Climate-driven extreme sea level events along the Indonesian coast during recent decades

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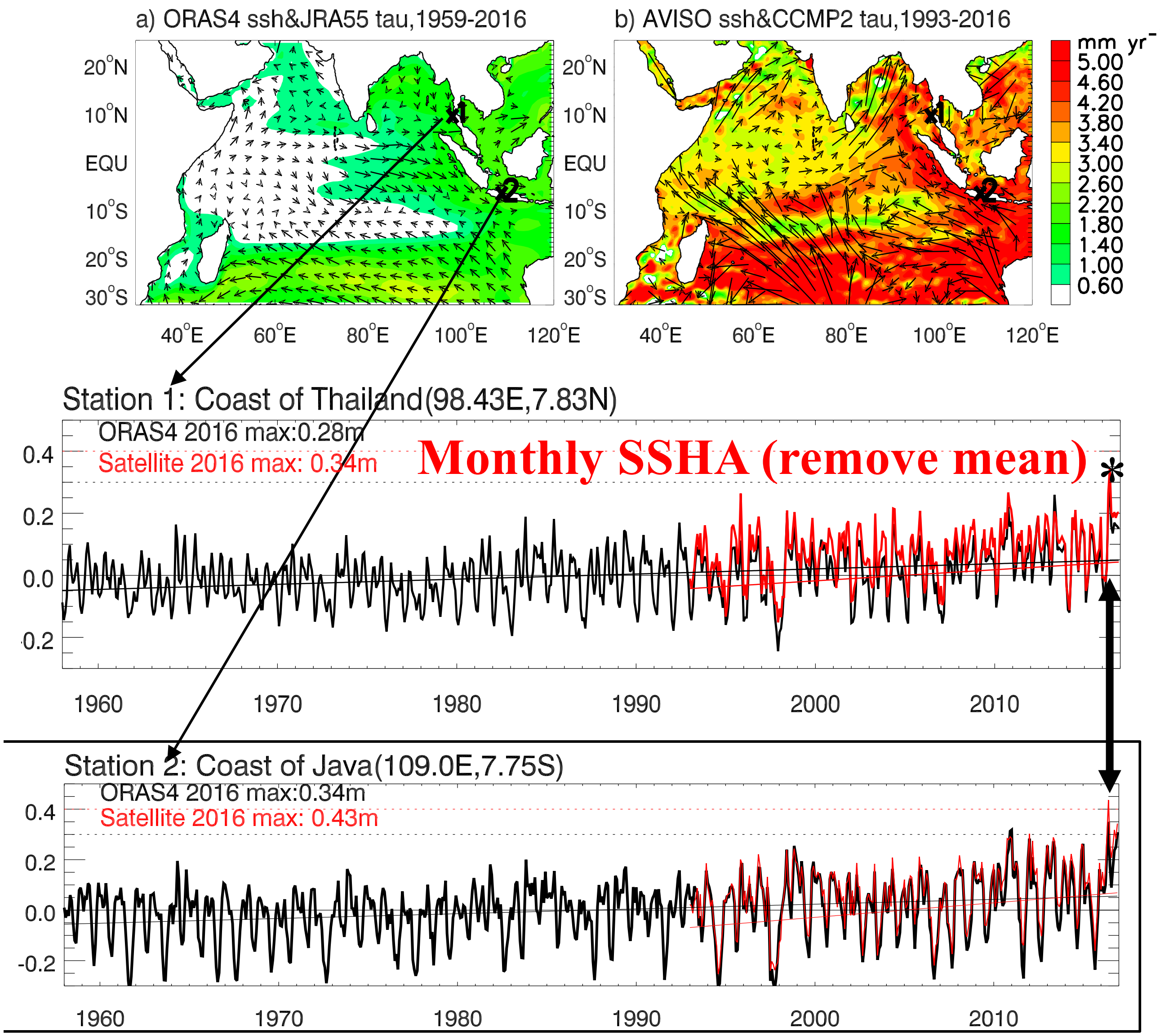
1. Motivation

Linear trend: 1959-2016   Satellite: 1993-2016



a) ORAS4 reanalysis SSH shows a rising trend along the east coast of tropical Indian Ocean (IO) from 1959-2016; corresponding to rising SSH, equatorial westerly winds enhance – panel a)

b) Trends of both SSH & westerly wind intensify during satellite altimetry era of 1993-2016 -panel b)

c) Time series of monthly ORAS4 and AVISO SSHA at two tide gauge locations N. & S of EQ show large-amplitude variabilities especially at Java coast (station 2), with extreme SSHA >0.4m in 2016.

Causes for the extremes remain unclear.

Goal:

Use 26yr satellite altimeter SSHA from 1993-2018 combined with in situ observations and climate-model experiments, to document the extreme SSH surge events along the Indonesian coast and understand their causes.

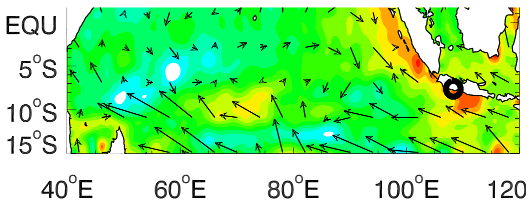
Indonesia Floods and Landslides such as the events occurred in 2016 have been reported: https://reliefweb.int/disaster/ls-2016-000051-idn:

According to the National Agency for *Disaster* Management, during May-June of 2016, "…*flood triggered by high tide and heavy rainfall occurred across 12 provinces in Sumatra, Java, Bali and Nusa Tenggara. At least 5,900 houses and temporary stalls were damaged and more than 30,000 houses were flooded*"

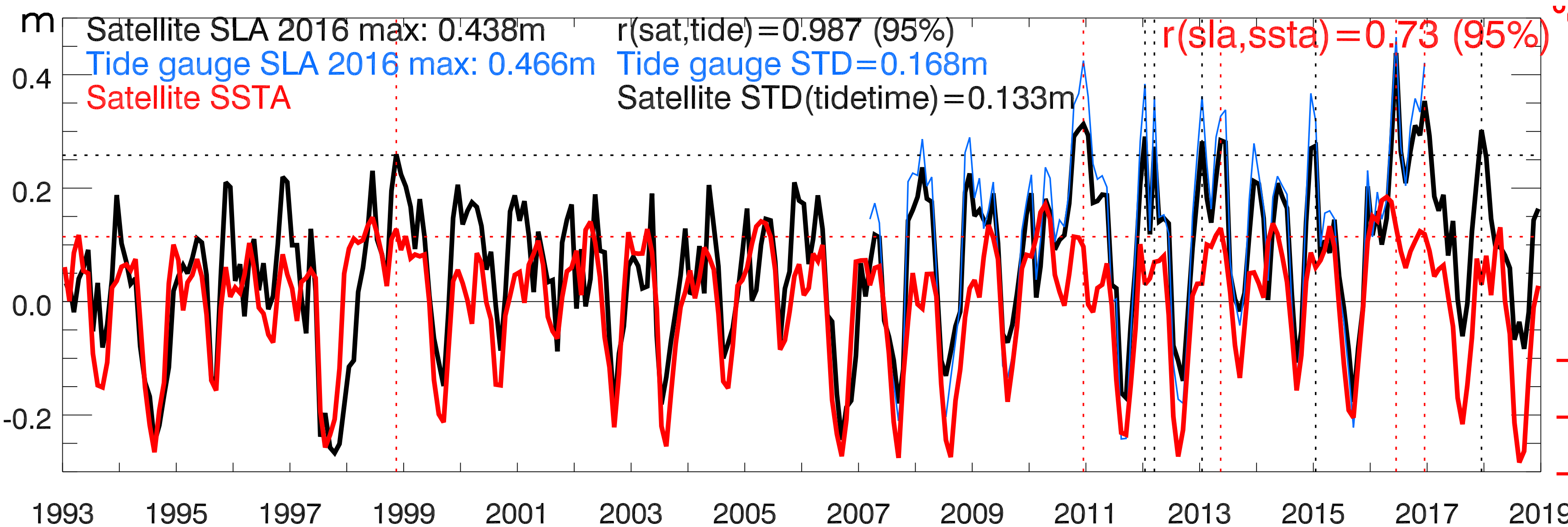
2. Approach

- **Observational analysis: n situ & satellite data:**
  Tide gauge (GIA & IB corrected);
  satellite sea surface height (SSH); satellite winds and OLR;
- **Ocean-atmosphere Reanalysis:**
  Ocean – ORAS4; Atmosphere – JRA55-do;
- **Performed Ocean Model Experiments:**
  (a) ROMS: tropical Indian Ocean (30E–110E, 46S-32N), 1/3° x 1/3 ° & 40 levels; JRA55-do forcing fields from 1959-2017
  (b) HYCOM: Indo-Pacific basin (55S-55N, 19E–68W); 1/3° x 1/3° within the tropics (25S-25N); 35 layers; forced by 3day ERA-20C fields for 1940-2010 then ERA-Interim from 2011-2016
- **Coupled Global Climate Model experiments**:
  NCAR CESM1 (40 members) & CMIP6 24 models (189 members) & global thermosteric SLA from 11 models (83 members);
  10member ensemble of CESM1 Pacific Pacemaker experiments to assess tropical Pacific SST forcing on Indian Ocean variability

3. Results: Observed extreme SSH events

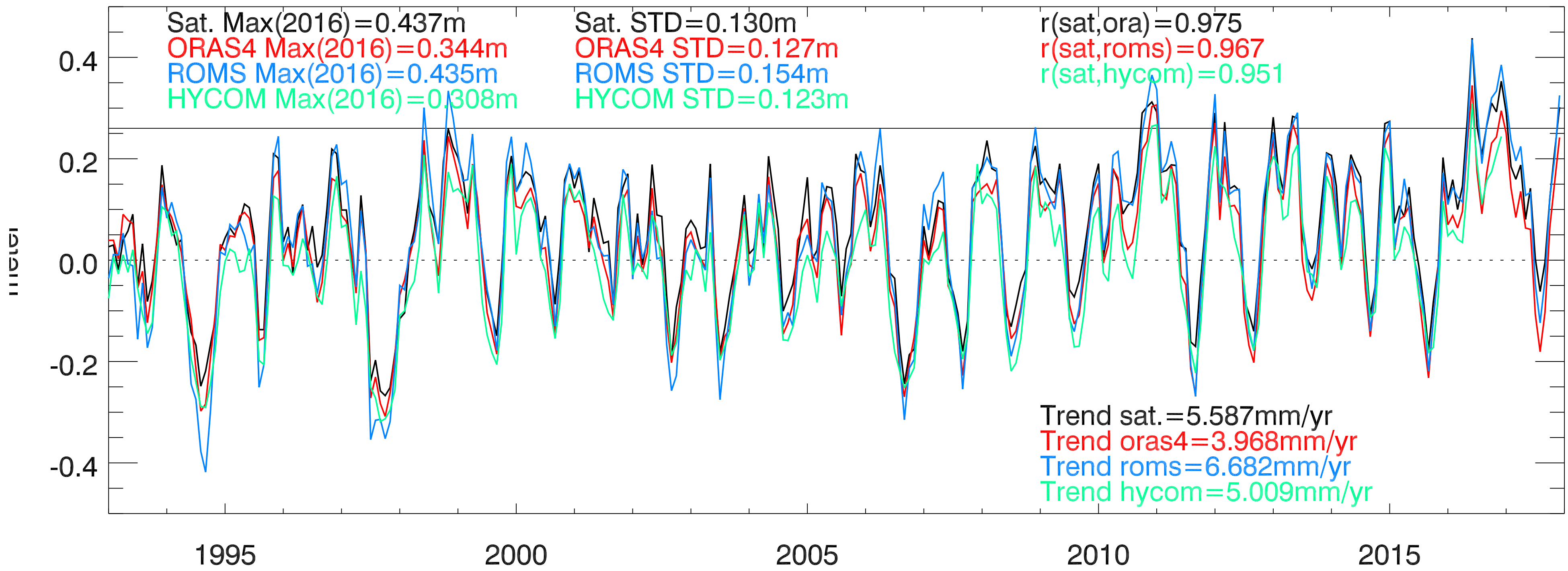


Time series of monthly SSHA from tide gauge at Cilacap B station of Java coast from 2007-2016 (blue curve) & satellite altimeter from 1993-2018 (black) & satellite SSTA (red).

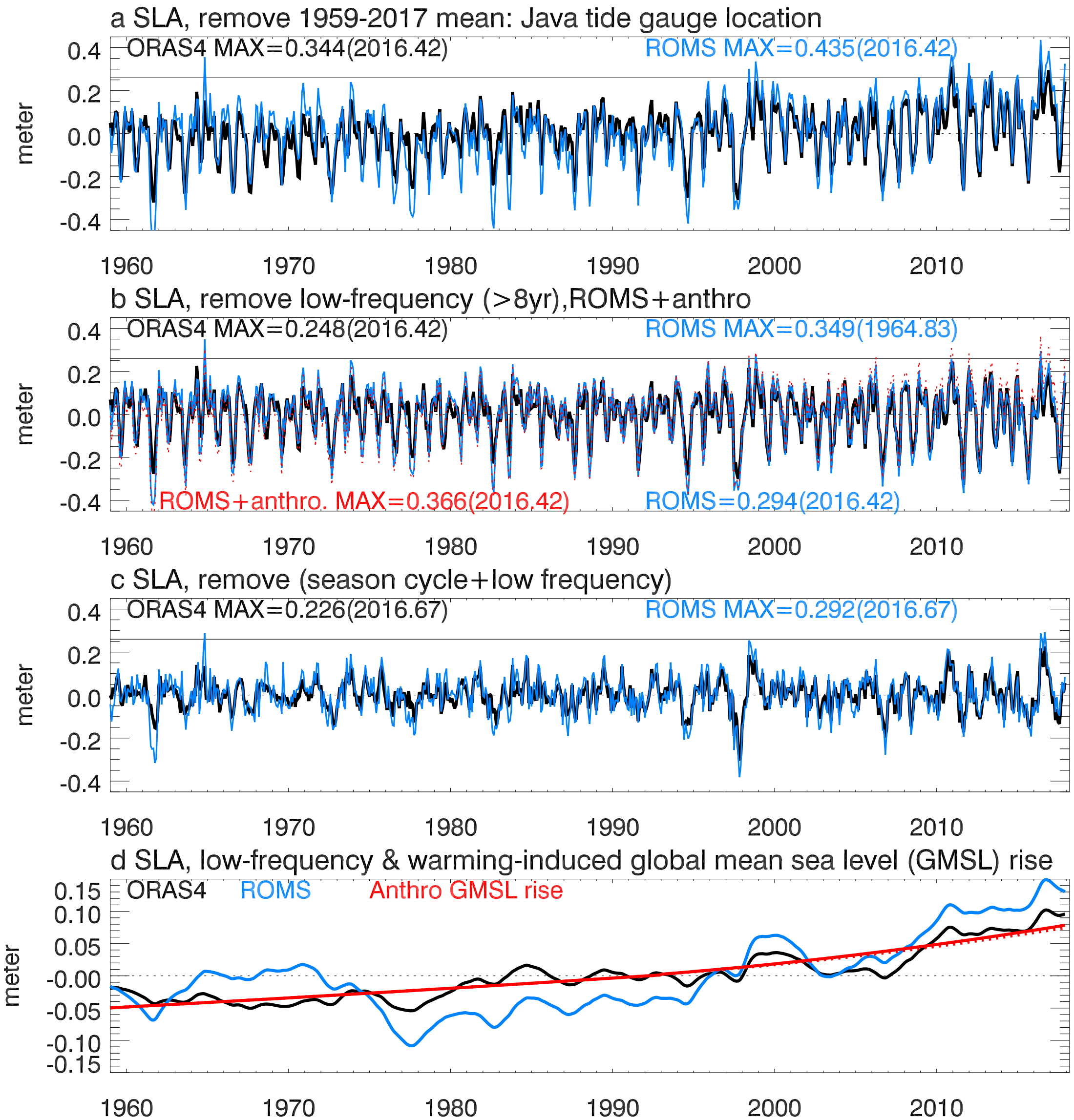


- **Satellite SSHAs agree very well with tide gauge data at Java coast except for weaker magnitude for some events, with correlation r=0.987; satellite altimeter data can be used to study SSH surges along Indonesian coast;**
- **SSHAs exceeding 2 Standard Deviations (STD) of satellite data (horizontal dashed line) are identified as extreme events (or surges); 10 SSH surges are identified (vertical-dotted lines);**
- **Five of the 10 SSH surges are accompanied by heat surges (red line)**

- **The extreme SSH events are well simulated by OGCMs: ROMS & HYCOM especially ROMS, which was forced by JRA55-do forcing fields;**
- **Most SSH surges occurred in the past decade.**



Monthly SLA (units: m) from multiple satellite merged altimeter data (black), ORAS4 reanalysis data (ocean model assimilated observed data including the altimeter data; red), simulations from ROMS (blue) and HYCOM (green) ocean general circulation models. Corrections for the effects of sea level pressure are made for ROMS and HYCOM outputs using HadSLP2 sea level. pressure. The horizontal solid line shows 2 standard deviations of satellite SSHA from 1993-2017. The mean of 1959-2017 is removed For satellite data, the mean of ORAS4 is removed.



1) SSH surges frequency occur since ~2010 in both ORAS4 & ROMS -a);

2) This pattern disappeared after removing linear trend & 8yr lowpassed SSHA -b), suggesting that decadal & longer timescale SSHAs are the major cause for the frequent occurrence of SSH surges since ~2010;

3) SSH Surge magnitudes further reduce for most events when mean seasonal cycle is further removed -c), suggesting that SSHAs superimposing on high sea level season can have larger impacts on coastal regions;

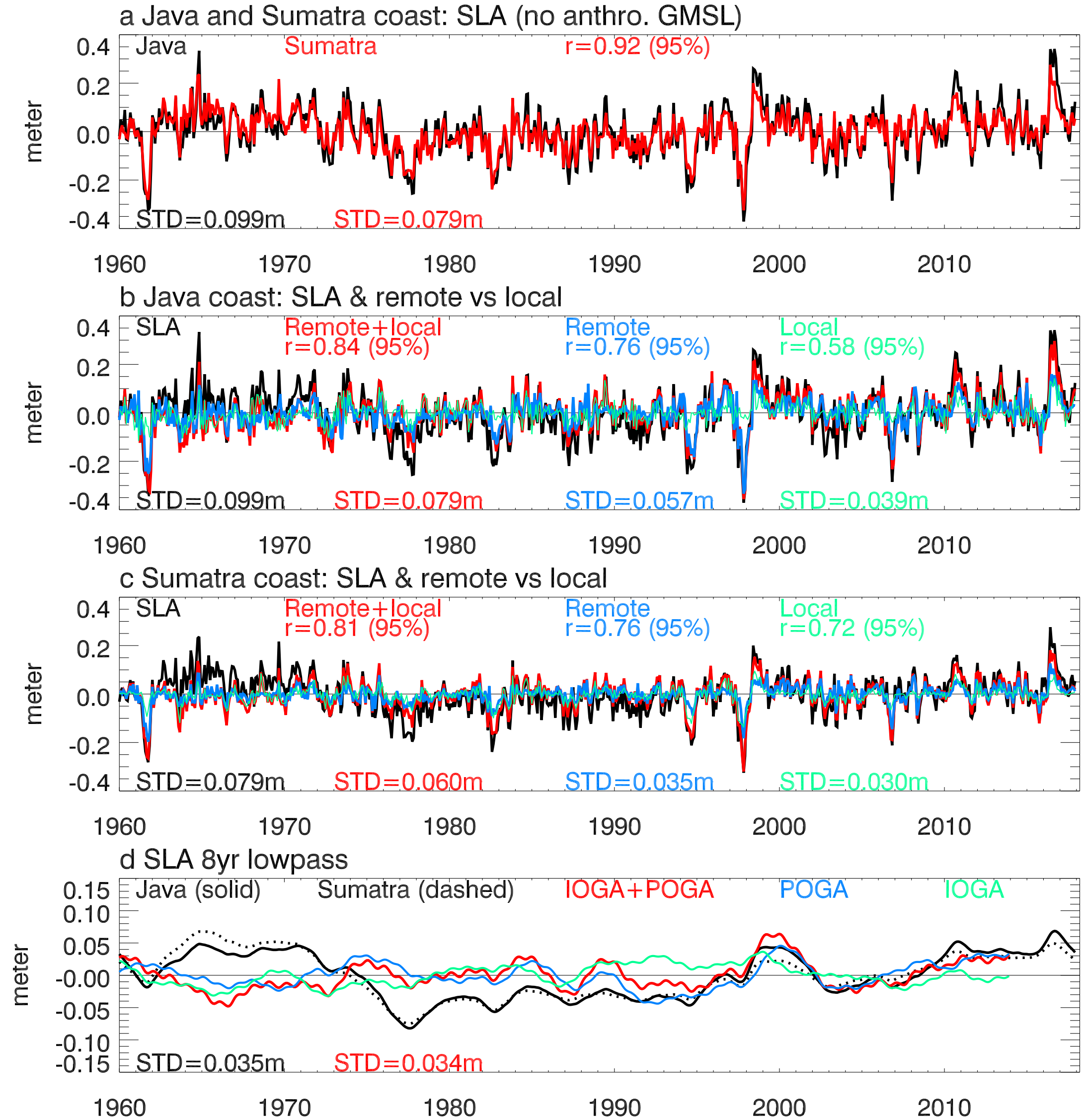
4) When only anthropogenic-induced global mean sea level rise (SLR) is removed, ~ half of SSH surges went below 2STD, suggesting that anthropogenic SLR accounts for ~50% of the frequency of SSH surges & natural variability accounts for the other half – d).

*Time series of monthly SSHA (m) at Java tide gauge location from ORAS4 reanalysis (black), ROMS model (blue) and global sea level rise due to anthropogenic warming (Church et al. 2013). **a**. SLA with 1959-2017 mean removed; **b**. SLA with decadal variability (8yr lowpass) and linear trend removed; **c**. Same as **b** but further remove mean seasonal cycle, and the red dashed line is the sum of ROMS (blue) and anthropogenic sea level rise (red in panel **d**); **d**. Decadal variability + linear trend (the part removed in **b** and **c**), anthropogenic warming induced global mean sea level (GMSL) rise based on reconstructed (satellite observed) global sea level data before (after) 1993..*

1) ROMS simulation and Bayesian Dynamic linear model (DLM) results suggest that remote forcing from zonal wind along Indian Ocean equator, together with local longshore wind forcing, explains the SSHA surges along both Sumatra and Java coasts – panels a)-c);

2) Surface wind associated with a negative Indian Ocean Dipole (nIOD) largely accounts for the 2016 extreme sea level surge;

3) CESM1 Pacemaker experiments suggest that the trend and decadal variations (with anthropogenic SLR remoted) result mainly from the Pacific SST forcing via atmospheric bridge, with Indian Ocean SST having some weaker influence – d).



Monthly SSHA (m) time series (with anthropogenic global SLR removed) averaged for Java and Sumatra coastal areas from ROMS model, Bayesian Dynamic Linear Model (DLM) to estimate remote versus local wind forcing, and CESM1 Pacemaker experiments that isolate the Indian and Pacific Ocean SST forcing. ***a****. ROMS SLAs averaged for Java coast (black) and Sumatra coast (red) for 1960-2017, after removing anthropogenic SLR;* ***b****. ROMS SLAs averaged for Java coast, SSHAs forced by the remote equatorial zonal wind stress (blue), local longshore wind stress (green) and their sum (red);* ***c****. Same as b but for Sumatra coast;* ***d****. decadal and longer-term SSHAs from ROMS for Java coast (black solid) and Sumatra coast (black dotted); dynamic SSHAs from 10-member ensemble average of CESM1 experiment with Pacific Ocean SST forcing (blue), Indian Ocean SST forcing (green) and their sum (red) from 1950-2013.*

4. Summary and conclusions

1) Bordering tropical East Indian Ocean, the low-lying Indonesia islands are highly vulnerable to global SLR & extreme sea level events; satellite altimeter data agree very well with tide gauge observations along Java coast and are used to detect sea level extremes;

2) The no. of extreme SSHAs (>0.25m) has apparently increased since ~2010, and the strongest event occurred in 2016 with sea level rise >0.4m, which is comparable to the sea level surges induced by high tide and storms in this near equatorial area;

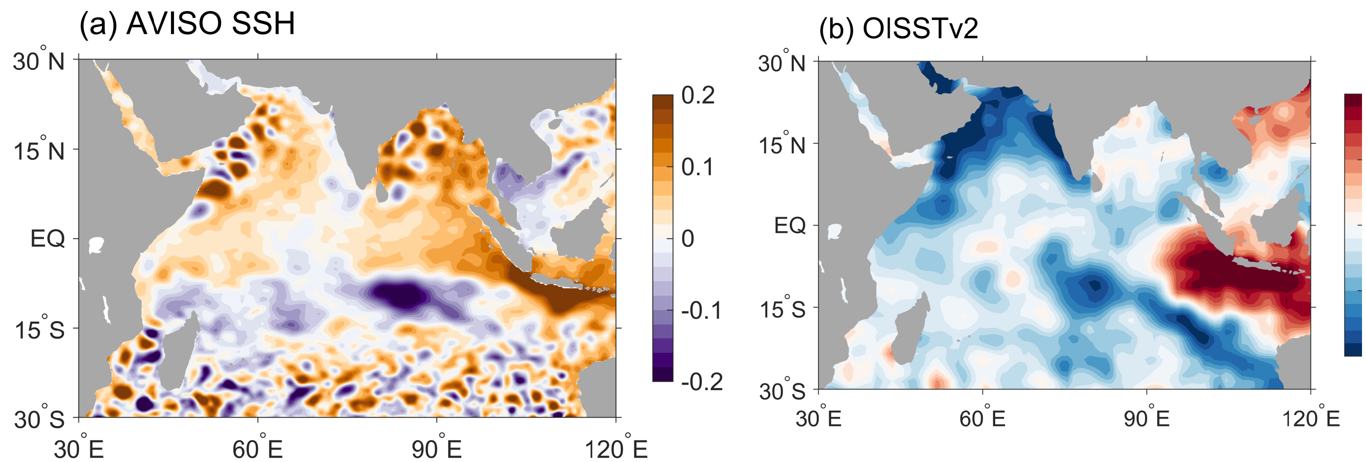
3) The SSH surges are primarily driven by the varying surface winds remotely from the equator and locally near the shore; while winds associated with negative Indian Ocean Dipole (nIOD) – a coupled ocean-atmosphere mode of climate variability at interannual timescale – explain over half of the extreme sea level magnitude in 2016, surface winds induced by Pacific SST anomalies cause accelerated sea level rise in the past decade; together with the climate-change induced global SLR and contribution from seasonal cycle, they account for over 40% of the 2016 extreme sea level amplitude.

5. Future research

Note that the 2016 has two super surges, one occurred in boreal spring and one in boreal fall. Both events are accompanied by heat surges (red line of slide 5). These surges are associated with large-scale SSHA and SSTA, i.e., marine heatwaves (MHWs) off Indonesian coast. See figure below.

What are the causes for the large-scale, long-lasting MHWs and SSH surges? These are important science issues to address.

Monthly SSHA & SSTA (seasonal cycle removed) for Oct 2016



6. Acknowledgement

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