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A western boundary upwelling system response to recent climate variation (1960–2006)

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ABSTRACT

In this paper, it was hypothesized that coastal upwelling increases in western boundary current influenced regions due to global warming. A state-space decomposition of the alongshore wind stress time-series exhibited an intensification during the "upwelling season" in the last 20 years (1988–2008), which agrees well with the above hypothesis. However, when applying the same decomposition to a temperature time-series at Qinglan station (located at the eastern Hainan coast) over the past 50 years (1960–2006), a negative trend was found. This indicates that the simple relation between alongshore wind stress and upwelling strength is not valid in the study area, but that other non-local factors might influence the inter-annual variability of the upwelling significantly. To identify these possible non-local effects, results of a model simulation were analyzed. From these model data an acceptable relationship between the non-locally driven western boundary current and the strength of the upwelling can be inferred. Furthermore, an "SST (sea surface temperature) upwelling index" was introduced, calculated by the simulated offshore–onshore temperature difference. This index exhibits a good correlation with the Qinglan "observational upwelling time-series", demonstrating that the latter is a good indicator of the upwelling trend. Finally, it is shown that inter-annual oscillations of employed temperature records correlate well with the El Niño signal.

1. Introduction

Upwelling is of fundamental importance in coastal marine systems, hence further elucidation of the relationship between climate and upwelling is a high research priority (Harley et al., 2006). Stronger wind fields along ocean margins, caused by different warming trends between land and oceans, might lead to enhanced coastal upwelling (Bakun, 1990). This hypothesis has been widely tested in eastern boundary upwelling systems (Schwing and Mendelssohn, 1997; Snyder et al., 2003; Lemos and Sansö, 2006; McGregor et al., 2007; Vargas et al., 2007). As global warming affects upwelling signals on the large scale, Schwing and Mendelssohn (1997), Mendelssohn and Schwing (2002) developed a state-space model to separate seasonal changes from long-term changes, and also used this technique to discover trends in different current systems. Nevertheless, this hypothesis has not been tested for western boundary upwelling systems by revealing the relationship between climate and upwelling on a global scale.

The upwelling systems along the western boundary of the oceans are relatively transient phenomena and biologically less important since the upwelled water is not as nutrient-rich as along the eastern boundaries (Mann and Lazier, 2006). Most of them show a strong seasonality (related to monsoon dynamics), e.g. the upwelling in the Bay of Bengal (Shetye et al., 1991) and the Somali upwelling system (McCreary et al., 1996). The upwelling system studied in this paper (i.e., upwelling off eastern Hainan coast) also exhibits a strong seasonality (Fig. 1, Su and Pohlmann, 2009). However, under certain conditions the seasonal upwelling has been proven also to be productive and critical to global productivity (Nair et al., 1989). According to the theory of Bakun (1990), we suggested an intensification of the upwelling strength at the western boundary of the ocean due to the global warming. The upwelling at the western coast of the ocean normally is superimposed by a strong western boundary current, which has also been found in the South China Sea (SCS) (Su, 2004). This current has a significant influence on the circulation pattern on the northern shelf of the SCS. As upwelling is not a temporally continuous and spatially uniform process, it is very difficult to quantify an integrate indices for a certain location. For example, intensified upwelling has been found as a result of shoreward advection of dense deep water meeting the broad shelf

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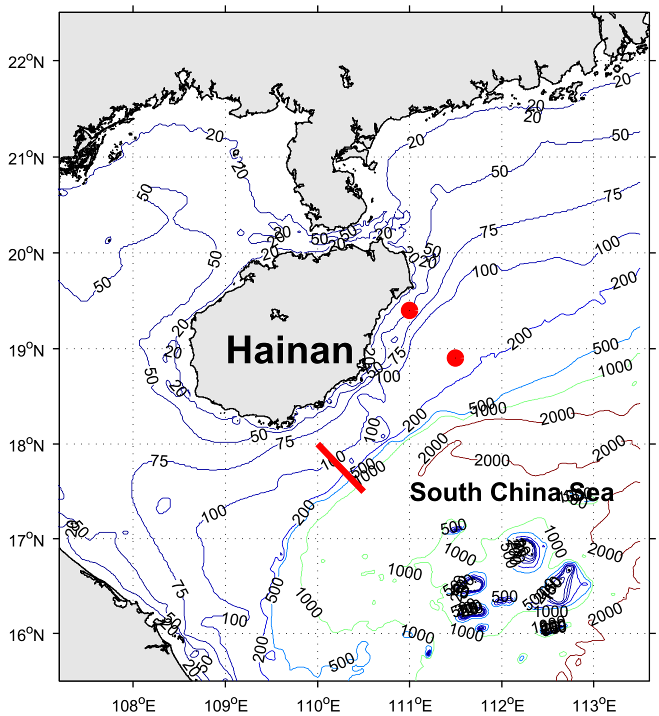

Fig. 1. The topography of the study area, off eastern Hainan coast, located in the northwest of the SCS. Two red dots represent the offshore (111.5°E, 19°N) and onshore (111°E, 19.5°N) grid points to calculate the SST difference from the numerical model results. The offshore–onshore SST difference is one of the methods to calculate the upwelling indices in this study. The red line is a section in the path of the Dongsha current (a western boundary current in the SCS). To understand the influence of the large scale circulation in the SCS on the local condition off eastern Hainan coast, the surface currents across this section are calculated in this study. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

in the northern SCS (Gan et al., 2009). Su et al. (2011) found that the frequent storm events have a significant influence on the inter-annual change of the upwelling strength. We evaluated the upwelling indices calculated by time series and offshore–onshore sea surface temperature (SST) difference to test this hypothesis. Since there is lack of a confident database, we combine the model results with observational data to examine the correlation between those upwelling indices and to elucidate the governing mechanism.

El Niño produces the most prominent sub-decadal climate variability in the study area. Xie et al. (2003) found, in mid-summer after a canonical El Niño year (1998) that the basin-wide cooling effect did not take place, leading to a strong basin-wide warming. Since 1990s, canonical El Niño events have become less frequent (Latif et al., 1997). Recent studies revealed that the ratio between El Niño Modoki (anomalous warming events occur in the central equatorial Pacific) and canonical El Niño will increase as much as five times under global warming (Ashok et al., 2007; Yeh et al., 2009). El Niño events have occurred in rapid succession in the period from 1990 to 1994 which was unusual (Trenberth and Hoar, 1996). How the coastal systems respond to the decadal variability under recent climate change is an interesting topic to pursue (Chang et al., 2008; Weng et al., 2009).

The recent studies based on observations and numerical modeling demonstrated the existence of upwelling regions around Hainan Island (Lü et al., 2008; Su and Pohlmann, 2009; Jing et al., 2009). However, the previous studies focused on the "event" scale (upwelling events), and hence the understanding of upwelling trends on a larger scale in the northern SCS is still missing. The northern SCS is situated between the western Pacific warm pool and the Tibetan Plateau, which already indicates its important role in the global climate system (Wong et al., 2007). The aim of this study is to understand the inter-annual variability of the upwelling off the eastern Hainan coast in a changing climate and its relation to sub-decadal climate variability (El Niño). The conclusion of this study in particular implies how a weak coastal upwelling system responds to the climate variability.

2. Data and models

2.1. Observational time-series data and state-space decomposition

The monthly averaged time-series data from samples at Qinglan station (110.8°E, 19.5°N, Fig. 1) was used in this study, including temperature, salinity and tidal elevation. This time-series data was used to calculate the inter-annual upwelling variation off the eastern Hainan coast. We only analyzed the temperature data since the factors influencing the inter-annual variability of salinity and sea surface elevation are complex and therefore not within the scope of this study. The review of the smoothing methods used for time-series decomposition could be found in Schwing and Mendelssohn (1997). Following their concept, we estimated the trend of the upwelling. It is assumed that each observational time-series has four components

$$y(t) = T(t) + S(t) + I(t) + e(t), \quad t = 1, \tau, \tag{1}$$

where $T(t)$ is the unobserved time-dependent mean-level (trend), $S(t)$ is the seasonal component, $I(t)$ is the irregular term (autocorrelated), and $e(t)$ is the stationary and uncorrelated component.

Different methods to obtain the terms given in Eq. (1) existed in state-space model. We decided to estimate the trend after the decomposition of the seasonal ($S(t)$) and the irregular terms ($I(t)$). To constrain the seasonal component, we used a common method, where each month of the year was averaged over all the years in the data samples (Fig. 2a). The inter-annual change of the seasonal components can be ignored (Fig. 2b). The irregular term $I(t)$ in Eq. (1) was estimated by means of a first order autoregression (normally denoted as AR(1), Fig. 2c). After removing $S(t)$ and $I(t)$, a one year running mean was applied to remove the observational error ($e(t)$, Fig. 2d). Since the upwelling season is from May to October off eastern Hainan coast, we calculated the mean value of the trend terms ($T(t)$) from May to October and defined it as our "observational upwelling time-series". We also applied this state-space decomposition method to "SST upwelling indices", "simulated upwelling time-series" and alongshore wind stress.

2.2. "SST upwelling indices"

A traditional coastal upwelling index could also be defined by temperature difference between offshore and nearshore waters, denoted "SST upwelling indices" in this paper. A positive SST upwelling index indicates an upwelling event. Of course, we could calculate SST upwelling indices via satellite infrared measurement, however, long-term high resolution satellite SST data are unavailable. Hence, numerical model results were used to calculate SST upwelling indices. In this study, we defined "SST upwelling index" as the SST difference between one grid point offshore (111.5°E, 19°N) and the other grid point near the coast (111°E, 19.5°N, Fig. 1). We introduced different upwelling indices that were not aiming at validating model results. Instead the best understanding of the relationship between "upwelling time-series" and "SST upwelling indices" should be achieved. It should be noted that we applied state-space decomposition to this "SST upwelling indices" when we compared it with "upwelling