Upper circulation in Bone Bay and its relation to biogeochemical distribution: from observation and model

P Widyastuti¹,³*, A S Atmadipoera¹, I W Nurjaya¹, N M Natih¹ and A Priatna²

¹Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, Bogor Agricultural University, Bogor, Indonesia
²Centre for Fisheries Research, Agency for Marine and Fisheries Research and Human Resources, Ministry of Marine Affairs and Fisheries, Indonesia
³PT Hatfield Indonesia, Bogor, Indonesia

*E-mail: priskacaca@gmail.com

Abstract. The surrounding waters and the physical mechanisms within the ocean are playing a major role to bring nutrients to Bone Bay, field observation in October 2014 and analysis of numerical modeling were conducted in order to understand the pattern of water circulation, as well as the variability of seawater transport and its impacts to the biogeochemical distribution. The results of the observation show that the distribution of salinity is lower in locations closest to the gulf (Transect A) and higher towards the furthest locations from the gulf (Transect D), followed by the pattern of other parameters (temperature, dissolved oxygen, and chlorophyll-a). This happened due to the low current speed in the Flores Sea during the time of observation hence no water flowed into the gulf which was dominated by freshwater from rivers. It is confirmed by the transport model that shows that seawater is transported strongly to the north from January to March and due to the topography at the mouth of the gulf, the water accumulates and forms an eddy which transports water to the south in April until the next few months. This explains the distribution of phytoplankton and zooplankton inside the gulf from January to March.

Keywords: Bone Bay, observation, upper circulation

1. Introduction

The Bone Bay, located in the centre of Indonesian Seas, is one of the most biologically productive areas in the tropical region. Data in 2016 show that the total fish production in the areas surrounding the Bone Bay – South Sulawesi and Southeast Sulawesi – reaches 480,572 tons [1]. Since Bone Bay is directly connected with the Flores Sea to its south, it is assumed that this picturesque setting enables Bone Bay to hold such high primary productivity [2]. Major physical mechanism also exists in the area of Bone Bay which may influence its water mass characteristic, for example the Indonesian Throughflow (ITF) where its main pathway to Indonesia is located in the Makassar Strait on the western side of Bone Bay and the Asian Monsoon (i.e. Southeast Monsoon and Northwest Monsoon) which occurs seasonally in Indonesia [3].

Fish are generally attributed to biogeochemical cycles by their dependency on primary production for food. The biogeochemical variables themselves are distributed to certain areas by physical processes in
the waters, mainly on the upper layers where influence from the atmosphere exists. Researchers investigated the relation of an oceanographic condition caused by the circulation in the seawater surface to the distribution of fish in Bone Bay. The abundance of skipjack tuna (Katsuwonus pelamis), the most potential species of big pelagic in Bone Bay, was indicated to be correlated with the change of sea surface temperature (SST) as identified by [4] who found that skipjack catches tended to be higher at an SST anomaly of -0.05 – 0.20°C in this area. This is also associated with the season – i.e. higher during Northwest Monsoon – as shown in the result of a study by [5], with SST and chlorophyll-a (Chl-a) range from 29.9 to 31.0°C and 0.12 to 0.22 mg m⁻³, and the primary production peaked at 5.3 – 11.62 g C m⁻² per month. Another study discovered that skipjack was found at thermal fronts in Bone Bay, occurring in the area with negative SST anomaly of -2.14 – 0.65°C [6].

However, the previous studies are limited to the analysis of satellite imagery and the calculation of several oceanographic parameters (SST, Chl-a) only. As the surrounding waters and the physical mechanisms within the ocean are taking a major role to bring nutrients from and to Bone Bay, it is important to have a better understanding on the ocean dynamics that would drag the water mass and its contents and thus influence the primary productivity in Bone Bay.

Through an assessment using observation and model approaches, we investigated the upper circulation in Bone Bay that aimed to analyse the circulation pattern, water mass stratification, variability of water transport and its relation to the biogeochemical distribution by calculating and visualizing the exchange of seawater that enters and exits the bay. Since fish populations, mostly pelagic, are linked to ocean biogeochemistry, understanding the relation of the physical and biogeochemical dynamics will give us information to understand how seawater circulation can drive the nutrients in Bone Bay which would control the fish abundance in this area.

2. Methods

2.1. Study area

Bone Bay is located in the southern part of Sulawesi Island, which connects several districts in South Sulawesi Province and West Sulawesi Province with districts in North Sulawesi Province. The bottom topography of Bone Bay (figure 1a) is bordered by Takabonerate Islands on the south and Palopo waters on the north. A broad less than 500 m depth areas are found in the northern side of the bay, eastern side of Sinjai and Kolaka, and around Kabaena Islands. More than 1500 m depth is found in ocean basin between Kolaka and Wajo/Bone at the centre of the bay, and the other two basins (Selayar Basin and Bone Basin) are in the southern side of the bay with more than 2000 m depth. The observation took place on October 15-19, 2014 while the data processing for both observation and model was conducted in 2015 and 2018.

![Figure 1. Study area in Bone Bay: a) Bathymetry with Transect AB (red line) for transport calculation and b) ADCP stations and CTD track in Bone Bay on October 2014.](image)
2.2. Data

2.2.1. Observation. The oceanographic measurement was carried out in October 2014. The track was set in a zigzag pattern that cuts off the bay area from the west to the east (figure 1b), which was aimed to obtain the cross sections in several aspects. Conductivity, Temperature, Depth (CTD) profiling was conducted from the surface to 100 m depth and measured in 12 points for the parameter temperature, salinity, dissolved oxygen (DO), Chl-a, and pH using CTD Seabird 19 Plus; sea surface current was measured using Acoustic Doppler Current Profiler (ADCP) CODAS RDI 200 kHz from 5 to 20 m depth along the track; and seawater was sampled for the analysis of Chl-a in 24 points along the track.

2.2.2. Model. Outputs from models were used in this study as shown in table 1. The output from the Regional Ocean Modeling System (ROMS) was used to obtain the climatological average of oceanic and biogeochemical parameters (i.e. zonal, meridional, temperature, salinity, oxygen, phytoplankton, and detritus), while the output from the Infrastructure Development of Space Oceanography (INDESO) was used to analyze the variability as well as to generate the biogeochemical data from PISCES model. Additionally, the tidal model output from TPXO 7.2 was used in the analysis of tidal fluctuation.

Table 1. List of model outputs used in this study.

| Data range | Resolution |
|------------|------------|
| Climatological model ROMS | 10 simulation years, 1/36° or 3 km |
| Inter-annual model INDESO | January 2008 – December 2014, 1/12° or 9.25 km |
| Tide model TPXO 7.2 | October 2014, 1/4° or 27.78 km |

2.3. Data processing and analysis

2.3.1. Hydrodynamic model. The model used in this study was the Regional Ocean Modeling System, ROMS [7, 8] in its version with 2-way nesting capability (ROMS-AGRI) [9, 10]. ROMS is a hydrostatic, free-surface, primitive-equation ocean model with curvilinear coordinates in the horizontal on an Arakawa C-grid and has been developed for a realistic simulation of the interactions between the coastal regions and the open ocean. Open boundary condition and baroclinic velocity were interpolated using the methods developed previously [11], with the Orlanski type of radiation condition was applied. Free surface and depth-averaged current on boundary condition were created using Flather method [12]. Analysis of boundary conditions was divided into two parts, with surface boundary conditions (z=η) and with bottom boundary conditions (z = −H). The equations for surface boundary conditions are:

\[
\frac{\partial \eta}{\partial t} = w 
\]

\[
K_{MV} \frac{\partial u}{\partial z} = \frac{\tau_x}{\rho_0} 
\]

\[
K_{MV} \frac{\partial v}{\partial z} = \frac{\tau_y}{\rho_0} 
\]

\[
K_{TV} \frac{\partial T}{\partial z} = \frac{Q}{\rho_0 C_p} 
\]

\[
K_{SV} \frac{\partial S}{\partial z} = \frac{S (E-P)}{\rho_0} 
\]

The \(\tau_x\) and \(\tau_y\) are wind stress at x and y directions; \(u, v,\) and \(w\) are 3-D velocity fields; \(\rho_0\) is seawater density; \(\rho = 1025 \text{ kg m}^{-3}\) and \(C_p = 4.1855 \times 10^3 \text{ PSI}\); \(T\) is mixed layer depth temperature; and \(K_v\) is vertical diffusivity coefficient (estimated by ROMS KPP scheme). While the equations for bottom boundary conditions are:

\[
\bar{u} \cdot \nabla (-H) = w 
\]

\[
K_{MV} \frac{\partial u}{\partial z} = -C_d |\bar{u}| u / \rho_0
\]
\[ K_{Mu} \frac{\partial v}{\partial z} = -c_d |\mathbf{u}| v \rho_0 \]  
(8)

\[ K_{Tv} \frac{\partial T}{\partial z} = 0 \]  
(9)

\[ K_{Sv} \frac{\partial S}{\partial z} = 0 \]  
(10)

The Eq. (6) is a kinematic equation, Eq. (7) and Eq. (8) are bottom friction equations in x and y, and Eq. (9) and Eq. (10) are bottom flux equations for temperature and salinity.

Transport was obtained using the following transport stream function as derived from the Sverdrup relation:

\[ \nabla^2 \psi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \]  
(11)

2.3.2. Biogeochemical model: NPZD. ROMS was coupled with a biogeochemical model that calculates the source and sink terms for the biological and chemical components. The biogeochemical model is a nitrogen-based NPZD-type model (Nutrient-Phytoplankton-Zooplankton-Detritus), computing 5 state variables: nitrate (NO$_3$), phytoplankton (Phyt), zooplankton (Zoo) and detritus (Det), all in nitrogen unit (mmol N m$^{-3}$) with additionally chlorophyll-a (mg m$^{-3}$) which derived from the phytoplankton using carbon:chl-a ratio [13], [14], [15]. Based on [16], the scheme of nitrogen and carbon flux presented in figure 2. The 3D time evolution of the concentration of any of the biogeochemical variables (Bi) is influenced by diffusion, horizontal advection, vertical mixing and the biogeochemical processes that act as sink or source for the variable:

\[ \frac{\partial B_i}{\partial t} = \nabla \cdot K \nabla B_i - u \cdot \nabla_h B_i - (w + w_{sink}) \frac{\partial B_i}{\partial z} + SMS(B_i) \]  
(12)

\( K \) is the eddy kinematic diffusivity tensor, \( u \) is the horizontal velocity, \( w \) and \( w_{sink} \) are the vertical velocity and the vertical sinking rate of the biogeochemical variable (all particulated variables, except zooplankton), respectively. The biogeochemical processes included in SMS for each variable (Eq.11) represent the conceptual description that follows. Phytoplankton uptakes nitrate (NO$_3$) at a rate that is dependent on the instantaneous nitrate concentration and light intensity (PAR: photosynthetically available radiation) and further constrained by temperature (T). The nutrient (NO$_3$) limitation of the growth rate, \( \mu(NO_3) \), is calculated by a Michaelis-Menten function.

\[ \mu(NO_3) = \frac{NO_3}{K_{NO_3} + NO_3} \]  
(13)

\( K_{NO_3} \) is the half-saturation constant for nitrate uptake by phytoplankton. T and PAR limitation of the phytoplankton growth rate, \( \mu(T, PAR) \), follows the equations of [17] (Eq. 13) and [18] (Eq. 14) modified to include \( \theta \).

\[ \mu(T, PAR) = \frac{\mu(T) \cdot \alpha PAR \cdot \theta}{\sqrt{\mu(T)^2 + (\alpha PAR \cdot \theta)^2}} \]  
(14)

\[ \mu(T) = \ln 2 \cdot 0.851 \cdot (1.066)^T \]  
(15)
2.3.3. **Transport calculation.** Estimation of transport along Transect AB in 5.5°S was calculated by integrating the meridional component against the transect length and depth following the below equation [20]:

\[ Q_{vA-B} = \int_{A}^{B} \int_{0}^{z} v \, dx \, dz \]  

(16)

It is an estimation of transport volume (in Sverdrup Sv; 1 Sv=10^6 m^3 s^-1), A is the limit of longitude 120.4°E, B is the limit of longitude 121.9°E, z is the bottom limit of depth (in this study z=500 m), and v is a meridional component.

2.3.4. **Time series analysis.** Time series of meridional transport was filtered using Hanning Smoother. The following equation defines the Hanning window:

\[ \omega(n) = 0.5 - 0.5 \cos \frac{2\pi n}{N} \]  

(17)

For \( n = 0, 1, 2, \ldots, N-1 \), where \( N \) is the length of the window and \( \omega \) is the window value. To calculate the periodicity of current and the transport volume, we used the Continuous Wavelet Transform (CWT) method [21]. The wavelet analysis aims to find the time-frequency or the time-period distribution over a time series, i.e. how the power changes. The CWT analysis was applied to the time series of volume transport in transect A-B as described previously in section 2.3.2. CWT equation is expressed as follows:

\[ C(\text{scale}, \text{position}) = \int_{-\infty}^{\infty} f(t) \psi(\text{scale}, \text{position}, t) \, dt \]  

(18)

\( C \) is wavelet coefficient, \( f(t) \) is time series data, and \( \psi \) is mother wavelet. The CWT analysis used wavelet as band pass filter which is grouped in time and scale thus \( \eta = s \cdot t \) and is normalized in energy unit.

2.4. **Model Validation**

SST and Chl-a from the model were validated with daily averaged SST and Chl-a from NOAA-AVHRR satellite image (figure 3). Both model and satellite data were averaged monthly using a climatology mode. Correlation values of SST and Chl-a are 0.84 and 0.94, which show a high correlation between
the model and satellite data. In other words, the model can represent very well the real condition of the waters and can be applied to model Bone Bay area.

Figure 3. Validation between ROMS model and NOAA-AVHRR data 2007-2012 for: SST (a) and Chl-a (b) (ROMS output; Satellite data; Standard deviation).

3. Results and Discussions

3.1. Field observation

We first evaluated the data resulted from field observation to describe the general characteristics of Bone Bay’s water mass during October 15-19, 2014. Data from CTD were extracted and plotted using Ocean Data View. In order to see whether there was an exchange of water mass from the outside to the inside of the gulf and vice versa, vertical structure of relevant oceanic parameter was created as shown by the salinity distribution in figure 4 (distribution of other parameters is not shown in this paper). Increase in salinity was clearly showed from Transect A (stations inside the gulf) towards Transect D (stations at the mouth of the gulf), particularly from the surface up to 50 m depth. This implies that during the observation period the water mass inside the gulf had no interference from the water mass outside the gulf which should have higher salinity, characterizing open ocean water.

The horizontal profile (figure 5) confirmed that there was a specific pattern between salinity inside the gulf and at the mouth of the gulf even until 100 m depth, followed by the fluctuation of other parameters i.e. temperature and DO. While salinity as the key parameter to depict the characteristics of the water showed a distinct fluctuation between stations, there was a unique pattern that appeared in Chl-a tending to be higher in 30 to 100 m depth in contrast to the upper and below this layer. pH, however, was higher in the middle of the gulf. The explanation of this finding will be discussed together with model results in the next chapter.

The distribution of parameters taken from observation seems to be influenced by the discharge of rivers that flow to Bone Bay. This was also indicated in a study previously that assumed the difference in physical property of water mass in Southern Sulawesi waters, particularly around Selayar Island which is located at the mouth of the Bone Bay, is strongly influenced by local factor i.e. rainfall and river discharge [22]. Data from BPS in 2015 marked the existence of strong discharges from rivers in South Sulawesi and Southeast Sulawesi that flow to Bone Bay which ranged from 2.4 to 144.7 m³ s⁻¹ (data in daily average). The known sources were from Palakka River, Kalamisu River, Tangka River, Aparang River, Bungadidi River and L.Tamboh River. The biggest discharge (144.7 m³ s⁻¹) was found in Tangka River, Sinjai – South Sulawesi which becomes the most input of freshwater to Bone Bay.
When strong enough, both atmospheric and oceanic forcing can contribute to the circulation pattern in a semi-enclosed water and form currents that drive the exchange of water with the open ocean that carries higher salinity [24]. Nevertheless, the vector of the current during observation (figure 6) shows that current in the surface moved the water mass dominantly to the south from the inside of the gulf and began to head westward at the middle of the gulf. This deflection continued to the mouth of the gulf which turned the flow back to the north in the west side of the gulf, indicating a formation of eddy. Similarly, this pattern applied to the lower layers (10 m, 15 m and 20 m depth) with a weaker speed.
These results suggest that forcing to transport waters from the open ocean was rather small to give impact on the existing circulation.

As the currents appear to bring the water towards the outside of the gulf, with some of them drive the water back to the circulation of eddy, this leads us to assume that the water inside the gulf during the observation period was dominated by local water mass. By locating the extrema in salinity associated with particular water mass, we can describe the ‘water type’ using the Temperature-Salinity (T-S) diagram [28], as shown in figure 7. The water mass in all stations have salinity ranging from 33.2 to 34.6 PSU, with the salinity minimum in the TS curve is at about 29°C. Taking into account the classification of the world’s water masses [28], these characteristics do not fit into any of water type. In other words, no external water mass exist during observation in Bone Bay as what found in the open ocean, where the introduction of different water masses may occur [29].

Figure 6. Sea current vector on October 2014 resulted from ADCP in various depth.
The physical movement in the water mass, represented by the current vector, during observation corroborates the analysis of the distribution pattern of the physical and chemical parameters. Few studies in other gulfs [33] observed that this might associate with temporal variability as a result of the dynamics process around the area. Previous study identified fewer thermal front areas inside the gulf of Bone in October with lower fish biomass (indicated by skipjack catch) compared to the other months of observation [37]. Analysis of seawater sampled in 24 stations showed that the average of Chl-a is at 8.6 x 10^5 gr m^-3. This value is rather low as fish are mostly congregated inside the gulf of Bone at higher Chl-a, as found for big pelagic fish at 2 to 4 x 10^-4 gr m^-3 [38], for anchovies at 0.5 to 1 x 10^-3 gr m^-3 [39] and for small pelagic fish at 7 to 9 x 10^-4 gr m^-3 [40] from April to September 2017. These ranges of Chl-a are the characteristics of seawater in the Flores Sea [41] and were found in a certain period in this area, suggesting that there is a transport of water mass showed by the temporal fluctuation of this parameter in Bone Bay. Thus, it is needed to assess the distribution of oceanographic (physical and biogeochemical) parameters in a wider spatial and temporal variation from model results.

3.2. Model
The second analysis was applied to the results of ROMS output which were simulated for 10 years. This allows us to have a broader view to get into more details that have not been captured by field observation. For instance, a clear contrast is marked at the beginning of West Season, pointing out the highest speed of the current in Transition Season II. During these seasons, strong currents appear from the west enabling the water mass from the southern side of Bone Bay to enter the gulf. This strong current is identified as the Indonesian Throughflow (ITF) passing by the Flores Sea with Makassar Strait as its main pathway [44]. Surface current from the model (figure 8) in October confirms the pattern that was discussed in the previous chapter. In this month, or the period of Transition Season II, the surface current has such weak speed showing that there is only a small movement of water mass into the gulf. The drop of the speed starts during the East Season or here represented in July.
Figure 8. Current at 10 m depth in the 10th year of simulation. Figures are displayed based on selected month representing the season i.e. January (JAN) for West Season, April (APR) for Transition Season I, July (JUL) for East Season and October (OCT) for Transition Season II.

The current speed of ITF in Makassar Strait is usually stronger during Southeast Monsoon (July to September) with maximum along velocity of -0.8 m/s near 120 m and decreasing during the transition to the Northwest Monsoon [47]. An eastward propagation of fresh surface waters from the eastern Java Sea to the Flores Sea and the Banda Sea occurred from November to May, before reaching the outflow straits [49]. This drives the strong current from Makassar Strait ITF to pass through small islands on the southern side of Bone Bay, leading the water to enter Bone Bay. Meanwhile, from June to October, south-easterly wind speeds are fully developed and stronger ITF occurred in Makassar Strait, driving most of the water mass to be recirculated to the ITF pathway with only a small amount flows to Selayar Strait as indicated by the formation of an eddy in Southern Sulawesi Sea [47].

We applied a low-pass filter on the time series of meridional transport to remove the unwanted high-frequency components. Data were filtered for 31 days before being averaged climatologically (figure 9). Climatological transport of meridional component shows a seasonal pattern which indicates a transportation of water mass southward (to the outside of bay) in February and July and northward (to the inside of bay) in January, April, September and November onwards. Using CWT, we are able to identify the periodicity of meridional transport that was found in 4-16 days, as shown by the red box in figure 10. Most strong signals were intensified on 4-8-day periods, with a scarce distribution of signals in 8-16-day periods. This result is in agreement with a study which found periodicities of 2, 4-5, 8-10 and 14-18 days similar to the tidal variability with periods of planetary waves [50]. Thus we used the output from tide model to obtain the tidal fluctuation in Bone Bay (figure 11). Tides during October 2014 have a periodicity of 15 days, as similar to the result of CWT analysis. Given several factors identified in Bone Bay circulation as described above (ITF, monsoon, tidal), analysis on the cross-correlation between variables will come in a separate paper, which will reveal the major factors that have strong influence to the circulation pattern.

Transport model output (figure 12) shows the existence of water mass exchange that is found in January (West Season) when the water mass flows to the inside of the gulf. The topography of Bone Bay plays a role in accumulating the water mass in the mouth of the bay and forms a cyclonic eddy in the middle of the eddy which drives the water mass southward in April (Transition Season I). The cyclonic eddy is found in the area where water mass transport accumulates in Bone Basin. In October, transport of water into the north is weak, confirming the observation result that most of the water mass flow to south during this month yet small transport still exists in the basin. Therefore, there is an indication that the Bone Basin constitutes an important passage for the exchange of water masses between Bone Bay and the Flores Sea.
Figure 9. Time series of daily transport volume in transect A-B (see Figure 1a) from January 1, 2008, to September 4, 2011 (upper figure) and a monthly average of transport volume (climatology) from January 1, 2008, to September 4, 2011 (lower figure).

Figure 10. CWT modulus of transport volume in transect A-B (see figure 1a).

Figure 11. Hourly elevation of sea level that represents tidal fluctuation in October 2014. Data is extracted in the coordinates of 5.5S and 121.25E, or as shown by the star on the inset, and presented as an anomaly.
3.3. Biogeochemical Distribution

SST is one of the key oceanographic parameters to study the biogeochemical distribution of seawater. Spatially, SST tends to be lower on the outside of the gulf compared to the SST on the inside of gulf. The seasonal cycle of temperature (figure 13) marked the high variation of SST during West Season to Transition Season I and the low variation of SST during East Season to Transition Season II. Patterns on a monthly basis (not included in this paper) show that SST is enhanced from October to May and decrease on June to August. SST in October from the model is around 30 °C which is in agreement with the observation result. This is similar to a study which found that SST reaches its peak in November-December and back to the lowest SST in July and August [51]. Variability of SST found in this area is assumed to take place as an impact of monsoonal winds blowing over South Sulawesi [42] which affects the variability of Chl-a as well.

Similarly, the salinity varies between East Season and West Season (figure 14). The salinity in West Season represented in January is high inside the gulf, but low outside the gulf. Salinity in East Season represented in August tends to uniform or has value with narrow range both inside and outside the gulf. This difference of salinity between two seasons is assumed to be caused by strong current from Java Sea during West Season [49] which drives the water mass from open ocean with high salinity heading eastward, entering the inside of the gulf, while the fresher water mass from the Java Sea flows to the eastern part of Sulawesi hence the water outside the gulf has less salinity. This mechanism is driven by the Northwest Monsoon wind from December to February. In vertical view, salinity in January is higher at deeper layer (100 – 250 m), but salinity in August is higher in the surface.

The overall variation of biogeochemical parameters is similar to the concentration of Chl-a (figure 15). Biogeochemical parameters inside Bone Bay reaches the lowest value during East Season. Based on the seasonal cycle of phytoplankton (figure 15b), it is known that phytoplankton is higher in the southeast area in January, meanwhile, it is higher in the southwest area in August. Zooplankton is higher inside the bay in January as well as detritus and phytoplankton. As discussed in the previous chapter, seawater is transported strongly in January due to the existence of a basin at the mouth of the gulf which forms an eddy. Several oceanographic studies have found that fish distribution and abundance are linked with oceanic fronts and eddies, i.e in the Mediterranean Sea [52], in North Pacific [53] and in Bone Bay – Flores Sea [54]. The distribution of biogeochemical parameters is also in agreement with the current pattern which distributes the phytoplankton, zooplankton and detritus to be inside of Bone Bay, in...
response to the mechanism during East Season, bringing the waters with higher nutrients. This indicates that the ocean dynamics affect the biogeochemical concentrations due to the seawater circulation that can drive waters with high nutrients to flow to the Bone Bay.

![Figure 13. Temperature (°C) at 10 m depth in the 10th year of simulation. Figures are displayed based on selected month representing the season i.e. January (JAN) for West Season, April (APR) for transition season I, July (JUL) for East Season and October (OCT) for transition season II.](image)

**Figure 13.** Temperature (°C) at 10 m depth in the 10th year of simulation. Figures are displayed based on selected month representing the season i.e. January (JAN) for West Season, April (APR) for transition season I, July (JUL) for East Season and October (OCT) for transition season II.

![Figure 14. Salinity (‰): a) at 10 m depth and b) vertical section in the 10th year of simulation. Figures are displayed based on selected month representing the season i.e. January (JAN) for West Season and August (AUG) for East Season.](image)

**Figure 14.** Salinity (‰): a) at 10 m depth and b) vertical section in the 10th year of simulation. Figures are displayed based on selected month representing the season i.e. January (JAN) for West Season and August (AUG) for East Season.
Figure 15. Distribution of biogeochemical parameters at 10 m depth: a) Chl-a (mg m⁻³), b) phytoplankton (mmol Nm⁻³), c) zooplankton (mmol Nm⁻³) and c) detritus (mmol Nm⁻³). Figures are displayed based on selected month representing the season i.e. January (JAN) for West Season and August (AUG) for East Season.

4. Conclusion

Analyses on the upper circulation in Bone Bay both from observation and model are complementary and confirm the hypothesis that there is an exchange of waters from and to the inside of the gulf. Observation results during October 15-19, 2014 illustrated that water mass flew to the outside of the gulf and the water mass inside the gulf was dominated by water salinity. This indicates that the exchange of water mass from the outside of the gulf is small hence the biogeochemical variables are low in this period. It is confirmed by the model output of oceanic parameters that reveal a similar pattern in October.

The model also helps to view a larger spatial and temporal context of the changes found during the West Season (December to February) which indicate a flow of current from the outside of the gulf towards the inside of the gulf. Vertical profile during observation shows that water mass is well-mixed (no stratification) and it is dominated by local water mass. Transport model reveals that seawater is transported strongly to the north from January to March and due to the topography at the mouth of the gulf, the water accumulates and forms an eddy which transports water to the south in April until the
next few months, explaining the distribution of phytoplankton and zooplankton inside the gulf during East Season.

The overall results give us a picture of how the biogeochemical distribution in Bone Bay relies on the seawater circulation. Here we also find promising signs that using a combination of model and observation could provide valuable insights into the links between physical processes and biogeochemical variables that are important for the fish population and ecosystem dynamics.

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