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ABSTRACT

It is found from literature on impact of changes in climate and the resultant rise in sea level, that the scenarios, which are presumed for estimating the rise in Sea Level are stranded on a lot of doubts. Projections by different teams of scientists and real time data from IPCC's predictions do not always match and mostly rather differ. Various models so far considered, grounded on mathematical and statistical methods are anticipated to experience unforeseen variation due to the present unpredictable behaviour of the ice sheets. Studies about the contribution from Antarctica itself towards rise in Sea Level predicts abrupt variations in different projections and accordingly the importance of detailed study on Marine Ice Instability has been highlighted in this paper. The phenomenon related to MISI and MICI has been stressed upon to arrive at more correct projections on Sea Level Rise in coming decades and centuries.

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It is found from literature on impact of changes in climate and the resultant rise in sea level, that the scenarios, which are presumed for estimating the rise in Sea Level are stranded on a lot of doubts. Projections by different teams of scientists and real time data from IPCC's predictions do not always match and mostly rather differ. Various models so far considered, grounded on mathematical and statistical methods are anticipated to experience unforeseen variation due to the present unpredictable behaviour of the ice sheets. Studies about the contribution from Antarctica itself towards rise in Sea Level predicts abrupt variations in different projections and accordingly the importance of detailed study on Marine Ice Instability has been highlighted in this paper. The phenomenon related to MISI and MICI has been stressed upon to arrive at more correct projections on Sea Level Rise in coming decades and centuries.

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I. INTRODUCTION

One of the most important effects of anthropogenic warming in our globe is Rise in Sea Level, which appears as a major challenge to the Civilization as all coastal places with human habitation are likely to face catastrophic inundation threatening migration, health and economic challenges around the world. Due to the complex nature of interactions within seas, troposphere, ice and land, profound doubts remain about the resultant rise in sea level arising out of changes in climate. Scale of longstanding GMSL rise for coming centuries is essential to be known for effective planning of adaptation and mitigation pathways and policies.

II. BACKGROUND

It is highlighted in IPCC's AR-VI (2021), that the global rise in temperature would reach 1.5°C in the 2030s, then again will increase to 1.6°C, and then show a downward trend with temperatures dropping back down to 1.4°C at the top of the century. The Agreement at Paris (2015) resolved the necessity of keeping warming in our globe below 2° C than pre-industrial levels by 2100, with an attempt to restrict the rise within 1.5°C by 2050 or before. However, as per Glasgow Climate Summit (2021), in the next two decades our planet is irrevocably heading towards warming by 1.5° C over preindustrial times. As per existing declarations by countries the globe is now in the direction of 2.7°C minimum rise in temperature by 2100. If this scenario doesn't change globally the rise in sea level will linger much after this century also [1]. From review of some papers presented below it's found that there are plenty of doubts in realistic estimation of Rise in Sea Level.

III. LITERATURE REVIEW

Parris et al. (2012) found various possibilities in imminent rise of GMSL by 2100, up to a high-end of 2.0 m with a low-end of 0.2 m with two optimized intermediate high and low position from 1.2 m to 0.5 m (Figure 1).It is stated that the low scenario represents the inferred trend in rise of GMSL adding an additional amount of about 5 cm over the rise in last century, while the high scenario represents another model under more extreme land-ice contributions with an upper limit of GMSL rise. The midway situations signify the upper-end predictions for rise as per IPCC AR4-B1 scenario (Intermediate-Low), and more than a few semi-empirical revisions (Intermediate-High) [2].

Bamber and Aspinall (2013) attempted to ascertain a consensus amongst numerous experts and presumed an unchanging rate of likely rise in sea level, by 2100. They considered the above pre-industrial temperatures up to an increase of 3.5°C, matching with a medium range scenario for emissions of carbon. The average proportion of rise in the seawater level was considered to be 5.4 mm per year by 2100, just only from the Antarctic and Greenland ice sheets, as agreed upon by these experts. After merging the consequences of molten ice and glaciers, along with that from expansion of ocean due to warming, the average estimation for rise in sea level by 2100 was predicted by them to be within the range of 33 to 132 cm. Although they did not rule out the uncertainty on this guesstimate, it was stated to be the best estimate, according to them [3].

Golledge et. al. (2015) observed that the runaway ice loss from Antarctica will cross a tipping point prior to 2100, pledging the planet to have a rise in sea level up to 2 m by 2100 and 15 m by 2300 [4]. Whereas the currents in the top 100 m of the ocean's surface are driven by winds, they stated that currents flowing thousands of meters below surface are driven by thermohaline circulation. This happens due to differences in the water's density, temperature (thermo) and salinity (haline) and inter hemispheric atmospheric cooling at local level is triggered due to reduction of temperature in the bottom water level at Antarctic [4].

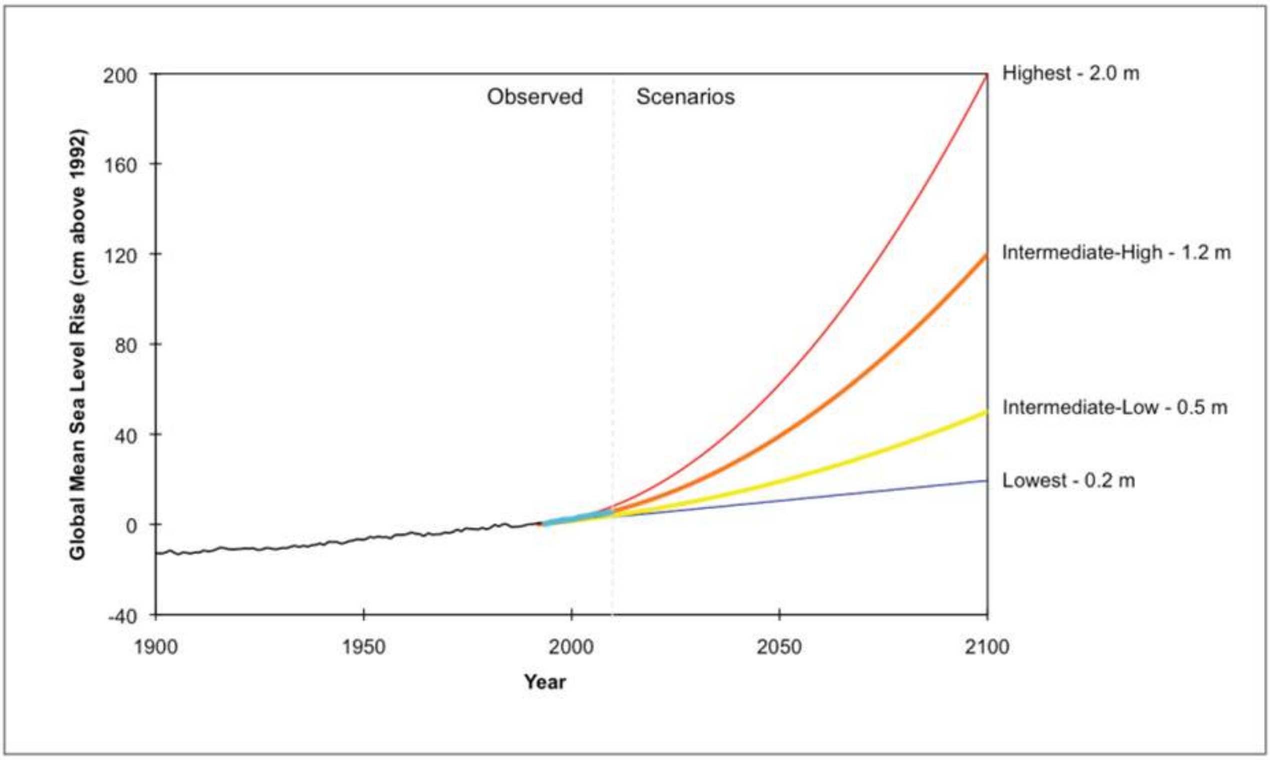

Figure 1: The rise scenarios in Global mean sea level. Source: NOAA - 2012 [2]

Pollard et al. (2015) explained that as per physical characteristics, the subaerial ice cliffs are prone to collapse due to their self-weight when the height of the cliff exceeds 90 meters. Such instability called MICI (Marine Ice Cliff Instability) leads to failure of ice-cliffs and retreat of ice sheets [5].

Landerer, F. W et. al (2015) revealed that Sea-level rise is accelerating, but the future rate is uncertain. Acceleration is mostly due to increased thermal expansion of the top two kilometers of the oceans which amplified melting of icebergs. A large portion of Antarctica below sea level is subject to melting from below, due to warm water. It causes the ice sheet to peel off the ocean floor, accelerating the flow of the glacier towards the sea. According to reports from the satellite named-GRACE (Gravity Recovery and Climate Experiment), the melting of Antarctica has fast-tracked by a factor of five in recent decades. Uncertainty in forecasting Sea level rises from Antarctica is emphasized [6].

J. Hansen et.al. (2016) highlighted a layer of the cold meltwater at the ocean's surface layer which acts like a lid and facilitates ice melting by increasing subsurface ocean warming. The layer of lid with low-density detains the warming below especially at ice shelf grounding lines where a restraining force develops which limits discharge of the ice sheet [7].

David Docquier (2016) pointed out that warm water at the base of ice shelves (basal) increases the melting, which in turn pushes back the grounding line and the resultant thinned ice-shelves exert less buttressing effect which causes perturbation to Ice sheet and disturbs the stability [8].

Sweet et.al. (2017) on scrutiny of several peer-reviewed publications came out with a physically plausible rise in GMSL due to instability of Antarctic ice-sheet itself within 2.0 m to 2.7 m. The values considered by Paris et al. [2] were revised and they recommended an upper-bound "extreme" scenario for rise in GMSL up to 2.5 m (0.5 m higher) by the year 2100 [9].

Garner et al. (2018) found projections of SLR vacillates and somewhat are usually found more than IPCC's projections. Windows for upper projection regarding SLR predictions are not same across various studies, in reality projections persist to remain ambiguous. According to them a gap in scientific knowledge related to assessing the probable rise in seawater level is evident as per the widely varying results obtained from different studies [10].

Andrew Shepherd et. al. (2018) from the IMBIE team, an international collaboration of scientists known as 'Ice-sheet Mass-Balance Inter-Comparison Exercise' investigated the Antarctic Ice-Sheet and its balance of mass. Regarding the processes responsible for active loss of the AIS, they found absence of proper technical explanations existed till the recent AR5 estimates, Subsequently the integration of the concept of instabilities particularly regarding numerical models for ice sheet was in progress. A high-impact scenario (with low-probability) for future sea level rise resulted in IPCC-AR6, where rise in GMSL up to 2 meters (Figure 1) was not ruled out by 2100 [11].

“Dow, Christine F et. al. (2018) explained MISI as one of the main catalysts for breaking and evacuation of the ice-sheets, stuck on sloping beds underneath sea level. Peripheral ice gets removed by ice cliff failure, which exposes taller ice cliffs more unstable and the process continues. Also, MICI can further increase because of surface melt through ponding and hydro fracture [12].

Jonathan L. Bamber (2019), based on the uncertainties of emission and melting ice volume, suggested that the rise in GMSL being up to 145 cm for contribution from Antarctic contribution by 2100 has 5% chances [13].

Horton et. al. (2020) documented that a group of scientists exercised a repeat survey in 2020, which was earlier conducted in 2014 to find projections for future GMSL rise. Relative 1986–2005, a team of 106 experts projected a rise of 0.30–0.65 m by 2100, and 0.54–2.15 m in GMSL by 2300, under RCP2.6.

This same team however, under RCP 8.5, projected a rise of 0.63–1.32 m by 2100, and a rise of 1.67–5.61 m by 2300 in GMSL. The

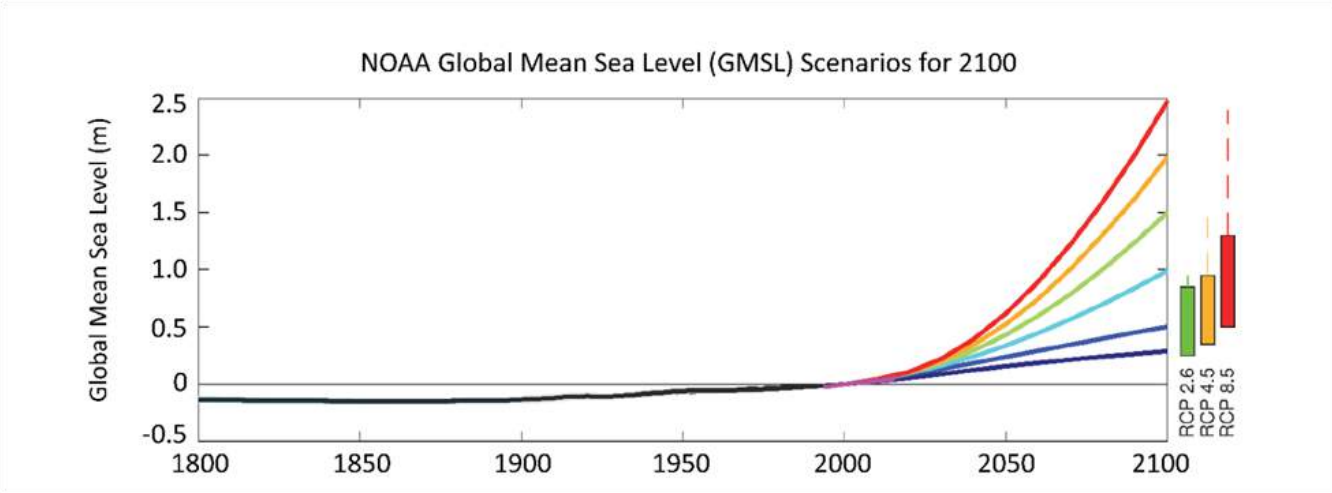

Figure 2: Scenarios for 2100 regarding rise in GMSL (6 coloured lines) [9]

projections for 2100 by these experts in 2020 remained similar with that obtained during the survey in 2014, whereas the projection for 2300 was more than that found in 2014. The experts projected that under the scenario of higher-emissions the rise in GMSL will cross the upper range estimated by IPCC AR5 (0.98 m) and the probability of such exceedance was 42% in the earlier survey (2014) whereas in the recent survey (2020), it was 45%. The cause of such uncertainties in upper-end estimates was diagnosed to be quantum of meltwater from the Antarctic Ice Sheet and its contribution to GMSL from the [14]. Frank Pattyn et al. (2020) had strong positive feedback that Antarctic Ice may yield a larger order of magnitude in Sea Level Rise. How quickly and how plentiful the quantum of melted water will be contributed from Antarctica remains a point of uncertainty. Being its base grounded below sea level on a slope towards inner, the West AIS is stated to have the volume with capacity to raise level of sea by 5.3 m, whereas the East AIS with marine basins has a far greater potential of contribution in rise in sea level up to 52.2 m [15].

Stef Lhermittea et al. (2020) mentioned that the glaciers in Antarctica are changing fast with possible large consequences in global sea level. They also stated that the processes controlling weakening of Ice-sheets and shifting of the contact position at ground is not fully clear. It was indicated by them that 'Thwaites Glacier' also known as 'Doomsday Glacier' will certainly contribute 65 cm. or more to global sea water, if it collapses, which will be sufficient to inundate New York, Shanghai, Miami, Tokyo and Mumbai etc. and will swallow islands like Kiribati, Tuvalu and Maldives. The glacier has already spewed ice into the ocean twice than that in the 1990s. More than 1000 billion tons of ice loss has happened since 2000, the flow speed being doubled in 30 years [16].

Lowry et al (2021) opined that the impact of scenarios of emission on future loss of ice from Antarctic is not expected to arise just within the 21st century. Dynamic ice sheet model simulations under various emissions scenarios of greenhouse gas had overlaps. The period was undis- tinguishable and it was inferred that the impact from the Ice Sheets of Antarctica towards rise of sea level in future is mostly indeterminable. Scientific community requires a focused effort to understand and identify the processes affecting the melting of the Antarctic Ice Sheet (AIS) which is the biggest capacity indefinite supplier to rise in sea level in future. It is indicated that the 21st century's warming situation will control the resulting long-term contribution on sea water- level from the Ice Sheets of Antarctica. It is possible that between the uppermost and lowermost scenarios of emissions in succeeding centuries, there can be multimeter differences in sea level [17].

Edwards et al. (2021) while projecting rise in sea level from the contributions of ice, showed a widespread variety of predictions for Antarctica's future contribution to rise in GMSL. According to a statistical assessment, relative to the 1995–2014 baseline, out of an overall rise in GMSL up to 62–101 cm, the melt water from ice of Antarctica will add 14–32 cm. Because of inadequate understanding of melting processes, it is seen that the IPCC AR6 projections [6] vary from these projections [18].

DeConto, R.M et al. (2021), recognized the deep uncertainties in probabilistic projections in sea level with contributions from Antarctica further to the middle of the 21st century after the Paris Agreement. For the SSP 5–8.5 scenario, when MICI and MISI are accounted for, a higher estimate in rise amounting to 20–53 cm for GMSL is likely by 2100 from Antarctic's contribution itself. The target set by the Paris agreement regarding emission will be met only if the global emissions trajectory tracks SSP 1–2.6, the lower-emission scenario. In that case ice loss to the ocean from Antarctica and its contribution to Rise in Sea Level by 2100 is likely to be meaningfully lower i.e., 12–31 cm by 2100 and about 100 cm by 2300 [19].

Chakraborty et al (2021) observed that reports from different groups of scientists and their models have regenerated the ambiguity of uncertainty to a greater extent, although starting from studies through statistical forecast, numerical modeling including actual measurement of rise in sea level from Satellite Altimetry, scientists have taken recourse. There are comments which have either intensified or decreased the rate of the global rise in mean sea level. [20]

Colleoni et al. (2022) pointed out that as melting ice sheets do not lead to uniform Sea level Rises all over the globe, this further confounds understanding the niche contributions from Antarctic itself. Due to rearrangement of ocean water due to flow of melt ice into the ocean, the gravitational field and rotational state of Earth changes. Land also rises due to exertion of less pressure on the land below by the remaining ice. It is suggested that substantial loss of ice from Antarctica can be barred only by restricting emissions of greenhouse gasses within RCP 2.6 scenario. It was also opined that emissions in the coming decades will largely impact the quantity of melt water from the ice sheets of Antarctica for raising sea water level globally. In Higher-emission scenarios by the year 2300, ice loss from Antarctica is likely to contribute to an increase of sea level by 0.6–3 meters [21].

II. MARINE ICE INSTABILITY

4.1 Marine Ice Sheet Instability

A sheet of ice supported on the sea bed level is a marine ice sheet. Seawater being denser than ice, marine ice sheets can only remain stable when the mass of the ice sheet exceeds the mass of the seawater displaced by the ice (Archimedes' principle) and the ice below water level remains in place by the load of ice over it. The thinning of ice (due to melting) when it reaches a threshold value, the ice below water floats and warm water enters below it. After basal melting [8], thinning of the ice shelf decreases the buttressing effect supporting the interior grounded ice. Pollard et al. (2015) [5] and David Docquier (2016) [8] opined that in such conditions the retreat of Ice sheets gets accelerated. The grounding line shifts and such resultant retreat of the ice sheet was first termed as MISI or Marine Ice Sheet Instability by Mercer, J. H. (1978) [22]. Due to warming when surface meltwater increases, hydro fracture takes place causing ice-shelf calving and meltwater drainage into crevasses goes on. This hypothesis of Marine Ice Sheet Instability considers that due to warming in ocean melting of ice increases, particularly when the ice rests on a reverse slope gradient (from coast towards interior of marine sheet) due to lesser buttressing force from inside the ice and shifting of the grounding line controls the stability of ice sheet [25].

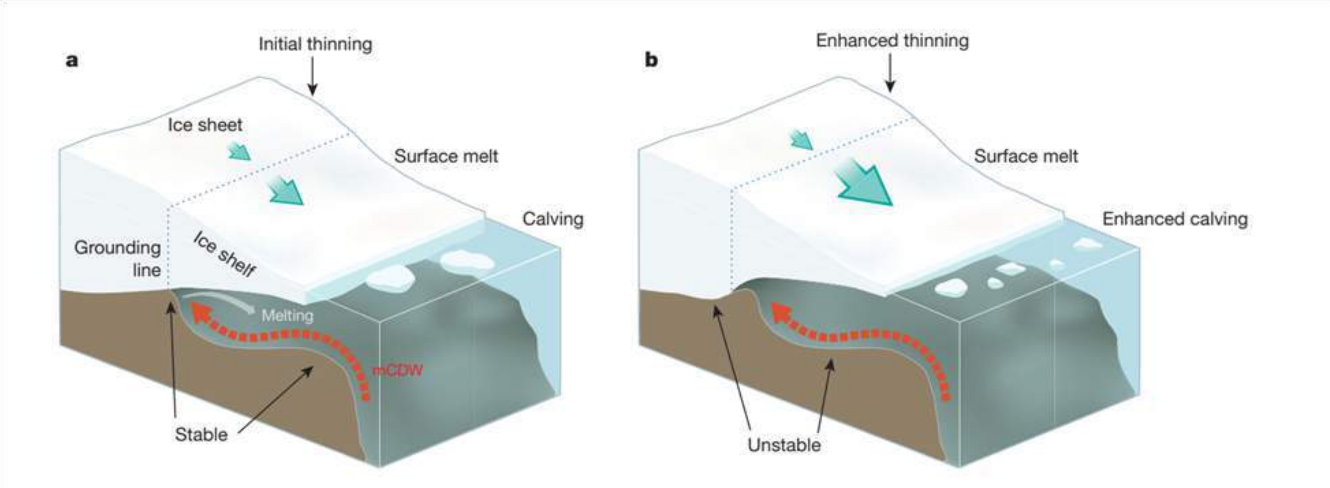

Figure 3: Schematic representation of MISI with (a) an initial stable grounding-line position and (b) an unstable grounding-line after the incursion of warm modified Circumpolar Deep Water (mCDW) [26]

Figure 4 shows the schematic representation of the phenomenon. When the ice at the grounding line is in upper position then the upstream grounding line retreats which stops only after a new stable position is reached. When the bedrock slopes down from the coast towards the interior of the marine ice sheet, the grounding line is not stable (in the absence of back forces provided by ice shelves). The position and migration of this grounding line control the stability of a marine ice sheet. Historically, blame for the sudden breakdown of the Larsen B ice shelf at Antarctica2002) into the ocean has been given to this mechanism by Vaughan et al. (2008) as summers (preceded the event [23].

4.2 Marine Ice Cliff Instability

The section of ice exposed to the ocean or air above the waterline which actually becomes the calving face is known as the ice cliff. The formative and conceptual differences between Ice Sheet and Ice Cliffs are shown in the pictures in Figure 5. When the increasingly tall unstable ice cliffs are exposed due to reduction of buttressing effect at the bottom, the cliff collapses. When the strains ("stretching" forces) inside ice cliffs longitudinally are too large for it to sustain, the taller subaerial vertical cliff along the ice margins turns out to be structurally more unstable, which triggers catastrophic failure of the cliff into deep basins. The combined effect of surface melt, shifting of the grounding line as well as hydrofracturing is known as MICI [Marine Ice Cliff Instability]. Helsinki Discrete Element Model popularly known as 'HiDEM' is a particle model which is used for determining the fracture and resultant calving of retreating marine glaciers by simulation of the elastic behaviour through Finite Element Analysis. Such parameterization [27] assists for critical representation for retreat via ice-cliff failure in models. If certain conditions are met and ice-cliff height increases with each failure occurrence, the ice-cliff failure process can become self-sustaining. It is observed that glacier-retreat rates rise non-linearly with ice-cliff height. Figure 6 shows the schematic representation of MICI and the collapse of the ice cliff.

V. CONCLUSION

Question remains whether Antarctica will empty itself into the ocean or as a cascading effect pull the adjacent ices also, which eventually may contribute towards a few meters of rise in sea-level. Satellite altimetry reports have already shown signs of fast depletion of ice. Prediction of the sea level rise by mid-century or top of it, happens to be an extremely complex task, which other than global warming in fact also basically depends on both MISI & MICI. Mercer, J. H. (1978) predicted these as a threat to disaster [22] and Vaughan, David G. (2008) reiterated the potential for ice destabilization in a runaway fashion which will contribute to comparatively faster rise in sea level [23]. Scientists are sure about the acceleration of Rise in Sea Level in future decades and centuries. Currently there are limitations in our understanding in ice flow and sliding, with historical constrained iterative statistical ice sheet simulations. It is confirmed that under high- emissions scenarios, contribution towards sea water level from the Antarctic Ice Sheet will not be the same from low-emission scenarios for centuries. It is seen that there are plenty of concepts regarding scenarios and innumerable number of papers exist in literature with historical data and stochastically obtained projections regarding Sea Level Rise. There is no shortcut to save our planet from Sea Level Rise. With concerted effort, different nations have already started planning for reduction of burning fossil fuel, go for reducing emissions and thereby try to limit the warming.

Marine Ice Sheet (Source: Science.org)

Marine Ice Cliff (Source :SciTechDaily.com)

Figure 4: Marine Ice Sheet & Marine Ice Cliff

It may be said without hesitation that ironically the climate has started behaving erratically and the civilisation is heading towards catastrophe. In established cold countries, occasions of very high temperature are unprecedentedly seen to occur, whereas unexpected snowfall is found occurring intermittently even at the desert countries. Extreme weather events, storms are happening more frequently than expected.

On random review of the papers in the last decade it is observed that the expected global sea level rise till 2100 or beyond on account of global warming may lie in a range of say 25 cm to as high as 2.5 to 3 m or even more, which mainly will depend on Instability phenomenon of Marine Ice viz. MISI and or MICI. In this paper the authors intend to stress upon continuous elaborate studies on Instability phenomenon of Marine Ice as already highlighted by Chii Yun Tsai et.al. (2020); stating that improved knowledge about the interactions between climate scenario and ice sheets and also how ice sheets would react to future changes and variability in climate are extremely important for vigorously guesstimating the influence of AIS to SLR [24]. It is opined that even if the increase of temperature be kept under control as per Paris Agreement and Glasgow Summit, a severe uncertainty remains on how fast and how much the Icebergs will seriously melt, which can lead to a disaster in our world.

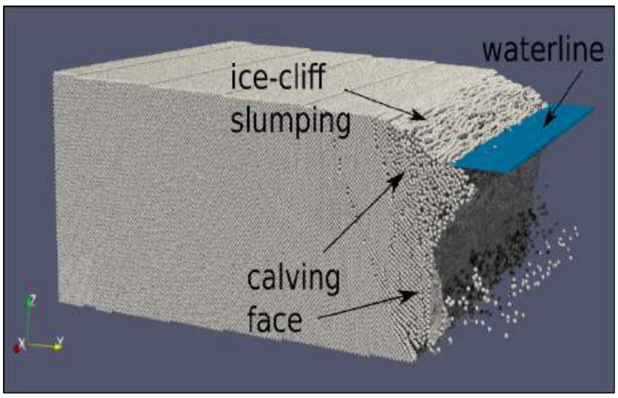

Figure 5: Schematic representation of collapse of an ice-cliff [27]

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