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A Short Review on Causes of Sea Level Rise for Climate Monitoring

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Abstract. Sea level rise has currently become a major issue for climate change. It has globally drawn attention because as time passes, global sea levels will continue to rise at an accelerating rate in the 21st century. It will cause a serious impact on environmental problems such as coastal inundation, salt intrusion, coastal erosion, and other phenomena. These scenarios lead to earth problems in which land and oceans continue shifting due to climate change, posing a threat to the very existence of all living beings in the coming years. As a result, climate monitoring is critical for tracking the change. Therefore, this paper reviews the physical factors that contribute to sea level rise. The main contributors for sea level rises, such as ice melting from land into the ocean, thermal expansion, a slowing of the Gulf Stream, and land sinkage, are being discussed. This paper also emphasises the studies of regional sea level, and sea level rate changes. Finally, this review will be discussed in order to clarify the causes of sea level rise issues for human society.

1. Introduction

Sea level rise plays a crucial role in ocean monitoring and climate studies. Every government level works toward finding answers to ensure the issues are given top-level attention in all aspects of planning. According to Intergovernmental Panel on Climate Change (IPCC), rising sea levels would increase the frequency of significant sea level events during high tides and heavy storms [1]. Rising sea levels, for example, will put significant pressure on areas with a lot of people and low-lying coastal cities all over the world [2]. It comes as an important aspect of climate change since it reflects a dynamic interaction between the contributions of land and ocean processes in local, global, and regional scales [3]–[5].

The sea level is estimated relative to the Earth's surface. Based on tide gauges and geological data, RSL have been estimates for the last few centuries. Nowadays, satellite altimeter has been used to determine the absolute sea level for the last two decades. Rising sea level also can be determined by Global Mean Sea Level (GMSL). GMSL known as the average height of all the Earth's oceans that has risen, implying a change in the ocean's depth. Changes in local mean sea level typically differ from changes in GSML because factors dominant at regional and local scales impact global mean change [6].



A variety of factors cause climate change. According to the State of the Climate report [7], in the scenario of global warming, seven (7) indicators are expected to increase, namely, the temperature of the air on the land, medium atmosphere (troposphere), ocean heat content, water vapour, sea level, surface temperature, and ocean temperature. On the contrary, three (3) indicators, such as Greenland's mass and Antarctic ice sheets (ice attached to the Earth), a net decrease in volume, and significant reductions in the extent of Arctic Sea ice, are projected to decrease (see Figure 1).

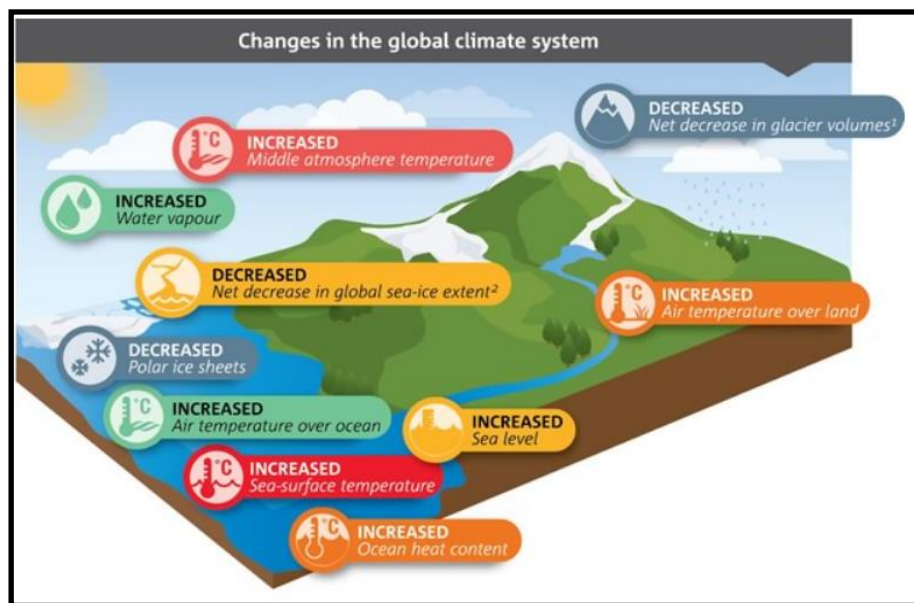


Figure 1. Ten indicators for the global climate system changes [7]

In general, Earth's climate can be understood as changes in global weather patterns for certain locations and periods, and it will continue to change over time. Many environmental scientists agree that anthropogenic activities, such as burning fossil fuel, cutting down trees, and burning forests, contribute to global warming by causing changes in the Earth's air pollution. Fossil fuels have been combusted due to anthropogenic contributions to increase atmospheric greenhouse gas (GHG) concentrations [8]. For the last decade, the sea level has risen constantly due to many effects, such as more water arising from melting glaciers and ice sheets, as well as the seawater expansion during warming. These situations are related to global warming. Previous assessments have discovered that the resulted from ice loss, groundwater storage, and ocean thermal expansion cannot be synchronized with the increases of GMSL, implying that sea level changes and specific contributions are poorly constrained [9]. Thus, this paper will review the reasons for sea level rise contribution to climate resilience.

2. Sea level rise contribution

According to [10], the main contributors in rising sea level are heat expansion, ice melting, and land sinkage. The major drivers of the current GMSL rising subordinate by ocean thermal, ice sheets loss, the mass exchange of fresh water between the sea and an inland water reservoir, as well as changes in groundwater storage [11]. Therefore, two main causes will be extensively discussed in this paper to address the contributing sea level rise.

2.1. Thermal expansion

In the context of the ocean, thermal expansion refers to the increase in the volume of seawater when the temperature of the water rises. During the last 60 years, the IPCC [12] has shown a significant greenhouse gases GHG increase. For example, during the previous six decades, the anthropogenic CO²

emission from the atmosphere was 2040 ± 310 gigatonnes (GT), and a similar trend was followed by the amount of CH_4 and N_2O [12] (see Figure 2).

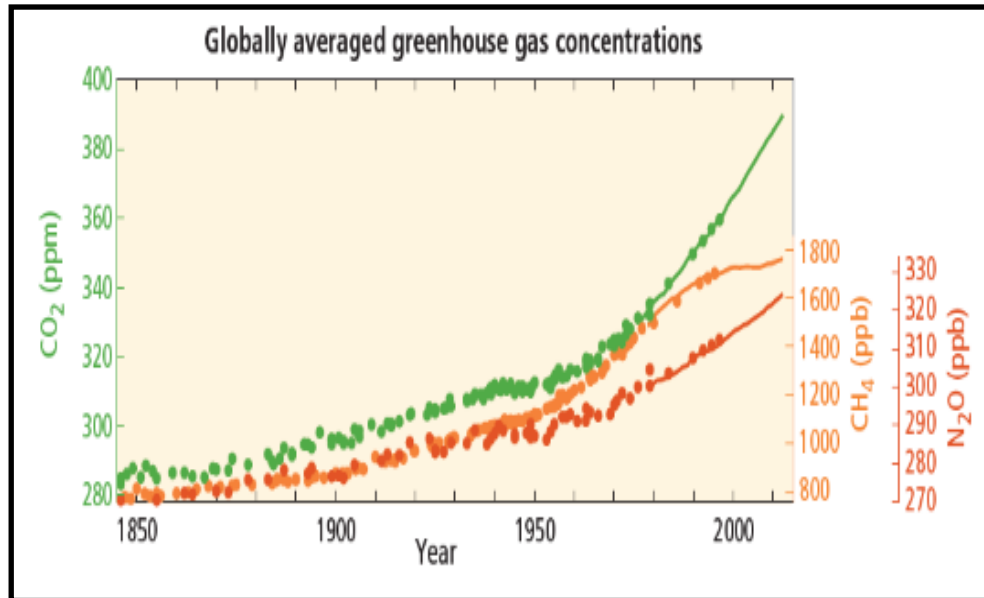


Figure 2. The global average of greenhouse gas concentrations [12]

The rapid growth since the 1950s shows that GHGs have constantly increased atmospheric CO_2 , CH_4 , and N_2O concentrations. These emissions remain in the atmosphere, with around 40% deposited on land (plants and soil) and the ocean's remainder. One of the reasons for the rise in global sea level is thermal expansion. It has already enclosed islands, worldwide beaches, and low coastlines. Millions of people living on or near the continental shores and the islands will suffer from global warming. According to a report (2014) by IPCC, the ocean warmed by 0.11° for every decade (from 1971 to 2010), and the first 750m from the sea surface warmed by 0.99° . The rate of thermal expansion accelerates as temperature rises [13], and the thermosteric component has the most critical role in explaining sea level variations. [14], [15]. According to the hypotheses, sea level fluctuation in a warming ocean must rise relative to temperature variability [16]. Therefore, sea level has increased significantly since 1950 as a result of thermal expansion of seawater.[17]–[20].

According to this study, [21] showed that variations in ocean heat content (OHC) were minimal before 1980. Since 1990, OHCs have risen continuously and it reach deeper ocean layers. Due to its huge heat capacity, the ocean has held 93% of the excess heat accumulated in the climate system due to GHG emissions over the last 50 years, while only 7% of global warming warms the atmosphere as well as melts land ice and sea [22], [23]. The effects of sea surface warming are expected to be felt across the ocean depths after a significant delay due to expansion of the heat capacity in the ocean. As a result, global sea levels will continue to rise for centuries because the ocean is not in equilibrium.

Anthropogenic actions like combustion of fossil fuels have increased GHG emissions, which has warmed the Earth's atmosphere and oceans as well as contributed to sea level rise [24]. As a government tries to mitigate climate change, it is critical to understand how different gas mitigation strategies contribute to this goal. [24] demonstrate that short-term GHGs contribute to the expansion of ocean heat in a much longer time scale compare to atmospheric lifetime activities taken to reduce short-term gas emissions, which could avert millennia of extra future sea level rise.

Furthermore, as a result of continuous greenhouse warming, as indicated by nonlinear features, the thermal expansion property of seawater cause the tendency of the global scale for sea levels to become increasingly in relation to changes in temperature. [16]. Changes in coastal flooding and erosion that go

beyond the expected rise in sea level would be influenced by this trend [25], and it depends regardless on whether sea temperature variability increases or not in the future. Future ocean temperature oscillations will result in higher sea level changes, potentially altering coastal risks as the seas continue to warm. Thermal expansion occurs at all water temperatures and is a major cause of past and present sea level variation.

2.2. Ice melting from land into the ocean

Besides, global thermal expansion of ocean and the ice melting in a warming of the climate has been highlighted as another factor contributing to GMSL rise. Almost all glacier mass balance studies have been used to estimate the glacier's contribution to sea level rise due to ice melt [26], [27]. As a result, Greenland's glaciers and the Antarctic ice sheet are rapidly melting, changing regional hydrology [28], increasing natural hazards [29], and most critically, raising the global sea level [30]. In contrast, the sea level will rise, resulting in the ocean enclosing the coast's cities. Besides, the glaciers are losing more mass and speeding up faster than the Antarctic and Greenland ice sheets. [31] discovered that a mass loss rate of 48 ± 16 gigatons per year over a decade could compensate for 6-9 percent of the observed acceleration in sea level rise. In fact, it is equivalent to [32] studies that it contributed 21% of the observed rise in sea level or 0.74 ± 0.04 mm/yr⁻¹, assuming that all meltwater reached the ocean.

Prior to the 1990s, the ice sheets mass balance was considered moderate due to lack of adequate measurements. However, the lack of limited mass loss observations and the evolution of glaciers during the satellite era is only partially known geographically [33]. Since the 1990s, the ice sheet's influence on sea level rise has increased [34], it has surpassed glacial ice as the greatest contributor of barystatic in sea level rise [29]. According to [34], it generates probability distributions with extended upper tails influenced by process-ice-sheet interaction using structured expert judgment, and by 2100, a total global SLR greater than 2 m is within the 90% uncertainty range for a high emission scenario. The number is twice more than the value that the IPCC had put forward in the Fifth Assessment Report. Therefore, as the temperature rises, the ice sheet melts faster as the water eventually runs into the ocean will cause the sea level to rise.

3. Overview on sea level measurements

The impact of SLR on the world and society varies depending on various local factors: ocean currents and upstream floods, variation in land height, and monsoon season [35]. A tide gauge and a satellite altimeter are two of the instruments used to measure sea level. Generally, the tide gauge is used as a level staff that shows the water level, which means the sea level measured by TGs is termed as the "relative sea level" since it is compared to a reference point fixed to the Earth's crust. [36]. Tidal data is vital for numerous coastal activities, including maintaining the safety of ship cargo, navigation, sound engineering, habitat protection, and preservation [37]. Since 1993, the Permanent Service Mean Sea Level (PSMSL) already manages the tide gauge network in term of data collection, analysis, and interpretation.

However, the development of satellite altimetry has allowed research connected to climate change, such as sea level rise, to be examined further in a more comprehensive approach. With the advancement of radar and laser altimetry system, through potential altimetry missions and also from their spatio-temporal monitoring applications for the Earth's systems, they can help in measuring the sea level rise [38]. Figure 3 shows the conceptual framework for deriving sea level and tidal anomaly. Sea level anomaly from the altimetry data is the difference between the time-dependent sea surface height (SSH) and the mean sea surface (MSS), where SSH is calculated by subtracting satellite orbit height (H_{SALT}) and altimeter range (R_{SALT}) [39]. Besides, tidal anomalies can also be calculated as apparent mean sea level (A_{MSL}) with an average sea level (\bar{X}_{MSL}) [40]. From that, a sea level rate can be computed from the two observations to estimate rising in sea level.

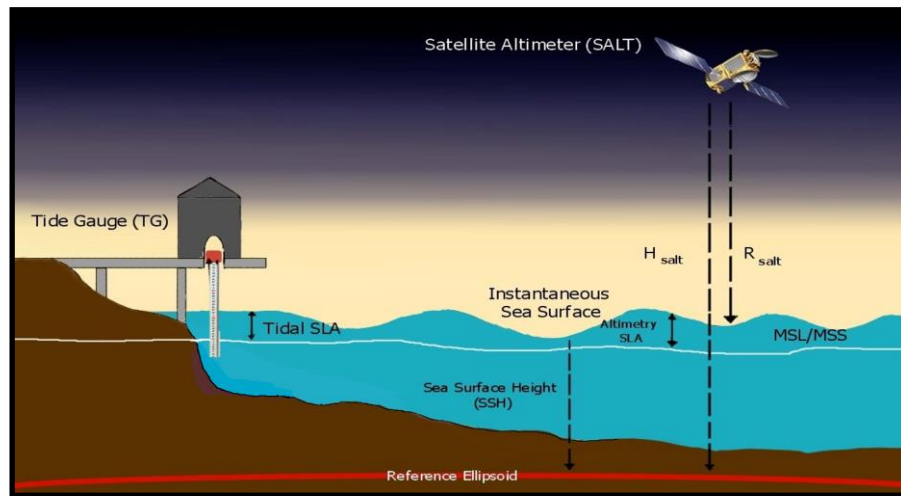


Figure 3. The conceptual framework in deriving sea level anomaly by integrating satellite altimeter and coastal tide gauge.

4. Sea Level Change

Like the Earth's, the ocean's surface is uneven, and the sea level does not remain constant globally. The GMSL is the average risen height of all the Earth's oceans, implying a change in the ocean's depth. Ocean's depth has primarily been initiated by ice melt and thermal expansion [12]. Besides, sea level variation is caused by various factors: the timescales and extreme sea levels can cause catastrophic coastal flooding. As the global sea level rises, understanding sea level fluctuations over time and space scales and elucidating the underlying processes becomes key and critical for coastal management and planning [41].

According to Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO), it is confirmed that, from January 1993 until September 2020, GMSL has increased to a rate of 3.42 mm/year [42] calculated from the TOPEX, Jason-1, Jason-2, Jason 3, ERS-1, ERS-2, Envisat, Cryosat-2, Sentinel 3A, and Saral mission data as showed in Figure 4. As discussed in 2.1, thermal expansion contributes significantly to rising sea levels. However, glaciers and ice caps also contributed significantly to rise in sea level between 1961 and 2003, at a pace of 0.50 ± 0.18 mm/year [43].

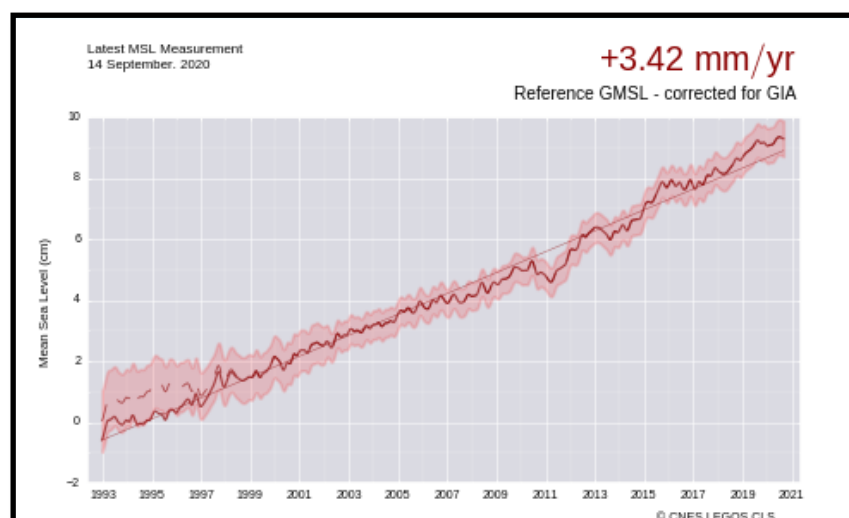


Figure 4. The reference mean sea level [42]

Table 1 summarised the various contributions to rate of sea level over last few decades for tide gauge (1961-2003) and satellite altimeter (1993-2003). According to the tide gauge, only $23 \pm 9\%$ of the reported rate of sea level rise can be attributed to thermal expansion. Also, [44] discovered the same phenomenon after calculating the steric sea level change in three maritime zones during the preceding 50 years. He determined that it was too minimal by using data from nine (9) tide gauges station for the observed sea level based on a factor. Thermal expansion is substantially greater than land ice, contributing 1.2 ± 0.4 mm /yr for satellite altimeters. These increases could result from decadal variability rather than acceleration [43]. However, the difference of 0.3 ± 1.0 mm /yr remains constant.

Table 1. Estimated global sea level rise rate for each contribution [43]

Contributor	Rising sea levels rate (mm/year)	
	Tide Gauge	Altimeter
Heat Expansion	0.43 ± 0.12	1.60 ± 0.50
Ice Caps and Glaciers	0.50 ± 0.18	0.77 ± 0.22
Greenland's Ice Cap	0.05 ± 0.12	0.21 ± 0.07
Antarctic's Ice Cap	0.14 ± 0.41	0.21 ± 0.35
Average of contributor rates	1.10 ± 0.50	2.80 ± 0.70
Measured sea level	1.80 ± 0.50	3.10 ± 0.70
Difference (Measured -Average)	0.70 ± 0.70	0.30 ± 1.00

5. Previous Studies & Discussion

Globally, the trend of sea level rise varies significantly by region. Moreover, the sea level rise pattern on a geographical scale can result in a different process. According to [45], the GMSL rise rate since 1900 has changed over time, and it estimates on a basic process. Figure 5 shows an observed GMSL trend over 1900 until 2018. Besides, observed trends of the sea level and decadal variation are comparable with the total contributions from ocean warming, ice loss, and terrestrial water storage shown (see Figure 5). Previous studies by [45] show since 1900, glacier mass loss also has accounted for two times as much rise in sea level compared to thermal expansion, while since 1970, sea level rise caused by Greenland's ice melt and the rising temperature of the ocean. Based on factors, thermal expansion and ice melting become major contributors to sea level rise.

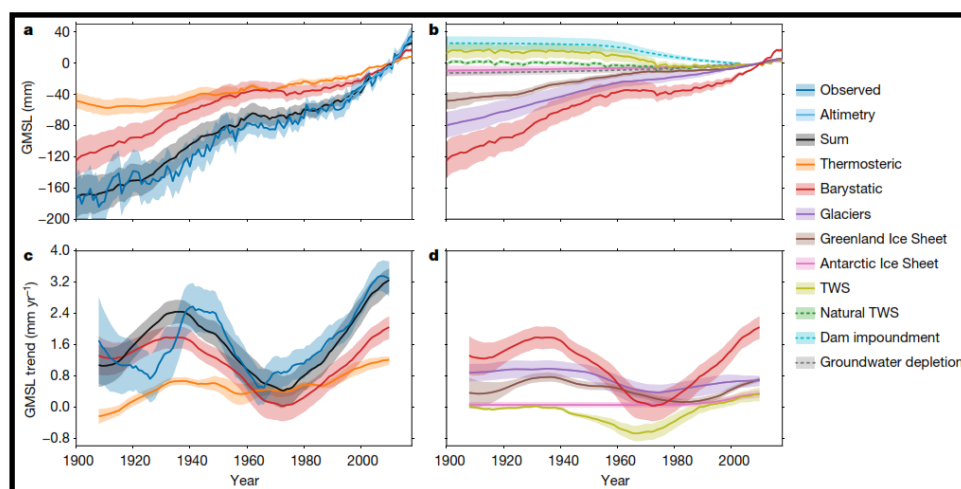


Figure 5. The observed of GMSL and its process contribution [45].

Meanwhile, in Southeast Asia (SEA) sea level rise poses a particular danger to an archipelago and densely populated country like Indonesia. [46] conducted a study on sea level in Dumai Indonesia rise between 4.80 to 5.61 mm/yr. Sea levels in the tropical Western Pacific area east of the Philippines rose by 5-7 mm/yr between 1993 and 2015, which is about twice the global rate in rising sea level [47]. Mostly sea level rise in SEA is depends on natural or anthropogenic processes and [36], Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO), which are natural ocean oscillations [47] and tropical cyclones with wind speeds originate from hot waters in the tropical region [48]. Unlike Singapore straits associated with sea level rise, regionally, seasonal sea level variability is induced by ENSO-modulated monsoons; and locally, the strongest force is produced by astronomic tides [49].

Besides, several other factors contribute to the sea level rise. For instance, seasonal and annual precipitation levels. Seasonal change can have a significant impact on how long the monsoon season lasts [50] in affected countries, including Malaysia, Myanmar, and Thailand. Two major monsoons alter the climate of Southeast Asia. From May to September, the region's climate is shifted by the summer Southwest Monsoon; during the winter, Northeast Monsoon changes the climate from November to February. Tropical storms and depressions primarily originate in Southeast Asia, the South China Sea, and the Indian Ocean (Madden-Julian oscillation) [51].

Locally, for the Malaysian region, [52] discovered that from 1993 to 2015, the mean sea level of the Malaysian seas has been rising at a rate of 3.37 ± 0.13 mm/year for the Malacca Straits, the South China Sea, 5.00 ± 0.10 mm/year for the Celebes Sea, and the Sulu Sea, with mean 4.17 ± 0.16 mm/yr. Then, Malaysia as an example also associated with nonlinear factors like ocean basin shape, water volume [40], and La Nina and El Nino episodes, which is the east-central Equatorial Pacific sea surface temperatures fall below the normal range [53], [54].

Based on the previous findings, it can be concluded that rising sea levels will continue for centuries. Generally, natural disasters cannot be prevented because it natural in nature. However, we can reduce the impact by the amount of GHG you produce each day. As GHG is a major contributor to sea level rise. Additionally, measures like coastal defences, beach replenishment and offshore barriers, and mangrove growth need to be implemented to mitigate the harmful impacts of sea level rise. They should be integrated into the local policy, planning and resilience-building plans in the area. As a result, governments and non-governmental organisations must play a vital role in formulating retreat, accommodation, and protection strategies.

6. Conclusion

In conclusion, climate change was initiated by the causes of sea level rise which led to a various outcome, mainly in rising global sea level. The GMSL has risen over time and is anticipated to rise even faster in the 21st century. In fact, it has been numerous studies on sea level rise in Malaysia, but the arguments for why sea levels continue to rise are still weak. It found that rising sea level in the 20th century was primarily caused by the increase of water mass to the oceans and the loss of glacier mass. Since 1900, it has contributed twice as much to the rise in sea level as thermal expansion. Meanwhile, 28% of the world's population lives in coastal areas, including 11% of those who live on ground below 10 metres above sea level (Special Report on IPCC). Thus, risk assessment and adaptation planning can be improved by providing knowledge on understanding ocean climate through long-term continuous observation.

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