Title: The multi-millennial Antarctic commitment to future sea-level rise

Published: 2015

Abstract: Atmospheric warming is projected to increase global mean surface temperatures by 0.3 to 4.8 degrees Celsius above pre-industrial values by the end of this century1. If anthropogenic emissions continue unchecked, the warming increase may reach 8–10 degrees Celsius by 2300 (ref. 2). The contribution that large ice sheets will make to sea-level rise under such warming scenarios is difficult to quantify because the equilibrium-response timescale of ice sheets is longer than those of the atmosphere or ocean. Here we use a coupled ice-sheet/ice-shelf model to show that if atmospheric warming exceeds 1.5 to 2 degrees Celsius above present, collapse of the major Antarctic ice shelves triggers a centennial- to millennial-scale response of the Antarctic ice sheet in which enhanced viscous flow produces a long-term commitment (an unstoppable contribution) to sea-level rise. Our simulations represent the response of the present-day Antarctic ice-sheet system to the oceanic and climatic changes of four representative concentration pathways (RCPs) from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change3. We find that substantial Antarctic ice loss can be prevented only by limiting greenhouse gas emissions to RCP 2.6 levels. Higher-emissions scenarios lead to ice loss from Antarctic that will raise sea level by 0.6–3 metres by the year 2300. Our results imply that greenhouse gas emissions in the next few decades will strongly influence the long-term contribution of the Antarctic ice sheet to global sea level.

Title: Synthesizing long-term sea level rise projections – the MAGICC sea level model v2.0

Published: 2017

Abstract: Sea level rise (SLR) is one of the major impacts of global warming; it will threaten coastal populations, infrastructure, and ecosystems around the globe in coming centuries. Well-constrained sea level projections are needed to estimate future losses from SLR and benefits of climate protection and adaptation. Process-based models that are designed to resolve the underlying physics of individual sea level drivers form the basis for state-of-the-art sea level projections. However, associated computational costs allow for only a small number of simulations based on selected scenarios that often vary for different sea level components. This approach does not sufficiently support sea level impact science and climate policy analysis, which require a sea level projection methodology that is flexible with regard to the climate scenario yet comprehensive and bound by the physical constraints provided by process-based models. To fill this gap, we present a sea level model that emulates global-mean long-term process-based model projections for all major sea level components. Thermal expansion estimates are calculated with the hemispheric upwelling-diffusion ocean component of the simple carbon-cycle climate model MAGICC, which has been updated and calibrated against CMIP5 ocean temperature profiles and thermal expansion data. Global glacier contributions are estimated based on a parameterization constrained by transient and equilibrium process-based projections. Sea level contribution estimates for Greenland and Antarctic ice sheets are derived from surface mass balance and solid ice discharge parameterizations reproducing current output from ice-sheet models. The land water storage component replicates recent hydrological modeling results. For 2100, we project 0.35 to 0.56 m (66 % range) total SLR based on the RCP2.6 scenario, 0.45 to 0.67 m for RCP4.5, 0.46 to 0.71 m for RCP6.0, and 0.65 to 0.97 m for RCP8.5. These projections lie within the range of the latest IPCC SLR estimates. SLR projections for 2300 yield median responses of 1.02 m for RCP2.6, 1.76 m for RCP4.5, 2.38 m for RCP6.0, and 4.73 m for RCP8.5. The MAGICC sea level model provides a flexible and efficient platform for the analysis of major scenario, model, and climate uncertainties underlying long-term SLR projections. It can be used as a tool to directly investigate the SLR implications of different mitigation pathways and may also serve as input for regional SLR assessments via component-wise sea level pattern scaling.

Title: Risk of isolation increases the expected burden from sea-level rise

Published: 2023

Abstract: The typical displacement metric for sea-level rise adaptation planning is property inundation. However, this metric may underestimate risk as it does not fully capture the wider cascading or indirect effects of sea-level rise. To address this, we propose complementing it by considering the risk of population isolation: those who may be cut off from essential services. We investigate the importance of this metric by comparing the number of people at risk from inundation to the number of people at risk from isolation. Considering inundated roadways during mean higher high water tides in the coastal United States shows, although highly spatially variable, that the increase across the United States varies between 30% and 90% and is several times higher in some states. We find that risk of isolation may occur decades sooner than risk of inundation. Both risk metrics provide critical information for evaluating adaptation options and giving priority to support for at-risk communities.

Title: Loss of cultural world heritage and currently inhabited places to sea-level rise

Published: 2014

Abstract: The world population is concentrated near the coasts, as are a large number of Cultural World Heritage sites, defined by the UNESCO. Using spatially explicit sea-level estimates for the next 2000 years and high-resolution topography data, we compute which current cultural heritage sites will be affected by sea-level rise at different levels of sustained future warming. As indicators for the pressure on future cultural heritage we estimate the percentage of each country's area loss, and the percentage of current population living in regions that will be permanently below sea level, for different temperature levels. If the current global mean temperature was sustained for the next two millennia, about 6% (40 sites) of the UNESCO sites will be affected, and 0.7% of global land area will be below mean sea level. These numbers increase to 19% (136 sites) and 1.1% for a warming of 3 K. At this warming level, 3–12 countries will experience a loss of more than half of their current land surface, 25–36 countries lose at least 10% of their territory, and 7% of the global population currently lives in regions that will be below local sea level. Given the millennial scale lifetime of carbon dioxide in the atmosphere, our results indicate that fundamental decisions with regard to mankind's cultural heritage are required.

Title: Dynamics of sea level rise and coastal flooding on a changing landscape

Published: 2014

Abstract: Standard approaches to determining the impacts of sea level rise (SLR) on storm surge flooding employ numerical models reflecting present conditions with modified sea states for a given SLR scenario. In this study, we advance this paradigm by adjusting the model framework so that it reflects not only a change in sea state but also variations to the landscape (morphologic changes and urbanization of coastal cities). We utilize a numerical model of the Mississippi and Alabama coast to simulate the response of hurricane storm surge to changes in sea level, land use/land cover, and land surface elevation for past (1960), present (2005), and future (2050) conditions. The results show that the storm surge response to SLR is dynamic and sensitive to changes in the landscape. We introduce a new modeling framework that includes modification of the landscape when producing storm surge models for future conditions.

Title: Anthropogenic forcing dominates global mean sea-level rise since 1970

Published: 2016

Abstract: Sea-level change is an important consequence of anthropogenic climate change, as higher sea levels increase the frequency of sea-level extremes and the impact of coastal flooding and erosion on the coastal environment, infrastructure and coastal communities1,2. Although individual attribution studies have been done for ocean thermal expansion3,4 and glacier mass loss5, two of the largest contributors to twentieth-century sea-level rise, this has not been done for the other contributors or total global mean sea-level change (GMSLC). Here, we evaluate the influence of greenhouse gases (GHGs), anthropogenic aerosols, natural radiative forcings and internal climate variability on sea-level contributions of ocean thermal expansion, glaciers, ice-sheet surface mass balance and total GMSLC. For each contribution, dedicated models are forced with results from the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model archive6. The sum of all included contributions explains 74 ± 22% (±2σ) of the observed GMSLC over the period 1900–2005. The natural radiative forcing makes essentially zero contribution over the twentieth century (2 ± 15% over the period 1900–2005), but combined with the response to past climatic variations explains 67 ± 23% of the observed rise before 1950 and only 9 ± 18% after 1970 (38 ± 12% over the period 1900–2005). In contrast, the anthropogenic forcing (primarily a balance between a positive sea-level contribution from GHGs and a partially offsetting component from anthropogenic aerosols) explains only 15 ± 55% of the observations before 1950, but increases to become the dominant contribution to sea-level rise after 1970 (69 ± 31%), reaching 72 ± 39% in 2000 (37 ± 38% over the period 1900–2005).

Title: The vulnerability of Indo-Pacific mangrove forests to sea-level rise

Published: 2015

Abstract: Sea-level rise can threaten the long-term sustainability of coastal communities and valuable ecosystems such as coral reefs, salt marshes and mangroves1,2. Mangrove forests have the capacity to keep pace with sea-level rise and to avoid inundation through vertical accretion of sediments, which allows them to maintain wetland soil elevations suitable for plant growth3. The Indo-Pacific region holds most of the world’s mangrove forests4, but sediment delivery in this region is declining, owing to anthropogenic activities such as damming of rivers5. This decline is of particular concern because the Indo-Pacific region is expected to have variable, but high, rates of future sea-level rise6,7. Here we analyse recent trends in mangrove surface elevation changes across the Indo-Pacific region using data from a network of surface elevation table instruments8,9,10. We find that sediment availability can enable mangrove forests to maintain rates of soil-surface elevation gain that match or exceed that of sea-level rise, but for 69 per cent of our study sites the current rate of sea-level rise exceeded the soil surface elevation gain. We also present a model based on our field data, which suggests that mangrove forests at sites with low tidal range and low sediment supply could be submerged as early as 2070.

Title: Salt marsh persistence is threatened by predicted sea-level rise

Published: 2016

Abstract: Salt marshes buffer coastlines and provide critical ecosystem services from storm protection to food provision. Worldwide, these ecosystems are in danger of disappearing if they cannot increase elevation at rates that match sea-level rise. However, the magnitude of loss to be expected is not known. A synthesis of existing records of salt marsh elevation change was conducted in order to consider the likelihood of their future persistence. This analysis indicates that many salt marshes did not keep pace with sea-level rise in the past century and kept pace even less well over the past two decades. Salt marshes experiencing higher local sea-level rise rates were less likely to be keeping pace. These results suggest that sea-level rise will overwhelm most salt marshes’ capacity to maintain elevation. Under the most optimistic IPCC emissions pathway, 60% of the salt marshes studied will be gaining elevation at a rate insufficient to keep pace with sea-level rise by 2100. Without mitigation of greenhouse gas emissions this potential loss could exceed 90%, which will have substantial ecological, economic, and human health consequences.

Title: Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding

Published: 2018

Abstract: Sea levels are rising, with the highest rates in the tropics, where thousands of low-lying coral atoll islands are located. Most studies on the resilience of these islands to sea-level rise have projected that they will experience minimal inundation impacts until at least the end of the 21st century. However, these have not taken into account the additional hazard of wave-driven overwash or its impact on freshwater availability. We project the impact of sea-level rise and wave-driven flooding on atoll infrastructure and freshwater availability under a variety of climate change scenarios. We show that, on the basis of current greenhouse gas emission rates, the nonlinear interactions between sea-level rise and wave dynamics over reefs will lead to the annual wave-driven overwash of most atoll islands by the mid-21st century. This annual flooding will result in the islands becoming uninhabitable because of frequent damage to infrastructure and the inability of their freshwater aquifers to recover between overwash events. This study provides critical information for understanding the timing and magnitude of climate change impacts on atoll islands that will result in significant, unavoidable geopolitical issues if it becomes necessary to abandon and relocate low-lying island states.

Title: Can We Model the Effect of Observed Sea Level Rise on Tides?

Published: 2018

Abstract: The link between secular changes in the lunar semidiurnal ocean tide (M2) and relative sea level rise is examined based on numerical tidal modeling and the analysis of long-term sea level records from Europe, Australia, and the North American Atlantic coasts. The study sets itself apart from previous work by using a 1/12° global tide model that incorporates the effects of self-attraction and loading through time-step-wise spherical harmonic transforms instead of iteration. This novel self-attraction and loading implementation incurs moderate computational overheads (some 50%) and facilitates the simulation of shelf sea tides with a global root mean square error of 14.6 cm in depths shallower than 1,000 m. To reproduce measured tidal changes in recent decades, the model is perturbed with realistic water depth changes, compiled from maps of altimetric sea level trends and postglacial crustal rebound. The M2 response to the adopted sea level rise scenarios exhibits peak sensitivities in the North Atlantic and many marginal seas, with relative magnitudes of 1–5% per century. Comparisons with a collection of 45 tide gauge records reveals that the model reproduces the sign of the observed amplitude trends in 80% of the cases and captures considerable fractions of the absolute M2 variability, specifically for stations in the Gulf of Mexico and the Chesapeake-Delaware Bay system. While measured-to-model disparities remain large in several key locations, such as the European Shelf, the study is deemed a major step toward credible predictions of secular changes in the main components of the ocean tide.

Title: Is the detection of accelerated sea level rise imminent?

Published: 2016

Abstract: Global mean sea level rise estimated from satellite altimetry provides a strong constraint on climate variability and change and is expected to accelerate as the rates of both ocean warming and cryospheric mass loss increase over time. In stark contrast to this expectation however, current altimeter products show the rate of sea level rise to have decreased from the first to second decades of the altimeter era. Here, a combined analysis of altimeter data and specially designed climate model simulations shows the 1991 eruption of Mt Pinatubo to likely have masked the acceleration that would have otherwise occurred. This masking arose largely from a recovery in ocean heat content through the mid to late 1990 s subsequent to major heat content reductions in the years following the eruption. A consequence of this finding is that barring another major volcanic eruption, a detectable acceleration is likely to emerge from the noise of internal climate variability in the coming decade.

Title: Communicating future sea-level rise uncertainty and ambiguity to assessment users

Published: 2023

Abstract: Future sea-level change is characterized by both quantifiable and unquantifiable uncertainties. Effective communication of both types of uncertainty is a key challenge in translating sea-level science to inform long-term coastal planning. Scientific assessments play a key role in the translation process and have taken diverse approaches to communicating sea-level projection uncertainty. Here we review how past IPCC and regional assessments have presented sea-level projection uncertainty, how IPCC presentations have been interpreted by regional assessments and how regional assessments and policy guidance simplify projections for practical use. This information influenced the IPCC Sixth Assessment Report presentation of quantifiable and unquantifiable uncertainty, with the goal of preserving both elements as projections are adapted for regional application.

Title: A High-End Estimate of Sea Level Rise for Practitioners

Published: 2022

Abstract: Sea level rise (SLR) is a long-lasting consequence of climate change because global anthropogenic warming takes centuries to millennia to equilibrate for the deep ocean and ice sheets. SLR projections based on climate models support policy analysis, risk assessment and adaptation planning today, despite their large uncertainties. The central range of the SLR distribution is estimated by process-based models. However, risk-averse practitioners often require information about plausible future conditions that lie in the tails of the SLR distribution, which are poorly defined by existing models. Here, a community effort combining scientists and practitioners builds on a framework of discussing physical evidence to quantify high-end global SLR for practitioners. The approach is complementary to the IPCC AR6 report and provides further physically plausible high-end scenarios. High-end estimates for the different SLR components are developed for two climate scenarios at two timescales. For global warming of +2°C in 2100 (RCP2.6/SSP1-2.6) relative to pre-industrial values our high-end global SLR estimates are up to 0.9 m in 2100 and 2.5 m in 2300. Similarly, for a (RCP8.5/SSP5-8.5), we estimate up to 1.6 m in 2100 and up to 10.4 m in 2300. The large and growing differences between the scenarios beyond 2100 emphasize the long-term benefits of mitigation. However, even a modest 2°C warming may cause multi-meter SLR on centennial time scales with profound consequences for coastal areas. Earlier high-end assessments focused on instability mechanisms in Antarctica, while here we emphasize the importance of the timing of ice shelf collapse around Antarctica. This is highly uncertain due to low understanding of the driving processes. Hence both process understanding and emission scenario control high-end SLR.

Title: Predicting marsh vulnerability to sea-level rise using Holocene relative sea-level data

Published: 2018

Abstract: Tidal marshes rank among Earth’s vulnerable ecosystems, which will retreat if future rates of relative sea-level rise (RSLR) exceed marshes’ ability to accrete vertically. Here, we assess the limits to marsh vulnerability by analyzing >780 Holocene reconstructions of tidal marsh evolution in Great Britain. These reconstructions include both transgressive (tidal marsh retreat) and regressive (tidal marsh expansion) contacts. The probability of a marsh retreat was conditional upon Holocene rates of RSLR, which varied between −7.7 and 15.2 mm/yr. Holocene records indicate that marshes are nine times more likely to retreat than expand when RSLR rates are ≥7.1 mm/yr. Coupling estimated probabilities of marsh retreat with projections of future RSLR suggests a major risk of tidal marsh loss in the twenty-first century. All of Great Britain has a >80% probability of a marsh retreat under Representative Concentration Pathway (RCP) 8.5 by 2100, with areas of southern and eastern England achieving this probability by 2040.

Title: Salt Marsh Dynamics in a Period of Accelerated Sea Level Rise

Published: 2020

Abstract: Salt marshes are dynamic systems able to laterally expand, contract, and vertically accrete in response to sea level rise. Here, we present the grand challenges that need to be addressed to fully characterize marsh morphodynamics. The review focuses on physical processes and quantitative models. Without predictive models, it is impossible to determine the future marsh evolution under accelerated sea level rise. In these models, one of the challenges is to resolve both horizontal and vertical dynamics within the same framework. Vertically, the marsh has to accumulate enough material to contrast rising water levels. Horizontally, marsh erosion at the ocean side must be compensated by landward expansion in forests, lawns, and agricultural fields. The dynamics of the marsh-upland boundary are still not fully understood and will require more research in the upcoming years. The complexity of marsh vegetation is seldom captured in predictive models of marsh evolution. More research is needed to understand the effects of each species or species assemblages on hydrodynamics and sediment transport. Here, we further advocate that a sediment budget resolving all sediment fluxes in a marsh complex is the most important metric of marsh resilience. Characterization of these fluxes will enable to connect salt marshes to other landforms and to unravel feedbacks controlling the evolution of the entire coastal system. Current models of marsh evolution rely on sparse data sets collected at few locations. Novel remote sensing techniques will provide high-resolution spatial data that will inform a new generation of computer models.

Title: Flood damage costs under the sea level rise with warming of 1.5 °C and 2 °C

Published: 2018

Abstract: We estimate a median global sea level rise up to 52 cm (25–87 cm, 5th–95th percentile) and up to 63 cm (27−112 cm, 5th—95th percentile) for a temperature rise of 1.5 °C and 2.0 °C by 2100 respectively. We also estimate global annual flood costs under these scenarios and find the difference of 11 cm global sea level rise in 2100 could result in additional losses of US$ 1.4 trillion per year (0.25% of global GDP) if no additional adaptation is assumed from the modelled adaptation in the base year. If warming is not kept to 2 °C, but follows a high emissions scenario (Representative Concentration Pathway 8.5), global annual flood costs without additional adaptation could increase to US$ 14 trillion per year and US$ 27 trillion per year for global sea level rise of 86 cm (median) and 180 cm (95th percentile), reaching 2.8% of global GDP in 2100. Upper middle income countries are projected to experience the largest increase in annual flood costs (up to 8% GDP) with a large proportion attributed to China. High income countries have lower projected flood costs, in part due to their high present-day protection standards. Adaptation could potentially reduce sea level induced flood costs by a factor of 10. Failing to achieve the global mean temperature targets of 1.5 °C or 2 °C will lead to greater damage and higher levels of coastal flood risk worldwide.

Title: River Deltas and Sea-Level Rise

Published: 2022

Abstract: Future sea-level rise poses an existential threat for many river deltas, yet quantifying the effect of sea-level changes on these coastal landforms remains a challenge. Sea-level changes have been slow compared to other coastal processes during the instrumental record, such that our knowledge comes primarily from models, experiments, and the geologic record. Here we review the current state of science on river delta response to sea-level change, including models and observations from the Holocene until 2300 CE. We report on improvements in the detection and modeling of past and future regional sea-level change, including a better understanding of the underlying processes and sources of uncertainty. We also see significant improvements in morphodynamic delta models. Still, substantial uncertainties remain, notably on present and future subsidence rates in and near deltas. Observations of delta submergence and land loss due to modern sea-level rise also remain elusive, posing major challenges to model validation.

Title: Amplification of flood frequencies with local sea level rise and emerging flood regimes

Published: 2017

Abstract: The amplification of flood frequencies by sea level rise (SLR) is expected to become one of the most economically damaging impacts of climate change for many coastal locations. Understanding the magnitude and pattern by which the frequency of current flood levels increase is important for developing more resilient coastal settlements, particularly since flood risk management (e.g. infrastructure, insurance, communications) is often tied to estimates of flood return periods. The Intergovernmental Panel on Climate Change's Fifth Assessment Report characterized the multiplication factor by which the frequency of flooding of a given height increases (referred to here as an amplification factor; AF). However, this characterization neither rigorously considered uncertainty in SLR nor distinguished between the amplification of different flooding levels (such as the 10% versus 0.2% annual chance floods); therefore, it may be seriously misleading. Because both historical flood frequency and projected SLR are uncertain, we combine joint probability distributions of the two to calculate AFs and their uncertainties over time. Under probabilistic relative sea level projections, while maintaining storm frequency fixed, we estimate a median 40-fold increase (ranging from 1- to 1314-fold) in the expected annual number of local 100-year floods for tide-gauge locations along the contiguous US coastline by 2050. While some places can expect disproportionate amplification of higher frequency events and thus primarily a greater number of historically precedented floods, others face amplification of lower frequency events and thus a particularly fast growing risk of historically unprecedented flooding. For example, with 50 cm of SLR, the 10%, 1%, and 0.2% annual chance floods are expected respectively to recur 108, 335, and 814 times as often in Seattle, but 148, 16, and 4 times as often in Charleston, SC.

Title: Framework for High-End Estimates of Sea Level Rise for Stakeholder Applications

Published: 2019

Abstract: An approach to analyze high-end sea level rise is presented to provide a conceptual framework for high-end estimates as a function of time scale, thereby linking robust sea level science with stakeholder needs. Instead of developing and agreeing on a set of high-end sea level rise numbers or using an expert consultation, our effort is focused on the essential task of providing a generic conceptual framework for such discussions and demonstrating its feasibility to address this problem. In contrast, information about high-end sea level rise projections was derived previously either from a likely range emerging from the highest view of emissions in the Intergovernmental Panel on Climate Change assessment (currently the Representative Concentration Pathway 8.5 scenario) or from independent ad hoc studies and expert solicitations. Ideally, users need high-end sea level information representing the upper tail of a single joint sea level frequency distribution, which considers all plausible yet unknown emission scenarios as well as involved physical mechanisms and natural variability of sea level, but this is not possible. In the absence of such information we propose a framework that would infer the required information from explicit conditional statements (lines of evidence) in combination with upper (plausible) physical bounds. This approach acknowledges the growing uncertainty in respective estimates with increasing time scale. It also allows consideration of the various levels of risk aversion of the diverse stakeholders who make coastal policy and adaptation decisions, while maintaining scientific rigor.

Title: Potential sea-level rise from Antarctic ice-sheet instability constrained by observations

Published: 2015

Abstract: Large parts of the Antarctic ice sheet lying on bedrock below sea level may be vulnerable to marine-ice-sheet instability (MISI)1, a self-sustaining retreat of the grounding line triggered by oceanic or atmospheric changes. There is growing evidence2,3,4 that MISI may be underway throughout the Amundsen Sea embayment (ASE), which contains ice equivalent to more than a metre of global sea-level rise. If triggered in other regions5,6,7,8, the centennial to millennial contribution could be several metres. Physically plausible projections are challenging9: numerical models with sufficient spatial resolution to simulate grounding-line processes have been too computationally expensive2,3,10 to generate large ensembles for uncertainty assessment, and lower-resolution model projections11 rely on parameterizations that are only loosely constrained by present day changes. Here we project that the Antarctic ice sheet will contribute up to 30 cm sea-level equivalent by 2100 and 72 cm by 2200 (95% quantiles) where the ASE dominates. Our process-based, statistical approach gives skewed and complex probability distributions (single mode, 10 cm, at 2100; two modes, 49 cm and 6 cm, at 2200). The dependence of sliding on basal friction is a key unknown: nonlinear relationships favour higher contributions. Results are conditional on assessments of MISI risk on the basis of projected triggers under the climate scenario A1B (ref. 9), although sensitivity to these is limited by theoretical and topographical constraints on the rate and extent of ice loss. We find that contributions are restricted by a combination of these constraints, calibration with success in simulating observed ASE losses, and low assessed risk in some basins. Our assessment suggests that upper-bound estimates from low-resolution models and physical arguments9 (up to a metre by 2100 and around one and a half by 2200) are implausible under current understanding of physical mechanisms and potential triggers.

Title: Role of perturbing ocean initial condition in simulated regional sea level change

Published: 2017

Abstract: Multiple lines of observational evidence indicate that the global climate has been getting warmer since the early 20th century. This warmer climate has led to a global mean sea level rise of about 18 cm during the 20th century, and over 6 cm for the first 15 years of the 21st century. Regionally the sea level rise is not uniform due in large part to internal climate variability. To better serve the community, the uncertainties of predicting/projecting regional sea level changes associated with internal climate variability need to be quantified. Previous research on this topic has used single-model large ensembles with perturbed atmospheric initial conditions (ICs). Here we compare uncertainties associated with perturbing ICs in just the atmosphere and just the ocean using a state-of-the-art coupled climate model. We find that by perturbing the oceanic ICs, the uncertainties in regional sea level changes increase compared to those with perturbed atmospheric ICs. Thus, in order for us to better assess the full spectrum of the impacts of such internal climate variability on regional and global sea level rise, approaches that involve perturbing both atmospheric and oceanic initial conditions are necessary.

Title: Coevolution of Extreme Sea Levels and Sea‐Level Rise Under Global Warming

Published: 2023

Abstract: Design of coastal defense structures like seawalls and breakwaters can no longer be based on stationarity assumption. In many parts of the world, an anticipated sea‐level rise (SLR) due to climate change will constitute present‐day extreme sea levels inappropriate for future coastal flood risk assessments since it will significantly increase their probability of occurrence. Here, we first show that global annual maxima sea levels (AMSLs) have been increasing in magnitude over the last decades, primarily due to a positive shift in mean sea level (MSL). Then, we apply non‐stationary extreme value theory to model the extremal behavior of sea levels with MSL as a covariate and quantify the evolution of AMSLs in the following decades using revised probabilistic sea‐level rise projections. Our analysis reveals that non‐stationary distributions exhibit distinct differences compared to simply considering stationary conditions with a change in location parameter equal to the amount of MSL rise. With the use of non‐stationary distributions, we show that by the year 2050 many locations will experience their present‐day 100‐yr return level as an event with return period less than 15 and 9 years under the moderate (RCP4.5) and high (RCP8.5) representative concentration pathways. Also, we find that by the end of this century almost all locations examined will encounter their current 100‐yr return level on an annual basis, even if CO2 concentration is kept at moderate levels (RCP4.5). Our findings highlight the importance of considering the non‐stationary nature of sea levels in coastal risk assessments.

Title: Communicating Climate Change Oceanically: Sea Level Rise Information Increases Mitigation, Inundation, and Global Warming Acceptance

Published: 2019

Abstract: Cognitive impediments and global warming's gradual pace, among other factors, have inhibited some people from detecting climate change's everyday effects. This results in global warming often being perceived as a non-urgent, non-personal, threat that inhibits larger-scale collective action combatting climate change and public will regarding such action. Extreme weather events that global warming causes or exacerbates (e.g., hurricanes, flooding, heat, and droughts), however, are memorable due to their high emotional, social, and economic costs. Sea level rise is an especially salient American issue, given recent heightened storm surges and the large population-segment who live in or near coastal areas with dangerous flooding risks. In this experiment, we show that providing American participants with U.S-specific information about the economic and/or geographic/cartological effects and risks of sea level rise results in (a) an increased acceptance of oceanic rise as a phenomenon that is concerning and caused by global warming, and (b) an increased acceptance, in general, of global warming's anthropogenic nature. Communicating sea level rise information also led to (c) a general decrease in nationalism and (d) changes in the perceived effectiveness of mitigation strategies for sea level rise--specifically (d₁) a decrease in the perceived effectiveness of constructing sea walls / dikes and (d₂) an increase in the perceived effectiveness of phasing out fossil fuel usage.

Title: Quantifying the contribution of temperature, salinity, and climate change to sea level rise in the Pacific Ocean: 2005-2019

Published: 2023

Abstract: In recent decades, Pacific Ocean's steric sea level anomaly (SSLA) has shown prominent patterns among global sea level variations. With ongoing global warming, the frequency and intensity of climate and sea level changes have increased, particularly in the tropical Pacific region. Therefore, it is crucial to comprehend the overall trends and mechanisms governing volumetric sea level changes in the Pacific. To accurately quantify the spatiotemporal evolution characteristics of density-driven sea level change in the Pacific Ocean (PO) from 2005 to 2019, we decomposed temperature and salinity into linear trends, interannual variations, seasonal variations, and residual terms using the STL (seasonal-trend decomposition based on loess) method. To evaluate the influence of ocean temperature, salinity, and climate change on density-driven sea level change and its underlying mechanisms, we decompose temperature as well as salinity changes through into the Heaving (vertical displacements of isopycnal surfaces) and Spicing (density-compensated temperature and salinity change) modes. The findings reveal an average steric sea level rise rate of 0.34 ± 0.16 mm/yr in the PO from 2005 to 2019. Thermosteric sea-level accounts for 82% of this rise, primarily due to seawater temperature rise at depths of 0-700 m caused by Heaving mode changes. Accelerated SSLA increase via the thermosteric effect has been connected to interactions between greater Ekman downwelling from surface winds, and enhanced ocean stratification.

Title: Climate change under a scenario near 1.5 °C of global warming: monsoon intensification, ocean warming and steric sea level rise

Published: 2010

Abstract: Abstract. We present climatic consequences of the Representative Concentration Pathways (RCPs) using the coupled climate model CLIMBER-3α, which contains a statistical-dynamical atmosphere and a three-dimensional ocean model. We compare those with emulations of 19 state-of-the-art atmosphere-ocean general circulation models (AOGCM) using MAGICC6. The RCPs are designed as standard scenarios for the forthcoming IPCC Fifth Assessment Report to span the full range of future greenhouse gas (GHG) concentrations pathways currently discussed. The lowest of the RCP scenarios, RCP3-PD, is projected in CLIMBER-3α to imply a maximal warming by the middle of the 21st century slightly above 1.5 °C and a slow decline of temperatures thereafter, approaching today's level by 2500. We identify two mechanisms that slow down global cooling after GHG concentrations peak: The known inertia induced by mixing-related oceanic heat uptake; and a change in oceanic convection that enhances ocean heat loss in high latitudes, reducing the surface cooling rate by almost 50%. Steric sea level rise under the RCP3-PD scenario continues for 200 years after the peak in surface air temperatures, stabilizing around 2250 at 30 cm. This contrasts with around 1.3 m of steric sea level rise by 2250, and 2 m by 2500, under the highest scenario, RCP8.5. Maximum oceanic warming at intermediate depth (300–800 m) is found to exceed that of the sea surface by the second half of the 21st century under RCP3-PD. This intermediate-depth warming persists for centuries even after surface temperatures have returned to present-day values, with potential consequences for marine ecosystems, oceanic methane hydrates, and ice-shelf stability. Due to an enhanced land-ocean temperature contrast, all scenarios yield an intensification of monsoon rainfall under global warming.

Title: Coevolution of Extreme Sea Levels and Sea‐Level Rise Under Global Warming

Published: 2023

Abstract: Design of coastal defense structures like seawalls and breakwaters can no longer be based on stationarity assumption. In many parts of the world, an anticipated sea‐level rise (SLR) due to climate change will constitute present‐day extreme sea levels inappropriate for future coastal flood risk assessments since it will significantly increase their probability of occurrence. Here, we first show that global annual maxima sea levels (AMSLs) have been increasing in magnitude over the last decades, primarily due to a positive shift in mean sea level (MSL). Then, we apply non‐stationary extreme value theory to model the extremal behavior of sea levels with MSL as a covariate and quantify the evolution of AMSLs in the following decades using revised probabilistic sea‐level rise projections. Our analysis reveals that non‐stationary distributions exhibit distinct differences compared to simply considering stationary conditions with a change in location parameter equal to the amount of MSL rise. With the use of non‐stationary distributions, we show that by the year 2050 many locations will experience their present‐day 100‐yr return level as an event with return period less than 15 and 9 years under the moderate (RCP4.5) and high (RCP8.5) representative concentration pathways. Also, we find that by the end of this century almost all locations examined will encounter their current 100‐yr return level on an annual basis, even if CO2 concentration is kept at moderate levels (RCP4.5). Our assessment accounts for large uncertainty by incorporating ambiguities in both SLR projections and non‐stationary extreme value distribution parameters via a Monte Carlo simulation.

Title: Role of perturbing ocean initial condition in simulated regional sea level change

Published: 2017

Abstract: Multiple lines of observational evidence indicate that the global climate has been getting warmer since the early 20th century. This warmer climate has led to a global mean sea level rise of about 18 cm during the 20th century, and over 6 cm for the first 15 years of the 21st century. Regionally the sea level rise is not uniform due in large part to internal climate variability. To better serve the community, the uncertainties of predicting/projecting regional sea level changes associated with internal climate variability need to be quantified. Previous research on this topic has used single-model large ensembles with perturbed atmospheric initial conditions (ICs). Here we compare uncertainties associated with perturbing ICs in just the atmosphere and just the ocean using a state-of-the-art coupled climate model. We find that by perturbing the oceanic ICs, the uncertainties in regional sea level changes increase compared to those with perturbed atmospheric ICs. Thus, in order for us to better assess the full spectrum of the impacts of such internal climate variability on regional and global sea level rise, approaches that involve perturbing both atmospheric and oceanic initial conditions are necessary.

Title: Communicating Climate Change Oceanically: Sea Level Rise Information Increases Mitigation, Inundation, and Global Warming Acceptance

Published: 2019

Abstract: Cognitive impediments and global warming’s gradual pace, among other factors, have inhibited some people from detecting climate change’s everyday effects. This results in global warming often being perceived as a non-urgent, non-personal, threat that inhibits larger-scale collective action combatting climate change and public will regarding such action. Extreme weather events that global warming causes or exacerbates (e.g., hurricanes, flooding, heat, and droughts), however, are memorable due to their high emotional, social, and economic costs. Sea level rise is an especially salient American issue, given recent heightened storm surges and the large population-segment who live in or near coastal areas with dangerous flooding risks. In this experiment, we show that providing American participants with U.S-specific information about the economic and/or geographic/cartological effects and risks of sea level rise results in (a) an increased acceptance of oceanic rise as a phenomenon that is concerning and caused by global warming, and (b) an increased acceptance, in general, of global warming’s anthropogenic nature. Communicating sea level rise information also led to (c) a general decrease in nationalism and (d) changes in the perceived effectiveness of mitigation strategies for sea level rise–specifically (d₁) a decrease in the perceived effectiveness of constructing sea walls / dikes and (d₂) an increase in the perceived effectiveness of phasing out fossil fuel usage. Overall, we find that communicating striking information about this oceanic by-product of global warming is an effective way to motivate acceptance and engagement with the issue of climate change in a reasonably broad manner. The experimental findings replicate, extend, and dovetail with prior experiments by our laboratory, bringing up to six the number of brief interventions (i.e., of roughly five or fewer minutes) that have been proven to increase people’s science-normative beliefs about global warming. Our laboratory’s website, HowGlobalWarmingWorks.org, offers samples of these materials, which additionally include surprising statistics, textual and video explanations of global warming’s mechanism, and a contrast of Earth’s temperature rise since the 1880’s versus the U.S. stock market rise since then

Title: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise

Published: 2011

Abstract: Ice sheet mass balance estimates have improved substantially in recent years using a variety of techniques, over different time periods, and at various levels of spatial detail. Considerable disparity remains between these estimates due to the inherent uncertainties of each method, the lack of detailed comparison between independent estimates, and the effect of temporal modulations in ice sheet surface mass balance. Here, we present a consistent record of mass balance for the Greenland and Antarctic ice sheets over the past two decades, validated by the comparison of two independent techniques over the last 8 years: one differencing perimeter loss from net accumulation, and one using a dense time series of time-variable gravity. We find excellent agreement between the two techniques for absolute mass loss and acceleration of mass loss. In 2006, the Greenland and Antarctic ice sheets experienced a combined mass loss of 475 ± 158 Gt/yr, equivalent to 1.3 ± 0.4 mm/yr sea level rise. Notably, the acceleration in ice sheet loss over the last 18 years was 21.9 ± 1 Gt/yr2 for Greenland and 14.5 ± 2 Gt/yr2 for Antarctica, for a combined total of 36.3 ± 2 Gt/yr2. This acceleration is 3 times larger than for mountain glaciers and ice caps (12 ± 6 Gt/yr2). If this trend continues, ice sheets will be the dominant contributor to sea level rise in the 21st century.

Title: Contribution of Antarctica to past and future sea-level rise

Published: 2016

Abstract: Polar temperatures over the last several million years have, at times, been slightly warmer than today, yet global mean sea level has been 6–9 metres higher as recently as the Last Interglacial (130,000 to 115,000 years ago) and possibly higher during the Pliocene epoch (about three million years ago). In both cases the Antarctic ice sheet has been implicated as the primary contributor, hinting at its future vulnerability. Here we use a model coupling ice sheet and climate dynamics—including previously underappreciated processes linking atmospheric warming with hydrofracturing of buttressing ice shelves and structural collapse of marine-terminating ice cliffs—that is calibrated against Pliocene and Last Interglacial sea-level estimates and applied to future greenhouse gas emission scenarios. Antarctica has the potential to contribute more than a metre of sea-level rise by 2100 and more than 15 metres by 2500, if emissions continue unabated. In this case atmospheric warming will soon become the dominant driver of ice loss, but prolonged ocean warming will delay its recovery for thousands of years.

Title: Contemporary Sea Level Rise

Published: 2010

Abstract: Measuring sea level change and understanding its causes has considerably improved in the recent years, essentially because new in situ and remote sensing observations have become available. Here we report on most recent results on contemporary sea level rise. We first present sea level observations from tide gauges over the twentieth century and from satellite altimetry since the early 1990s. We next discuss the most recent progress made in quantifying the processes causing sea level change on timescales ranging from years to decades, i.e., thermal expansion of the oceans, land ice mass loss, and land water–storage change. We show that for the 1993–2007 time span, the sum of climate-related contributions (2.85 ± 0.35 mm year−1) is only slightly less than altimetry-based sea level rise (3.3 ± 0.4 mm year−1): ∼30% of the observed rate of rise is due to ocean thermal expansion and ∼55% results from land ice melt. Recent acceleration in glacier melting and ice mass loss from the ice sheets increases the latter contribution up to 80% for the past five years. We also review the main causes of regional variability in sea level trends: The dominant contribution results from nonuniform changes in ocean thermal expansion.

Title: Sea level rise and its coastal impacts

Published: 2013

Abstract: Global warming in response to accumulation of human-induced greenhouse gases inside the atmosphere has already caused several visible consequences, among them increase of the Earth's mean temperature and ocean heat content, melting of glaciers, and loss of ice from the Greenland and Antarctica ice sheets. Ocean warming and land ice melt in turn are causing sea level to rise. Sea level rise and its impacts on coastal zones have become a question of growing interest in the scientific community, as well as in the media and public. In this review paper, we summarize the most up-to-date knowledge about sea level rise and its causes, highlighting the regional variability that superimposes the global mean rise. We also present sea level projections for the 21st century under different warming scenarios. We next address the issue of the sea level rise impacts. We question whether there is already observational evidence of coastal impacts of sea level rise and highlight the fact that results differ from one location to another. This suggests that the response of coastal systems to sea level rise is highly dependent on local natural and human settings. We finally show that in spite of remaining uncertainties about future sea levels and related impacts, it becomes possible to provide preliminary assessment of regional impacts of sea level rise.

Title: The rate of sea-level rise

Published: 2014

Abstract: Present-day sea-level rise is a major indicator of climate change1. Since the early 1990s, sea level rose at a mean rate of ∼3.1 mm yr−1 (refs 2, 3). However, over the last decade a slowdown of this rate, of about 30%, has been recorded4,5,6,7,8. It coincides with a plateau in Earth’s mean surface temperature evolution, known as the recent pause in warming1,9,10,11,12. Here we present an analysis based on sea-level data from the altimetry record of the past ∼20 years that separates interannual natural variability in sea level from the longer-term change probably related to anthropogenic global warming. The most prominent signature in the global mean sea level interannual variability is caused by El Niño–Southern Oscillation, through its impact on the global water cycle13,14,15,16. We find that when correcting for interannual variability, the past decade’s slowdown of the global mean sea level disappears, leading to a similar rate of sea-level rise (of 3.3 ± 0.4 mm yr−1) during the first and second decade of the altimetry era. Our results confirm the need for quantifying and further removing from the climate records the short-term natural climate variability if one wants to extract the global warming signal10.

Title: Sea-Level Rise from the Late 19th to the Early 21st Century

Published: 2011

Abstract: We estimate the rise in global average sea level from satellite altimeter data for 1993–2009 and from coastal and island sea-level measurements from 1880 to 2009. For 1993–2009 and after correcting for glacial isostatic adjustment, the estimated rate of rise is 3.2 ± 0.4 mm year−1 from the satellite data and 2.8 ± 0.8 mm year−1 from the in situ data. The global average sea-level rise from 1880 to 2009 is about 210 mm. The linear trend from 1900 to 2009 is 1.7 ± 0.2 mm year−1 and since 1961 is 1.9 ± 0.4 mm year−1. There is considerable variability in the rate of rise during the twentieth century but there has been a statistically significant acceleration since 1880 and 1900 of 0.009 ± 0.003 mm year−2 and 0.009 ± 0.004 mm year−2, respectively. Since the start of the altimeter record in 1993, global average sea level rose at a rate near the upper end of the sea level projections of the Intergovernmental Panel on Climate Change’s Third and Fourth Assessment Reports. However, the reconstruction indicates there was little net change in sea level from 1990 to 1993, most likely as a result of the volcanic eruption of Mount Pinatubo in 1991.

Title: Future sea level rise dominates changes in worst case extreme sea levels along the global coastline by 2100

Published: 2023

Abstract: We provide the magnitude of a worst case scenario for extreme sea levels (ESLs) along the global coastline by 2100. This worst case scenario for ESLs is calculated as a combination of sea surface height associated with storm surge and wave (100 year return period, the 95th percentile), high tide (the 95th percentile) and a low probability sea level rise scenario (the 95th percentile). Under these conditions, end-of-21st century ESLs have a 5% chance of exceeding 4.2 m (global coastal average), compared to 2.6 m during the baseline period (1980–2014). By 2100 almost 45% of the global coastline would experience ESLs above the global mean of 4.2 m, with up to 9–10 m for the East China Sea, Japan and North European coastal areas. Up to 86% of coastal locations would face ESLs above 3 m (100 year return period) by 2100, compared to 33% currently. Up to 90% of increases in magnitude of ESLs are driven by future sea level rise, compare to 10% associated with changes in storm surges and waves. By 2030–2040 the present-day 100 year return period for ESLs would be experienced at least once a year in tropical areas. This 100-fold increase in frequency will take place on all global coastlines by 2100.

Title: Sea level rise projections up to 2150 in the northern Mediterranean coasts

Published:2023

Abstract: Vertical land movements (VLM) play a crucial role in affecting the sea level rise along the coasts. They need to be estimated and included in the analysis for more accurate Sea Level (SL) projections. Here we focus on the Mediterranean basin characterized by spatially variable rates of VLM that affect the future SL along the coasts. To estimate the VLM rates we used geodetic data from continuous global navigation satellite system stations with time series longer than 4.5 years in the 1996–2023 interval, belonging to Euro-Mediterranean networks and located within 5 km from the coast. Revised SL projections up to the year 2150 are provided at 265 points on a geographical grid and at the locations of 51 tide gauges of the Permanent Service for Mean Sea Level, by including the estimated VLM in the SL projections released by the Intergovernmental Panel on Climate Change (IPCC) in the AR6 Report. Results show that the IPCC projections underestimate future SL along the coasts of the Mediterranean Sea since the effects of tectonics and other local factors were not properly considered. Here we show that revised SL projections at 2100, when compared to the IPCC, show a maximum and minimum differences of 1094 ± 103 mm and −773 ± 106 mm, respectively, with an average value that exceeds by about 80 mm that of the IPCC in the reference Shared Socio-economic Pathways and different global warming levels. Finally, the projections indicate that about 19.000 km2 of the considered Mediterranean coasts will be more exposed to risk of inundation for the next decades, leading to enhanced impacts on the environment, human activities and infrastructures, thus suggesting the need for concrete actions to support vulnerable populations to adapt to the expected SL rise and coastal hazards by the end of this century.

Title: Expert assessment of sea-level rise by AD 2100 and AD 2300

Published: 2014

Abstract: Large uncertainty surrounds projections of global sea-level rise, resulting from uncertainty about future warming and an incomplete understanding of the complex processes and feedback mechanisms that cause sea level to rise. Consequently, existing models produce widely differing predictions of sea-level rise even for the same temperature scenario. Here we present results of a broad survey of 90 experts who were amongst the most active scientific publishers on the topic of sea level in recent years. They provided a probabilistic assessment of sea-level rise by AD 2100 and AD 2300 under two contrasting temperature scenarios. For the low scenario, which limits warming to <2 °C above pre-industrial temperature and has slowly falling temperature after AD 2050, the median ‘likely’ range provided by the experts is 0.4–0.6 m by AD 2100 and 0.6–1.0 m by AD 2300, suggesting a good chance to limit future sea-level rise to <1.0 m if climate mitigation measures are successfully implemented. In contrast, for the high warming scenario (4.5 °C by AD 2100 and 8 °C in AD 2300) the median likely ranges are 0.7–1.2 m by AD 2100 and 2.0–3.0 m by AD 2300, calling into question the future survival of some coastal cities and low-lying island nations.

Title: Ice sheet contributions to future sea-level rise from structured expert judgment

Published: 2019

Abstract: Despite considerable advances in process understanding, numerical modeling, and the observational record of ice sheet contributions to global mean sea-level rise (SLR) since the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change, severe limitations remain in the predictive capability of ice sheet models. As a consequence, the potential contributions of ice sheets remain the largest source of uncertainty in projecting future SLR. Here, we report the findings of a structured expert judgement study, using unique techniques for modeling correlations between inter- and intra-ice sheet processes and their tail dependences. We find that since the AR5, expert uncertainty has grown, in particular because of uncertain ice dynamic effects. For a +2 °C temperature scenario consistent with the Paris Agreement, we obtain a median estimate of a 26 cm SLR contribution by 2100, with a 95th percentile value of 81 cm. For a +5 °C temperature scenario more consistent with unchecked emissions growth, the corresponding values are 51 and 178 cm, respectively. Inclusion of thermal expansion and glacier contributions results in a global total SLR estimate that exceeds 2 m at the 95th percentile. Our findings support the use of scenarios of 21st century global total SLR exceeding 2 m for planning purposes. Beyond 2100, uncertainty and projected SLR increase rapidly. The 95th percentile ice sheet contribution by 2200, for the +5 °C scenario, is 7.5 m as a result of instabilities coming into play in both West and East Antarctica. Introducing process correlations and tail dependences increases estimates by roughly 15%.

Title: Unprecedented threats to cities from multi-century sea level rise

Published:2021

Abstract: A portion of human-caused carbon dioxide emissions will stay in the atmosphere for hundreds of years, raising temperatures and sea levels globally. Most nations' emissions-reduction policies and actions do not seem to reflect this long-term threat, as collectively they point toward widespread permanent inundation of many developed areas. Using state-of-the-art new global elevation and population data, we show here that, under high emissions scenarios leading to 4 ∘C warming and a median projected 8.9 m of global mean sea level rise within a roughly 200- to 2000-year envelope, at least 50 major cities, mostly in Asia, would need to defend against globally unprecedented levels of exposure, if feasible, or face partial to near-total extant area losses. Nationally, China, India, Indonesia, and Vietnam, global leaders in recent coal plant construction, have the largest contemporary populations occupying land below projected high tide lines, alongside Bangladesh. We employ this population-based metric as a rough index for the potential exposure of the largely immovable built environment embodying cultures and economies as they exist today. Based on median sea level projections, at least one large nation on every continent but Australia and Antarctica would face exceptionally high exposure: land home to at least one-tenth and up to two-thirds of current population falling below tideline. Many small island nations are threatened with near-total loss. The high tide line could encroach above land occupied by as much as 15% of the current global population (about one billion people). By contrast, meeting the most ambitious goals of the Paris Climate Agreement will likely reduce exposure by roughly half and may avoid globally unprecedented defense requirements for any coastal megacity exceeding a contemporary population of 10 million.

Title: Oyster reefs can outpace sea-level rise

Published: 2014

Abstract: In the high-salinity seaward portions of estuaries, oysters seek refuge from predation, competition and disease in intertidal areas1,2, but this sanctuary will be lost if vertical reef accretion cannot keep pace with sea-level rise (SLR). Oyster-reef abundance has already declined ∼85% globally over the past 100 years, mainly from over harvesting3,4, making any additional losses due to SLR cause for concern. Before any assessment of reef response to accelerated SLR can be made, direct measures of reef growth are necessary. Here, we present direct measurements of intertidal oyster-reef growth from cores and terrestrial lidar-derived digital elevation models. On the basis of our measurements collected within a mid-Atlantic estuary over a 15-year period, we developed a globally testable empirical model of intertidal oyster-reef accretion. We show that previous estimates of vertical reef growth, based on radiocarbon dates and bathymetric maps5,6, may be greater than one order of magnitude too slow. The intertidal reefs we studied should be able to keep up with any future accelerated rate of SLR (ref. 7) and may even benefit from the additional subaqueous space allowing extended vertical accretion.

Title: The causes of sea-level rise since 1900

Published: 2020

Abstract: The rate of global-mean sea-level rise since 1900 has varied over time, but the contributing factors are still poorly understood1. Previous assessments found that the summed contributions of ice-mass loss, terrestrial water storage and thermal expansion of the ocean could not be reconciled with observed changes in global-mean sea level, implying that changes in sea level or some contributions to those changes were poorly constrained2,3. Recent improvements to observational data, our understanding of the main contributing processes to sea-level change and methods for estimating the individual contributions, mean another attempt at reconciliation is warranted. Here we present a probabilistic framework to reconstruct sea level since 1900 using independent observations and their inherent uncertainties. The sum of the contributions to sea-level change from thermal expansion of the ocean, ice-mass loss and changes in terrestrial water storage is consistent with the trends and multidecadal variability in observed sea level on both global and basin scales, which we reconstruct from tide-gauge records. Ice-mass loss—predominantly from glaciers—has caused twice as much sea-level rise since 1900 as has thermal expansion. Mass loss from glaciers and the Greenland Ice Sheet explains the high rates of global sea-level rise during the 1940s, while a sharp increase in water impoundment by artificial reservoirs is the main cause of the lower-than-average rates during the 1970s. The acceleration in sea-level rise since the 1970s is caused by the combination of thermal expansion of the ocean and increased ice-mass loss from Greenland. Our results reconcile the magnitude of observed global-mean sea-level rise since 1900 with estimates based on the underlying processes, implying that no additional processes are required to explain the observed changes in sea level since 1900.

Title: Sea-level rise and human migration

Published: 2019

Abstract: Anthropogenic sea-level rise (SLR) is predicted to impact, and, in many cases, displace, a large proportion of the population via inundation and heightened SLR-related hazards. With the global coastal population projected to surpass one billion people this century, SLR might be among the most costly and permanent future consequences of climate change. In this Review, we synthesize the rapidly expanding knowledge of human mobility and migration responses to SLR, providing a coherent roadmap for future SLR research and associated policy. While it is often assumed that direct inundation forces a migration, we discuss how mobility responses are instead driven by a diversity of socioeconomic and demographic factors, which, in some cases, do not result in a migration response. We link SLR hazards with potential mechanisms of migration and the associated governmental or institutional policies that operate as obstacles or facilitators for that migration. Specific examples from the USA, Bangladesh and atoll island nations are used to contextualize these concepts. However, further research is needed on the fundamental mechanisms underlying SLR migration, tipping points, thresholds and feedbacks, risk perception and migration to fully understand migration responses to SLR.

Title: Sea-Level Rise: From Global Perspectives to Local Services

Published: 2022

Abstract: Coastal areas are highly diverse, ecologically rich, regions of key socio-economic activity, and are particularly sensitive to sea-level change. Over most of the 20th century, global mean sea level has risen mainly due to warming and subsequent expansion of the upper ocean layers as well as the melting of glaciers and ice caps. Over the last three decades, increased mass loss of the Greenland and Antarctic ice sheets has also started to contribute significantly to contemporary sea-level rise. The future mass loss of the two ice sheets, which combined represent a sea-level rise potential of ∼65 m, constitutes the main source of uncertainty in long-term (centennial to millennial) sea-level rise projections. Improved knowledge of the magnitude and rate of future sea-level change is therefore of utmost importance. Moreover, sea level does not change uniformly across the globe and can differ greatly at both regional and local scales. The most appropriate and feasible sea level mitigation and adaptation measures in coastal regions strongly depend on local land use and associated risk aversion. Here, we advocate that addressing the problem of future sea-level rise and its impacts requires (i) bringing together a transdisciplinary scientific community, from climate and cryospheric scientists to coastal impact specialists, and (ii) interacting closely and iteratively with users and local stakeholders to co-design and co-build coastal climate services, including addressing the high-end risks.

Title: Estimating global mean sea-level rise and its uncertainties by 2100 and 2300 from an expert survey

Published: 2020

Abstract: Sea-level rise projections and knowledge of their uncertainties are vital to make informed mitigation and adaptation decisions. To elicit projections from members of the scientific community regarding future global mean sea-level (GMSL) rise, we repeated a survey originally conducted five years ago. Under Representative Concentration Pathway (RCP) 2.6, 106 experts projected a likely (central 66% probability) GMSL rise of 0.30–0.65 m by 2100, and 0.54–2.15 m by 2300, relative to 1986–2005. Under RCP 8.5, the same experts projected a likely GMSL rise of 0.63–1.32 m by 2100, and 1.67–5.61 m by 2300. Expert projections for 2100 are similar to those from the original survey, although the projection for 2300 has extended tails and is higher than the original survey. Experts give a likelihood of 42% (original survey) and 45% (current survey) that under the high-emissions scenario GMSL rise will exceed the upper bound (0.98 m) of the likely range estimated by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, which is considered to have an exceedance likelihood of 17%. Responses to open-ended questions suggest that the increases in upper-end estimates and uncertainties arose from recent influential studies about the impact of marine ice cliff instability on the meltwater contribution to GMSL rise from the Antarctic Ice Sheet.

Title: Sea level rise impacts on estuarine dynamics: A review

Published: 2021

Abstract: Sea level rise (SLR) poses a hazard to ecosystems and economies in low-lying coastal and estuarine areas. To better understand the potential impacts of SLR in estuaries, a comprehensive review of existing theory, literature, and assessment tools is undertaken. In addition, several conceptual models are introduced to assist in understanding interlinked estuarine processes and their complex responses to SLR. This review indicates that SLR impacts in estuaries should not be assessed via static (bathtub) approaches as they fail to consider important hydrodynamic effects such as tidal wave amplification, dampening, and reflection. Where hydrodynamic models are used, the existing literature provides a relatively detailed understanding of how SLR will affect estuarine hydrodynamics (e.g., tides and inundation regimes). With regards to the current understanding of, and ability to model, the connections between altered hydrodynamics (under SLR) and dependent geomorphic, ecological, and bio-geochemical processes, significant knowledge gaps remain. This is of particular concern as there is currently a paradigm shift towards more integrated and holistic management of estuaries. Estuarine management under accelerating SLR is likely to become increasingly complex, as decision-making will be undertaken with uncertainty. As such, this review highlights that there is a fundamental requirement for more sophisticated and interdisciplinary studies that integrate physical, ecological, bio-geochemical, and geomorphic responses of estuaries to SLR.

Title: Predicting Sea Level Rise Using Artificial Intelligence: A Review

Published: 2023

Abstract: Forecasting sea level is critical for coastal structure building and port operations. There are, however, challenges in making these predictions, resulting from the complicated processes at various periods. This study discussed the continual development of the application and forecasting approaches for sea level rise, in standard and advanced modeling versions. To date, the tide gauge and satellite altimetry are the commonly used approaches for sea level measurement. Tide gauges are mostly deficient in typical offshore circumstances; but however, this may be compensated for with satellite altimetry, a complementing technique. With technological improvement, sea level measurement may be forecasted using a variety of computer science approaches known as artificial intelligence, including machine learning and deep learning; capable of extracting information and formulating relationships from the given dataset. Its potential and extensive advantages led to a sharp growth in its recognition among hydrologists. The most successful techniques for enhancing these approaches include hybridization, ensemble modeling, data decomposition, and algorithm optimization. These advanced techniques are a prominent study area and a viable strategy for determining intelligent forecasts of sea level rise with sufficient lead time. For improved performance, the modeling requires incorporating numerous input parameters, such as precipitation, wind direction, ocean current, and sea surface temperature; for better representing the process, thus reducing forecast error and uncertainty. Deep learning is more effective and enhances existing machine learning models for forecasting future sea level rise due to its automatic feature extraction and memory-storing capability.

Title: Coastal Migration due to 21st Century Sea-Level Rise

Published: 2021

Abstract: Rising mean and extreme sea-levels and induced increased coastal flooding are expected to lead to massive coastal migration if coasts are not protected. Using a wide range of sea-level rise (SLR) scenarios, socioeconomic pathways and discount rate assumptions, 21st century coastal migration is assessed at global scale assuming local cost-benefit optimal protection decisions for about 12,000 coastal segments with homogeneous coastal and socioeconomic characteristics. Costs considered include investment and maintenance cost for protection, migration cost in the case of no protection, and expected annual damage to assets by extreme sea-level events that over-top existing protection. Robust decisions in favor of protection over all scenarios are found for about 3% of the global coastline, covering 78% of global coastal population and 92% of global coastal floodplain assets. For the remaining 97% of global coastline cumulative 21st century land loss ranges from 60,000 to 415,000 km2 and coastal migration ranges from 17 to 72 million people. Big countries with long uninhabited coastlines suffer the biggest land losses. In absolute terms big countries in South and South-east Asia account for the highest coastal migration, while in relative terms small island nations suffer most. Global cost of 21st century SLR can be lowered by factor two to four if local cost-benefit decisions also consider, next to protection, coastal migration as an adaptation option.

Title: The transient sensitivity of sea level rise

Published: 2021

Abstract: Recent assessments from the Intergovernmental Panel on Climate Change (IPCC) imply that global mean sea level is unlikely to rise more than about 1.1 m within this century but will increase further beyond 2100. Even within the most intensive future anthropogenic greenhouse gas emission scenarios, higher levels are assessed to be unlikely. However, some studies conclude that considerably greater sea level rise could be realized, and a number of experts assign a substantially higher likelihood of such a future. To understand this discrepancy, it would be useful to have scenario-independent metrics that can be compared between different approaches. The concept of a transient climate sensitivity has proven to be useful to compare the global mean temperature response of climate models to specific radiative forcing scenarios. Here, we introduce a similar metric for sea level response. By analyzing the mean rate of change in sea level (not sea level itself), we identify a nearly linear relationship with global mean surface temperature (and therefore accumulated carbon dioxide emissions) both in model projections and in observations on a century scale. This motivates us to define the “transient sea level sensitivity” as the increase in the sea level rate associated with a given warming in units of meters per century per kelvin. We find that future projections estimated on climate model responses fall below extrapolation based on recent observational records. This comparison suggests that the likely upper level of sea level projections in recent IPCC reports would be too low.

Title: Global costs of protecting against sea-level rise

Published: 2021

Abstract: Sea levels will rise, even with stringent climate change mitigation. Mitigation will slow the rate of rise. There is limited knowledge on how the costs of coastal protection vary with alternative global warming levels of 1.5 to 4.0 °C. Analysing six sea-level rise scenarios (0.74 to 1.09 m, 50th percentile) across these warming levels, and five Shared Socioeconomic Pathways, this paper quantifies the economic costs of flooding and protection due to sea-level rise using the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework. Results are presented for World Bank income groups and five selected countries from the present to 2100. Annual sea flood damage costs without additional adaptation are more influenced by socio-economic development than sea-level rise, indicating that there are opportunities to control risk with development choices. In contrast, annual sea dike investment costs are more dependent on the magnitude of sea-level rise. In terms of total costs with adaptation, upper middle, low middle and low income groups are projected to have higher relative costs as a proportion of GDP compared with high income groups. If low income countries protected now, flood costs could be reduced after 2050 and beyond. However, without further adaptation, their coasts will experience growing risks and costs leaving them increasingly reliant on emergency response measures. Without mitigation or adaptation, greater inequalities in damage costs between income groups could result. At country level, annual sea flood damage costs without additional adaptation are projected to rapidly increase with approximately 0.2 m of sea-level rise, leaving limited time to plan and adapt.

Title: Communicating future sea-level rise uncertainty and ambiguity to assessment users

Published: 2023

Abstract: Future sea-level change is characterized by both quantifiable and unquantifiable uncertainties. Effective communication of both types of uncertainty is a key challenge in translating sea-level science to inform long-term coastal planning. Scientific assessments play a key role in the translation process and have taken diverse approaches to communicating sea-level projection uncertainty. Here we review how past IPCC and regional assessments have presented sea-level projection uncertainty, how IPCC presentations have been interpreted by regional assessments and how regional assessments and policy guidance simplify projections for practical use. This information influenced the IPCC Sixth Assessment Report presentation of quantifiable and unquantifiable uncertainty, with the goal of preserving both elements as projections are adapted for regional application.

Title: Timing of emergence of modern rates of sea-level rise by 1863

Published: 2022

Abstract: Sea-level rise is a significant indicator of broader climate changes, and the time of emergence concept can be used to identify when modern rates of sea-level rise emerged above background variability. Yet a range of estimates of the timing persists both globally and regionally. Here, we use a global database of proxy sea-level records of the Common Era (0–2000 CE) and show that globally, it is very likely that rates of sea-level rise emerged above pre-industrial rates by 1863 CE (P = 0.9; range of 1825 [P = 0.66] to 1873 CE [P = 0.95]), which is similar in timing to evidence for early ocean warming and glacier melt. The time of emergence in the North Atlantic reveals a distinct spatial pattern, appearing earliest in the mid-Atlantic region (1872–1894 CE) and later in Canada and Europe (1930–1964 CE). Regional and local sea-level changes occurring over different time periods drive the spatial pattern in emergence, suggesting regional processes underlie centennial-timescale sea-level variability over the Common Era.

Title: Risk of isolation increases the expected burden from sea-level rise

Published:2023

Abstract: The typical displacement metric for sea-level rise adaptation planning is property inundation. However, this metric may underestimate risk as it does not fully capture the wider cascading or indirect effects of sea-level rise. To address this, we propose complementing it by considering the risk of population isolation: those who may be cut off from essential services. We investigate the importance of this metric by comparing the number of people at risk from inundation to the number of people at risk from isolation. Considering inundated roadways during mean higher high water tides in the coastal United States shows, although highly spatially variable, that the increase across the United States varies between 30% and 90% and is several times higher in some states. We find that risk of isolation may occur decades sooner than risk of inundation. Both risk metrics provide critical information for evaluating adaptation options and giving priority to support for at-risk communities.

Title: Trends in Europe storm surge extremes match the rate of sea-level rise

Published:2022

Abstract: Coastal communities across the world are already feeling the disastrous impacts of climate change through variations in extreme sea levels1. These variations reflect the combined effect of sea-level rise and changes in storm surge activity. Understanding the relative importance of these two factors in altering the likelihood of extreme events is crucial to the success of coastal adaptation measures. Existing analyses of tide gauge records2,3,4,5,6,7,8,9,10 agree that sea-level rise has been a considerable driver of trends in sea-level extremes since at least 1960. However, the contribution from changes in storminess remains unclear, owing to the difficulty of inferring this contribution from sparse data and the consequent inconclusive results that have accumulated in the literature11,12. Here we analyse tide gauge observations using spatial Bayesian methods13 to show that, contrary to current thought, trends in surge extremes and sea-level rise both made comparable contributions to the overall change in extreme sea levels in Europe since 1960 . We determine that the trend pattern of surge extremes reflects the contributions from a dominant north–south dipole associated with internal climate variability and a single-sign positive pattern related to anthropogenic forcing. Our results demonstrate that both external and internal influences can considerably affect the likelihood of surge extremes over periods as long as 60 years, suggesting that the current coastal planning practice of assuming stationary surge extremes1,14 might be inadequate.

Title: Atmospheric and oceanic circulation altered by global mean sea-level rise

Published: 2023

Abstract: Over recent decades, the rate of global mean sea-level rise has increased, although the magnitude—tens of centimetres—remains small from a geological perspective. Such a modest rise in sea level presents a challenge when attempting to assess its global climate impacts, as the signal is weak. However, in previous warmer geological periods, sea levels reached up to tens of metres higher than the present levels. These palaeoclimate periods offer a unique opportunity to investigate the climate effects of higher sea levels. Here, using climate simulations of the Last Interglacial period and a set of present-day sea-level sensitivity experiments, we highlight the importance of global mean sea-level rise in modulating global climate. The lowering of terrestrial elevation and deepening of oceanic bathymetry due to a spatially uniform rise in sea level reorganizes atmospheric and oceanic circulations. Our simulations of the Last Interglacial show that considering this aspect of global mean sea-level rise in isolation from changes associated with land–sea masks or freshwater input reduces the long-lasting model–data mismatch in the Southern Hemisphere. Furthermore, the present-day sensitivity experiments demonstrate that a slight increase in global mean sea level causes substantial adjustments in the global climate, particularly at mid–high latitudes.

Title: The ability of societies to adapt to twenty-first-century sea-level rise

Published: 2018

Abstract: Against the background of potentially substantial sea-level rise, one important question is to what extent are coastal societies able to adapt? This question is often answered in the negative by referring to sinking islands and submerged megacities. Although these risks are real, the picture is incomplete because it lacks consideration of adaptation. This Perspective explores societies’ abilities to adapt to twenty-first-century sea-level rise by integrating perspectives from coastal engineering, economics, finance and social sciences, and provides a comparative analysis of a set of cases that vary in terms of technological limits, economic and financial barriers to adaptation and social conflicts.

Title: Under-estimated wave contribution to coastal sea-level rise

Published: 2018

Abstract: Coastal communities are threatened by sea-level changes operating at various spatial scales; global to regional variations are associated with glacier and ice sheet loss and ocean thermal expansion, while smaller coastal-scale variations are also related to atmospheric surges, tides and waves. Here, using 23 years (1993–2015) of global coastal sea-level observations, we examine the contribution of these latter processes to long-term sea-level rise, which, to date, have been relatively less explored. It is found that wave contributions can strongly dampen or enhance the effects of thermal expansion and land ice loss on coastal water-level changes at interannual-to-multidecadal timescales. Along the US West Coast, for example, negative wave-induced trends dominate, leading to negative net water-level trends. Accurate estimates of past, present and future coastal sea-level rise therefore need to consider low-frequency contributions of wave set-up and swash.

Title: Future response of global coastal wetlands to sea-level rise

Published: 2018

Abstract: The response of coastal wetlands to sea-level rise during the twenty-first century remains uncertain. Global-scale projections suggest that between 20 and 90 per cent (for low and high sea-level rise scenarios, respectively) of the present-day coastal wetland area will be lost, which will in turn result in the loss of biodiversity and highly valued ecosystem services1,2,3. These projections do not necessarily take into account all essential geomorphological4,5,6,7 and socio-economic system feedbacks8. Here we present an integrated global modelling approach that considers both the ability of coastal wetlands to build up vertically by sediment accretion, and the accommodation space, namely, the vertical and lateral space available for fine sediments to accumulate and be colonized by wetland vegetation. We use this approach to assess global-scale changes in coastal wetland area in response to global sea-level rise and anthropogenic coastal occupation during the twenty-first century. On the basis of our simulations, we find that, globally, rather than losses, wetland gains of up to 60 per cent of the current area are possible, if more than 37 per cent (our upper estimate for current accommodation space) of coastal wetlands have sufficient accommodation space, and sediment supply remains at present levels. In contrast to previous studies1,2,3, we project that until 2100, the loss of global coastal wetland area will range between 0 and 30 per cent, assuming no further accommodation space in addition to current levels. Our simulations suggest that the resilience of global wetlands is primarily driven by the availability of accommodation space, which is strongly influenced by the building of anthropogenic infrastructure in the coastal zone and such infrastructure is expected to change over the twenty-first century. Rather than being an inevitable consequence of global sea-level rise, our findings indicate that large-scale loss of coastal wetlands might be avoidable, if sufficient additional accommodation space can be created through careful nature-based adaptation solutions to coastal management.

Title: Evolution of 21st Century Sea Level Rise Projections

Published:2018

Abstract: The modern era of scientific global-mean sea level rise (SLR) projections began in the early 1980s. In subsequent decades, understanding of driving processes has improved, and new methodologies have been developed. Nonetheless, despite more than 70 studies, future SLR remains deeply uncertain. To facilitate understanding of the historical development of SLR projections and contextualize current projections, we have compiled a comprehensive database of 21st century global SLR projections. Although central estimates of 21st century global-mean SLR have been relatively consistent, the range of projected SLR has varied greatly over time. Among studies providing multiple estimates, the range of upper projections shrank from 1.3–1.8 m during the 1980s to 0.6–0.9 m in 2007, before expanding again to 0.5–2.5 m since 2013. Upper projections of SLR from individual studies are generally higher than upper projections from the Intergovernmental Panel on Climate Change, potentially due to differing percentile bounds or a predisposition of consensus-based approaches toward relatively conservative outcomes.

Title: Disaster on the horizon: The price effect of sea level rise

Published: 2019

Abstract: Homes exposed to sea level rise (SLR) sell for approximately 7% less than observably equivalent unexposed properties equidistant from the beach. This discount has grown over time and is driven by sophisticated buyers and communities worried about global warming. Consistent with causal identification of long-horizon SLR costs, we find no relation between SLR exposure and rental rates and a 4% discount among properties not projected to be flooded for almost a century. Our findings contribute to the literature on the pricing of long-run risky cash flows and provide insights for optimal climate change policy.

Title: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016

Published: 2019

Abstract: Glaciers distinct from the Greenland and Antarctic ice sheets cover an area of approximately 706,000 square kilometres globally1, with an estimated total volume of 170,000 cubic kilometres, or 0.4 metres of potential sea-level-rise equivalent2. Retreating and thinning glaciers are icons of climate change3 and affect regional runoff4 as well as global sea level5,6. In past reports from the Intergovernmental Panel on Climate Change, estimates of changes in glacier mass were based on the multiplication of averaged or interpolated results from available observations of a few hundred glaciers by defined regional glacier areas7,8,9,10. For data-scarce regions, these results had to be complemented with estimates based on satellite altimetry and gravimetry11. These past approaches were challenged by the small number and heterogeneous spatiotemporal distribution of in situ measurement series and their often unknown ability to represent their respective mountain ranges, as well as by the spatial limitations of satellite altimetry (for which only point data are available) and gravimetry (with its coarse resolution). Here we use an extrapolation of glaciological and geodetic observations to show that glaciers contributed 27 ± 22 millimetres to global mean sea-level rise from 1961 to 2016. Regional specific-mass-change rates for 2006–2016 range from −0.1 metres to −1.2 metres of water equivalent per year, resulting in a global sea-level contribution of 335 ± 144 gigatonnes, or 0.92 ± 0.39 millimetres, per year. Although statistical uncertainty ranges overlap, our conclusions suggest that glacier mass loss may be larger than previously reported11. The present glacier mass loss is equivalent to the sea-level contribution of the Greenland Ice Sheet12, clearly exceeds the loss from the Antarctic Ice Sheet13, and accounts for 25 to 30 per cent of the total observed sea-level rise14. Present mass-loss rates indicate that glaciers could almost disappear in some mountain ranges in this century, while heavily glacierized regions will continue to contribute to sea-level rise beyond 2100.