Sea level extremes and compounding marine heatwaves in coastal Indonesia

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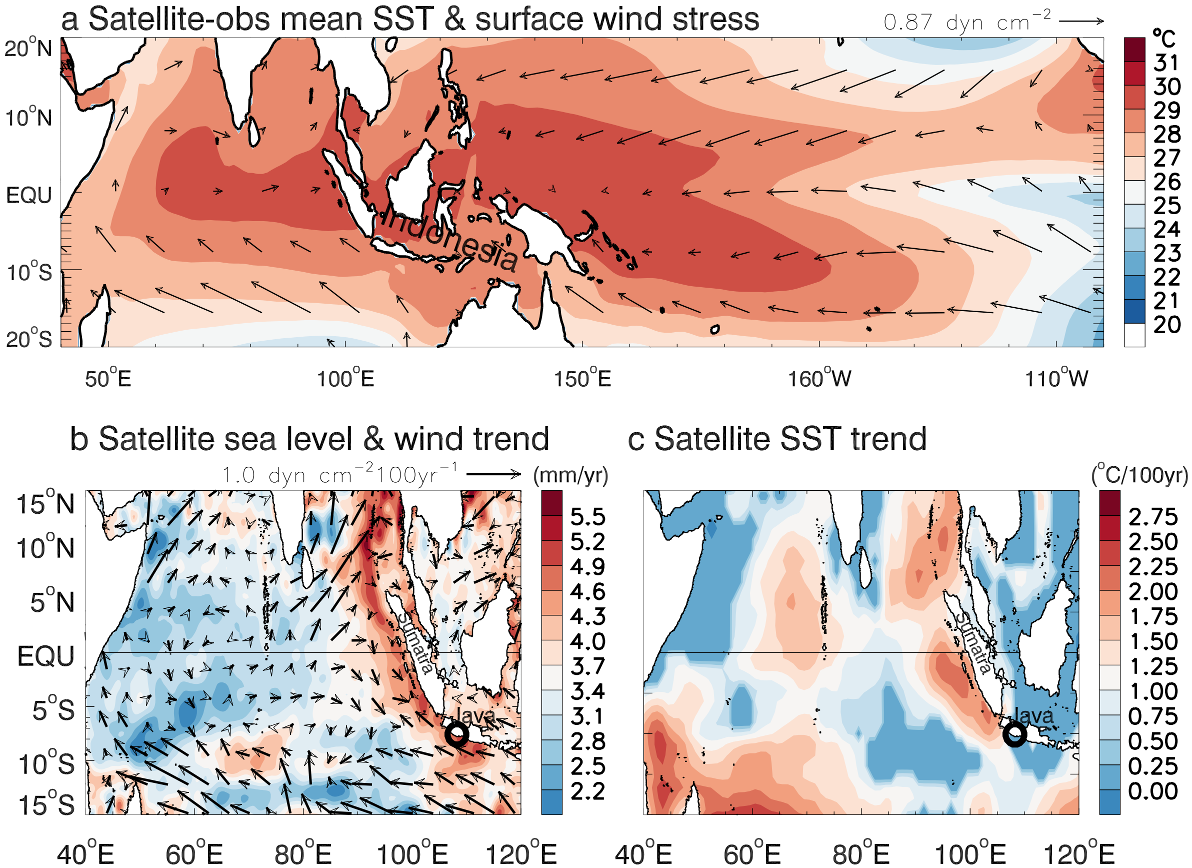
Motivation



a. Satellite observed 30yr mean (1989-2018) sea surface temperature (SST) and surface wind stress.
b. Linear trend of satellite sea level and CCMP surface wind stress from 1993-2018.
c. Linear trend of satellite SST for 1993-2018. Tide gauge location at Java coast is marked by “**o**” in **b** and **c**; its data is shown later.

Located at the confluence of the tropical east Indian and west Pacific Oceans, Indonesia is strongly influenced by monsoon, Indian Ocean Dipole (IOD), and ENSO. Rapid urbanization of Java island , population growth & fast sinking due to ground water extraction, further increase vulnerability to climate-change induced rising sea level. **While sea level Height EXtreme (HEX) events and marine heatwaves can have large ecological, economic, and social consequences individually, in combination they can be much more devastating, which are becoming more common in a warming climate. Yet, integrated studies of HEX and the compounding effect of a marine heatwave – dubbed Compound Height-Heat EXtreme (CHHEX) – are limited thus far.**

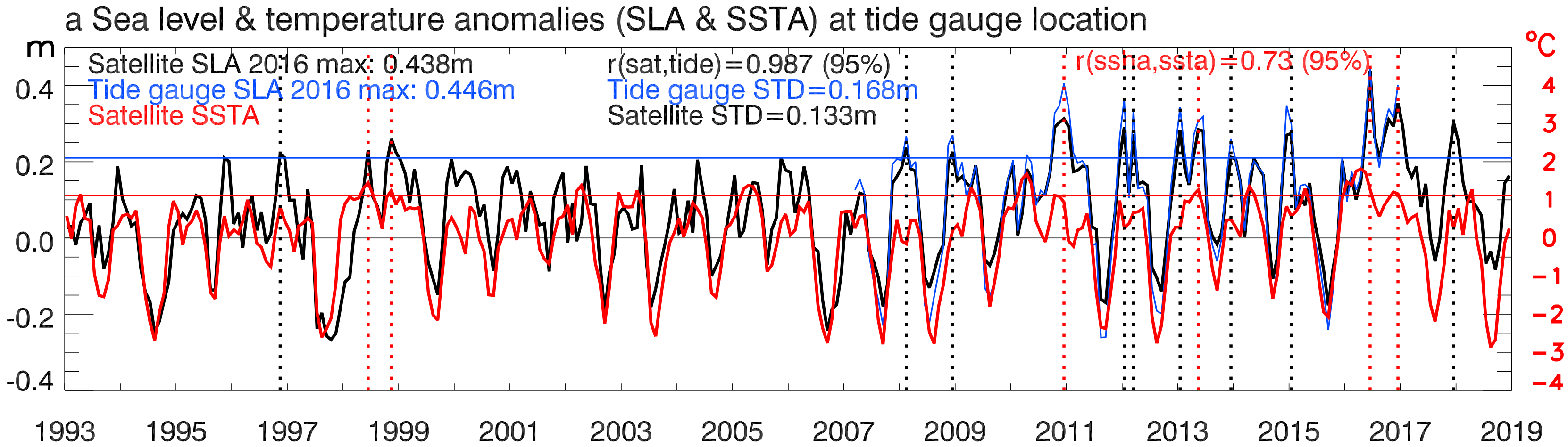
Goals

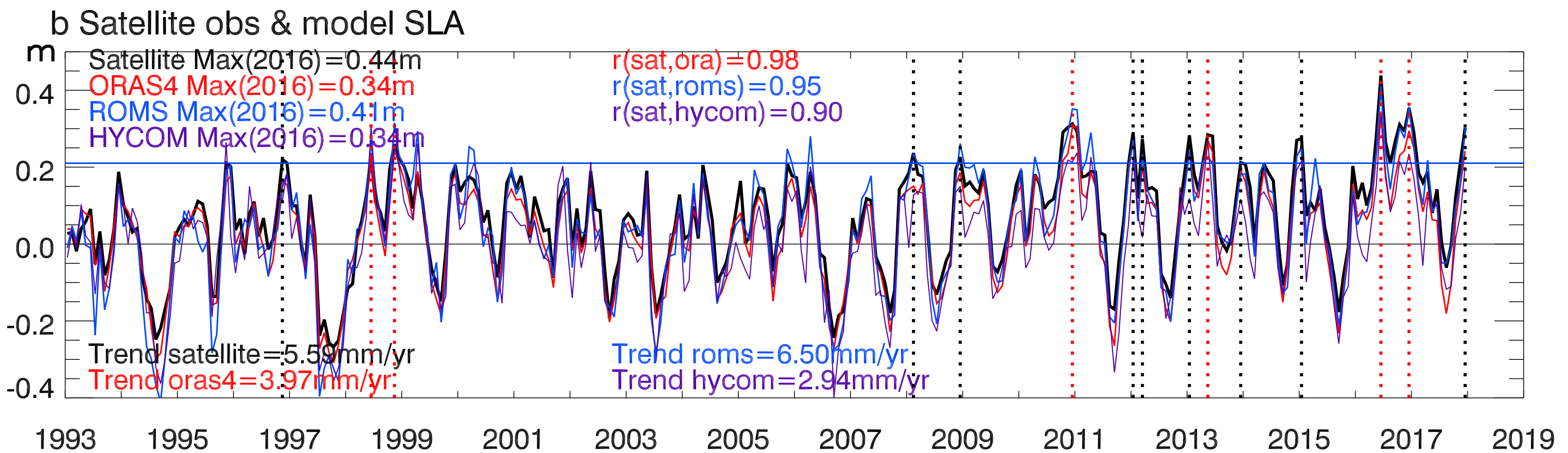
- **Detect HEX and CHHEX events around Indonesian coasts of the Indian Ocean in recent decades, using satellite and *in situ* observations;**

- **Understand their causes by performing model experiments using OGCMs (ROMS and HYCOM) and a global coupled model (CESM1), together with analyzing results from CMIP6 model historical simulations.**

Major period of interest:
1993-pres;
Also extend to 1960-pres to put our results into a longer-term context

Results



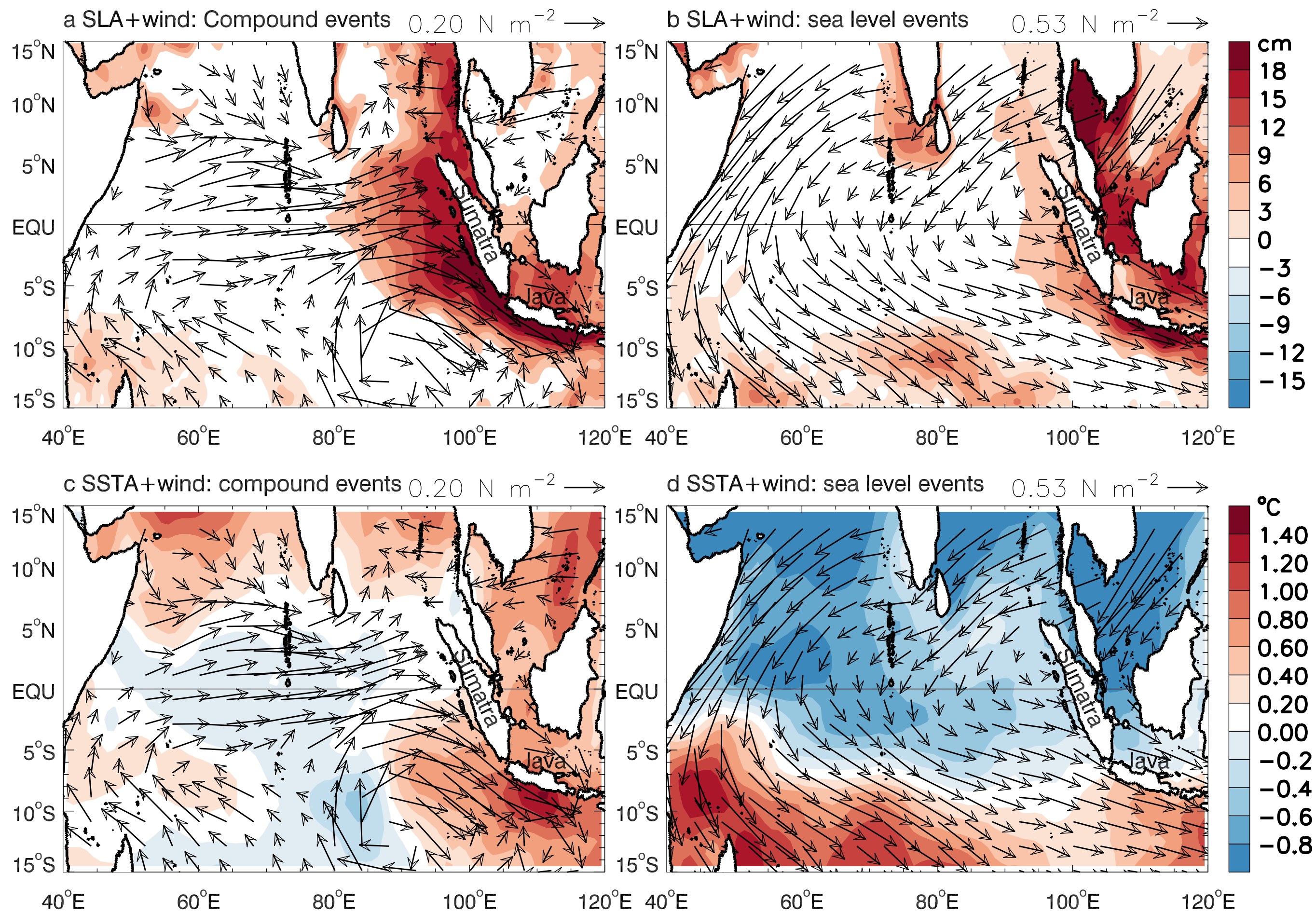


- Java tide gauge (blue) SLA & satellite altimetry SLA (black) detect 15 Height EXtreme (HEX) events, with maximum monthly SLA being 0.44m (0.45m) in satellite (tide gauge) observation (**panel a**)
- Most HEXs & Compound Height-Heat EXtremes (CHHEXs)(>90th percentile) occur in 2010-2017 period (**panel a**)
- 3) All HEXs are well represented by ORAS4 reanalysis (red) & simulated by ROMS (blue) & HYCOM (purple); ROMS agrees best with satellite SLA (black) (**panel b**)

Structures of HEX & CHHEX events along Indonesian coast

CHHEXs (a & c):
High SLAs spread over entire east Indian Ocean coast (a) but Marine Heatwaves (MHWs) are confined to Indonesian coast (c)

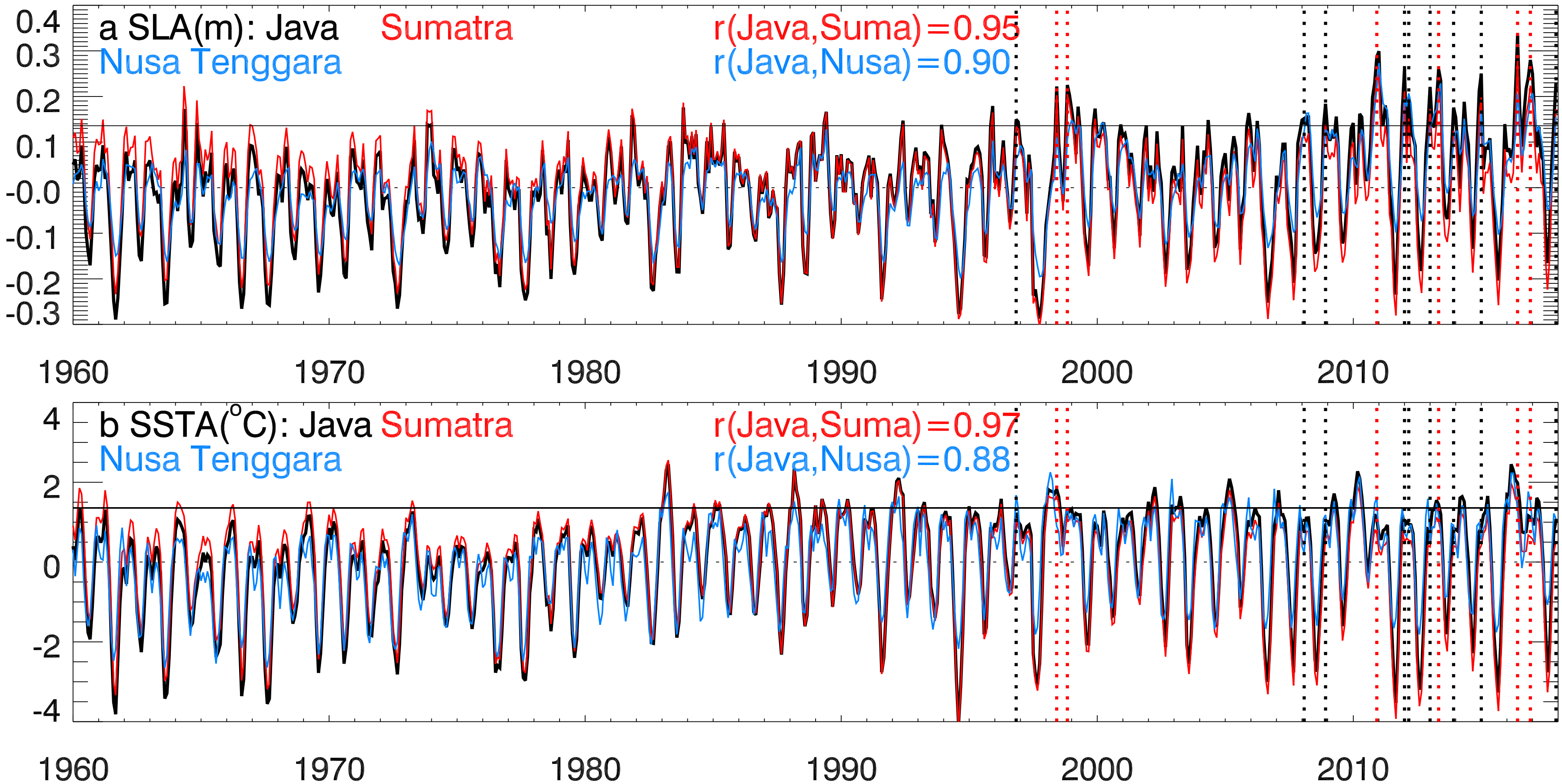
HEXs (b & d):
SLAs are more regionally confined to Indonesian coast (b), & there are no MHWs (SSTA did not exceed 90th percentile)



Composites of satellite monthly sea level anomaly (SLA), surface wind stress anomaly, and sea surface temperature anomaly (SSTA) for the peak months of 6 CHHEXs (a & c) and 9 HEX alone events.

SLAs for HEXs and SLAs & SSTAs for CHHEXs are coherent along the Indonesian coasts (South Sumatra, Java & Nusa Tengara)

Coherent SLAs and SSTAs for HEXs & CHHEXs along Indonesian coast

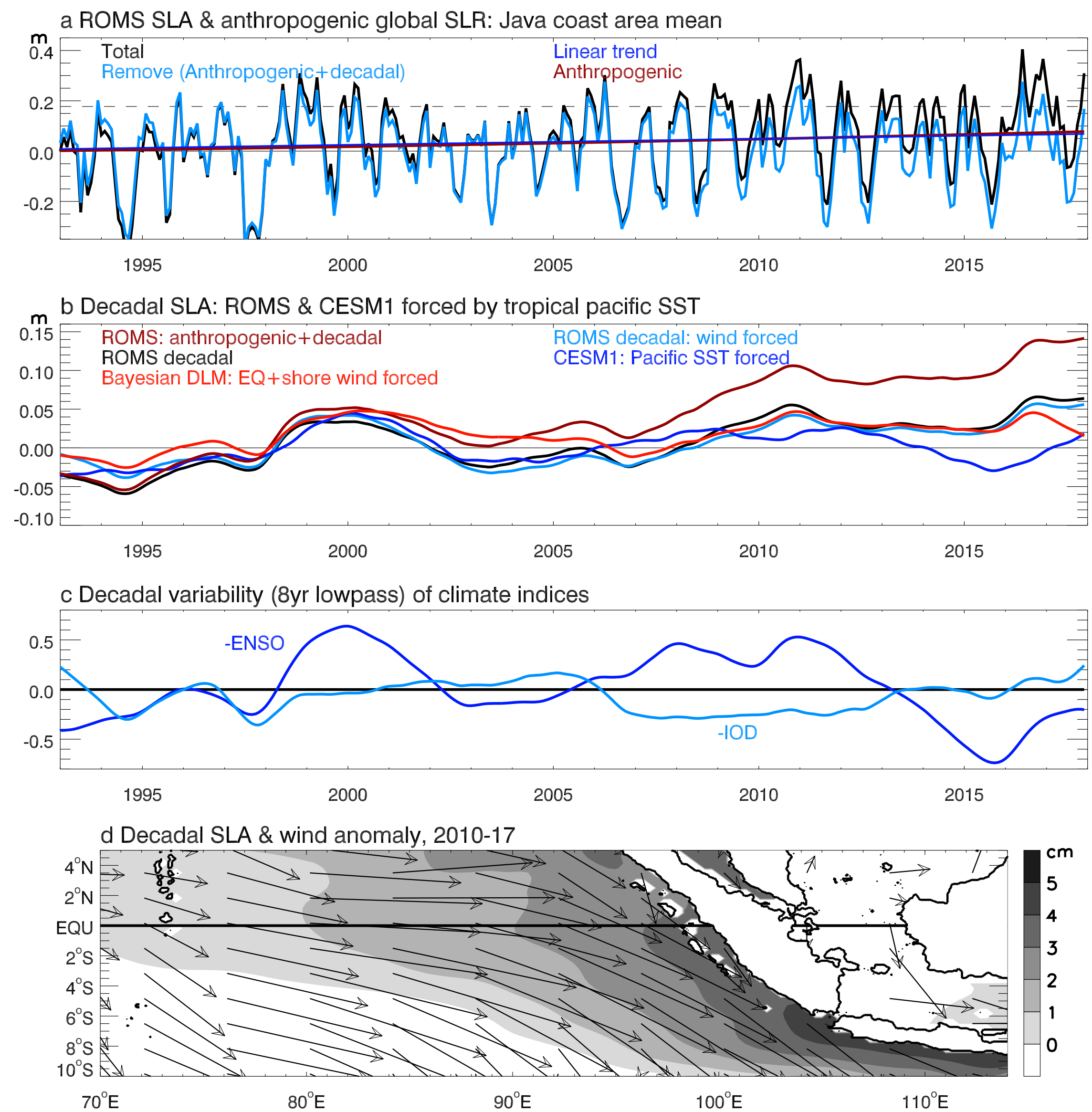


Time series of ORAS4 monthly mean SLA and SSTA averaged over Java coast (106E-114E, 7S-9S; black), Southern Sumatra coast (102E-105E,3S-6S; red), and east of Java along Nusa Tenggara coast (114E-120E, 8.5S-10S; blue) from 1960-2017. **a**, SLA; **b**, SSTA. (black horizontal line: 90th percentile). Vertical dotted lines: peak months of 15 HEX events with black indicating the nine HEX-alone events and red indicating six Compound Height and Heat EXtreme (CHHEX) events.

We fill focus on Java coast below

Question 1: Why do most HEXs occur during 2010-2017?

- **Decadal increase of SLAs from 2010-2017 causes increased no. and magnitudes of HEXs** *(compare black & blue curves of a)*
- Anthropogenic global sea level rise (GSLR) (red line in a) & internal decadal climate variability (black in b) contribute roughly equally to the increased SLA during 2010-2017
- Internal decadal SLAs (compare dark red & black in b) results from tropical Pacific forcing associated with IPO (blue in b and c; CESM1 experiments) & decadal variability of Indian Ocean Dipole (cyan of b and c; ROMS experiment)
- Negative IPO & positive to negative transition of decadal IOD are associated with EQ westerly & longshore northwesterly winds; they cause EQ & coastal mass/heat convergence, raising sea level (thus positive SLA) during 2010-2017 (red line in b & panel d).

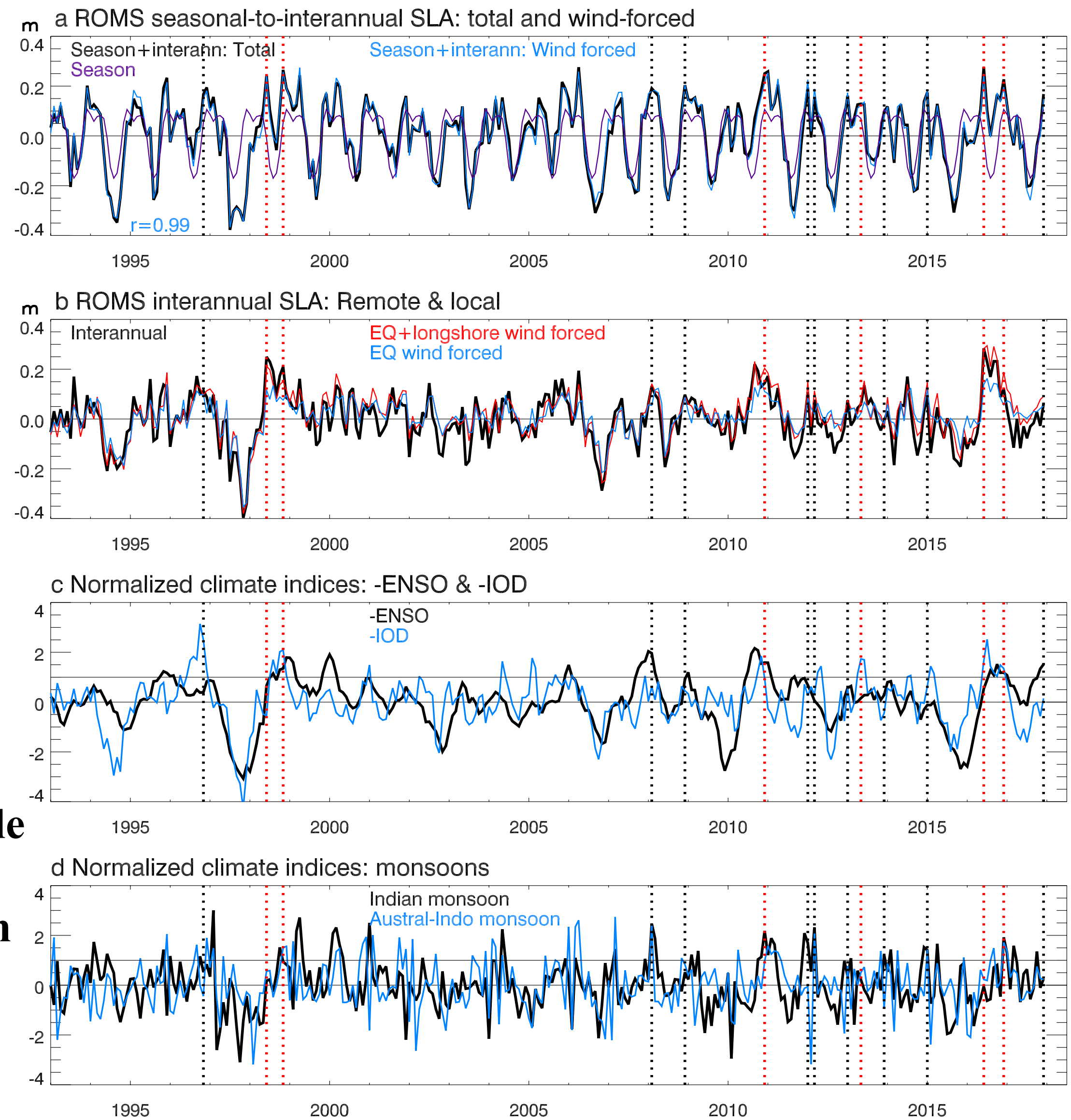


Causes for Individual HEX alone and CHHEX events

- **OGCM experiments show that individual peaks of all 15 HEXs are wind driven** (black & blue of a); **both equatorial (EQ) westerlies and longshore northwesterlies contribute to interannual SLAs** (panel b)

- **Most HEX alone events** (dotted vertical black lines) **occur in Dec-Mar; when EQ and longshore wind anomalies cause HEXs, they enhance seasonal northwest monsoon winds & reduce SST by increasing vertical mixing, causing HEX alone events**.

- **Most CHHEXs** (dotted vertical red lines) **occur in May-June & Nov-Dec, when negative IOD and La Nina co-occur. While EQ westerlies & longshore northwesterly wind anomalies cause HEXs, they weaken the seasonal southwest monsoon winds, suppress coastal upwelling cooling and increase SSTA, causing CHHEXs**

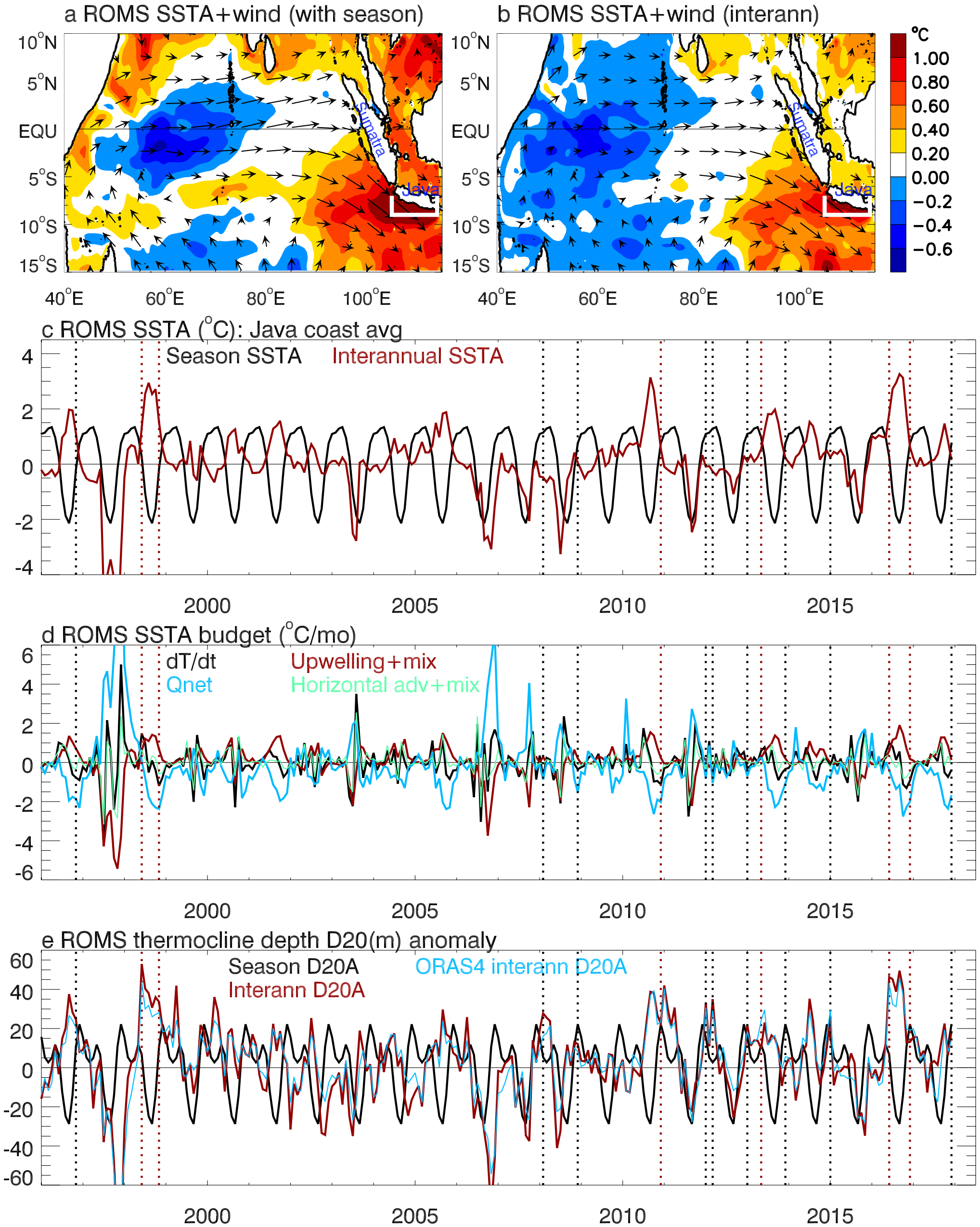


Budget analysis that support the causes for CHHEXs

- Interannual warm SSTAs associated with negative IOD and La Nina enhance the seasonal warm SSTAs during the IOD initiation in June and peak-to-decay period of Nov-Dec (panels a-c), causing the CHHEX events.

- Reduced upwelling and weakened vertical mixing (red line of d) plays a dominant role in causing the warm SSTAs of the CHHEXs (red vertical dotted lines)

- The reduced upwelling is also reflected by the deepened thermocline (red of panel e), agreeing well with the warm interannual SSTAs (red of c).



Summary and Discussion

- Satellite altimeter data, together with tide gauge observations, along Java coast identify 15 Height EXtremes (HEXs) from 1993-2018, with maximum monthly magnitude of ~0.45m.

- Most HEXs occur during the 2010-2017 period, due to the combined influence of anthropogenic sea level rise and internal decadal climate variability associated with negative IPO & phase transition of decadal IOD.

- Both HEX alone events and Compound Height-heat EXtremes (CHHEXs) are driven by equatorial westerly and longshore northwesterly wind anomalies.

- For most HEXs, which occur during December-March, downwelling favorable northwest monsoon winds are enhanced but enhanced vertical mixing limits surface warming; for most CHHEXs, wind anomalies associated with a negative Indian Ocean Dipole (IOD) and co-occurring La Niña weaken the southeasterlies and cooling from coastal upwelling during May-June and November-December.

Our findings emphasize the important interplay between anthropogenic warming and climate variability in affecting regional extremes.

Acknowledgement

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