Simulation of tsunami effects on sea surface salinity using MODIS satellite data

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Abstract. Remote sensing technology has been recognized as powerful tool for environmental disaster studies. Ocean surface salinity is considered as a major element in the marine environment. In this study, we simulate the 2004 tsunami's impact on a physical ocean parameter using the least square algorithm to retrieve sea surface salinity (SSS) from MODIS satellite data. The accuracy of this work has been examined using the root mean of sea surface salinity retrieved from MODIS satellite data. The study shows a comprehensive relationship between the in situ measurements and least square algorithm with high $r^2$ of 0.95, and RMS of bias value of ±0.9 psu. In conclusion, the least square algorithm can be used to retrieve SSS from MODIS satellite data during a tsunami event.

1. Introduction
On December 24, 2004, a massive 9.2 earthquake occurred off the island of Sumatra. It generated a deadly series of tsunamis that swept Indonesia, India, Madagascar, and Ethiopia. The death toll was estimated to be in the neighbourhood of 300,000 to 350,000. This was one of the greatest losses of life due to a major natural catastrophe in modern history. Furthermore, the Christmas tsunami was so powerful it actually sped up the rotation of earth, reducing the length of its sidereal day. The earthquake that spawned also caused the Earth to vibrate all over by as much as 1 cm[1]. In this regard, one critical question that may be raised is what the tsunami effects on the ocean physical properties such as temperature and salinity? In fact, there are not many studies which have been conducted to answer this question. Temperature and salinity are the main parameters used to understand ocean circulation. Both parameters can produce vertical current movement because of their gradient changes. In addition, water density changes are a function of gradual changes of temperature and salinity. Also, climate change, marine pollution and coastal hazards are basically controlled by the dramatic changes in sea surface salinity (SSS) [2].

Previous empirical research provides conclusive evidence on the use of mathematical algorithms such as the least square algorithm to acquire comprehensive and accurately patterns of sea surface salinity (SSS) from different remote sensing sensors (i.e. passive and active sensors) [3]. The main objective of this study is to implement the linear least square algorithm for understanding the effect of a tsunami on SSS using MODIS satellite data. In fact, there are many studies have offered a great promise for using MODIS for retrieving SSS [4,5,6].

2. Least square algorithm
In this section, we present the theoretical model of the split window method that relates to MODIS sea surface salinity with in situ salinity measured by thermal infrared sensors, these include multi-channel methods. We assume the MODIS image radiance $I$ within multi-channels $i$ have a linear

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A relationship with measured sea surface salinity ($SSS$). According to [3] and [4], a useful extension of linear function of $k$ channels as in

$$SSS_{MODIS} = \beta_0 + \sum_{i=1}^{k} \beta_j I_{ij} \quad I = 1, 2, \ldots, n$$

where the retrieval Sea Surface Salinity $SSS_{MODIS}$ in Scalar notation, from MODIS data, the least squares estimators of the regression coefficients are $\beta_0, \beta_1, \ldots, \beta_k$ and $k$ is a number of selected MODIS radiance bands which equals 7 bands. Therefore, the fitted regression model to retrieve the Sea Surface Salinity from MODIS data ($SSS_{MODIS}$) is

$$SSS_{MODIS} = I \beta$$

where $\beta$ is the ordinary least squares estimator of $b$ to distinguish it from other estimators based on the least squares idea. According to [7] $\beta$ is given by

$$\beta = (I' I)^{-1} I' SSS$$

In general, $SSS$ is an $(n \times 1)$ vector of the Sea Surface Salinity ($SSS$) observations from MODIS radiance data $I$ which is and $(n \times p)$ matrix of the levels of independent variables. In addition, $I'$ $SSS$ is a $(p \times 1)$ column vector [7]. In this form it is easy to see that $I' I$ is a $(p \times p)$ symmetric matrix [4]. The model, written in terms of the $SSS_i$ observations, is

$$SSS_i = b_0 + \sum_{j=1}^{k} b_j I_{ij} + \varepsilon_i, \quad i = 1, 2, 3, \ldots, n$$

It is simpler to solve the normal equations if they are expressed in matrix notation. We now give a matrix development of the normal equations that parallels the development of equation (4). Following [4], root mean square of bias (RMS) is used to determine the level of algorithm accuracy by comparing with in situ sea surface salinity. Further, linear regression model used to investigate the level of linearity of sea surface salinity estimation from MODIS data. The root mean square of bias equals

$$RMS = \left[ \frac{1}{N} \sum_{i=1}^{N} (SSS_{MODIS} - SSS_{in-situ})^2 \right]^{0.5}$$

The time integrations are performed to determine the possible improvement of RMS. In doing so, simulations and retrievals were performed within a two-month period and for each grid point, the retrieved SSS was averaged over six days during the MODIS satellite different times over passes.

3. Results and Discussions

Three MODIS data sets have been examined for studying the impact of the tsunami on SSS along Acheh coastal waters (Figure 1) pro and post tsunami events December 23rd, 26th and 27th 2004. These data are available on the MODIS website (www.modis.gsfc.nasa.gov). Moderate Resolution Imaging Spectroradiometer (MODIS) has 1 km spatial resolution and having 36 bands which are the range from 0.405 – 14.285μm. The MODIS satellite takes 1 to 2 days to capture all the scenes in the entire world, acquiring data in 36 spectral bands over a 2330 km swath.
Figure 1. MODIS data used in this study along Acheh coastal waters.

Figure 2 shows the variation of the retrieved SSS from MODIS data pre and post tsunami events. Clearly the SSS are increasing during and post tsunami 26\textsuperscript{th} and 27\textsuperscript{th} December 2004 as compared to pre tsunami event on 23\textsuperscript{rd} December 2004. The maximum SSS of 35 psu and 38 psu are found on 26\textsuperscript{th} and 27\textsuperscript{th} December 2004 (Figures 2b and 2c), respectively. The smallest SSS is found in pre tsunami event data, with 30 psu on 23\textsuperscript{rd} December 2004. This work differs from [8] and [9].

Figure 2. Retrieved SSS from MODIS (a) pre (b) during and (c) post tsunami event.

Table 1 shows the accuracy of the retrieved SSS from MODIS data compared to the in situ measurements obtained from the NOAA web site. Clearly, the retrieved SSS using the least square algorithm has the highest accuracy with $r^2$ of 0.95 and root mean square errors of 0.9. This indicates that the least square algorithm can be considered to be a reliable method for retrieving SSS from MODIS data.
Table 1: Statistical summary of accuracy assessments

| Periods        | $r^2$ | RMSE |
|---------------|-------|------|
| Pro tsunami   | 0.94  | 0.9  |
| During tsunami| 0.95  | 1.1  |
| Post tsunami  | 0.96  | 1.2  |

However, this result does not agree with [6]. In fact, they have acquired a RMS ±1.63 that is considerably higher than the RMS of this study. This could be due to the fact that they have implemented the linear regression model without concerning themselves with the residual errors which occur due to the uncorrelated relationship between MODIS radiance data and in situ measurements. Furthermore, using the least squares method derives a curve that minimizes the discrepancy between the estimated SSS from MODIS data and in situ data. This means that using the new approach based on the least squares method, can minimize the sum of the residual errors for the estimating SSS from MODIS data. Clearly tsunami had a great effect on physical ocean parameters that also effected Ch concentrations as mentioned on

4. Conclusions

This study has illustrated a new method to retrieve Sea Surface Salinity (SSS) from MODIS satellite data. The Least Square Method has been applied to investigate the impact of the 2004 tsunami on SSS spatial pattern variations along the Acheh coastal waters. This study shows significant variations in the values of SSS before, during and after the tsunami event. The maximum salinity was observed after the tsunami with 38 psu as compared to pre and during tsunami event. In conclusion, the least square algorithm is an appropriate method to retrieve SSS from MODIS satellite data. It is clear that the tsunami had significant effects on the physical ocean properties of salinity.

References

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