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# MALAYSIAN SEA WATER LEVEL PATTERN DERIVED FROM 19 YEARS TIDAL DATA

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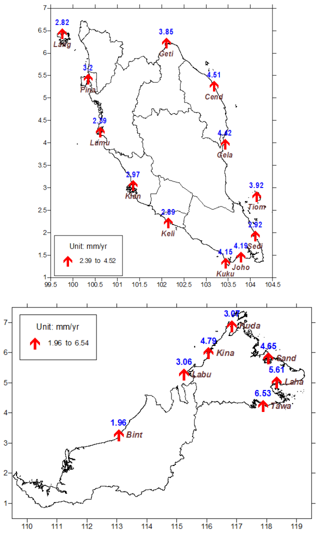
## Graphical abstract



## Abstract

Long-term water level changes have generally been estimated using tidal data. Tide gauges are common tools used to determine the continuous time series of relative water level. This paper presents an effort to interpret the water level from tidal data over Malaysian seas. There are 21 tide gauge stations involved and taken from Permanent Service for Mean Sea Level (PSMSL) with monthly averaged data from 1993 to 2011. The monthly tidal data is then converted to tidal sea level anomaly. For sea level trend analysis, robust fit regression is employed. Next, the sea levels were analysed based on the pattern of seasonal variation and extreme meteorological effects such as El-Nino and La-Nina. In summary, the relative sea level trend in Malaysian seas is rising and varying from 2 to 6.5 mm/yr. This study offers valuable sea level information to be applied in wide range of climatology, related environmental issue such as flood and global warming in Malaysia.

*Keywords*: Tidal Data, Sea Level, Robust Fit Regression, Time-series Analysis, Malaysian Seas

## Abstrak

Perubahan paras air jangka masa panjang secara amnya telah dianggarkan menggunakan data pasang surut. Tolok pasang surut adalah alat yang biasa digunakan untuk menentukan siri masa yang berterusan bagi paras air relatif. Kertas kerja ini membentangkan satu usaha untuk mentafsir paras air daripada data pasang surut sekitar perairan Malaysia. Terdapat 21 stesen tolok pasang surut yang terlibat dan diambil daripada *Permanent Service for Mean Sea Level* (PSMSL) dengan data purata bulanan dari tahun 1993 hingga 2011. Data pasang surut bulanan kemudian ditukarkan kepada anomali paras laut pasang surut. Bagi analisis trend paras laut, regresi 'robust fit' telah digunakan. Seterusnya, paras laut dianalisa berdasarkan kepada corak variasi bermusim dan kesan meteorologi melampau seperti El-Nino dan La-Nina. Secara kesimpulannya, trend paras laut relatif di perairan Malaysia semakin meningkat dan berubah dari 2 ke 6.5mm/tahun. Kajian ini memberikan maklumat paras laut yang berguna untuk digunakan dalam pelbagai kajian iklim, berkaitan isu-isu alam sekitar seperti banjir dan pemanasan global di Malaysia.

*Kata kunci:* Data Pasang Surut, Paras Laut, Regresi Robust Fit, Analisis Siri Masa, Perairan Malaysia

## 1.0 INTRODUCTION

In general, a tide gauge is a simple graduated staff or other reference on which the water level can be visually identified. The setting-up of tide gauge is to estimate a continuous time series of sea level. This technique has been used to determine the water level as far back as the 17th century [19]. Tidal observations via tide gauge can be surprisingly accurate if carefully and faithfully executed. However, to be useful for most investigations of climate change, a record of water levels should be temporally long and dense (the longer the better). In addition, the record must maintain internal consistency in spite of repairs, replacements, and changes of tide gauge technology. Generally, a tide gauge record tides, effects of ocean circulation, meteorological forcing of water, local or regional uplift or subsidence at the measurement site and errors inherent to the gauges [6]. With so many factors involved in maintaining a consistent record over an extended time such as a century or more, a cooperative international program is necessary. Tidal observation also determining the characteristic behaviour during the sudden climate change i.e. El-Nino/La Nina events, the Northeast Monsoon, Northwest Monsoon and Tsunami [1].

Lately, much issues discussed are related to the cause of the sea level rise; yet it must be understood that the cause may only be determined with accurate data. Aforementioned, the rate of the sea level from tide gauge data is influenced by vertical land motion due to active tectonic activities in the region [4], [5]. The release of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) in 2007 was followed by much debate both in media and scientific community, especially on the sea level rise issues [13]. This was due to the fact that sea level rise is one of the most devastating effects of global climate change that will have far-reaching consequences for a majority of the world's population and natural system [16] as illustrated in Figure 1.

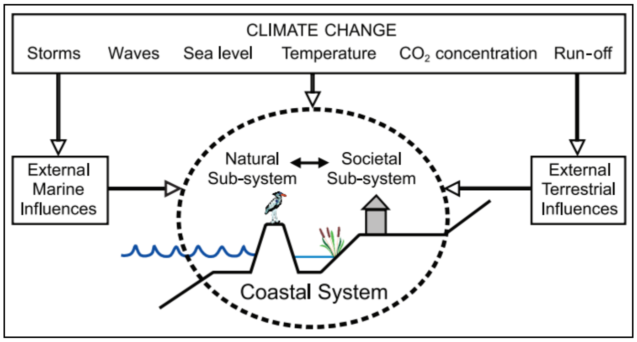


**Figure 1** Schematic framework representing major climate change factors, including external marine and terrestrial influences [16]

Although there is great uncertainty about rates, range and specific time periods in which global sea levels will increase [11], [19], [10], [17], currently sea level rise is becoming one of the most imperative impacts of climate change, which will progress well beyond the 21st century [15], [11], [20], [21], [18].

The Permanent Service for Mean Sea Level (PSMSL) has been responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges since 1933. The PSMSL centre is based at the Proudman Oceanographic Laboratory in United Kingdom. The PSMSL manages sea level data from nearly 200 national authorities. The tidal data can be accessed freely through http://www.psmsl.org/. Currently, there are more than 2000 tide gauges installed worldwide [22].

In Malaysia, the Department of Survey and Mapping Malaysia (DSMM) is the main government agency in Malaysia responsible for the acquisition, processing, archiving, and dissemination of tidal data. DSMM is also responsible to submit all tide gauge station data in Malaysia to PSMSL in monthly and yearly average. Currently, there are 12 tidal stations along the coast of Peninsular Malaysia (West Malaysia) and 9 tidal stations along the coast of Sabah and Sarawak (East Malaysia). Table 1 presents all the Malaysian tide gauge stations' name and date of establishment. Usually, the outputs from each tide gauge station conducted by DSMM are the hourly heights of sea level, daily, monthly and yearly mean sea level values, time and heights of high water and low water, tidal marigrams, 29-day tidal analysis and tide predictions [14].

**Table 1** List of tide gauge stations and date of installation [6]

| | TIDE GAUGE STATION | | ESTABLISHED DATE |
|---|---|---|---|
| PENINSULAR MALAYSIA | 1. | Pulau Langkawi | Nov. 1985 |
| | 2. | Pulau Pinang | Nov. 1984 |
| | 3. | Lumut | Nov. 1984 |
| | 4. | Port Klang | Dec. 1983 |
| | 5. | Tanjung Keling | Nov. 1984 |
| | 6. | Kukup | Nov. 1985 |
| | 7. | Johor Bahru | Dec. 1983 |
| | 8. | Tanjung Sedili | Oct. 1983 |
| | 9. | Pulau Tioman | Nov. 1985 |
| | 10. | Tanjung Gelang | Dec. 1983 |
| | 11. | Cendering | Oct. 1984 |
| | 12. | Geting | Oct. 1983 |
| EAST MALAYSIA | 13. | Kuching | Feb. 1996 |
| | 14. | Bintulu | Aug. 1992 |
| | 15. | Miri | Jan. 1993 |
| | 16. | Labuan | Dec. 1995 |
| | 17. | Kota Kinabalu | Jun. 1987 |
| | 18. | Kudat | Oct. 1995 |
| | 19. | Sandakan | Aug. 1993 |
| | 20. | Lahad Datu | Oct. 1995 |
| | 21. | Tawau | Jun. 1987 |

Each tide gauge station in Malaysia consists of a tide gauge protective house, stilling or tide well; tide staff and several reference benchmarks, one of which is referred to as the tide gauge bench mark [2]. The tide gauge measures water level heights with respect to the zero mark on the tide staff. Surveys on the tide gauge site are performed regularly to account for any settling of the site. Tide gauges may also move vertically with the region as a result of post-glacial rebound, tectonic uplift or crustal subsidence [3]. This greatly complicates the problem of determining global sea level change from tidal data. Figure 2 illustrates the most typically used tide gauge measurement system: a float operating in a stilling well.

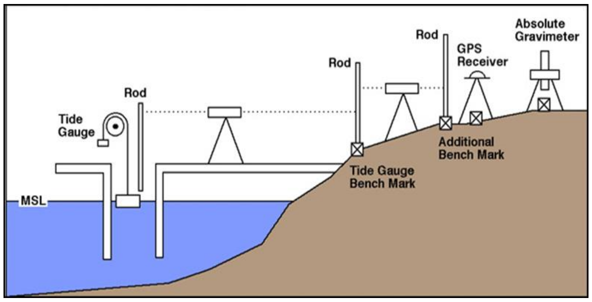


**Figure 2** Schematic of a tide gauge measurement system [7]

## 2.0 METHODOLOGY

In Malaysia, tide gauge stations are normally installed along the coasts or near islands to measure sea level. Sea level recorded by tide gauges is relative to the benchmark tied to the Earth's crust; hence it is known as relative sea level. It basically records the sea level by taking into account the vertical land motion as well. In order to derive the rate of the relative sea level, all the tide gauge stations listed in Table 1 are used in these studies.

### 2.1 Sea Level Anomaly Determination from Tidal Data

All 21 Malaysian tide gauge stations (see Figure 3) are involved which are taken from Permanent Service for Mean Sea Level (PSMSL) with monthly averaged data. It is necessary to convert the tide gauge data (which is referring to zero tide gauges) to sea level anomaly for sea level interpretation. The sea level anomaly from tidal data is the difference between sea surfaces to some long term mean sea level by subtracting the apparent monthly tidal data with the mean of tidal data. The reference level used for the computation of the sea level anomaly at all tide gauges in this study is the mean of tidal data from year 1993 and up to 2011.

Table 2 and 3 present the yearly mean sea level average and the means for all tide gauge stations.

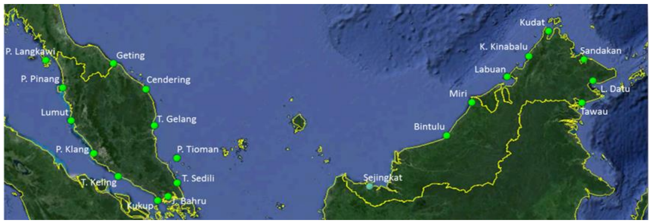


**Figure 3** The distribution of tide gauge stations in Malaysia

**Table 2** Yearly mean sea level average above zero tide gauges and its mean (in metre) for Peninsular Malaysia

| | Tide Gauge Station | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | West Coast | | | | | | | East Coast | | | | |
| **Year** | **P. Langkawi** | **P. Penang** | **Lumut** | **P. Kelang** | **T. Keling** | **Kukup** | **J. Bahru** | **T. Sedili** | **P. Tioman** | **T. Gelang** | **Cendering** | **Geting** |
| **1993** | 2.211 | 2.708 | 2.184 | 3.625 | 2.847 | 3.983 | 2.833 | 2.384 | 2.806 | 2.775 | 2.187 | 2.297 |
| **1994** | 2.169 | 2.629 | 2.140 | 3.578 | 2.809 | 3.956 | 2.847 | 2.388 | 2.817 | 2.774 | 2.183 | 2.286 |
| **1995** | 2.232 | 2.690 | 2.218 | 3.657 | 2.871 | 4.021 | 2.877 | 2.407 | 2.844 | 2.813 | 2.222 | 2.309 |
| **1996** | 2.242 | 2.706 | 2.223 | 3.669 | 2.870 | 4.018 | 2.854 | 2.421 | 2.820 | 2.802 | 2.212 | 2.323 |
| **1997** | 2.121 | 2.582 | 2.121 | 3.540 | 2.763 | 3.931 | 2.824 | 2.381 | 2.808 | 2.782 | 2.188 | 2.298 |
| **1998** | 2.226 | 2.712 | 2.206 | 3.654 | 2.865 | 4.006 | 2.849 | 2.404 | 2.829 | 2.803 | 2.207 | 2.284 |
| **1999** | 2.259 | 2.731 | 2.245 | 3.691 | 2.898 | 4.048 | 2.888 | 2.440 | 2.867 | 2.839 | 2.243 | 2.327 |
| **2000** | 2.273 | 2.742 | 2.249 | 3.737 | 2.900 | 4.050 | 2.884 | 2.436 | 2.862 | 2.833 | 2.240 | 2.271 |
| **2001** | 2.272 | 2.744 | 2.245 | 3.698 | 2.898 | 4.050 | 2.898 | 2.438 | 2.864 | 2.835 | 2.248 | 2.329 |
| **2002** | 2.190 | 2.665 | 2.172 | 3.610 | 2.830 | 3.988 | 2.880 | 2.414 | 2.836 | 2.807 | 2.215 | 2.287 |
| **2003** | 2.224 | 2.693 | 2.193 | 3.644 | 2.858 | 3.988 | 2.882 | 2.431 | 2.815 | 2.820 | 2.236 | 2.307 |
| **2004** | 2.215 | 2.697 | 2.186 | 3.632 | 2.844 | 3.990 | 2.858 | 2.414 | 2.834 | 2.807 | 2.222 | 2.297 |
| **2005** | 2.242 | 2.689 | 2.210 | 3.653 | 2.825 | 3.993 | 2.827 | 2.375 | 2.810 | 2.815 | 2.194 | 2.250 |
| **2006** | 2.168 | 2.648 | 2.164 | 3.613 | 2.827 | 4.012 | 2.867 | 2.409 | 2.844 | 2.818 | 2.232 | 2.307 |
| **2007** | 2.202 | 2.693 | 2.196 | 3.635 | 2.858 | 4.032 | 2.854 | 2.410 | 2.845 | 2.814 | 2.222 | 2.305 |
| **2008** | 2.266 | 2.752 | 2.252 | 3.660 | 2.906 | 4.068 | 2.916 | 2.450 | 2.884 | 2.861 | 2.260 | 2.348 |
| **2009** | 2.253 | 2.728 | 2.222 | 3.707 | 2.890 | 4.043 | 2.884 | 2.431 | 2.870 | 2.850 | 2.243 | 2.343 |
| **2010** | 2.308 | 2.775 | 2.264 | 3.744 | 2.927 | 4.081 | 2.944 | 2.453 | 2.906 | 2.876 | 2.297 | 2.357 |
| **2011** | 2.282 | 2.744 | 2.233 | 3.673 | 2.911 | 4.072 | 2.951 | 2.490 | 2.919 | 2.899 | 2.309 | 2.406 |
| **Mean** | **2.229** | **2.701** | **2.206** | **3.654** | **2.863** | **4.017** | **2.875** | **2.420** | **2.846** | **2.822** | **2.229** | **2.312** |

**Table 3** Yearly mean sea level average above zero tide gauges and its mean (in metre) for East Malaysia

| | Tide Gauge Station | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Sarawak | | | Sabah | | | | | |
| **Year** | **Miri** | **Bintulu** | **Sejingkat** | **Labuan** | **K. Kinabalu** | **Kudat** | **Sandakan** | **L. Datu** | **Tawau** |
| **1993** | 1.909 | 1.891 | - | - | 2.479 | - | 2.624 | - | 2.651 |
| **1994** | 1.965 | 1.894 | - | - | 2.490 | - | 2.700 | - | 2.670 |
| **1995** | 1.992 | 1.902 | - | - | 2.514 | - | 2.702 | - | 2.690 |
| **1996** | 2.011 | 1.932 | - | 2.953 | 2.540 | 2.630 | 2.748 | 2.848 | 2.722 |
| **1997** | 1.958 | 1.889 | 5.688 | 2.894 | 2.479 | 2.572 | 2.673 | 2.752 | 2.639 |
| **1998** | - | 1.908 | 5.698 | 2.909 | 2.498 | 2.568 | 2.681 | 2.817 | 2.706 |
| **1999** | - | 1.966 | 5.736 | 2.990 | 2.580 | 2.670 | 2.789 | 2.903 | 2.788 |
| **2000** | - | 1.959 | 5.746 | 2.997 | 2.582 | 2.672 | 2.791 | 2.898 | 2.786 |
| **2001** | - | - | 5.696 | 2.992 | 2.587 | 2.663 | 2.783 | 2.875 | 2.753 |
| **2002** | - | 1.932 | 5.689 | 2.899 | 2.528 | 2.596 | 2.716 | 2.807 | 2.696 |
| **2003** | - | 1.908 | 5.671 | 2.936 | 2.524 | 2.608 | 2.739 | 2.791 | 2.677 |
| **2004** | - | 1.898 | 5.683 | 2.932 | 2.516 | 2.600 | 2.730 | 2.785 | 2.672 |
| **2005** | - | 1.890 | 5.666 | 2.910 | 2.504 | 2.586 | 2.705 | 2.802 | 2.685 |
| **2006** | - | 1.896 | 5.675 | 2.933 | 2.529 | 2.625 | 2.753 | 2.856 | 2.744 |
| **2007** | 2.083 | 1.881 | 5.632 | 2.948 | 2.540 | 2.632 | 2.743 | 2.845 | 2.741 |
| **2008** | 2.134 | 1.929 | 5.675 | 2.997 | 2.596 | 2.718 | 2.797 | 2.935 | 2.824 |
| **2009** | 2.137 | 1.979 | 5.690 | 2.995 | 2.593 | 2.665 | 2.806 | 2.908 | 2.783 |
| **2010** | 2.134 | 1.970 | - | 2.987 | 2.581 | 2.648 | 2.765 | 2.899 | 2.794 |
| **2011** | 2.159 | 1.980 | - | 3.014 | 2.594 | 2.699 | 2.812 | 2.912 | 2.793 |
| **Mean** | **2.048** | **1.922** | **5.688** | **2.955** | **2.540** | **2.634** | **2.740** | **2.852** | **2.727** |

## 2.2 Long-Term Time Series Analysis of Sea Level Using Robust Fit Technique

The time series of the sea level from tide gauge in this study was quantified using robust fit regression analysis. Robust fit analysis is a standard statistical technique that concurrently deals with solution determination and outliers' detection where in this study, a linear trend is fitted to the annual sea level time series of each station in an Iteratively Re-weighted Least Squares (IRLS) technique [9]. Depending on the deviations from the trend line, weights of measurements are adjusted accordingly. The trend line is then re-fitted. The process is repeated until the solution converges. The weights of the observations ($w_i$) are readjusted by the adopted bi-square weight function, whose relationship with normalised residuals, ($u_i$) can be written as [9]:

$$w_i = \begin{cases} (1-(u_i)^2)^2 & |u_i| < 1 \\ 0 & |u_i| \geq 1 \end{cases} \tag{1}$$

Where,

$$u_i = \frac{r_i}{K.S.\sqrt{1-h_i}}$$

| | |
|---|---|
| $r_i$ | : Residuals, |
| $h_i$ | : Leverage, |
| S | : Mean absolute deviation divided by a factor 0.6745 to make it an unbiased estimator of standard deviation |
| K | : A tuning constant whose default value of 4.685 provides for 95% asymptotic efficiency as the ordinary least squares assuming Gaussian distribution |

Figure 4 illustrates an example of the robust fit technique theory using a scatter plot. A scatter plot of the data together with its trends shows that the robust fit is less influenced by the outliers than the ordinary least-squares fit.

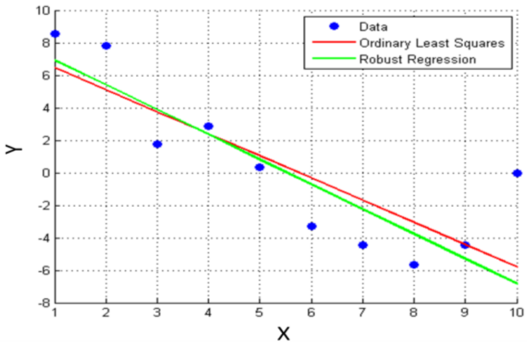


**Figure 4** Comparison between robust fit regression and ordinary least squares [12]

## 3.0 RESULTS AND DISCUSSION

The interpretation of relative sea level variation and rate using long time series of tidal data along coastlines of Malaysia were discussed extensively in this section. As discuss in the Section 2.0, the time span on this study occurs for 19 years from year 1993 to 2011. This is to ensure one complete polar motion cycle of 18.6 years since diurnal and semidiurnal changes in polar motion have attributed to the effects of ocean tides [8].

The relative sea level were analysed based on the pattern of seasonal variation and extreme meteorology effects such as El Nino and La Nina.

### 3.1 Analysis on Relative Sea Level Variation

In order to interpret the long term sea level pattern at tide gauge stations, the time series of the monthly tidal sea level anomaly (after conversion) are plotted. Figure 5, 6 and 7 represent the monthly tidal sea level anomaly at tide gauge stations in the west coast of Peninsular Malaysia, east coast of Peninsular Malaysia, and the coast of Sabah and Sarawak, respectively.

In the west coast of Peninsular Malaysia, where the coastline faces the Strait of Malacca, the pattern of sea level clearly shows that it is divided into three categories. The monthly tidal sea level anomaly at Pulau Langkawi, Pulau Pinang, Lumut and Port Klang is closely consistent between them. Meanwhile, Tanjung Keling and Kukup tide gauge stations seem to have a similar pattern of the monthly tidal data. Referring to Figure 5, the tide pattern shows a prominent semi diurnal characteristic for the west coast of Peninsular Malaysia; thus there are two complete tidal oscillations, daily. Due to the fact that the Malacca Straits is shallow and has rather narrows waters, the long term tidal pattern seems irregular.

In addition, the effect of the 1997 to 1998 El Niño and La Niña on sea level is clearly visible at Pulau Langkawi, Pulau Pinang, Lumut and Port Klang tide gauge stations as sea level drops below normal values late 1997 (El Niño), goes back to normal mid-1998, and overshoots a little at the end of 1998 (La Niña). In contrast, Johor Bahru tide gauge station which is located at the southern part of Peninsular Malaysia has a different pattern of monthly tidal sea level anomaly (Figure 5). This is due to the tidal complexities at this region, as an interchange between semi diurnal regime in the west and the diurnal regime in the east occurs here.

The east coast of Peninsular Malaysia meets the South China Sea. All the tide gauge stations at this coastline have interesting results where the monthly tidal sea level anomaly variations demonstrates a very good agreement in the patterns and have an almost similar pattern of seasonal variation (see Figure 6). The tidal sea level anomaly variations range from approximately -0.3 to 0.4 m for the entire time series data, with only the tide gauge station at Geting in the north showing bigger values. From Figure 6, all the east coast tide gauge stations have a smaller difference in tidal range than those of the west coast and its main diurnal constituents are most predominant

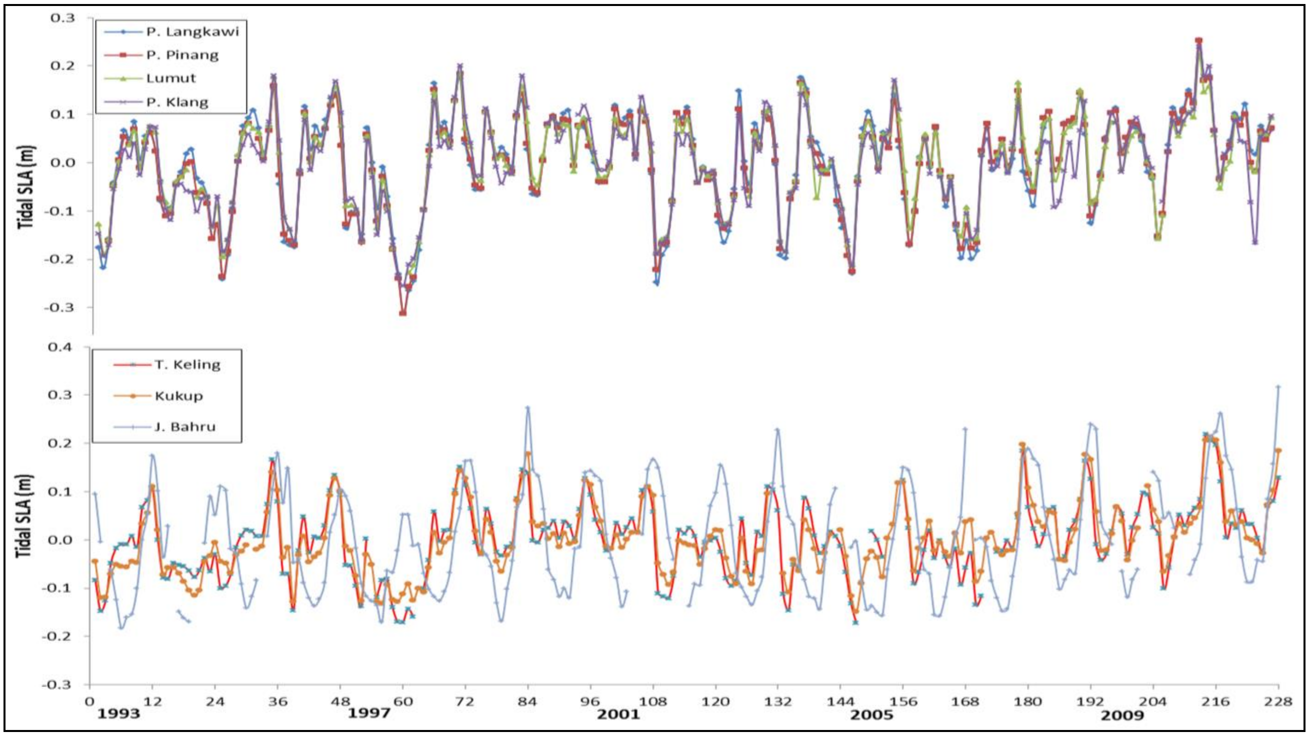


**Figure 5** Monthly tidal sea level anomaly at tide gauge stations in the west coast of Peninsular Malaysia

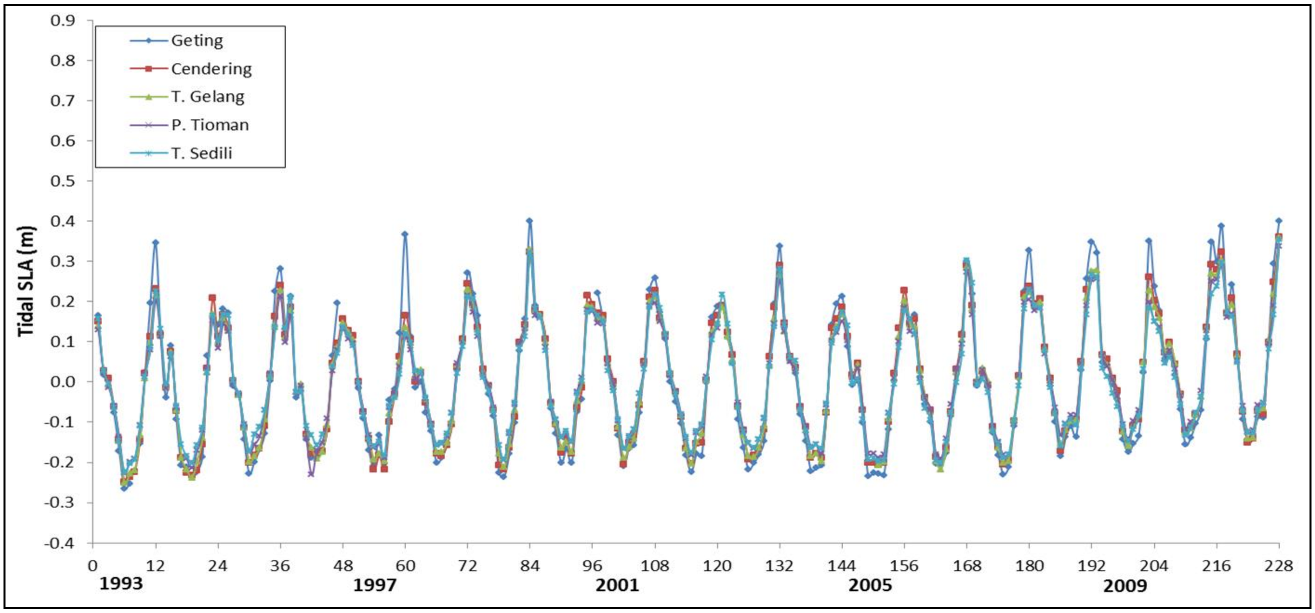


**Figure 6** Monthly tidal sea level anomaly at tide gauge stations in the east coast of Peninsular Malaysia

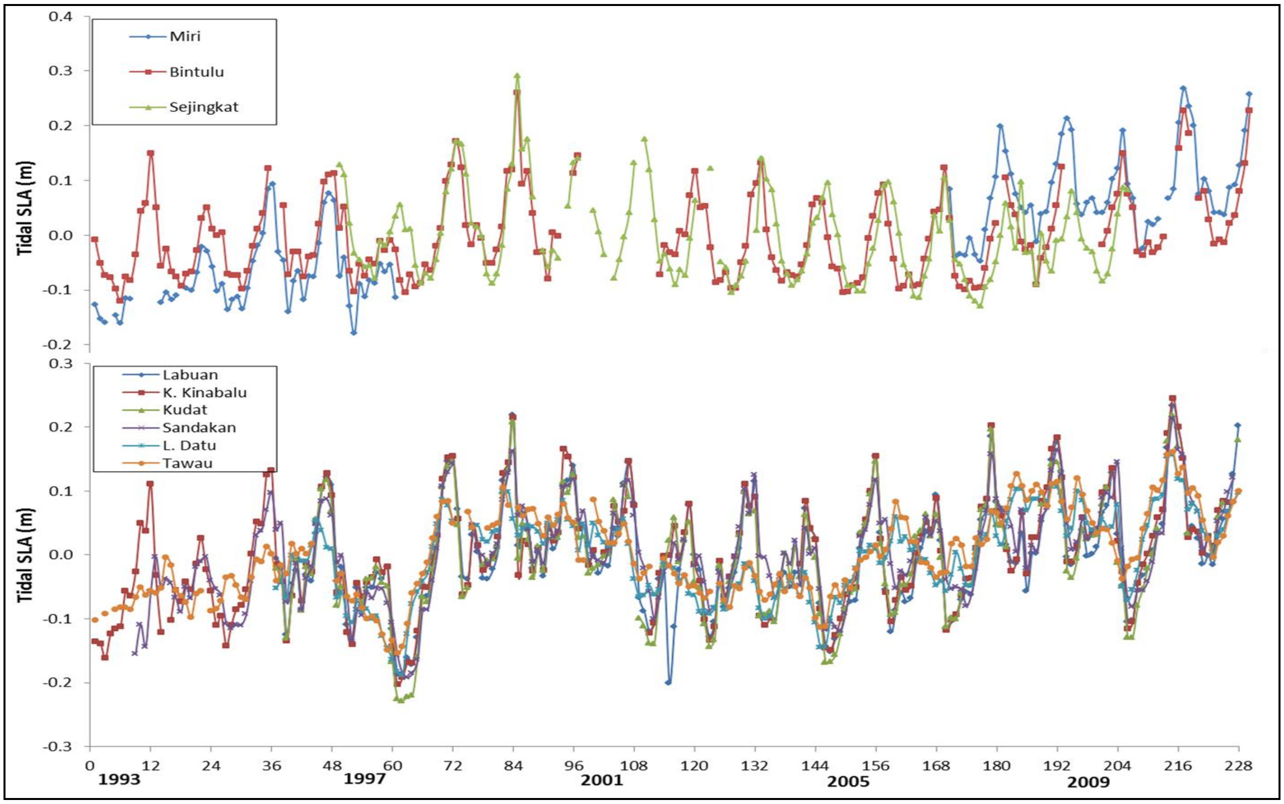


**Figure 7** Monthly tidal sea level anomaly at tide gauge stations in the coast of Sabah and Sarawak

As for Sabah and Sarawak, the long term pattern of the monthly tidal sea level anomaly can clearly be grouped by its patterns as well (see Figure 7). There exist irregularities at Miri and Sejingkat tide gauge stations due to errors or missing data. Although the coastline of Miri, Bintulu and Sejingkat tide gauge stations faces the South China Sea, same as the tide gauge stations in the east coast of Peninsular Malaysia, it exhibits a clear short-term periodic circulation (annual cycle) with a slightly longer term modulation compatible with the solar cycle.

Meanwhile, the monthly tidal sea level anomaly variations at Labuan, Kota Kinabalu, Kudat, Sandakan, Lahat Datu and Tawau seem to have similar patterns and variations. The monthly tidal variations range from about -0.2 to 0.2 m at these stations. Once again, as in the tide gauge stations in the west coast of Peninsular Malaysia, the effect of El Niño on the sea level was clearly visible when the sea level began to fall abnormally late 1997 and reverted to normal after 1998.

## 3.2 Analysis on Relative Sea Level Rate

The relative sea level rate analysis of the available tidal data around Peninsular Malaysia, and Sabah and Sarawak coastlines are performed using robust fit regression technique in MATLAB. Figure 8 presents the plot of time series analysis using robust fit regression at the Cendering tide gauge station. The red line represents the original (observed) monthly tidal data while the blue line illustrates the robust fit simulation line after applying Iteratively Re-weighted Least Square (IRLS). The black dotted line represents the linear trend using robust fit regression. From the curves in Figure 8, the relative sea level trend over the 19-year period (1993 to 2011) at Cendering is at a rate of 4.51 ± 0.54 mm yr$^{-1}$.

The relative sea level trend rates for all tide gauge stations in Peninsular Malaysia, and Sabah and Sarawak are shown in Table 4. In this study, tide gauge stations at Miri and Sejingkat are excluded for further analysis due to the rates of those locations are likely to be incorrect because of discontinuity and errors within the data.

Miri station has a long data gap: from January 1998 to December 2006. Meanwhile, at the Sejingkat station, the calculated relative sea level rate is negative. In addition, since January 2010, PSMSL's data bank did not publish the tidal data at Sejingkat anymore. They believe that there is a problem with the Sejingkat station.

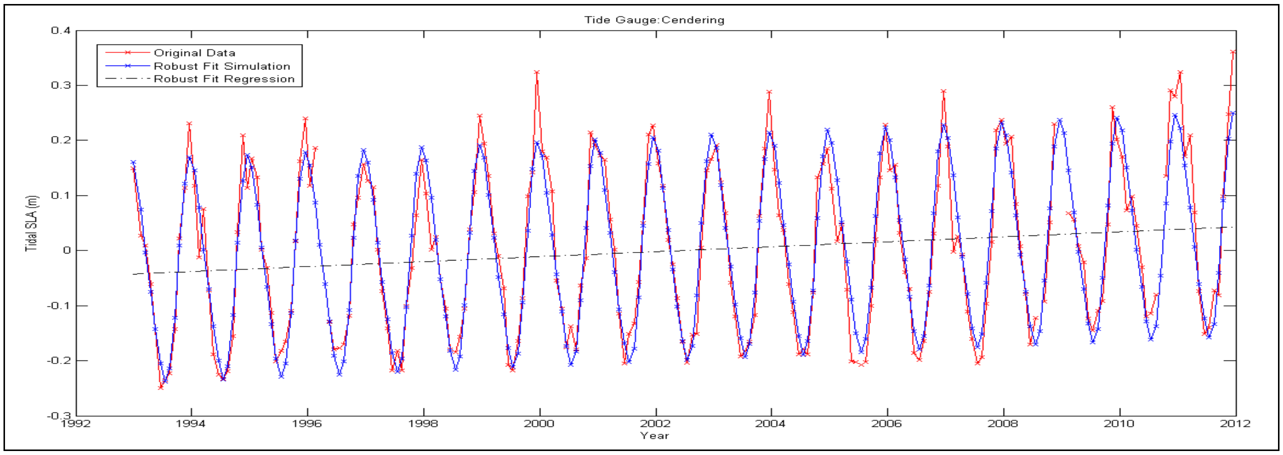


**Figure 8** Plot of relative sea level trend at Cendering tide gauge station using robust fit regression analysis. The tidal data is monthly averaged

**Table 4** Relative sea level rates (mm yr$^{-1}$) calculated by robust fit regression analysis of tidal data from tide gauges around the Malaysian coastlines

| Location | | Start | End | Rate (mm/yr) |
|---|---|---|---|---|
| West Coast | P. Langkawi | Jan 1993 | Dec 2011 | 2.82 ± 0.86 |
| | P. Pinang | Jan 1993 | Dec 2011 | 3.20 ± 0.84 |
| | Lumut | Jan 1993 | Dec 2011 | 2.39 ± 0.83 |
| | Port Klang | Jan 1993 | Dec 2011 | 2.97 ± 0.90 |
| | Tg. Keling | Jan 1993 | Dec 2011 | 2.89 ± 0.69 |
| | Kukup | Jan 1993 | Dec 2011 | 4.15 ± 0.61 |
| | Johor Bahru | Jan 1993 | Dec 2011 | 4.19 ± 0.49 |
| East Coast | Geting | Jan 1993 | Dec 2011 | 3.85 ± 0.67 |
| | Cendering | Jan 1993 | Dec 2011 | 4.51 ± 0.54 |
| | Tg. Gelang | Jan 1993 | Dec 2011 | 4.42 ± 0.50 |
| | P. Tioman | Jan 1993 | Dec 2011 | 3.92 ± 0.49 |
| | Tg. Sedili | Jan 1993 | Dec 2011 | 2.92 ± 0.51 |
| | Sejingkat* | Jan 1997 | Dec 2009 | -4.50 ± 0.80 |
| | Bintulu | Jan 1993 | Dec 2011 | 1.96 ± 0.54 |
| Sabah and Sarawak | Miri* | Jan 1993 | Dec 2011 | 10.83 ± 0.56 |
| | Labuan | Jan 1996 | Dec 2011 | 3.06 ± 0.86 |
| | Kota Kinabalu | Jan 1993 | Dec 2011 | 4.79 ± 0.68 |
| | Kudat | Jan 1996 | Dec 2011 | 3.07 ± 1.02 |
| | Sandakan | Jan 1994 | Dec 2011 | 4.65 ± 0.70 |
| | LahatDatu | Jan 1996 | Dec 2011 | 5.61 ± 0.99 |
| | Tawau | Jan 1993 | Dec 2011 | 6.53 ± 0.72 |

*Data error or missing

In this study, the annual and semi-annual cycle effect has been removed to compute the relative sea level trend at the tide gauge stations. However, the tidal data has not been corrected for glacial isostatic adjustment (GIA), atmospheric pressure loading and other land motions like tectonics, subsidence, etc. From Table 4, the finding shows clearly that the linear trend from robust fit regression do exist in the relative sea level around the coastlines of Peninsular Malaysia, and Sabah and Sarawak. The trends vary quite significantly from one location to another and the trend rates of the monthly tidal data variations are positive (excluding the Miri and Sejingkat stations), indicating an overall rise in relative sea level around the coasts of Malaysia.

In the west coast of Peninsular Malaysia, the rate of relative sea level ranges from 2.39 ± 0.83 mm yr$^{-1}$ at Lumut and 4.19 ± 0.49 mm yr$^{-1}$ at Johor Bahru. Taking the average of all tide gauge stations in the west coast of Peninsular Malaysia, the relative sea level trend is about 3.23 ± 0.75 mm yr$^{-1}$ for the period of 19 years tidal data (1993 to 2011). Meanwhile, in the east coast of Peninsular Malaysia, the highest rate of relative sea level rise occurs at Cendering with 4.51 ± 0.54 mm yr$^{-1}$ and the lowest rate occurs at Tanjung Sedili with 2.92 ± 0.51 mm yr$^{-1}$. The average of relative sea level trends from 1993 to 2011 for east coast of Peninsular Malaysia is estimated at 3.92 ± 0.54 mm yr$^{-1}$.

In Sabah and Sarawak, the relative sea level trend ranges from the lowest rate at Bintulu with 1.96 ± 0.54 mm yr$^{-1}$ and the highest rate at Tawau with 6.53 ± 0.72 mm yr$^{-1}$. The average of the relative sea level trend in this coast is estimated at a rate of 4.24 ± 0.79 mm yr$^{-1}$. By combining the relative sea level trend of the three coasts, it exhibits an average sea level trend of approximately 3.80 ± 0.69 mm yr$^{-1}$ for the coastlines of Malaysia (solely based on tidal data). The Malaysian coastlines tidal rate is higher than the generally accepted global sea level rate from the world-wide tide gauge data of 1.8 ± 0.5 mm yr$^{-1}$ for the period of 1961 to 2003 that was reported by [11].

Next, Figure 9 presents the map of relative sea level trend vectors over the Malaysian seas. The map is created based on 19 tide gauge stations along the coastlines of Malaysia (excluding the Miri and Sejingkat stations) in the time frame of the 19-year tidal data (from 1993 to 2011). The spatial tide gauge stations are well distributed along Malaysia's coastlines except in the west coast of Sabah and Sarawak where only the Bintulu station is included in the plotting of the trend maps. Thus, the tidal data is limited in the west coast of Sarawak. From Figure 9, the highest relative sea level rise occurs at the north-east region of Peninsular Malaysia and south-west sector of Sabah. Overall analysis for the relative sea level rate concludes that there is a rise in relative sea level around the coasts of Malaysia with the range varying from 2 to 6.5 mm yr$^{-1}$ over 19-year tidal data from 1993 to 2011.

## 4.0 CONCLUSION

In this study, the finding shows clearly that the linear trend from robust fit regression do exist in the relative sea level around the coastlines of Peninsular Malaysia, and Sabah and Sarawak. The trends vary quite significantly from one location to another and the trend rates of the monthly tidal data variations are positive (excluding the Miri and Sejingkat stations). Overall analysis for the relative sea level rate concluded that there is a rise in relative sea level around the coasts of Malaysia with the range varying from 2 to 6.5 mm/yr. This study offers valuable sea level information to be applied in wide range of climatology, related environmental issue such as flood and global warming in Malaysia.

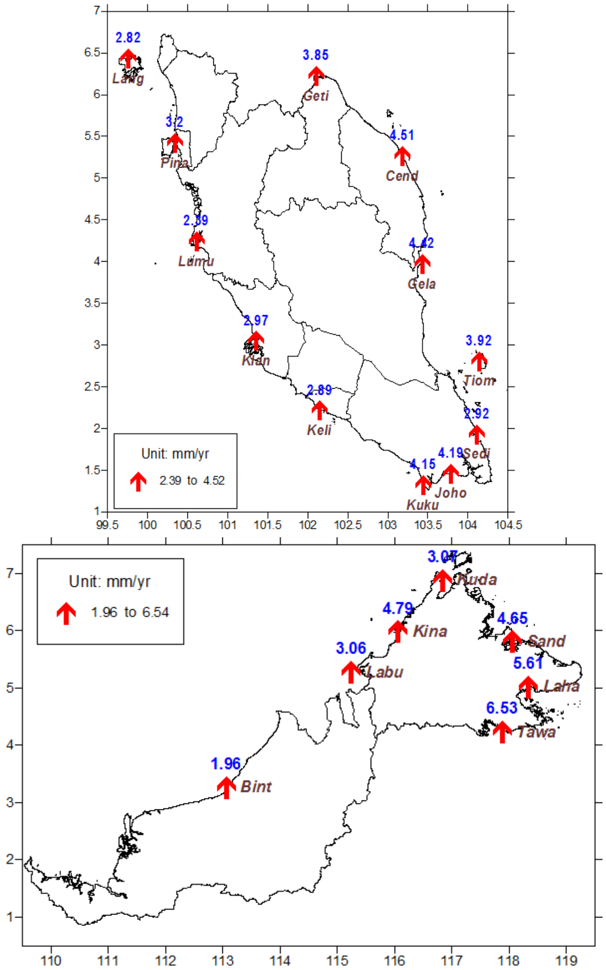


**Figure 9** Relative sea level trend vectors over the Malaysian seas. The trend is calculated over 19-year tidal data from 1993 to 2011. Units are in mm yr$^{-1}$. The arrow indicates a rise in sea level rate

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## Nomenclature

| | | |
|---|---|---|
| PSMSL | - | Permanent Service for Mean Sea Level |
| MATLAB | - | Matrix Laboratory |
| DSMM | - | Department of Survey and Mapping Malaysia |
| IRLS | - | Iteratively Re-weighted Least Squares |
| GIA | - | Glacial Isostatic Adjustment |
| IPCC | - | Intergovernmental Panel on Climate Change |

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