Modeling small-pelagic fish biomass in the Indonesian seas: climate variability and climate change impacts

A F Koropitan¹, Nabil¹ and T Osawa²,³,⁴

¹ Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, IPB University, Dramaga, Bogor 16680, West Java, Indonesia
² Center for Research and Application of Satellite Remote Sensing, Yamaguchi University
³ Regional Satellite Application Center for Disaster Management, Japan Aerospace Exploration Agency (JAXA)
⁴ Center for Remote Sensing and Ocean Sciences (CReSOS), Udayana University

*Email: alan@apps.ipb.ac.id

Abstract. The present study uses the Community Earth System Model, version 1–Biogeochemistry [CESM1(BGC)] to examine the influence of climate variability and climate change on small pelagic fish biomass in the Indonesian seas. The fish biomass was calculated based on a fish production model according to primary production and energy transfer at the tropic level. The primary production data were obtained from results of CESM1(BGC) model from 1850 to 2015. Empirical orthogonal function (EOF) analysis of the calculated fish biomass identifies three regions in the Indonesian seas that are associated with coastal upwelling. These regions are located in (1) southern coast of Central Java Province until west-coast of West Sumatra Province, (2) southern coast of Central Java Province until the southern coast of Bali Province, and (3) Banda-Arafura Seas. Fish production variability in these regions exhibits semiannual, annual, and IOD-ENSO related signals. Climate change impact for RCP 4.5 scenario produces ‘fish stock increase status’ in 2025 for the three regions, while the ‘fish stock current status’ will recur in 2050, except for the western part of Sumatra (part of region-1) which alters to ‘fish stock decrease status’.

Keywords: climate change, IOD-ENSO, Small pelagic fish, the Indonesian seas, upwelling

1. Introduction

Fisheries productivity, particularly small pelagic fishes in the Indonesian seas are mainly controlled by complex oceanographic processes, such as monsoonal wind, seasonal coastal upwelling, and internal mixing in the continental slope and sill-depth regions for nutrient supply. It is well known that the seasonal upwelling in the Indonesian seas occurs during the southeast monsoon in June-August, as described in detail previously [1]. Then, it comes to the relationship of the upwelling phenomena with El Niño–Southern Oscillation (ENSO). Susanto et al. [2] highlighted that the upwelling in the southern coast of Java until parts western coast of Sumatera extends in both times (into November) and space (closer to the equator of the west coast of Sumatera) during El Niño event. In addition, they reported that during El Niño (La Niña), the Indonesian throughflow carries colder (warmer) water that shallowing (deepening) thermocline depth and enhancing (reducing) the upwelling magnitude in the regions.

The seasonal upwelling regions are crucial for fishery production since the upwelled waters from the sub-surface produce high nutrient concentration in the surface waters. The influence of the El Niño event on the seasonal upwelling subsequently produces phytoplankton bloom in the regions within days and
finally affects the upper trophic level within months. Regarding the influence of El Niño event on fish production, Oily Sardine (Sardinella lemuru) in Bali increased four months after Chlorophyll-a bloomed in November 1997 [3]. The Oily Sardine production has reached 8000 tons per month during March-August 1998 as a result of El Niño effect while in the normal year is only one-half. The analysis [3] was based on monthly mean Chlorophyll-a data derived from Ocean Color Thermal Scanner (OCTS) sensor and Sea-viewing Wide Field-of-View Sensor (SeaWiFS) during 1997-1999 and landing data of Sardinella lemuru during 1997-1999. In addition, despite their paper only discussed Indian Ocean Dipole Mode (IOD), the 1997–1998 El Niño was regarded as one of the strongest ENSO events in recorded history.

Global warming is now becoming worse where CO\textsubscript{2} concentration in the atmosphere has increased by almost 50% in 2019 from 277 ppm in 1750 [4]. At this level, IPCC [5] highlighted that there has not been such a level of atmospheric CO\textsubscript{2} concentration during at least 2 million years. The RCPs (Representative Concentration Pathways) scenario is a climate change scenario adopted by IPCC [6] in the Fifth Assessment Report (AR5). The RCP4.5 scenario considers a stabilized greenhouse gas emission that peaks in the middle of the twenty-first century, where the anthropogenic radiative forcing of 4.5 W/m\textsuperscript{2} stabilizes before 2100. The RCP4.5 is a medium stabilization scenario. Related to the global warming impact in the Indonesian seas, Iskandar et al. [7] reported an increasing trend of sea surface temperature (SST) on average at 0.19 ± 0.04°C/decade where the global SST warming trend is lower than the SST trend in the Indonesian seas.

Concerning global warming's impact on the marine ecosystem, a 3-dimension ecosystem-biogeochemical model of NEMURO (North Pacific Ecosystem Model Used for Regional Oceanography) has been implemented for the western North Pacific. The report [8] suggested that the global warming simulation showed increases in vertical stratification of the ocean water column due to rising temperatures in the surface water. In addition, the calculated nutrient and Chlorophyll-a concentrations in the surface water decrease at the end of the 21st century, while the dominant phytoplankton group shifts from diatoms to other small phytoplankton. However, the temperature rise becomes a favourable temperature for phytoplankton growth despite the decrease in nutrients. Therefore, the global warming simulation in the region showed increases in net primary production (NPP). The report also found that regeneration rates increase, which contributes to the increase in NPP through nutrient supply in the surface water. Considering the complex oceanographic processes and global warming impact, the present study aims to investigate the influence of climate variability and climate change on small pelagic fish biomass in the Indonesian seas by applying the CESM1(BGC) model output.

### 2. Model Description and Method

The CESM1(BGC) is part of a Coupled Model Intercomparison Project Phase 5 (CMIP5). All CMIP5 model outputs are provided by Asia-Pacific Data Research Center (APDRC - http://apdrc.soest.hawaii.edu/datadoc/cmip5.php accessed on 10 January 2019). The CESM is a continuation of the Community Climate System Model, version 4 (CCSM4). CCSM4 combines land, atmosphere, ocean, and sea-ice components as a fully coupled global climate model [9]. In comparison to the CCSM4, the CESM1(BGC) provides a land-ice model as an optional addition and alternative to use different atmospheric models. CESM1(BGC) comprises the whole global carbon cycle, including an ocean biogeochemistry module. Besides the historical model output, this study adopts the model output of RCP4.5 scenarios in 2025 and 2050 as a climate change scenario. The design of CESM1(BGC) RCP4.5 simulations was described in detail by Moore et al. [10], whereas the data set of model output is also provided by the APDRC.

CESM1(BGC) could reproduce a relatively robust representation of the ocean–carbon cycle response to climate variability but weak in regional detail and the strength of teleconnections [11]. The ocean carbon biogeochemistry in CESM1(BGC) is represented by the ocean Biogeochemical Elemental Cycle model embedded within the CESM ocean component. The BEC ecosystem model is built on the classical nutrient–phytoplankton– zooplankton–detritus food web model. There are three phytoplankton...
functional types (PFT; diatoms, “small” pico–nano phytoplankton, and diazotrophs) and one zooplankton class with PFT-specific grazing rates. Phytoplankton growth is determined by temperature, multi-nutrient (N, P, Si, and Fe) limitation, and light availability. Riverine inputs into the model ocean carry no dissolved tracers and thus only contribute to the freshwater balance.

Related to ocean components, the CESM1 is based on the Parallel Ocean Program, version 2 (Pop 2) [12], a z-level hydrostatic primitive equation model. The CESM ocean component is integrated with a nominal horizontal resolution of 1° x 1° and 60 vertical levels [11]. The horizontal grid has enhanced resolution in the tropics and high latitudes. The vertical grid spacing is 10m in the upper 160m and varies with depth below, increasing to 250m by a depth of 3500m, then remaining constant to the model bottom at 5500m. In addition, a monthly temporal resolution is provided by APDRC for the CMIP5 model output.

To estimate pelagic fish production, we implement a fish production model [13], which is approximately 10% from transfer efficiency in the trophic level, as follows:

\[ FP = PP \times (ET)^{(TL-1)} \]  

(1)

where

- \( FP \): fish production (mg C/m²)
- \( PP \): primary production (mg C/m²)
- \( ET \): energy transfer (10%)
- \( TL \): trophic level

The ratio of fish biomass and carbon wet weight is estimated at 9 : 1, following [13]:

\[ FB = FP \times 9 \]  

(2)

where:

- \( FB \): fish biomass (ton)
- \( FP \): fish production (mg C/m2).

Primary production is a model output of the calculated primary organic carbon production by all types of phytoplankton based on CESM1(BGC).

We perform an Empirical Orthogonal Function (EOF) in transforming the multidimensional signal into spatial variability pattern and temporal function [14]. The EOF method can extract the principal components (PCs) of patterns in a time series. The calculated spatial patterns or PCs represent the variance, where the EOF-1 explains most of the variance, EOF-2 for the second dominant, followed by EOF-3, and so on. The calculated temporal function explains the amplitude and time scale of the time series that provides an important period of spatial variability pattern. This study uses software of PyFerret (http://ferret.pmel.noaa.gov/), which could accommodate time series analysis of such CESM1(BGC) model output and calculated fish production with a big matrix.

3. Results and Discussion

3.1. Spatial and Temporal Patterns

The EOF analysis of calculated fish from 1850 – 2015 explains the spatial pattern of EOF-1 and EOF-2 is 53% and 12%, respectively, as shown in Figure 1. Those two spatial patterns contribute significantly by 65% of the total variances. EOF-1 shows an intensification of positive score in a region located between the southern coast of West Java Province to the western coast of Lampung Province in the southern Sumatera (named as region-1). EOF-2 shows intensification of positive score in two regions: between the south coast of West Java Province to the south coast of Bali Province (named as region-2), and in the Banda-Arafura Seas (region-3).

A positive score in the three regions means an increasing trend of fish biomass in the respective region. We calculated that the fish biomass trend of region-1, region-2, and region-3 are 2.5 ton/1°x1° per decade, 1.4 ton/1°x1° per decade, and 1.3 ton/1°x1° per decade, respectively. It implies a similar increasing trend with the calculated net primary production in the three regions. In comparison with
other studies, we found that a recent study [15] showed an increasing trend of sea surface Chlorophyll-a concentration (SSC) with a value of 0.1–0.2 mg/m³ per decade along the south coast of the Sumatra and Java Islands (region-1 and region-2). Their study was based on satellite remote sensing imageries from 1997-2020.

The strong signal near Sunda Strait (EOF-1) might be influenced by the Java Sea waters that contain high nutrients and Chlorophyll-a concentrations due to riverine inputs. In this case, the mechanism is related to the strong intra-seasonal along-strait flow from the Java Sea into the Indian Ocean induced by the SSH gradient (pressure difference) along the Sunda Strait [15,16]. On the other hand, the strong signal in EOF-2 represents seasonal upwelling event forced by the southeast monsoon.

![Figure 1. EOF-1 (a) and EOF-2 (b) of monthly mean of calculated fish biomass from 1850 – 2015.](image)

To clarify which frequency dominates the upwelling pattern, we investigated the power spectra of each region (Figure 2) as summarized by EOF-1 and EOF-2. For the entire three regions, those significant periods are 4, 6, 12, 45, 55, 65, and 70 months, which represent semi-annual, annual, and IOD-ENSO related signals (4-7 years) respectively. The three regions have a strong annual signal that dominates the total variability which is associated with the upwelling regions during southeast monsoon, as discussed in the beginning. Unlike previous findings [2], Xu et al. [15] highlighted that these interannual SSC anomalies are strongly associated with IOD-induced anomalous upwellings along the south coast of the Sumatra and Java Islands, where IOD events often lag that of ENSO by 6–11 months.

3.2. Climate Change Impact

Figure 3 represents model results of the SST differences between mean SST of 1980-2005 and climate change scenario of RCP 4.5 in 2025 (Figure 3a) and 2050 (Figure 3b). Region 3 shows slightly higher increase of SST difference (0.8-0.9°C) compare to region-1 and region-2 (0.6-0.7°C) in 2025. The SST difference is still decreasing to around 0.4°C for the three regions in 2050, except for the Sunda Strait (0.7-0.8°C). The SST drop in 2050 is relevant to the RCP 4.5 scenario, which requires major greenhouse gasses to decline by 2040-2045 and cease to increase by 2050. Terrestrial impact and local warming in the Java Sea might contribute to the remaining warmer SST in the Sunda Strait, as shown in Figure 3c. Regarding the SST distribution, an increasing trend of local Ekman pumping is related to wind stress data in the calculation [15], especially for the 1980-2005 mean condition case in the south coast of the Sumatra and Java Islands. On the contrary, other study [17] reported significant negative trends of wind stress along the southern coast of Java might reduce the Ekman pumping, particularly during the upwelling season in the months of May to October. They [17] used wind data from the NCEP CFSR database [18] with a horizontal resolution of approximately 0.3° × 0.3° and a time interval of 6 h from 1 January 1982 to December 2010. Hence, their results are different from [15] which applied the trend calculation for the whole years from 1 January 1998 to 31 December 2019.
Figure 2. The frequency spectra of the three regions; region-1 (a), region-2 (b), and region-3 (c).

Figure 3. Model results of SST (°C) differences between 1980-2005 mean condition and climate change scenarios of RCP 4.5 in 2025 (a) and in 2050 (b). The mean SST (°C) condition of 1980-2005 is shown in (c).

In addition to the association of wind stress, Ekman pumping, and SST, study from Varela et al. [19] reported that subsurface layers had experienced a cooling trend over the last three decades along the south coast of Java, although wind stress showed a negative trend. They proposed that the combination of horizontal advection particularly the South Java Current [20-21] and vertical entrainment due to upwelling is still efficient to bring cooler water (and nutrient-rich water) to the surface.

Differences of the amount of fish biomass between the 1980-2005 mean condition and the RCP 4.5 scenario in 2025 and 2050 are presented in Figure 4. The focus is still on the three upwelling regions in
the Indonesian seas. In general, fish biomass distribution tends to increase by 10-20 kilotons in 2025 for the three regions. It is due to favourable temperature conditions associated with the global warming scenario of RCP 4.5, which stimulate higher primary production compared to the 1980-2005 mean condition. In 2050, for region-2 and region-3, the fish biomass distribution is likely to reverse back to the 1980-2005 mean condition. However, part of region-1 on the western coast of Sumatra will decrease by -10 kilotons until -20 kilotons compared to the 1980-2005 mean conditions. Although the fish production in upwelling regions reaches its peak during the southeast monsoon period, it is argued that the combination of horizontal advection and vertical entrainment during the southeast monsoon might be responsible for the remaining unchanged fish biomass distribution which neutralizes the total fish production during the whole year of 2050. The decrease of fish biomass distribution on the western coast of Sumatra tends to be affected by the climate change impact for the long term trend in 2050. However, there is a possibility of some increases when modulated by IOD and ENSO.

Figure 4. The calculated fish biomass (kiloton) difference between the 1980-2005 mean condition and climate change scenario of RCP 4.5 in 2025 (a) and 2050 (b). Visualization of this results used Ocean Data View [22].

4. Conclusion

There are three regions associated with seasonal upwelling during southeast monsoon in the Indonesian seas that provide a positive trend for fish production. The three regions are located in the southern coast of West Java Province to the western coast of Lampung Province (south Sumatera); the southern coast of West Java Province to the southern coast of Bali Province, and the Banda-Arafura Seas. These regions are important fishing grounds in the Indonesian waters, particularly on small pelagic fishes. The fish production variability in these regions has semi-annual, annual, and IOD-ENSO related signals. Climate change impact through scenario in CESM1(BGC) RCP4.5 simulations demonstrates a ‘fish stock increase status’ in 2025 for the three regions. Furthermore, simulation result suggests that the ‘fish stock current status’ will return in 2050, except for the western part of Sumatra (part of region-1) a reversal condition of ‘fish stock decrease status’ may occur.

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