

Altimeter-era emergence of the patterns of forced sea-level rise in climate models and implications for the future

John T. Fasullo^{a,1} and R. Steven Nerem^b

^aClimate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, CO 80301; and ^bSmead Aerospace Engineering Sciences, Colorado Center for Astrodynamics Research, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309

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The satellite altimeter record has provided an unprecedented database for understanding sea-level rise and has recently reached a major milestone at 25 years in length. A challenge now exists in understanding its broader significance and its consequences for sea-level rise in the coming decades and beyond. A key question is whether the pattern of altimeter-era change is representative of longer-term trends driven by anthropogenic forcing. In this work, two multimember climate ensembles, the Community Earth System Model (CESM) and the Earth System Model Version 2M (ESM2M), are used to estimate patterns of forced change [also known as the forced response (FR)] and their magnitudes relative to internal variability. It is found that the spatial patterns of 1993–2018 trends in the ensembles correlate significantly with the contemporaneous FRs (0.55 ± 0.10 in the CESM and 0.61 ± 0.09 in the ESM2M) and the 1950–2100 FRs (0.43 ± 0.10 in the CESM and 0.51 ± 0.11 in the ESM2M). Unforced runs for each model show such correlations to be extremely unlikely to have arisen by chance, indicating an emergence of both the altimeter-era and long-term FRs and suggesting a similar emergence in nature. Projected patterns of the FR over the coming decades resemble those simulated during the altimeter era, suggesting a continuation of the forced pattern of change in nature in the coming decades. Notably, elevated rates of rise are projected to continue in regions that are susceptible to tropical cyclones, exacerbating associated impacts in a warming climate.

sea level | climate variability | climate change | satellite altimetry

Sea-level rise is among the most societally and ecologically impactful manifestations of a changing climate, yet our understanding of its historical variations and projections of its future evolution contain significant uncertainty (1–3). A major advance in its understanding has been provided by satellite altimetry since 1993 (4). At 25 y in length, this climate data record is based on the combined data records of the TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 satellites and has provided near-global coverage of open ocean sea level with remarkable accuracy and temporal sampling (samples accurate to ~ 1 – 2 cm every ~ 10 d). As a key climate metric, global mean sea level has drawn particular attention and with averaging in space and time, can be estimated for the global annual mean to ~ 1 mm, with an observed rate of rise during the altimeter era of about 3.0 ± 0.4 mm/y and an acceleration of 0.084 ± 0.025 mm/y² (1σ) (5).

Altimetry has served as the basis for various other insights. For example, it has become evident that regional rates of rise can vary substantially from the global mean, with spatial variations that can be several times larger than the global average rate of rise (1–3). Our physical understanding and causal attribution of such spatial variations, however, remain limited, and the extent to which such variations are indicative of long-term trends is unclear (2, 6, 7). However, this understanding is key to regional stakeholders (2, 8), as it shapes expectations regarding whether observed trend patterns will persist in the coming decades unabated or are merely transient deviations from the global mean rate of rise, thus holding promise for a possible near-term reversal. Here, climate model simulations

are used to address these and related questions, with the goal of determining whether the response in sea level to external forcing has been a major contributor to the pattern of altimeter-era trends.

Altimeter-Era Sea-Level Trends

The observed regional trends estimated from just over 25 y of satellite altimeter measurements are shown in Fig. 1 with the global mean background rate of rise both included (Fig. 1A) and removed (Fig. 1B). The global mean raw trend averages ~ 3.0 mm/y, and regional rates of rise are positive in all regions except for a few eddy-scale areas near the major Northern Hemisphere western boundary currents (the Kuroshio in the western north Pacific Ocean and the Gulf Stream in the North Atlantic Ocean) that perhaps reflect shifts in these currents; near Greenland, where gravitational effects can be important (9); and in the Southern Ocean (10, 11). Sea-level changes due to eddies and shifting currents are locally offset in regional averages by near-equal and opposite trends in their immediate vicinity. In this work, a focus is given to the broad-scale deviations in regional sea level that have profound significance, particularly along coastlines (2, 11, 12). In many regions and particularly in the tropics and in the eastern Indian, western Pacific, and subtropical Atlantic Ocean basins, rates of rise exceed the global average substantially and have roughly doubled the altimeter-era rate of rise (>3 mm/y) (red regions in Fig. 1B). In contrast, rates of rise in the eastern basins have been below the global mean, in some areas by over 1 mm/y (blue regions in Fig. 1B), substantially offsetting global mean changes (8, 12). The strongest large-scale deficits from the global mean rate of rise are evident in the Southern Ocean, and these can reach magnitudes exceeding 3 mm/y, entirely offsetting global mean rise, and have been associated with reduced rates of warming due to circumpolar upwelling (13).

Significance

Regional patterns of sea-level rise have been observed from satellites since 1993 and are associated with increased coastal impacts in many regions. It is unknown whether such patterns will be transient, arising from natural climate variations, or persistent, driven by external climate forcing. Here, using climate model ensembles, we demonstrate that forced changes are likely to have contributed significantly to observed altimeter-era patterns of rise and that these patterns may persist for decades to come, with increased intensity as climate change progresses.

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¹To whom correspondence should be addressed. Email: fasullo@ucar.edu.

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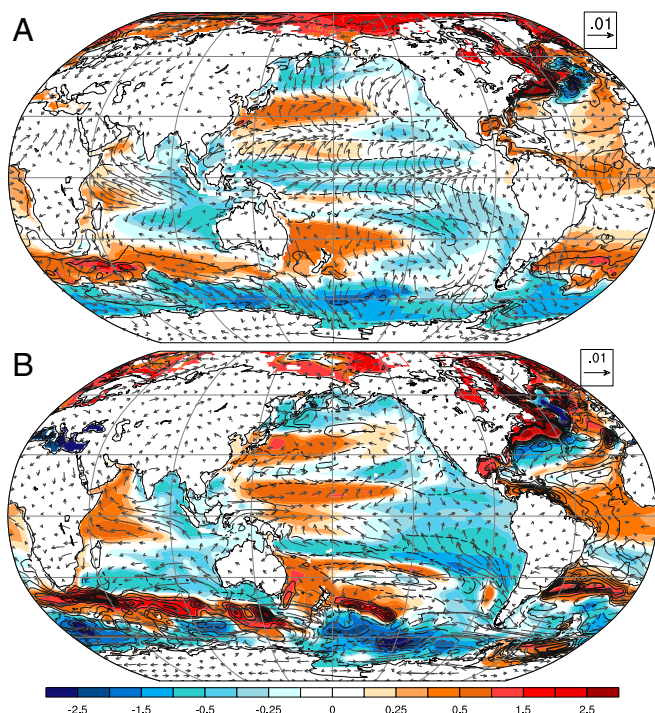


Fig. 2. The 1993–2018 FR in sea level (millimeters per year; global mean removed), near-surface winds (vectors; meters per second per year; mean retained), and ocean heat content (contour lines; spacing of 10^7 J/m² per year) estimated from ensemble mean trends in (A) the CESM and (B) the ESM2M. Heat content changes are shown as a function of depth and in greater detail in *SI Appendix, Figs. S8, S10, and S11*.

developed above. Lastly, after the FR has been found to emerge, an additional important question then arises as to whether a simulated FR is realistic. This question, while only tangentially related to the question of emergence, can be addressed by comparing trend patterns in altimetry with the distribution of patterns simulated in the LEs. Where the observed trend correlations lie outside of the ensemble range, biases in model variability or FRs are likely to exist.

Important caveats exist when using climate models to study sea level. Some models do not permit changes in global ocean volume, while many do not fully represent the processes that influence the total ocean mass. Dynamic ice sheets are currently not represented in most climate models, including those used here, and gravitational effects and land motion driven by ice mass loss are not represented in any current climate model (2, 29, 30). The limited resolution at which the models are run also precludes simulation of eddies in the open ocean, resulting in poor representation of western boundary currents and their extensions and an adequate treatment of coastal ocean dynamics. However, for understanding broad-scale changes in the open ocean, it is the changes in ocean heat content, near-surface winds, and salinity that are dominant, and climate models have long been able to resolve these aspects, although a role for small-scale interactions remains plausible and model validation is needed (25). Here, we use LEs based on 40 members of the Community Earth System Model (CESM) (26) spanning from 1920 to 2100 and 30 members of the Geophysical Fluid Dynamics Laboratory Earth System Model Version 2M (ESM2M) (31) run from 1950 to 2100. For the 20th century through 2005, estimated historical forcings (14) are imposed in these simulations, while from 2005 to the remainder of the 21st century, forcings are prescribed from a business-as-usual climate scenario entailing increases in greenhouse gas concentrations and reductions in anthropogenic aerosol emissions [also known as

Representative Concentration Pathway 8.5 (RCP8.5)] (32), both of which are likely to influence sea level.

Simulated Patterns of Change

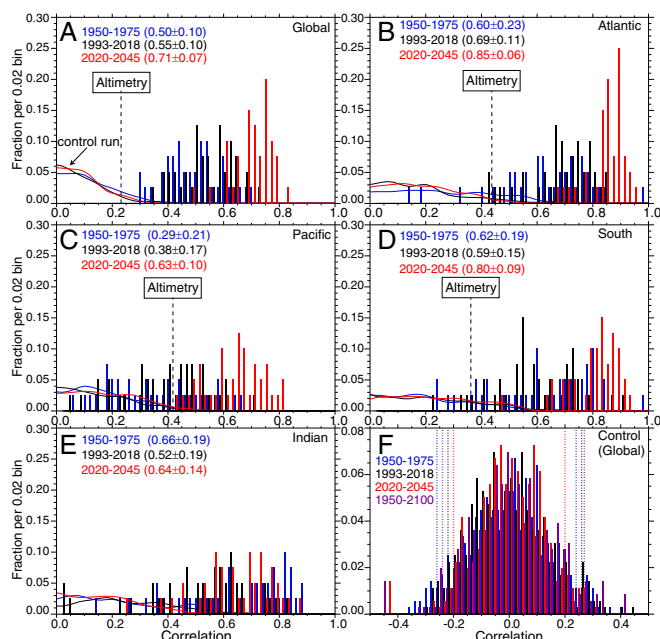
The altimeter-era (1993–2018) FR trends in sea level and near-surface winds for the CESM and the ESM2M LEs are shown in Fig. 2, where the global mean rise has been removed to highlight regional patterns. The FRs estimated from annual mean trends are shown, as seasonal contrasts in the FRs are small, with patterns for June through August and December through January correlating at 0.91 for the CESM and 0.99 for the ESM2M (*SI Appendix, Fig. S1 and Table S1*). In most regions, the FR sea-level trends are statistically significant based on the ensemble mean trend exceeding its $\pm 2\sigma$ range across ensemble members (*SI Appendix, Fig. S2*). Various similarities in the altimeter-era FR are apparent across the two models, and these include a broad-scale relative increase in sea level in the western subtropical Pacific, tropical and northern Atlantic, and subtropical southern Atlantic and Pacific Oceans. Pronounced rates of rise are also evident in the southern midlatitude Indian Ocean near 40° S. Decreases in relative sea level are simulated in the eastern and northern Pacific, eastern and subtropical southern Indian, and polar Southern Oceans. Global ocean FR pattern correlations between the CESM and the ESM2M are strong at 0.50 for the altimeter era (Table 1), although there are likely limits to how well each model depicts nature (*Discussion*). Accompanying the sea-level trends are FR trends in the near-surface wind field that include an intensification of meridional convergence in the tropical central and eastern Pacific Oceans, easterly anomalies in the Indian Ocean, and westerlies in the Southern Ocean. Disagreement between the models is largest in the western tropical Pacific Ocean, where the CESM simulates a decrease in sea level, while ESM2M simulates an increase, despite both models simulating westerly surface wind FR trends. Overall, the basin-scale FR trend pattern correlations between the two models are modest at 0.37, 0.52, 0.57, and 0.54 for the Atlantic, Southern, Pacific, and Indian Ocean basins, respectively (Table 1). It is particularly notable that relative rates of rise associated with the FR are of comparable magnitude with the global mean rate of rise and that the general structure of changes simulated in the LEs in many regions resembles those in the altimeter record (Fig. 1B).

Estimates of the forced sea-level trends can also be derived for 1950–1975 (*SI Appendix, Fig. S3*), for the coming decades (2020–2045) (Fig. 3), and for 1950–2100 (*SI Appendix, Fig. S4*). It is noteworthy that the FR from 1950 to 1975, when aerosol forcing of climate increased substantially, contrasts considerably between models ($r = -0.21$) (Table 1) and with the altimeter era ($r = -0.30$ for CESM, $r = 0.04$ for ESM2M) and subsequent FRs, highlighting both the transient nature of the FR and associated limitations in pattern scaling approaches to estimate it. In contrast, the altimeter-era FR trend is well correlated with those simulated for 2020–2045 ($r = 0.72$ for CESM, $r = 0.76$ for ESM2M) and for 1950–2000 (Table 2 and *SI Appendix, Table S2*) but with an intensity that increases notably in the future (Figs. 2 and 3). The pattern correlations of the model FRs also become increasingly similar, with the

Table 1. Pattern correlations between the FRs in the CESM and the ESM2M across various time periods

Time period	Global	Atlantic	Southern	Pacific	Indian
1950–1975	−0.21	−0.08	−0.20	−0.32	−0.26
1993–2018	0.50	0.37	0.52	0.57	0.54
2020–2045	0.63	0.59	0.67	0.81	0.51
1950–2100	0.76	0.70	0.78	0.88	0.69

The correlations demonstrate general agreement between the models' long-term FRs while highlighting disagreement in their FRs for the mid-20th century.



both the tide gauge and altimeter sea-level records, must account for this time-varying character. In contrast, it is reasonable to expect 21st century patterns of forced change to largely be persistent, and thus, pattern-scaling approaches for prediction may be warranted. In addition, the model ensembles show that the spatial patterns of the FR and major modes of internal variability, such as the El Niño/Southern Oscillation and the Pacific Decadal Oscillation (PDO), are likely to be correlated, perhaps strongly so. As a consequence, efforts to characterize the patterns of these internal modes empirically may be subject to the conflation of internal and forced variability. For both the tide gauge record, which experiences continual changes in available data over time (43) and a general spatial sampling challenge (43, 44), and the altimeter record, during which large changes in the PDO exist (20, 21), this conflation represents a significant source of uncertainty.

Given the socioeconomic and ecological importance of sea-level rise, narrowing uncertainty in these outstanding issues is imperative. Continuation of the altimeter record and exploration

with climate models and complementary sources of data remains a promising path forward for narrowing existing uncertainties.

Methods

The CESM and ESM2M climate models include coupled component models for the atmosphere, land, ocean, and sea ice. The CESM atmospheric component resolution is about 1° (288 longitude × 192 latitude), while the ESM2M atmospheric resolution is about 2° (144 longitude × 90 latitude). Ocean resolution for both models is variable in latitude and averages about 1°. The CESM ensemble initial conditions differ only in a round-off level perturbation to air temperature (25), while the ESM2M initial conditions were taken from different days in January 1950 to generate ensemble spread (31).

The datasets analyzed during this study are available on the Earth System Grid (<https://www.earthsystemgrid.org>, www.cesm.ucar.edu/projects/community-projects/GLENS/).

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