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Uncertainties in Prediction of Future Sea Level Rise Due to Impact of Climate Change

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

On reviewing the development of the research methodologies on climate change and sea level rise during the last two decades, it is observed that the assumed scenarios for apprehending the rise in global temperature are grounded on a lot of uncertainties. The real-time data varies from IPCC's predictions. The gradual transition on the emission pathway scenarios from SRES (2000) till RCPs in AR5 of IPCC depicts the conceptual difference between the two concepts in scenarios. SRES represented detailed socio-economic-based scenarios, but RCPs are based on the capacity of a gas affecting the change in energy in the atmosphere due to GHG emissions known as Radiative Forcing. Considering the possible range of the radiative forcing values in 2100, AR5 of IPCC considers the four RCPs numbered as 2.6,4.5, 6.0 and 8.5 as per greenhouse gas concentration trajectories (not emissions). The present condition of melting of ice sheets at Antarctica and Greenland is quite high and it is understood that such melting will continue. Even in a situation, if the anthropogenic emission of GHGs is immediately stopped, the self-sustained melting will continue. Models so far being based on numerical and probabilistic approaches are expected to undergo abrupt change because of the current inconsistent ice sheet dynamics. Considering deep

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uncertainty in socio-political and economic changes amongst nations, the importance of usability of model hierarchy for the complex science of climate change is becoming unforecastable, in the prevalent ice dynamics during accelerated warming situations. In reality, the predictions are becoming less reliable. Possibility of the scenarios likely to be changed are apprehended during the advent of CMIP6 and the variations in contributing factors in the form of SSPs in the upcoming IPCC AR6, in 2022 and it is indicated that the research may take a new turn. A multidisciplinary approach to research with minimum uncertainty ina more precise and finer manner is the need of the day.

Keywords: SRES; RCP; SSP; IPCC; AR6.

ABBREVIATIONS

SRES : Special Report on Emissions Scenarios
IPCC : The Intergovernmental Panel on Climate Change
AR5 : Assessment Report 5
RCP : Representative Concentration Pathway
GHG : Green House Gas
SSP : Shared Socio-economic Pathways
AR6 : Assessment Report 6

1. INTRODUCTION

Historically, it reveals from real-time data that the projected and observed data for sea level rise widely varies from region to region [1]. There are variations in sea-level change projections which are more often uncertain [1]. The patterns of predictions largely vary because the determination of projections stands upon a lot of uncertainties in the complex geophysical processes. Over the years, the projections of sea level rise were based on certain assumed scenarios on the severity of global emissions of Greenhouse gases. [1]. The scenarios have transformed from the initial assumptions made in SRES, and is going to be re-evaluated in upcoming SSPs, which till now are intermittently based on RCPs. However, as these scenarios depend upon societal decisions and the needs of human civilization, they vary from nation to nation.

There are four categories for sources of uncertainty viz. from (1) ice-sheet (2) anthropogenic (3) limitations of model/data and from (4) atmosphere and ocean. The transition from SRESs to SSPs routed through RCPs along with various approaches to resolving the uncertainties has been reviewed and it is felt that societal decisions on scenarios will majorly influence the actual real-time sea-level rise. The recent concept of partitioning the uncertainties may perhaps even lead to more accuracy in projections.

2. REVIEW

The Intergovernmental Panel on Climate Change (IPCC) considered four families of emission pathways in SRES (special report on emissions scenarios). A distinctly different storyline for each family was assumed in the direction for future developments to make each of the four storylines different in increasingly irreversible ways. At the beginning of the millennium, climate change likely to take place in this century has been evaluated when it has been acknowledged by scientists that the scenario will depend on how human societies would develop in terms of demographics and economic development, technological change, energy supply and demand, land use, regional development etc. [1].

In 1995, Coupled Model Intercomparison Projects (CMIP) was established for studying the output of general circulation models (GCMs) as under World Climate Research Program (WCRP) [2]. The initial one was modified in 1996 as CMIP2 (1996) and revised to CMIP3 (2010), whereas, now CMIP6 is in the offing after IPCC's Fifth Assessment Report (AR5) considered CMIP5 (2013).

Due to complex interactions within the climate system, human activities have led to unprecedented changes in the earth's atmosphere, though it is difficult to clearly delineate the characteristics of climate change associated with natural and anthropogenic forcing. There are credible evidences to show that such changes have the potential to influence earth's climate. It is also stated that significant differences exist at regional levels in spite of the fact that meteorological data has recorded overall warming around the earth [3]. Human activities like the emission of greenhouse gases or land use changes result in external forcing. It is generally believed that external forcing-induced climate change is predictable. But in reality, such predictions have limitations as population change, economic policy, technological changes are hardly accurately predictable. Because of the unpredictability itself, climate projections are based on carefully constructed assumed scenarios [3]. As an example, particularly over the northwestern parts of India, most models project enhanced precipitation during the monsoon season, wherein the magnitudes of projected changes differ considerably from one model to the other [3].

From a sustainability point of view, under United Nations Human Settlement Programme (UN-HABITAT), it is observed that the resulting sea level rise due to anthropogenically caused global warming is the largest challenge in our planet. It is also pointed out that severe weather risk and seawater rise pose increasing threats in coastal areas. It is indicated that threat to cities due to sea level rise is only one part whereas more extreme weather patterns such as intense storms are another [4].

Compounding uncertainties in Sea Level Rise Assessments have been uncovered stating that there are many barriers that impede adaptation to climate change, including lack of data, information, and resources; inflexible institutions; perceptions of risk; lack of funding and leadership; scale mismatches; and above all the uncertainty [5].

Unless the current trend in the rise of global mean temperature is reversed, the increasing Global mean sea level will continue to rise beyond the year 2100. It is established that sea level rise over the last century has been dominated by ocean warming and loss of glaciers. But sensitivity suggested important contributions should also be expected from the Ice Sheets at Greenland and the Antarctic. Ice Sheet at the Antarctic holds more than half of Earth's freshwater and is by far the largest potential source for global sea-level rise under future warming conditions. The rising trend of Global mean temperature may decline slowly due to inertia in climate and global carbon system if greenhouse gas emissions reduce. But uncertainty remains on how much sea-level commitment is expected for different levels of global mean temperature increase. It is opined those additional strategies to better constrain the sea-level commitment will be necessitated [6].

While formulating a proposal to avoid conflict between sea level rise and the coming uncertainties, it is widely acknowledged that climate change will alter the world over the coming century. However, it is unclear how different regions of the globe will be affected by this change. No straight prediction is possible for some particular place, in terms of heat and precipitation. The melting of the great ice sheets and glaciers will continue, and perhaps, melt even faster. As a result, the rise in oceans will persist over the next century up to order of one meter [7].

Climate and its elements are undoubtedly the most important factors for all types of life forms on the earth, as evidenced by erratic precipitation, glacier melting, bleach of coral, shifting of tree lines including rising in sea level [8]. The anthropogenic causes are already acknowledged and newer complexities in climate scenarios are also well-known, because of their variation from the past. Considering records through modern instrumentation, historical temperature analysis, and global precipitation studies, there is a need for a clear discrepancy between climate change and global warming [8].

Lange (2014) documented various aspects of uncertainties in sea level change. They illustrated that global sea level is estimated using averaged measurements from a worldwide network of coastal tide-gauges or from satellite-borne instruments. Being the worldwide average, it does not appear to be fruitful for local coastal evaluation. Rather, local relative sea level measured at specific locations depend upon the direction and rate of movement of the underlying land (tectonic change) in different parts of the world. Local sea-levels are rising or falling and from geological evidence over long periods of time (millions of years), the sea level changes are assessed. According to them, however, these long-term changes suggest that any sea-level rise in response to temperature increase decelerate rather than accelerate over time. Based on the past, it is stated with certainty at different locations around the world, that future sea-level will continue to change at differing rates and in different directions. The authors mentioned two steps - understanding of past rates of change, present environmental conditions and theoretical analysis and projection of likely changes. The maximum rate and duration of natural sea-level rise are recorded to be about 30 mm/year over periods of a century and typically less than 10 mm/year, has been taking place over the last 10,000 years as slow global sea-level rise [9].

Trenberth et al. (2014) stressed upon that there is an imbalance in energy flows in and out of the earth system. They stated that "Warming" being the phenomenon of extra energy, can manifest in many ways like rising of surface temperatures, melting Arctic Sea ice, increasing the water cycle and altering storms. It was inferred that most of the excess energy goes into the ocean. They focused on the need to monitor the energy imbalance with direct measurements to find where the energy goes and quantifying how climate change is manifested. They strongly opine key issues for Earth from an overall energy standpoint are the actual energy imbalance at the surface and top of the atmosphere. While assessing the exchanges among the climate system components (atmosphere, ocean, land, and cryosphere) and the changes in phase especially of water involving latent energy (ice, liquid, and vapour), they also agree that a major part of the anthropogenic heat (90%) is absorbed in the oceans and only the remaining goes for melting of ice, both terrestrial and at sea [10].

Unnikrishnan et al. (2015) documented the trends in Sea-level-rise based on estimates derived from satellite altimeter and tide-gauge data of the Indian coasts for the last two decades. From Altimeter data analysis during 1993–2012 period, they noted that the rate of sea-level rise (3.2 mm/year) is rather spatially homogeneous over most of the north Indian Ocean and matches with the trend of mean sea-level's global rise in the corresponding period. They also recorded the notable exception in the northern and eastern coasts of the Bay of Bengal, which experienced larger trends (5 mm/year and more). Finding the trends derived from altimeter data as higher than those estimated from tide-gauge records over longer periods, they targeted for an improved understanding of the mechanisms behind this accelerated sea-level rise recorded over the past two decades. The nonconformity was highlighted as uncertainties between the methods of measurement. They opined that the modeling concepts may land up afresh depending on how the meltwater reacts with unforeseen atmospheric changes. The major caveat to derive the reliable multidecadal sea level rise on Indian Ocean is believed to be lack of long-term sea-level observations. Satellite altimetry provides high-resolution sea-level measurements since 1992 but that is inadequate for reliable estimates of regional sea-level rise trends [11].

Cozannet et al. (2015) during evaluating uncertainties on flooding due to the rise of sea level observed that the frequency of coastal flooding events has changed. They highlighted the need for accounting variability of storm surge patterns and sea-level rise to provide quantitative insight into the relative importance of contributing uncertainties over the coming decades accurately. Considering IPCC projections for sea level rise, a global sensitivity analysis was applied on an urban low-lying coastal site located in the north-western Mediterranean, where the yearly probability of damaging flooding could drastically grow after 2050 [12].

Sorokin Lionid et al. (2015) while investigating on European Airports reiterated their concern about radical uncertainties in sea level rise. The importance of climate scientists' divergent opinions about the sea level rise and its consequences for decision-makers was highlighted. The team opined those new scientific uncertainties on SLR's evolution essentially meant a lack of reliable scientific knowledge which in turn is linked with the decision-makers' liability resulting from scientific uncertainty. Considering baseline scenarios in IPCC AR5 for the increase in global mean surface temperature without additional mitigation, they called for internationally synchronized fast mitigation and preventive measures to combat with the detrimental situation [13].

Oddo. C. Perry et al. (2017) stressed upon the hypothesis of Decision Making under Deep uncertainties in storm surge and sea-level rise projections for risk analysis from the point of view of Operations Research. They stated that the flood adaptation model produces potentially myopic solutions when formulated using traditional mean-centric decision theory as the risk-based adaptation strategies remain silent on certain potentially important uncertainties. They explained the concept of 'Deep uncertainty' as a condition in which analysts cannot correctly anticipate: (1) the appropriate models for interactions amongst variables, (2) the probability distributions and/or (3) the desirability of alternative outcomes. They found deep structural uncertainties that have large effects on the model outcome, with the storm surge parameters accounting for the greatest impacts. Global sensitivity analysis effectively identifies important parameter interactions that local methods overlook, which could have critical implications for flood adaptation strategies [14].

Baker Alexander et al. (2017) reckoned that the WAIS (West Antarctic Ice Sheet) is going through rapid disintegration and also noted published projections as widely divergent. To quantify the deeply uncertain contributions from West Antarctic Ice Sheets, they presented a set of probabilistic semi-empirical models of the climate and sea-level contributions from thermal expansion along with contributions from the ice sheets at Antarctic & the Greenland including those from the glaciers and the small ice caps. Three projections following RCP8.5 based on three collapse scenarios at WAIS are (i) no collapse (0 cm), (ii) mid-range estimate (79 cm in 2100) and (iii) high case (3.3 m). Full disintegration WAIS within a couple of decades were thought. They found a high range of deep uncertainty in sea-level projections (Fig. 1), as the range usually involves both the estimates and a probabilistic construal of the surrounding uncertainties. It is noted that the uncertainty of the sea-level projections represented in CMIP5 climate models at "open ocean" increases while approaching nearer to the coast. The climate models can predict sea-level rise explicitly due to changes in ocean circulation and density because of global thermal expansion. However, the contributions from land water storage, glaciers and ice-related components are determined using offline models considering boundary conditions derived from temperature and precipitation. The models do not always represent important coastal processes, like sedimentation and erosion changes associated with changes in waves and tides, etc. Compilation of the uncertainties in mean sea-level projections is seen to be strongly depending on the emission scenario globally (Fig. 2). It was emphasized by them that the future climate forcing will to a large extent be dependent on future decisions of human [15].

Mach et al. (2017), taking stock of recent advances and challenges in 'Next Generation of Assessment' acknowledged deep uncertainty and reviewed the climate change assessment. They relied upon quantitative/qualitative evidence, expert judgements, exploring futures and interactions between experts and decision-makers. They opined that in the current era of climate and broader global change, integrative assessment considering both opportunities and pitfalls can bolster decisions about uncertain futures for sustainability. The need for integrative assessment is identified to enlist what is known and what is not [16].

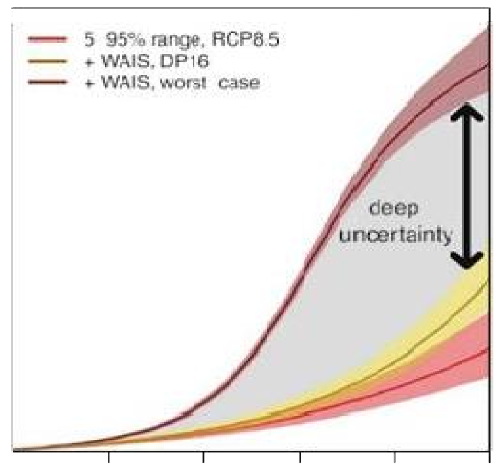

Fig. 1. Future sea-level projections including a deeply uncertain contribution of the WAIS [Scientific Reports volume 7, 3880 (2017)]

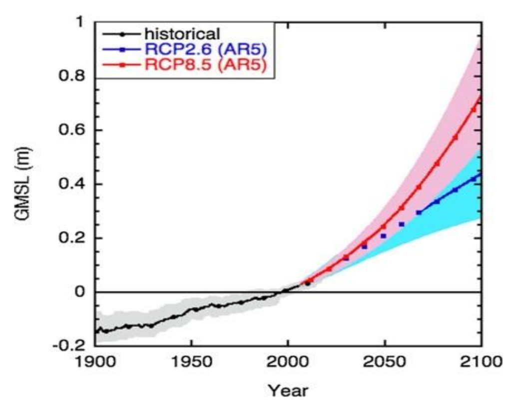

Fig. 2. Uncertainties in GMSL compiled over the period 1900–2100 [Church et al. (2013)].

2.1 Controversies

Garner et al. (2018) strongly noted the fact that upper projection windows for SLR projections are not uniform across different studies. They discoursed that very often, future SLR remains deeply uncertain in reality. Projections of SLR from individual studies varies from one another and rather generally found higher than the upper projections assessed by IPCC. The accuracy of the research outputs was expressed as ambiguous. The authors categorically raised doubts, and distrusted the correctness of the research outputs. The widely varying range reflected uncertainties in scientific knowledge related to the processes contributing to SLR, reflected in assumptions used to produce projections [17].

Le Bars Dewi (2018) explained that the uncertainty of total sea level projections obtained by adding the contributions from thermal expansion, glaciers, and ice sheets', depends on the correlation between the uncertainties of the contributing factors. In an attempt to model the correlation structure and its time dependence, the author observed that the correlation primarily arises from uncertainty of future global mean surface temperature which predominantly correlates with almost all contributors. They acknowledged the acceleration of the sea level rise in this century. However, they mentioned that unfortunately numerical models, based on a physical understanding of the relevant processes of the complex systems like the Earth's climate, do not yet include all of the important processes driving future sea level. It is highlighted that glaciers and ice caps are large enough to contribute to sea level rise, but the main physical processes determining their response to climate change are still uncertain. The long-time scale of adjustment and sensitivity to small circulation and temperature biases still make it challenging to include them in fully coupled models. The problem of dependence of sea level contributors is also more di□cult to understand because it is not about events that correlate in time, for which we have a good intuition, but about events that correlate in the ensemble of possible futures that is a more abstract concept [18].

Mehta et al. (2019) introduced the heuristic of the 'above', 'middle' and 'below' to understand the uncertainty perspectives on climate change in Indian perspective. They studied sea level rise at three places viz. at Sundarbans, at Kutch and at Mumbai. The authors referred the cataclysmic flooding over Mumbai on July, 2005 due to about 944 mm of rain poured within 24 hours. It has been acknowledged that due to macro trends such as temperature extremes and sea level rise climate science is dealing with uncertainties. They barely appreciated understanding the effects at the local level due to downscaling challenges and also intersections with other drivers of change. They emphasized on the 'envelope of uncertainty' that intersects with political, social, cultural, economic and scientific domains [19].

Kopp et. al. (2019) while evaluating the usability of recent researches, identified that sea level rise involves natural and human systems with long lags, irreversible losses and deep uncertainty in anthropogenic emissions, ice sheet dynamics, variability in tides and storms. They opined that given the political, economic, and technological complexities involved, there is no sacrosanct way of estimating the relative probability of different future emissions. Accounting for deep uncertainty involves interactions of sea-level change, geomorphology, socioeconomics, human responses, risk management, adaptation strategies, political and economic viability etc. The usability of sea-level science being a pressing concern warrants finding long-term sea-level projections by grappling with the stated deep uncertainties. More clarity and stable understanding of the relationship between long-term trends and the impacts of short-lived extreme events, and the ways in which the physical coast responds to increasingly frequent flooding is the prime need of the day. It is also stated that it requires more cognizance of the political economy [20].

Kopp et al. (2019) argued for management of the risks of sea level rise and explained in their paper about the two increasingly well understood forms of ice□sheet instability, i.e., MISI (Marine Ice Sheet Instability) and MICI (Marine Ice Cliff Instability). Because of limited scientific agreement on the key conceptual models, they mentioned 'Deep Uncertainty' to be same as 'Ambiguity'. The inherent uncertainties related to impacts of sea-level rise obtained from Probabilistic Approaches, Dynamic Ocean Circulation Model, Bathtub model for inundation has been discoursed. Interestingly, the extent of uncertainty has been explained by equating it with gambling. For illustrating the implication, it has been commented that in general, all else being equal, humans exhibit a preference for the less ambiguous gamble [21].

Slater et al. (2020) recently found that due to ice dynamics in Antarctica and surface melting in Greenland, the ice-sheet losses track with the upper range of sea-level predictions, stated in the IPCC Fifth Assessment Report. They impressed that short-term variability in the atmosphere, oceans and climate must be accounted in the Ice-sheet models for accurately predicting sea-level rise. They mentioned that Ice dynamic contributions were derived from ice-sheet models forced by, but not coupled to, atmospheric and oceanic model outputs. In this way, the atmosphere and ocean can impact the ice sheet but not vice versa. Advances in ice-sheet modelling are expected in 2022 through ISMIP6 (Ice-sheet Model Intercomparison project for CMIP6), which will deliver process-based projections forced by output from coupled atmosphere–ocean GCMs in AR6 of IPCC report [22].

Garbe et al. (2020) recently documented the hysteresis of the Antarctic Ice Sheet mentioning that a comprehensive stability analysis of the Ice Sheets at the Antarctic for different amounts of global warming was not available so far and they found that the Antarctic Ice Sheet exhibits thresholds, on the multitude of temperature, beyond which ice loss is irreversible. They observed that the ice sheet's temperature sensitivity is 1.3 meters of sea-level equivalent per degree of warming up to 2 degrees above pre-industrial levels. Between 2 and 6 degrees, this will almost double to 2.4 meters per degree of warming and for per degree of warming between 6 and 9 degrees would increase to about 10 meters. More than half of Earth's freshwater resources are held by the Antarctic Ice Sheet which comprises an ice mass equivalent to 58 m of global sea-level rise. Its future evolution and the associated sea-level change are therefore of profound importance to coastal entity ecosystems and economies. It will be determined by the interplay between a number of negative (dampening) and positive (amplifying) feedbacks. The largest uncertainty in projections of future Sea level rise is constituted from unknown mass loss from the Ice Sheets at Antarctic [23].

Rander et al. (2020) reiterated that disregarding the seriousness of the risk of climate change will be too dangerous. They reported their findings from their new climate model Earth System Climate Interpretable Model(ESCI MO). They stated that for global warming, the earth has already past a point of no return. They observed that even if globally the society stops all emissions of man-made GHGs immediately, self-sustained melting of ice will continue for hundreds of years. The report stated that melting (in ESCIMO) is the result of a continuing self-continued rise in the global temperature. Global warming is the combined effect of physical processes viz. melting of the Arctic ice, increase of water vapour (driven by higher temperatures), and variation of GHG concentrations in the atmosphere. They have categorically mentioned that huge amount of CO_2 is required to be extracted from the atmosphere to stop over the self-sustained warming. They stated that rise in water vapour in the atmosphere and the further rise in the temperature which causes increased release of carbon from melting permafrost are due to anthropogenic causes. At this juncture in plain language, it means that 'There is nothing we can do to stop the oncoming effects of climate change' [24].

Maher et al. (2020) clarified that there is no single unique hierarchy and no one model is suitable for all purposes. A suitable model hierarchy needs to be constructed based on the key scientific questions of interest and even for a given scientific problem, individual scientists will make different, perhaps equally defensible, choices. Their confidence in global warming projections does not yield from blind faith in GCMs output; rather fundamentally supported by basic physical laws. However, those laws have little quantitative predictive capability for Earth's climate. At the other extreme, when comprehensive models are forced into the warmer regimes that may lie in our planet's future, comparing parametrizations is difficult. The suggested purpose of the model hierarchy is to provide a pathway connecting robust physical laws to a complex reality. Even it was declared by the authors that, arguments remain if only a few are useful whereas all models are wrong [25].

Haasnoot et al. (2020) narrated about the large uncertainty on how potential ice-mass loss from Antarctic large can rapidly contribute to rise in sea level during the second half of this century. They also explained the impact of sea level rise from the said ice-mass loss on the coastal adaptation strategy of the low-lying country like The Netherlands. As sea levels rise faster and higher, they forecast that sand nourishment volumes to maintain the Dutch coast in 2100, may increase 20 times larger than to date. The world-renowned storm surge barriers will need to close at increasing frequency until closed permanently. Intensified saltwater intrusion will reduce freshwater availability while the demand will be rising. Anticipating deep uncertainty, they inferred that high SLR scenarios help to enable timely adaptation and to appreciate the value of emission reduction and monitoring of the Antarctica contribution to SLR [26].

Pattyn et al. (2020) published their view that Ice Sheets at the Antarctic are losing mass at an accelerating pace, which is likely to continue over the coming decades and even centuries. For unmitigated scenarios, they expressed their concern on the uncertainty about how fast and upto what extent Antarctica will contribute to sea level rise. They also mentioned the role of bed bathymetry and the relation between global warming ocean dynamics. They felt that linear extrapolations of present-day observed melt rates are assumed because of uncertainty only. Mostly, focusing on unmitigated climate scenarios, such as Representative Concentration Pathway (RCP) 8.5, simple parameterizations of ice-ocean melting rates are generally applied. They suggested to organize large international intercomparison projects to attain accuracy in the representation of physical processes in current ice sheet models [27].

Gregory et al. (2020) studied the evolution of the Greenland ice sheet under a range of constant climates (typical of those projected for the end of the present century) using a dynamical ice sheet model coupled to an atmospheric general circulation model, found an irreversible large future decline of the ice sheets at Greenland. They studied the multimillennial future evolution of the Greenland ice sheet for various magnitudes of anthropogenic climate change in experiments with constant climates using an AGCM interactively coupled to a dynamic ice sheet model. They also pointed out snow albedo as a particularly important uncertainty considering that removal of the ice sheet is reversible with the highest choice of albedo [28].

Horton et al. (2020) recently documented the variability of GMSL (global mean sea-level) projections obtained from various studies. They observed that considering the same emission scenario even has led to confusion amongst decision-making communities because of variation in results. They highlighted that under Representative Concentration Pathway (RCP) 2.6, a team of 106 experts projected a likely (central 66% probability) of GMSL rise (relative to 1986–2005) upto 0.30–0.65 m by 2100 and 0.54–2.15 m by 2300 respectively. It is opined that to make informed mitigation and adaptation decisions, knowledge of the uncertainties related to sea level rise are vital. They also pointed out that the same team of experts projected a likely GMSL rise of 0.63–1.32 m by 2100, and 1.67–5.61 m by 2300 under RCP 8.5. The Ice Sheets at Antarctic and Greenland being the largest potential contributors to GMSL rise, experts identified the Antarctic Ice Sheet as the greatest source of uncertainty which accounted for 23% of responses for 2100 and 21% for 2300. They invited the experts to explain about their greatest source of uncertainty under both RCP 2.6 and RCP 8.5 for their estimates for 2100 and 2300. To avoid biases in influencing respondents' opinion the authors categorically decided to use open-ended questions about their sources of uncertainty and resources regarding sea-level rise estimates. Under two temperature scenarios from the upper and lower extremes of the RCP 2.6 and RCP 8.5, the anticipated GMSL change for centuries during the periods 2000–2100 and 2000–2300 are presented (Fig. 3) [29].

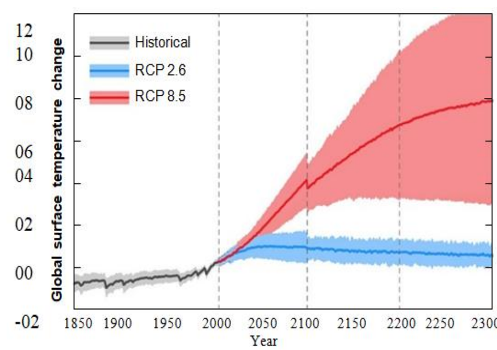

Fig. 3. Global annual mean surface air temperature projections correspond to the lower (RCP 2.6; blue) and upper (RCP 8.5; red) greenhouse gas scenarios modified from IPCC AR54 [29]

Wal et al. (2019) indicated the contribution of each GMSL term to the total variance in projected sea level change over the twenty-first century (Fig. 4). As a matter of fact, combination of melting of glaciers and ice caps along with thermal expansion of the ocean, the dynamics of glacier is certainly going to change. An increase in snow content at any place, will steepen the surface gradients near the edge of the Ice Sheet. Discharging more icebergs into the ocean glaciers will flow faster, and as a consequence, this will negate any impact of the increased snowfall, in mitigating sea level rise. It is opined that because of these factors, the Ice Sheets are vulnerable to rapid melting, which may raise sea level upto 3.3 m within 500 years. Such rates are common in the geological record.

However, the authors commented that these dynamic behaviours are too difficult to predict by simulating even by our most complex computer models. Climate models are not yet characteristically joined to glacier and ice sheet models. An additional uncertainty remains as the impact of freshwater fluxes from melting land ice on the ocean circulation is not yet precisely simulated [30].

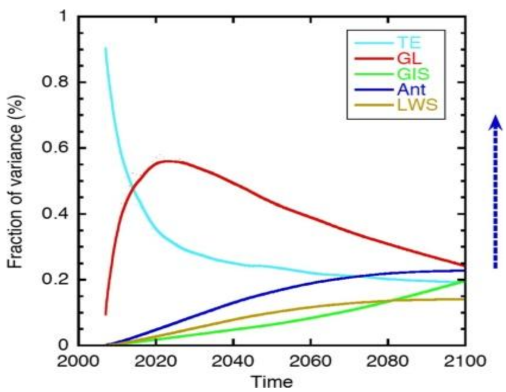

Fig. 4. Relative contribution of thermal expansion (TE), glaciers (GL), the Greenland ice sheet (GIS), Antarctica (Ant) and land water storage changes (LWS) The dotted blue line indicates qualitatively the increase in the dynamic contribution of the Antarctic ice sheet if marine-based sectors of Antarctica collapse [30]

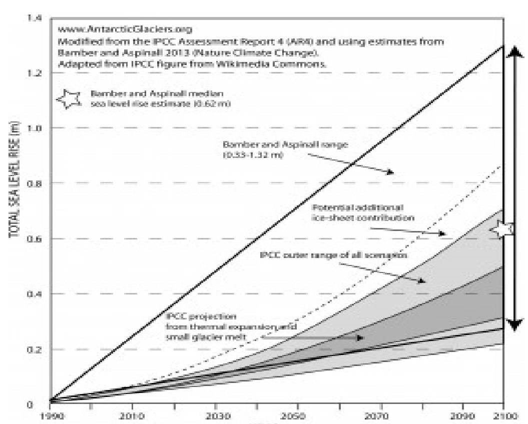

Fig. 5. Comparison of projection for Sea level rise to 2100 [Source: (antarcticglaciers.org June 2020)]

2.2 Assurance

Bamber and Aspinall (2013) to untangle the existing thorny problem modified the IPCC sea level rise estimates and assumed a uniform rate of sea level rise, (Fig 5). They pooled different assessments in order to reach a consensus from numerous experts on likely sea level rise by 2100. The authors considered an increase of 3.5°C above pre-industrial temperatures to match a mid-range carbon emissions scenario. The average rate of rise in sea level was found to be 5.4 mm per year by 2100 AD as agreed upon by these experts from just the Greenland and Antarctic ice sheets. With 62 cm being the average estimate for sea level rise by 2100, combining the effect of melting of glaciers and ice caps in addition with thermal expansion of ocean ; Bamber and Aspinall came out with a range of 33-132 cm. It is still uncertain, but according to them it is the best estimate till now [31].

2.3 Partitioning

Marzeion et al. (2020) recently came out with partitioning the uncertainties from five different sources with the aim to find a more precise assessment. These are: (1) glacier model uncertainty, including uncertainty from any downscaling of atmospheric conditions internal to the glacier model, which causes any two glacier models to project different glacier evolution even if the boundary and initial conditions are identical; (2) climate model uncertainty, which causes two GCMs to respond differently to identical radiative forcing, and which enters the glacier model projections through the boundary conditions (when calculating the surface mass balance); (3) scenario uncertainty, which reflects the uncertainty of the future radiative forcing affecting the GCM projections; (4) internal climate variability, that is, natural fluctuations of climate that arise without any changes in the radiative forcing of the climate system; and (5) uncertainties in the glacier inventory, such as initial glacier volume and area. The remaining four being independent, the scenario uncertainty (3) is conceptually different from the other sources of uncertainty, instead of a lack of knowledge about it, or approximations from natural dependent on future decisions from society, the authors considered the total variance across the ensemble as

$$\text{Variance}_{tot} = \text{Variance}_{gla} + \text{Variance}_{GCM} + \text{Variance}_{RCP} + \text{Variance}_{nat},$$

Where Variance_{gla} is the variance across different glacier models, Variance_{GCM} is the variance across different GCMs, Variance_{RCP} is the variance across different RCPs, and

Variance $_{nat}$ is the variance caused by natural variability. They predicted that overall, 18 % of their ice mass will be lost by the glaciers in a low-emission scenario, whereas in a high-emission scenario, the loss will be around 36% contributing roughly about 79 or 159 mm of rise of sea level by 2100 [32].

3. CONCLUSION

Detailed diverse information on climate, society, economy, adaptation and mitigation are required to predict future climate change impacts. IPCC AR5 suggests a global RCP-SSP-SPA Scenario framework considering Representative Concentration Pathways, Shared Socio-economic Pathways, and Shared Climate Policy Assumptions. There are not many such applications of this new global framework perhaps because of the challenge of multidimensional complex changes and the scale thereof. Combining both expert-based and participatory methods, one multi-scale integrated hybrid scenario approach was applied in three deltas (i) the Volta delta (Ghana), (ii) the Mahanadi delta (India), and (iii) the Ganges-Brahmaputra-Meghna (GBM) delta (Bangladesh/India). Combined with three SSP-based socio-economic scenarios (SSP2, SSP3, SSP5) a climate scenario encompassing a wide range of impacts (RCP8.5) were generated. Minimum intervention, System efficiency enhancement, Economic capacity expansion, and System restructuring -these four-adaptation policies were considered. the importance of multi-scale (combined top-down and bottom-up) and participatory (joint expert-stakeholder) scenario methods for combating uncertainty in adaptation decision-making was established [33].

While the entire planet is under threat, the seriousness of the risk of climate change are certainly too dangerous to be disregarded. From the foregoing collection of information from randomly selected scientific papers published in last two decades, it is concluded that deep uncertainties remain in the research of climate change and the resultant sea level rise. From the chronology of emission scenarios considered in SRES to RCPs in AR5 and further upcoming transition to SSPs in AR6, along with the advent of CMIP6 and also the current scenario of fast melting of ice sheets at Antarctica and Greenland reaffirms the complexity and uncertainties. Climate Science being undoubtedly a very complex multidisciplinary subject, varying reports from different schools of thought of groups of scientists and their considered models has re-established the uncertainty to a great extent. It is hoped that some clue for newer research approaches may be obtained from AR6 of IPCC. Because of accelerated melting in Antarctica and Greenland, the following are of to be noted as matter of utmost concern:

- ‘There is nothing we can do to stop the oncoming effects of climate change’- (Rander et al., 2020) pessimistically opines;
- The disputes persist if only a few are useful whereas all models are wrong (Maher et al., 2020).
- There are ups and downs in control on gigatons of carbon dioxide -despite the axiom that climate change is number one threat to global population.
- Production of oil coal and gas must fall by 6% per year to keep global heating under target until 2030, as agreed in the Paris accord.
- But nations are planning for 2% production increases per year. G20 countries from coronavirus recovery are funding 50% more to fossil fuels than to clean energy.
- Fact remains that the world is doubling on fossil fuel- Great Barrier Coral Reef is deteriorating from World Heritage.
- Uncertainties in ocean circulation models, barotropic vorticity, escalating heat call for more finer precise research to arrive at an optimized adaptation strategy.
- Such unresolved uncertainties raise the question whether the research on sea level rise is going to take a new turn in the ensuing decade starting from 2021.

It is felt that the uncertainties and turns on research will predominantly be dependent on societal decisions i.e., on the sanctity of the scenarios which are going to take place.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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