

## The Malaysian Seas: Variation of Sea Level Observed by Tide Gauges and Satellite Altimetry

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Since a decade, satellite altimetry has demonstrated its capability in measuring temporal change of the global mean sea level with precision better than 1 mm/year. In altimetry data processing, the recently updated environmental and geophysical corrections were applied. The analysis of Topex data presented here is based on monthly averages using GOT00.2b ocean tide model. Sea level trends are estimated from 1.5 to 8.9 mm/year using two decades of tide gauges observations along coastal of Malaysia. Comparison of  $1^{\circ} \times 1^{\circ}$  areas at the tide gauge locations nearby Topex track clearly show good agreement in pattern and trend of sea level variations. Here, sea level variations for four areas in the Malaysian Seas have been investigated using ten years of Topex altimetry data. The time series of dynamic sea surface elevation clearly show El Niño effect on the end of 1997 and sea level rising in the Malaysian Seas. Linear terms of sea level variation for those areas are estimated at rates between 6.3 – 14.7 mm/year.

### 1. Introduction

Long-term sea level height variations are an important indicator for climate changes. Over a long period, coastal tide gauges have provided the main technique to measure sea level changes. But since the past three decades, observations from satellite have provided dramatic descriptions of sea level variability but the spatial scales, which could be reliably studied were limited by orbit uncertainty. However, Topex-Poseidon was launched at last decade and the orbits are determined accurately from globally distributed network of laser and DORIS stations. Therefore, Topex-Poseidon is now used as reference for other satellites in multi satellites processing.

Although satellite altimetry records are still short compared to tide gauge data sets, this technique appears to give promising result for the sea level change because it provides sea level measurement with large coverage. A precision better than 1mm/year on measurement of global sea level change can be obtained using Topex-Poseidon. This is one of the remarkable results given by satellite altimetry (Nerem et al.,1995).

Cecile et al. (2001) analyses the global mean sea level rise at rate 2.5mm/year. On time scale longer than 1 year, global mean sea level change can results from two main causes: (i) volume change due to seawater density change in response to temperature and salinity variations (the two parameters having opposite effects on sea level) and (ii) mass change due to exchange of water with atmosphere and continents, including glaciers and ice sheets, through precipitation, evaporation, river runoff, and ice melting.

## 2. Topex Data Processing

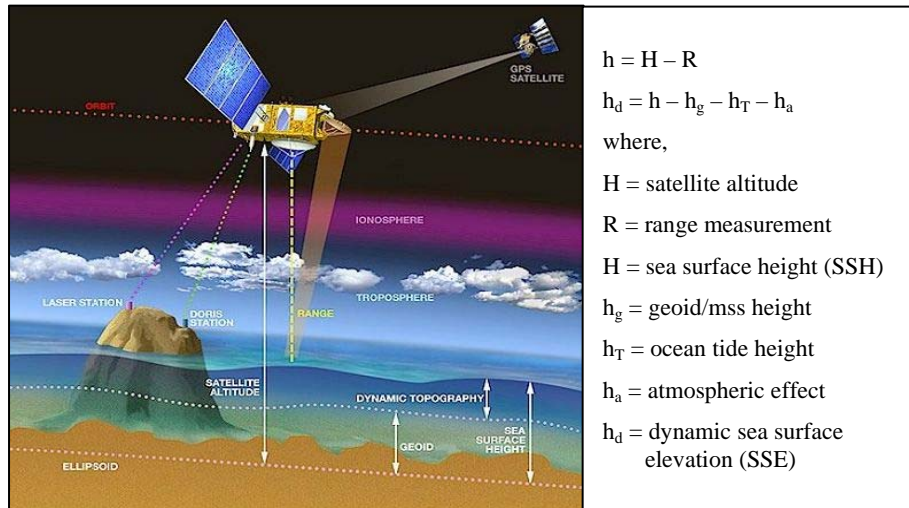
The Topex-Poseidon satellite, carrying two altimeters, Topex and Poseidon, was launched in August 1992 to study large-scale ocean circulation and its temporal variations (Fu et al., 1994). The satellite has been placed on a 66° inclined orbit at 1336km altitude. The orbital repeatability (or orbital cycle, i.e., time interval for the satellite ground tracks to exactly superimpose) is 9.916 days. This corresponds to an inter-track spacing of 350km at the equator. Altimeter range measurements are provided at 1-second interval, i.e., about 6 km along. In this study, only Topex data are being considered.

**Table 1:** Geophysical corrections applied to Topex data

Corrections	Model
Orbit	JGM-3
Inverse Barometer	1013.3 mbar
Dry Tropo	ECMWF
Wet Tropo	ECMWF
Ionospheric	Smooth Dual-Freq.
Earth Tide	Applied
Ocean Tide	GOT00.2b/FES2002
Loading Tide	GOT00.2b/FES2002
Geoid/MSS	CLS01 MSS
Pole tide	Applied
Sea State Bias	BM3/BM4

Topex phase A data covering the time span of about 10 years (from January 1993 through July 2002, cycles 11-364) are used in this study. Data retrieval and analysis were carried out using Radar Altimeter Database System (RADS). Table 1 summarizes the various corrections applied to the Topex altimeter range measurements. The corrections include the

ionospheric delay, dry and wet tropospheric corrections, solid Earth and ocean tides, ocean tide loading, pole tide, electromagnetic bias (EMB) and inverse barometer (IB) correction.



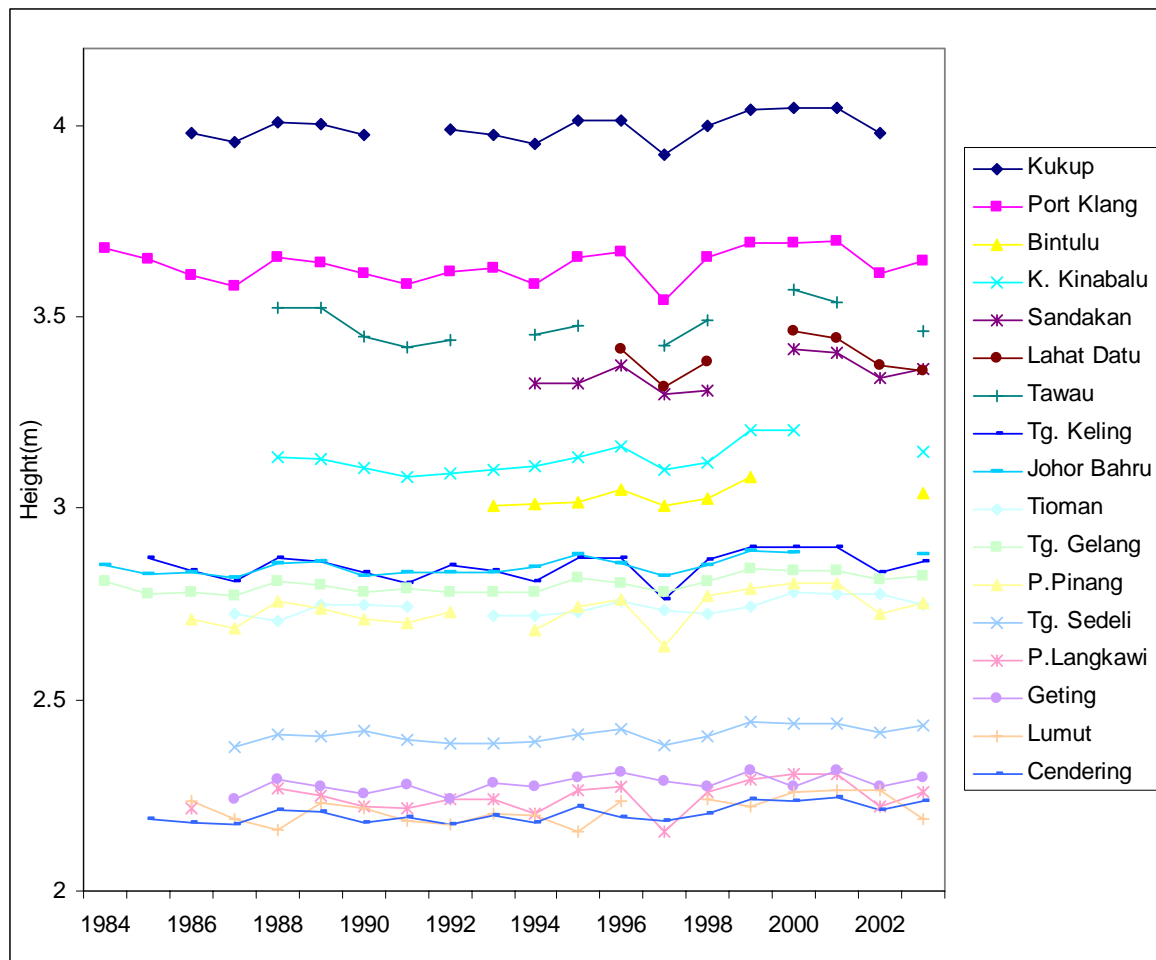
**Figure 1:** Principle of satellite altimetry

The Topex orbits are based on the JGM-3 geopotential model (Tapley et al., 1996). Instantaneous sea surface heights (SSH) above the ellipsoid used as reference for the satellite altitude are generated along the satellite tracks from the difference between the radial component of the orbit and the corrected altimeter range measurement. Since we are interested in the time-variable component of SSH, e.g., the sea surface height above the geoid or mean sea surface (MSS), the static part, i.e., the height of the geoid above the reference ellipsoid, has been removed from SSH data at each latitude-longitude location. For this purpose, the mean sea surface CLS01 is being used as reference surface.

For the purpose of mapping the geographical distribution of the sea level variations over the past 10 years, the IB correction to individual SSH measurements is applied while the global mean pressure is fixed at 1013mb. The later correction is an instantaneous static local response of the sea level to atmospheric pressure variations, the total pressure at the ocean bottom is assumed to be constant. The standard sea level correction is expressed through the relationship:  $-0.9948 (P - P_{ref})$  (cm) where P is the instantaneous local surface pressure (in rob) and  $P_{ref}$  is the reference pressure.  $P_{ref}$  is assumed constant (value of 1013.3 mb is used), according to Minster et al. (1995). In the following, the instantaneous sea surface height is referenced to the CLS01 mean sea surface after removal of atmospheric effect and ocean tide. This is so called the sea surface elevation (SSE).

### 3. Local Mean Sea Level Observed by Tide Gauges

A network of 21 continuously operating tide gauge stations has been established since 1984 along the coastal areas of Malaysia. The main objective of the establishment of the network is to enable continuous time series of sea level heights to be obtained for the purpose of establishing a vertical datum for the nation. The available tidal records and their MSL values are given in Figure 2.



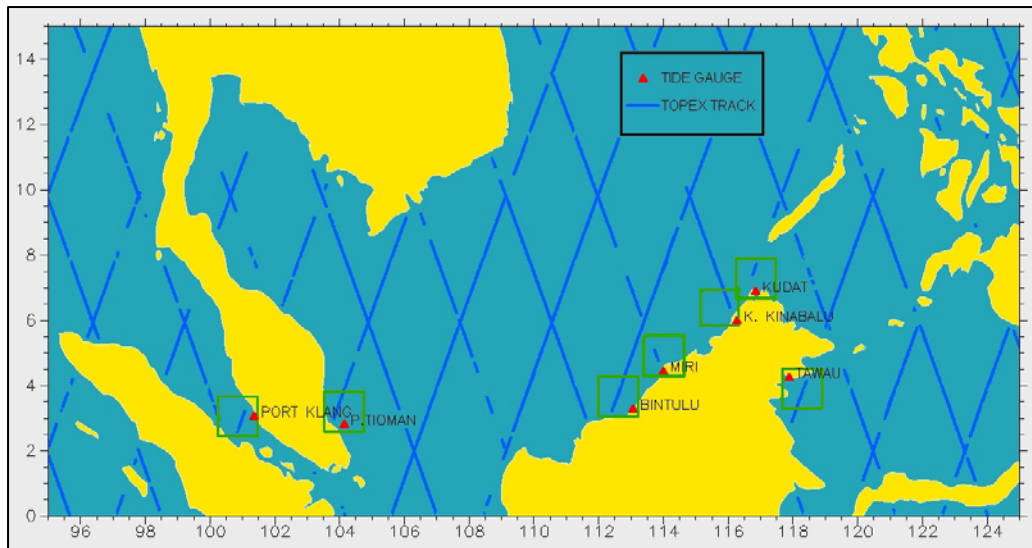
**Figure 2:** Yearly mean sea levels measured by tide gauge stations in Malaysia

The trend rates are given in Table 2. It shows that trends do exist in the sea level height around Malaysia and varies quite significantly from one location to another. Also, the linear trends of the MSL variations are positive, indicating an overall rise in the sea level around the coast of Malaysia. The rising trend ranges from 1.6 mm/year at Tanjung Keling on the west coast to 2.4 mm/year at Tanjung Gelang on the east coast of peninsular. Taking the average of the group, it indicates that relative sea level trend in Peninsular Malaysia is about 2.5 mm/year. In Sabah and Sarawak, the rate of sea level rise at Bintulu and K. Kinabalu are estimated at 8.6 mm/year and 5.9 mm/year. For other locations, the rates are incorrect due to non-continuous and short period of available data.

**Table 2:** Estimated sea level rise of Malaysia from tide gauges

Location of Tide Gauge		Data Used	Linear Trend (mm/yr)
West Coast Peninsular	P. Langkawi	1986 – 2003	2.5
	P. Pinang	1986 – 2003	3.6
	Lumut	1986 – 2003	2.8
	Port Klang	1984 – 2003	1.5
	Tg. Keling	1985 – 2003	1.6
	Kukup	1986 – 2002	2.5
	Johor Bahru	1984 – 2003	2.4
East Coast Peninsular	Tg. Sedeli	1987 – 2003	2.6
	P. Tioman	1987 – 2003	2.5
	Tg. Gelang	1984 – 2003	2.4
	Cendering	1985 – 2003	2.9
	Getting	1987 – 2003	2.3
Sabah & Sarawak	Bintulu	1993 – 1999	8.6
	K. Kinabalu	1988 – 2000	5.9
	Sandakan	1984 – 2003	6.2
	Lahat Datu	1996 – 2003	1.6
	Tawau	1988 – 2001	2.0

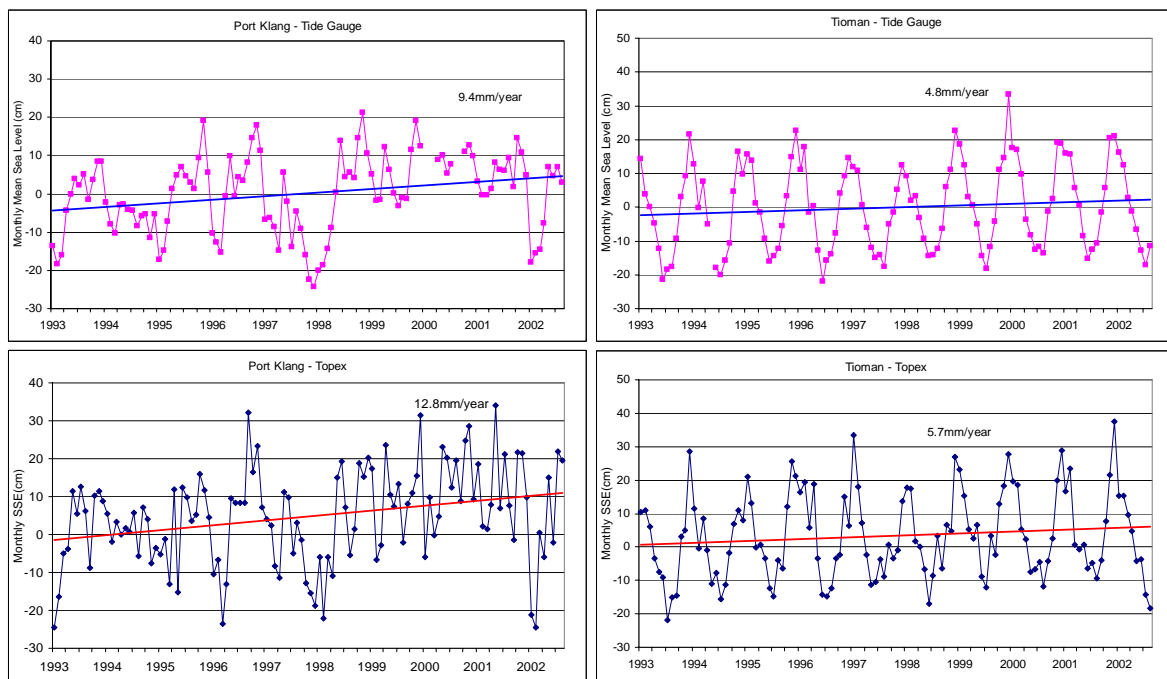
#### 4. Comparison of Topex Data Nearby Tide Gauge Locations



**Figure 3:** Selected  $1^{\circ} \times 1^{\circ}$  areas nearby to tide gauges

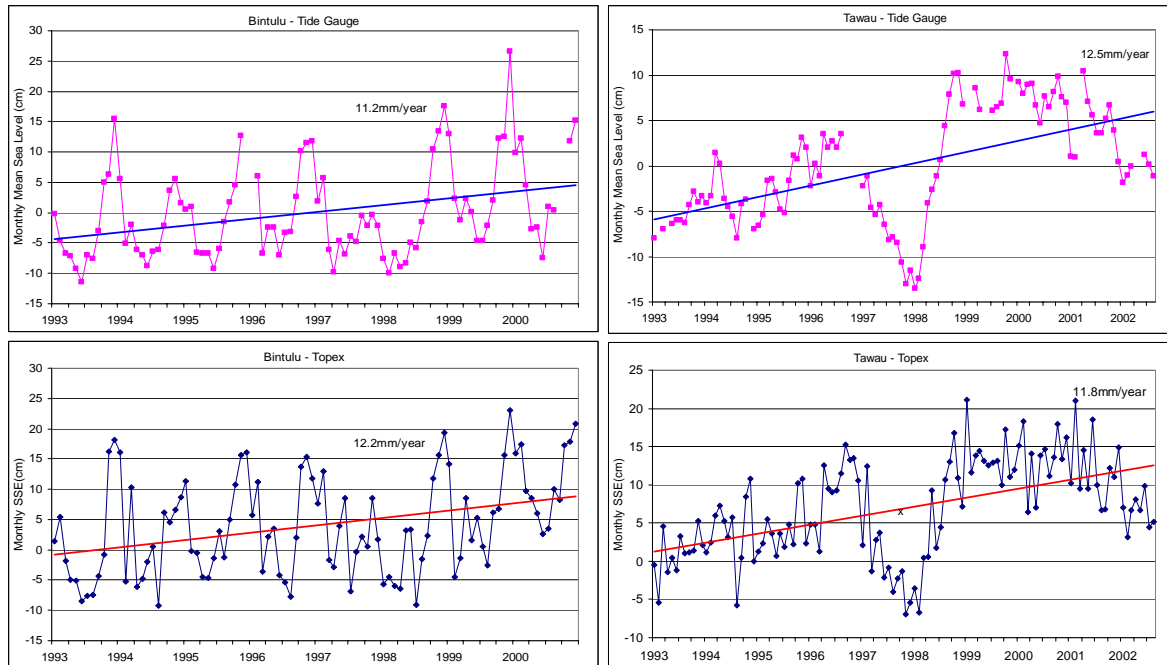
The comparison of sea level heights between satellite altimetry and tide gauge has been used to validate the results from Topex. Seven  $1^{\circ} \times 1^{\circ}$  areas were chosen for the comparison, where the Topex tracks are nearby to tide gauge locations (Figure 3). The standard corrections were applied to the Topex data (Table 1). Ocean tide and inverse barometer were also corrected for the Topex data, as they canceled out in the monthly average of tide gauges data. Somehow, loading tide and earth tide were applied to Topex data but not to the tide gauges data, therefore they show up as the differences between Topex and tide gauge results.

Figure 4 and 5 show the variation of sea level obtained from Topex and tide gauge in Port Klang, Tawau, Tioman and Bintulu areas. Similarity in the pattern of sea level variations indicates good agreements between Topex altimetry and tide gauge stations. Due to the narrowness of Malacca Strait, sea level variation at Port Klang area appears to be noisy than other areas.



**Figure 4:** Sea level rise at Port Klang and Tioman from tide gauge and Topex

Linear trend for Topex and tide gauge measurements are evaluated over the same period at each area in order to produce comparable results. The rate of sea level rise obtained from tide gauge in Port Klang is about 9.4 mm/year. However, satellite altimetry estimated a different rate, which is 12.8 mm/year. For P.Tioman, Bintulu and Tawau areas, both techniques showed better agreements in the trend of sea level rise, where the rate observed by tide gauge is 4.8, 11.2 and 12.5 mm/year respectively, and the rate observed by satellite altimetry is 5.7, 12.2 and 11.8 mm/year respectively.



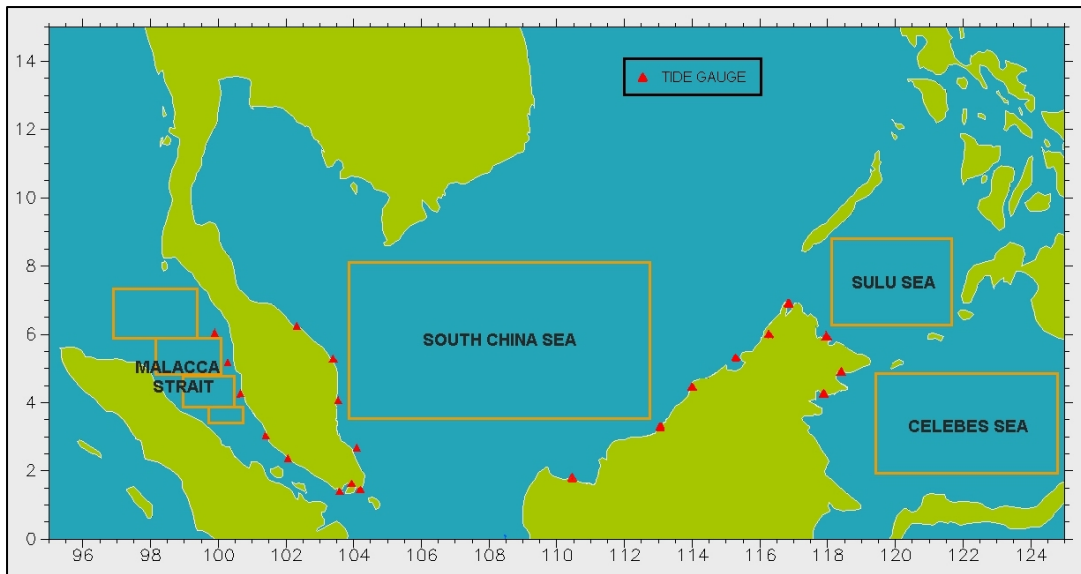
**Figure 5:** Sea level rise at Bintulu and Tawau from tide gauge and Topex

Overall, the differences of linear trend between Topex and tide gauge are consider small, within -3.4 to 1.0 mm/year (Table 3). However, Port Klang and Kudat appear to have the biggest difference due to the quality of noisy data. These results basically encourage us to estimate the rate of sea level rise in Malaysian Seas using Topex data.

**Table 3:** Linear trend of sea level from tide gauges and Topex

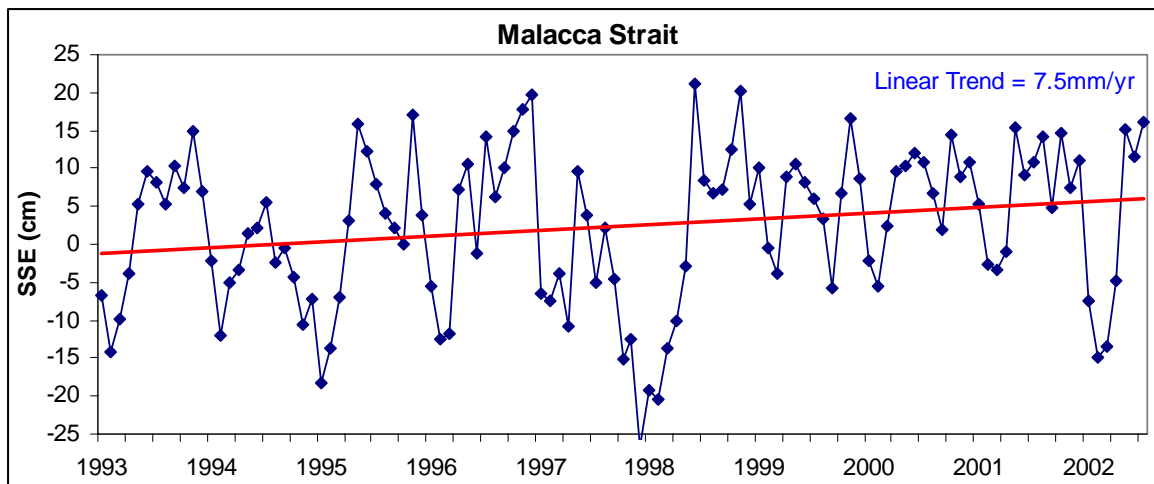
Location	P.Klang	P.Tioman	Bintulu	Tawau	Miri	K.Kinabalu	Kudat
Data Used	1993 - 2003	1993 - 2003	1993 - 2000	1993 - 2003	1994 - 1997	1993 - 2002	1996 - 2002
Linear Trend (Tide Gauge)	9.4 mm/yr	4.8 mm/yr	11.2 mm/yr	12.5 mm/yr	7.2 mm/yr	12.3 mm/yr	10.1 mm/yr
Linear Trend (Topex)	12.8 mm/yr	5.7 mm/yr	12.2 mm/yr	11.8 mm/yr	6.5 mm/yr	11.3 mm/yr	12.4 mm/yr
Diff. (Tide Gauge - Topex)	-3.4 mm/yr	-0.9 mm/yr	-1.0 mm/yr	0.7 mm/yr	0.7 mm/yr	1.0 mm/yr	-2.3 mm/yr

## 5. Mea Sea Level Variation from Topex



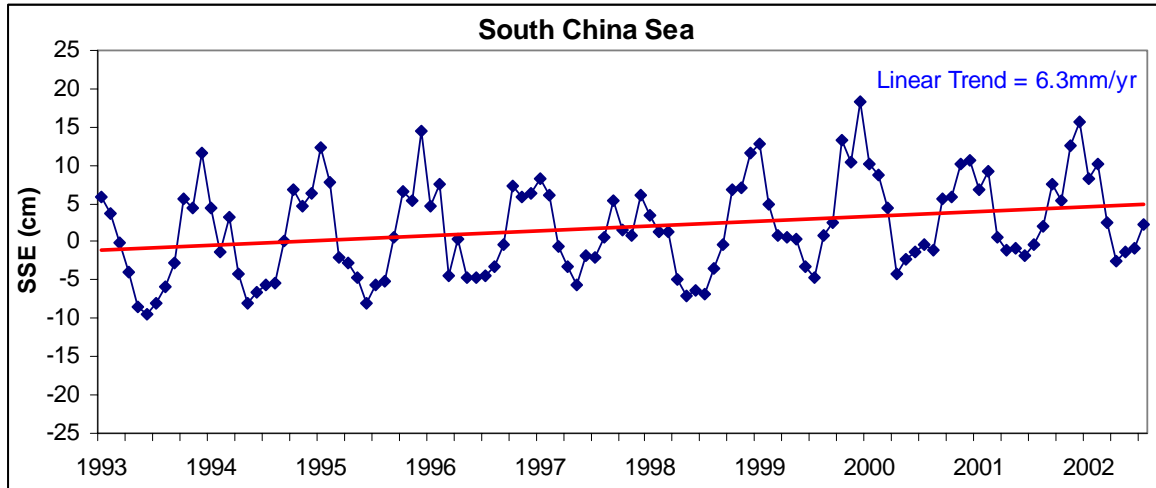
**Figure 6:** Study areas

It is well known that Topex is able to provide sea level observations with higher spatial resolution than tide gauge. To investigate the sea level variation of Malaysian Seas, four study areas were selected (Figure 6): South China Sea, Sulu Sea, Malacca Strait and Celebes Sea. Global Ocean Tide (GOT00.2b) model was employed in the process of data reduction. The time series of mean sea level were derived from the averages of monthly altimeter data.



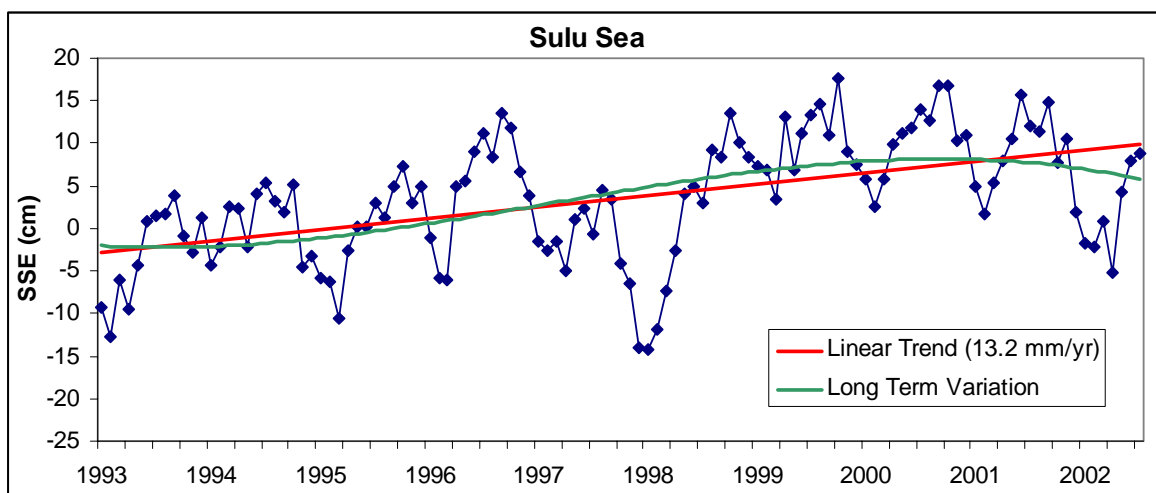
**Figure 7:** Sea level time series of Malacca Strait



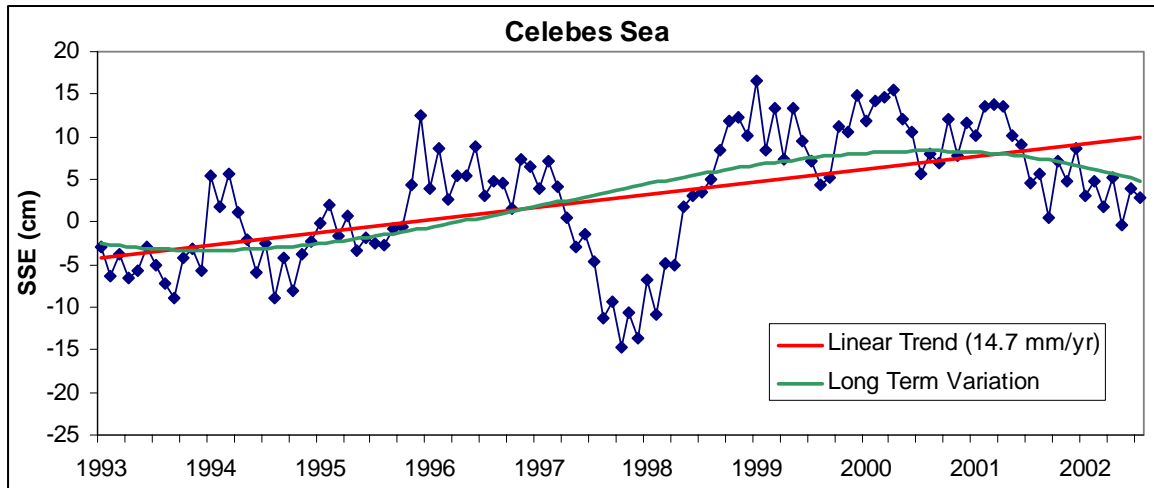


**Figure 8:** Sea level time series of South China Sea

For both South China Sea and Malacca Strait, the rise of Mean Sea Level is clearly visible from altimeter data. Figure 7 depicts that the tide model applied does not fit very well in the shallow Malacca Strait where the short-term ocean circulation seems to be rather noisy. This is due to the fact that Malacca Strait is a narrow and shallow water area. However, the short-term periodic circulation of mean sea level is being revealed at the open South China Sea as shown in Figure 8. Figure 7 and 8 summarized the results of Mean Sea Level variation computations for Malacca Strait and South China Sea. Using the straight line fitting, the sea level rise for Malacca Strait and South China Sea are estimated at 7.5 mm/year and 6.3 mm/year respectively.



**Figure 9:** Trend and long term variation of sea level for Sulu Sea



**Figure 10:** Trend and long term variation of sea level for Celebes Sea

Mean Sea Level variations for Sulu Sea and Celebes Sea are shown in Figure 9 and 10. Both areas indicate similar pattern of sea level variations, and tide model seems to fit well to these areas. The rates of mean sea level rise are estimated at 13.2 mm/year and 14.7 mm/year respectively. The effect of El-Nino on sea level is clearly visible where the sea level begins to fall in 1997 and back to normal in the middle of 1998. The fitting of 3<sup>rd</sup> order polynomial is to model the long term variations for those areas. The two neighboring seas seem to have interesting common pattern of sea level fall after year 2000. We need more records of sea level data to study the long term variation and climate changes.

## 5. Conclusion

Satellite altimetry records may still be too short to detect any long term sea level rise possibly associated with global warming and the results discussed above may hardly be comparable to those based on multi-decadal tide gauge records. However, the comparison of near-simultaneous Topex and tide gauges observations showed good agreement, and therefore both techniques are competitive. The Topex derived sea level time series reveal that since 1993 to 2002, the mean sea level in Malaysia Seas has been rising at a rate of between 6.3 – 14.7 mm/year. As longer time series become available, confidence on the results will increase. Satellite altimetry will then provide important constraints on climate models through the determination of absolute sea level changes, hence allowing an estimate of the 'true' volume and mass changes of the oceans at inter-annual time scales.

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