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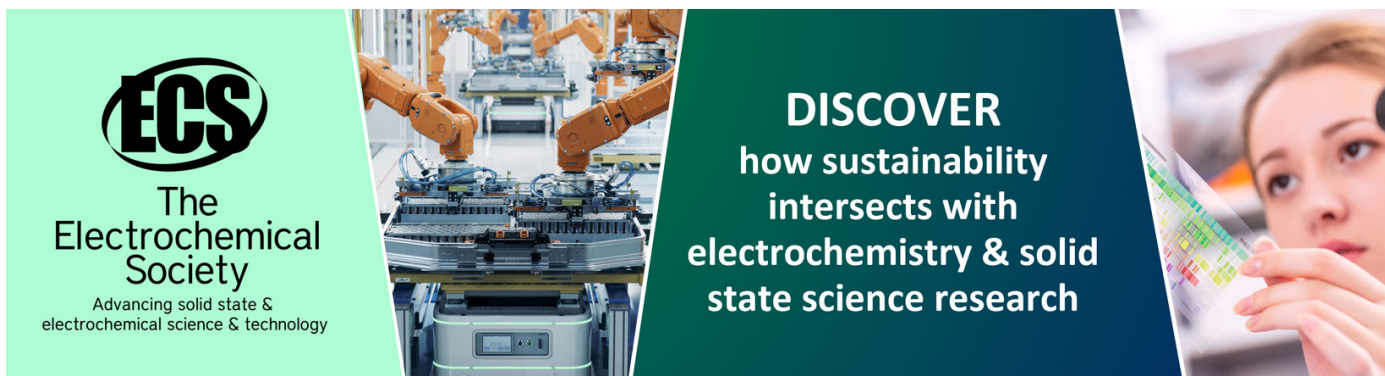
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A Lagrangian study of upwelled waters in the Northern Arafura Sea

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Abstract. The Arafura Sea is a relatively shallow water basin (less than 200 m) which is subjected to monsoonal winds and affected by the Banda Sea circulation. During the southeast monsoon (May to September) there is evidence of upwelling in this region which is indicated by the cooler SST (Sea Surface Temperature) and elevated chlorophyll concentration, especially at the coast of Papua (northern Arafura Sea). In order to address the origin of the upwelled waters masses, a numerical study using Lagrangian particles was utilized. The model was run backward in time to trace the trajectory of the particles arriving at the northern Arafura Sea, particularly in the upper 50 meters. Each particle was traced backward for three months with the arrival date August 31, 2014, as it is representative for an upwelling month. By this experiment we can identify the origin of the particles on June 1, including their depth, which arrive in the northern Arafura Sea. The daily velocity fields of the 3-D model HAMSOM (HAMBURG Shelf Ocean Model) application to the Banda and Arafura Sea for 2014 were used to force the Lagrangian particle-tracking experiment. In general, 76.2% (62%) of particles arriving in 2.5 m (22.5 m) depth, originated from the upper 50 m of the Ceram and Banda Sea. In addition, particles originating from the depth interval 50-100 m contribute 19.6% (26.8%) to the number of particles arriving in 2.5 m (22.5 m) depth. On the other hand, for particles arriving in 47.5 meter depth 46% are originating from the upper 50 m of the southeastern Arafura Sea and 42% from a depth below 100 m of the eastern Banda Sea.

1. Introduction

The Arafura and Banda Seas circulation has a strong seasonal variation in response to the monsoon climate forcing [1]. They subjected to the winds from the west from November to March (northwest monsoon) and from the east from May to September (southeast monsoon) [1, 2]. Wyrтки (1961) postulated the occurrence of upwelling during the southeast monsoon in the region, with downwelling during the northwest monsoon [2]. During the southeast monsoon, the west-going surface current would gradually remove the warm, low-salinity surface water imported during the northwest monsoon, which would be partly replaced by colder, more saline, subsurface water [3].

During southeasterly monsoon, widespread phytoplankton blooms develop in a large area in the northern Arafura Sea [4]. Satellite data indicate that phytoplankton blooms exist in



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near-coastal waters of the Arafura Sea year-round, likely as a consequence of continuous river discharges [4]. However, high chlorophyll concentration in the Arafura Sea was evidently not due to river runoff but to the enrichment of the upper, less saline layer by vertical mixing with the nutrient-rich deeper water [5]. The model findings by Kämpf (2015) also indicate that the undercurrents are the principal source of nutrient-rich Banda Sea slope water for the region [4].

This work addresses the origin of upwelled waters along the northern Arafura Sea during the upwelling season. We apply a Lagrangian particle model run back in time, in order to trace the origin and pathways of these waters.

2. Methods

2.1. The Hydrodynamic model

The hydrodynamic simulation was performed using 3-D baroclinic numerical model HAMSOM (HAMBurg Shelf Ocean Model) [6]. HAMSOM was built in Arakawa-C grid coordinate system with a horizontal resolution of 4' (approximately 7.42 km). The vertical grid resolution is based on a z-coordinate system with 45 layers of increasing thickness from 5 m for the most upper layer to few hundred meters for the deep layer. HAMSOM is forced by meteorological fields obtained by NCEP/NCAR reanalysis data [7]. On the open boundary, the tides (13 tidal constituents) from TPXO Global Tidal Solution [8] and temperature-salinity fields obtained from the global model MPI-OM (Max-Planck Institute Ocean Model) [9] were introduced. In addition, HAMSOM is also forced by the daily freshwater discharge from 191 rivers obtained from WaterGAP [10]. The topography for the model was composed from ETOPO5 [9].

2.2. The Lagrangian model

The daily velocity fields for 2014 were used to force the Lagrangian particle-tracking experiment. We chose 2014 as it represents the condition of a normal year, without El Niño or La Niña. The particles were released at the coast of Papua, within the limits 5°-8°S from the surface layer to the bottom. Each particle was traced backward for three months (92 days) with the arrival date of August 31, 2014, as it is representative for an upwelling month.

There are two processes acting on the particles, namely advection and diffusion [11]. Since this work utilized the backward simulation, only the advection process was included. The particle will be transported according to the velocities interpolated from the Eulerian grid onto the Lagrangian grid [11]. The following example is the calculation of the particle movement in x-direction from the initial position x_1 to the new position x_2 given by equation (1) [11]:

$$x_2 = \frac{\left(u_w + x_1 \frac{\partial u}{\partial x}\right) e^{\frac{\partial u}{\partial x} \Delta t} - u_w}{\frac{\partial u}{\partial x}} \quad (1)$$

Where u_w is the current velocities at the west side of the grid [11]. The detailed explanation is given in Pohlmann and Puls (1994) and Mayer (1995) [12, 13].

3. Results and discussion

This work focus on the upwelled water in the upper 50 m. For simplification, we only consider the particles that arrive at 2.5 m, 22.5 m, and 47.5 m. They will be referred as 2.5-m, 22.5-m, and 47.5-m particles, respectively. Since this work utilized the backward run, the terms particle initial position (PIP) and particle end positions (PEP) will refer to particle locations at the end and beginning of the backward simulations, respectively [14]. The following discussion will mention some names of the region, namely Ceram Sea, Banda Sea, northern Arafura Sea, and southeastern Arafura Sea. They will be written as CS, BS, NAS, and SEAS, respectively. The discussion is divided into two parts, i.e. particles origin and pathways.

3.1. Particle origin

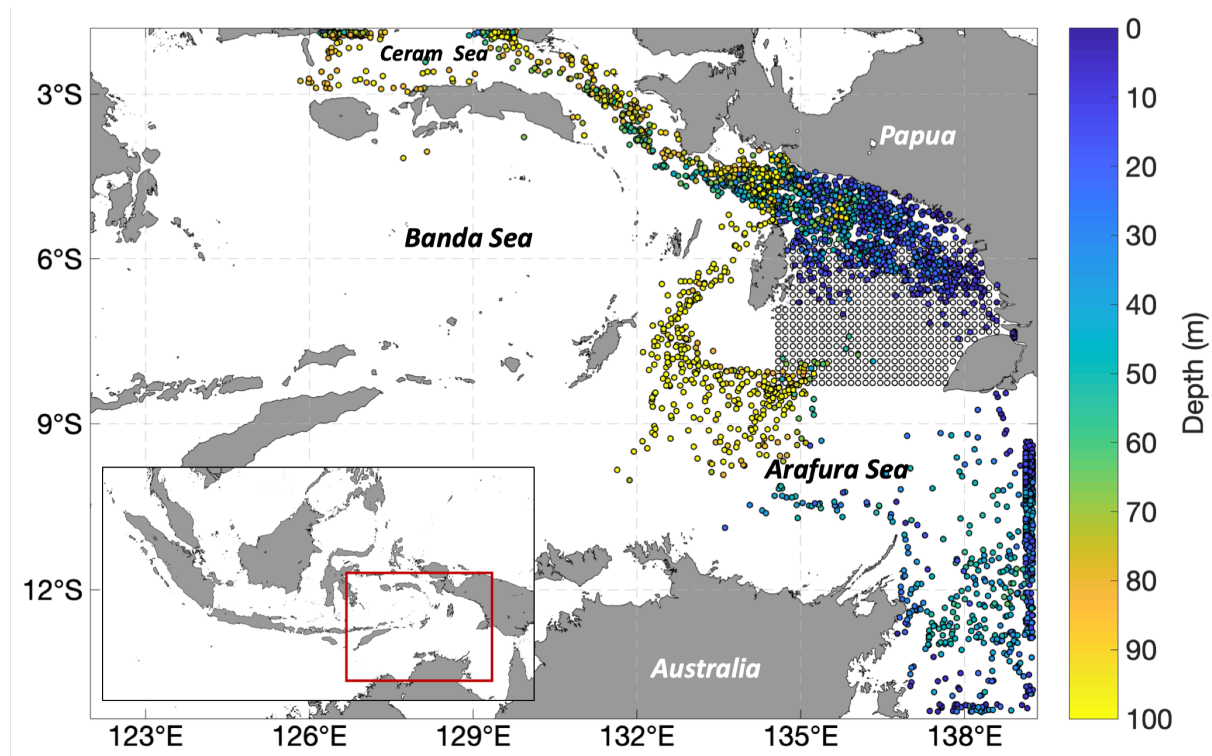


Figure 1. Lagrangian PIP distribution on 1st of June 2014 (after 92 days of a backward simulation). Symbol color correspond to particle origin depth. Region of arrival or PEP marked in black circles.

During the peak of the southeast monsoon, from June to August 2014, the wind blows northwestward. The wind-stress generates the surface current directed to the west and northwest. This surface current removed the surface water of the NAS. The surface water is replaced by the water coming from some sources. One of them is coming from the surface layer of the SEAS (figure 1). The particle from the surface of the SEAS was advected northwestward, in line with the wind direction.

The other water sources are coming from the CS and eastern BS. The particles originated from the deep layer (>100 m). According to the PIP distribution (figure 1), more particles originated from the north rather than the south side. Particularly, the CS and BS dominantly contributed as the source of the upwelled water in the NAS.

In general, the depth interval 0-50 contributes to the highest number of particles arriving in the NAS (figure 2). The number of 76.2% (62%) of 2.5-m (22.5-m) particles, originated from the upper 50 m. The second highest source is from the depth interval 50-100 m. It contributes 19.6% (26.8%) to the number of 2.5-m (22.5-m) particles. In addition, almost half of the 47.5-m particles originated from the upper 50 m and the other half from below 100 m. The small percentage (12%) originated from the depth interval 50-100 m.

The histogram (figure 2) shows that the particle percentage decreases towards depths. Specifically, this pattern can be seen on the particle origin percentage of 2.5-m and 22.5-m. The anomaly is found in particle 47.5-m where the majority of particle percentage is distributed in the upper 50 m and below 100 m. This pattern shows as if the upward movement in the water column is discontinued. The water particle upwelled in 50-100 m is less than below 100

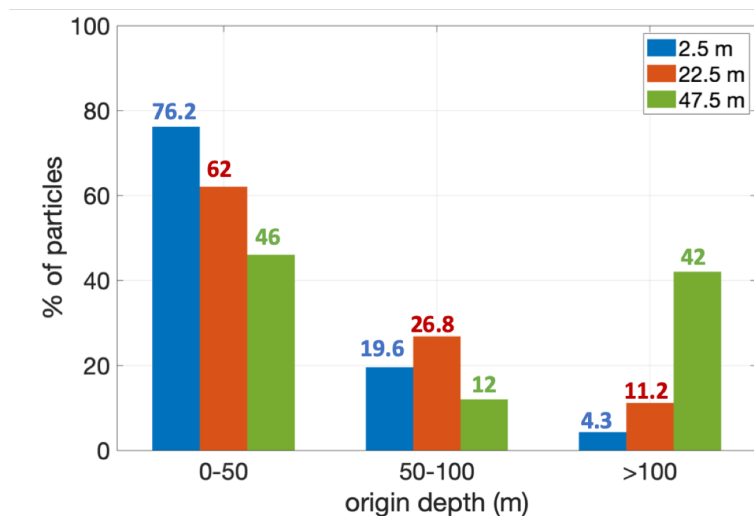


Figure 2. Histogram of the origin depth of 2.5-m (blue), 22.5-m (red), and 47.5-m (green) particles.

m. However, since histogram cannot show the particle location, therefore this anomaly can be explained by considering the PIP. It is expected that the particles originate from 50-100 m and below 100 m are coming from CS and BS. They contribute to 46% and 42% of particle 47.5 m, respectively. Moreover, the particles from the upper 50 m originate from SEAS.

3.2. Pathways

According to the particles trajectories (figure 3), the three major pathways leading to the arrival zone can be identified (figure 4). There are three major pathways: Ceram, eastern Banda, and southeastern Arafura Sea. The Ceram pathway brings the water from the northern side all the way down to the NAS. The eastern Banda pathways, as shown in figure 4 is the branch of the Ceram pathway. The water moves to the south, then turn eastward and enter the NAS. The third pathway is the southeastern Arafura Sea (SEAS). There, the water mostly originates from the upper 50 m.

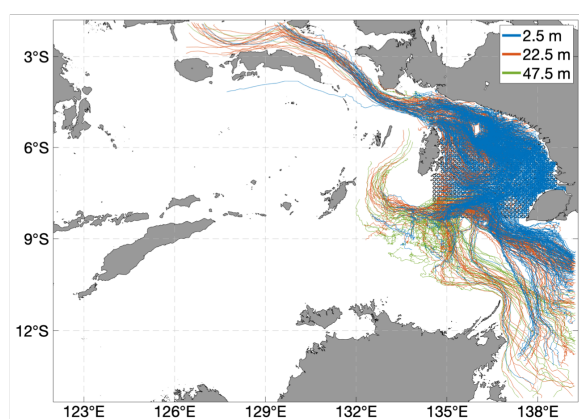


Figure 3. Particles trajectories. Blue, red, and green lines show trajectories of 2.5-m, 22.5-m, and 47.5-m particles, respectively. Region of arrival marked in black circles.

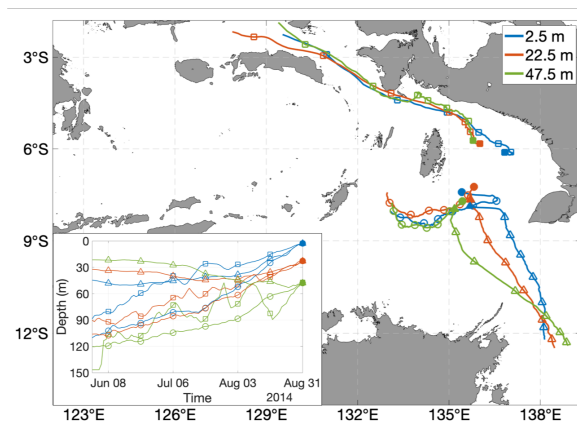


Figure 4. Mean trajectory path. The symbol $\square$, $\circ$ and $\triangle$ indicate the three major pathways: CS, eastern BS, and SEAS. The filled symbols indicate the position of 2.5-m (blue), 22.5-m (red), and 47.5-m (green) particles.

The trajectory path (figures 3 and 4) from SEAS shows that the water particles move to the northwest. This movement of water particle following the wind direction during June–August, which is northwestward. It is caused by the depth of SEAS which relatively shallow. The bathymetry in the middle region is less than 100 m and near the coast is less than 50 m. Therefore, the current circulation is highly influenced by the wind pattern and the water tend to be well-mixed.

On the other hand, the Ceram pathway (figure 3) carry the water particle from below 100 m (figure 1). This region is one of the pathways of water mass flows from the Pacific to Indian Oceans, which knows as Indonesian Throughflow (ITF) [15]. The depth of particle origin in CS is below 100 m. It is associated with the primary depth of ITF that is within the top 500 m [16, 17]. Besides, during the southeast monsoon, ITF reaches its maximum [18]. Since the model boundary forcing are retrieved from the global ocean model, the ITF signal can be represented in the regional model. As it is outside the scope of this work, thus the further study needs to carry out.

The previous study stated that the principal source of the nutrient-rich water in the Arafura Sea during the southeast monsoon is coming from the Banda Sea slope water [4]. However, the backward trajectories reveal otherwise. The results indicate that the dominant source of the upwelled water is coming from the north.

4. Conclusions

In general, 76.2% (62%) of particles arriving in 2.5 m (22.5 m) depth, originated from the upper 50 m of the Ceram and Banda Sea. In addition, particles originating from the depth interval 50–100 m contribute 19.6% (26.8%) to the number of particles arriving in 2.5 m (22.5 m) depth. On the other hand, for particles arriving in 47.5 meter depth 46% are originating from the upper 50 m of the southeastern Arafura Sea and 42% from a depth below 100 m of the eastern Banda Sea.

Acknowledgement

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