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UNDERSTANDING THE MECHANISM OF SEASONAL UPWELLING AND DOWNWELLING AT THE SOUTHERN COAST OF MAKASSAR STRAIT

MEKANISME SEASONAL UPWELLING DI SELAT MAKASSAR BAGIAN SELATAN

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ABSTRACT

The mechanism of temporary upwelling and downwelling in the southern coast off Makassar Strait, Indonesia is determined not only by the wind-driven coastal during southeast monsoon (SEM) and northwest monsoon (NWM) but also by meeting of two current systems based on previous research. During SEM, water mass of the Flores Sea in eastern area meets the throughflow water coming from northern of Makassar Strait and flow together to Java Sea and this causes upwelling occur. But during NWM, water mass of the Java Sea western area meets the through flow water and flow together to southern cost of Celebes Island and causes downwelling occur. The first mechanism is well proven but the second one need more investigation.

Twenty years of data result obtained from numerical simulation over the Makassar Strait and adjacent waters are used to describe the seasonal characteristic and mechanism of upwelling in this region. The 3D baroclinic ROMS (Regional Ocean Model System) from Rutgers version was simulated from 1995 to 2014.

The climatological results show the existing of upwelling and downwelling clearly identified by the decreasing or increasing of sea surface temperature ± 2ºC and also increasing or decreasing of surface salinity ±0.5 Psu compared by surrounding waters. The evidence of upwelling starts on June, maximum intensity in August and disappears on September following the easterly wind during southeast monsoon. But downwelling start on December, maximum intensity in January and disappears on February. The mixed layer depth becomes shallow and there is an uplift water from the thermocline to the surface at the upwelling occur, but when downwelling occur the mixed layer depth becomes deeper. The instability of water column was detected from the Brunt-Väisälä frequency (N2) and Richarson number (Ri). By calculating the vorticity and investigate the current circulation we detect the eddy formation in southern part of the Celebes Island at Java Sea and Flores Sea and suggested due to the meeting of current system. We found the Ekman transport is moving to the southern direction offshore of Celebes Island and produces the upwelling during SEM. But when NWM occur, Ekman transport is moving to the northern direction from offshore to the Celebes Island and produce downwelling.

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1. INTRODUCTION

The waters of the southern Makassar Strait have been identified as temporary upwelling areas (Nontji, 1987) and based on insitu water mass scale studies it is known that temporary upwelling occurs in the east season or Boreal Summer Monsoon (JJA), characterized by high surface salinity and low SST in the vicinity (Wyrtki, 1961; Illahude and Groves, 1970; Hadikusuma, 2006). This is evidenced by the relatively high concentration of chlorophyll-a in this region during the same season, but low in other seasons (Putriningsih, 2011; Setiawan and Kawamura, 2011; Syah and et al., 2014). The concentration of chlorophyll-a in this season is more influenced by temporary upwelling than the run off of the river from the surrounding land (Illahude, 1978; Inaku, 2011).

Temporary upwelling phenomenon in the waters of the southern Strait of Makassar start at June, peaking in August and ending at October with a pattern Spreading move southwest (Inaku, 2011). Based on previous researches mentions that the formation of temporary upwelling in these waters is caused by circulation currents. In the eastern seasons the currents from the north of the Strait of Makassar meet with the current coming from the Flores Sea. The second meeting of current circulation has These different characteristics cause the occurrence dragging of surface water mass Southward towards the Java Sea resulting upwelled water (Wyrtki, 1961; Illahude and Groves, 1970). But some research of temporary upwelling others mention that the formation of temporary upwelling in these waters Caused by Ekman Transport generated by southeast monsoon (SEM) winds and some research indicate occurrence of temporary downwelling phenomenon in the same area when northwest monsoon (NWM) active (Habibi et al., 2010; Inaku, 2011; Sukoraharjo et al., 2011).

These earlier studies have shown and explained About temporary upwelling and downwelling phenomenon in the southern waters of Makassar Strait. About that location allegedly to be temporary upwelling and downwelling area, time of occurrences and also spreading pattern and mechanisms of temporary upwelling and downwelling in these waters. Other than that some previous studies also discussed the role of ARLINDO in the mechanism of temporary upwelling. The mechanism of temporary upwelling and downwelling in the southern coast off Makassar Strait, Indonesia is determined not only by the wind-driven coastal during southeast monsoon (SEM) and northwest monsoon (NWM) but also by meeting of two current systems based on previous research. During SEM, water mass of the Flores Sea in eastern area meets the throughflow water coming from northern of Makassar Strait and flow together to Java Sea and this causes upwelling occur. But during NWM, water mass of the Java Sea western area meets the through flow water and flow together to southern cost of Celebes Island and causes downwelling occur. The first mechanism is well proven but the second one need more investigation.

2. DATA AND METHODOLOGY

This research have used data from numerical 3D simulation of Regional Ocean Model System version Rutgers (ROMS Rutgers) from 1995 to 2014 simulated by (Sofian, 2015). The model simulation results have 4 km spatial resolutions in the horizontal direction (x and y) and there are 20 vertical layer layers. The total number of cells in the x-axis direction is 1200 cells (89ºE to 151ºE) and in the y-axis direction 625 cells (-15ºN to 21ºS). The variables used in this research include horizontal current components (u-and -v components), vertical currents (w-component), temperature, salinity, density, SSH and zonal and meridional wind components (u-and -v components).

This research uses descriptive methods and statistical methods. Descriptive method is applied to analyze the distribution of oceanographic parameters. The statistical methods is applied to analyze the relationship between the Ekman transport with a total mass transport away from South Sulawesi (South Sulawesi total transport) and mass transport away from South Sulawesi due to the vorticity (vorticity transport) with total mass transport of South Sulawesi.

3. RESULTS AND DISCUSION

In July 2005, Marine and Fisheries Ministry of Indonesia (KKP) and Lamont Doherty Earth Observatory (LDEO) have been taken water mass data along as Makassar Strait especially around Labani Chanel. Temperature data from this observation has been used to verify of ROMS Rutgers 3D simulation results by (Wira, 2016). These verification result showed a good number (Fig. 1). Total stasiun was used to verificate is 10 stasiun and the location it is around Labani Chanel. Verification result between ROMS result data and insitu data is showing that ROMS result data capable to describe oceanography characteristics of waters in this study area, with R^2 value around 0.9901-0.9988 (Geofary, 2016).

Distribution SST showing that seasonal upwelling occur in southern cost of South Sulawesi and spread to southeastern, starts on June, maximum intensity in August and disappears on September following the easterly wind during SEM (Fig. 2.). Upwelling occur in southern coast of South Sulawesi start from June and vanish at September. It's can see from SST reduction (2.6°-3°C) at this place compared with surrounding as same as previous research (Inaku, 2011), but downwelling occur in same area start from January and vanish at March. Generally Inaku (2011) study results using satellite imagery Modis level 1 (2009 - 2010) shows the same result with these research, i.e. upwelling location is southern coast of South Sulawesi, upwelling period starts in June and ends in September with August as peak of upwelling. Habibi et al (2010) in his research using OISST reanalysis data found similarity that there is a decrease of SST around ± 2ºC indicated there is an upwelling phenomenon in the same region. There is no research exactly describing about downwelling phenomenon in these area, but from distribution SST showed increased SST at this area compared with surrounding and these is result as same as like Habibi et all (2010) research.

Same as SST, distribution sea surface salinity showing that seasonal upwelling occur in southern cost of South Sulawesi and spread to southeastern, starts on June, maximum intensity in August and disappears on September following the easterly wind during SEM (Fig. 3.). Distribution of sea surface salinity climatology. Upwelling occur in southern coast of South Sulawesi start from June and disappear at September. It's can see from sea surface salinity increase (1.4-1.7 Psu) at this place compared with surrounding as same as previous research (Wrytki, 1961), but downwelling occur in same area start form January and vanish at March.

To analyze the characteristic of temperature of the column of waters mass in the research area, the analysis of temperature distribution in 3 meridional transect representing the waters of South Sulawesi (Fig. 4.). Analyze BB' transect not only showing phenomenon of upwelling but we can find downwelling too. Downwelling occur in southern cost of South Sulawesi start on January and disappears on September following the westerly wind during NWM (Fig. 5.). Form BB' transect we can analyze any upwelled waters at June, July, August and September but downwelling at January, February and March. Analyze of temperature distribution and meridional current components on the BB' transects (v and w) showed the occurrence of deepening of the mixed layer depth, these indicate of downwelling phenomenon in the west season (DJF) in South Sulawesi (119.7ºBT and -5.712ºLS). The downwelling phenomenon indicate by downwelled waters surface movement and also shown by the meridional component current vector moving downwards to the inner layer (Fig. 5.).

The occurrence of downwelling is seen in January and February, where the mass of water moving toward the waters near the mainland of South Sulawesi, causing the formation of downwelling. In this season (DJF) temperatures and salinity at mixed layers in December respectively ranged from 26.33º-29.68ºC, in January ranged from 26.49º-29.16ºC and in February ranging from 25.97º-28.85ºC (Fig. 5.).

Analyze of temperature distribution and meridional current components on the BB' transects (v and w) showed the occurrence of deepening of the mixed layer depth, shows upwelling in the east season (JJA), which is characterized by the movement of water mass to the surface (Fig. 5.). In June the upwelling phenomenon in this region is clearly marked by the water mass movement from a depth of ± 30 m (upwelling depth) to the surface and also characterized by thinning of the thermocline layer with a temperature distribution in the mixed layer of 27.1º-27.9ºC (Fig. 5.). These phenomenon because surface water mass moving to south away from land, so that the mass of water below it rises to the surface to fill the void. In July there was a rise in surface current velocity, which made deeper upwelling depths of up to ± 50 m and thermocline depth rising to a depth of 10 m with a temperature distribution in the mixed layer ranging from 27.1º-27.2ºC (Fig. 5.). August is the peak of upwelling in these area, vertical current strengthening followed by increasing of upwelling depth up to ± 70 m depth and thinning of thermocline layer with a surface temperature 26,65ºC and visible expansion of upwelling area (Fig. 5.).

To analyze the characteristic of temperature, salinity and stability of the column of waters mass in the research area, the analysis of temperature distribution, salinity, Brunt- Väisälä frequency (N^2) and Richardson number (Ri) in 8 station representing the waters of South Sulawesi (Fig. 6.).

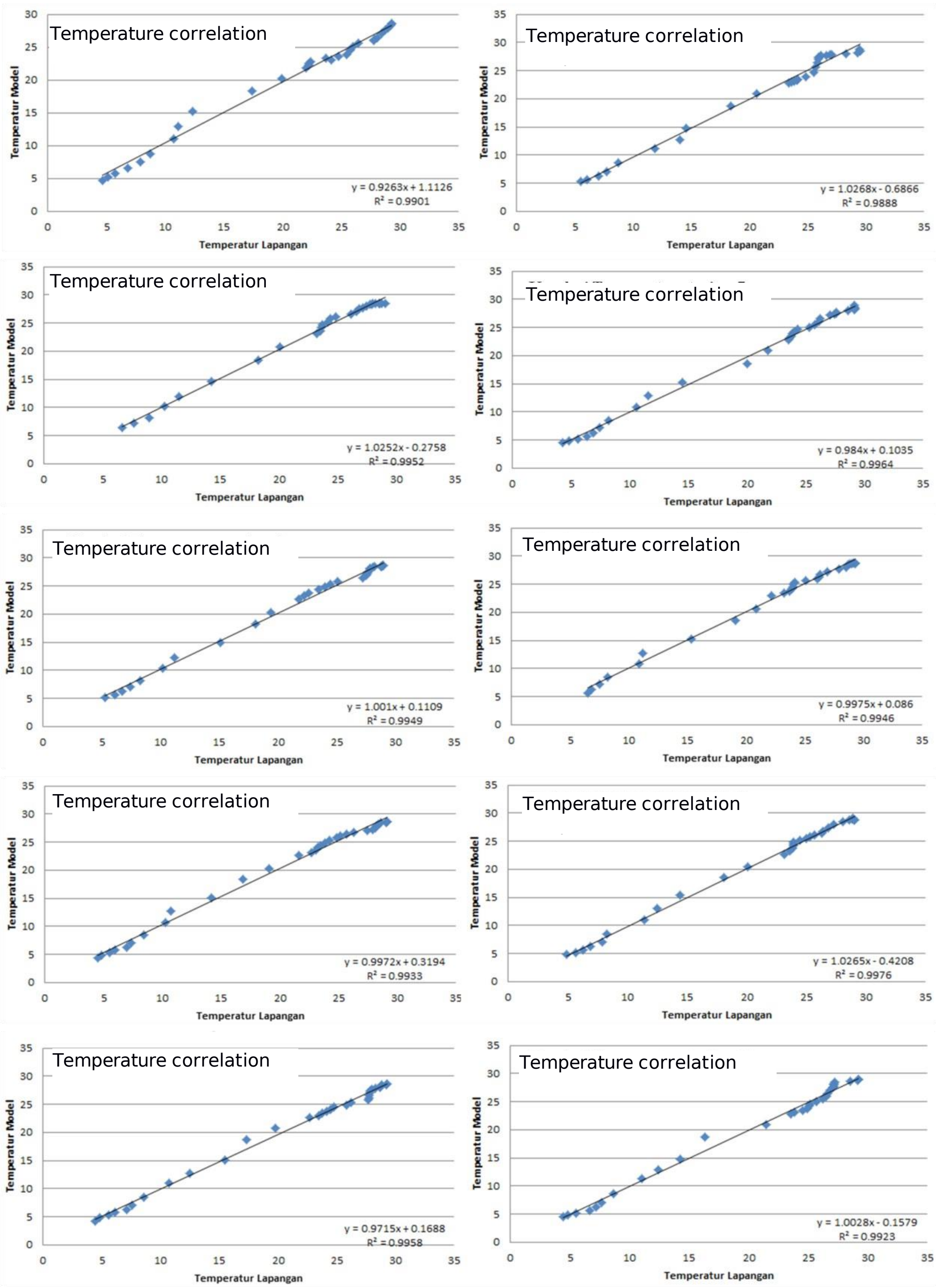

Fig. 1. Scatter plots of observation temperature and simulation temperature of ROMS Rutgers.

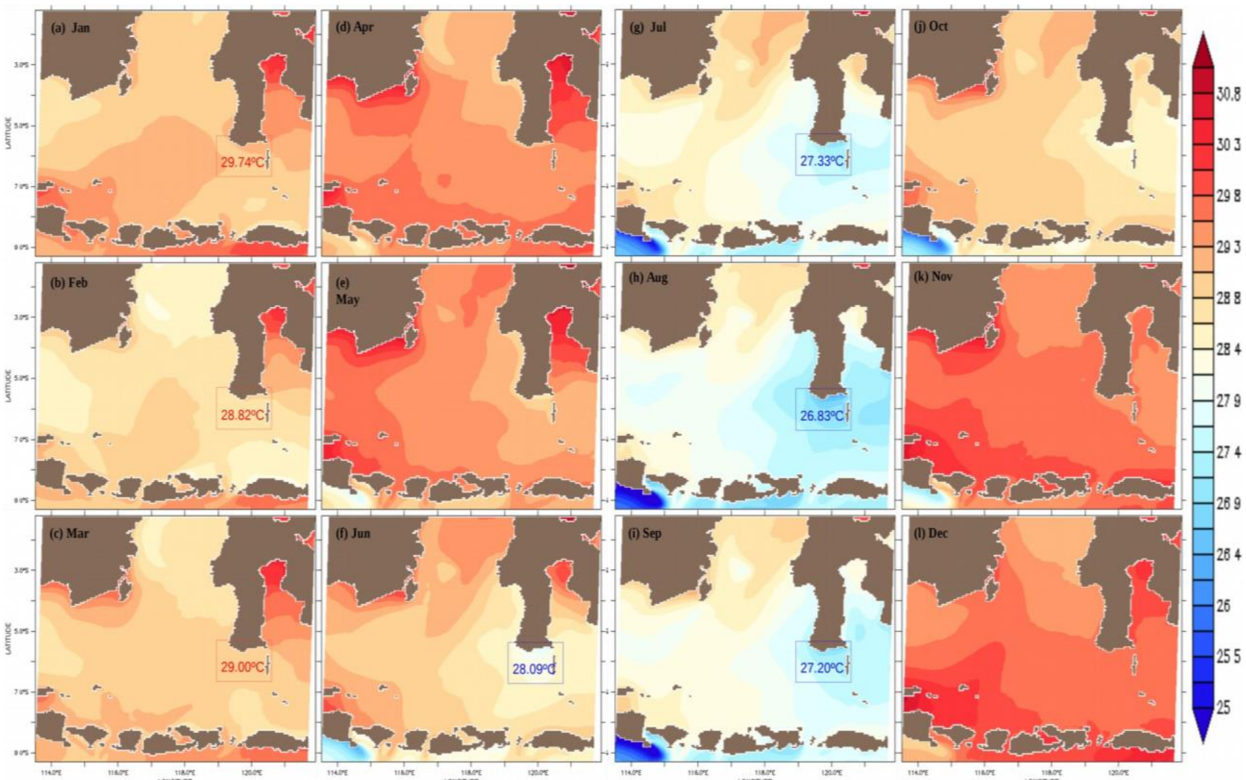

Fig. 2. Distribution of SST climatology in southern coast of Makassar Strait, upwelling area be marked with blue square and downwelling area be marked red square.

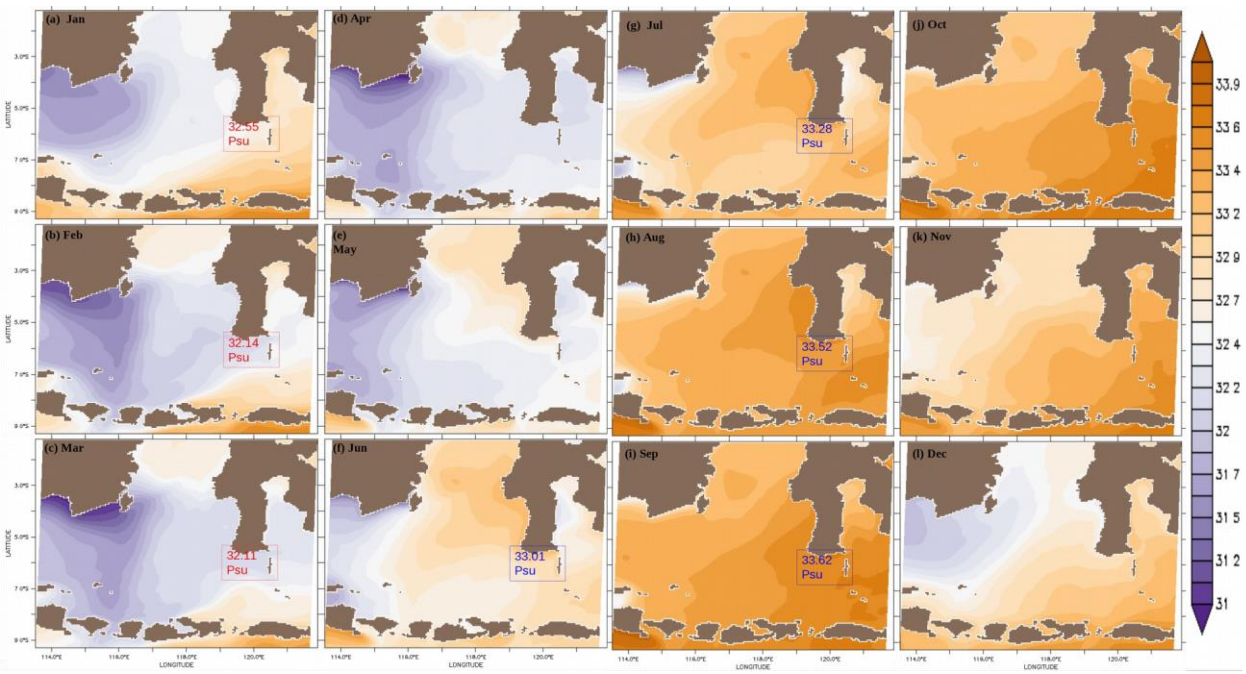

Fig. 3. Distribution of sea surface salinity climatology in southern coast of Makassar Strait, upwelling area be marked with blue square and downwelling area be marked red square.

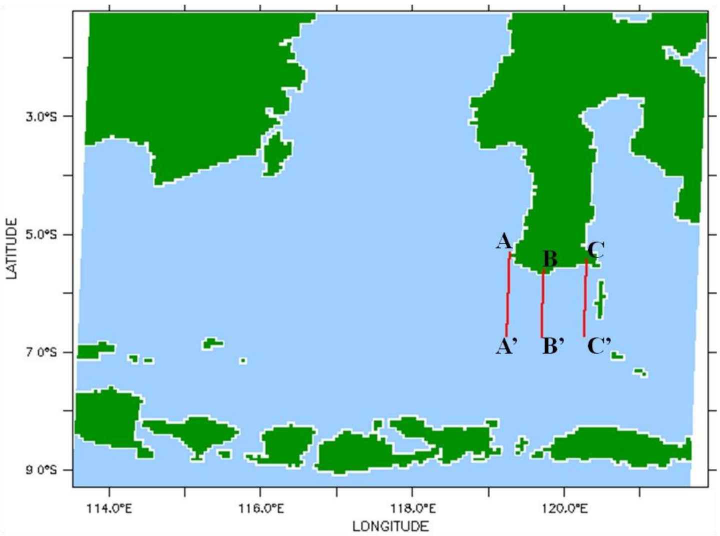

Fig. 4. Transec BB' map. In this section, we will show temperature and current meridional transect to analyze seasonal upwelling and downwelling.

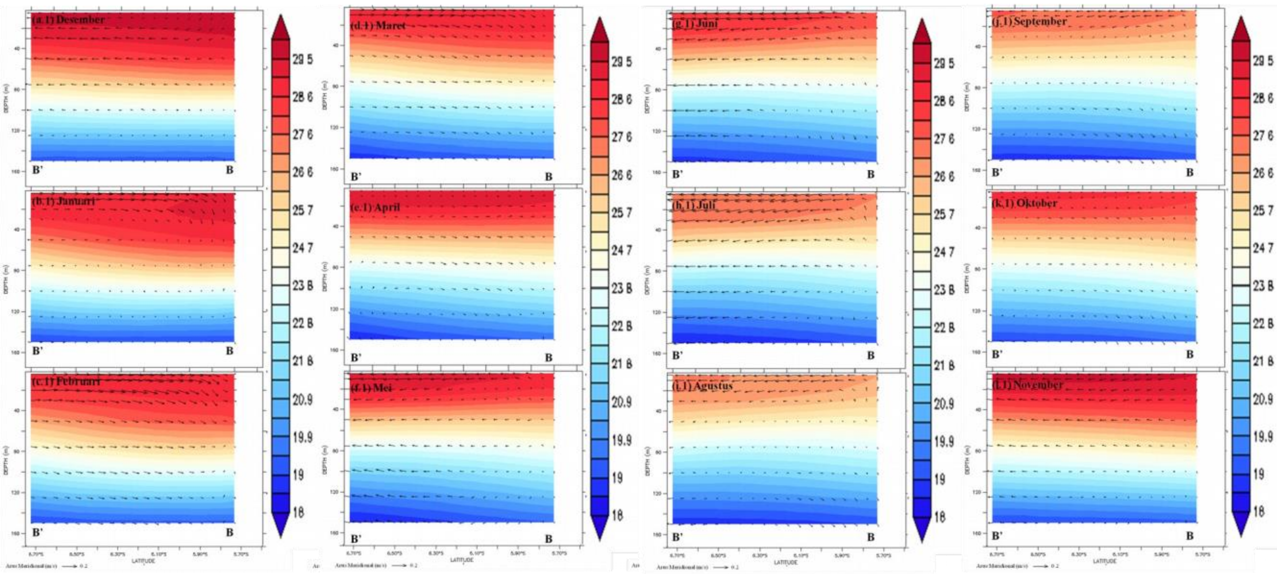

Fig. 5. Climate temperature profile towards depth in transect BB' in South Sulawesi

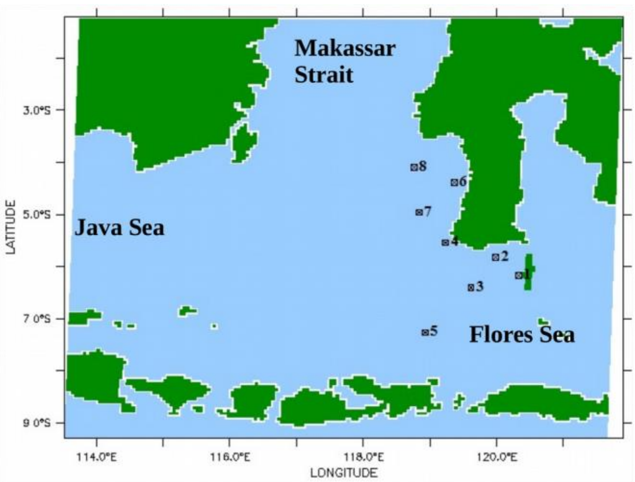

Fig. 6. Station analysis map. Around eight station used for analysis temperature, salinity, N2, Ri on depth distribution, to knowing characteristic of seasonal upwelling in study area.

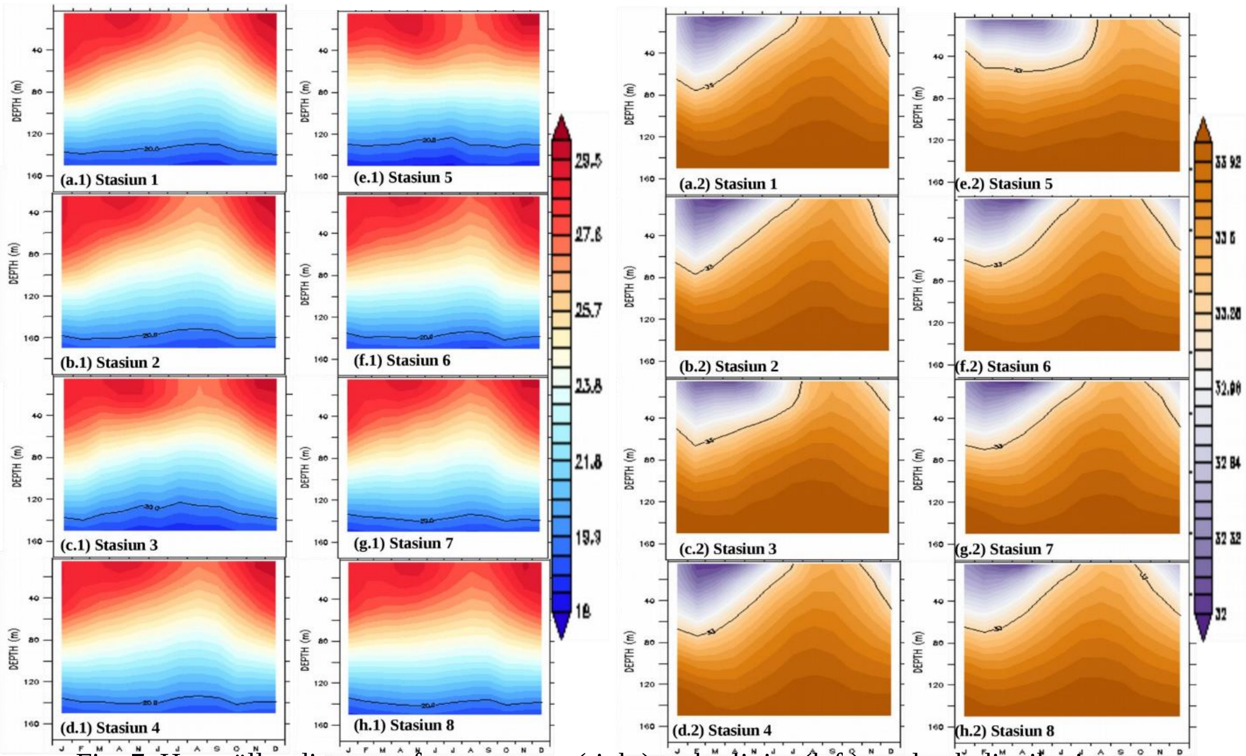

Fig. 7. Hovmöller diagram of temperature (right) and salinity (left) on depth distribution.

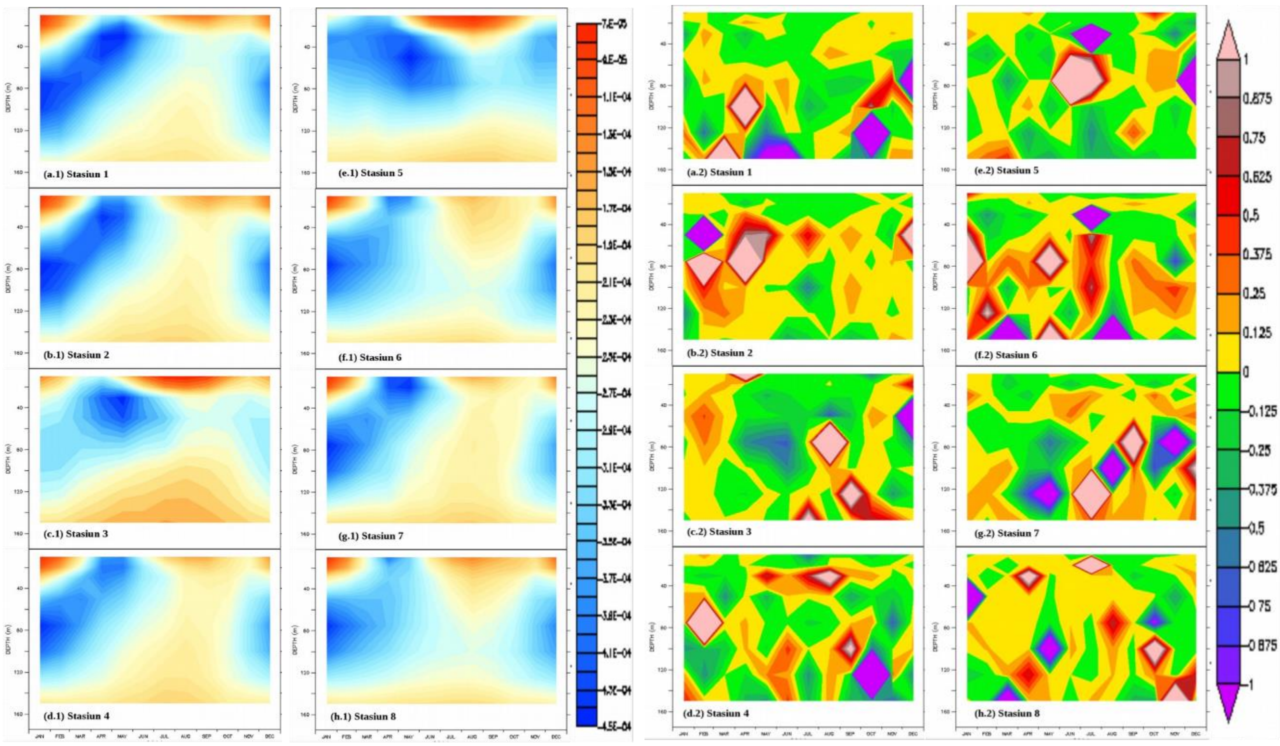

Fig. 8. Hovmöller diagram of N^2 (right)and Ri (left) on depth distribution.

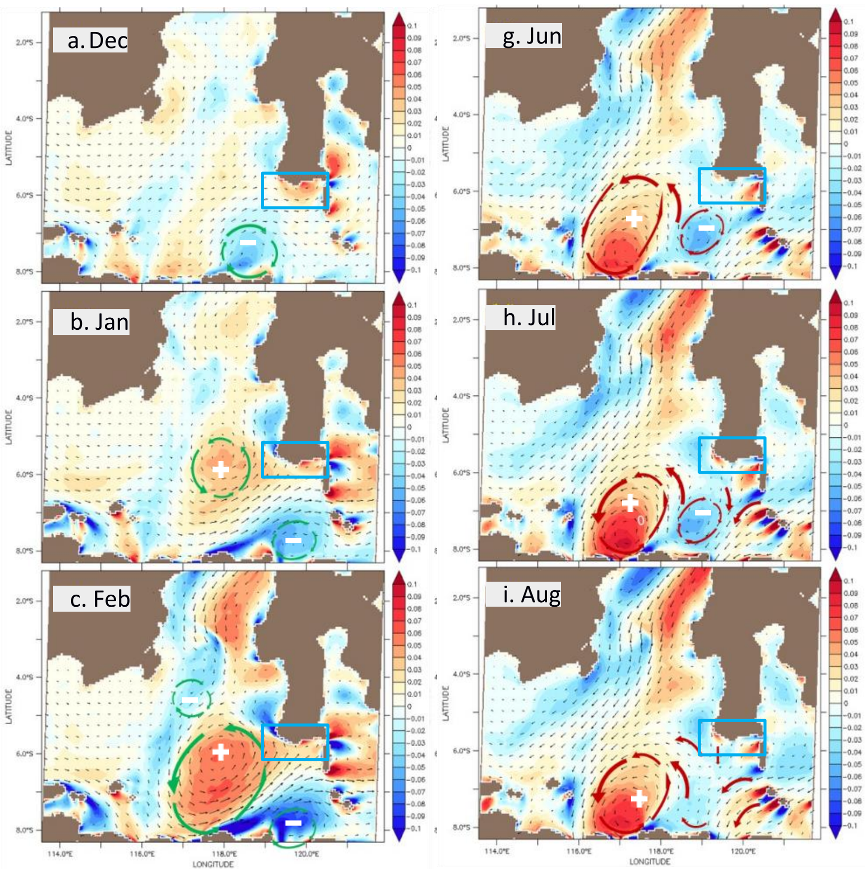

Fig. 9. Distribution of vorticity overlaid with sea surface current climatology. Meeting two current system between throughflow water with Java sea current system and Flores sea current system.

The mixed layer depth becomes shallow and there is an uplift water from the thermocline to the surface (Fig. 7.). It's can see upwelled waters start from June and disappear at September.Temperature distribution from the surface to a depth of 130 m each station, generally showed the same pattern of decreased in temperature of waters in June-September. However different with temperature distribution, salinity of waters increased beginning to show up in July, it strengthened in August and ended in October (Fig. 7.). Analyzes in stations 1, 2, 3 and 4 look mixed layer dwindling every month until it reaches the surface in June – September and thicken back in October (Fig. 7.). This is in contrast to the general theory that in the eastern season (JJA), mixed layer in the study area will be thickened due to strong stirring by southeast monsoon wind. So the answer of these is the upwelling phenomenon, where the waters mass from the depth movement to the surface and thinning the mixed layer. Analysis on station 5 representing waters off the coast of South Sulawesi showed a relatively stable mixed layer, but thinning reached the surface in July - September and thickened back in October (Fig. 7.). Analysis of the distribution of temperature and salinity at stations 6, 7 and 8 shows that the mixed layer is depleted every month until it reaches the surface in July - September and thicken again in October (Fig. 7.).

The instability of water column was detected from the Brunt-Väisälä frequency (N^2) and Richarson number (Ri) (Fig. 8.) N^2 value showed that thermocline and pycnocline layer wane start June until September at station 1, 2, 3 and 4. Ri value showed that turbulence occur at same station. Analyze the cross section distribution of N^2 values, shows each station have the same pattern of decreasing N^2 values in thermocline layer and pycnocline (Fig. 8.). The significantly decline of N^2 values is because gradient of density increasingly enlarged. The same pattern is also obtained in the North China Sea south (Pu et al, 2006), in Marguerite Bay western Antarctic peninsula (Wallace et al., 2008) and also in the waters of the Strait Alor (Purwandana et al., 2014). The decreased of N^2 value in the thermocline layer shows that the thermocline layer is a more stable layer than the mixed layer and the inner layer. The distribution analysis of N^2 values at stations 1, 2, 3 and 4 shows that in May - November the thermocline layer rises to reach the surface (Fig. 8.). The thermocline layer disappears from June to October due to the reduced distribution of N^2 values and this indicates the instability of the water clump at a depth of 100 m to the surface. The highest instability of the water column at a depth of 30 m is indicated by a low N^2 value. The N^2 value distribution analysis shows the thermocline layer at station 5 is very close to the surface (Fig. 8.). This layer of mixed layers began to disappear in June-September indicating the instability of the water column caused by upwelling that formed in June-September at this station. Analysis of the distribution of N^2 values at stations 6, 7 and 8 shows almost the same results as at stations 1, 2, 3 and 4, that is, the presence of a thermocline layer with water column instability seen at a depth of less than 20 m to the surface. An analysis of the Ri values is performed to see an indicated of turbulence in the water column which may resulted instability of water column and allow for upwelling. The Ri values describe the relationship of water mass instability to the velocity of the inner currents (Pond and Pickard, 1983). Empirically when $Ri>0.25$ then turbulence can not be formed despite any the speed gradient (Pond and Pickard, 1983). Using second criterion of Richardson's Numbers ($0 <Ri <0.25$) and the Pond and Pickard criteria (1983) to see indications of turbulence in the water column, generally the Ri values in each Station show an indicated any turbulence/ mass mixing (Fig. 8.). The distribution of the values of Ri in June-September at stations 1, 2, 3, 4, 5, 6, 7 and 8 indicates the occurrence of turbulence where the successive Ri values at each station are station 1 ranges from $-0.5<Ri<0,8$ and the mean Ri= -0.0002, station 2 ranged from $-0.6<Ri<0.6$ and mean Ri= -0.02, station 3 ranged from $-0.7<Ri<0.3$ and average Ri=0.1, station 4 ranged $-0.7 <Ri<0.8$ and mean Ri= 0.02, station 5 ranged from $-0.6 <Ri<0.8$ and average Ri= 0.007, station 6 ranged from $-0.4 <Ri<0.9$ and mean Ri= 0.06, station 7 ranged $-0.8 <Ri<0.7$ with mean Ri= 0.006, station 8 ranged from $-0.3 <Ri<0.8$ with an average of Ri= 0.02. From the statistical analysis and the distribution of Ri values shows that in general the water column in the eight stations is unstable and allows for turbulence and allows occurrence of upwelling. By calculating the vorticity and investigate the current circulation we detect the eddy formation in southern part of the Celebes Island at Java Sea and Flores Sea and suggested due to the meeting of current system (Fig. 8.).

We found the Ekman transport is moving to the southern direction offshore of Celebes Island and produces the upwelling during SEM, while the effect of eddy formation enhanced the upwelling in the same direction. We found too, during NWM occur, Ekman transport is moving to the northern direction from offshore to the Celebes Island and produce downwelling. Phenomenon of upwelling that occurs in the southern waters of South Sulawesi caused the movement of the water moving southward from the land, while the phenomenon of downwelling in this area is caused by the movement of the moving water mass to the north approaching the land.

The result of Ekman transport analysis shows the small coriolis frequency value that is 1.49 × 10-5 s, the small coriolis frequency value is because this area is close to the equator. Nevertheless Ekman's transport is still established, this is probably due to the southeast winds blowing so strong that led to the formation of Ekman transport to the south towards the Java Sea. The results of the Ekman transport analysis indicate the presence of water mass transport southward to the Java Sea that occurred in June- September ranged from 3.82 Sv to 5.47 Sv with an average of 4.65 Sv.

In the western seasons (DJF) visible vortices are formed due to the circulation of the Java Sea current circulation which encounters the current circulation from the north of Makassar Strait (Fig. 9.). In the west season (DJF) there is a large scale negative vorticity located just south of NTB. This vorticity is formed by the current circulation of the Java Sea with the circulation of currents from the north of the Makassar Strait (Fig. 9.). This vorticity causes the surrounding water mass away from the center of negative vortices to form a circulation of currents moving towards South Sulawesi, leading to the formation of small-scale positive vortices in the region. This positive vorticity causes the accumulation of surface water mass or negative divergence (convention), causing downwelling in South Sulawesi.

In the east season (JJA) the southeast monsoon strengthens which moves the current circulation from the Flores Sea which then meets with the circulation from the north of the Makassar Strait (Fig. 9.). The second encounter of this current circulation forms the same vorticity system in the west season and one transition (Fig. 9.). The difference between these two vorticity systems is seen in negative vortices that are weakening and moving northward towards South Sulawesi. In addition this season also occurs strengthening the circulation of currents and water mass transport from the northern Strait of Makassar that strengthens the intensity of shipping the water mass of South Sulawesi to the south (Fig. 9.).

In June large-scale positive and negative vortices caused the effect of water mass dragging from South Sulawesi by the current circulation from the north of Makassar Strait getting stronger, forming divergences in South Sulawesi indicating upwelling in this region (Fig. 9.). The upwelling that occurred in South Sulawesi is getting stronger until August which is marked by the strengthening of divergence areas. The strengthening of this divergence is the result of the weakening of negative vortistas so that the positive vortices are more dominant so that the drawing of water mass to the center of positive vorticity is strengthened, it also strengthens the water mass of South Sulawesi to the south.

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