Reconciling the Process-based Projection Method with the Semi-Empirical Method for Accurate Future Predictions of Sea Level Change

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Personal

Ever since I was little, my parents have constantly taken me to the Museum of Natural History in New York City. As soon as I rushed through the old wooden doors of the building, I rushed past the dinosaurs, down the stairs, and ran down the hallway to find myself standing in front of the gigantic blue whale. Marine creatures have always inspired me; they're always out of sight, yet so fascinating. Thus I've always struggled, trying to incorporate this fascination of mine into my school studies somehow. Unfortunately, marine biology was not an emphasis in my school's biology course.

One day, it hit me- literally. Hurricane Sandy had crashed into Long Island during fall of 2012. Despite the well-meaning efforts of scientists and the U.S. government, the hurricane had made unprecedented blows to coastal communities. I was stunned by how unprepared everyone was. Homes were destroyed due to flooding; power was gone for weeks. More importantly, livelihoods were ruined. The government had failed to predict the extent of the flooding- not due to any fault of the government or the scientists involved, but because of the extremely complex nature of sea level change. Just like the animals that inhabited the oceans, the sea itself was just as mysterious and fascinating to me. It could be so serene and calm, yet so destructive.

Thus I discovered the fascination of studying entire ecosystems. Biological environments are becoming more vulnerable to the effects of climate change, as the biology reaches the forefront of ecological issues. I want to solve environmental problems and help to protect natural resources and plant and animal wildlife. Humans aren't the only organisms living on this planet; we should be able to make sure everything else can survive the future as well.

1. Introduction

As a large component of climate change, sea level is an important aspect of the natural earth, yet there still exists significant gaps in understanding how sea level change functions (Meyssignac & Cazenave, 2012). Tides and oceans will cause future inundation and erosion along the coastline, and it is necessary to monitor the mechanisms of sea level change- not only for current day sea level, but for future sea level modeling as well. However, the field of sea level research consists of extremely disparate and complex disciplines, including glaciology, geodesy, and geology (Cronin 2012). Very few observations have verified predicted patterns or fingerprints of relative sea level (RSL) due to the intricate nature of sea level (Douglas, 2008). The extreme complexity of sea level research significantly limits scientists' abilities to accurately predict and account for future sea level change (Moore et al., 2013).

Rising sea level, in conjunction with climate change, has the potential to lead to significant societal disruption over the next century. With the global mean rate of increase in relative sea level (RSL) at 1.7 mm/yr, which is predicted to accelerate to 3.88 mm/yr over the last decade of the 21st century, can lead to destructive effects- not only the obvious harms such as flooding. In fact, saltwater intrusion is a large implication for contamination of sources of drinking water; irrigation is thus also potentially affected, with large amounts of farmland becoming useless as RSL increases (Hartig, Kolker, Mushacke, & Fallon, 2002; Rice, Hong, & Shen, 2012). Further understanding of RSL is therefore required for improved preparation and mitigation strategies for potential consequences of increased RSL (Shepard et al., 2012).

1.1 Approaches to predicting sea level change

The International Panel of Climate Change (IPCC) utilizes procedures known as process-based projections to predict sea level change. The mean sea level data from 1971-2010 is fitted to various models of climate change, which are based on thermal expansion of water and global surface air temperature (Cronin, 2012). The model has 7 different components: thermal expansion, glaciers, Greenland surface mass balance (SMB), Greenland ice sheet dynamics, Antarctic SMB, Antarctic ice sheet dynamics, and land water storage. For each component, an equation is used to model each process in terms of their contribution to future sea level as a function of greenhouse gas emissions (Church et al., 2013; Galassi & Spada, 2013).

The process-based projection method used by the IPCC has been noted as the standard for future RSL measure, but there are present limitations within its methodology. Most significantly, the process-based model fails when there is insufficient understanding of the processes involved. For instance, ice sheet dynamics is a poorly understood process, and scientists have been unable to create consistent and accurate equations to model ice sheet dynamics. The omission of rapid ice sheet dynamics contributions in the IPCC's 4th Assessment report highlights the lack of understanding of ice sheet dynamics, which led to the results' drastic underestimation of future RSL (Cronin, 2012).

There is trouble with the consistency and accuracy of models for ice sheet dynamics due to lack of knowledge for processes such as calving. Calving, the splitting off of ice from ice sheets, accounts the majority of ice mass loss from Antarctica and about 50% from Greenland. Calving is expected to be one of the significant contributions of the Antarctic ice sheet in the future, but it is poorly understood (Bamber & Riva, 2010). Specifically, there is no established model that incorporates complex processes such as calving and thus the equation used to model future RSL is lacking the information of important processes. Generally, the factors of Antarctic surface mass balance, Greenland ice sheet dynamics, and Antarctic ice sheet dynamics have been shown to have large uncertainties, and must be researched in order to improve future RSL projections (Moore et al., 2013).

Moreover, the most recent publication by the IPCC was published before a breakthrough study concerning the Antarctic ice sheet, indicating that a new model for RSL must be created. The IPCC was unable to incorporate new data that indicates faster acceleration of melting along the Western Antarctic Ice Sheet, and the inevitability of collapse in the distant future (Sutterley et al., 2014). In fact, current-day sea level change is only following the uppermost bounds of the prediction calculations from the IPCC report in 1990, thus highlighting the shortcomings in the process-based projections of the IPCC (Solomon et al., 2007).

In contrast, another model that was first brought up as a promising alternative to the process-based model is the semi-empirical model. Observations using sea level response to temperature changes in the past, future sea level change is predicted as a function of temperature. Elements of a semi-empirical approach could be much more effective in projecting sea level change. Semi-empirical approaches- when predicting sea level- have statistically been shown to lead to higher predictions than process-based projections. Thus it is likely that semi-empirical 3 approaches would have been much more accurate in predicting current-day sea level change compared to the 1990 IPCC report (which consistently underestimated the RSL rise by 10 cm per year; Solomon et al., 2007).

1.2 Use of the process-based projection model and the semi-empirical model

Though both the process-based model and the semi-empirical model have their own merits, they have never been used in conjunction with each other. By replacing the uncertain factors (such as Greenland and Antarctic melting and ice sheet dynamics) with data from the semi-empirical method, the strengths of the process-based model would still be preserved while negating the weaknesses. This has never been done before previously due to the nature of the semi-empirical model, which is not divided into parts like the process-based model (Geruo, Wahr, & Zhong, 2013). Since a semi-empirical model's use is limited to only the near future, it is suitable to make the assumption that the percentage of each factor compared to observed sea level would stay constant into the future. Thus adapting the semi-empirical projection values to the observed values for each factor (thermal expansion, glaciers, Greenland SMB, Antarctic SMB, Greenland ice sheet dynamics, Antarctic ice sheet dynamics, land water storage) would yield reliable and more accurate rates than the process-based models.

2. Purpose

The IPCC's process-based projections have shown clear limitations for determining future RSL, as they fail to take into consideration the inability to model key processes such as ice sheet dynamics and calving, which highlights the need for a more accurate and efficient method of projecting future RSL change. Predictions would be able to be created consistently and accurately with a better understanding of the 7 components involved in the IPPC's model (thermal expansion, glaciers, Greenland SMB, Antarctic SMB, Greenland ice sheet dynamics, Antarctic ice sheet dynamics, land water storage).

This study aims to rectify IPCC limitations for RSL predictions by 1) analyzing IPCC projections, and 2) establishing the combined process-based and semi-empirical approach as a reliable way to measure future predictions, as a proof of concept by showing this combined model is a more reliable predictor of current sea level change than the previous IPCC predictions. Since the process-based model is a sum of the underlying contributions to sea level, a more improved model can be created by identifying which elements of the process-based model are inaccurate and replacing the process-based data with semi-empirical data.

3. Methods

3.1 Process-Based Projections

3.1.1 Thermal Expansion

All process-based projections were based on the IPCC Assessment Report 5, Climate Change 2013 (Stocker et al., 2013). The methods were based on the IPPC's procedure to determine whether their process-based model was valid and accurate. Firstly, global mean sea level rise due to thermal expansion during the 21st century was calculated from a set of 21 CMIP5 Atmosphere-Ocean Global Circulation Models (AOGCMs). The systematic drift and error within the AOGCMS was removed by subtracting a polynomial fit as a function of time, which was able to control thermal expansion time series and prevent the data from being skewed. The resulting global mean temperature change values were then converted to thermal expansion using the expansion efficiency of heat appropriate to each AOGCM. The correlation between heat content change and thermal expansion is very high, so the relationship was treated as linear (Sun, Grandstaff, & Shagam, 1999).

3.1.2 Glaciers

Next the contributions of glaciers (mass loss in all regions excluding Greenland and Antarctica from 2006 onwards) were calculated. Calculation of the contributions of glacier icemass variations to RSL change involves two components: (1) a model for the mass variations and (2) a theory for calculating a solution for RSL that accounts for deformation of Earth dues to the redistributed mass load and that is gravitationally self-consistent. An approximate model for changes in the mass of glaciers was developed using spherical caps having mass rates and accelerations that matched published GIS mass rates and accelerations (Khan et al., 2010;

Svendsen et al., 2013; Sutterley et al., 2014). These studies used time-dependent global gravity fields from the NASA Gravity Recovery and Climate Experiment (GRACE) mission.

A parameterized scheme was fitted separately to results from each of the global glacier models as stated in Stocker et al., (2013), which were used to make projections using output from several AOGCMs (Brunnabend et al., 2012). It should be noted that glaciers' contribution denotes pure melt water as well as any resultant crustal deformation.

3.1.3 Greenland and Antarctic SMB

Then, the change in the Greenland surface mass balance (SMB) was calculated (Gornitz & Seeber, 1990). The change in Greenland ice sheet SMB, which excluded changes in ice sheet topography, was computed from Eq. 1,

$$\mathbf{G_e = -71.5T - 20.4T^2 - 2.8T^3} \qquad \text{(Eq.1)}$$

where G_e represents changes in the Greenland ice sheet, and T represents temperature. The ice sheet SMB change G(t) was integrated in time to obtain the change in ice sheet mass, starting in 2006.

The change in Antarctic ice sheet SMB was also calculated using Eq. 1. The SMB was assumed to be due solely to an increase in accumulation, which was estimated using the results of Gregory & Huybrechts (2006). The effect of increased accumulation on the dynamics of the Antarctic ice sheet was taken into, and mass balance changes were integrated in time to obtain the change in ice sheet mass, starting from 2006.

3.1.4 Ice Sheet Dynamics

To calculate the contributions for ice sheet dynamics (for both Greenland and Antarctica), contributions from rapid ice sheet dynamics at the start of the projections were taken to be half of the observed rate of loss for 2005-2010 from Greenland and all of the observed rate of loss from Antarctica, based on Peltier (2009). For each ice sheet, a quadratic function of time was fitted which begins at the minimal initial rate and reaches the minimum final amount. A constant 1.5mm was added to the contribution from the Greenland ice sheet and 2.5 mm to the contribution from the Antarctic ice sheet to account for past observational data that affected the ice sheets before 2005.

3.1.5 Land Water Storage

A similar method was used for the land water storage (referring to groundwater storage and aquifers) as the ice sheet dynamics (Stocker et al., 2013). The land water contributions were treated as uncorrelated with the magnitude of global warming (Carton, 2011), so land-water storage was assumed not to vary significantly with climate change.

3.2 Semi-Empirical Projections and the Combined Model

For the factors that showed significant differences from the observed data, semi-empirical projections replaced process-based data to form the combined model. As semi-empirical projections calculate projections for the entirety of sea level, they do not normally account for individual factors. As a result, for each factor (thermal expansion, glaciers, Greenland surface mass balance, Greenland ice sheet dynamics, Antarctic surface mass balance, Antarctic ice sheet dynamics, and land water storage), percentages were calculated compared to observed sea level. Each percentage was multiplied by the semi-empirical total as detailed in Rahmstorf (2007). An initial assumption was made that the percentage of each factor compared to observed sea level would stay constant into the future. The relationship was then modeled into the future projections, as outlined by Rahmstorf (2007; Bamber & Riva, 2010). Due to the underlying assumption of the semi-empirical model, the semi-empirical values are only valid for the near future, since the contributions to climate change are likely to vary in the future.

To create the combined model that reconciled process-based projections and semiempirical projections, the data for each factor in the process-based model (thermal expansion, glaciers, Greenland SMB, Antarctic SMB, Greenland ice sheet dynamics, Antarctic ice sheet dynamics, land water storage) was compared to its observational counterpart for the period 2007- 2015. A student t-test was performed to determine whether each factor was significantly different from the observed data for that factor. A p-value of less than 0.05 was considered to be significant. If the predicted data was significantly different from the observed, then the data was replaced with the semi-empirical counterpart.

4. Results/Discussion

4.1 Evaluating the IPCC's Projections

Table 1. Rates of RSL change and temperature change for each of the IPCC's scenarios and observed values. The SRESA-1B scenario was most similar to observed.

	Observed	SRESA-1B	RCP-26	RCP-45	RCP-60	RCP-85
RSL	0.00362	**0.00366**	0.00390	0.00384	0.00377	0.00382
Temperature	0.0095	**0.02207**	0.03468	0.02874	0.02874	0.02625

The first aim of this study was to analyze the IPCC's extent of knowledge about RSL from their 5th Assessment Report. The IPCC's results were divided into 5 different scenarios: SRES-1B, RCP-26, RCP-45, RCP-60, and RCP-85 (Stocker et al., 2013). The scenarios all describe different conditions of anthropogenic forcing of global warming (Solomon et al., 2007). During the brief period of 2007-2015 (the time period in which the future projections and observed sea level coincide), the SRESA-1B scenario's future projections were found to be closest to observed sea level values. The observed rate was 0.362 cm/yr, with the SRESA-1B having a rate of 0.366 cm/yr (Table 1). Of the 5 scenarios, SRES-1B is the most moderate in terms of describing future global warming because no drastic acceleration in climate change is noted, but the scenario also describes no large efforts to ameliorate the effects of climate change (Sallenger et al., 2012). The other scenarios all deviate from the observed values by about 0.02 cm/yr. However, the degree of error of the IPCC has been drastically reduced between the 4th and the 5th report, indicating that the understanding of sea level change has been greatly 7 advanced (Sella et al., 2007). Further, the range of predictions has narrowed considerably since the First Assessment Report by the IPCC (Fig. 1). The similarity of the observed to the predicted results indicate that, currently sea level change is progressing mostly as expected, since the SRESA-1B scenario has been the most accurate scenario since the 3rd IPCC report (Tsimplis, Spada, & Flemming, 2011). Ultimately the IPCC's sea level projections for the 5th Assessment Report have been very accurate for the SRESA-1B scenario, aside from a few deviations.

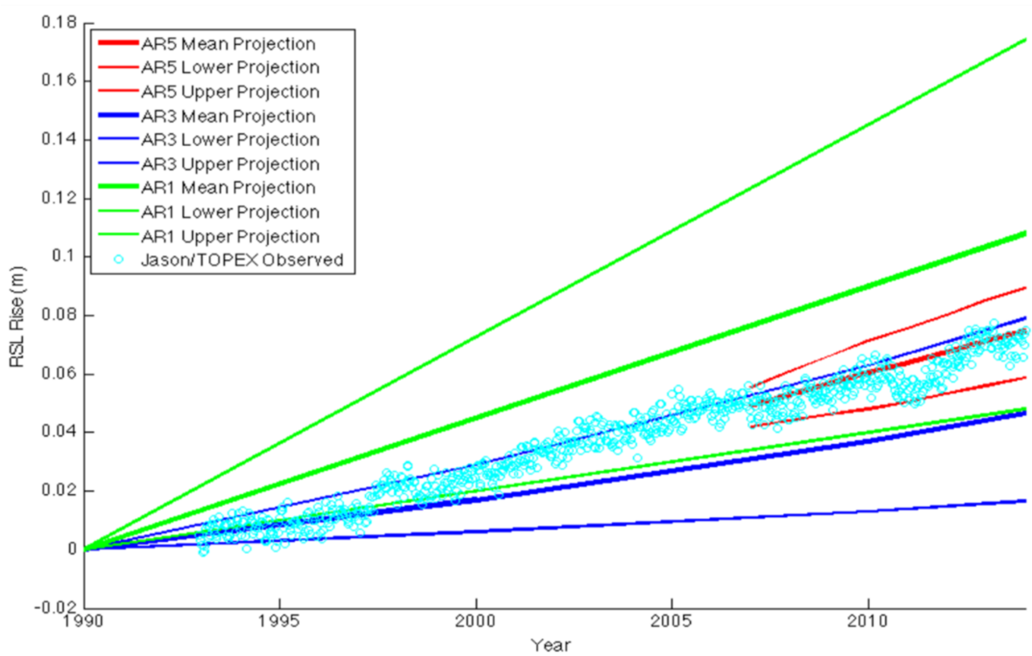

Fig. 1 Comparison of observed sea level to IPCC predictions from 1990-2015, for the 1st Assessment Report (1990), 3rd Assessment Report (1995), and the 5th Assessment Report (2013). Note the 5th Assessment Report predictions, which are narrower in scope and more accurate than the previous two reports

A few important limitations can be identified with the IPCC predictions. Firstly, there is a slight, but consistent, systematic error with the IPCC's predictions by about 0.5 cm every year.

The IPCC values consistently overestimate the value of sea level (Table 1; Fig. 1). The overestimation contrasts with the past IPCC's reports, in which they consistently underestimated the effects of sea level change (Fig. 2). Though the error may appear small, the yearly error is about 1.5 times the rate of projected sea level rise. Further, it is important to note the systematic error present in the projections, shown by the residuals. The majority of the values being under the x-axis indicates that necessary improvements must be made possible by using elements of the semi-empirical model; systematic error indicates that the IPCC's errors are not due to deviations in data, but instead errors within the methods (Fig. 2). The errors are due to the individual components of the process-based projection model, such as inaccuracies within the ice sheet dynamics model portion. Table 1 Rates of RSL change and temperature change for each of the IPCC's scenarios and observed values. The SRESA-1B scenario was most similar to observed.

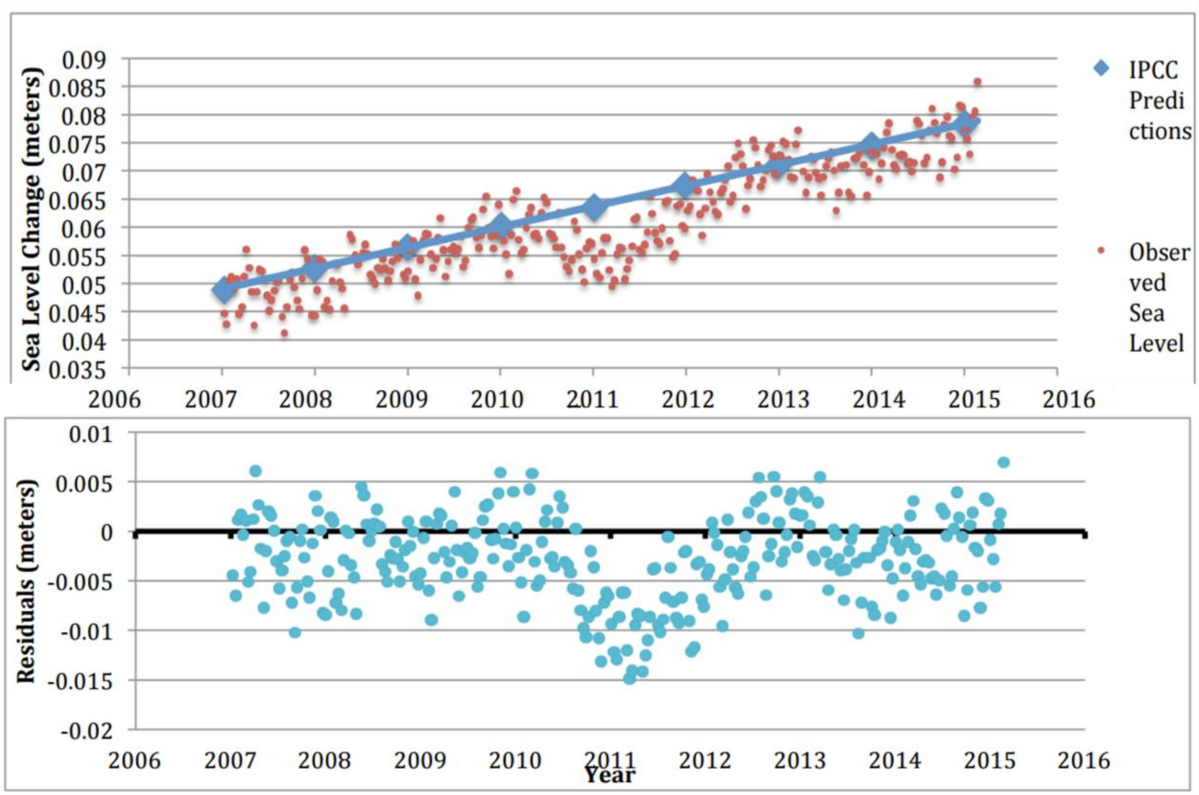

Fig. 2 Comparison of observed sea level to IPCC predictions from 2007-2015, for the 5th Assessment Report, with residuals. Note the consistent overestimation of IPCC predictions compared to the observed RSL values

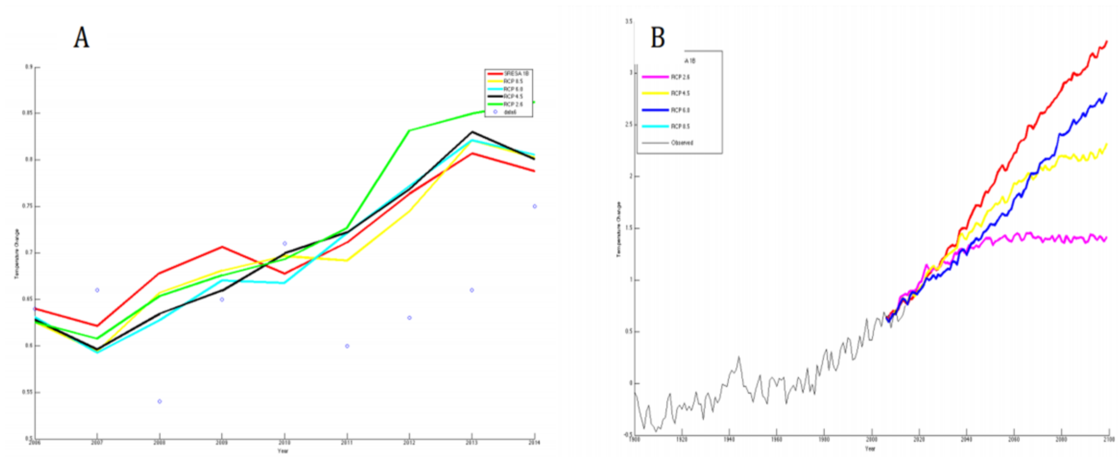

Fig. 3 Observed temperature compared to different temperature projections made by the IPCC for 2007-2015, for RCP scenarios 2.6, 4.5, 6.0 ,8.5 and SRESA-1B. (A) Values for the period 2007-2014. (B) Values for the period 1900-2100

In order to elucidate which elements of the process-based projection model are inaccurate, the IPCC's temperature projections were examined, since temperature directly correlates to effects of climate change. For the period of 2007-2015, once again the SRES-1B scenario showed the most accurate temperature rate, compared to the observed (Table 2; $p>0.05$). Though the difference was not significant between the observed data and SRESA-1B predictions, the SRESA-1B's values were over twice the value of the observed temperature rate, indicating some concern for the inaccuracy of the IPCC's predictions (Fig. 3). The same was true for each other set of temperature projections. Since the process-based elements are all based on the temperature projections, the root of the IPCC's deviations within their predictions lie with the inaccurate temperature projections.

To find the exact cause of deviation within the IPCC's process-based projection, the individual factors and components were analyzed. The 7 factors: thermal expansion, glaciers, Greenland surface mass balance (SMB), Antarctic SMB, Greenland ice sheet dynamics, Antarctic ice sheet dynamics, and land-water storage were examined in particular. Of the 7 different factors, only 3 were found to have insignificant differences compared to observed: thermal expansion, Greenland ice sheet dynamics, and land-water storage a (Fig. 4; $p>0.05$). The other factors had significant differences, and were determined to be the cause of the error within the IPCC's process-based projection model.

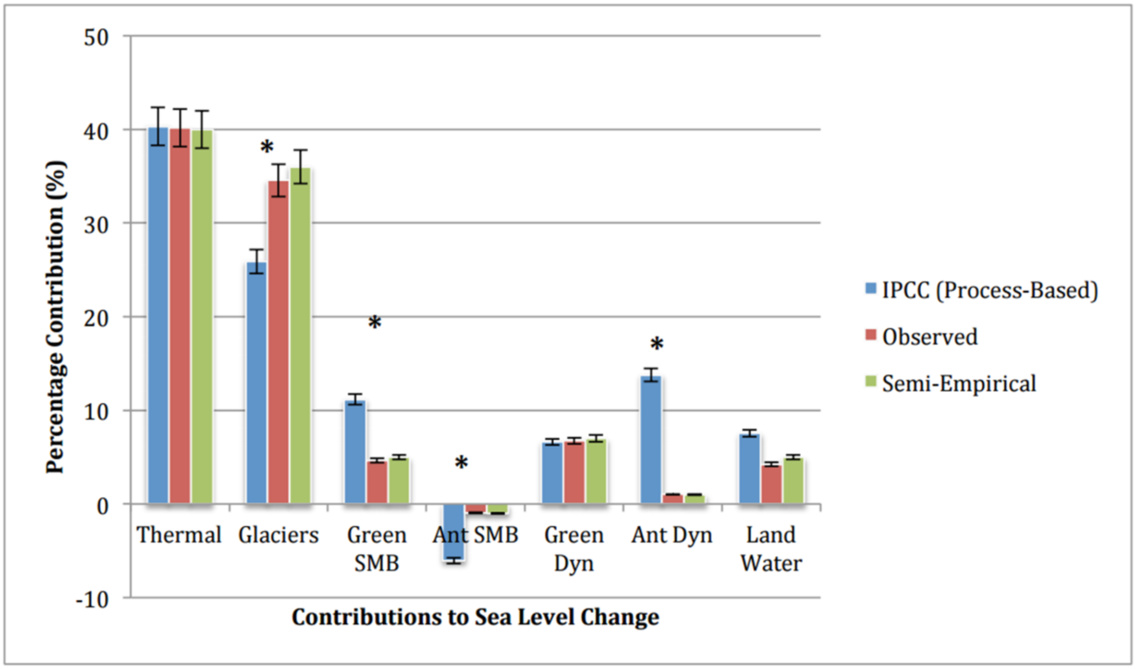

Fig. 4 Comparison of percentage contributions of factors affecting sea level. Note the deviations for glaciers, Greenland SMB< Antarctic SMB< Antarctic ice sheet dynamics. *P<0.05 indicates significance between process-based and observed

Contrary to initial assumptions based on literature, ice mass loss factors were incorrect within the IPCC's process-based model. Specifically, Glaciers, and Greenland SMB were expected to be relatively accurate, due to the large number of studies creating equations to model ice melt and resulting sea level rise. A possible cause for the error within Greenland SMB may lie within a significantly increasing acceleration in ice loss along the western edge of the ice sheet (Velicogna et al., 2007). The inaccuracy within the Antarctic SMB was expected, since the IPCC 5th Assessment Report was published before the breakthrough study that detailed accelerated loss on the West Antarctic Ice Sheet (Sutterley et al., 2014). The lack of understanding for Antarctic ice sheet dynamics was justifiable, due to the lack of knowledge and consistent equations that model processes such as calving and ice shelf melt. However, the inaccuracies within the individual components in the model highlight a lack of understanding or misconception of how to model these processes, necessitating future investigation.

Both the inconsistencies in the IPCC's temperature predictions as well as the individual components in the process-based projection model suggest that the IPCC is not accurate for the right reasons (Cronin, 2012). Even though the systematic error is slight, and the projected rate of observed sea level is very close to the observed rate, the parameters used in the model are not accurate (Fig 4; Fig 5; Lombard et al., 2005). Specifically, the inaccuracy of the temperature projections, which influence all the other components in the model, means that the IPCC is only accurate in their projections through chance, not through valid data (Leatherman, Zhang, & Douglas, 2000).

Thus the inaccurate factor data was replaced by the respective semi-empirical counterpart. For Glaciers, Greenland SMB, Antarctic SMB, and Antarctic ice sheet dynamics, The semi-empirical model showed much greater accuracy for the factors that the process-based model was inaccurate for ($p<0.05$)

The accuracy of the combined model was then determined. When the semi-empirical model is applied to form the combined model, the combined model shows a better following of the trend of observed sea level. By replacing Greenland SMB, Antarctic SMB, Antarctic ice sheet dynamics, and Glaciers, the process-based model's limitations were negated. For instance, it follows the minute variations that are exhibited by RSL, as it relies on past empirical data and is thus much more accurate ($p<0.05$).The IPCC's process-based fails to capture slight variations that are present within RSL changes. Furthermore, there is no systematical error present in the combined model. There is neither consistent underestimation nor consistent overestimation, indicating that the combined model is a more accurate representation of future RSL than the

IPCC's process-based projection model (Fig. 5; Siddall & Milne, 2012; Peltier, 1996). It is important to note that the residuals for the combined model show a more evenly distributed trend across the x-axis.

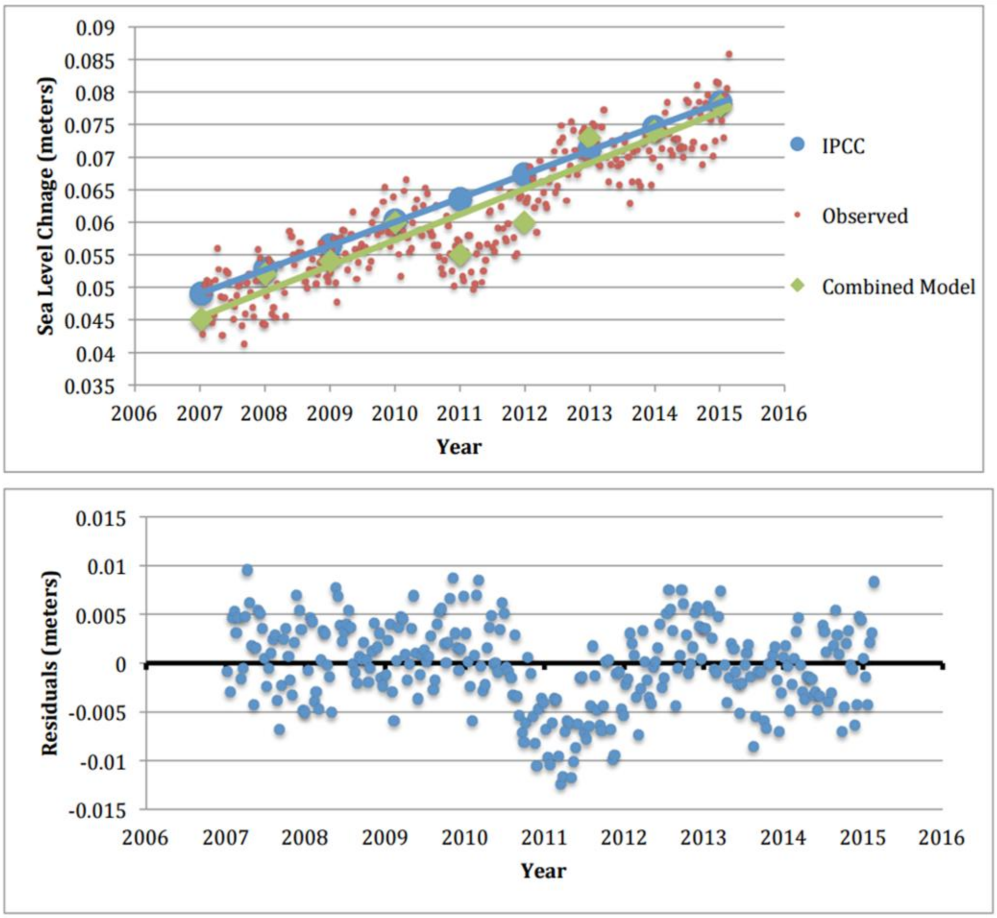

Fig. 5 Comparison of IPCC projections, new combined model projections, and observed sea level, with residuals of the combined model. Combined model follows variation closely of the observed values, and shows no systematic error

In contrast to the IPCC's model, the combined model is not only accurate, but it is also accurate within its individual components. When each of the 7 factors is compared to the observed data, the percent contributions add up much more accurately, specifically for the glacial melting and ice sheet dynamics factors. If the combined model were to be extended into the future, it could be a more accurate indicator of future climate change, allowing scientists a greater understanding of global warming's effects (Kolker & Hameed, 2007).

5. Conclusion

This study has clarified that there exist many limitations within the IPCC's method of predicting RSL changes; namely the limitations within current understanding of sea level prevent the models from being wholly accurate, especially concerning ice sheet dynamics and calving processes. The data confirms that there are large gaps in understanding of glaciers and ice sheets by today's top scientists (Grinsted, 2010). Identifying the incorrect elements in the IPCC's model will allow a clear understanding of how to improve current models.

A model that combines empirical and process-based data as a superior model for predicting sea level change was established. It is an alternative to the frequent process-based models that are used by most scientists today (Houston & Dean, 2011), and it confirms that the semi-empirical model is a completely viable option for predicting sea level to researchers, if combined with the semi empirical model with the process-based model within the next 100 years (Lopes dos Santos et al., 2010; Mitrovica et al., 2001). It is significant to note that the accuracy of this model highlights clear conceptual inaccuracies for the processes contributing to sea level. It also emphasizes that governmental procedures (and thus lack of government preparation for flooding and consequences of sea level change) that have to be established to be better prepared for more accurate predictions. The combined model's predictions of RSL can be used by 13 agencies and governments to create accurate short term predictions of sea level and be better prepared for consequences such as flooding.

However, one limitation of the combined model is that the combined model is only a short term solution. In theory, the process-based model would be a more accurate long-term predictor of RSL change, since it does not have to rely on past empirical data (Moore et al., 2013). Though the semi-empirical model has been shown to be accurate, it is possible that past empirical data will not be able to predict RSL in the future. As a result, future investigations necessitate the investigation into the processes that impede the creation of more accurate process-based models. Specifically, calving is a process that should be aimed to be modeled, as it will be a major contributor to RSL in the future (Orlic & Pasaric, 2013). In general, the field of ice sheet dynamics is not well understood, and models should be created to map out the contributions from ice sheets, specifically for Greenland and Antarctic SMB, Antarctic ice sheet dynamics, and glaciers.

In addition to improving process-based models, future investigations should aim to create regionalized models that predict future RSL. Currently, most models are global ones that yield global averages of RSL. However, since RSL is unique for every region due to the different processes that affect different locations, a regional model for predicting sea level change should also be created (Ponte, 2006; Winkelmann et al., 2012) For certain locations it is necessary to consider their unique factors (such as plate tectonics for Japan or California). Current real-time regional models, such as Estimating the Circulation & Climate of the Ocean (ECCO), may provide useful insight into how to predict sea level for the future in different locations.

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