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Climate-driven sea level extremes compounded by marine heatwaves in coastal Indonesia

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The low-lying coastal and island regions are vulnerable to sea level rise and extreme events. Compounded by marine heatwaves, sea level extremes have devastating impacts on coastal community and marine ecosystems. As long tide gauge records are sparse, sea level extremes around Indonesia are poorly understood, and the Compound Height-Heat EXtreme (C-HHEX) events remain unexplored. Here we combine *in situ* and satellite observations with model simulations, to investigate the long-lasting (>1 month) sea level extremes and C-HHEXs along Indonesian coasts of the Indian Ocean since the 1960s. We find that 90 % (80 %) of the extreme sea level (C-HHEX) events, with a maximum monthly sea level anomaly of 0.45m, are clustered in an 8yr period of 2010-2017, due to anthropogenic global sea level rise and decadal enhancement driven by changing surface winds associated with a combined invigoration of the Indian and Pacific Walker Cells, atmospheric overturning circulations in east-west direction. Remote and local surface wind anomalies associated with negative phases of the Indian Ocean Dipole (IOD) - enhanced by La Niña – drive individual C-HHEX events under a precondition of shallow thermocline (a region of subsurface ocean with temperature decreases rapidly downward). By contrast, winds associated with monsoon and its intraseasonal oscillations force the sea level alone events under a deep thermocline condition. We conclude that the shoaling thermocline in eastern Indian Ocean under anthropogenic warming and global sea level rise favorably precondition the ocean for stronger and more frequent sea level extremes and C-HHEXs, increasing the environmental stress on Indonesia.

Extreme sea level events are one of the most consequential impacts of climate change¹⁻³. Global sea level rise over the past century has magnified flooding and caused clear-sky floods in many coastal regions around the world⁴. While much emphasis has been placed on extreme sea levels

induced by storms and high tides on daily time scales⁵, the interplay of longer-lasting sea level extremes driven by intraseasonal-to-interannual climate variability with decadal variability and anthropogenic warming has received less attention. As the dominant mode of interannual climate variability across tropical oceans, the El Niño and Southern Oscillation (ENSO⁶) induces long-lasting sea level extremes⁷⁻¹⁰ and increases the frequency of storm surges¹¹ along the west coasts of the South and North Americas during its positive phase (i.e., El Niño). El Niño also generates intense and more frequent marine heatwaves in the eastern Pacific Ocean¹²⁻¹⁴, causing disastrous impacts in many coastal areas of the Americas. While individual sea level extremes and marine heatwaves in isolation can have large ecological, economic, and social consequences^{15,16}, in combination they can be much more devastating^{17,12} and the compound extremes in earth's climate system (e.g., heatwave and drought) are becoming more common in a warming climate¹⁸. Yet, integrated studies of sea level extremes and marine heatwaves – dubbed Compound Height-Heat EXtreme (C-HHEX) events - are still in its infancy. A better understanding of extremes and their compounds will improve risk assessments, decadal prediction and future projections of high-impact events^{17,19}.

The Indian Ocean rim region hosts one-third of the world's population mostly from developing countries with low-lying coastal areas that are highly vulnerable to climate variability and change. Located at the confluence of the tropical eastern Indian Ocean and western Pacific and being home for diversified coral reefs, Indonesia experiences rapid urbanization on Java island and population growth in low-lying areas, which further increase its vulnerability to climate change^{1,3}. Detecting and understanding sea level extremes and C-HHEX along Indonesian coast in a changing climate will help predict these events, and therefore

achieve informed decision making. Although each ocean may have some unique aspect, results from this study may be translated to other regions of the world's oceans.

Here, for the first time, we use *in situ* and satellite observations to detect climate-driven extreme sea level and C-HHEX events that last for one to a few months around Indonesian coasts of the Indian Ocean since 1993. This time period represents the satellite altimetry era when accelerated global sea level rise has been detected and attributed largely to human-induced climate change²⁰⁻²². To assess the extremes in a longer-term context, we extend our analysis to the 1960s using reanalysis products that are model hindcasts assimilated observational data. To understand the causes for these extremes, we carry out model experiments using two independent ocean general circulation models - the Regional Ocean Modelling System (ROMS²³) and the Hybrid Coordinate Ocean Model (HYCOM²⁴) - and a global Earth system model, the Community Earth System Model version 1 (CESM1²⁵) of the National Center for Atmospheric Research. To quantify the effects of remote versus local wind forcing, we employ a Bayesian dynamical linear model²⁶. To assess the impacts of external forcing (natural plus anthropogenic) on regional sea level, we analyze the results from large ensemble experiments of Coupled Model Intercomparison Project phase 6 (CMIP6) assessed in the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6). See Methods section for details.

Detection of the extreme events Satellite altimeter data from 1993-2018²⁷ show rapid sea level rise along the east coasts of tropical Indian Ocean, with a rising rate of 5.12 ± 0.17 mm/yr near the tide gauge station at Java coast (Fig 1a) compared to the 3.1 ± 0.3 mm/yr global mean rise^{20,21,28}. Accompanied with the rapid sea level rise is weak sea surface warming at the Java coast and stronger warming along southern coast of Sumatra (Fig 1b). Overlying the rising trend

88 there are large year-to-year variations, as shown consistently by the ~10yr Java tide gauge record
 89 – the longest record along the Indonesian coast of the Indian Ocean²⁹ - and satellite altimeter data
 90 at the nearest location off the coast (~18km southeast of the tide gauge; Fig 1c). The altimeter
 91 data detect ten extreme sea level events during the 26yr (1993-2018) period, with monthly mean
 92 sea level anomalies (SLAs) exceeding two standard deviations (0.26m). The tide gauge record
 93 agrees exceptionally well with the altimeter data (correlation 0.99), albeit with somewhat larger
 94 amplitudes³⁰⁻³² likely because the tide gauge contains long-period tide signals but satellite
 95 altimeter data removes them²⁷. It is also possible that monthly tide gauge data includes signals of
 96 storm surges, which cannot be adequately resolved by altimeter data. The good agreement
 97 between satellite and tide gauge observations suggests that large-scale ocean circulation
 98 dynamics dominate small-scale coastal processes in causing SLAs along Java coast, where the
 99 shelf is narrow and continental slope is steep. Therefore, satellite altimeter data can well
 100 represent Java coastal SLAs and can be used to detect sea level extremes in this region. The
 101 SLAs along southern Sumatra coast are highly coherent with those of Java (supporting Fig S1).

 102 Most strikingly, nine of the ten sea level extremes occur in the recent decade (2010-2017) with
 103 only the weakest event occurring in 1998 during the entire 26yr altimeter period (Fig 1c). This
 104 situation is more evident for a longer period of 1960-2017 using the European Centre for
 105 Medium-Range Weather Forecasts (ECMWF) ocean analysis/reanalysis system 4 (ORAS4)
 106 data³³ and ocean model simulations (supplementary Fig S2). Five of the ten are compounded by
 107 marine heatwaves³⁴ (defined in Methods), and four of the five C-HHEX events occur during
 108 2010-2017 (Fig 1c and supplementary Table S1). The strongest compound event happened in
 109 June 2016, when monthly mean sea level rose by ~0.44m (0.45m) from satellite (tide gauge)
 110 observation and sea surface temperature (SST) warmed by 1.84°C (>99th percentile). This sea

level magnitude is near the lower end of the 0.5-1m amplitudes of tropical storm and high tide surges on daily timescales with a return period of 100yrs along the Indonesian coasts⁵, where storm impacts are relatively weak compared to higher-latitude coastal oceans³⁵. While sea level signals of the C-HHEX events can encompass the entire Southeast Asian coasts (Fig 2a), the associated marine heatwaves are confined to Indonesian coast east of Sumatra and extend hundreds of kilometers offshore (Fig 2c). By contrast, the sea level alone extremes without marine heatwaves are overall weaker and confined to the Indonesian coasts (Figs 2b, 2d). Here, we retain the seasonal cycle when identifying the extremes as in recent studies^{12,34,36} because coastal inundation and marine ecosystems are sensitive to the full sea level and temperature values.

Causes for sea level extremes To understand why extreme sea level events occur more frequently in the past decade, we analyze the ORAS4 reanalysis data and ocean model simulations from ROMS and HYCOM. Both the reanalysis data and model simulations well capture the satellite observed SLAs near Java coast (correlation 0.95-0.98; Fig 1d), albeit with some quantitative differences. The reanalysis data – which assimilated satellite altimeter data – underestimate the rising trend and amplitudes of individual events, and more underestimations are seen in HYCOM simulation (Fig 1d) partly due to the Indo-Pacific regional HYCOM with closed boundary conditions cannot properly simulate global sea level rise. By contrast, ROMS captures the full magnitudes of extreme events detected by altimeter data, with overestimation for some events as in tide gauge observation (Figs 1c-1d, blue lines). This is likely because ROMS, which is forced by 3hourly forcing fields, contains storm surge signals like the tide gauge data. Due to the stronger amplitudes, more extremes are identified in tide gauge record and ROMS simulation based on the 0.26m threshold. However, the increased occurrence of

extreme events in the past decade is evident in all datasets. Since this study aims to understand long-lasting climate driven extremes, we focus on the events identified by monthly altimeter observations. The high sea level events along southern Sumatra coast are highly coherent with those of Java but with weaker amplitudes (Fig S1).

After removing the slowly varying decadal-to-interdecadal component, collectively referred to as ‘decadal’ hereafter, the pattern of increased occurrence disappears (Fig 3a and Supplementary Fig S2), suggesting that it is the decadal SLAs of 0.1-0.2m during 2010-2017 that boosts up the frequency of sea level extremes. The decadal SLAs consist of anthropogenically-induced global sea level rise^{1,22} and internal climate variability (Fig 3a, red & green lines). During the altimeter era of 1993 onward, the anthropogenic effect causes 2.8mm/yr global sea level rise^{1,21,28}, contributing ~50% of the decadal SLAs of the past decade near Java coast. On a regional scale, the impact of external forcing (natural plus anthropogenic) on dynamical sea level that excludes global mean near Indonesian coast is weak (< 2cm) with large uncertainties³⁷, based on the large ensemble experiments of multiple CMIP6 models (supporting Fig S3).

For the internal decadal variability component, a combined invigoration of surface westerly winds over the tropical Indian Ocean and easterly winds in the tropical Pacific, which represent intensified Indian and Pacific Walker Cells (the atmospheric zonal overturning circulations over tropical Indo-Pacific basin), is the main cause. The enhanced equatorial westerly surface winds during 2010-2017 pile up water and thus increase sea level in the eastern basin; meanwhile, strengthened northwesterly longshore winds of southern Sumatra and Java coasts cause surface Ekman mass convergence toward the coasts and further enhance sea level there (Fig 4). Portions of these winds, however, result from remote forcing by the Interdecadal Pacific Oscillation

(IPO³⁸), as suggested by the agreement between the wind-generated decadal SLA and climate model simulations that isolate tropical Pacific sea surface temperature forcing using CESM1 (Fig 3b, solid blue and purple lines). During the global surface warming hiatus period of 2003-2012 when the easterly trade winds intensify in the tropical Pacific and the IPO is in its negative phase³⁹, the Pacific forcing is the major cause for the upward sea level trend, and wind stress forcing alone cannot fully explain the rising rate (compare green, blue and purple lines of Fig 3b). While the enhanced Indian Ocean westerly winds tend to reduce the Indonesian Throughflow (ITF) from the Pacific to the Indian Ocean by increasing sea level on the Indian Ocean side (Fig 4), the dramatic strengthening of surface easterly trades intensifies sea level in western tropical Pacific, causing unprecedented enhancement of the ITF during the hiatus period⁴⁰⁻⁴⁷. The enhanced ITF mass and heat transports⁴⁰⁻⁴⁷ contribute to the decadal sea level rise along the Indonesian coast from 2003-2012, with the effect of salinity being weak in this coastal area⁴⁸. The enhanced surface winds over the tropical Indian Ocean associated with monsoons and especially those associated with decadal variability of the Indian Ocean Dipole (IOD⁴⁹⁻⁵¹; Fig 3b, dotted blue) account for the rise since 2012.

While anthropogenic forcing and internal decadal variability increased the frequency of occurrence of sea level extremes in the past decade, what are the causes for individual events? Experiments using ocean general circulation models and the Bayesian dynamical linear model show that surface wind stress forcing is the deterministic cause for all extremes identified (Fig 3c; supplementary Fig S4b). The equatorial westerly wind anomalies (Fig 2a) cause Ekman mass convergence to the equator, raising sea level. The high sea level signals propagate eastward as equatorial Kelvin waves, which subsequently propagate poleward as coastally trapped waves upon impinging on the eastern boundary, inducing coherent sea level surges along the entire

southeast Asian coasts (Fig 2a). Meanwhile, the local northwesterly longshore winds along southern Sumatra and Java coasts induce coastal Ekman mass convergence, accumulate water to Indonesian coast and enhance the remotely forced equatorial signals (Figs 2a-2b). The longshore winds play important roles for some events especially for the sea level alone events (Figs 2b and 3c).

For all of the five sea level alone events, the anomaly amplitudes evidently reduce when the mean seasonal cycle is removed (Fig 3c, thick and thin black lines), suggesting that when moderate interannual SLAs occur in the high sea level season of Indonesia in Dec-Mar, they can cause severe coastal inundation (Figs 3c & S4c; Table S1). By contrast, not all of the compound events are aided by seasonal cycle. For instance, the strongest C-HHEX event of June 2016 occurred in the low sea level season of Indonesia, when southeasterly monsoon winds prevail and the high SLA results entirely from interannual variability (Fig 3c; supporting Fig S5).

Compound Height-Heat EXtreme (C-HHEX) vs sea level alone events The five C-HHEXs all occur during the years of negative IOD with four occurring with La Niña, the negative phase of the El Niño-Southern Oscillation (ENSO⁶; Fig 3d and Table S1). The IOD and ENSO are the dominant modes of interannual climate variability over the tropical Indo-Pacific basin, and they are associated with basin-scale anomalies of atmospheric convection, surface wind and sea surface temperature. Because IOD events generally develop in boreal summer and peak in Sep-Nov^{49,50}, they are phase-locked with the upwelling and low sea level season in the tropical eastern Indian Ocean including the Indonesian coast (Figs 3c & 5c, black curves), when southeasterly trade winds cause Ekman transports that move the warmer surface water offshore, shoal the thermocline and upwell colder subsurface water to the surface (supporting Figs S5 &

S6). With the precondition of shallow thermocline, the equatorial westerly and longshore northwesterly wind anomalies associated with the negative IOD - which are enhanced by La Niña for four of the five C-HHEX events - raise sea level (Fig 2a; supporting Fig S4b), deepen the thermocline (i.e. downwelling) and reduce cold water upwelling, causing large-amplitude interannual marine heatwaves and sea level extremes that last for several months (red curves of Figs 3c & 5c; supporting Figs S5 & S7). The importance of subsurface processes in causing the marine heatwaves is quantitatively assessed by the mixed layer heat budget analysis using ROMS output (Fig 5d). While the interannual warm anomalies are largely compensated by the seasonal cooling during July-October, they are less compensated or even enhanced by the seasonally warm temperatures and high sea levels during the IOD initiation (May-June) and decay (Nov-Dec) periods (Figs 3c, 5c & S5-S7), causing the C-HHEX events near Indonesian coast (Figs 5a-5b). The warmer upper ocean may further increase sea level due to thermal expansion.

As a comparison, the five sea level alone events all occur during the Dec-March deep thermocline (i.e. downwelling) season. Even though the wind-driven coastal mass convergence still raises sea level, it does not apparently increase surface temperature due to the presence of a deep thermocline that reduces the sensitivity of sea surface temperature to changes in cold water upwelling rates (Figs 3c & 5c; supporting Fig S8). These events are not associated with negative IOD or La Niña; rather, they are driven by the shorter lasting equatorial and longshore wind anomalies associated with Indian and Australian monsoon^{52,53}, such as the ~60 intraseasonal oscillations that give rise to the January and March 2012 sea level events (Figs 3c-3d; supporting Fig S9). Indeed, winds associate with atmospheric intraseasonal oscillations⁵⁴⁻⁵⁶ also help intensify the sea level peak of June 2016 C-HHEX event (Fig S10) and significantly weaken the

224 Indonesian Throughflow transport into the Indian Ocean from the Pacific⁵⁷, further weakening
 225 the already reduced Throughflow due to the negative IOD⁵⁸. Since this paper focuses on long-
 226 lasting extremes, the impacts of atmospheric intraseasonal oscillations will be investigated and
 227 reported in a future research. Note that SLAs represent changes of mass and heat of the entire
 228 water column, whereas sea surface temperature variability can be controlled by surface heating
 229 process and is little affected by subsurface when thermocline is deep. Therefore, some marine
 230 heatwave events are not associated with sea level extremes and vice versa.

231 The consistencies among tide gauge data, satellite observation, reanalysis product and various
 232 model simulations demonstrate that the extreme sea level and C-HHEX events detected here
 233 exceed data and model uncertainties. Satellite altimetry, which suffers from land contamination
 234 near coasts, only provides data over the shelf away from the coasts. Yet, here the altimeter data
 235 successfully represent and therefore are used to detect sea level extremes along Indonesian coast
 236 of the Indian Ocean. This is because changes in large-scale ocean circulations driven by remote
 237 and local winds – instead of local smaller scale shelf processes – determine the long-lasting sea
 238 level extremes in this region. This result points to the importance of continued tide gauge and
 239 satellite observations in detecting and understanding coastal sea level extremes in a changing
 240 climate. The agreements among different models on the controlling mechanisms lend further
 241 confidence in our results.

242 Our new results show that individual extreme events induced by strong intraseasonal-to-
 243 interannual climate variability (monsoon, negative IOD and La Niña), their constructive
 244 interferences, and interplay by decadal climate variability and global sea level rise generate the
 245 long-lasting (> 1 month) extreme sea level and C-HHEX events along Indonesian coast with
 246 frequent occurrence in the past decade. Climate model projections, however, suggest that

continued anthropogenic warming will reduce the number of negative IOD events due to a mean state change toward a shallower thermocline in the eastern pole and a deeper thermocline in the western pole of the IOD⁵⁹⁻⁶¹. Even though the deeper thermocline in the western pole could weaken the magnitude of temperature anomalies and thus negative IOD index, the shallower thermocline in the eastern pole – with continued global sea level rise and anthropogenic warming albeit with a slower warming rate in this area⁶⁰ – favorably preconditions the ocean for stronger sea level extremes and C-HHEXs in coastal Indonesia, when forced by downwelling-favorable winds associated with internal climate variability. This would aggravate the climate change induced social, environmental and ecological stresses on Indonesia.

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Figure legends

Figure 1: Trend map and timeseries of satellite-observed sea level, surface wind, and sea surface temperature (SST) and a tide gauge record at Java coast, marked by “o” in **a** and **b**. **a**, Linear trend of satellite sea level and cross-calibrated multiplatform (CCMP) surface wind stress from 1993-2018. **b**, Linear trend of satellite SST for 1993-2018. **c**, Time series of monthly mean sea level anomaly (SLA) from tide gauge station Cilacap B during 2007-2016 (blue curve); data from Permanent Service for Mean Sea Level, 2020 after correction for Glacial Isostatic Adjustment and inverted barometer effect) and from the multiple-satellite-merged altimeter data at the nearest grid point (black). The SLAs are relative to a 60yr mean (1958-2017) of ECMWF Ocean Reanalysis System 4 (ORAS4) data at the nearest location. Values exceeding 2 standard deviations (STD) of altimeter data (horizontal blue line) are identified as extreme events (indicated by vertical-dotted lines). Red dotted lines indicate sea level extremes cooccurred with marine heatwaves, dubbed Compound Height and Heat EXtremes (C-HHEX) events. **d**, Monthly SLAs from satellite (black, same as that of **c**), ORAS4 reanalysis data (red), simulations from two independent ocean general circulation models: ROMS and HYCOM (blue and green). See methods for data and models.

Figure 2. Composite of satellite-observed monthly sea level anomaly (SLA), surface wind stress anomaly, and sea surface temperature anomaly (SSTA) for the peak months of five compound height and heat extremes (C-HHEX) and five sea level alone extreme events. All anomalies are relative to 1993–2018 mean. **a & b**, Composites of SLA (color) and surface wind stress (arrows) for C-HHEX and sea level events; **c & d**, The same as **a & b** but for their corresponding SSTA and surface wind stress. Wind vectors are the average for the event peak month and the preceding month, considering the propagation time of equatorial Kelvin waves that impact SLA and SSTA.

Figure 3. Time series of monthly sea level anomalies (SLAs) averaged over Java coastal area (Supplementary Fig S2), anthropogenically-induced global mean sea level rise (GMSLR) and climate

indices. Calculations are done for 1960-2017 period but only 1993-2017 is shown for clarity. The 1960-2017 mean is removed from each series. **a**, ROMS simulated total SLA (black), anthropogenic GMSLR (red), ROMS natural decadal SLA (8yr lowpass filtered with anthropogenic GMSLR removed; green), and ROMS seasonal-to-interannual SLA (blue). **b**, ROMS decadal SLA (green), SLA caused by remote equatorial wind and local longshore wind assessed from Bayesian Dynamic Linear Model (DLM; blue), SLA from the 10-member ensemble mean of Pacific Pacemaker experiment using Community Earth System Model version 1 (CESM1) – assessing the impacts of tropical Pacific sea surface temperature anomaly (purple) – and index of the Interdecadal Pacific Oscillation (IPO; dotted purple). Labels on the right indicate normalized indices of IPO and decadal variability of Indian Ocean Dipole (IOD). Decadal variability of Indian and Australian-Indonesian monsoon winds follow IPO index and thus not shown. **c**, ROMS seasonal-to-interannual SLA (thin black), interannual SLA with seasonal variability removed (thick black), interannual SLA forced by remote equatorial and local longshore winds (red), and SLA forced only by remote equatorial wind (blue). **d**, Normalized indices of the El Niño-Southern Oscillation (ENSO; red), IOD (blue), Indian monsoon wind index (black; one month lead) and Australian-Indonesian monsoon index (green). See Methods for more details.

Figure 4. Internal decadal (8yr lowpass filtered) anomalies of surface wind stress (arrows) and sea level (color) averaged for 2010-2017, based on the monthly JRA55-do reanalysis winds that force the ROMS (see methods) and ROMS simulated SLAs relative to the 1960-2017 mean. Linear trend of winds and anthropogenic global mean sea level are removed before we apply the 8yr lowpass filter.

Figure 5. Composites of ROMS simulated sea surface temperature anomaly (SSTA) and surface wind anomalies (from JRA55-do reanalysis data that force ROMS) for the five C-HHEXs and time series of SSTA averaged in Java coastal area (Fig S2). **a**, Composite SSTA (color) and surface wind (arrows) anomalies with the 1993-2017 mean removed but seasonal variability

453 retained to be consistent with Fig 2 from observations. **b**, The same as **a** but with seasonal
454 variability removed. **c**, Timeseries of mean seasonal variability (black) and variability with
455 seasonal anomaly removed which primarily represents interannual variability (red). **d**, Terms of
456 heat budget analysis for SSTA (red curve in **b**): time changing rate of SSTA from all processes
457 (dT/dt , black), from net surface heat flux (blue), from subsurface processes (upwelling+mixing,
458 red) and horizontal advection+mixing (green). Units: degree per month.

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 467 Sea Level, 2020 after correction for Glacial Isostatic Adjustment and inverted barometer effect) and from
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 469 60yr mean (1958-2017) of ECMWF Ocean Reanalysis System 4 (ORAS4) data at the nearest location.
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 471 extreme events (indicated by vertical-dotted lines). Red dotted lines indicate sea level extremes co-
 472 occurred with marine heatwaves, defined as SSTA exceeding 90th percentile (horizontal red line). These
 473 events are dubbed Compound Height and Heat EXtremes (C-HHEX). **d**, Monthly SLAs from satellite
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 484 time of equatorial Kelvin waves that impact SLA and SSTA.

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 493 decadal SLA (green), SLA caused by remote equatorial wind and local longshore wind assessed from Bayesian
 494 Dynamic Linear Model (DLM; blue), SLA from the 10-member ensemble mean of Pacific Pacemaker experiment
 495 using Community Earth System Model version 1 (CESM1) – assessing the impacts of tropical Pacific sea surface
 496 temperature anomaly (purple) – and index of the Interdecadal Pacific Oscillation (IPO; dotted purple). Labels on the
 497 right indicate normalized indices of IPO and decadal variability of Indian Ocean Dipole (IOD; dotted blue). Decadal
 498 variability of Indian and Australian-Indonesian monsoon winds follow IPO index and thus not shown. **c**, ROMS
 499 seasonal-to-interannual SLA (thin black), interannual SLA with seasonal variability removed (thick black),
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Methods

Tide gauge data, satellite observations and ocean reanalysis product

The tide gauge data²⁹ at station Calicap B of Java coast from 2007-2016 were downloaded from the Permanent Service for Mean Sea Level (PSMSL) 2020:

<https://www.psmsl.org/data/obtaining/>, and were corrected for Glacial Isostatic Adjustment (GIA) and Inverted Barometer (IB) effects that were provided by PSMSL along with the tide gauge data. No land movement correction was done due to the lack of GPS data within 10km of the tide gauge station⁶².

The satellite altimeter data²⁷ (both two-satellite and all-satellite) were download from Copernicus Climate Change Service (C3S) (2018): Sea level daily gridded data for the global ocean from 1993 to present, European Union, under license agreement V1.2 (Nov 2019),

<https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global?tab=overview>.

Monthly mean of the all-satellite data are used in Figure 1, and the timeseries shown in Figure 1c is from the nearest grid point approximately 18km southeast of the Java tide gauge station. Using the two-satellite data yields similar results except for slightly weaker amplitudes for some extreme events.

The Cross-Calibrated Multi-Platform (CCMP) Satellite derived winds^{63,64} were downloaded from <http://www.remss.com/measurements/ccmp/>. The National Oceanic and Atmospheric Administration (NOAA) blended satellite sea surface temperature (SST) data⁶⁵ are publicly available at: <https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>.

The European Centre for Medium-Range Weather Forecasts (ECMWF) operational ocean analysis/reanalysis system version 4 (ORAS4)³³ monthly sea level and temperature data, which

are used to infer thermocline depth (the depth of 20°C isotherm), from 1958-2017 are obtained from <https://www.ecmwf.int/en/research/climate-reanalysis/ocean-reanalysis>. The ORAS4 data are ocean model hindcasts assimilated observational data, including satellite altimeter data.

Estimates of anthropogenic global sea level rise

First, we obtained the monthly global mean sea level (GMSL) data from CSIRO available for 1880-2013²² (ftp://ftp.csiro.au/legresy/gmsl_files). Then we combine this dataset from 1880-1992 with NASA monthly GMSL data from 1993-2019²⁸ downloaded from http://podaac.jpl.nasa.gov/dataset/MERGED_TP_J1_OSTM_OST_ALL_V42⁶⁶ and choose the 1960-2019 period. Two methods were used to assess the anthropogenic GMSL rise (GMSLR): (1) Since anthropogenic effect (thermal expansion, land ice melting and land water storage) explains ~90% of the GMSL in recent decades^{1,67}, we use 90% of the quadratic fits of GMSL (i.e., fitted GMSLR*0.9) to represent anthropogenic GMSLR; the quadratic fits are done individually for the 1960-1992 and 1993-2019 periods to consider SLR acceleration in recent decades; (2) For the 1993-2019 satellite period, we use the climate-change induced acceleration of 0.084mm yr⁻²²¹ to estimate the anthropogenic GMSLR, and keep the 1960-1992 period the same as in (1). The two curves are almost identical.

CMIP6 climate model simulations

The coupled model intercomparison project phase 6 (CMIP6) large ensemble experiment results, with ensemble members of each model ranging from 10-50 (Supporting Figure S3), were obtained from <https://esgf-node.llnl.gov/projects/cmip6/>.

568 **Climate mode indices and definition of marine heatwaves (MHWs)**

569 The monthly HadISST data available since 1870⁶⁸ are used to calculate climate mode indices.

570 The climatological seasonal cycle is removed before we calculate the indices. Climate events are
571 defined as indices exceeding one standard deviation. The Niño3.4 index, which is the timeseries
572 of SST anomaly (SSTA) averaged for (120°W-170°W, 5°S-5°N), is used to represent ENSO.
573 ENSO is the most dominant mode of climate variability, which is associated with strong SSTA
574 in the tropical Pacific Ocean and has large impacts on global climate. It develops during boreal
575 summer and peaks during boreal winter (Dec-Feb). Its negative (cold) phase is referred to as La
576 Niña, and positive (warm) phase is called El Niño.

577 The tripole index⁶⁹ of the Interdecadal Pacific Oscillation (IPO), is defined as the difference
578 between SSTA averaged in the equatorial basin (10°S–10°N, 170°E–90°W) subtracts the SSTA
579 average between the north Pacific (25°N–45°N, 140°E–145°W) and south Pacific (50°S–15°S,
580 150°E–160°W) regions. The IPO is highly correlated with decadal variability of ENSO⁷⁰, with
581 its negative phase being referred to as La Niña-like and positive (warm) phase being El Niño-like
582 SSTA pattern.

583 The dipole mode index, defined as the SSTA difference between tropical western Indian Ocean
584 (50°E-70°E, 10°S-10°N) and tropical eastern Indian Ocean (90°E-110°E, 0°-10°S), represents
585 the Indian Ocean Dipole (IOD⁴⁹). In general the IOD develops in boreal summer and peaks
586 during boreal fall (Sep-Nov). Its negative phase is associated with warm SSTA and deeper
587 thermocline in the eastern pole and cold SSTA and shallower thermocline in the western pole.

588 The monthly wind shear index⁵² is used to represent Indian monsoon variability, which is the
589 zonal wind U at 850hPa (U850) averaged over (40°E-110°E, EQ-20°N) subtracts that of 200hPa

(U200): U850(40-110E,EQ-20N)-U200(40-110E,EQ-20N). The Australian-Indonesian monsoon index⁵³ is defined as U850 anomaly averaged over (110°E-130°E, 15°S-5°S). Both are calculated from NCEP1 reanalysis winds⁷¹. Decadal variability of the Indian monsoon index is highly correlated with the IPO index, with correlation coefficient $r=0.68$ (>95%) for the 1960-2017 period. The Australian-Indonesian monsoon is also significantly correlated with the IPO, with $r=0.42$ (>95%) from 1960-2017. The decadal variability of IOD⁵¹ however is independent of the IPO with $r<0.1$ ^{72,73}.

The NOAA blended satellite SST data⁶⁵ are used to detect marine heatwaves (MHWs). The MHWs are defined as SST anomalies exceeding 90th percentile for a 30yr baseline period of 1990-2019, following previous studies on MHWs^{12,34,36}. Based on this definition, mean seasonal cycle is retained when identify MHW events; this is because marine ecosystems are sensitive to the full variability magnitudes.

Ocean general circulation model (OGCM) and coupled climate model experiments

Two OGCMs were used to carry out experiments: The HYbrid Coordinate Ocean Model (HYCOM²⁴) and the Regional Ocean Modeling System (ROMS²³). A recent version of HYCOM was set up for the Indo-Pacific basin (19°E–68°W, 55°S–50°N) with 35 hybrid layers and 1/3° resolution in tropical & subtropical basins and gradually transiting to 1° in middle-high latitudes. Closed boundary conditions are used in the open ocean regions at northern, southern and part of western boundaries where 5° sponge layers are applied to relax model temperature and salinity to WOA13 monthly climatology. Two experiments were performed for the 1940-2016 period, forced with daily ERA-20th century reanalysis from 1940-2010 and ERA-Interim fields from 2011-2016^{45,46,74}; HYCOM main run (MR) & HYCOM EXP run. The MR is the complete

612 solution, and the EXP run is the same as the MR except for fixing the forcing fields used to
613 calculate heat and freshwater fluxes to their climatology but keeping daily wind stress forcing as
614 in the MR. Solutions from EXP isolates wind stress-driven sea level and SST variability. Due to
615 the closed boundaries in open ocean areas, global sea level rise is not properly represented and
616 thus the Indian Ocean basin mean is removed from our analysis (e.g., Fig S4).

617 The ROMS is configured for the tropical Indian Ocean (30–110°E, 46°S to 32°N) with a
618 horizontal resolution of $1/3^\circ \times 1/3^\circ$ and 40 vertical sigma layers⁷⁵, and forced by 3hourly
619 Japanese 55-year atmospheric reanalysis - drive ocean (JRA55-do⁷⁶) fields (e.g, surface wind,
620 heat flux and precipitation) available from <https://climate.mri-jma.go.jp/~htsujino/jra55do.html>.
621 Along the eastern and southern boundaries, the mixed radiation-nudging boundary condition is
622 used, where temperature, salinity, and horizontal velocity are relaxed to the monthly values of
623 ORAS4 reanalysis data with the nudging time scale of 360 days (3 days) for the outflow (inflow)
624 case. With the open ocean boundary conditions, global sea level rise influence is included, and
625 there is no constraint for volume conservation over the Indian Ocean basin as is demonstrated by
626 the rapid basin-mean sea level rise (not shown).

627 To assess the role played by ENSO on interannual timescale and IPO on decadal timescale in
628 affecting Indian Ocean sea level, we perform a ten-member ensemble of the Pacific Ocean-
629 Global Atmosphere (POGA) pacemaker experiments using National Center for Atmospheric
630 Research (NCAR) Community Earth System Model version 1 (CESM1²⁵) from 1920-2019. In
631 this experiment ensemble, SST in the central and eastern tropical Pacific is restored to
632 observations but is fully coupled to the atmosphere elsewhere. The 10-member ensemble mean
633 fields of POGA experiments estimate the Pacific impacts on the Indian Ocean through both
634 atmospheric bridge and oceanic connection via the Indonesian Throughflow. Even though the

635 model has some biases⁷⁷, their results provide valuable assessments of remote forcing from the
 636 Pacific especially in the context of analyzing these results with observations and standalone
 637 OGCM simulations, as we have done here.

638 **ROMS mixed layer heat budget analysis**

639 Time evolution of the mixed layer temperature, T_{mix} , is governed by the following equation:

$$\begin{aligned}
 640 \quad & \frac{\partial T_{mix}}{\partial t} = \underbrace{\frac{Q_{net}}{\rho C_p h} - \frac{Q_{sw}(z = -h)}{\rho C_p h}}_{\text{Surface heat flux}} \\
 641 \quad & \underbrace{-\frac{1}{h} \int_{-h}^0 \left(u \frac{\partial T}{\partial x} \right) dz - \frac{1}{h} \int_{-h}^0 \left(v \frac{\partial T}{\partial y} \right) dz + \frac{1}{h} \int_{-h}^0 \nabla_h \cdot (\kappa_h \nabla_h T) dz}_{\text{horizontal advection \& mixing}} \\
 642 \quad & \underbrace{-\frac{1}{h} \int_{-h}^0 \left(w \frac{\partial T}{\partial z} \right) dz - \frac{1}{h} (\kappa_v \frac{\partial T}{\partial z})_{z=-h} - \frac{\Delta T}{h} \frac{\partial h}{\partial t}}_{\text{Subsurface process}}.
 \end{aligned}$$

643 where T is the sea water temperature, ρ represents the sea water density, C_p is the specific heat of
 644 the sea water, (u, v, w) denote zonal, meridional and vertical velocity, respectively, and h is the
 645 mixed layer depth. The mixed layer depth h is defined as a depth at which the potential density
 646 increases by 0.01 kg/m^3 from the sea surface. Q_{net} is the net surface heat flux and $Q_{sw}(z =$
 647 $-h)$ is the shortwave radiation at the bottom of the mixed layer. Additionally, κ_H and κ_v are
 648 horizontal and vertical mixing coefficients, and ΔT is the temperature difference between the
 649 mixed layer and upper thermocline. The first two terms on the right-hand side represent the
 650 surface heat flux forcing; the third-to-fifth terms are zonal advection, meridional advection and
 651 horizontal mixing. The last three terms represent subsurface processes: vertical advection,

vertical mixing, and entrainment, respectively. The mixed layer heat budget is closed in the ROMS experiment^{75,78}.

The Bayesian dynamical linear model

To quantify forcing by remote equatorial wind and local longshore wind on sea level variability along the Indonesian coast, we apply the Bayesian dynamic linear model (DLM) with two predictors. The Bayesian DLM consists of two equations: an “observation equation” analogous to the conventional multiple linear regression model (equation (1) below), and a “state equation” that controls the dynamical evolution of coefficients b_i ($i=0,1,2$) represented by equation (2).

$$Y(t) = b_0(t) + b_1(t)X_1(t) + b_2(t)X_2(t) + \varepsilon(t), \quad \varepsilon(t) \sim N(0, V(t)), \quad (1)$$

$$b_i(t) = b_i(t-1) + w_i(t), \quad w_i(t) \sim N(0, W_i(t)). \quad (2)$$

In equation (1), X_1 and X_2 are the predictors, and $Y(t)$ is the predictand. The state equation (2) means that the predictive distribution of b_i at each time step t (i.e., *posterior*) is updated based on its previous step $t-1$ distribution (i.e., *prior*) and the probability of observations Y conditional on b_i at time t (i.e., the *likelihood*) using Bayes theorem²⁶. Coefficients b_i are obtained by applying Kalman filtering and smoothing, with the regression coefficient of conventional linear regression as its initial guess^{79,80}. The $b_0(t)$ term represents a time-varying “intercept” whose variability is unexplained by the predictors X_i , while the b_i terms represent the non-stationary influence of X_i on Y , which is superior to the conventional regression model with stationary b_i which can only estimate stationary impacts of the predictors⁷⁹. Terms $\varepsilon(t)$ and $w_i(t)$ are independent white noises or errors, distributed normally with a mean of 0 and variances of $V(t)$ and $W_i(t)$. Here, we use zonal wind stress anomalies averaged over the equatorial area (65°E-95°E, 5°S-5°N) and longshore wind stress averaged along Sumatra and Java coast (supporting

Figure S2) as the two predictors (X_1 and X_2) and sea level anomalies along Indonesian coast as the predictand, $Y(t)$. Time series of the equatorial wind (X_1) leads Java coast sea level anomaly by one month to consider the propagation time of equatorial Kelvin wave, but the local longshore wind has no lag.

Code and data availability

Results from the OGCM experiments using ROMS and HYCOM, CESM1 Pacific Pacemaker experiments and the Bayesian dynamic linear model, together with the IDL and Matlab codes for carrying out the analyses, are available upon request.

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742 **Authors contributions**

743 W.H. led the project and did the main analyses and writing, L.Z. analysed CMIP6 model results
744 and carried out the experiments of the Bayesian Dynamic Linear Model and CESM1 extension
745 from 2013 to 2019, G.A.M., A.H., N.R. and G.S. carried out the CESM1 experiments from
746 1920-2013, helped setup the CESM1 extension experiments and did the post-processing, SK and
747 TT performed the ROMS experiments and provided the mixed layer heat budget analysis results,
748 M.J.M. contributed to the scientific results through stimulating discussions and analysis, A.C.
749 contributed to the analysis and discussion of satellite altimeter data, and B.J.W. helped to
750 confirm the effects of atmospheric intraseasonal oscillations. All authors contributed to writing
751 the paper.

Figures

Figure 1

Trend map and timeseries of satellite-observed sea level, surface wind, and sea surface temperature (SST) and a tide gauge record at Java coast, marked by "o" in a and b. a, Linear trend of satellite sea level and cross-calibrated multiplatform (CCMP) surface wind stress from 1993-2018. b, Linear trend of satellite SST for 1993-2018. c, Time series of monthly mean sea level anomaly (SLA) from tide gauge

station Cilacap B during 2007-2016 (blue curve); data from Permanent Service for Mean Sea Level, 2020 after correction for Glacial Isostatic Adjustment and inverted barometer effect) and from the multiple-satellite-merged altimeter data at the nearest grid point (black). The SLAs are relative to a 60yr mean (1958-2017) of ECMWF Ocean Reanalysis System 4 (ORAS4) data at the nearest location. Values exceeding 2 standard deviations (STD) of altimeter data (horizontal blue line) are identified as extreme events (indicated by vertical-dotted lines). Red dotted lines indicate sea level extremes cooccurred with marine heatwaves, dubbed Compound Height and Heat EXTremes (C-HHEX) events. d, Monthly SLAs from satellite (black, same as that of c), ORAS4 reanalysis data (red), simulations from two independent ocean general circulation models: ROMS and HYCOM (blue and green). See methods for data and models. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Composite of satellite-observed monthly sea level anomaly (SLA), surface wind stress anomaly, and sea surface temperature anomaly (SSTA) for the peak months of five compound height and heat extremes (C-HHEX) and five sea level alone extreme events. All anomalies are relative to 1993–2018 mean. a & b, Composites of SLA (color) and surface wind stress (arrows) for C-HHEX and sea level events; c & d, The

same as a & b but for their corresponding SSTA and surface wind stress. Wind vectors are the average for the event peak month and the preceding month, considering the propagation time of equatorial Kelvin waves that impact SLA and SSTA. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Time series of monthly sea level anomalies (SLAs) averaged over Java coastal area (Supplementary Fig S2), anthropogenically-induced global mean sea level rise (GMSLR) and climate indices. Calculations are done for 1960-2017 period but only 1993-2017 is shown for clarity. The 1960-2017 mean is removed from each series. a, ROMS simulated total SLA (black), anthropogenic GMSLR (red), ROMS natural decadal SLA (8yr lowpass filtered with anthropogenic GMSLR removed; green), and ROMS seasonal-to-interannual SLA (blue). b, ROMS decadal SLA (green), SLA caused by remote equatorial wind and local longshore wind assessed from Bayesian Dynamic Linear Model (DLM; blue), SLA from the 10-member ensemble mean of Pacific Pacemaker experiment using Community Earth System Model version 1 (CESM1) – assessing the impacts of tropical Pacific sea surface temperature anomaly (purple) – and index of the Interdecadal Pacific Oscillation (IPO; dotted purple). Labels on the right indicate normalized indices of IPO and decadal variability of Indian Ocean Dipole (IOD). Decadal variability of Indian and Australian-Indonesian monsoon winds follow IPO index and thus not shown. c, ROMS seasonal-to-interannual SLA (thin black), interannual SLA with seasonal variability removed (thick black), interannual SLA forced by remote equatorial and local longshore winds (red), and SLA forced only by remote equatorial wind (blue). d, Normalized indices of the El Niño-Southern Oscillation (ENSO; red), IOD (blue), Indian monsoon wind index (black; one month lead) and Australian-Indonesian monsoon index (green). See Methods for more details.

Figure 4

Internal decadal (8yr lowpass filtered) anomalies of surface wind stress (arrows) and sea level (color) averaged for 2010-2017, based on the monthly JRA55-do reanalysis winds that force the ROMS (see methods) and ROMS simulated SLAs relative to the 1960-2017 mean. Linear trend of winds and anthropogenic global mean sea level are removed before we apply then 8yr lowpass filter. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Composites of ROMS simulated sea surface temperature anomaly (SSTA) and surface wind anomalies (from JRA55-do reanalysis data that force ROMS) for the five C-HHEXs and time series of SSTA averaged in Java coastal area (Fig S2). a, Composite SSTA (color) and surface wind (arrows) anomalies with the 1993-2017 mean removed but seasonal variability retained to be consistent with Fig 2 from observations. b, The same as a but with seasonal variability removed. c, Timeseries of mean seasonal variability (black) and variability with seasonal anomaly removed which primarily represents interannual variability (red). d, Terms of heat budget analysis for SSTA (red curve in b): time changing rate of SSTA from all processes (dT/dt , black), from net surface heat flux (blue), from subsurface processes (upwelling+mixing, red) and horizontal advection+mixing (green). Units: degree per month. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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