Underlying drivers of decade-long fluctuation in the global mean sea-level rise

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Abstract
Natural climate variability can mask the background trend of global mean sea-level (GMSL) caused by global warming. Recent advances in satellite measurements and ocean heat-content estimates have enabled the monitoring of GMSL budget components and provide insights into ocean effects on the Earth's energy imbalance and hydrology. We observed a decadal fluctuation in GMSL rise, which coincides with an increasing trend in the 2010s after the warming ‘hiatus’ during the 2000s, and demonstrated that the rate of sea-level rise can be attributed to climate-related decadal fluctuations in ocean heat storage and hydrology. Since ~2011, the decadal climate variability has resulted in additional ocean mass gain (271 ± 89 Gt yr⁻¹) from glacier-free land water storage and increased ocean heat uptake (0.28 ± 0.17 W m⁻²), increasing the GMSL rise rate by 1.4 ± 0.4 mm yr⁻¹. The suggested estimates of sea-level and Earth's energy budgets highlight the importance of natural variability in understanding the impacts of the ongoing sea-level rise.

1. Introduction
Globally, the mean sea level has increased ~20 cm over the past century, and has been rising by nearly 3 mm yr⁻¹ during the period of 1993–2017 (Church et al 2013, Ablain et al 2017, WCRP Global Sea Level Budget Group 2018 (hereafter WCRP)). The change in the global mean sea level (GMSL) rate has been primarily attributed to the effect of thermal expansion in ocean, mass loss from glaciers and ice sheets, and changing land water storage (LWS) (Shepherd et al 2012, Wada et al 2012, Gardner et al 2013, Marzeion et al 2014). The GMSL budget was estimated by WCRP (2018), comparing the sum of all sea-level components with the observed GMSL. The altimetry-based sea-level products showed an average rate of 3.1 mm yr⁻¹ in the GMSL trend over the altimeter era. The rate of sea-level rise has increased over the recent decades and has been faster since 2010s. The increases in the rate of sea-level rise are also not globally uniform (e.g. Church et al 2013). These results indicate that the rate of GMSL rise is perturbed by internal climate modes in the complex Earth's climate system. Although the secular trend of GMSL rise is a crucial indicator of ongoing global warming, the fluctuations on interannual to decadal timescales superimposed on this trend can also provide important clues for the role of oceans in Earth’s energy imbalance (EEI) and global hydrological cycle.

Natural climate variability on interannual to decadal timescales masks the background trend of the detected sea level, thereby changing the acceleration values over short timescales. Previous studies have shown that the GMSL responds to the interannual El Niño-Southern Oscillation (ENSO) variability (Boening et al 2012, Fasullo et al 2013, Cazenave et al 2014, Nerem et al 2018, Hamlington et al 2020). It has been reported that the sea level variations related to the ENSO are closely linked to the dominant changes in ocean heat storage and global hydrological cycle; however, the relative importance of these two contributions to GMSL variability has remained unclear. Piecuch and Quinn (2016) also raised the question of why the GMSL response to El Niño in 2015/2016 was much stronger than 1997/1998, although these two events were comparable in ENSO amplitude. They speculated in their discussion that other climate modes, like Pacific Decadal Oscillation
(PDO), exert an impact on GMSL (Newman et al 2016).

One factor that makes it difficult to understand the ENSO-related GMSL changes is the presence of decadal modes associated with the climate variability (Zhang and Church 2012, Hamlington et al 2019, Moreira et al 2021). The GMSL showed a sluggish rate of \( \sim 2.4 \text{ mm yr}^{-1} \) during the 2000s (WCRP 2018), despite the ocean gaining mass from ice sheets and glaciers. Climate-driven water exchanges between ocean and land contributed to this slowdown (Cazenave et al 2014, Reager 2016). This decade-long decrease in GMSL rate is also consistent with a pause in the global mean surface temperature increase, which is commonly called as the recent warming ‘hiatus’ (Engel et al 2014, Maher et al 2018). The global ocean has been suggested to absorb extra heat because of anthropogenic radiative forcing during the hiatus period (Chen and Tung 2014). However, more recent analyses and observations revealed that the ocean heat uptake has slowed down over the 2000s hiatus as compared to the recent decade after 2011 (Xie et al 2016, Von Schuckmann et al 2020, Loeb et al 2021). The rate of GMSL is increasing again after the surface warming hiatus (Yi et al 2015, Moreira et al 2021), along with a shift in the Pacific climate variability that has been shown to play a role in GMSL acceleration occurring on decadal time scales (Hamlington et al 2019). Based on analyses of ocean temperature data, Von Schuckmann et al (2020) revealed that the rates of ocean heat gain have been steadily increased over the past decades, but a rapid increase after the recent hiatus. More recently, a comparison between satellite observations of top-of-atmosphere (TOA) net radiation and in situ observations showed a decadal increase in EEI from mid-2005 to mid-2019 (Loeb et al 2021). These results indicated that heat gain in the oceans is increasing over the recent decade, but a direct comparison with the sea-level budget components and their relationship with natural climate variability is lacking.

Because the ocean stores over 90% of EEI in the form of ocean heat content (OHC) and reflects the changes in mass between the ocean and land, natural changes in OHC and exchange of water mass significantly affect the decadal trends of GMSL rise. Therefore, estimating climate-driven sea-level variations is essential to improve our understanding of ocean responses to the global climate system and associated rising sea levels in the future. Despite the significance of determining GMSL and its changes, the following aspects still remain unclear: (a) what are the internal modes that represent the changes in the GMSL rate on decadal timescales (Hamlington et al 2019); (b) how and to what extent does the ENSO interacts with decadal-scale fluctuations in the GMSL rate (Piecuch and Quinn 2016); and (c) what is the ocean’s role in the Earth’s energy budget (Llovel et al 2011, Johnson et al 2016). Herein, these issues are discussed by considering the influence of the Earth’s energy storage and global hydrology during the closure of sea-level budget.

2. Data and methods

We considered six different altimetry GMSL products from 1993 to 2018 to estimate GMSL budget during the altimetry era. These products were corrected for the effect of glacial isostatic adjustment and TOPEX-A instrumental drift (see details on the altimetry-based sea-level products in supplementary material). For a steric component of GMSL, we used three following reanalysis products: Ishii and Kimoto (2009) (hereafter IK), EN4 product from Good et al (2013), and NOAA product from Levitus et al (2012) for 1993–2017, except for IK available until 2012. After 2005, three Argo products from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), International Pacific Research Center (IPRC), and the SCRIPPS Institution of Oceanography (SCRIPPS) were also considered. Because of the Reanalysis (Argo) products are only available from the surface to 700 m (2000 m), the estimate for the deep ocean contribution of 700–2000 m (Chambers et al 2017) and deep ocean contribution (Perrey and Johnson 2010) was added over the whole datasets. For Greenland and Antarctic ice sheets, the Ice sheet Mass Balance Intercomparison Exercise (IMBIE) datasets are used in this study. The IMBIE provides an estimate of Ice Sheet data by using satellite altimeters, gravity, and input-output method (Shepherd et al 2012). Four global glaciers products were considered to estimate the contribution to GMSL (Cogley 2009, Leclercq et al 2011, Marzeion et al 2015, Zemp et al 2019). For LWS, the Gravity Recovery and Climate Experiment (GRACE) mascon (JPL RL06Mv2) solution from 2002 to 2017 is used in this study. Prior to the GRACE launch, the reanalysis datasets from Modern-Era Retrospective Analysis for Research and Applications (MERRA) and MERRA-2 (Reichle et al 2011, Reichle et al 2017) were considered (see more details on steric and mass datasets in supplementary material).

To extract time-varying trends in all components of sea-level budget, we used an ensemble empirical mode decomposition (EEMD) method, which has been widely used in many geophysical climatology applications (Huang and Wu 2008, Ezer 2013, Ji et al 2014, Chen et al 2017). The EEMD is an advanced method that improved the mode mixing problem in empirical mode decomposition. This method is designed to separate the original signals into several intrinsic mode functions (IMFs) and a secular trend, i.e. a residual (Huang et al 1998). The IMFs of EEMD have been acquired as an ensemble average of IMFs separated from the original data sets added by Gaussian white noise. Figure S2 (available online at stacks.iop.org/ERL/16/124064/mmedia) shows the
EEMD results for all components, which demonstrate seven IMFs and residual trend in ascending order from high to low frequency. Based on spectral analysis, the EEMD-derived IMFs can be grouped into four major time-scale components: High-frequency, ENSO-scale Interannual variability, decadal-scale variability and a residual as the intrinsic trend. Details about EEMD method and the results of significance test and ending effect of a large El Niño in 2015/2016 are also given in supplementary material.

3. Decade-long fluctuation in GMSL

3.1. Temporal evolution of sea-level rise rate
We assessed the GMSL budget in terms of different contributions, using a number of available datasets for altimetry-based sea levels as well as mass and steric components (figure 1(a)). Ensemble means were applied for all sea-level budget components. The temporal evolution of altimetric GMSL agrees well with the sum of all the components (figure 1(a), upper) and the linear trend difference between the two GMSLs is small (0.01 mm yr$^{-1}$), thereby representing the GMSL budget closure and consistency of different datasets. These records show the sea-level fluctuations superimposed on the dominant background trend, with particularly significant ENSO-related changes in the GMSL rise.

To diagnose the temporal change of sea-level rise rate over recent decades, we extracted decadal-scale variability from all components of the GMSL budget by using EEMD method. Throughout the altimeter era, a distinct decade-long fluctuation with a peak period of $\sim$12 years was identified in the ensemble mean GMSL as well as in the sum of all components (figure 1(b), upper), which were in phase with a downward shift during the recent hiatus in the 2000s and in phase with an upward shift subsequently (figure 1(b), bottom). Without an intrinsic trend (i.e., a residual trend), the GMSL rates display a transition trend from positive to negative during the surface warming slowdown; however, this trend transitioned back to positive in 2011 (see figure S3(b)), which corresponds to a recent resumption of surface warming after the decade-long hiatus (Hu et al 2019, Lenssen et al 2019). This decadal fluctuation extracted from the EEMD method is also supported by the first mode of the empirical orthogonal function (EOF) analysis, which is derived using a successive five year running mean of the altimetric sea-level data with a linear trend removed (figure S5). The decadal pattern from the EOF analysis is very similar to a decadal fingerprint, which is represented by the sea-level regression in regard to the EEMD-determined decadal mode (figure S6(a)), indicating the robustness of decadal sea-level variability from EEMD analysis. These results show that the decadal GMSL fluctuation is separated...
from the interannual modes (i.e. periods of 3–7 years) and the intrinsic trend, thereby supporting the results of previous studies that have used different methods; e.g. the multiple linear regression (Zhang and Church 2012, Moreira et al 2021) and the cyclo-stationary EOFs (Hamlington et al 2017, 2019).

3.2. Decadal GMSL fluctuation associated with Pacific climate variability

We further identified a strong relationship between the decadal modes of sea-levels and the Pacific decadal variability obtained from the EEMD of the PDO (figure 2). Over the altimeter period, the transition times agreed well between the sea level components and the Pacific decadal variability, showing a distinct transition around 2011 that is consistent with the recent resumption of surface warming after the 2000s hiatus. The Pacific decadal mode has its largest correlation with both the GMSL and steric sea level at near-zero lag; however, there is a seven month lag with the LWS. The spatial patterns of the regressed EEMD-derived decadal GMSL and PDO mode are also agree (figures S6(a) and (b)), suggesting a relationship between sea level and natural variability on decadal timescale. This suggests that the climate-driven decadal mode strongly contributed to slowing the GMSL rise rate during the hiatus and increasing the trend rate after the hiatus. Furthermore, there is a possible link between these climate-driven fluctuations and sunspot activity (dashed red line in figure 2), which is known to exhibit a cycle that lasts approximately 11 years (Hathaway 2015). It has been noted that the cycle of solar forcing can be amplified to produce a measurable climate response on decadal timescale through at least two mechanisms of 'top-down' stratospheric response and 'bottom-up' coupled ocean-atmosphere surface response (e.g. White et al 1997, Kodera and Kuroda 2002, van Loon et al 2004, Haigh et al 2005, Matthes et al 2006, Meehl et al 2009). The sunspot activity on a decadal timescale is in phase with the Pacific decadal variability and the GMSL fluctuation, but their correlations lag at a maximum of ∼30 months. This relation is evident from the regression pattern of sea level onto the decadal sunspot activity (figure S6(c)), which shows that there is oceanic response to the solar cycle on decadal timescales. Previous observational and modeling studies have shown a delayed surface response at 1–3 years after the solar cycle (Gray et al 2013, Hood et al 2013) and proposed a mechanism that involves interaction between atmosphere and OHC in the mixed layer (Scaife et al 2013, Misios et al 2016). More recently, analysis by Lin et al (2021) identified the solar activity-induced the SST footprint in Northeast Pacific that modulates the background surface temperature in the Pacific and the associated Central Pacific (CP) ENSO activity on decadal timescales. However, there are still some uncertainties, not only in the reliability and characteristic of observational solar activity signals but also in understanding of the mechanisms (e.g. Gray et al 2013). Because of the complex processes in air-sea feedback, the physical mechanisms that lead to the impact of the solar cycle on the climate are not fully understood, and thus further investigations are required in the future; nevertheless, the findings from previous studies showed that the solar cycle on decadal timescale can be a relevant source of decadal climate variability both on global and regional scales. These comparisons suggest that the decadal fluctuation in GMSL reported here is a distinct and robust signal associated with the earth’s climate system, which is different from the ENSO-related interannual variability.

We also note that the climate decadal mode can result in the modulation of GMSL response to ENSO.
events (figure 3). The El Niño in 2015/2016 was one of the strongest events in history, which was comparable to the El Niño events in 1997/1998. The strengths of amplitude were comparable between these two events; however, the sea-level response to El Niño was weaker during the 1997/1998 El Niño than during the 2015/2016 El Niño (figure 3(a)) as previously discussed in Piecuch and Quinn (2016) and WCRP Global Sea Level Budget Group (2018). To examine how the decadal mode modulates with the GMSL response to ENSO events, the contributions of interannual and decadal variability to the observed three-month mean GMSL (with an intrinsic trend removed) were analyzed (figure 3(b)). The decadal mode contributed to \( \sim 23\% \) of a decline in GMSL during the El Niño in 1997/1998, but made a positive contribution of \( \sim 21\% \) to the GMSL rise in the 2015/2016 El Niño. With the decadal mode removed, the sea-level responses to the two strong El Niño events show a similar amplitude (\( \sim 5.3 \) mm in 1997/1998 and \( \sim 5.4 \) mm in 2015/2016). The decadal mode also has a positive contribution (\( \sim 28\% \)) to the largest decline in the 2010/2011 La Niña, as discussed in previous studies (Boening et al 2012). Our analysis shows that the GMSL responses to ENSO can be depressed or amplified by the relation with the Pacific decadal mode. Recent studies suggested the differences in underlying dynamics between the 1997/1998 and 2015/2016 extreme El Niños (Paek et al 2017, Long et al 2020). Paek et al (2017) argued that the 2015/2016 event is not a pure tropical forced Eastern Pacific (EP) El Niño but a mixture of the EP and the CP El Niños, emphasizing the CP El Niño dynamics more affecting on the 2015/2016 event than on the 1997/1998 event. Unlike the EP El Niño, the CP El Niño events include strong decadal signals associated with air-sea feedback in mid-latitudes and Pacific climate modes (Chiang and Vimont 2004, Yu and Kim 2011) and become more remarkable after 1980s (Lee and McPhaden 2010). The atmospheric circulation and global water cycle from the CP El Niños may contribute more to the GMSL fluctuation on decadal time scale, leading to higher sea-level in 2015/2016 event than in 1997/1998 event.

4. Climate-driven LWS

To investigate the response of global hydrology and ocean heat storage to climate decadal variability, the following two decadal periods were compared: 2002–2010 (i.e. hiatus period) and 2011–2017. Prior to the GRACE record that extends back to 2002,
global hydrological models estimated the trend and fluctuation of total LWS. However, there were still uncertainties regarding the ability of model to simulate the interannual to decadal variability in global LWS (Scanlon et al. 2018). Moreover, the uncertainty in the OHC calculation that arises from insufficient sampling and instrumental biases was mainly observed for the period before the early 2000s; that is, the pre-Argo period (Durack et al. 2014). Therefore, we used the GRACE and Argo-based products to estimate the global patterns of decadal trends in the LWS and OHC for the two analysis periods. The global estimate of the GRACE trend over 2002–2010 revealed an increasing LWS (wetting) at low latitudes, and decreasing LWS (drying) at the mid-latitude of the southern hemisphere (figure 4); these results coincides with previous GRACE studies (Chen et al. 2010, Reager et al. 2016). The latitudinal trends in LWS shifted since 2011 and showed a distinct pattern of low latitude drying and mid-latitude wetting, which is more prominent in the southern hemisphere. The decadal trend shift resulted

Figure 4. Global map of LWS trend (gigatons per year) and its zonal total trend (gigatons per year per 1/2 degree grid) in (a) in 2002–2010 and (b) 2011–2017. (c) Time series of global LWS (green) from GRACE and land precipitation (yellow) from GPCP. The linear trend throughout the GRACE period was removed to highlight climate-driven decadal trend shift in LWS. The dashed lines indicate the linear trends in 2002–2010 and 2011–2017. The LWS uncertainties are shown in colored shades.
from changes in the LWS regime since 2011; that is, the wet conditions transformed to dry conditions at low latitudes, while the opposite effect was observed at mid-latitudes (Hamlington et al. 2017). The spatial distributions of the LWS trend strongly resembled the LWS pattern regressed on the EEMD-determined decadal mode of the PDO (figure S(a)), thereby implying an important decadal persistence in the Earth’s climate systems (Hamlington et al. 2017). The GRACE-derived LWS was consistent with the observed land precipitation from the Global Precipitation Climatology Project in the decadal trends and in its interannual variations throughout the GRACE period (figure 4(c)). There was a delayed (maximum correlation at seven months) response of LWS to the precipitation in land. When the precipitation falls onto land, much of it soaks into the ground as infiltration and some water infiltrates deep into the ground and recharges groundwater in aquifers. This process can make a time lag response of LWS to precipitation (Eagleson 1978). Previous studies demonstrated a delayed response between LWS and precipitation (Humphrey et al. 2016, Zhang et al. 2019). The lags between LWS and precipitation are about 1–3 months in the low- and mid-latitude basins. However, the effect of seasonal snowpack accumulation and the melting process causes the longer lag (6–9 months) response of LWS to precipitation at high latitude (Humphrey et al. 2016, Zhang et al. 2019).

The glacier-free LWS contributed 0.14 ± 0.11 and 1.04 ± 0.21 mm yr⁻¹ to the sea level rise during the first and second decades of the GRACE period, respectively (figure 6). Because the net LWS changes estimated here include human- and climate-driven components in storage, an Intergovernmental Panel on Climate Change estimate (Church et al. 2013) of direct human-induced LWS changes (0.38 ± 0.12 mm yr⁻¹) was used to calculate the climate-driven LWS contribution to GMSL (Reager et al. 2016). Therefore, the climate-driven LWS suppressed the GMSL rise (−0.23 ± 0.16 mm yr⁻¹) during the hiatus period and subsequently enhanced it (0.66 ± 0.24 mm yr⁻¹), which suggests that the natural LWS variability significantly contributed to the

Figure 5. Global LWS and OHC fingerprints with respect to the PDO. (a) LWS and (b) OHC (0–2000 m) regressed onto the decadal mode of the PDO (shown in figure 2) over 2002–2017 and 2005–2017, respectively. Data sources are GRACE mascon solution (JPL RL06Mv2) for LWS and SCRIPPS for OHC, respectively. The cross-symbol areas indicate significance at the 95% confidence level determined using Student’s t-test.
decade-long shift in the GMSL. These LWS changes determined by GRACE indicate that naturally occurring variability in precipitation leads to decadal variations in the water exchange between ocean and land, thereby supporting the findings of several studies mentioned above.

5. Ocean effect on the earth energy imbalance

The steric contribution to the rise in GMSL arises from changes in OHC, which is the major factor sequestering the EEI resulting from rising CO₂ concentrations. To elucidate OHC fluctuations contributing to the rate of GMSL rise, we analyzed the temperature profiles recorded by Argo array floats since 2005, which provided a reliable OHC estimate over 0–2000 m (Cheng et al. (2015)). Global maps of OHC (derived from the SCRIPPS product) trends over the two decadal periods revealed that since 2011, the trend has been changing toward an opposite trend compared to that of the preceding period (figure 7). It is manifest from the regression pattern of the EEMD-determined decadal mode of the PDO that there are global ocean responses to Pacific climate variability (figure 5(b)), which agree with the linear trend patterns of the OHC. In 2005–2010, the OHC showed strong warming trends in the eastern/southeastern Indian and western tropical Pacific oceans; a warming structure was also centered in the western/central North Pacific, and surrounded by cooling along the west coast of North America. With the PDO transitioning back to positive since 2011, the spatial patterns of the OHC trend were reversed; this was accompanied by a positive (warming) trend in the EP ocean and a negative (cooling) trend in the western tropical Pacific and northern and southeastern Indian oceans. The Pacific patterns of the decadal OHC trend are linked to the PDO-related trade trends on a decadal timescale, i.e. a strengthening of trade winds during the 2000s, followed by a weakening trend of trade winds since 2011. Climate-altered trade wind results in changes of the upper-ocean circulations, redistributing heat in the Pacific (Merrifield et al. 2012, Moon et al. 2013, England et al. 2014, Hamlington et al. 2014, Cha et al. 2018, Maher et al. 2018). The trend reversal was also observed in the North Atlantic, with warming in the subtropical gyre and cooling in the subpolar gyre; this result indicates a significant influence of ocean circulation on heat redistribution. It is worth noting that the decadal OHC trend of subpolar gyre in the North Atlantic may be attributed to the shifts in the melting rate of Greenland Ice Sheet (GIS). For instance, the cooling in the subpolar gyre since 2011 contributed to the slowdown of mass loss in the GIS, which is consistent with the findings of a recent study (IMBIE Team 2020) that identified a persistent increase in ice loss rate prior to 2012. The combined impacts of warming and cooling regions in the OHC resulted in a GMSL fluctuation that can be caused by decadal-scale climate variability. The other two datasets (i.e. IPRC and JAMSTEC) also show the decadal trend shifts of global OHC, which generally
Figure 7. Global map of upper-2000 m OHC trend (joules per year) from the SCIRPPS data during (a) 2005–2010 and (b) 2011–2017. (c) Ensemble mean of globally integrated OHC (black) based on three Argo products and their individual values (colored lines). The shaded areas denote one standard deviation around the mean. (d) Comparison between the yearly OHC (black) and TOA net energy storage (blue). Each component was detrended for the study period. The OHC uncertainties (black bar) are shown at one standard error of the mean, and TOA annual random errors (blue bar) are based on Johnson et al (2016).

agreed with the pattern of SCIRPPS (figure S8, see more details on the comparison between the Argo products in supplementary material).

The globally integrated OHC calculated from the surface to a 2000 m, based on the three Argo products, is shown in figure 7(c). Despite some spread around the ensemble mean, all datasets show an increase in global OHC since 2005, which demonstrates that the estimates of ocean warming are robust. The time series of annual global OHC revealed that the rate of ocean heat uptake was slower prior to 2011 and faster after 2011. To directly compare OHC with the satellite-observed Earth’s energy storage, time-integrated TOA net flux estimated from the Clouds and the Earth’s Radiant Energy System (CERES) measurement was used; the Argo-based OHC tracked the phase of the TOA net energy storage reasonably well (figure 7(d)). Yearly variations of global OHC and CERES TOA net energy storage were correlated at 0.53; this was in good agreement with the results
of previous works (Johnson et al. 2016, Llovel and Terray 2016, Johnson and Birnbaum 2017, Loeb et al. 2021).

To illustrate the OHC contribution to the Earth’s energy budget, we estimated the EEI during and after the warming hiatus in terms of the heating rate applied over the Earth’s surface area; this was achieved by combining Argo-observed upper-2000 m OHC with previously published estimates of heat uptake, using the deep ocean and non-ocean terms (figure 8). The global volume-integrated OHC trend (figure 7(c)) demonstrates that the planetary heating rates are $0.37 \pm 0.15$ W m$^{-2}$ over 2005–2010 and $0.65 \pm 0.18$ W m$^{-2}$ over 2011–2017 (per unit of Earth’s surface of $5.1 \times 10^{14}$ m$^2$). Considering a constant heating rate of $0.099 \pm 0.066$ W m$^{-2}$ at ocean depths below 2000 m depth (Purkey and Johnson 2010), as well as the sum of non-ocean terms by Von Schuckmann et al. (2020), we obtained a net heat uptake of $0.55 \pm 0.12$ and $0.85 \pm 0.10$ W m$^{-2}$ for 2005–2010 and 2011–2017, respectively. The comparison between the two periods indicates that the global ocean gained more heat energy from 2011 onwards ($0.30 \pm 0.16$ W m$^{-2}$), as compared with the previous period. The EEI estimated from the latest release of CERES satellite data was $0.60 \pm 0.10$ W m$^{-2}$ for 2005–2010 and $0.95 \pm 0.10$ W m$^{-2}$ for 2011–2017, which indicates a close correspondence between two completely independent EEI estimates on decadal time scales. These EEI estimates were not distinguishable within the uncertainty and thus, the increase in the ocean heat uptake since 2011 seems to be robust. The benefits of these two independent approaches are also demonstrated in a recent study by Loeb et al. (2021) that showed a robust positive trend in EEI from mid-2005 to mid-2019 due to mainly changes in clouds, water vapor, and trace gases. Figure 8 further demonstrates the agreement with the EEI obtained from the altimetry minus GRACE residual approach (Levitus et al. 2012, Fu 2016). These results enhance the confidence in all three complementary climate observing systems (Meyssignac 2019). Furthermore, the consistency shown here suggests that there was no shortfall in closing the global energy budget during the 2000s; this was in contrast to the so-called ‘missing energy’ problem (Trenberth and Fasullo 2010).

6. Conclusion and discussions

Understanding the GMSL responses to natural variability can provide important information on the ocean’s role in controlling the Earth climate system (Trenberth and Fasullo 2010, Leuliette and Willis 2011). In this study, we conducted observational analyses to examine the decade-scale fluctuation in GMSL rate and its connection to variations in ENSO, while discussing the impact of climate decadal variability on the Earth’s energy budget and global hydrological cycle. The resulting relationship among sea-level rise, precipitation, ocean warming, and TOA net flux demonstrates a physically consistent expression of decadal climate variability on global scales. Based on the analysis conducted here, the following results can be highlighted: (a) a distinct decadal fluctuation in the rate of GMSL has been identified; (b) the GMSL responses to interannual ENSO signals can be modulated at times of transition in the Pacific
decadal mode; (c) both the steric and LWS components account for a large fraction of the decadal fluctuation in the GMST rate; and (d) the change in ocean heat uptake before and after 2011 is consistent with TOA net energy flux within observation uncertainties and linked to the Pacific decadal climate variability.

Our results can further clarify the ocean’s role in EEI, global hydrology, and perspectives on ongoing sea-level change. An ongoing GMST rise can be influenced by climate-driven signals that can accelerate or decelerate the underlying sea-level trend for decadal time periods. Furthermore, the estimate conducted here illustrates the utility of completely independent datasets for the cross validation of EEI by emphasizing the consistency of thermal energy in the Earth system (Loeb et al. 2021). Although systematic errors of space observations and in situ uncertainties still remain large owing to unsampled regions and/or mapping choices, efforts to extend both satellite measurements and Argo records with ongoing development of Deep Argo floats (Johnson et al. 2015) will allow better monitoring of EEI changes and give accurate data-sets to estimate the role of ocean in the Earth’s energy and GMST rise in the future (Llovel and Terray 2016).

Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

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References
Ablain M, Legeais J F, Prandi P, Marcos M, Fenoglio-Marc L, Dieng H B, Benveniste J and Cazenave A 2017 Satellite altimetry-based sea level at global and regional scales Surv. Geophys. 38 7–31
Boening C, Willis J K, Landerer F W, Nerem R S and Fasullo J 2012 The 2011 La Niña: so strong, the oceans fell Geophys. Res. Lett. 39
Cazenave A, Dieng H-B, Meyssignac B, Von Schuckmann K, Decharme B and Berthier E 2014 The rate of sea-level rise Nat. Clim. Change 4 558–61
Cha S C, Moon J H and Song Y T 2018 A recent shift toward an El Niño-like ocean state in the tropical Pacific and the resumption of ocean warming Geophys. Res. Lett. 45 11–885
Chambers D P, Cazenave A, Champollion N, Dieng H, Llovel W, Forsberg R, Von Schuckmann K and Wada Y 2017 Evaluation of the global mean sea level budget between 1993 and 2014 Surv. Geophys. 38 309–27
Chen J L, Wilson C R and Tappy B D 2010 The 2009 exceptional Amazon flood and interannual terrestrial water storage change observed by GRACE Water Resour. Res. 46 W12526
Chen X and Tung K K 2014 Varying planetary heat sink led to global-warming slowdown and acceleration Science 345 897–903
Chen X, Zhang X, Church J A, Watson C S, King M A, Monselesan D, Legresy B and Harig C 2017 The increasing rate of global mean sea-level rise during 1993–2014 Nat. Clim. Change 7 992–5
Cheng L, Zheng F and Zhu J 2015 Distinctive ocean interior changes during the recent warming slowdown Sci. Rep. 5 1–11
Chiang J C and Vimont D J 2004 Analogous Pacific and Atlantic meridional modes of tropical atmosphere–ocean variability J. Clim. 17 4145–58
Church J A et al 2013 Climate change 2013: the physical science basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T F Stocker et al (Cambridge: Cambridge University Press)
Cogley J G 2009 Geodetic and direct mass-balance measurements: comparison and joint analysis Ann. Glaciol. 50 96–100
Durack P J, Gleckler P J, Landerer F W and Taylor K E 2014 Quantifying underestimates of long-term upper-ocean warming Nat. Clim. Change 4 999–1005
Eagleson P S 1978 Climate, soil, and vegetation: 1. Introduction to water balance dynamics Water Resour. Res. 14 705–12
England M H, McGregor S, Spence P, Meehl G A., Timmermann A, Cai W, Gupta A S, McPhaden M J, Purich A and Santoso A 2014 Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus Nat. Clim. Change 4 222–7
Ezer T 2013 Sea level rise, spatially uneven and temporally unsteady: why the U.S. East Coast, the global tide gauge record, and the global altimeter data show different trends Geophys. Res. Lett. 40 5439–44
Fasullo J T, Boening C, Landerer F W and Nerem R S 2013 Australia’s unique influence on global sea level in 2010–2011 Geophys. Res. Lett. 40 4368–73
Fu -L-L 2016 On the decadal trend of global mean sea level and its implication on ocean heat content change J. Geophys. Res. Oceans 118 7064–16
Gray L J, Scaife A A, Mitchell D M, Osprey S, Ineson S, Hardiman S, Butchart N, Knight J, Sutton R and Kodera K 2013 A lagged response to the 11 year solar cycle in observed winter Atlantic/European weather patterns J. Geophys. Res. Atmos. 118 13405–20
Haigh J D 1996 The impact of solar variability on climate Science 272 981–4
Haigh J D, Blackburn M and Day R 2005 The response of tropospheric circulation to perturbations in lower-stratospheric temperature J. Clim. 18 3672–85
Hamlington B D, Cheon S H, Piecuch C G, Karnauskas K B, Thompson P R, Kim K-Y, Reager J T, Landerer F W and Frederikse T 2019 The dominant global modes of recent internal sea level variability J. Geophys. Res. 124 2750–68
Hamlington B D, Piecuch C G, Reager J T, Chandanpurkar H, Frederikse T, Nerem R S, Fasullo J T and Cheon S-H 2020 Origin of interannual variability in global mean sea level Proc. Natl Acad. Sci. USA 117 13983–90
Hamlington B D, Reager J T, Lo M-H, Karnaunaskeas K B and Leben R R 2017 Decadal separation of global water cycle variability from sea level rise Sci. Rep. 7 1–7

Hamlington B D, Strassburg M W, Leben R R, Han W, Nerem R S and Kim K 2014 Uncovering an anthropogenic sea-level rise signal in the Pacific Ocean Nature Clim Change 4 782–5

Hathaway D H 2015 The solar cycle Living Rev. Sol. Phys. 12 4

Hoogen L, Schimanke S, Spangenberg T, Bal S and Cubasch U 2013 The surface climate response to 11-yr solar forcing during northern winter: observational analyses and comparisons with GCM simulations J. Clim. 26 7489–506

Hu X, Jeong S A, Cai M, Taylor P C, Deng Y and Yang S 2019 Decadal evolution of the surface energy budget during the fast warming and global warming hiatus periods in the ERA-interim Clim Dyn 52 2005–16

Huang N E, Shen Z, Long S R, Wu M C, Shih H H, Zheng Q, Yan N C, Tung C C and Liu H H 1998 The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis Proc. R. Soc. A 454 903–95

Huang N E and Wu Z 2008 A review on Hilbert-Huang transform: method and its applications to geophysical studies Rev. Geophys. 46

Humphrey V, Gudmundsson L and Seneviratne S I 2016 Assessing global water storage variability from GRACE: trends, seasonal cycle, subseasonal anomalies and extremes Surv. Geophys. 37 357–95

IMBIE Team 2020 Mass balance of the Greenland ice sheet from 1992 to 2018 Nature 579 233–9

Ishii M and Kimoto M 2009 Reevaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections J. Oceanogr. 65 287–99

Ji F, Wu Z, Huang N E and Wu Z 2008 A review on Hilbert-Huang transform: method and its applications to geophysical studies Rev. Geophys. 46 438–45

Johnson G C, Lyman J M and Loeb N G 2016 Improving estimates of Earth’s energy imbalance Nat. Clim. Change 6 639–40

Johnson G C, Lyman J M and Purkey S G 2015 Informing deep argo array design using argo and full-depth hydrographic section data J. Atmos. Oceanic Technol. 32 2157–98

Kodera K and Kuroda Y 2002 Dynamical response to the solar cycle J. Geophys. Res. Atmos. 107 ACL–5

Leclercq P W, Oerlemans J and Cogley J G 2011 Estimating the glacier contribution to sea-level rise for the period 1800–2005 Surv. Geophys. 32 519

Lee T and McPhaden M J 2010 Increasing intensity of El Niño in Earth’s heating rate Geophys. Res. Lett. 37

Lennon N I L, Schmidt G A, Hansen J E, Menne M J, Persin A, Rudcy R and Zysy D 2019 Improvements in the GISTEMP uncertainty model J. Geophys. Res. Atmos. 124 6307–63

Leuthie W E and Willis J K 2011 Balancing the sea level budget Oceanography 24 122–9

Levitus S et al 2012 World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010 Geophys. Res. Lett. 39 L11003

Lin Y F, Yu J Y, Wu C R and Zheng F 2021 The footprint of the 11-solar cycle in Northeastern Pacific SSTs and its influence on the Central Pacific El Niño Geophys. Res. Lett. 48 e2020GL091369

Lloyd W, Becker M, Cazenave A, Jevrejeva S, Alkama R, Decharme B, Douville H, Ablain M and Beckley B 2011 Terrestrial waters and sea level variations on interannual time scale Glob. Planet. Change 75 76–82

Lloyd W and Terray L 2016 Observed southern upper-ocean warming over 2005–2014 and associated mechanisms Environ. Res. Lett. 11 124023

Loeb N G, Johnson G C, Thorsen T G, Lyman J M, Rose F G and Kato S 2021 Satellite and ocean data reveal marked increase in Earth’s heating rate Geophys. Res. Lett. 48 e2021GL093047

Long X, Widlansky M J, Schloesser F, Thompson P R, Annamalai H, Merrifield M A and Iou H 2020 Higher sea levels at Hawaii caused by strong El Niño and weak trade winds J. Clim. 33 3037–59

Maher N, England M H, Gupta A S and Spence P 2018 Role of Pacific trade winds in driving ocean temperatures during the recent slowdown and projections under a wind trend reversal Clim. Dyn. 51 321–36

Marzeion B, Cogley J G, Richter K and Parkes D 2014 Attribution of global glacier mass loss to anthropogenic and natural causes Geophys. Res. Lett. 41 919–21

Marzeion B, Leclercq P W, Cogley J G and Jarosch A H 2015 Brief communication: global reconstructions of glacier mass change during the 20th century are consistent Cryosphere 9 2399–404

Matthes K, Kuroda Y, Kodera K and Langematz U 2006 Transfer of the solar signal from the stratosphere to the troposphere: northern winter J. Geophys. Res. Atmos. 111

Meeth G A, Arbësler J M, Matthes K, Sassi F and van Loon H 2009 Amplifying the Pacific climate system response to a small 11-year solar cycle forcing Science 325 1114–8

Merrifield M A, Thompson P R and Lander M 2012 Multidecadal sea level anomalies and trends in the western tropical Pacific Geophys. Res. Lett. 39

Meyssignac B 2019 Measuring global ocean heat content to estimate the earth energy imbalance Front. Mar. Sci. 6 432

Mioso S et al 2016 Solar signals in CMIP-5 simulations: effects of atmosphere–ocean coupling Q. J. R. Meteorol. Soc. 142 928–41

Moon J, Song V T, Bromirski P D and Miller A J 2013 Multidecadal regional sea level shifts in the Pacific over 1958-2008 J. Geophys. Res. Oceans 118 7024–35

Moreira L, Cazenave A and Palanisamy H 2021 Influence of interannual variability in estimating the rate and acceleration of present-day global mean sea level Glob. Planet. Change 199 103450

Nerem R S, Beckley B D, Fasullo J T, Hamlington B D, Masters D and Mitchum G T 2018 Climate-change–driven accelerated sea-level rise detected in the altimeter era Proc. Natl. Acad. Sci. USA 115 2022–5

Newman M et al 2016 The Pacific Decadal Oscillation, revisited J. Clim. 29 4399–427

Paek H, Yu J Y and Qian C 2017 Why were the 2015/2016 extreme El Niño different? Geophys. Res. Lett. 44 1848–56

Piecuch C G and Quinn K J 2016 El Niño, La Niña, and the global sea level budget Ocean. Sci. 12 1165–77

Purkey S G and Johnson G C 2010 Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: contributions to global heat and sea level rise budgets J. Clim. 23 6336–51

Reager J T, Gardner A S, Famiglietti J S, Wiese D N, Eicker A and Lo M H 2016 A decade of sea level rise slowed by climate-driven hydrology Science 351 699–703

Reichle R H, Draper C S, Liu Q, Girotto M, Mahanama S P P, Koster R D and De Lannoy G J M 2017 Assessment of MERIS-2 land surface hydrology estimates J. Clim. 30 2937–60

Reichle R H, Koster R D, De Lannoy G J M, Forman B A, Liu Q, Mahanama S P P, Girotto M, Mahanama S P P, Koster R D and De Lannoy G J M 2017 Assessment of MERIS-2 land surface hydrology estimates J. Clim. 30 2937–60

Reichle R H, Koster R D, De Lannoy G J M, Forman B A, Liu Q, Mahanama S P P, Koster R D and De Lannoy G J M 2017 Assessment of MERIS-2 land surface hydrology estimates J. Clim. 30 2937–60

Reichle R H, Koster R D, De Lannoy G J M, Forman B A, Liu Q, Mahanama S P P, Koster R D and De Lannoy G J M 2017 Assessment of MERIS-2 land surface hydrology estimates J. Clim. 30 2937–60

Reichle R H, Koster R D, De Lannoy G J M, Forman B A, Liu Q, Mahanama S P P, Koster R D and De Lannoy G J M 2017 Assessment of MERIS-2 land surface hydrology estimates J. Clim. 30 2937–60

Scalise A A, Ineson S, Knight J R, Gray L, Kodera K and Smith D M 2013 A mechanism for lagged North Atlantic climate response to solar variability Geophys. Res. Lett. 40 434–9

Scalan R et al 2018 Global models underestimate large decadal declining and rising water storage trends relative to GRACE satellite data Proc. Natl. Acad. Sci. USA 115 E1080–E1089

Shepherd A et al 2012 A reconciled estimate of ice-sheet mass balance Science 338 1183–9

Trenberth K E and Fasullo J T 2010 Tracking Earth’s energy Science 328 316–7

van Loon H, Meeth G A and Arbësler J M 2004 A decadal solar effect in the tropics in July–August J. Atmos. Sol. Terr. Phys. 66 1767–78
Von Schuckmann K et al 2020 Heat stored in the Earth system: where does the energy go? Earth Syst. Sci. Data 12 2013–41
Wada Y, van Beek L P H, Sperna Weiland F C, Chao B F, Wu Y-H and Bierkens M F P 2012 Past and future contribution of global groundwater depletion to sea-level rise Geophys. Res. Lett. 39
WCRP Global Sea Level Budget Group 2018 Global sea-level budget 1993-p resent Earth Syst. Sci. Data 10 1551–90
White W B, Lean J, Cayan D R and Dettinger M D 1997 Response of global upper ocean temperature to changing solar irradiance J. Geophys. Res. Oceans 102 3255–66
Xie S P, Kosaka Y and Okumura Y M 2016 Distinct energy budgets for anthropogenic and natural changes during global warming hiatus Nat. Geosci. 9 29–33
Yi S, Sun W, Heki K and Qian A 2015 An increase in the rate of global mean sea level rise since 2010 Geophys. Res. Lett. 42 3998–4006
Yu J Y and Kim S T 2011 Relationships between extratropical sea level pressure variations and the central Pacific and eastern Pacific types of ENSO J. Clim. 24 708–20
Zemp M et al 2019 Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016 Nature 568 382–6
Zhang X and Church J A 2012 Sea level trends, interannual and decadal variability in the Pacific Ocean Geophys. Res. Lett. 39
Zhang Y, He B, Guo L and Liu D 2019 Differences in response of terrestrial water storage components to precipitation over 168 global river basins J. Hydrometeorol. 20 1981–99