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Analysis of longer period variation of the Kuroshio Current intrusion into the Luzon Strait using rectified wavelet power spectra

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ABSTRACT

Longer period variation of the Kuroshio into the Luzon Strait (LS) was identified using acoustic Doppler current profiler (ADCP) observations as well as pressure and temperature time series data recorded by two TDs (manufactured by the RBR Ltd.) at mooring station N2 (20°40.441′N, 120°38.324′E). The ADCP was deployed at depths of 50–300 m between July 7, 2009 and April 10, 2011, and the TDs at around 340 and 365 m between July 9, 2009 and July 9, 2011. Observations provide strong evidence of longer period variation of the Kuroshio into the LS using the Vector rotary spectra (VRS) and Rectified wavelet power spectra analysis (RWPSA). RWPSA of the observations allowed the identification of two types of dominant periods. The first type, with the strongest power spectral density (PSD), had a dominant period of 112 d and was found throughout the upper 300 m. For example, the maximum PSD for western and northern velocity components time series were 3800 and 3550 at 50 m, respectively. The maximum power spectral density decrease with deeper depths, i.e., the depth dependence of maximum PSD. The 112 d period was also identified in the pressure and temperature time series data, at 340 m and 365 m. Combined RWPSA with VRS and mechanism analysis, it is clear that the occurrence of the most dominant period of 112 d in the upper 300 m is related to the clockwise meandering of the Kuroshio into the LS, which is caused by westward propagating stronger anticyclonic eddies from the interior ocean due to the interaction of Rossby eddies with the Kuroshio. The second type of dominant period, for example a 40 d period, is related to the anticlockwise meandering of the Kuroshio. The final dominant period of 14 d coincides with the fortnightly spring-neap tidal period.

1. Introduction

The interaction between the Kuroshio current and the South China Sea (SCS) through the Luzon Strait (LS) has attracted significant attention in recent decades, as reviewed in Nan et al. (2015). Observational and numerical results have indicated that the northward Kuroshio current, located east of the LS, extends downward to about 700 m, and a westward intrusion from the Kuroshio occurs at depths of above 400 m in the LS (Yuan et al., 2007, 2008, 2009a, 2012a, 2012b, 2014a; Tseng et al., 2012). Many studies have focused on the westward intrusion of the Kuroshio into the SCS through the LS. Mechanisms driving the Kuroshio intrusion into the SCS are mainly related to seasonal variation of the East Asia monsoon (e. g., Metzger and Hurlburt, 1996; Qu, 2000; Fang et al., 2003, 2009; Cai et al., 2005, 2012; Liu et al., 2008; Qu et al., 2009). The westward intrusion is commonly stronger during winter than during summer. However, the El Niño Southern Oscillation (ENSO) also has a critical impact on the strength of the intrusion at the interannual time scale (e. g., Qu et al., 2004, 2009; Liu et al., 2008; Chen et al., 2010; Yuan et al., 2014a, 2014b). The intrusion tends to be stronger (weaker) during El Niño (La Niña) years, and this is one of the key processes conveying climate signals from the Pacific into the SCS. The Kuroshio intrusion may also affect internal wave generation in the LS (Du et al., 2008; Park and Farmer, 2013). However, to the best of our knowledge, there has been no observational or numerical study of longer period variations in the Kuroshio intrusion into the LS to date.

In the LS, most previous current measurement studies have analyzed short period variation (less than one month). For example, moored Long Ranger acoustic Doppler current profiler (ADCP) observations were made at station M1 (20°49′47″N, 120°48′37″E) from March to April 2002, and dominant periods were calculated using vector rotary spectra (VRS) (Yuan et al., 2009b). Yuan et al. (2009b) showed a dominant period of 14 d, namely the fortnightly spring-neap tidal period, at observed depths of 200 m and 800 m.

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Based on ADCP current measurements at mooring station M2 (20°59.961′N, 120°30.332′E) from April to Sept, 2008, Liao et al. (2011) also identified a dominant 14 d period in the upper 450 m layer. Additionally, based on mooring observations at M3 (20°03.828′N, 120°36.818′E) (see Fig. 1), Liao et al. (2012) suggested that the smooth variance with a fortnightly spring-neap tidal generated cycle is indicative of only astronomical forcing. However, the observational periods were too short to comprehensively cover the full spectrum of currents in the LS. To study low frequency variability of currents in the LS, continuous long time series observation is needed.

Based on observations from the World Ocean Circulation Experiment PCM-1 moored current meter array in the East Taiwan Channel at 24.5°N from September 19, 1994, to May 27, 1996 combined with TOPEX/Poseidon altimetry data, three limited frequency bands centered near periods of 100 days, 40 days, and 18 days were found (Yang et al., 1999, 2001; Zhang et al., 2001; Lee et al., 2001). On the 100-day timescale, Zhang et al. (2001) pointed that the Kuroshio transport entering the East China Sea is strongly related to meandering of the Kuroshio, which in turn is caused by westward propagating anticyclonic eddies from the interior ocean. Lee et al. (2001) also showed that the dominant current and transport variability occurred on 100-day timescales is caused by warm mesoscale eddys merging with the Kuroshio south of the array causing offshore meandering and flow splitting around the Ryukyu Islands.

In terms of analytical approach, power spectrum analysis of standard time series can be very useful in deriving the dominant periods of physical variables (e.g., velocity vectors, temperature, and pressure). Fourier power spectrum analysis (e.g., Welch, 1967) is the most popular approach for single time series and has been widely applied, with rotary spectra modifications for velocity vectors (Chen and Ma, 1991). However, these approaches are limited to stationary time series, while change in the oceanic environment is commonly non-stationary at different time scales, which complicates interpretation of Fourier power spectra. Wavelet analysis is considered superior to Fourier analysis because it unfolds a time series in both frequency and time domains (Torrence and Compo, 1998), it requires no assumption of stationarity, and can determine not only the dominant modes of variability in frequency but also how those modes vary over time (Torrence and Compo, 1998; Tzeng et al., 2012). However, standard wavelet power spectra can be greatly distorted or biased in favor of low frequencies and large scales (Liu et al., 2007, hereafter LLW07). Consequently, standard wavelet analysis of a time series composed of sinusoidal waves with the same amplitude but different frequencies cannot exactly replicate the spectral peaks, resulting in lower (or higher) peaks for high frequency (or low frequency) waves. This problem can be corrected using the rectified wavelet power spectra analysis (RWPSA) proposed in LLW07. RWPSA divides the spectrum by the scales so that spectral peaks of the same magnitude are similar in size (LLW07). LLW07 further suggested a physically consistent definition of energy for the wavelet power spectrum, based on the square of the transformation coefficient divided by its associated scale. The adjusted wavelet power spectrum results in a substantial improvement in the spectral estimate, allowing for comparison of spectral peaks across scales.

The present study has four objectives. The first is to document the time-varying velocity of currents above the 300 m level at mooring station N2 (20°40.441′N, 120°38.324′E) from July 2009 to March 2011, and the pressure and temperature time series data recorded by two TDs from July 9, 2009 to July 9, 2011 (Fig. 1). This provides a unique and valuable dataset because of the long period of observation. The second objective is to analyze the primary longer period data using vector rotary spectra (VRS) for the time series of subtidal current velocity vectors at different depths. The third objective is to analyze longer period variations of the Kuroshio into the LS using RWPSA. The last objective is to make comparison between the VRS analysis and RWPSA and to investigate causes of the dominant periods.

2. Data sources and characteristics of the Kuroshio intrusion into the LS

Mooring station N2 was deployed in the LS on July 7, 2009, and retrieved on September 20, 2011 (see Fig. 1). An acoustic Doppler current profiler (ADCP) with a maximum observational range of about 600 m was installed at the nominal depth of 315 m. Sensor depths actually ranged between 315 and 520 m (i.e., shallower

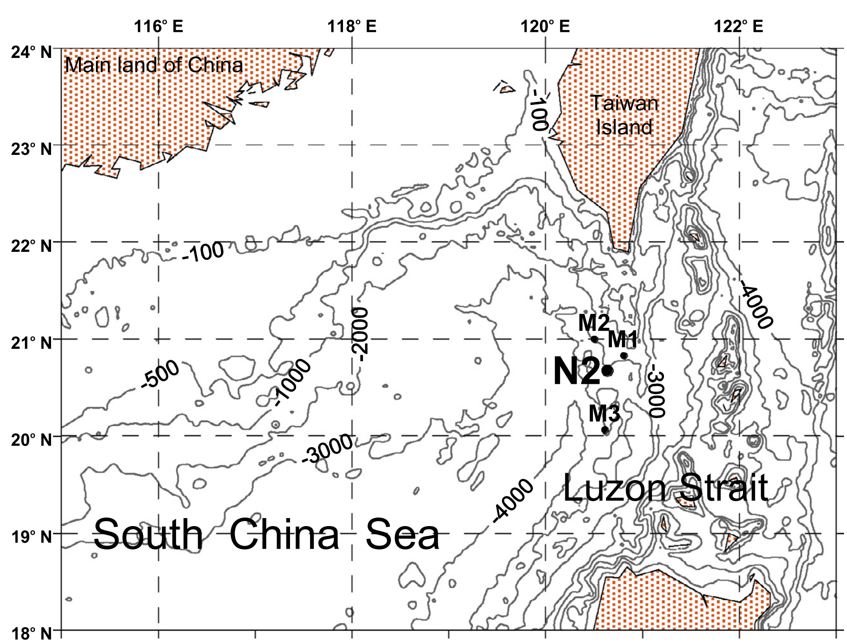

Fig. 1. Location of mooring station N2, M1, M2 and M3 and bottom topography of the Luzon Strait and adjacent areas.