Modeling Landscape Evolution of the Tweed Caldera Drainage Basin Under Different Climatic Scenarios Through the 26th Century

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Abstract

As anthropogenic forcing continues to rapidly change worldwide climate, consequential landscape impacts will continue to coincide. In this study, a landscape evolution model called Badllands (BAsin anD LANscape DynamicS) is utilized to project if and how the landscape of the Tweed Caldera catchment, in Eastern Australia, dynamically reacts to shifts in the local climate. Different climatic scenarios were modeled over the next five centuries. In order to model practical scenarios, local climate projections were taken from the Australian government and the IPCC in the form of four representative concentration pathways (2.6, 4.5, 6.0 & 8.5). Another three scenarios were run for the purpose of observing the landscape impacts of ice sheet tipping points being hit, specifically in the Antarctic Ice Sheet. Three final scenarios were run with sea levels held constant and increased precipitation rates in order to better understand the role that both precipitation and sea level play in impacting landscapes on a drainage basin scale. Model results show that changes within the local climate do subsequently impact the Tweed Caldera basin's dynamics and landscape. Basin impacts included heavy caldera erosion, significant amounts of inland/marine deposition, river avulsions, infill of inland bodies of water, inundation of ocean water, retreat of shorelines, progradation of shorelines at river mouths, delta formation, and flooding of upstream areas. All of these impacts varied (sometimes significantly) between scenarios and were highly dependent upon the rate and magnitude of climatic changes, mainly rates of sea level rise. This study, and others like it, can help bolster the understanding of regional impacts from climate change. This knowledge can help with the overall mitigation and/or prevention of these adverse impacts that are sure to be seen in the future as our climate continues to change.

Preface

This thesis started as an independent study at the University of Sydney with the Earthbyte geoscience research team, whom were kind enough to host me at their university and help me through the difficult beginning stages of this project. I chose to do this research because of my interest in studying climate change (the defining issue of our time) and its impacts. It is my belief that such scientific inquiry into global climate change and the consequences is an integral part of the mitigation and prevention of these impacts. This project would not have been possible without the Earthbyte team, Dietmar Muller, Tristan Salles, my advisors: Jen Kay, Jai Syvitski and Dale Miller as well as my supportive family and friends.

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Introduction

Greenhouse gases have been observed as rapidly increasing in the past century and will almost certainly continue to do so into the foreseeable future; in turn, significantly impacting the global climate (IPCC, 2001). Shifts in climate have impacts on landscapes, which are often perceived to be solely from sea levels either causing a retreat in shorelines due to an influx of ocean waters or a new shoreline to be exposed due to a decrease in sea levels. This ignores the highly complex, inland impacts that occur on a drainage basin and continental scale, heavily due to climatic forcing inflicted changes to erosion, transport, and sedimentation patterns.

In order to properly mitigate and adapt to future climate change induced hazards, a more in depth understanding of geomorphic processes and responses to climate change on differing spatial and temporal scales is essential (Pelletier et al., 2015). Because these impacts will greatly vary throughout the globe, it is imperative to better understand the effects regionally. One method used to do this, is studying impacts incurred by entire drainage basins. However, one significant problem that arises when using this method is, because catchments are dynamically unique, impacts from a changing climate can greatly vary from basin to basin and cannot be realistically generalized. In order to practically project these impacts, basins will need to be modeled individually. This study uses the Tweed Caldera drainage basin, in Eastern Australia, to model how the basin hypothetically could geomorphically react to different climates over the next 5 centuries.

According to Reisinger et al. in the IPCC's Australasia section of Assessment Report 5 (AR5), there is very high confidence that Australia's regional climate is changing and shows long term trends towards higher surface, air, and sea surface temperatures, more heat extremes, less cold extremes, and changed rainfall patterns (2014). Arguably, one of the most concerning and understated consequences of shifts in climae like these are the hydromorphic and geomorphic responses due to fluctuations in sedimentation patterns, which will be a main point of investigation in this project.

Towards the end of this century, coastal areas like the region being studied, are likely to start being more affected by factors other than thermal expansion of sea water; for example, loss of land-ice mass and shifts in the frequency and magnitude of sea level extremes (Church et al., 2013). In order to try and understand in what ways and who might be affected by variations in sea level, precipitation patterns, and landscapes we rely on model projections. Models are used to form predictions that can give us a better understanding of impacts from and vulnerabilities to the changing climate, but are not trusted as accurate predictions. This project in particular will use a landscape evolution model (LEM) called Badlands (acronym for Basin and Landscape Dynamics), in order to create a greater understanding of if and how, climate change impacts the evolution of drainage basins, specifically the Tweed Caldera basin. The goals of this paper are to:

1. Explain the process of modeling landscape evolution using the Badlands Landscape Evolution Model.
2. Project, analyze, and explain the evolution of the Tweed Caldera drainage basin under different projected climatic scenarios, as modeled in the Badlands LEM.
3. Assess the differences in landscape impact under different future climatic scenarios.

4. Investigate the importance of climatic factors, mainly precipitation and sea level, on the geomorphic evolution of drainage basins.
5. Discuss the results and the hypothetical implications.

Literature Review

Global Sea Level Rise

Past data on SLR, collected by measuring changes in long tide gauge records (Wöppelmann et al., 2009), shows a rise of 17cm in the global sea level throughout the 20th century (Nichols, 2011). The magnitude of this rise is projected and currently showing an increase, meaning sea levels will rise at a faster rate than suggested by analysis of previous data (Nichols, 2011). In 2007, the IPCC published their fourth assessment report (AR4), stating that the increasing sea levels are most likely due to human induced atmospheric warming. In 2013, the most recent IPCC report (AR5) stated that there is very high confidence global mean sea level rise has accelerated since the 1900's (Church et al., 2013).

Because predictions on future climate are complicated and uncertain, projections are split into multiple possible scenarios. These scenarios do not predict exact changes to climate and other variables (Moss et al., 2010; Van Vuuren et al., 2011), but instead show a statistical range for the predicted changes in these variables. The most noteworthy and innovative sea level model scenarios to date are derived from the Representative Concentration Pathways (RCPs), which were developed by scientists for the IPCC's AR5. These pathways consist of four scenarios that run from 2000 to 2100 (Collins et al., 2014). In all scenarios, the rise in the average global sea level is ~45% due to thermal expansion, ~45% due to land ice melting and the remaining 10% due to other factors caused by continually increasing emissions. Although projections of global sea level rise are extremely complicated due to uncertainties about thermal expansion and ice loss (Titus and Narayanan, 1995), scientists still have high confidence that sea levels will raise a minimum of 0.2 m and no more than 2.0 m by 2100 (Parris et al., 2012). Furthermore, according to Church et al., short-term regional sea level variations will most likely be due to dynamic changes caused by natural variability, with the possibility of a greater magnitude of impact in areas near rapidly melting ice sheets (2013).

Australia's Geologic Past

Throughout the Quaternary Period (past ~2.5 million years), Australia's coastline has significantly shifted due to changing climatic and oceanic patterns. According to the Australian Department of Climate Change, the variation from glacial to interglacial periods have been the main drivers in sea level fluctuations and subsequent landscape impacts due to the changes in ocean currents and temperature, atmospheric pressure, land ice mass, and sedimentation patterns (2009). The governmental organization also states that regional sea levels reached their current relatively stable levels (± 2 m) around the beginning of the current Holocene interglacial warm period (~6500 years ago). Previously, Australian sea levels had been about 120-140 meters lower during the last glacial maximum (~20,000 years ago) and 4-6 meters higher during the last interglacial period (~120,000-130,000 years ago) (Australia Department of Climate Change*,* 2009). During these periods the Australian landscape would have been extremely different with large amount of the continental shelf being exposed during the glacial maximum and seas reaching significant distances inland during the last interglacial period. With a current rate of warming that dwarfs that of anything seen within the interglacial cycles over the past ~1 million years (Solomon et al., 2007), the consequential effects on landscapes are relatively unknown. It is extremely important that attempts be made to better understand plausible landscape responses under relatively unprecedented warming scenarios.

Past Climatic Influence on Landscapes

Studies of the stratigraphic record globally have shown evidence of changes in the landscapes of drainage basins in response to shifting climatic conditions. Changing climates cause variations in temperature/aridity, extreme weather events and precipitation, which are all well known drivers of geomorphic, hydromorphic and biologic change (Figure 1) (Phillips, 2010; Wobus et al., 2010). These direct effects may be reinforced and or mediated via other indirect and interrelated processes such as rates of erosion and sedimentation, magnitude of discharge, vegetation, and sea level impacts (Phillips, 2010; Wobus et al., 2010). Changes to the dynamics of basins consequently trigger responses within the affected landscapes. Rivers and tributaries aggrade, avulse and incise into new areas, effectively carving into the landscape (Gregory and Chase, 1994; Smith 1994; Phillips 2010; Wobus et al. 2010). Deltas can prograde and subsequently form estuaries or an embayment at the mouth of rivers (Muto and Steele, 1992; Phillips, 2010). Relief and elevation of an entire region can drastically change (Van Geel and Waterbolk, 1996; Phillips, 2010). Coastlines can prograde causing marine regression, or the opposite may happen resulting in marine transgression (Quattrocchio et al., 2008). Infill may occur in riverine and/or lacustrine environments (Vandenberghe, 1993). All of these impacts from a changing climate are extremely sensitive, heavily reliant upon one another and will have their own subsequent consequences, including significant impacts on ecosystems and human societies.

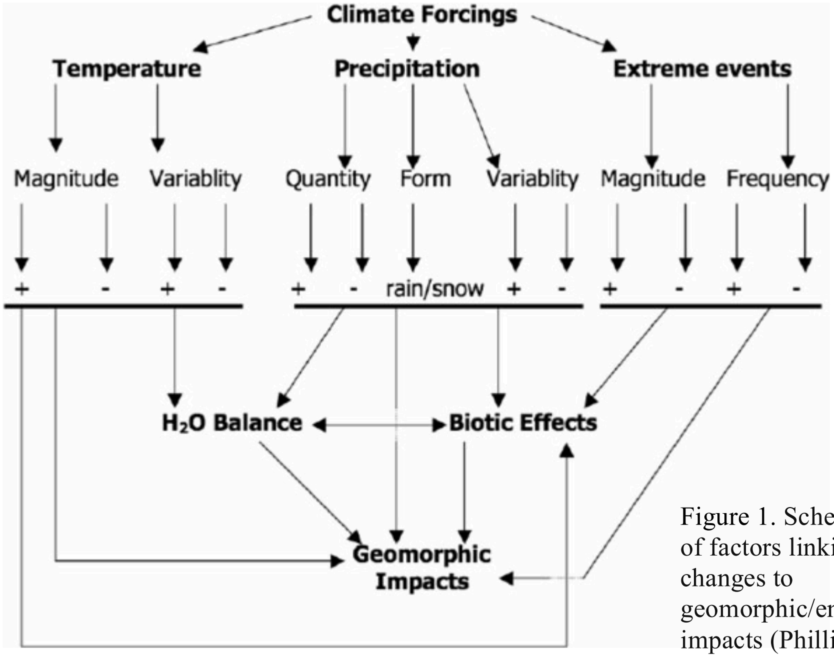

Figure 1. Schematic view of factors linking climate changes to geomorphic/environmental impacts (Phillips 2010).

Australian Sea Level Rise

The risks from rising sea levels in Australia are particularly alarming due to the fact that around 50% of Australia's addresses and population are located within 7 km of the coastline (Chen and McAneney, 2006). According to White et al. (2014), the trends of past and current sea level rise on the Australian coast are strongly correlated with the global mean sea level rise. Removing ENSO-related sea level changes, the annual mean regional sea level rise from 1966-2010 was 1.6 mm/a (± 0.5 mm) and from 1990-2010 was 2.2 mm/a (±0.5 mm). These changes, which are largest in the north and west, are mainly due to ocean variability, but also can be attributed to vertical land movements and changes in atmospheric pressure (White et al., 2014). Since most Australian sea level rise will be due to variation in the oceans, the regional ocean dynamics and contributors must be assessed. One system that has huge impacts on the ocean surrounding Australia is the Antarctic Circumpolar Current, which is predicted to shift southward due to an intensification in the velocity of the circulation, leading to higher sea level anomalies in the northern region of the circulation and lower in the southern (Wang and Cai, 2013). Another regionally important factor is the south pacific subtropical gyre, which when modeled using CMIP3, was projected to strengthen and subsequently intensify sea level rise in southeastern Australia (Zhang et al., 2013). With these factors in mind McInnes et al. looked at the projected regional sea level changes of 14 different locations around Australia's coast, analyzing data from multiple climate models. The results (Figure 2) showed an increase in the rate from global mean sea level values of 3.0 mm per year. For RCP 8.5 regional sea level rise reached 12 mm per year by 2100 at every location. For RCP 6.0 the rate stabilizes at about 7-8 mm per year in 2090 and stabilizes for RCP 4.5 at around 6 mm per year at 2060. Finally for RCP 2.6, accounting for heavy mitigation, the rate of SLR stabilizes much earlier than the other scenarios at 4 mm per year (McInnes et al., 2015). Past 2100, Global and Australian mean sea level rise is very difficult to predict and model, as it is entirely uncertain which RCP scenario will most closely reflect the climatic conditions that prevail this far into the future. Another reason there is great uncertainty of sea level rise past 2100 is because long term future sea level rise is extremely dependent on loss of mass from both the Greenland and West Antarctic Ice Sheets. This loss in land ice mass would mainly be due to atmospheric warming, which is estimated to range between 1 and 4°C (Church et al., 2013). The surface mass balance observations and projections are still uncertain and widely vary between different studies, but as technologies and resolution improves, these observations and projections will become more precise and realistic. According to an Australian government report on coastal vulnerabilities to climate change, there is a lack in research on climate change's impact on estuaries due to coastal flooding (Australia Department of Climate Change, 2009). The importance of estuaries to biodiversity, the fishing industry, tourism, human uses (ex. ports), coastal protection and more is well known (Glamore et al., 2016); therefore better understanding these impacts is essential. The Tweed Caldera basin contains multiple estuarine environments and the modeled impacts to these areas will be investigated in this study.

One of the main reasons sea level rise is of great concern is the consequential increase in frequency and magnitude of extreme weather events. Based on data from 29 Australian locations with reliable tidal records, extreme tidal events that previously happened every few years would be likely to occur every few days with a rise of just 0.5m (Antarctic Climate & Ecosystems Cooperative Research Centre, 2008). Another extreme event that has previously and will continue to affect the Australian region are tropical cyclones. Due to changing characteristics of tropical cyclones because of climatic changes (strong winds, low atmospheric pressures, high water vapor content) the risk of storm surge hazard has the potential to increase (McInnes et al., 2003). The Tweed Caldera drainage basin is especially vulnerable to tropical cyclones due to the massive floodplain that cuts through the center of the basin. These indirect consequences of SLR are not taken into account by Badlands, but should be kept in mind for future studies.

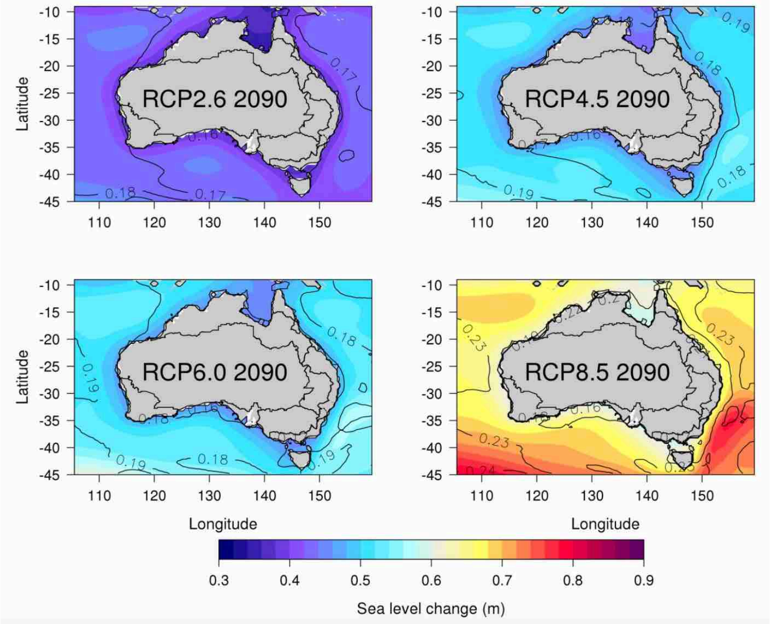

Figure 2. Predicted regional sea level changes (four emissions scenarios) for 2090 compared to 1986 to 2005. (McInnes et al. 2015)

Representative Concentration Pathways

Representative Concentration Pathways (RCP) are a set of standard scenarios mainly utilized by the scientific community to attempt to project future climatic conditions and their plausible consequential impacts. The scenarios take into account multiple conditions, such as greenhouse gas emissions, developments in technology, changes in energy generation and land use, global and regional economic circumstances and population growth (Van Vuuren et al., 2011). The RCPs were used in this study to simulate how reasonable future climatic scenarios could impact regional dynamics. There are four main pathways, each of which was developed by an Integrated Assessment Modeling (AIM) group. The number after each RCP represents the radiative forcing of each scenario, by the year 2100. RCP 2.6 is the “mitigation scenario” in which the goal is to keep global mean temperature below 2 °C and reduce greenhouse gas emissions, from 2010-2100, by 70% compared to a baseline scenario. RCP 4.5 is a stabilizing scenario in which radiative forcing is stabilized at 4.5 W m^{-2} and CO_2 concentration is stabilized at approximately 650 ppm by 2100. RCP 6.0 is another stabilizing scenario in which radiative forcing is stabilized at 6 W m^{-2} just after the year 2100 without overshoot. The last concentration pathway is RCP 8.5 or the business as usual scenario, which assumes the same increasing rate of population growth, a slower increase in income, modest rates of improvement in efficiency within the energy sector, modest rates of technological innovation and a lack of climate change policies; all contributing to a large worldwide demand for energy and significant amounts of greenhouse gas emissions (Riahi et al., 2011). RCP 8.5 is the pathway with the highest concentration of greenhouse gases and has the greatest climatic influence.

Precipitation

Another climatic factor that will significantly impact landscapes is changing annual precipitation patterns. With the current observable changes in climate, there is and will continue to be a resulting annual precipitation change in which the dry areas will get drier and the wet areas wetter (Trenberth, 2011). The mean annual precipitation for Australia, over the period of 1961-1990, was 648.3 mm per year. Over the 20th century, average rainfall in Australia increased slightly with a higher magnitude in the summer season (Collins & Della Marta, 1999) and regionally has been increasing in Eastern, Northern and Southern Australia (Hughes, 2003). The average for New South Wales in 2016 was 657.98 mm (Australian Government Bureau of Meteorology), but that region spans a massive area with significantly varying climates. Precipitation projections are particularly difficult in Australia because natural variability plays such a significant role. This is mainly due to El Nino Southern Oscillation (ENSO) being an important factor for the country’s precipitation and overall climate (Risbey et al., 2009), but is also due to other climatically influential factors such as the southern annular mode, the inter-decadal Pacific Oscillation, and the Indian Ocean dipole (Thompson and Wallace, 2000; Cai et al., 2009; Salinger et al., 2001). As stated in the IPCC’s AR5, precipitation averages observed from the Coupled Model Intercomparison Project Phase 5 (CMIP5), show with very high confidence, a decline in precipitation in southeastern Australia since the 1990’s (Reisinger et al., 2014), mainly due to the large drought that occurred there from 1996-2010, but was eventually pulled out by a La Nina. This clearly demonstrates the extreme control natural variability has on Australia’s climate and is the reason projections for precipitation in eastern Australia remain a large uncertainty (Reisinger et al., 2014). CMIP5 resulted in a projected -5% (± 22%) annual rainfall change in southeast Queensland from 1990 to 2090 (Irving et al., 2012). While average rainfall is predicted to have no significant change for the Eastern region of Australia through the 21st century, the intensity and frequency of extreme rainfall events are projected to increase with temperature. The Queensland Government released a study that predicted a 5% increase in rainfall intensity per °C of mean temperature gain (Queensland Government, 2010). Moreover, the region being modeled has an average rainfall of ~1611mm per year (baseline average from 1972-2017), approximately 1000 mm more than the average for New South Wales. This relatively high amount of precipitation is predicted to increase as wet areas are projected to get wetter.

Erosion and Deposition

A significant consequence of variations in sea levels and precipitation rates are the changes in erosional/depositional patterns, causing subsequent geomorphic and hydromorphic responses. These variations and their impact on landscapes are one of the main processes being studied in this project. According to a risk assessment done by the Australian Government's Department of Climate Change, the ability of natural processes to continue supplying sediments to the beach will eventually be overtaken by rising sea levels and an increase in high water level events, ultimately resulting in coastal recession (2009). The amount of such recession can be measured using the Bruun Rule, which says that shoreline recession due to sea level variation, directly relates to the slope of the shoreface and can occur at a rate of up to 100 times the amount of sea level rise (Nicholls and Stive, 2004).

The recession of coastlines has and will continue to have significant consequences for humans, as ~37% of the world's population lives in coastal areas (Segal, 1997). Coastal recession will also be accentuated by changing patterns of seabed erosion and sedimentation. The rate of recession is due to a mixture of the rate of sea level change, the shoreface profile, the height of the dune or friable cliff, and local sediment sources like estuaries or rivers (Australia Department of Climate Change, 2009). When picking an area to model, it was important to find a coastal makeup that will be impacted by these factors in order to more effectively attribute variations in climate to environmental changes. In this way, the results may show how coastal areas most vulnerable to erosion could be impacted over the next century and further. The most vulnerable coastal areas are made up of "unconsolidated sediments, such as beaches, dunes, and sand cliffs on the open coast of leaky embayments and on the shores of coastal lakes and lagoons" as well as soft sedimentary and weathered cliffs, especially cliffs made of calcarenite, which will erode more quickly as the face is more exposed to wave action (Australia Department of Climate Change, 2009). Unfortunately, the Badlands landscape evolution model does not account for wave action erosion, but these forces are still important to keep in mind.

Changes in sedimentation are being modeled throughout the Tweed Caldera catchment. Catchments are an entire landscape that is defined by the area in which all runoff water flows to and from that specific region. Drainage within basins is integral to everything within the area. Variations in one part of a catchment will almost certainly impact everything else within that catchment (https://www.ehp.qld.gov.au/water/catchmentcare.html). The erosion of rock that occurs within basins is transported as sediment downstream, where it will eventually deposit either in the main riverbed, into a lacustrine environment or into the ocean; all in which a change in sediment flux can have consequences within the local ecosystems and societies. These variations can affect coastal estuaries, coral reefs, sea grass ecosystems, and coastal fisheries (Syvitski et al., 2005). Additionally, according to Wetzel, too much sediment suspended in the water column can affect natural migrations of aquatic life and directly damage gills, as well as other organs (2001). Wetzel also states that increased fluxes of sediment will increase turbidity, subsequently creating a rise in water temperature, blocking sunlight, and decreasing oxygen levels (2001). High levels of deposition can cause alterations in a waterway's banks and direction as the sediment deposits within the waterway and the riverbeds aggrade (Zaimes and Emmanuel, 2006). Due to the relatively large amount of waterways (natural and manmade) within the

Tweed Caldera Catchment and their importance to the local human and wildlife communities, climate change induced impacts on these waterways will be a key factor that is investigated in this study.

Contributions of Ice Sheets to Sea Level Rise

One huge uncertainty that could greatly impact global mean sea level rise, and subsequently the global landscapes, is the response of the Antarctic Ice Sheet to climatic changes. In the past several million years, sea levels have seen increases of 6-9 meters and possibly higher from current levels, with the main contributor believed to be the Antarctic Ice Sheet (DeConto and Pollard, 2016). There is concern within the scientific community of the existence of cryospheric "tipping points" and when they will be hit. These tipping points are defined to exist if ice loss from climatic warming could not be recovered, even if the forcing returned to cooler conditions (Notz, 2009). Projections of past global mean sea levels during warm periods such as the Pliocene (~3 million years ago) and late Pleistocene interglacial periods show signs that the Antarctic Ice Sheet has a high sensitivity to temperature (Dutton et al., 2015). During the Pliocene the atmospheric CO2 concentration was ~400 parts per million (ppm), comparable to todays atmospheric concentration of ~409 ppm, yet one study shows that sea levels were 12-32 m higher than modern levels (95% confidence). This would require substantial contributions from the West Antarctic Ice Sheet (WAIS) and the East Antarctic Ice Sheet (EAIS), as well as some contribution from the Greenland Ice Sheet (Miller et al., 2012).

The WAIS is currently one of the most immediate ice sheets in danger of melting and contributing to global mean sea level rise. It contains 3.8 million km^3 of ice and if completely melted, would take over 10,000 years to re-accumulate to present levels (Oppenheimer, 1998). According to one study, there was an observed 5.5 ± 2 Gt/yr^2 decrease in surface mass balance of the Antarctic Ice Sheet from 1992 to 2011 (Rignot, 2011). The scientist that originally hypothesized that the WAIS could completely melt, John Mercer, figured that melt water on the surface of the ice sheet could percolate deep into the ice sheet and refreeze, releasing massive amounts of latent heat (1978). This heat would than bring large volumes of ice to their melting point, eventually causing complete collapse of the ice sheet (Mercer, 1978). Another factor that contributes to melting ice sheets is the retreat of the sheet onto a reverse sloping bed, which can trigger runaway marine ice sheet instability (Favier et al., 2014). Both the WAIS and the EAIS have many grounding zones that sit close to reversed sloping beds and although the WAIS is the most at risk to contribute to rising sea levels within the century, the EAIS has much thicker ice within these grounding zones and has the potential of raising sea levels by 20 meters if the basins are melted (Fretwell et al., 2013). A third driver of ice sheet melting is the fact that many ice shelves, such as the shelves in the Ross and Weddell seas, have very flat surfaces near sea level, making them extremely vulnerable to atmospheric warming (DeConto and Pollard, 2016). In this study, three model runs will account for plausible Antarctic ice sheet contributions to sea level rise under RCPs 2.6, 4.5 and 8.5, in order to show the huge potential ice sheets hold to massively change worldwide sea levels and landscapes.

Similar Studies

In the past, hydrology and geomorphology have often been separated and studied/modeled individually. With relatively recent increases in computational capacity and further development of LEMs, these two basin components can be coupled and a more holistic approach to modeling drainage basin evolution can be taken. This progress also allows for the modeling community to explore how climate plays into geomorphic and hydrologic processes, which is becoming more of a necessity as we see global temperatures rising, climates changing, and landscapes subsequently evolving in front of our eyes (Mann, 2000).

Past studies have been conducted studying drainage basin evolution due to climatic changes using a variety of different landscape evolution models. These studies have either been historical in the fact that they attempt to use stratigraphic data as evidence to connect historic climatic variations to geomorphic responses in catchment areas (Knox, 1972; Dorn, 1994; Bull, 1991; Coulthard et al., 2000; Peizen et al., 2001) or are modeling future evolution of a generic drainage basin (Willgoose et al., 1991; Tucker & Slingerland, 1997). The issue with the former, is that although these studies contribute important information for connecting sediment sinks to their sources, this type of historic dating does not provide indisputable connections between environmental and basin changes, and are also conducted over long Milankovitch timescales (10^4 - 10^5 years) or longer (10^6 - 10^7 years). The issue with the latter is that these studies fail to differentiate between the plethora of factors that vary on a basin to basin circumstance. For example, Schumm (1977, 1991) points out the importance of a number of different fluvial factors, which leads Blum & Tornqvist (2000) to conclude that “fluvial responses to climate change may be geographically circumscribed, nondeterministic and nonlinear.” This high variation of drainage basin response to changes in local climate and lack of unequivocal attribution to stratigraphic data demands more specified, attributable and provident modeling of catchments to both create a better understanding of region specific impacts and to "return to the catchment scale in fluvial geomorphology in order to understand how drainage basin structure modulates the effects of environmental change" (Richards, 2002). Furthermore, according to Coulthard et al. these extreme differences between catchments and their responses requires river basins and their catchments to be modeled individually in order to properly project downstream sediment routing and storage (2005).

More recently, landscape evolution modeling has been conducted on specific drainage basins at higher resolutions both spatially and temporally (Coulthard et al., 2005; Hancock et al., 2010; Coulthard et al., 2012). The LEMs used in these studies (CAESAR & SIBERIA) are grid-based models, in which problems arise when modeling landscape evolution. In order to avoid these issues, Badlands arbitrarily configures topography into a set of vertices which are then connected to form a Delaunay triangular irregular mesh (Salles & Hardiman, 2016).

Badlands Landscape Evolution Model

A brief description of the Badlands LEM is provided here, but for a more in depth explanation of the models operations and functions, readers are referred to Salles & Hardiman (2016). Badlands is a minimal numerical landscape and catchment model that efficiently solves for erosion, sedimentation, diffusion, and flexure using a set of empirical and physical laws (Figure 3) (Salles & Hardiman, 2016). It is important to note that Badlands does not differentiate between regolith and bedrock and assumes uniform substrate. The physics implemented by the model are simpler than the previously mentioned models (Coulthard et al., 2005; Hancock et al., 2010; Coulthard et al., 2012), but the purpose of Badlands is to take advantage of less complicated physics and provide an efficient parallel code to model landscape dynamics at high resolutions, with the ability to run scenarios over longer temporal scales. An irregular mesh is implemented in order to emphasize the areas with higher activity and prevent water flow directional bias that comes with regularly gridded models. One key feature of the model is the method of efficiently computing sediment transport and discharge by using a single-flow-direction approximation, which assumes water follows the path with the steepest slope. Badlands supplements this technique by splitting the catchment into a number of sub-catchments, which communicate with each other through lateral sediment fluxes within the channel network in an upstream to downstream order. This study will utilize Badlands functions to analyze dynamic changes across a drainage basin, over a geologically short time scale.

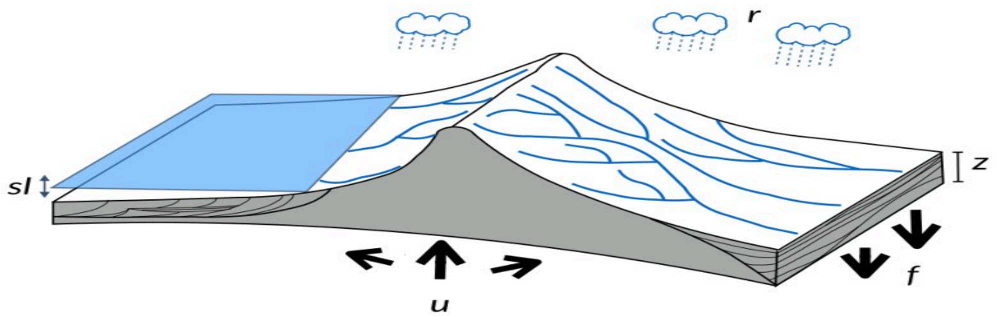

Figure 3. A schematic of two-dimensional landscape evolution model illustrating the main variables and forces simulated within Badlands: z is the surface elevation; r refers to rainfall, sl to sea-level fluctuations, f to the flexural isostasy, and u to tectonic uplift"(Figure 1. From Salles and Hardiman, 2016).

There are numerous LEMs currently available that are used for similar studies and have capabilities that parallel Badlands. CAESER, SIBERIA, CHILD, GOLEM, and CASCADE are examples of some of the LEMs that have been used more extensively within the field of study (Coulthard, 2001). The Badlands LEM was chosen for this study due to a multitude of factors. As previously mentioned, Badlands uses an irregular mesh, where as GOLEM, SIBERIA, and CAESAR all use a regular grid. This was important because TIN based models emphasize the areas of high activity (ie. river channels), which allows for a more precise projection of climate change effects on landscape. Due to this ability to model processes at higher resolutions, TIN based LEMs like Badlands are better suited for shorter timescales than other models, like GOLEM or CASCADE, which are better used for longer temporal scale simulations and can't account for the predicted geologically short term effects of climate change. The biggest advantage of Badlands is the model's efficiency, which comes from both an O (n)-efficient ordering method as well as the previously discussed sub-basin network partitioning method that is utilized (Salles, 2016). Along with these advantages, Badlands also has its limitations. As opposed to LEM's such as CHILD, CAESAR and GOLEM, Badlands does not take grain size or stratigraphy into account. Badlands also does not account for wave action erosion effects, which ignores an important factor in coastal response to sea level change. Future studies should look to use a coupled model in order to mitigate these limitations.

Methods

For this study, the model required inputs of topography in the form of a digital elevation model (DEM), bathymetric data, annual precipitation rates (m/a), an annual SLR rate (m/a), an erodibility coefficient and a simulation time structure. The model then used these varying inputs to drive erosion, sedimentation, aggradation, delta and shoreline progradation, marine transgression, river avulsion/incision and other landscape effects of the simulated Tweed Caldera environment.

Code Engine

Badlands is one of the many recently developed LEMs that is looking to further the understanding of surface processes and their different influencing factors. This field has been growing rapidly over the past couple of decades. In order to model these processes, Badlands uses a set of physical laws within its code engine (for an in depth description readers are referred to Salles & Hardiman, 2016). Under the assumptions previously talked about, Badlands projects the continuity of mass, using the equation: $\partial z/\partial t = U - \nabla \cdot q_s$, in which Z is elevation derived from the DEM, q_s is the downhill soil flux, $\nabla \cdot$ is the vector operator that controls spatial divergence and, for this study, U represents the rate of incision at hill slope boundaries. Sediment transport is modeled relative to the topographic gradient and discharge: $q_r = -\kappa_r (q_w)^m (\nabla z)^n$, where ∇z is the gradient in which sediment flux is oriented towards and q_w is the rate of discharge (m^2/yr). The channel incision rate is calculated relative to discharge (power function) where channel slope is positive: $\partial z/\partial t = -\kappa_r (q_w)^m (\nabla z)^n$, in which Badlands assumes sediment transport is equal to the local carrying capacity based on the stream power per unit width. Hillslope transport processes are parameterized using the simple creep law: $q_d = -\kappa_d \nabla z$, where transport is dependent upon local gradient and is scale-dependent.

Simulating the Environment

In order to virtually simulate the basin, topographic and bathymetric data in the form of a digital elevation model (DEM) was utilized. DEMs are 3 dimensional models of a terrain's surface derived from elevation data. The digital topography of the Tweed Caldera drainage basin was constructed using lidar, multi- beam, single-beam, satellite, and bathymetric data provided by Australian federal and state government agencies in the form of digital elevation models and compiled by the eAtlas 3DGBR project. Once the data from the DEMs was downloaded they could be transferred into ArcGIS. ArcGIS was used to transition from numerical data to a 3 dimensional map of the region. The DEM was then cropped down in order to only take into account the sources and sinks of the chosen catchment area. For the Tweed basin, DEMs needed cropping with a y latitudinal minimum = ~-28°, y latitudinal maximum = ~-29°, x longitudinal minimum = ~153.5°, and x longitudinal maximum = ~153° (Figure 4).

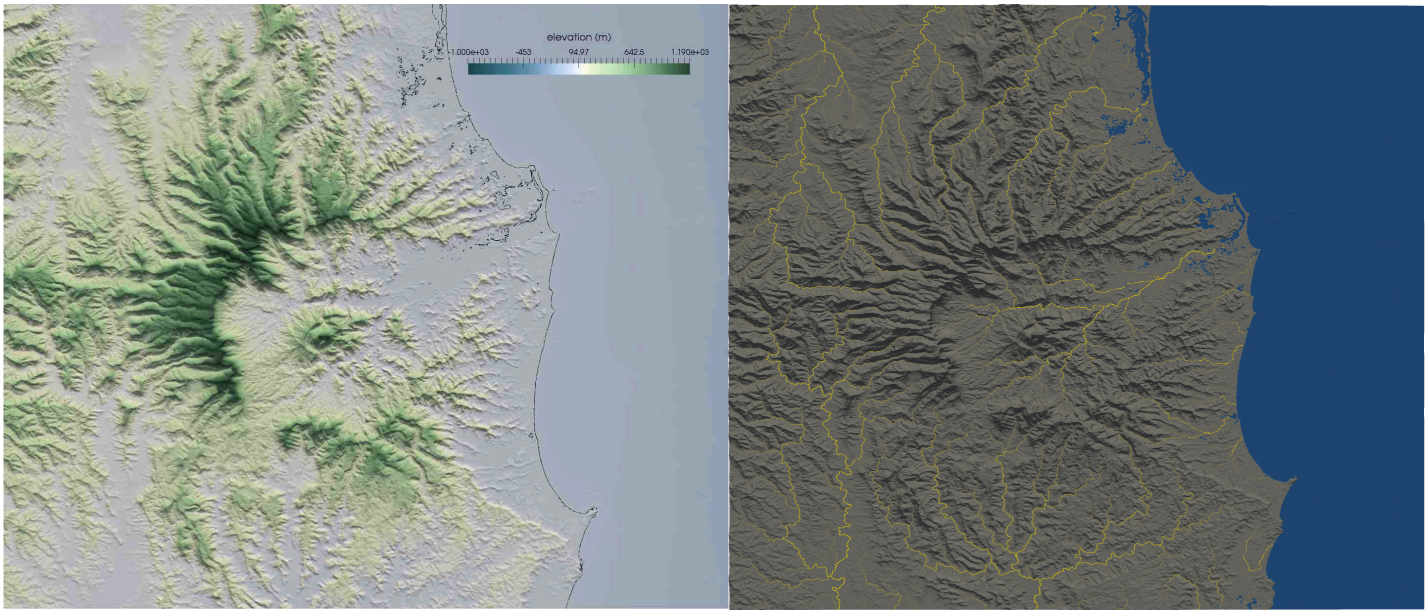

Figure 4. Mount Warning Caldera catchment DEM visualization. Elevation is visualized on the left with darker green colors representing higher elevation. The drainage network is visualized on the right, with the main river channel (Tweed River) in the center.

Although Badlands is able to model processes at relatively high resolutions, the lack of available high resolution elevation and bathymetric data for the drainage basin, resulted in the most appropriate DEM available being set at a resolution of ~100 m. This exemplifies the need for Australian government agencies to make high-resolution (25 m or greater) elevation and bathymetric data more readily available and easily obtainable. The data from the 3DGBR project is both spatially, in resolution and in coverage, a large improvement from the currently available data in the Australian Bathymetry and Topography grid (~250 m) (Whiteway*,* 2009). As models continue to advance and develop more capabilities, elevation/bathymetric data resolution and availability will need to evolve simultaneously. This will allow for more comprehensive studies that can offer a more in depth understanding of landscape evolution processes when met with climatic stress.

Study Site

The Mount Warning Shield Volcano (Figure 5) was chosen for this study due to the unique topography of the caldera that was created by over 23 million years of erosion which now defines the catchment area. Due to these millions of years of weathering, the caldera now exhibits three of the four stages of shield erosion: planeze in the western region of the caldera, residual mountain in the central northern and southern regions and skeleton in the most eastern areas of the caldera, in which the most erosion has occurred (Solomon, 1964) (Figure 5). The basin also contains multiple major river systems throughout the caldera, floodplain and surrounding valley, consisting of the Richmond, Tweed, and Brunswick sub-catchments. With a diameter of ~40km, the Mount Warning shield volcano is the largest erosion caldera south of the equator and one of the largest in the world. The caldera almost completely surrounds the volcanic plug (now mount warning). The entire caldera covers an area of approximately 1500 square miles and drains over a much greater area. The drainage modeled in this project reaches from its most northeastern point in the northern region of the Gold Coast, to its most southeastern point, approximately 105km south in Lennox. The shield volcano has three main tributaries that define the basin (north, central, and south), each having semi-dendritic headwaters originating in the escarpment walls of the caldera, forming a relatively circular pattern around the central mass (Solomon, 1964). The northern arm's main drainage system is made up of both the Nerang River, which drains the north facing slope of the caldera and discharges into the manmade waterways of the Gold Coast and Tallebudgera Creek which drains into Burleigh Heads. The southern arm is comprised of many different tributaries draining the southern slopes of the caldera, but one of the more active channels in that system is the Brunswick River; draining the caldera's southeastern region and discharging into the Pacific via Brunswick Heads. The third tributary consists mainly of the matured Tweed river, flowing directly east and meandering over the floodplain. Comprised of previously deposited alluvium, the Tweed River drains the caldera floor and discharges into the Pacific via Tweed Heads (Solomon, 1964).

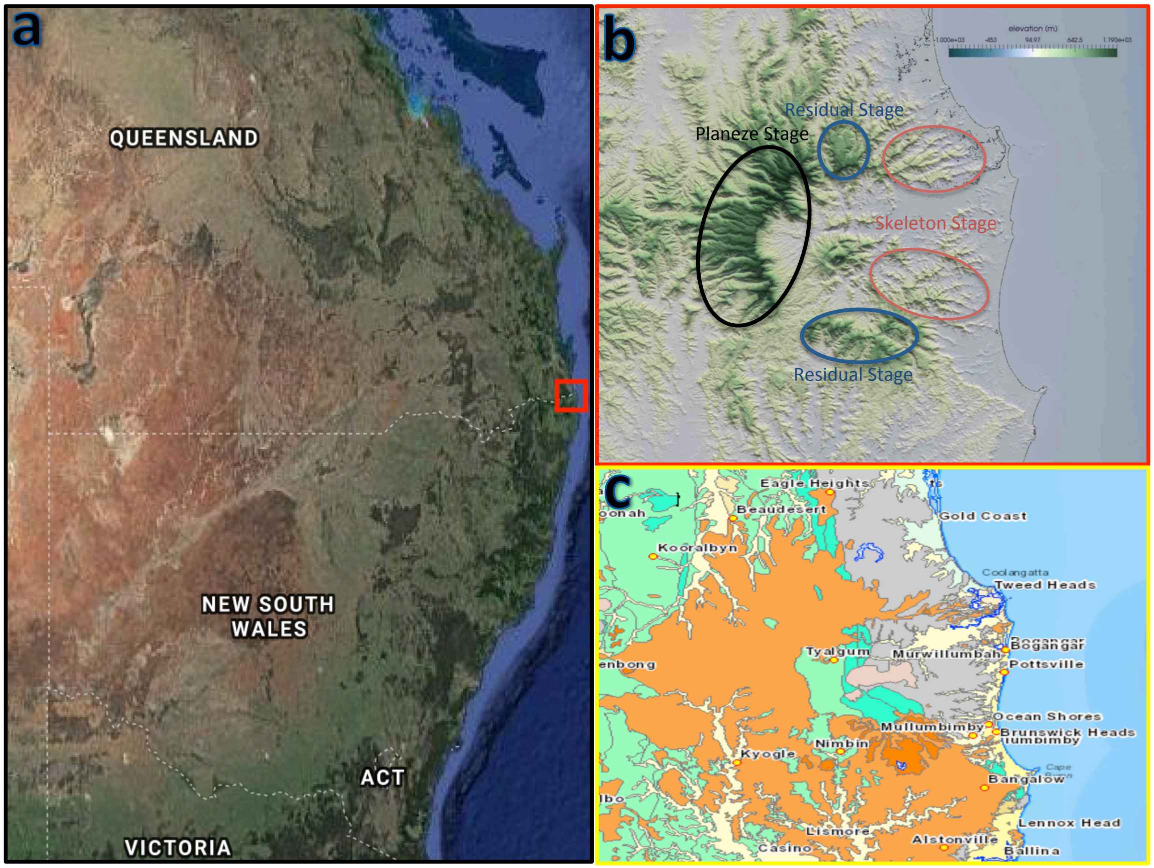

Figure 5. Study area. a) Location of the Tweed Caldera drainage basin within Australia. b) Elevation map of the caldera with the erosion stages labeled. c) Surface geology of the study site (orange = Cenozoic volcanic rock, light green = Jurassic period Metamorphosed rock) (Surface geology obtained from Commonwealth of Australia, Geoscience Australia 2017).

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Using Badlands

Once the DEMs were downloaded and cropped, the data was then converted into an ASCII text file with all X, Y and Z grid values. This ASCII file is essential for Badlands in order to properly utilize its TIN method, which performs triangulations based on the provided dataset (https://github.com/badlands-model/pyBadlands/wiki). The text file is called into the model via a pre-processing Jupyter notebook, in which the parameters can be inputted and adjusted. Four preliminary runs were put through the model, each corresponding with values from the four RCP scenarios, followed by three runs with only variations in precipitation rates, and three final runs that account for plausible WAIS/AIS melt scenarios. All model output is visualized using Paraview, in which deposition, erosion, discharge, elevation and landscape changes can be qualitatively analyzed. Quantitative analysis (ie. changes in gradient, elevation, discharge, curvature, etc.) is done through the Badlands post-processing notebook and visualized using Plotly.

Climatic Inputs

Realistic projections of precipitation and sea level rise were required as input for Badlands in order to output practical responses of the landscape. The mean annual precipitation rate, 1611 mm per year, observed from 1972 to 2017 at the Murwillumbah observation point was used as the baseline precipitation value for each model, beginning in 2020. This sight is set in between Tweed Heads and Mount Warning, or in the center of the region that is being modeled, and has a climate consistent with the humid subtropical climate of the rest of the catchment. Precipitation projection data was taken from "Climate Change in Australia" (climatechangeinaustralia.gov.au), in which data from a set of 50 current generation climate models for Australia were reviewed and given a confidence assessment (Clarke et al., 2011) (Table 1). It is noteworthy to mention that precipitation patterns in Australia are extremely difficult to project and largely uncertain. Since the majority of models show little change in precipitation patterns in northeastern New South Wales and the climate for the region is relatively wet, I used the higher end of the projections in order to show the effect of an increase in precipitation (+5%) for the most likely occurrence (-5% to +5%) by the end of the century. It is also important to note that this projection is for a region spanning from the coastline of the study site (wetter climate) all the way south to Sydney (drier climate), therefore there is significant potential for differences in smaller scale projections due to regional differences such as topography, coastal influences, etc. (climatechangeinaustralia.gov.au). Using this projection, the models average annual precipitation was incrementally increased every decade by 0.625% in order to see a 5% increase from baseline levels by the end of the century and a constant rate was kept past 2100.

	SLR (m) by 2100	ECP SLR (m) by 2500	Precipitation by 2100 (%)
RCP 2.6	0.4 (.26 - .55)	1.84	+5 (34% confidence -5 to 5)
RCP 4.5	0.47 (.32 - .63)	1.95	+5 (35% confidence -5 to 5)
RCP 6.0	0.47 (.33 - .63)	2.25	+5 (41% confidence -5 to 5)
RCP 8.5	0.62 (.45 - .82)	5.48	+5 (29% confidence -5 to 5)

Table 1. SLR, ECP SLR and precipitation values used for each RCP scenario and inputted into the Badlands model.

The regional northeastern New South Wales SLR predictions for current day to 2100 were derived from the Representative Concentration Pathways (CSIRO and Bureau of Meteorology, 2015), relative to the average from 1988 to 2005. The SLR projections from 2100 to 2500 are taken from Jevrejeva et al. and are global projections, which had to be used in this project due to the lack of regional sea level projection data past 2100. The values for Extended Concentration Pathways 4.5 and 6.0 are estimated from figure 8 in Jevrejeva et al. (2012), due to the non-specificity of the values for 2500 in the literature. In their study, a semi empirical model that is constrained by 300 years of tide gauge records, driven by various radiative forcing time series over the past 1000 years and assumes that SLR is a product of changes in dynamics and thermodynamics of the atmosphere, ocean and cryosphere, due to changes in radiative forcing (2012). In their study, the models solve for the equation: Seq = aF + B, in which they assume that for a global mean radiative forcing (F) there is an equilibrium sea level (Seq), where a is the sensitivity of sea level to a forcing change and B is a constant (Jevrejeva, 2012). See Figure 6 to visualize the different sea level curves.

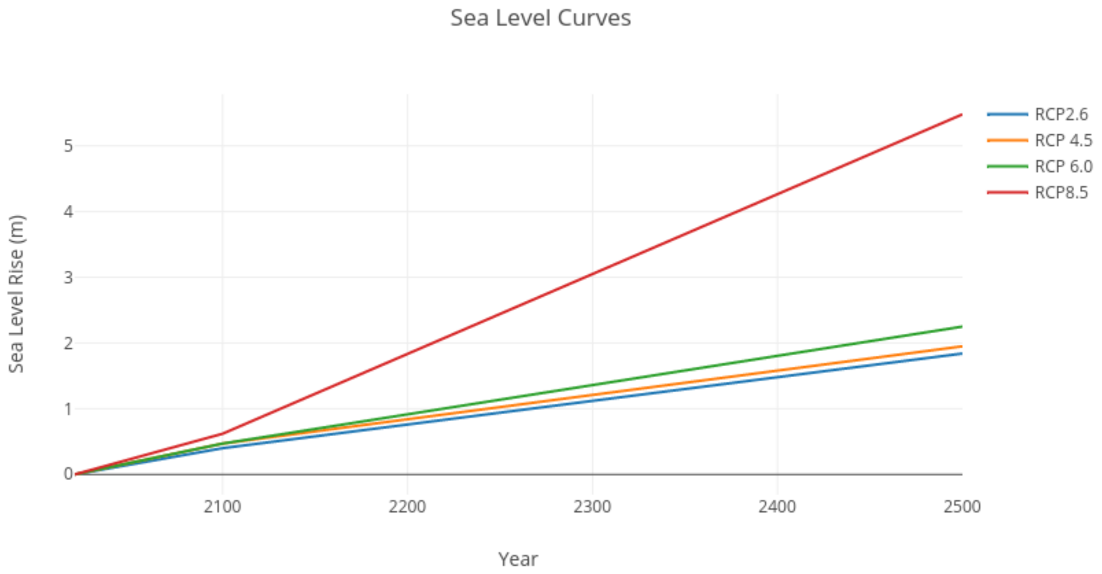


Figure 6. Sea level curves for each RCP model scenario, from the model start date (2020) to the model end date (2500).

The regional SLR data for present day to 2100 is based on the 5 to 95% range of model results for SLR, but should only be considered likely (greater than 66% probability) (CSIRO Bureau of Meteorology, 2015), while the SLR projections past 2100, along with all projections past 2100, have great uncertainties. The main uncertainty is the response of ice sheets to long-term ocean heat uptake and deep-water formation (Jevrejeva, 2012). It is important to note that the Extended Concentration Pathway estimates do not represent dependable scenarios, but are ‘what if’ experiments that are derived using the basic principles of each RCP and produced for the purpose of having available data sets for longer-term research (Vaughn, 2009). It is also important to mention that the ECPs do not consider SLR due to partial or complete collapse of the West Antarctic Ice Sheet, which would have a significant impact on global sea levels.

A third variable that has significant control over the impacts seen on the basin is the erodibility coefficient, which controls the magnitude of erosion at the surface of the simulated environment. In this study, the erodibility coefficient was set at 8 e^{-5} and kept constant throughout all runs. The coefficient is dependent upon lithology, precipitation rate, channel width, channel hydraulics and flood frequency within the region. The value used in this study is relatively high due to the fact that the Tweed Caldera basin is largely consistent of volcanic basaltic rock and some sandstone, both of which are vulnerable to erosion; conversely there are also some rhyolite conglomerates that are seen in many of the larger protruding rock formations (ie. Egg Rock or Mount Doughboy), due to there higher resistance to weathering (Solomon, 1964). The extreme slopes of the caldera, high regional precipitation rates and land use change from rainforest to highly erodible agricultural land also went into the decision to use a higher erodibility coefficient.

Adding Antarctic Ice Sheet Contributions

A study published in Nature, conducted by DeConto and Pollard, uses a newly improved numerical ice-sheet model, previously used to simulate past periods when the Antarctic Ice Sheet was melted to some degree, to project how Antarctica will evolve over the next 500 years (2016). In their study, three RCP scenarios (2.6, 4.5 and 8.5) are utilized within the ice-sheet model to project how much the Antarctic Ice Sheet could plausibly contribute to global mean sea level rise (DeConto and Pollard, 2016). The RCP and ECP scenario projections used for the initial model runs of my project did not take into account sea level rise caused by the melting of ice sheets. This is because there is very little confidence in any predictions on how the major ice sheets will react to the changing climate. In order to create a better understanding of fluvial and geomorphic responses of landscapes, specifically of the Tweed Caldera catchment, to the theoretical partial or complete collapse of the Antarctic Ice Sheet, SLR projections from DeConto and Pollard's study were added to the original SLR projections for the modeled region (Table 2). The values differ greatly from RCP 2.6 to RCP 8.5 because of the extreme sensitivities of ice sheets to warming, what are commonly referred to as "tipping points". For example, in the modeled RCP 2.6 scenario, the ice sheet has a substantially small response to warming, but under the RCP 4.5 scenario, almost the entire WAIS collapses by 2500, primarily because the retreat of Thwaites Glacier into the Aurora Basin and eventually deeper into the WAIS interior (DeConto and Pollard, 2016). In RCP 8.5, little effect is seen on ice by 2100 due to an increase in precipitation keeping most of the sheet stable, but by 2250 the entire WAIS collapses because of the extreme atmospheric warming and regional dynamics of Antarctica; eventually by 2500 retreat of ice into basins results in an AIS contribution of 6.82 m to global mean sea level rise (DeConto and Pollard, 2016).

	Additional SLR by 2100 (m)	Additional SLR by 2500 (m)
RCP 2.6	0.05	0.2
RCP 4.5	0.32	3.05
RCP 8.5	0.77	6.82

Table 2. Contributions of the Antarctic ice sheet to global mean sea level rise as modeled by DeConto and Pollard (2016), from 1950 – 2500.

Each value was added on top of the original RCP and ECP projections used in the previous model runs (see Figure 7 for a visualization of the sea level curves). All other variables including precipitation values and erodibility were kept unchanged and the model was run through 2500 AD for all three scenarios.

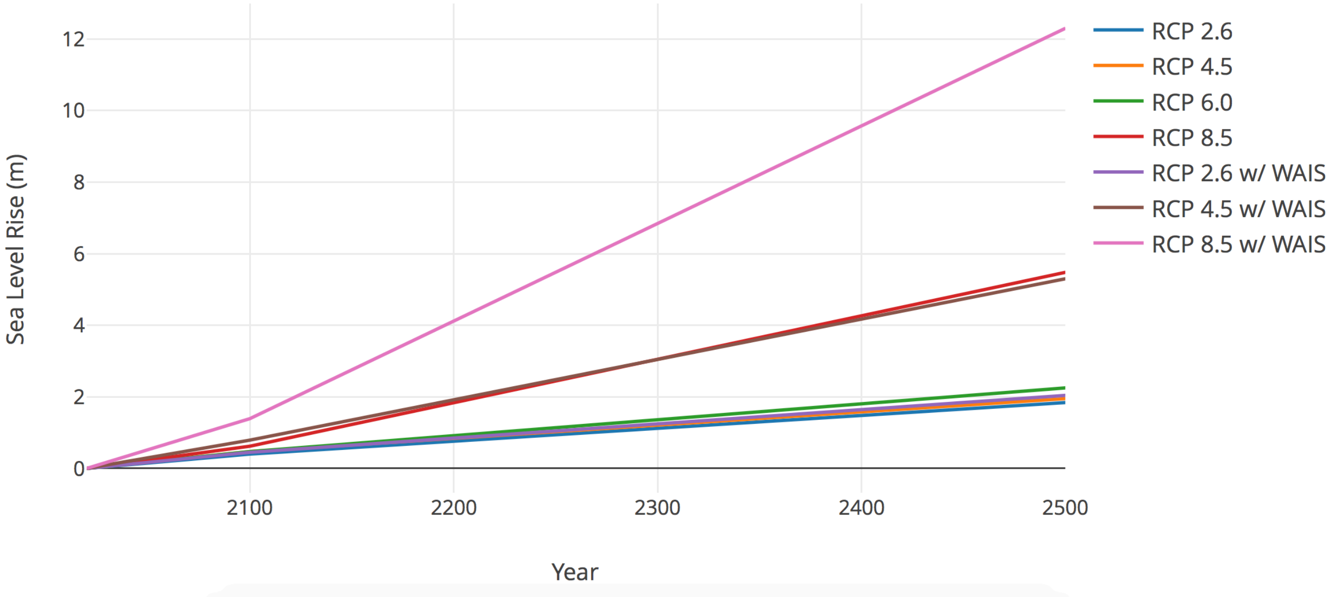


Figure 7. Sea level curves for AIS scenarios and RCP scenarios.

Precipitation Scenarios

There is much uncertainty of the magnitude of future precipitation changes, but there is virtual certainty that mean global precipitation will increase with average temperature (Collins et al., 2013). It is essential to understand how these changing precipitation patterns could affect landscapes, and specifically drainage basins. For the purpose of better understanding the amount of influence local precipitation rates have on the dynamics of surrounding landscape, specifically within the Tweed Caldera basin, three scenarios were created in which all variables, except annual average precipitation rates, are held constant. For scenario one, the precipitation values are the same as all the initial RCP model runs with a baseline precipitation value of 1.6 m/a and a 5% increase by

2100, followed by a constant rate of increase until 2500. The final two scenarios were run with the baseline precipitation value kept the same at 1.6 m/a, but a 10% and 15% increase by 2100 and the rate of increase kept constant until 2500. These scenarios were used to both compare the landscape impact of different plausible future precipitation scenarios and because many regions worldwide, including the chosen region, have extreme uncertainty of how precipitation could change. For this reason, an understanding of the impacts of a change in regional precipitation rates needs to be further studied.

Limitations and Assumptions

Regional sea level rise projections used for this project have some issues due to their coarse resolution (spatial resolution to the order of 1° of latitude/longitude). Global Climate Models (GCM) used for my sea level rise projections are not eddy resolving, do not accurately represent the absolute dynamics of ocean currents such as the East Australian Current and do not completely represent deep ocean and continental shelf interactions or smaller scale local coastal processes resulting in changes of coastline. As a result, the coastal response of sea levels to climate change contains additional uncertainties to those represented in GCMs. Furthermore, the South Pacific Ocean is projected to lead to a larger rise off the south-eastern Australian coastline; however the current low resolution models may not adequately represent how higher offshore sea levels are expressed at the coast (Climatechangeinaustralia.gov, technical report), which may result in slightly higher or lower sea levels than reported. Also, these GCMs do not represent processes such as fluvial and wave erosion, sediment transport, or land subsidence (Kim et al., 2006). One assumption made by the Badlands LEM is uniform substrate across the entire modeled area with an erodibility coefficient of 8 e^{-5}. This is an issue due to the fact that it creates an erosion/sedimentation response within the model that would likely not be seen in the actual basin, due to the variations in substrate across the catchment. Another limitation is the lack of vegetation dynamics being accounted for within the model and the absence of effects from wave action erosion, extreme see level events and extreme weather events; all of which are projected to change in magnitude and frequency (Australia Department of Climate Change, 2009). If modeled, coasts would almost certainly respond differently. In order to realistically take all catchment, shoreline and climatological processes into account, a coupled model is required.

Results

All 10 model scenarios were run and then analyzed qualitatively, using Paraview for visualization, and quantitatively, using python and Plotly. The model output visualizations and landscape impact analysis are shown within this section.

Representative Concentration Pathway 2.6

With relatively few climatic variations under RCP 2.6, compared to the rest of the scenarios, landscape response is expected to be more modest than any other modeled scenario. Output from the RCP 2.6 scenario shows how Badlands predicts the Tweed Caldera basin could dynamically evolve in a future where radiative forcing reaches 2.6 W/M² by 2100 followed by a constant rate of emissions until 2500 (Figure 8).

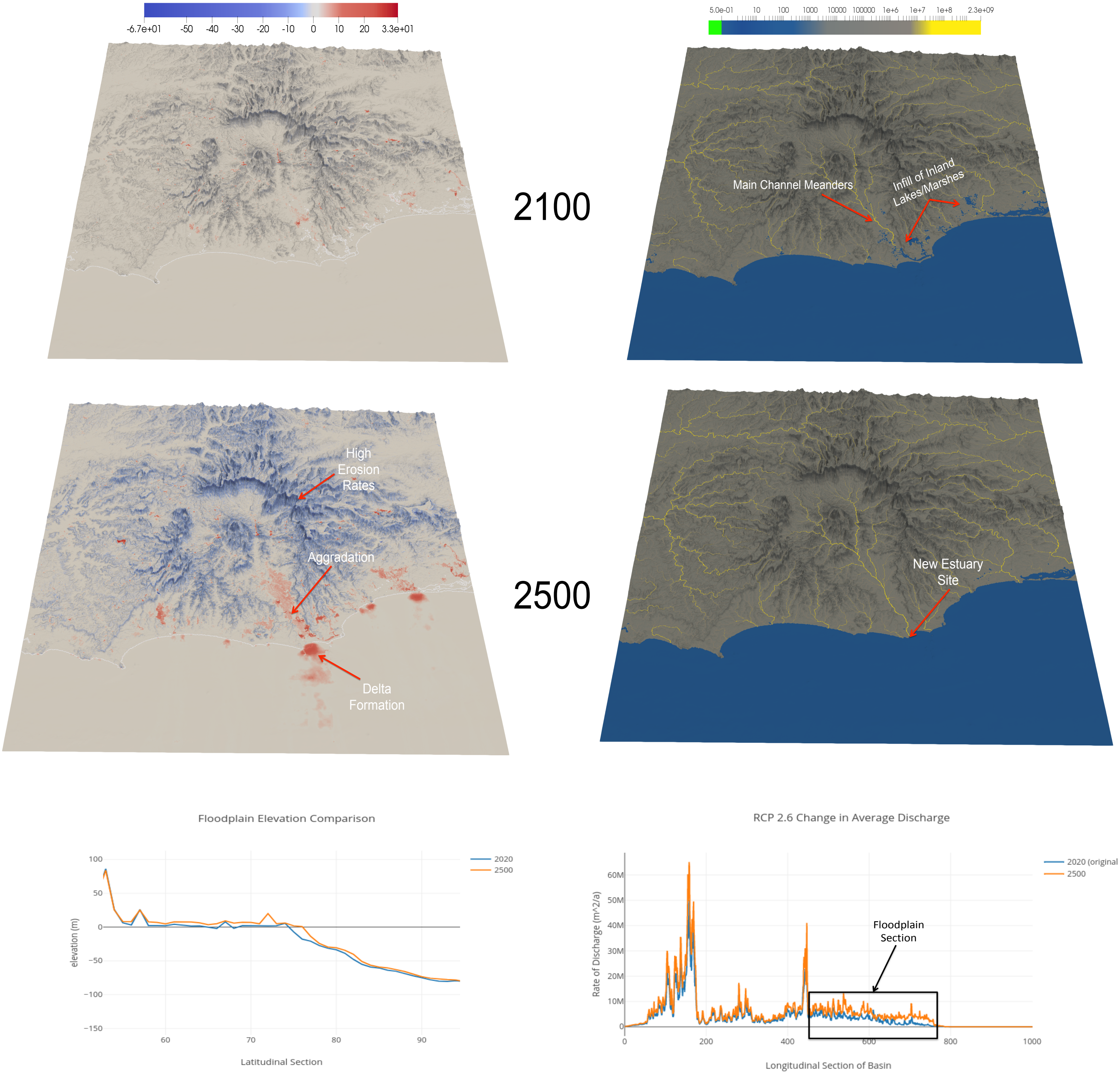
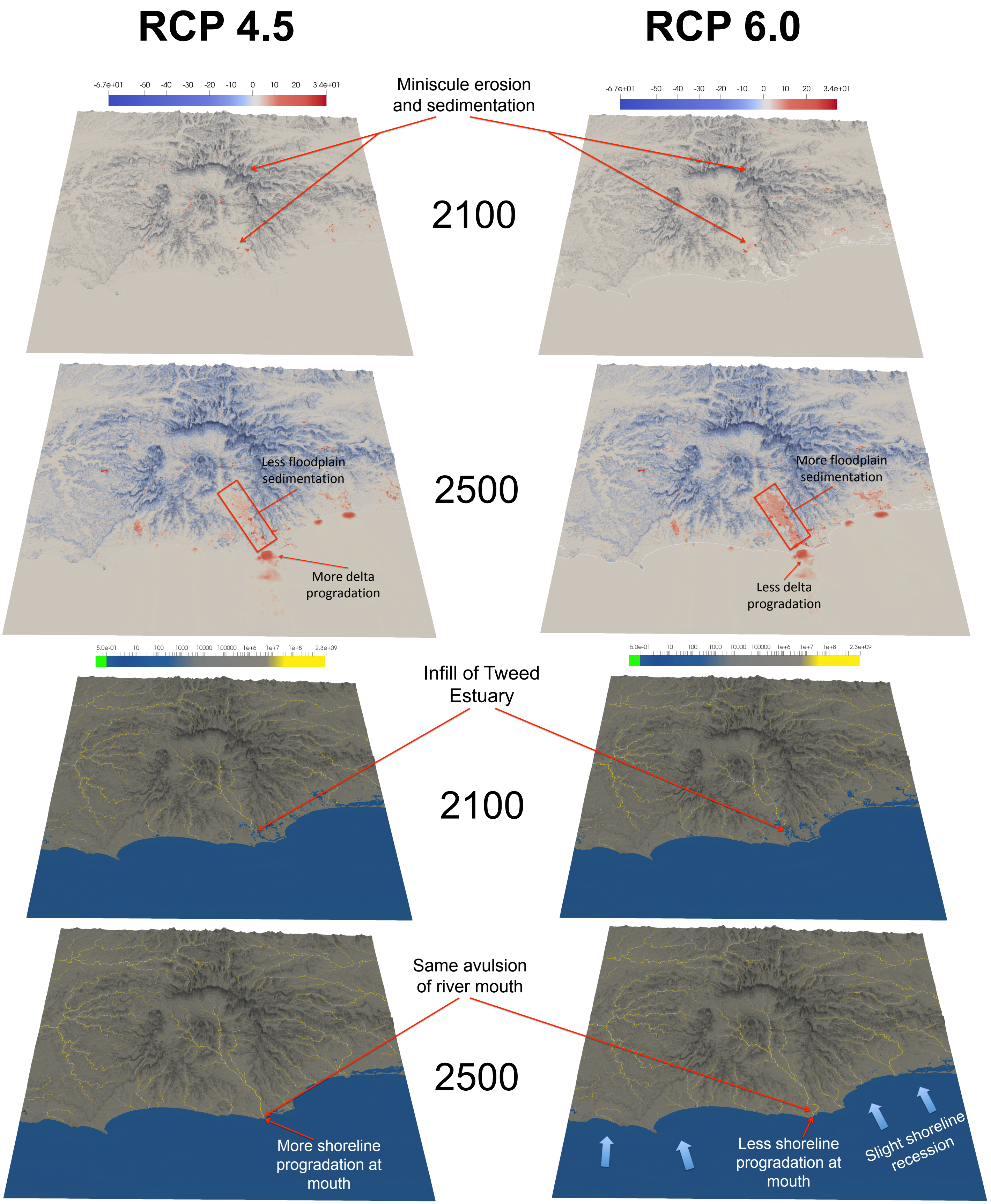


Figure 8. Time evolution of the Tweed Caldera basin under RCP 2.6 conditions. Erosion and Deposition is visualized on the left with darker red colors representing higher deposition and darker blue colors representing higher erosion, with the greatest change in average elevation (in the caldera section) within the basin shown below. Discharge is visualized on the right with brighter blue colors representing higher discharge rates and the average change in discharge throughout the entire basin from 2020 to 2500 shown below.

The main impacts to landscape that where observed in the model output were effects to the drainage network (ie. main channels and tributaries). These effects occurred in the form of river avulsions, changes in discharge, infill of inland bodies of water and bays and some progradation of shoreline at the mouths of major rivers. All of these impacts were due to the changing rates of erosion and deposition, which, in turn, were caused by a variation in the local climate. The increase in sea level for RCP 2.6 was so miniscule that no significant impact can be observed and conversely, in some areas the rate of delta formation at river mouths caused shorelines to prograde.

Representative Concentration Pathways 4.5 and 6.0

Due to the current amount of worldwide emissions, the future worldwide climate, over the next half millennium, is more likely to fall somewhere in between the RCP 4.5 and RCP 6.0 scenarios. Because local climatic variations between these two scenarios are small, impacts to the landscape of the Tweed Caldera basin are relatively similar under both scenarios (Figure 9).


RCP 4.5
RCP 6.0
-6.7e+01 -50 -40 -30 -20 -10 0 10 20 3.4e+01
-6.7e+01 -50 -40 -30 -20 -10 0 10 20 3.4e+01
Miniscule erosion and sedimentation
2100
Less floodplain sedimentation
More floodplain sedimentation
2500
More delta progradation
Less delta progradation
5.0e-01 10 100 1000 10000 100000 1e+6 1e+7 1e+8 2.3e+09
5.0e-01 10 100 1000 10000 100000 1e+6 1e+7 1e+8 2.3e+09
Infill of Tweed Estuary
2100
Same avulsion of river mouth
2500
More shoreline progradation at mouth
Less shoreline progradation at mouth
Slight shoreline recession

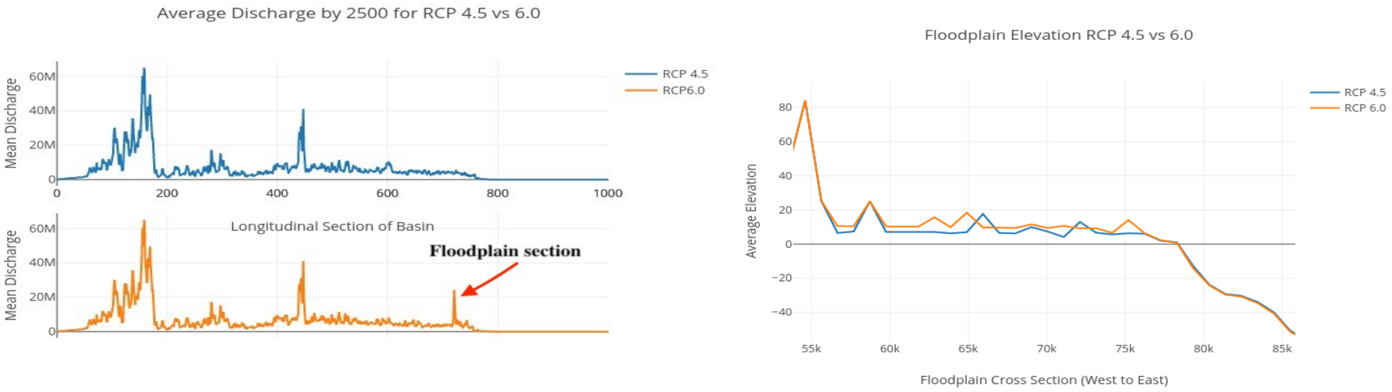
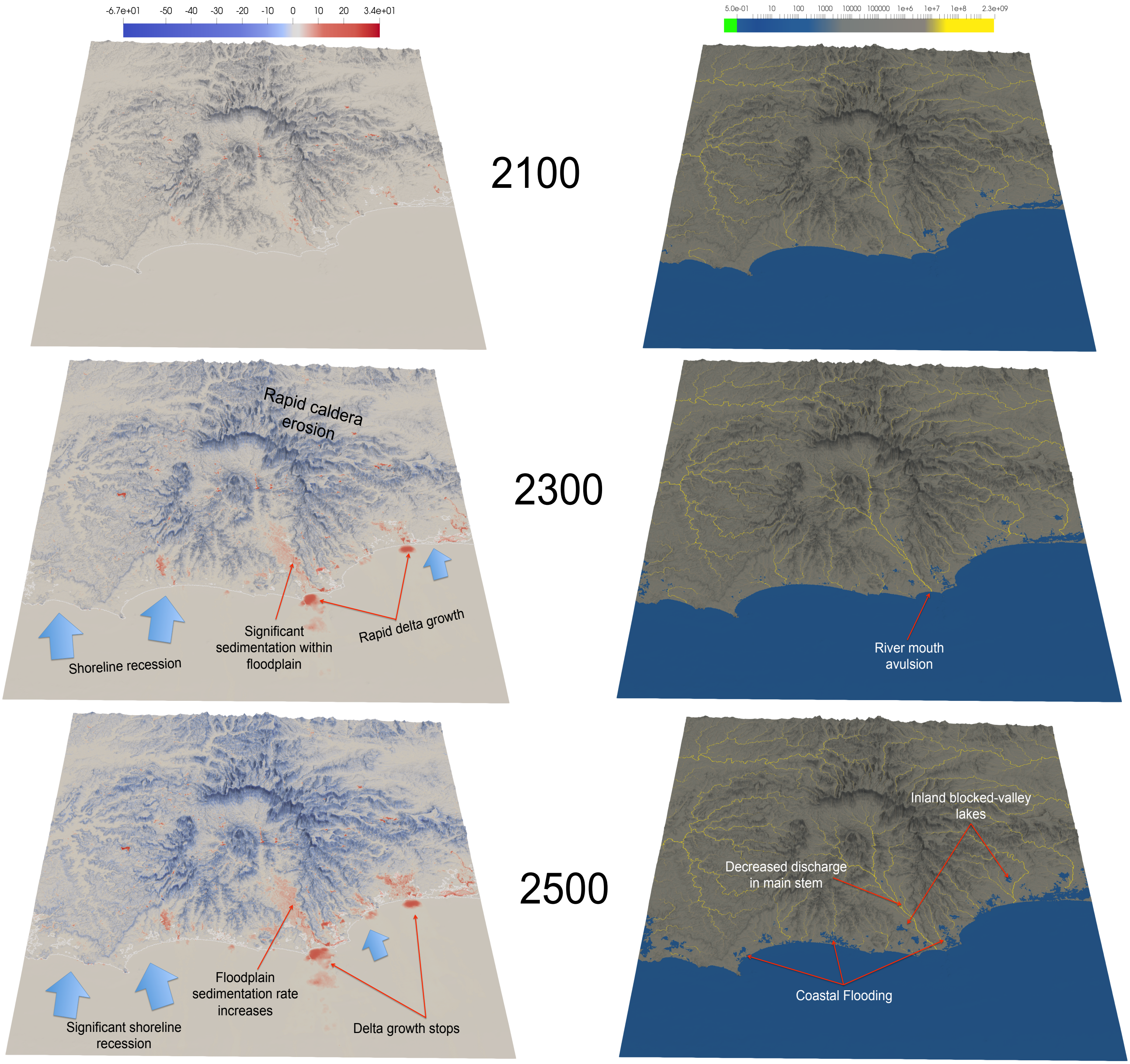


Figure 9. Comparison of RCP 4.5s and 6.0s visualization of erosion, deposition and discharge variations and the subsequent landscape impacts. Average discharge is compared at the bottom (left) as well as the average elevation for the floodplain section (right).

Comparatively, impacts under RCP 4.5 and 6.0 do not differ significantly by 2100, but by 2500 there is a noticeable contrast between the two landscapes. Under RCP 6.0 the floodplain experiences increased deposition compared to RCP 4.5, and in turn less sediment is discharged into the delta. This leads to denser and larger deltas and subsequently more shoreline progradation at the river mouth under RCP 4.5 conditions. Although sea level rise is relatively unnoticeable throughout the RCP 4.5 scenario, the slightly higher magnitude of sea level rise under RCP 6.0 causes an observable difference in the landscape dynamics.

Representative Concentration Pathway 8.5

RCP 8.5, relative to the past three scenarios, has a significant effect on the local climate. The consequential impacts from climate change to landscape are heavily accentuated under this scenario (Figure 10).



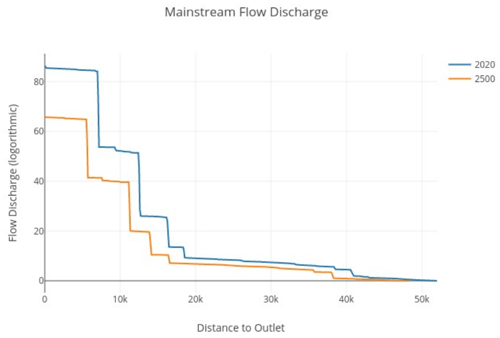


Figure 10. Visualization of RCP 8.5 model output, showing erosion and deposition (top) and discharge (middle), through 2500, as well as comparisons of mainstream discharge between 2020 and 2500 (bottom).

Under the “business as usual” scenario, sea level rise plays a much larger role in landscape impacts. Significant amounts of sediment are deposited into the ocean through the mainstream and feeding the delta, but once SLR becomes significant enough all marine deposition stops. This forces large amounts of sedimentation near the coast. Eventually, inundation due to dramatic SLR is the main force impacting the landscape.

Antarctic Ice Sheet Scenarios

Representative Concentration Pathway 2.6

Under RCP 2.6, DeConto & Pollard projected very miniscule contributions from the AIS to global sea level rise (2016). Model output shows an almost identical landscape reaction as RCPs 2.6 & 4.5, under this scenario (Appendix a).

Representative Concentration Pathway 4.5

Deconto and Pollard projected that the AIS would contribute significantly more to global sea level rise under RCP 4.5 due to tipping points being hit (2016). Model output shows a much more significant impact to the local landscape, with some new dynamics seemingly being involved as dramatic sea level increases are seen (Figure 11).

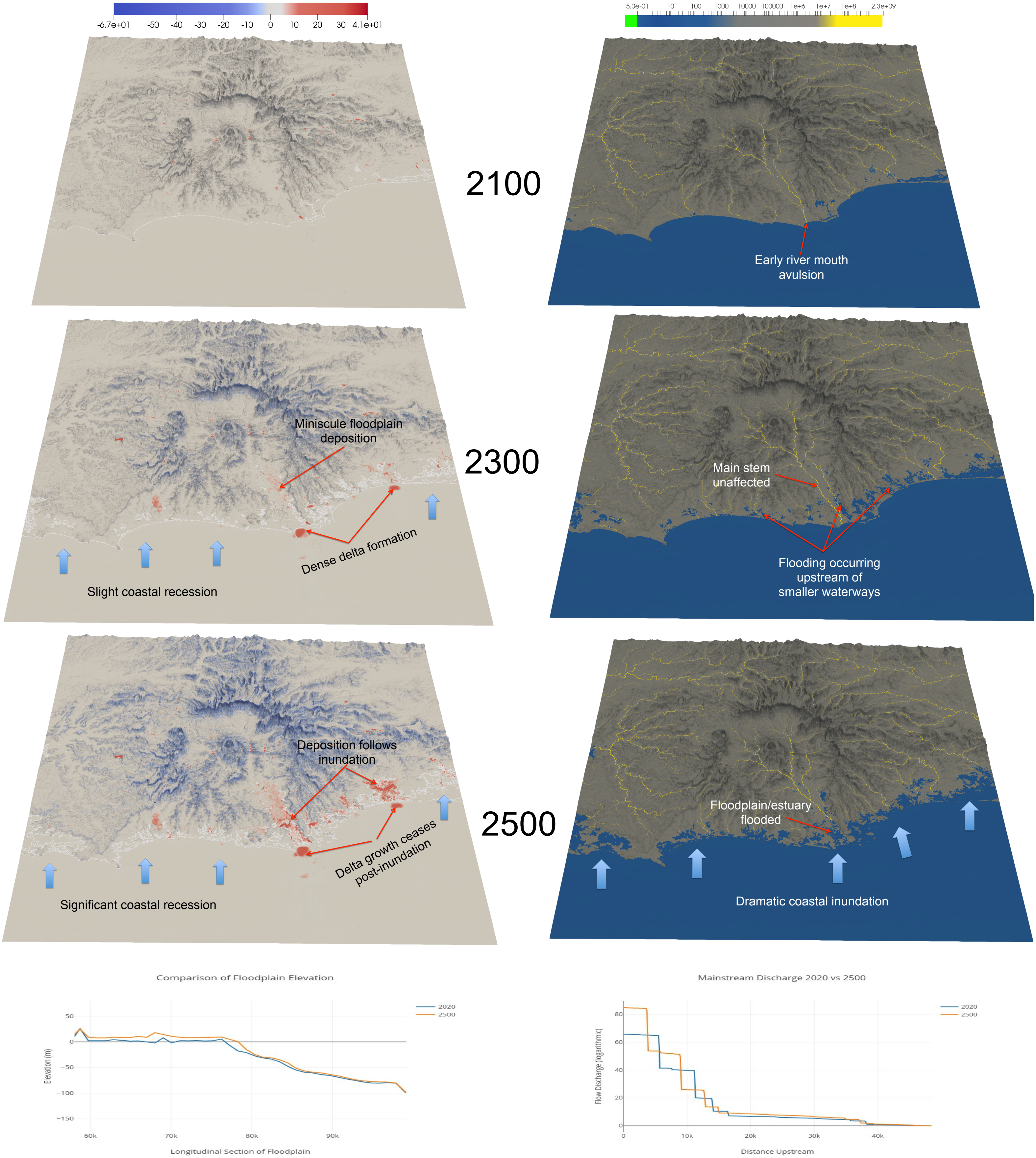


Figure 11. Visualization of RCP 4.5 with AIS contributions model output, showing erosion and deposition (top) and discharge (middle) through 2500, as well as comparisons of floodplain elevation and mainstream discharge between 2020 and 2500 (bottom).

The AIS 4.5 scenario is relatively similar to RCP 8.5 for the first couple centuries. Eventually, the tipping points hit in the AIS cause extreme amounts of SLR and this forces all deposition upstream, as well as massively inundating the entire coastline. This increase in floodplain sedimentation causes a rise in elevation by 2500. Sedimentation is rendered ineffective in impacting the landscape as the sea continues to rise at extreme rates.

Representative Concentration Pathway 8.5

Under the RCP 8.5 scenario, the AIS is projected to contribute a significant amount to global sea levels. Model output shows dramatic impacts to the local landscape as a consequence of the high rates of sea level rise (Figure 12). There also is seemingly a change in local dynamics caused by the magnitude and rate of environmental change.

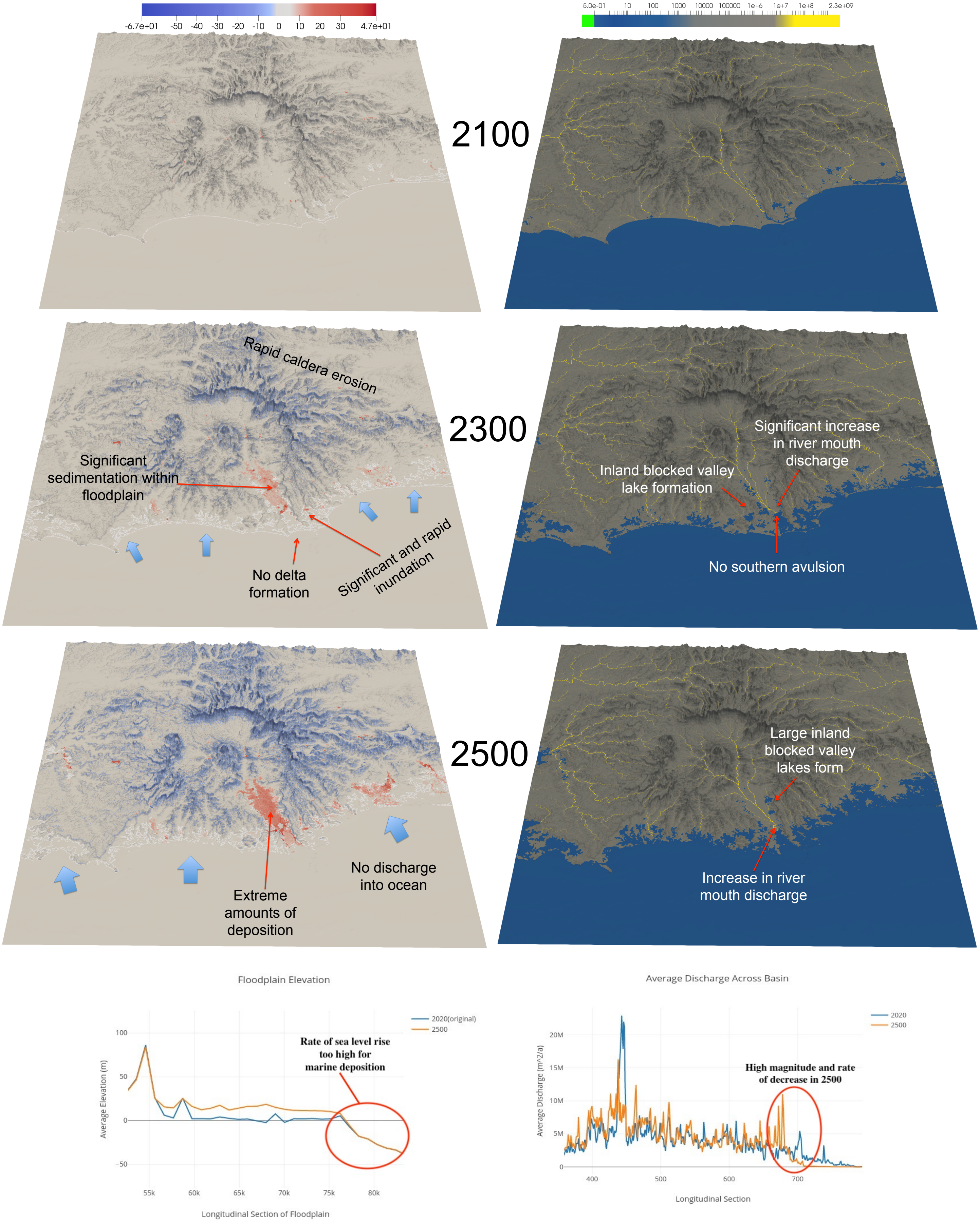


Figure 12. Visualization of RCP 8.5 with AIS contributions model output, showing erosion and deposition (top) and discharge (middle) through 2500, as well as comparisons of floodplain elevation and average basin discharge (focused on the coastal region) between 2020 and 2500 (bottom).

In the AIS 8.5 scenario, the rates of sea level rise are unimaginably high. This can be seen by the fact that no sediment ever gets deposited into the ocean, and is instead all being deposited within the floodplain. This results in the rise of the landscape by ~20 m in some areas of the floodplain. Inundation is so significant that the coastline is no longer recognizable within the first few centuries. Throughout the entire scenario, sea levels are the main control over landscape impacts.

Precipitation Scenario

Five Percent Increase by 2100

Under the first precipitation scenario, the same 10% increase in precipitation by 2100 is used, but sea levels are held constant. Model output shows a noticeably different impact when there is no variation in sea level (Figure 13).

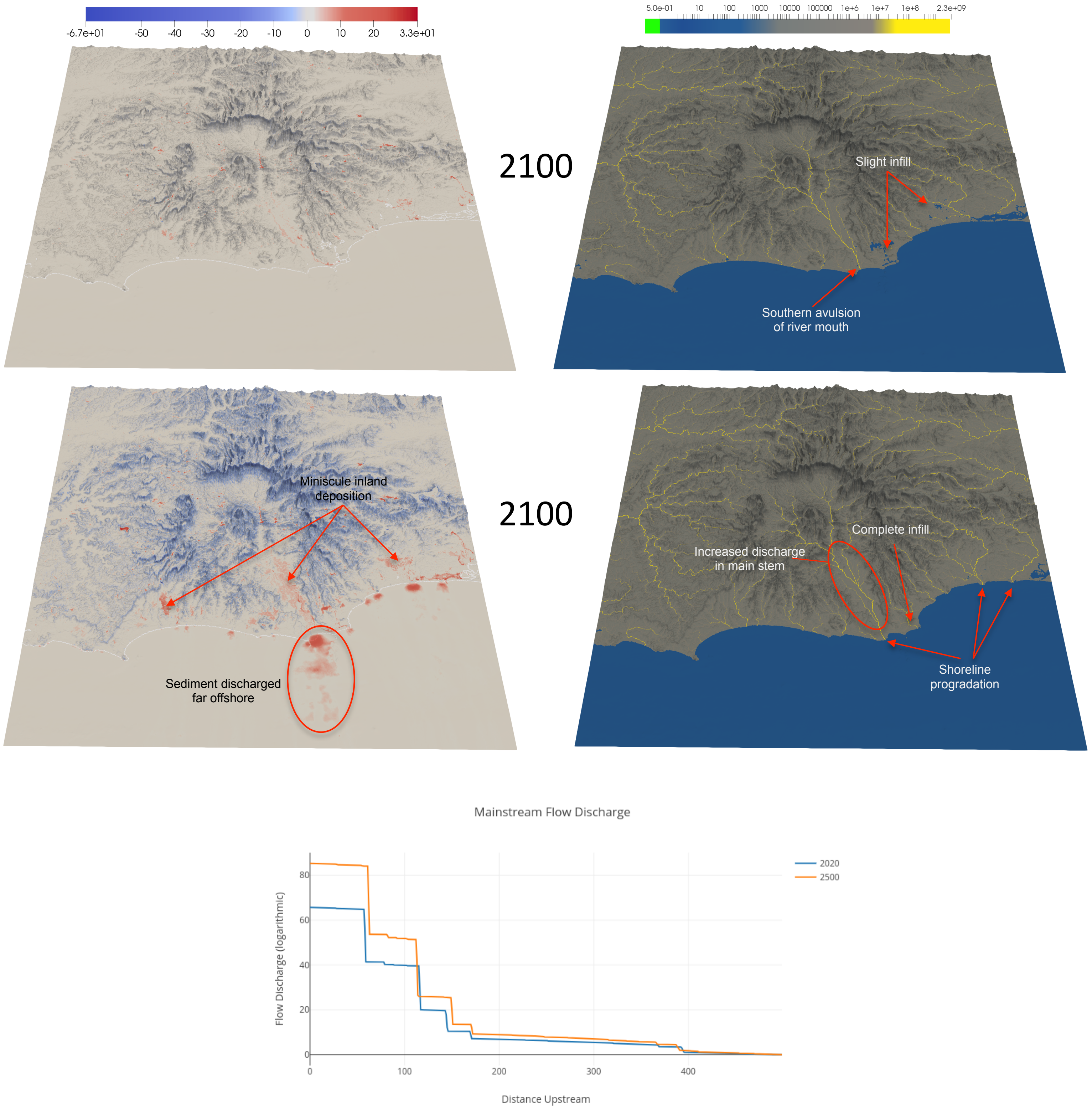
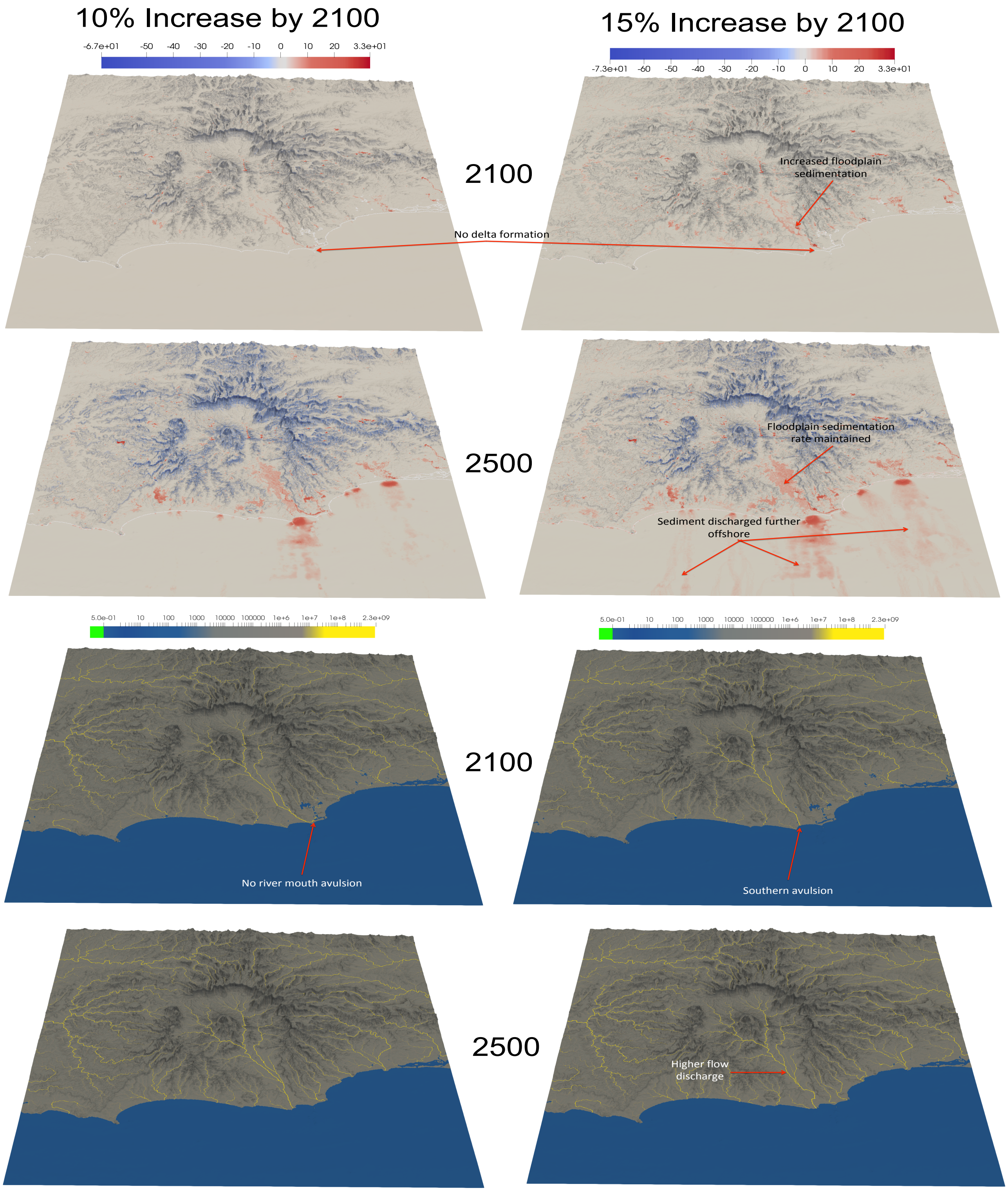


Figure 13. Visualization of the basin under a 5% increase in precipitation by 2100, followed by a constant rate. 2100 (left) 2500 (right)

Ten Percent and Fifteen Percent Increase by 2100

Under the precipitation scenarios, model output shows relatively the same dynamics occurring, but at different magnitudes. When the landscape was put under a stress of 10% and 15% increases to precipitation rates by 2100, most effects were seen within the floodplain and in the marine environments in which sediment is being discharged (Figure 14).



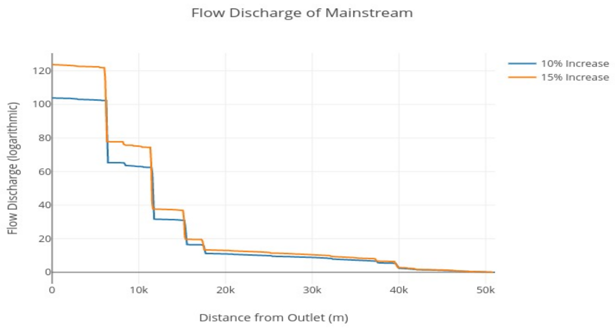


Figure 14. Comparison of precipitation scenarios with stable sea levels and a 10% (left) and 15% (right) increase in precipitation. Visualization of erosion, deposition, discharge variations and the subsequent landscape impacts are shown.

The precipitation scenarios illustrate how much of an influence sea level rise actually has on the landscape dynamics of this region. Comparatively, when holding sea levels constant, there is much less of an effect seen to the landscapes. Even with large increases in precipitation (10% & 15%), the landscape is fairly unaffected. Most sediment ends up in the oceans and massive deltas are formed. Some sediment does end up within the floodplain, but not enough is deposited to see the same kind of effects seen in other scenarios (RCP & AIS scenarios).

Scenario Comparisons

A qualitative analysis of the model output demonstrates some clear differences in the impacts to landscape between each climatic scenario. It is also clear that the majority of the effects occur in the floodplain of the caldera, where the Tweed River is transporting/depositing sediment. In order to better understand these effects, I analyzed the impacts of each scenario to elevation and discharge within the floodplain (Figures 8-14) as well as a comparison of these impacts between all the different climatic scenarios (Figures 15 & 16).

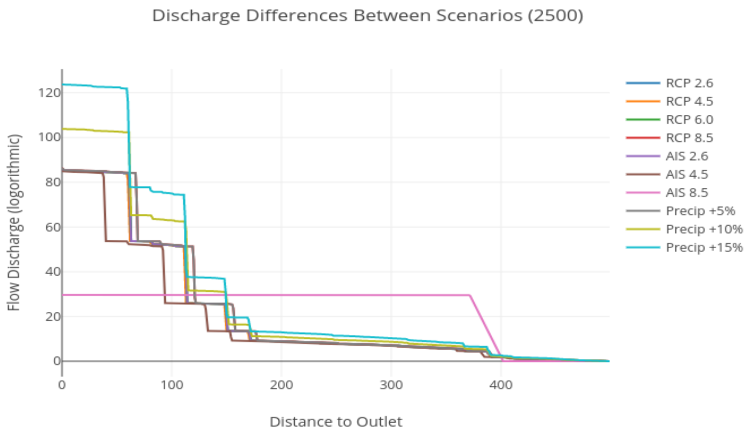


Figure 15. Comparison of discharge rates within the Tweed River by 2500, under different climatic scenarios.

Analyzing the differences between scenarios of discharge within the Tweed River by 2500 shows that climate not only impacts dynamics of the region, but that altering the magnitude and rate of change of climate can impact the dynamics differently. Under extreme scenarios like AIS 8.5, there are subsequent extreme impacts, but under for more mild scenarios like RCPs 2.6, 4.5 & 6.0, the impacts are relatively similar and a lot less extreme. The precipitation scenarios show that when sea levels are held constant, but precipitation is increased there is a significant increase in discharge throughout the stream. Even when precipitation rate are identical between precipitation scenario +5% and all the RCP/AIS scenarios, there is still a greater increase in discharge of the mainstream when sea level rise is not a factor.

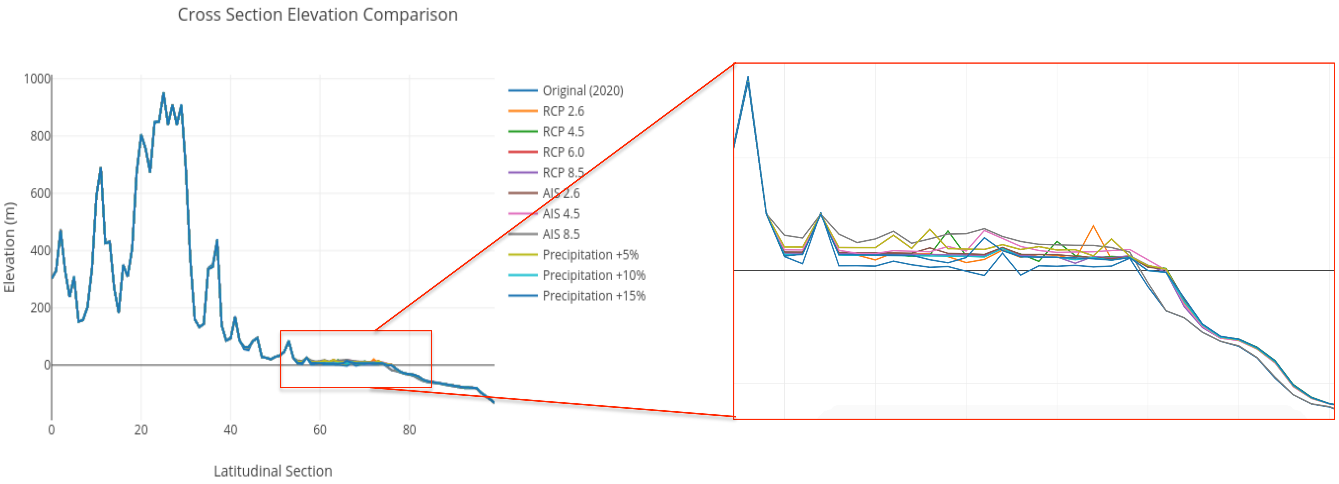


Figure 16. Cross section comparison of the elevation differences between scenarios by 2500 (left) and the cross section comparison zoomed in on the floodplain region (right).

Analyzing the comparison of impacts to elevation, again shows that climate does impact landscape and those impacts can differ under different climates. Figure 16 clearly shows that the greatest impact is experienced in the floodplain where elevation is increased in all scenarios (compared to 2020 levels), and to a lesser degree in areas of high relief where a decrease in elevation is seen due to erosion. Figure 16 also shows the differences in where the Tweed River meets the Pacific Ocean, which is further inland for the original (2020) conditions and the AIS 8.5 scenario, but is pushed further into the ocean under all other scenarios. Differences in deltas can also be seen in the areas under 0 meters elevation.

Discussion/Conclusion

In this study, I used Badlands to project how plausible future climatic scenarios could influence the local dynamics of the Tweed Caldera basin show that climate does impact landscape and local dynamics. Although the results are not being analyzed as actual projections, they can be useful for other conclusions. Based on the differences between the model output (basin impacts) of different model scenarios, I can conclude that climate does influence landscape evolution on a drainage basin scale; I also can observe where in the basin climate is having the most influence and how local dynamics (i.e. topography, fluvial dynamics, etc.) are playing a role in those impacts. Another observation that is potentially useful is the common impacts that occur in a majority or all of the scenarios. These reoccurring effects could be significant to the actual response of the modeled basin to climatic change, in the real world.

All scenarios see a relatively small basin wide elevation change by 2500 due to the erosion occurring. The effect is more prominent in the caldera areas with high relief. The effect is less prominent in the flatter areas of the basin and sometimes even reversed in the floodplain in which an increase in elevation can be seen when a cross section is taken and analyzed (Figures 9, 11 & 12). This impact to local elevation has much to do with the amount of sediment being eroded in each scenario and is therefore highly controlled by the changing precipitation rates, but as shown by the model output, it is also controlled by the rate of sea level rise. The model output demonstrates that sea levels have a control over where sediment is deposited (into the ocean or upstream). Once sea level rise reaches a certain threshold, sediment within the mainstream begins being deposited upstream throughout the floodplain rather than building deltas in the marine environments; the same effect is observed for the smaller streams throughout the catchment that are transporting sediment. This phenomenon can be observed with a SLR rate equal to and greater than that seen in RCP/ECP 4.5 (Figures 9, 10, 11, &12), but is absent in scenarios with lower or stable SLR rates (Figures 8, 13, 14 & Appendix A). This has to do with the control of accommodation (the available space for sediment to be deposited) on deposition and the impact that sea level changes have on accommodation space. With a rise in local relative sea levels, accommodation is simultaneously affected in a way that forces sediment to accumulate upstream within the river channels that are transporting sediment, as well as in the overbank areas. Due to the fact that the Tweed River is a mature stream, it has developed an equilibrium profile in which erosion is occurring in the upper tracts of the stream and subsequently being deposited in the marine environment, forming deltas. Once climatic changes are drastic enough to significantly impact stream dynamics via increased sediment loads and/or changes in accommodation, then the profile is disturbed and thrown out of equilibrium. This is seen in the majority of model runs, with the exception of the precipitation only scenarios. This demonstrates that local dynamics within the Tweed catchment are heavily influenced by sea levels and subsequently are sensitive to shifts in climate. This impact in the real world would have major socioeconomic and ecological consequences. Imbalances in the sediment load of rivers, like those seen in all model scenarios, can force changes in tidal marshes, shoaling, infill of channels, benthic and aquatic habitats and overall productivity (Phillips, 1991). The Tweed estuary is a World Heritage Area due to the ancient littoral rainforests, mangroves, saltmarshes, sea grasses and wildlife within (Tweed, 2018). Sudden changes to these environments would most likely have adverse impacts. Also, towns built around the waterways within the Tweed catchment (i.e. Tweed Heads, Gold Coast, Lismore, etc.) would have to deal with these environmental changes.

Some model scenarios show that although the overall shoreline pattern is a transgression, there can be regression at the mouths of rivers (Figures 8 & 9). This means that although sea level rise should be forcing a retreat of shorelines, there are some scenarios in which this effect can be overpowered at river mouths by the amount of sediment being eroded/transported. This effect is only seen in RCPs 4.5 and 6.0 in which sea level rise is moderate enough and erosion is significant enough to allow for shoreline transgression, with shoreline regression occurring only at select river mouths where the sediment load is large enough to allow for growth. Regression at the river mouths is accentuated under RCP 4.5 conditions compared to RCP 6.0, showing once again that sea level has a significant control on the local landscape evolution. This impact seen at the river mouth also coincides with changes in delta formation. In some scenarios, delta progradation occurs throughout most or the entirety of the model run (Figures 8, 9, 13 & 14). While under other scenarios with greater SLR influence, deltas either cease to be fed by the river or aren’t being noticeably generated from the beginning (Figures 10, 11 & 12). Changes to deltas can have significant ecological and socioeconomic impacts.

Infill of waterways and other bodies of water occurs throughout all scenarios due to the increased erosion caused by the increased precipitation rates. When SLR rates are relatively low (RCPs 2.6, 4.5, 6.0, AIS scenario 2.6 & precipitation scenarios) infill occurs quickly, causing river avulsions. In the higher SLR scenarios (RCP 8.5 & AIS scenarios 4.5 & 8.5), landscape response is much more complex. Coastal flooding occurs in all of these scenarios, mainly where rivers or streams are present (Figures10, 11 & 12). In extreme SLR scenarios, like AIS 4.5 and 8.5, all catchment response to the changing climate is essentially overpowered by the significant inundation that occurs by 2500. In scenarios in which sea level is significant enough, but not overpowering (RCP 8.5), or in the extreme SLR scenarios, but before the inundation effect is too overpowering, the formation of inland blocked-valley lakes can be observed. This is caused by the previously mentioned accommodation effect pushing deposition upstream. As the increased sediment load, caused by the increased erosion occurring, starts being deposited upstream and not into the deltas in the ocean, aggradation starts occurring. Many of the smaller tributaries of the mainstream, or some of the larger streams in the catchment, are unable to aggrade at the same rate as those larger streams. This essentially creates a natural dam and floods the smaller tributaries, effectively creating the inland blocked-valley lakes. The formation of these lakes would have ecological and socioeconomic impacts as they form within ecosystems and flood towns.

Another impact that is consistently seen throughout all model scenarios are changes in discharge at the mouth of the mainstream over time and between scenarios. This impact is most noticeable within the mainstream (Tweed River) and throughout the floodplain. This most likely is due to the increased sediment load over time and between scenarios. Increased sediment within streams, due to increased precipitation as well as sea level/accommodation forcing, results in variations in river discharge and downstream incision. Also, channel shape changes as the riverbeds aggrade and streams avulse, contributing to the changes in discharge.

The ice sheet scenarios projected by DeConto and Pollard that I applied to the Tweed Caldera basin and ran in Badlands vary greatly from RCP 2.6 to RCP 8.5. This has to do with tipping points being hit within the ice sheet due to warming, followed by rapid impacts to the AIS and global sea levels. As previously talked about, tipping points within ice sheets are a relatively uncertain concept. My model output is a good example of why a greater knowledge of tipping points within ice sheets needs to be better understood. Under AIS scenario 2.6 very miniscule impacts are observed (Appendix A), but under AIS scenarios 4.5 and 8.5 the impacts to the basin landscape are extreme. Inundation, as expected, is drastic and almost all sedimentation is stuffed within the floodplain. Landscape responses like these would have dire consequences for both human society's and ecosystems.

In general, the model output shows that when the Tweed Caldera drainage basin experiences a shift in climate, the subsequent impacts affect erosion, deposition, discharge, elevation, relief and the overall evolution the local landscape (hydromorphic and geomorphic). Specific landscape effects due to climatic changes are unique to each scenario and can differ greatly between each other. This shows that landscape impacts are unique to the rate and magnitude of climatic shifts and are relatively difficult to predict. The implications of this are that as predictions and models become more precise and representative of real world dynamics, studies will need to be specific towards smaller scale, local areas and climate. This will allow for a better understanding of the local dynamics and how they interact with environmental changes. This would also give more in depth insight into the future landscape impacts of climate change on a more refined regional scale.

This study started with the question: will future shifts in climate impact the landscape of the Tweed Caldera basin and if so what are the impacts. Overall, I was able to show that climate does indeed affect the chosen region's landscape and was able to give some insight into those effects. This study and other similar studies are essential as the world continues to see a more drastically and rapidly changing climate. The information LEMs, like Badlands, can give us is imperative for making decisions on the prevention and mitigation of climate change and its adverse impacts.

Suggestions

In the future, using the Monte Carlo method and running a large volume of models under random climatic inputs could give more statistically significant output that could be more easily analyzed. This method would allow for a more probable prediction of different landscape impacts of the chosen region. Also, coupling Badlands with a model that accounts for vegetation dynamics and shoreline erosion would improve model output and the subsequent conclusions of the study. These dynamics are extremely important for properly understanding the impacts from climate change to the region being modeled. Finally, in this study a lower resolution DEM (100 m) had to be used due to the lack of availability of higher resolution data. This demonstrates the need for the Australian government, and other governments, to either fund the collection of higher resolution data or make the data more readily available and/or easily accessible.

If similar scenarios and effects occur within a real world setting, governments will need to be extremely wary of these possible impacts and should have similar studies commissioned to gain more insight into how the unique region they live in could be impacted in the future. Coastal regions with floodplains (similar to the Tweed floodplain) will most likely be forced to either implement some forms of mitigation to these impacts or in the worst-case scenarios, abandon high-risk areas. These strategies will be extremely costly and impact a significant amount of people, due to the fact that the majority of people live in coastal areas. A better understanding of the interaction between a changing climate and the local dynamics of at-risk areas is essential in order to bring these costs down and possibly save lives.

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Appendices

Appendix A: