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Seasonal and interannual patterns of sea surface temperature in Banda Sea as revealed by self-organizing map

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ABSTRACT

Seasonal and interannual variations of sea surface temperature (SST) in the Banda Sea are studied for the period of January 1985 through December 2007. A neural network pattern recognition approach based on self-organizing map (SOM) has been applied to monthly SST from the Advanced Very High Resolution Radiometer (AVHRR) Oceans Pathfinder. The principal conclusions of this paper are outlined as follows. There are three different patterns associated with the variations in the monsoonal winds: the southeast and northwest monsoon patterns, and the monsoon-break patterns. The southeast monsoon pattern is characterized by low SST due to the prevailing southeasterly winds that drive Ekman upwelling. The northwest monsoon pattern, on the other hand, is one of high SST distributed uniformly in space. The monsoon-break pattern is a transitional pattern between the northwest and southeast monsoon patterns, which is characterized by moderate SST patterns. On interannual time-scale, the SST variations are significantly influenced by the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) phenomena. Low SST is observed during El Niño and/or positive IOD events, while high SST appears during La Niña event. Low SST in the Banda Sea during positive IOD event is induced by upwelling Kelvin waves generated in the equatorial Indian Ocean which propagate along the southern coast of Sumatra and Java before entering the Banda Sea through the Lombok and Ombai Straits as well as through the Timor Passage. On the other hand, during El Niño (La Niña) events, upwelling (downwelling) Rossby waves associated with off-equatorial divergence (convergence) in response to the equatorial westerly (easterly) winds in the Pacific, partly scattered into the Indonesian archipelago which in turn induce cool (warm) SST in the Banda Sea.

1. Introduction

The Banda Sea, outlined by the Southern Molucca islands (i.e. Seram, Sula and Buru islands) on the north and Nusa Tenggara Islands Chain on the south, is located on the route of Indonesian Throughflow (ITF) (Fig. 1). Part of the ITF waters flows through the Banda Sea via Flores Sea in the south and Halmahera and Seram seas in the north, before exiting to the Indian Ocean via Timor Sea and Ombai Strait (Wyrtki, 1961; Gordon and Fine, 1996), and through the Lombok Strait (Wyrtki, 1958; Gordon and Susanto, 2001). The upper part of this throughflow is an element of the global thermohaline circulation which links the Pacific and Indian Ocean (Gordon, 1986). Previous studies have confirmed the importance of this throughflow on the global ocean and climate circulation (Hirst and Godfrey, 1993; Godfrey, 1996; Schneider, 1998; Wajsowicz and Schneider, 2001; Lee et al., 2002).

The ITF water entering the Banda Sea experiences significant transformation. Ffield and Gordon (1992) have suggested that vertical mixing in the Banda Sea is responsible for the transformation of the incoming Pacific water characterized by subsurface salinity maximum into unique ITF water that has low salinity (Ffield and Gordon, 1992). In addition, strong tidal mixing in the Banda Sea enhances the mixing of deep and surface waters leading to the modification of sea surface temperature (SST) in this peculiar sea. This result is consistent with an early study that suggested the role of advection, air-sea flux and seasonal upwelling in controlling SST in the Banda Sea (Wyrtki, 1961). Moreover, Gordon and Susanto (2001) found that seasonal change in SST is associated with the local Ekman upwelling driven by the monsoonal winds. They showed that SST decreases to about 26.5 °C during the southeast monsoon, while it increases to about 29.5 °C during the northwest monsoon. Similarly, recent studies have also suggested that the monsoonal winds have a dominant influence on SST variability within the Indonesian seas region (Qu et al., 2005; Susanto et al., 2006; Kida and Richards, 2009).

Moreover, variability of the SST in the Indonesian region, including the Banda Sea, has shown to have an important role on climate variations in the Indo-Pacific sector, with important

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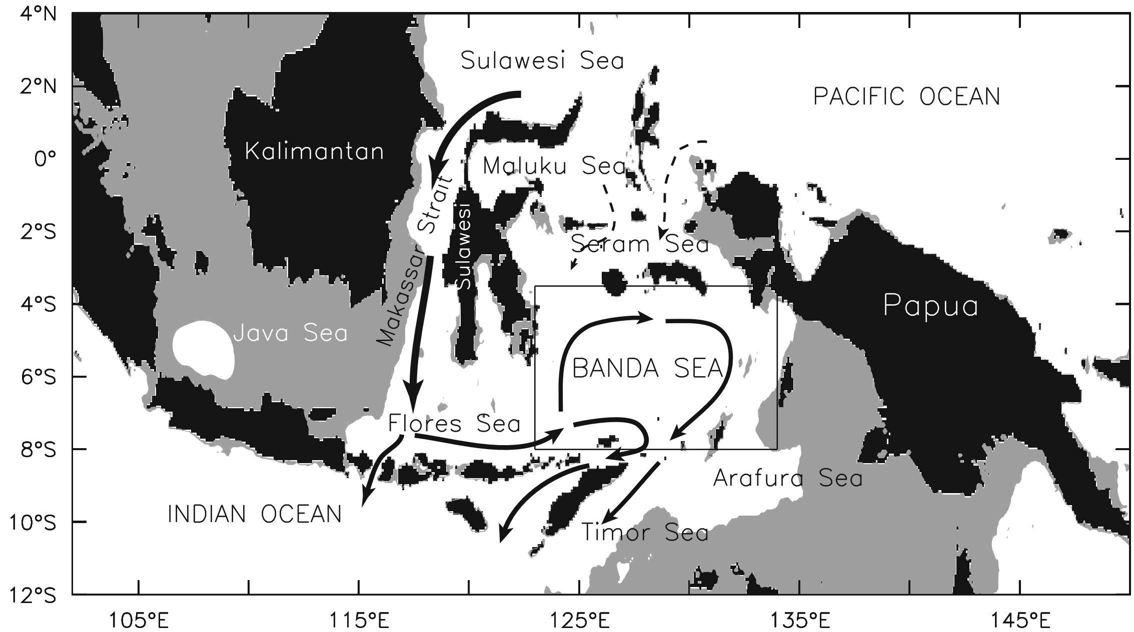

Fig. 1. The eastern Indonesian Seas and the location of Banda Sea bounded by box: 123°E–134°E, 8°S–3.5°S. The 100 m isobaths are shaded gray. The arrows indicate the Indonesian Throughflow.

consequences for global climate (Qu et al., 2005). Climate-model experiments show that precipitation over the western Pacific and western Indian Oceans is very sensitive to the SST variations in the Indonesian seas (Qu et al., 2005). Recent study has shown a robust correlation between SST and precipitation over the Maritime Continent (Dayem et al., 2007). High precipitation rates over the Maritime Continent are associated with high SST. They also suggested that the strength of the Walker Circulation is related to the precipitation rates over the Maritime Continent. When the precipitation increases, the surface easterlies over the tropical Pacific Ocean are strengthened leading to a strong Walker Circulation.

Understanding the SST variations in the Indonesian seas, including the Banda Sea, is critical for understanding tropical climate variability. However, study of the SST variability in this region within a season, from season to season and year to year is hindered by the dearth of in-situ observations. One of available SST data in this region which have high spatial resolution and long heritage (more than 20 years) is from the thermal infrared SST measurement of Advanced Very High Resolution Radiometer (AVHRR). This measurement, however, is sensitive to the presence of cloud leading to uneven data in time and space, in particular in the tropical ocean that is often covered by cloud. Taking advantage of one particular method that has proved useful in this respect so-called *self-organizing map* (SOM), this study further exploits the satellite-retrieved SST variations in the Banda Sea.

The SOM is one type of unsupervised Artificial Neural Network (ANN) that is mainly used for pattern recognition and classification (Kohonen et al., 1995; Kohonen, 2001). It is a nonlinear, ordered, smooth mapping of high-dimensional input data onto the elements of regular, low-dimensional array. The SOM has been applied widely to climate and meteorology (e.g. Hewitson and Crane, 2002; Cavazos, 2000; Hong et al., 2004) and oceanography (Richardson et al., 2003; Liu and Weisberg, 2005; Liu et al., 2006a; Cheng and Wilson, 2006; Iskandar et al., 2008; Tozuka et al., 2008). All these studies suggested that the SOM is a powerful tool for identifying patterns of continuous, dynamic processes in complex data sets.

The remainder of this paper is organized as follows. A brief description of the data and method used in this study is given in the next section. In Section 3, the seasonal and interannual variations of SST in Banda Sea are analyzed using the SOM. In particular, relationship between SST in the Banda Sea and ENSO as well as Indian Ocean Dipole/IOD (Saji et al., 1999; Webster et al., 1999; Murtugudde et al., 2000) phenomena is also discussed in this section. Finally, discussion and summary are given in the last section.

2. Data and method of analysis

2.1. Data

Monthly SST data set from the NODC/RSMAS AVHRR Oceans Pathfinder version 5.0 is used in the present study. The data cover the period from January 1985 to December 2007 with horizontal resolution of 4 km. The SST data have been prepared by calculating average in $0.25^\circ \times 0.25^\circ$ boxes between 123°E to 134°E and 8°S to 3.5°N (see Fig. 1a). The land was removed from the analysis, so that the input data consists of 808 sea pixels. The final input matrix consists of 808 columns (pixels) $\times$ 276 rows (months).

In order to explain the dynamics underlying the SST variations in the Banda Sea, monthly sea surface height (SSH) data with horizontal resolution of $1/3^\circ \times 1/3^\circ$ from the Archiving, Validation and Interpretation of Satellite Oceanography(AVISO) are used. In addition, the monthly winds from NCEP/NCAR reanalysis with spatial resolution of 2.5° are also used to estimate the Ekman upwelling and downwelling.

2.2. Self-organizing map (SOM)

Since the SOM is relatively new to oceanography, a brief description of the method is given here. Prior to the analysis, the input data are arranged into two-dimensional array with dimensions equal to *number of pixels per time step* $\times$ *number of time steps*. The SOM is then initiated by defining the shape and dimension of the SOM array, which depends on the complexity of the studied problem and the level of details desired in the analysis. In this