Variability of sea surface topography in coastal area (study case: Indonesia)

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Abstract. The deviation of the sea surface from the geoid reference surface is known as the Sea Surface Topography (SST). SST is caused by several physical phenomena such as ocean wave, tides, current and atmospheric pressure loading, and the main application of SST is to determine ocean circulation. To get the SST, we use Sea Surface Height (SSH) and Mean Dynamic Topography (MDT) based on 30 years of sea-level data derived from multi-mission of satellite Altimetry and geoid height (Undulation) from Global Gravitation Model EGM-2008. Indonesia is an archipelagic country in the equatorial region that lies between Indian and Pacific oceans. Its geographical setting will affect variability of Sea Surface Topography (SST) in the Indonesian Sea. The anomaly from SST is one of the oceanic parameters that play a crucial role in the ocean dynamic and its possible hazards. We found that the characteristics differ considerably from one place to another, depending on the bathymetric depth and type of sea. The mean SSH varies from about 40 meters and rises to the east up to a height of 80 meters. Likewise, the MDT value increased from 0.5 meters to the east to a height of 1.2 meters. In closed, narrow and shallow seas, the long time-series of those surfaces are less sensitive to the effects of El Niño and La Niña as well as global sea level rise. On the other hand, global sea level rise significantly affects the characteristic of both surfaces over open and deep seas. We hope by using more spatially dense data from multi-mission satellite altimetry, we can see more detail about the local phenomena that influence SST. By studying the variability of SST from more than one cycle (18.6 years) it is expected that it can be used to understand the dynamics of the coastal area in Indonesia.

1. Introduction

The deviation of the sea surface from the geoid reference surface is known as the Sea Surface Topography (SST). SST is caused by several physical phenomena such as ocean wave, tides, current and atmospheric pressure loading, and the main application of SST is to determine ocean circulation [1]. This phenomenon is caused by Geostrophic Force Balance, which is a Coriolis force that is equilibrium as a result of pressure gradients at sea level. El Nino, La-Nina, the Kuroshio, Gulf Stream and Antarctic Circumpolar Current are global ocean circulation from the above phenomena. Indonesia is an archipelagic country in the equatorial region that lies between Indian and Pacific oceans. Its geographical setting will affect variability of Sea Surface Topography (SST) in the Indonesian Sea. The anomaly from SST is one of the oceanic parameters that play a crucial role in the ocean dynamic and its possible hazards.
SST geodetic estimation can be done by using altimetry satellite measurement that measures the distance between satellites to instantaneous sea surface. To get the SST, in this research, we use Sea Surface Height (SSH) and Mean Dynamic Topography (MDT) based on more than 20 years of sea-level data derived from multi-mission of satellite Altimetry and geoid height (Undulation) from Global Gravitation Model EGM-2008. We hope by using more spatially dense data from multi-mission satellite altimetry, we can see more detail about the local phenomena that influence SST. By studying the variability of SST from more than one cycle (18.6 years) it is expected that it can be used to understand the dynamics of the coastal area in Indonesia.

2. Methods

2.1. Satellite altimetry and sea surface topography

Distance measurement between satellite and the sea surface is based on the round-trip travel time of microwave pulses emitted downward by the satellite radar multiplied with the pulse velocity. The independent tracking systems are used to compute the satellite’s three-dimensional position relative to a fixed Earth coordinate system. The profiles of sea surface height/sea level with respect to the reference ellipsoid are determined by combining these two measurements. Error of the measurement comes from several factors such as instrument design, calibration, validation, range corrections (ionosphere, troposphere and sea state bias), geophysical corrections (tides, geoid and inverse barometer), reference systems, precise orbit (satellite height) determination, different satellites with different sampling characteristics. Figure 1 presents the schematic diagram of satellite radar altimeter system and its principle to measure instantaneous sea surface height (ISSH) modified from [2]. Several type of sea surface are defined depend on the reference datum such as mean sea surface height (MSSH) and instantaneous sea surface height (ISSH) (for simplicity, later we call it sea surface height (SSH)) with mathematical surface – ellipsoid as reference surface and mean dynamic topography (MDT) and sea surface topography (SST) with physical surface – geoid as reference surface. The distance between satellite and sea surface is called altimeter range \( R \). The corrected range \( R_{corr} \) is related to the observed range \( R_{obs} \) as:

\[
R_{corr} = R_{obs} - dR_{dry} - dR_{wet} - dR_{ion} - dR_{sb}
\]

Where \( R_{obs} = ct/2 \) is the computed range from the travel time \( t \) observed by the on-board ultra-stable oscillator (USO), \( c \) is the speed of the radar pulse neglecting refraction, \( dR_{dry} \) and \( dR_{wet} \) are dry and wet tropospheric correction, \( dR_{ion} \) is ionospheric correction and \( dR_{sb} \) is sea-state bias correction. The range measurement is then converted to ellipsoidal SSH \( h_{SSH} \) by \( H_{ell} \) (satellite height determined through orbit determination) as follow

\[
h_{SSH} = H_{ell} - R_{corr}
\]

As a result, the sea surface height accuracy is directly related to the accuracy of the orbit determination. The orbit accuracy has improved from tens of meters on the first altimeters to about 1 cm on the most recent satellites and the resulting sea surface heights vary spatially between ±100 m with temporal variations up to ±10 m after range corrections [3].

The dynamic sea surface height signals related to oceanographic processes is the main focus of satellite altimeter field study which is normally on the sub meter scale. In order to isolate these, it is necessary to remove the dominant geophysical contributors to sea surface height variations. That contribution comes from geoid, tide and dynamic atmosphere corrections. The largest contribution to the measured sea surface height is the geoid correction. The sea surface height is reduced to meter scale by removing the permanent geoid signal and referencing the sea surface height to a given geoid model [4]. The temporal sea surface height variability is dominantly affected by ocean tide effect.
Ocean tides are the largest tidal component, but the correction also accounts for solid earth tides, loading tides, and pole tides. The last is the sea surface height variations due to the time varying atmospheric pressure loading is corrected by dynamic atmospheric. This correction normally involves a static response (inverse barometer) of the ocean to atmospheric forcing for low-frequency signals (longer than 20 days) combined with a correction for dynamic high-frequency variations (shorter than 20 days) in sea surface height [4].

Figure 1. Principle of satellite altimetry (modified [2])

The actual sea surface height \( h_{SSH} \) still contains the external geophysical signals from the sea surface height. It need correction for geophysical signals as a range correction to get dynamic sea surface height \( h_{DT} \) as follow

\[
h_{DT} = H_{ell} - R_{obs} - dh_{dry} - dh_{wet} - dh_{ion} - dh_{sb} - h_{geoid} - h_{tide} - h_{atm}
\]  

(3)

Where \( h_{geoid} \) is geoid correction, \( h_{tide} \) is tide correction, \( h_{atm} \) is dynamic atmosphere correction and all corrections are sea surface height corrections i.e., \( dR_{wet} = -dh_{wet} \), etc. Andersen and Scharroo (2011)[4] mentioned that by applying the geophysical corrections, and particularly the geoid correction, the sea surface \( h_{DT} \) height values are typically reduced from ranging up to 100 m to range up to a few meters.

Calman (1987) [1] mention that SST is superposition of Dynamic Topography/ Mean Dynamic Topography (time independent) and Dynamic Ocean Topography (time dependent). Dynamic Ocean Topography is a superposition of sea level changes to time caused by tides of sea water, wind, sea waves and atmosphere pressure loading. Furthermore, the height of SST \( h_{SST} \) value is obtained using the following equation

\[
h_{SST} = h_{SSH} - N - M_{DT}
\]  

(4)

Where \( N \) is a geoid undulation (height between geoid and ellipsoidal reference surface) and \( M_{DT} \) is the Mean Dynamic Topography. MDT is a superposition of all global ocean circulation [1] covering permanent ocean currents, meteorological effects, uneven salinity distribution, and sea water temperature. Variability of the \( h_{SST} \) in this study used sea level variation with respect to the geoid.

2.2. Multi satellite altimeter data processing

In this research, we use Radar Altimeter Database System (RADS), to retrieval and reduction sea level data from altimetry satellite. RADS are initiative archive and process by TUDelft, NOAA and Altimetrics LLC [5]. This system was installed in the frame of the SEAMERGES project at ITB –
Indonesia since 2005 as a mirror (reinstallation in 2016 for the latest development of algorithm), where EU-AUNP funded this project for sharing knowledge, methods and data exchange related to satellite altimetry, InSAR and GPS (www.deos.tudelft.nl/seamerges). Nowadays, RADS enables users to extract the data from several present and past satellite altimeter missions like GEOSAT, ERS1, ERS2, ENVISAT, TOPEX/Poseidon (T/P), Jason1, Jason2, CRYOSAT2 and SARAL. Figure 2 show the complete RADS system layout [6]. The SST from different satellite missions need to be adjusted by crossover adjustment for multisatellite missions to a ‘standard’ surface because of factors such as orbit error and inconsistency in the satellite orbit frame.

![Figure 2. RADS system layout [6]](image)

### Table 1. Selected altimetry satellite

| Satellite | Phase | Temporal Resolution (day) | Cycle | Inclination (degree) | Epoch | Equatorial Altitude (km) | Semi Major Axis (m) |
|-----------|-------|---------------------------|-------|----------------------|-------|--------------------------|-------------------|
| TOPEX     | A     | 9.9156                    | 364   | 66.04                | 25 Sept 1992 - 11 Aug 2002 | 1336 | 7714427.8                |
| POSEIDON  | A     | 9.9156                    | 361   | 66.04                | 1 Oct 1992 - 12 Jul 2002  | 1336 | 7714427.8                |
| JASON-1   | A     | 9.9156                    | 260   | 66.04                | 15 Jan 2002 – 26 Jan 2009 | 1336 | 7714427.8                |
| GFO-1     | A     | 17                        | 186   | 108.04               | 7 Jan 2000 – 17 Sept 2008 | 840  | 7166400                  |
| ENVISAT1  | A     | 35                        | 88    | 98.5429              | 14 May 2002 – 22 Oct 2010 | 712.4-799.8 | 7159495.65               |

There are three sources of editing criteria that can be used for the computation of fully-corrected sea surface height (SSH) anomaly (orbit - range - environmental corrections - mean sea surface) for all satellite mission when deriving the altimeter data in RADS, there are flag bits generated by the data processing chains, limits on altimetric parameters independent of range and on the environmental corrections used to correct the range. Selected satellite altimeter missions at Table 1 were merged and every footprint is calculated before interpolated into grid of area investigation. The value are calculated on daily solution and collected per month to get monthly solution. The corrections and models applied for altimeter processing in RADS have been summarized in Table 2, in which updated environmental and geophysical corrections were applied and the corrections were done by applying specific models for each satellite altimetry missions in RADS. The sea level data have been corrected for altimeter range corrected for instrument, orbital altitude, ionospheric delay, dry and wet
tropospheric corrections, sea state bias, solid earth and ocean tides, ocean tide loading, pole tide, electromagnetic bias and inverse barometer correction.

### Table 2. Corrections and models applied for altimeter processing in RADS

| Correction / Model       | Description                                                                 |
|--------------------------|-----------------------------------------------------------------------------|
| Orbit/Gravity Field      | All satellites: EIGEN GL04C ; ERS: DGM-E04/D-PAF                           |
| Dry Troposphere          | All satellites: Atmospheric pressure grids; ECMWF (Model)                  |
| Wet Troposphere          | All satellites: Radiometer measurement;                                    |
|                          | All satellite : Radiometer – Smoothed Dual Frequency; ERS/POSEIDON: NIC08  |
| Ionosphere               |                                                                            |
| Inverse Barometer        | IB (Model, Local Pressure)                                                 |
| Dynamic atmosphere       | All satellites: MOG2D                                                       |
| Solid Earth Tide         | Applied (Elastic response to tidal potential)                               |
| Ocean Tide               | All satellites: GOT4.8                                                      |
| Load Tide                | All satellites: GOT4.8                                                      |
| Pole Tide                | Applied (Tide produced by Polar Wobble)                                    |
| Sea State Bias           | All satellites: CLS non parametric ; ERS: BM3/BM4 parametric               |
| Reference                | DTU10 mean sea surface height                                               |
| Engineering flag         | Applied                                                                     |
| Applied reference frame biases (cm) | JASON1: -4.8, ERS1: +3.4,  |
|                          | ERS2: +7.3, ENVISAT: +5.2                                                   |
|                          | JASON2:+15.9                                                                |
|                          | TOPEX: Reference frame                                                      |

### 3. Results and Discussion

The research coverage area is between -15S/95E to 15N/150E, and spatial representation of the MSSH is shown in Figure 3 and the N from global gravitational model EGM2008 in Figure 4 that are used to analyze the sea-level pattern with respect to real potential surface (geoid) as SST.

The MSSH (Figure 3) have negative value around -45 m in Western Indonesia and continues increase to positive value up to 80 m in eastern Indonesia. In western part, the almost west-east pattern (in 10-degree distance) show smooth increasing value from about -45 m to 0 m at South China Sea. The rather random positive pattern (about 60-80 m) appear in central part, at northern part of Sulawesi from Makassar Strait, with gap (about 40-50 m) in Halmahera Double Subduction Area in between Sulawesi and Halmahera, and start to increase again smoothly to the eastern part after this gap. It looks like that SSH phenomena have positive correlation with bathymetry of each area. This SSH pattern at Indonesia area have positive correlation with its geoid undulation N (the difference between the geoid surface and the reference ellipsoid surface) in the whole area. The value is strongly influenced by the high value pattern of geoid undulation in the Indonesian region which has a negative value in the western part of Indonesia and changes regularly to a positive value towards Eastern Indonesia with a range of -90 m to + 90 m, based on the global EGM2008 undulation geoid data for long wave length type with degree 180° (Figure 4). In coastal areas, MSSH show different values (bias) compare to its regional trends, this is due to the quality of altimetry data that cannot be recorded properly in transition area between land and sea, and give noisy data results. Bias also appears for closed sea and shallow sea areas where altimetry data has a highly fluctuating cycle bias at SSH determination.
The MDT value for the Indonesian region is shown in Figure 5. Based on Vaníček et al. (2012)[7], MDT theoretical value ranges from ± 2 m and the value shown in Figure 5 corresponds to the theoretical criteria that the MDT value increased from 0.5 meters to the east to a height of 1.2 meters.

In general, the territory of Indonesia has varying MDT values, namely for the open sea area in the Indian Ocean and Pacific Ocean it looks to have values varying from 0.6 m to 1.0 m. From the west...
side of the Indian Ocean, the value of MDT experienced increase to the east via the south of the island of Java to Papua with a range of values from 0.6 m to 1.75 m. For the Pacific Ocean region, there are three MDT groups that are almost parallel with the east-west direction, which is in the range of 1.2-1.4 m for the area above latitude 10° N, ranging from 1.0-1.2 m for the region around latitude 10° N and ranges from 0.8-1.0 m for area below latitude 10° N. This represents the El Nino and La Nina phenomena.

Figure 6. Sea surface topography January-June 1992-2010
For closed areas or areas that are known to have shallow bathymetry depths such as in the Java Sea, MDT values tend to be higher than in deep sea areas. This is estimated as the impact of friction with the local bathymetric surface, while for coastal areas, the bias is still clearly influential due to high fluctuations because the signal power returns is smaller than in the open sea.

Figure 6 and Figure 7 show the variability of SST since 1992-2010 from January to December with the geoid as a reference surface. For the open sea area in the Indian Ocean, it can be seen that the SST value has the lowest value which is close to -0.2 m in March, and gradually increases to 0.1 m around September. For the Pacific Ocean region which is also an open sea, the lowest SST values range from November to December ranging from -0.2 m and experiencing the highest increase to more than 0.1 m around May. For closed sea areas such as in the Java Sea, the lowest SST values were seen around October and reached the highest SST values in January, then again to reach -0.2 in March. The increase in the SST value occurred also until June, and decreased again in July. Fluctuation occurred until October. For the South China Sea region, the SST value again varied with the lowest value in
June and gradually increased to a maximum in December. Whereas for the archipelago in Indonesia, the region around Banda and Sulawesi is seen to have the highest value of 0.2 m in April and has fallen to the lowest around August. Variations in the SST values for these various regions show a close relationship with bathymetry conditions and topographic boundaries that become the current constraints. In closed, narrow and shallow seas, the long time-series of those surfaces are less sensitive to the effects of El Niño and La Niña as well as global sea level rise. On the other hand, global sea level rise significantly affects the characteristic of both surfaces over open and deep seas.

4. Conclusion
In this study, we recognize that the MSSH, MDT and SST characteristics differ considerably from one place to another, depending on the geographic condition, bathymetric depth, type of sea and gravity field (material density contrast). In closed, narrow and shallow seas, the long time-series of those surfaces are less sensitive to the effects of El Niño and La Niña as well as global sea level rise. On the other hand, global sea level rise significantly affects the characteristic of both surfaces over open and deep seas. The MSSH-MDT-SST rates have positive correlation with geoid undulation, where the extreme SST value should be the next concern to get the precise geoid model for better MSSH-MDT-SST estimation. We also noticed that the derived MSSH-MDT-SST values are still affected by inaccurate altimetric wave-form due to reflection from near coastal areas and geoid undulation estimation. It is therefore our results should be further assessed to get more precise description of SST variability in the Indonesian water.

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