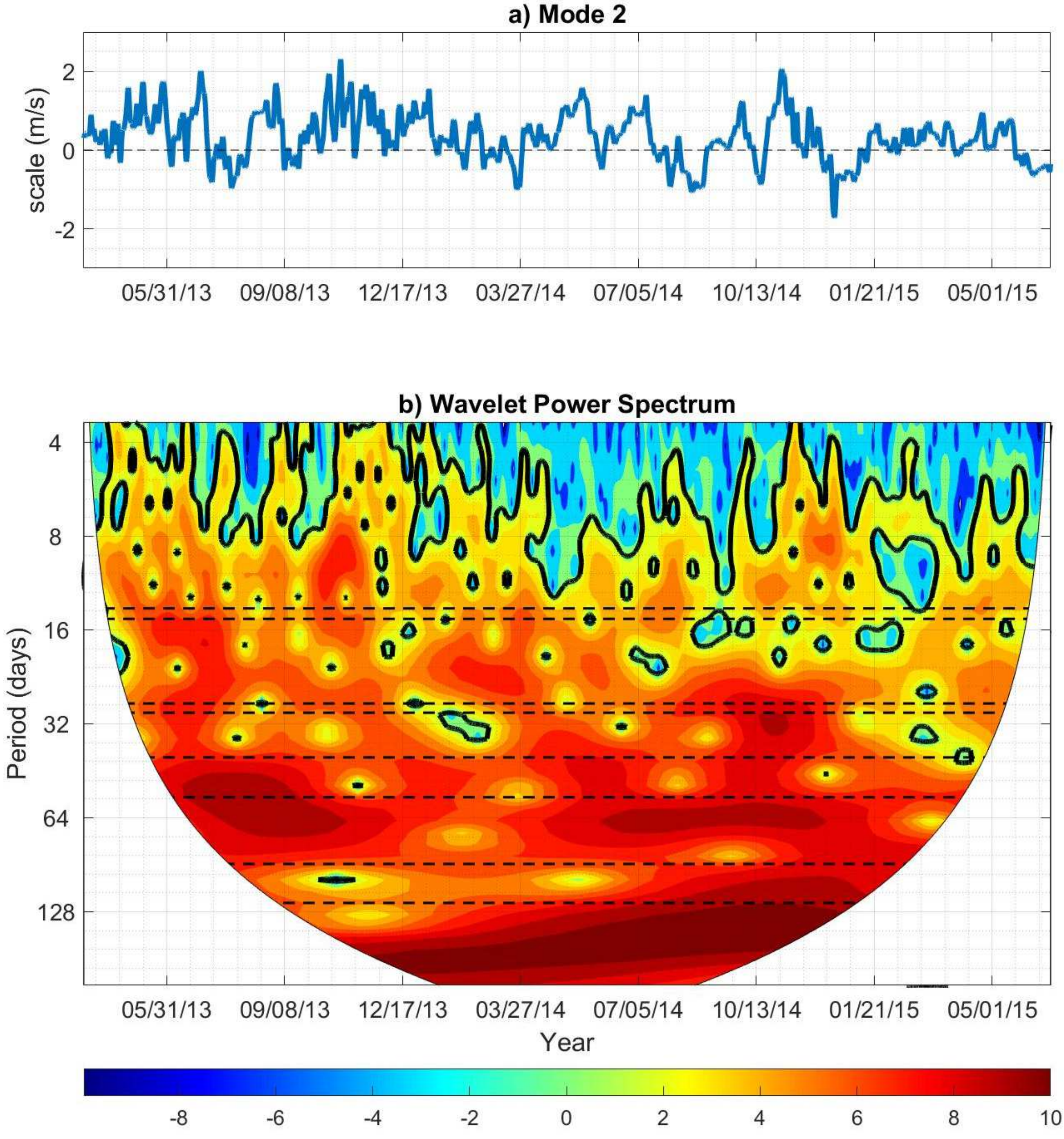


Figure 6. a) Scales or coefficients of Mode 1 shown in Figure 4b. b) Wavelet power spectrum (Morlet 4 wavelet) of Mode 2 for subtidal currents. Same as Figure 5.

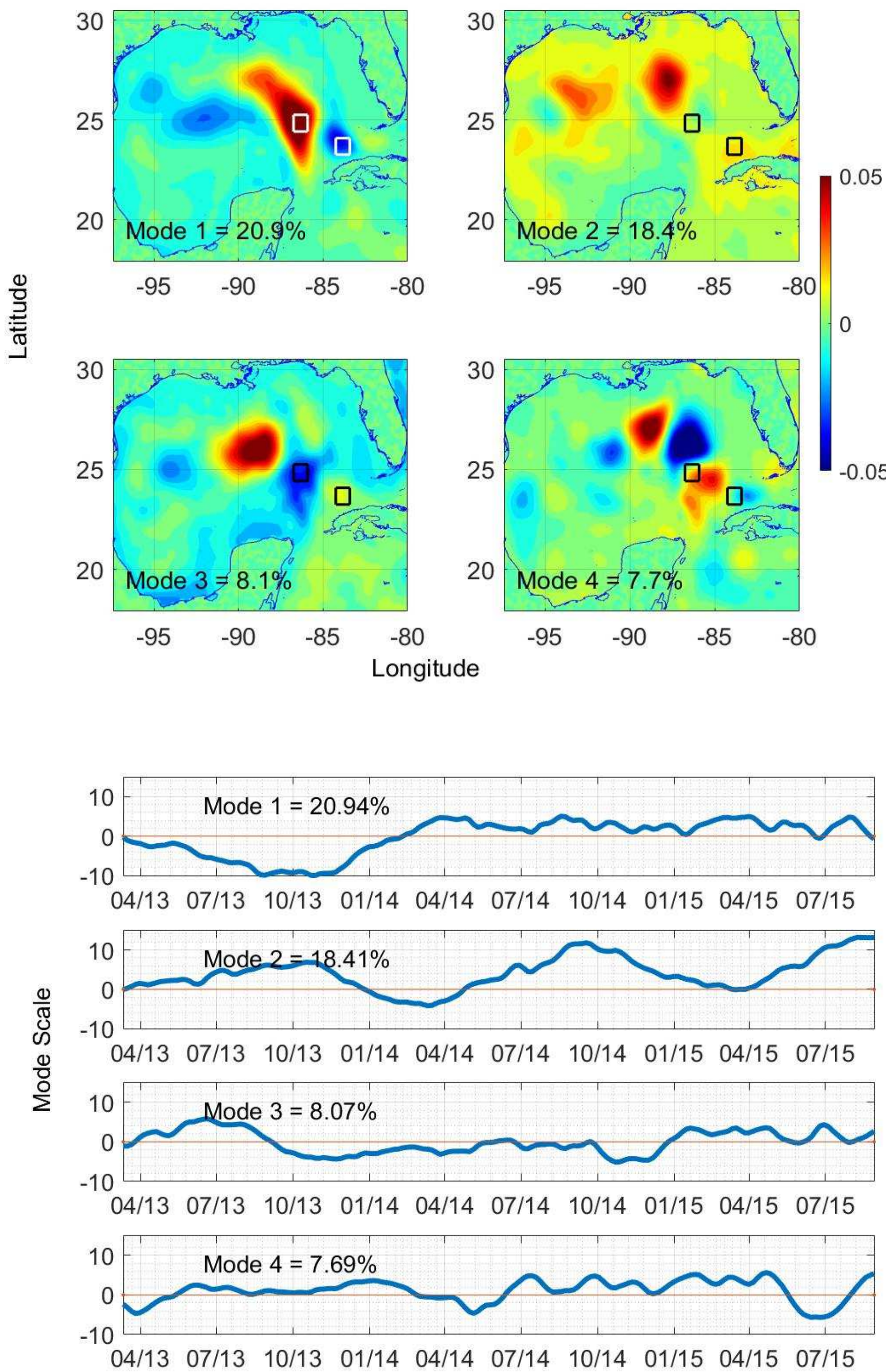


Figure 7. EOF analysis of SSHA for the period of ADCP observations. Shown on top are maps of first 4 eigenvectors and underneath are corresponding coefficients varying in time. Squares on maps indicate contrasting sites of water level variability shown in Figure 8.

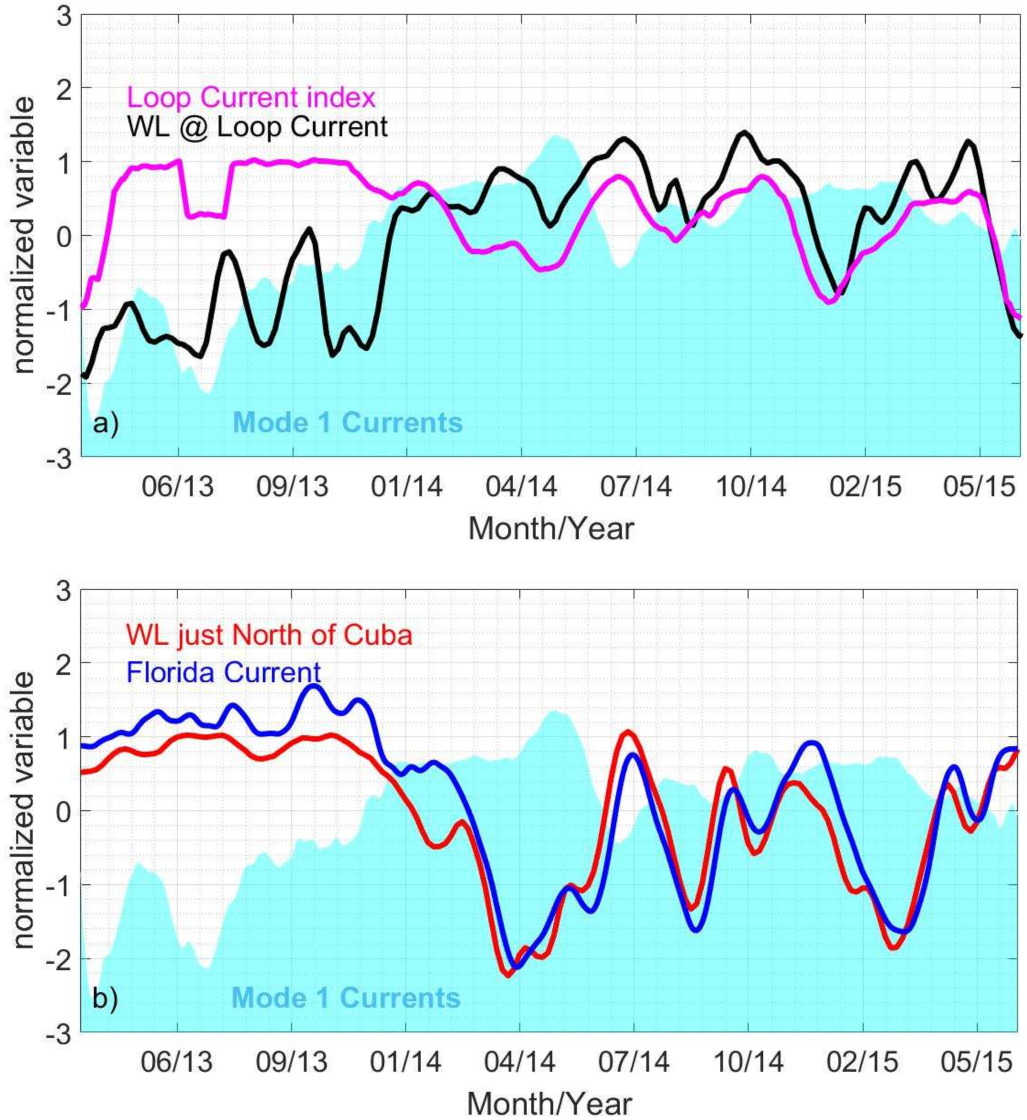


Figure 8. EOF Mode 1 for subtidal currents (shaded cyan signal) compared to Loop Current and Florida Current indices. a) The water level at Loop Current (WL @ Loop Current, black line) is the avearge at the northwestern square on the maps of Figure 7. The magenta line is derived from Kourafalou et al. (2018). b) The water level (WL) off the north coast of Cuba (red line) is the average of the southeastern square on the maps of Figure 7. All time series have been normalized by subtracting their mean and dividing by their standard deviation.

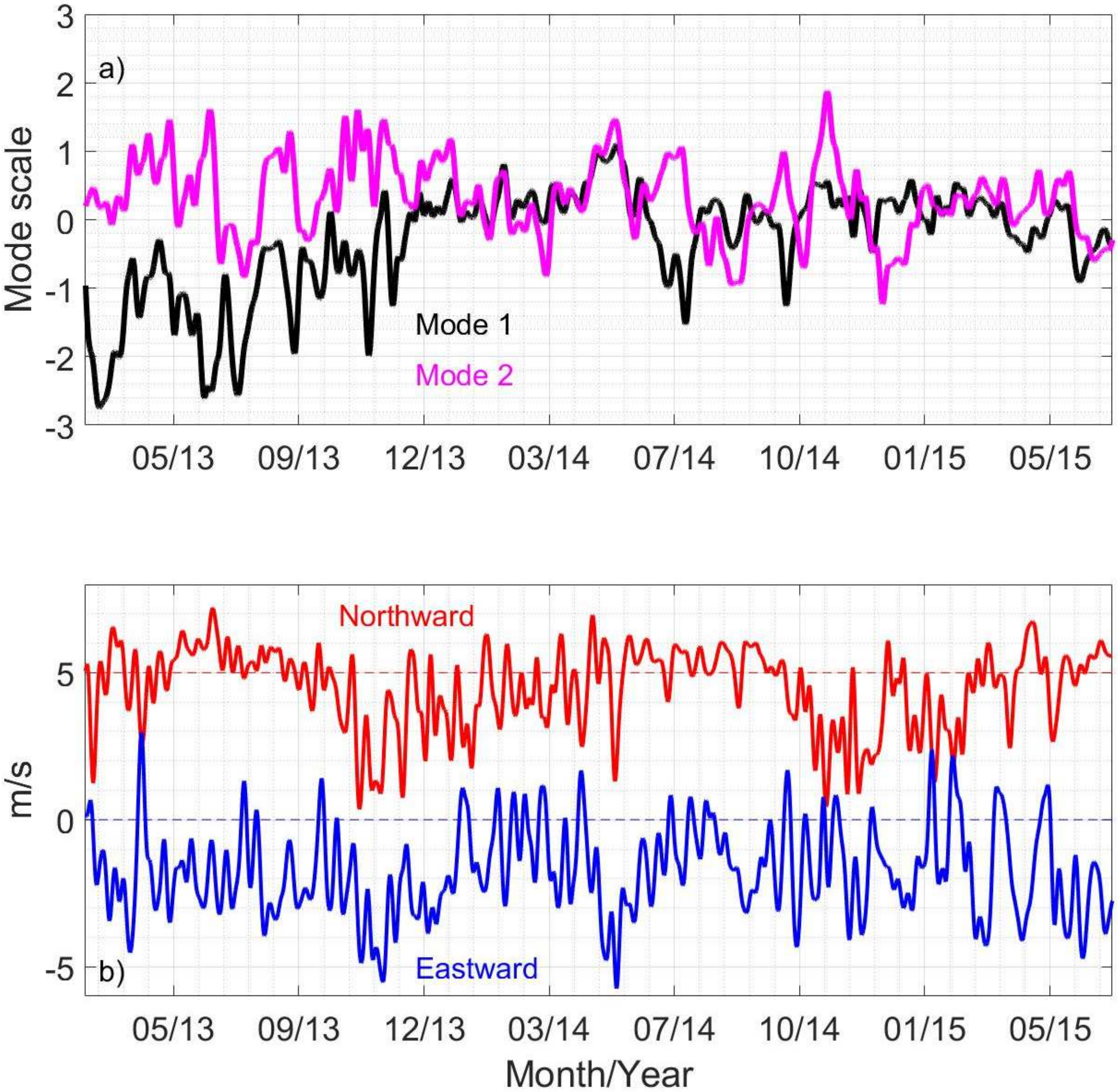


Figure 9. a) EOF Modes 1 and 2 for subtidal flows, and b) wind velocity components. All series have been filtered to 5 days. Wind veclocity components are drawn in the oceanographic convention (direction toward which they blow). The Northward component has been displaced upward by 5 m s^{-1} to improve visualization.

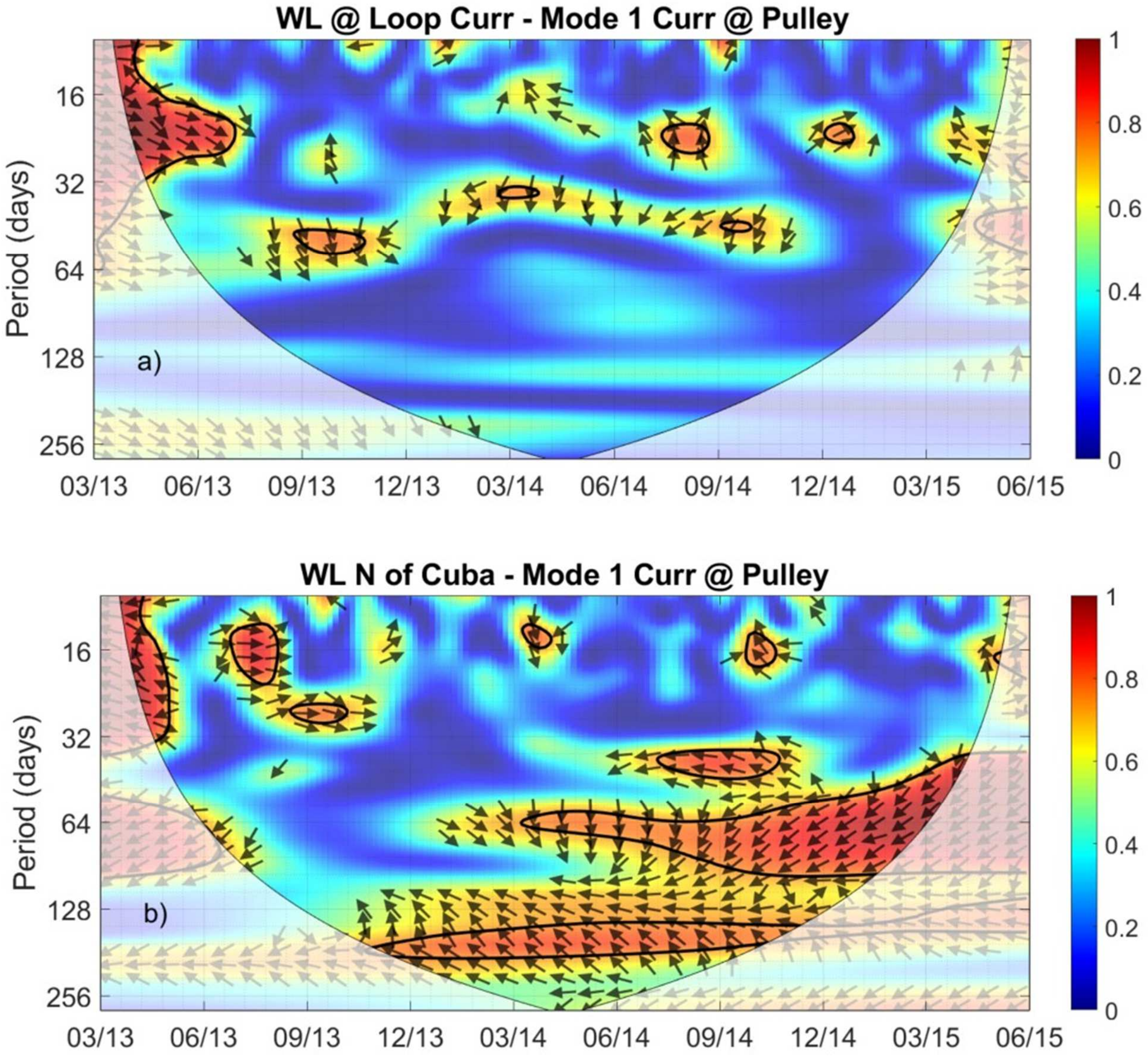
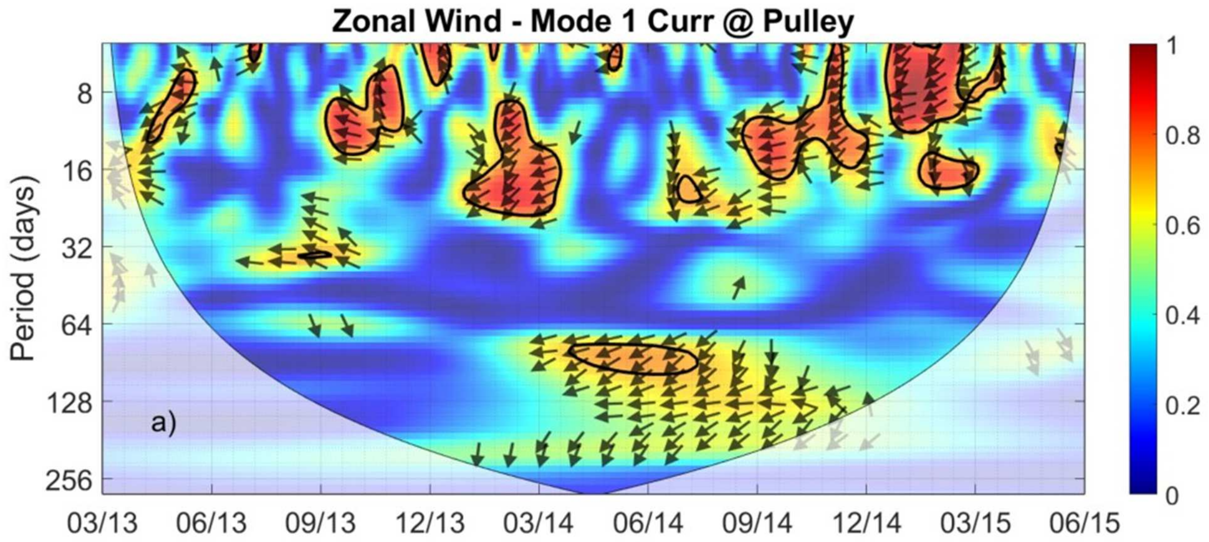


Figure 10. Wavelet coherence between a) Loop Current water level and Mode 1 for subtidal currents at Pulley Ridge, and b) water level to the NW of Cuba and Mode 1 for subtidal currents at Pulley Ridge. Thick black contour represents the 95% confidence level. Arrows denote phase lag between the two variables. Arrows pointing to the right represent that the fluctuations of both signals are in phase. Arrows pointing to the left indicate antiphase, and pointing upward describe a phase lag of 90°. Translucent white regions feature the cone of influence.



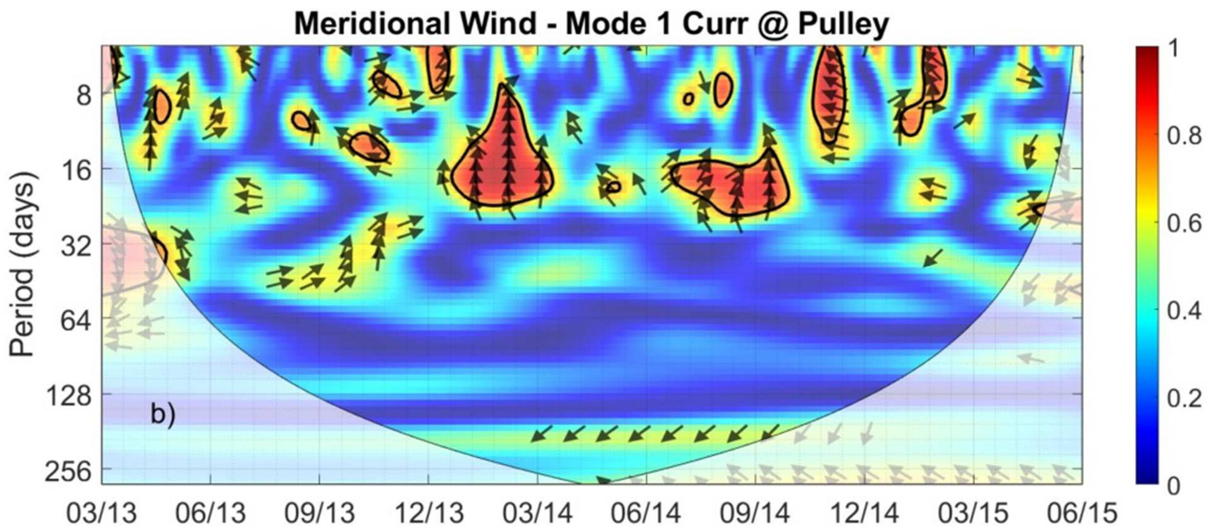


Figure 11. Wavelet coherence between a) east component of wind velocity and subtidal currents Mode 1 at Pulley Ridge, and b) north component of wind velocity and subtidal currents Mode 1 at Pulley Ridge. Thick black contour represents the 95% confidence level. Arrows denote phase lag between the two variables. Arrows pointing to the right represent that the fluctuations of both signals are in phase. Arrows pointing to the left indicate antiphase, and pointing upward describe a phase lag of 90°. Translucent white regions feature the cone of influence.