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Global contributions to extreme sea levels at reef coastlines

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Causes of coastal flooding (***total water level***)
- A superposition of water level contributions

Still Water Level **(SWL)**

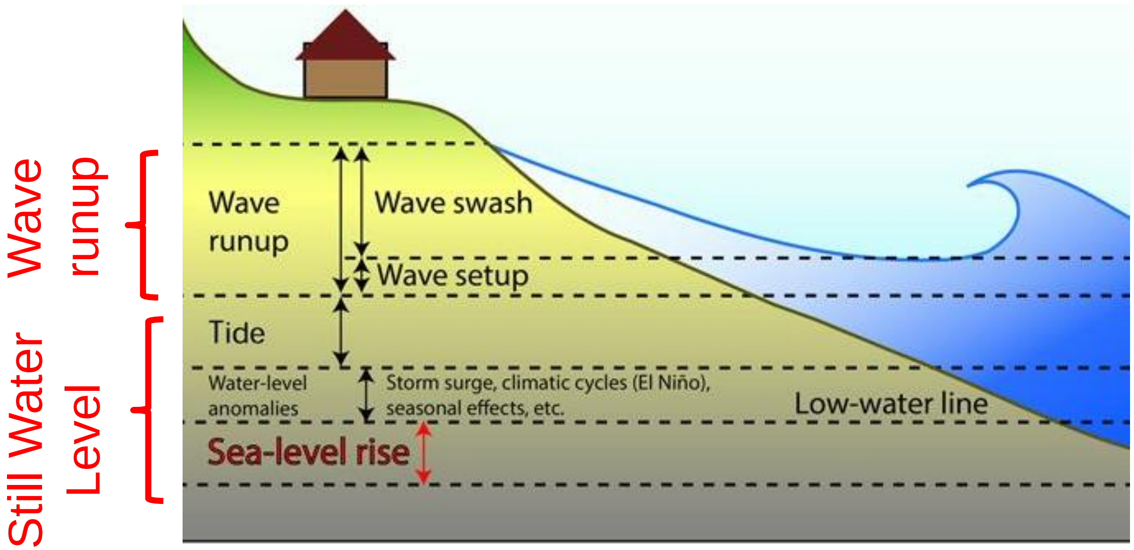
- Tides
- Atmospheric (storm) surge
- Seasonal and inter-annual variability
- Sea level rise

Wave runup **($R_{2\%}$)**

- Waves (swash excursion)
- ***Wave setup***

Total Water Level **(TWL)**

$$TWL = SWL + R_{2\%}$$



(Vitousek et al. 2017)

Objectives of the study

Conduct a global analysis of reef coastlines to:

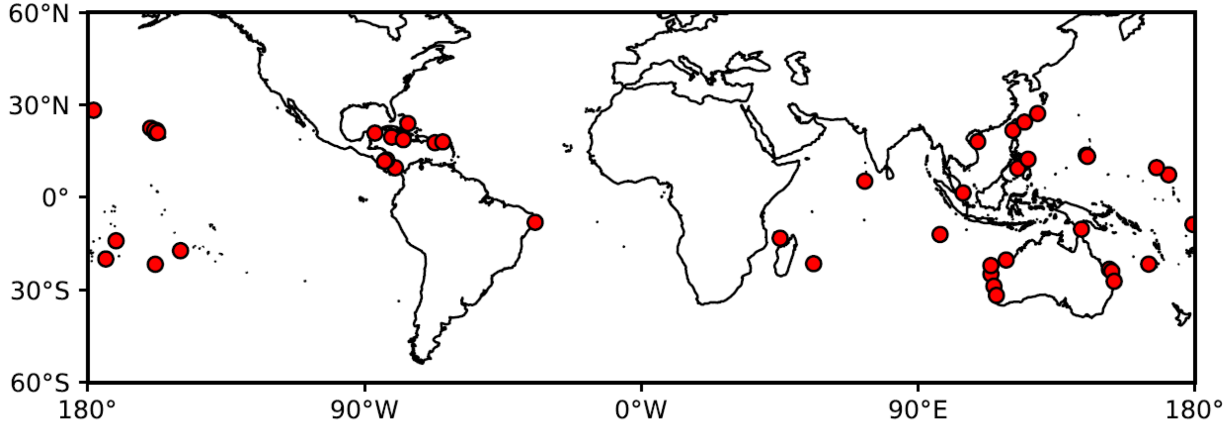
- Assess how different sources of water level variability drive extreme sea level (ESL) events at <u>fringing</u> reef coastlines
- Understand the role of still water level variability versus wave setup to ESLs
- Identify how regional ocean processes and global climate cycles (e.g. ENSO) influence the probability of ESLs

Focus on analysing changes over the last ~30 years

Study sites and bathymetry

A case study of *initially* 60 reefs chosen based on:

- Global coverage
- Coastlines with fringing reefs where bathymetry is known
- Sites with hydrodynamic observations (waves and water levels)

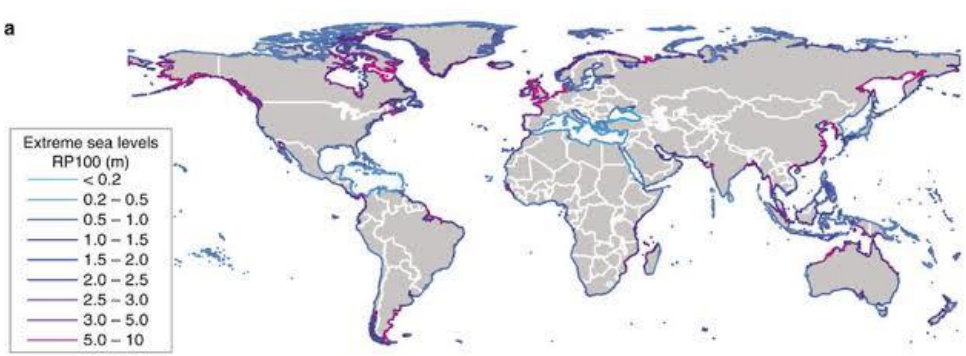


-> Extend to reef coastlines globally (with assumptions)

Data sources: still water level variability

<u>**Global Tide and Surge Reanalysis (GTSR)**</u> **(hourly)**

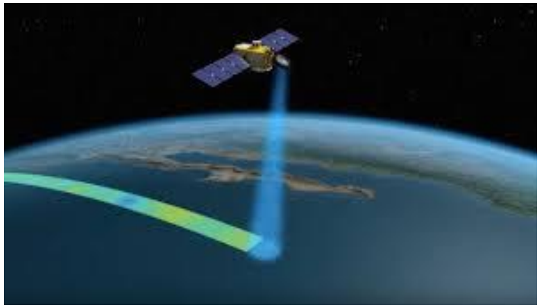
- Predictions of tides and atmospheric surges (1979-2018)
- ERA5 atmospheric forcing

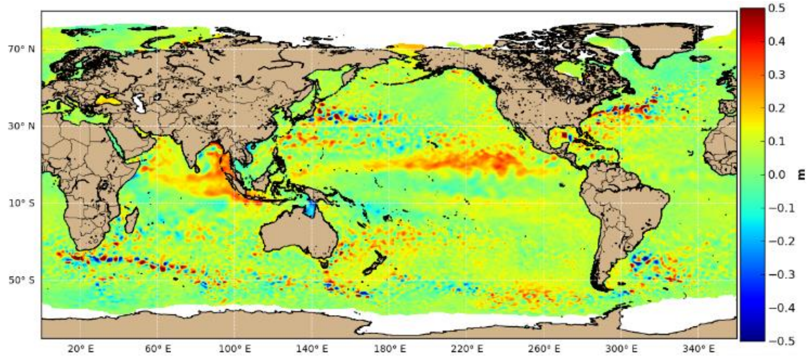


Muis et al. (2016)

<u>**Satellite altimetry**</u> **(monthly gridded)**

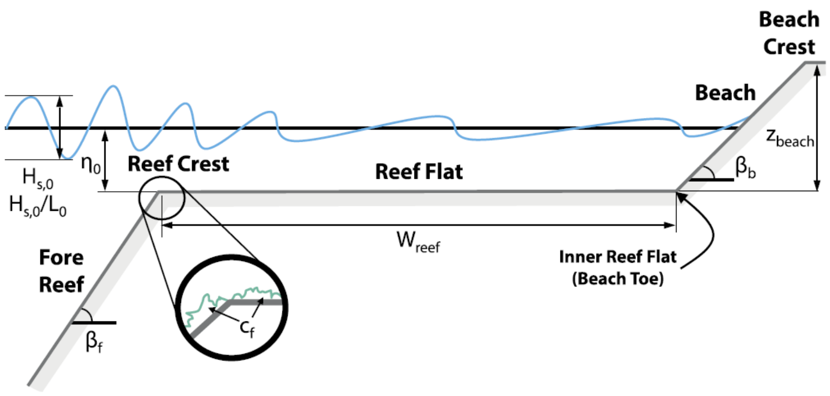
- Seasonal and inter-annual variability
- Mean sea level rise





Data sources: wave setup

- Wave conditions from ERA5
- Extracted reef bathymetry profiles for the 60 fringing reef study sites
- Focus on bulk geometrical properties of the reef morphology, particularly:
  - ✓ Reef flat width (W_r)
  - ✓ Reef flat depth (h_r) – relative to MSL



Some consistency (defined ranges) among the 60 sites considered

$$W_r = 280 \pm 140 \text{ m}$$
$$h_r = 1.2 \pm 0.7 \text{ m}$$

Data sources: wave setup

- Wave runup contributions derived from the BEWARE database (Pearson et al. 2016)
- Based on large number (174,372) of phase-resolving wave model simulations using XBeach with schematized bathymetry

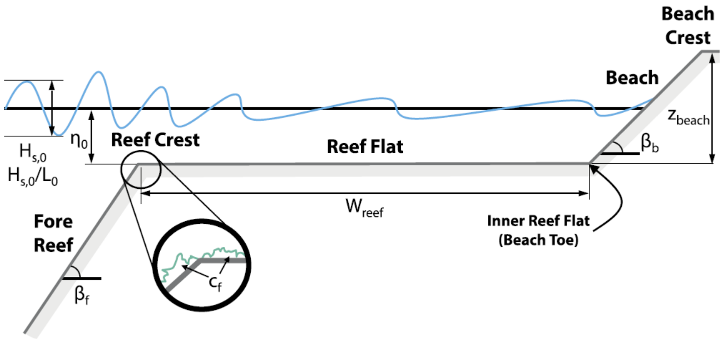


Table 1
Primary XBeach Non-Hydrostatic Model Input Parameters and Their Values

Parameter	Symbol	Units	Values
Offshore water level	η_0	m	−1.0, −0.5, 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0
Offshore significant wave height	H_0	m	1, 2, 3, 4, 5
Offshore wave length	L_0	m	–
Offshore wave steepness	H_0/L_0	–	0.005, 0.001, 0.050
Fore reef slope	β_f	–	1/2, 1/10, 1/20
Reef flat width	W_{reef}	m	0, 50, 100, 150, 200, 250, 300, 350, 400, 500, 1,000, 1,500
Beach slope	β_b	–	1/5, 1/10, 1/20
Coefficient of friction	c_f	–	0.01, 0.05, 0.10

Wave runup, wave setup

$$R_{2\%}, R_{setup} = f\ \text{(reef geometry, wave conditions, still water level)}$$

Water level decomposition example (Ningaloo Reef, NW Australia)

Contributions have distinct time-scales -> allows them to be decomposed

Total Water Level

$$TWL = SWL + R_{setup}$$

Still Water Level

$$SWL = \eta_{SLR} + \eta_{interannual} + \eta_{seasonal} + \eta_{surge} + \eta_{tide}$$

Total Water Level

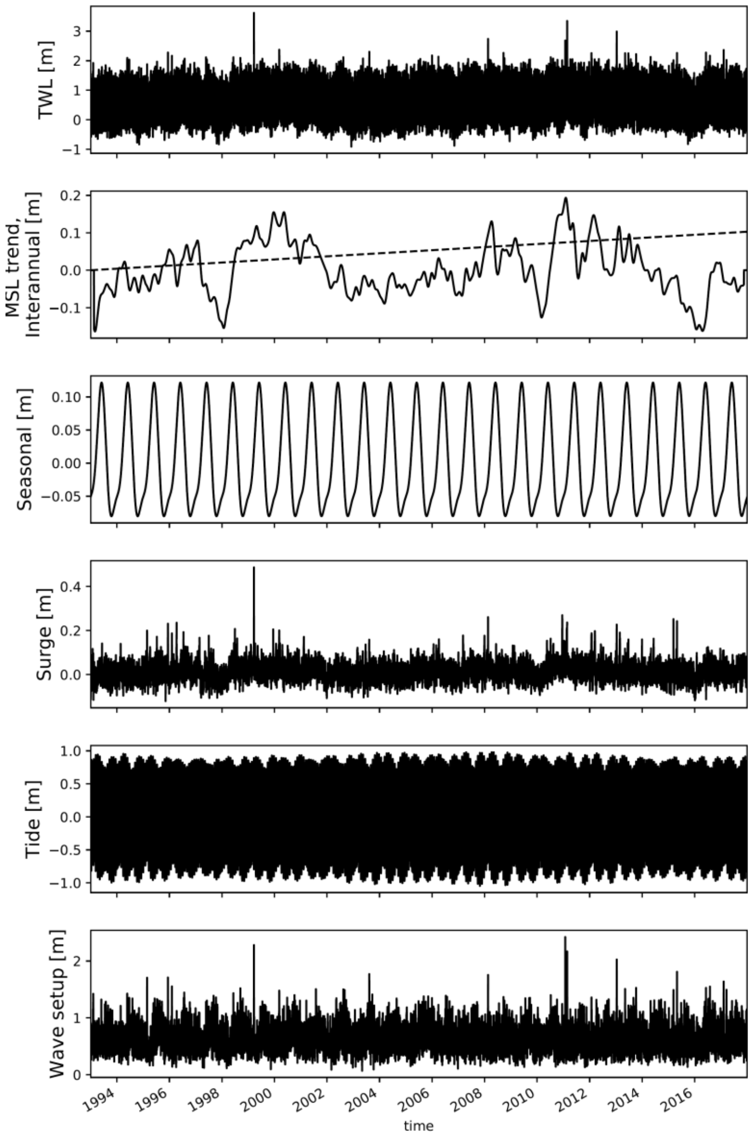
MSL rise, Interannual $(\eta_{SLR}, \eta_{\text{interannual}})$

Seasonal $(\eta_{seasonal})$

Surge (η_{surge})

Tide (η_{tide})

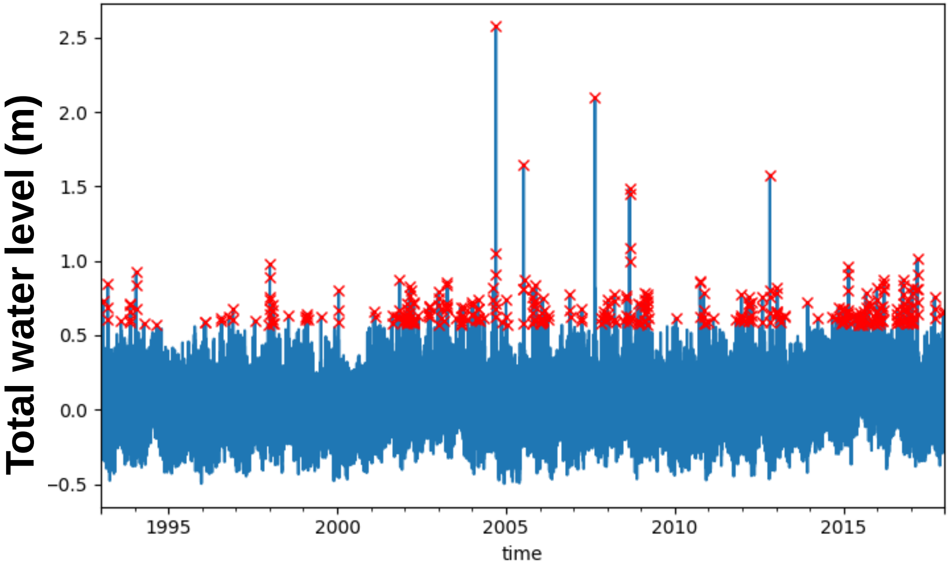
Wave setup (R_{setup})



Analysis approach

Identifying extreme events

- Extreme events identified as the top 2% of sea level values separated by at least 3 days
- Isolate how individual water level contribution caused the extreme event
- Analyse regional trends in water level drivers over the study period

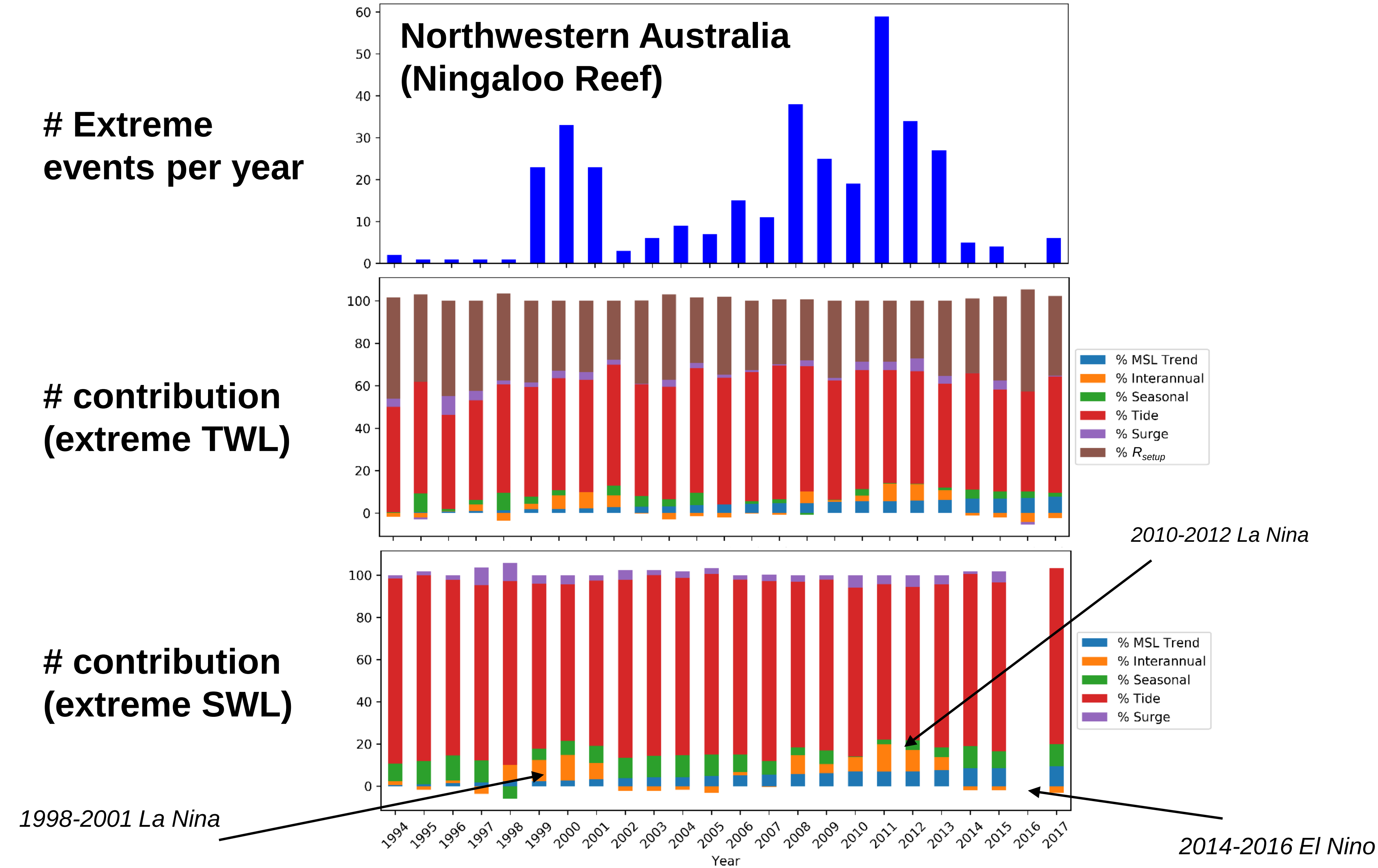


Evolving contributions to extreme coastal water levels (example)

Extreme events per year

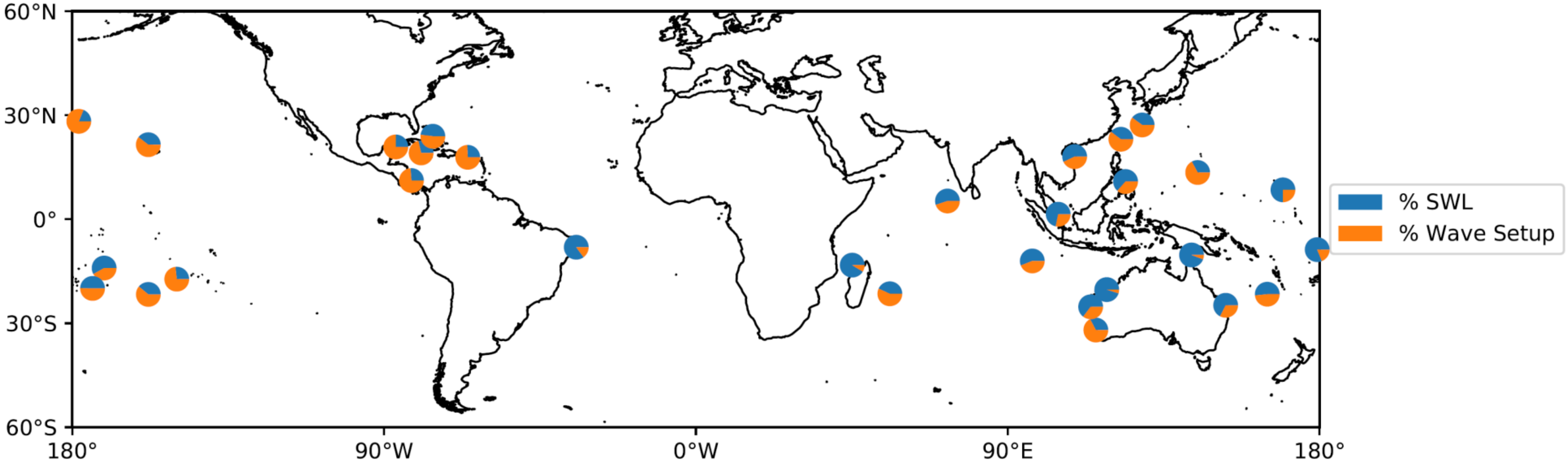
contribution (extreme TWL)

contribution (extreme SWL)



Global drivers of extreme sea level events

Still Water Level vs. wave setup contributions to extreme events



- In general, both make important contributions to driving ESL events

Global drivers of extreme sea level events (Still Water Level contributions)

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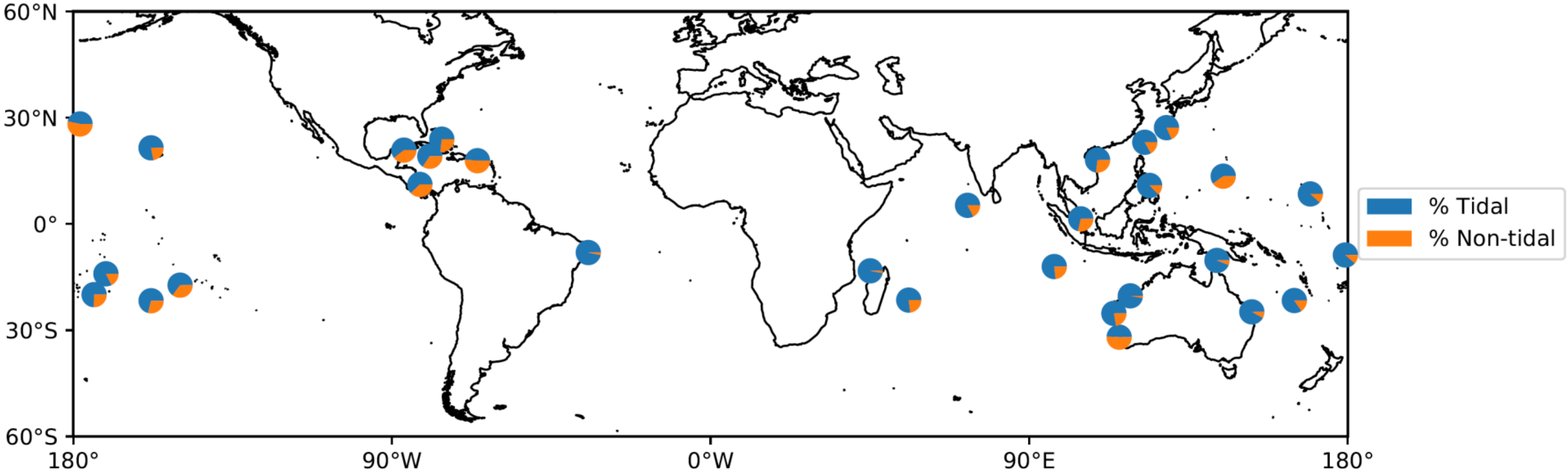
<u>Tidal versus non-tidal contributions to SWL extremes</u>

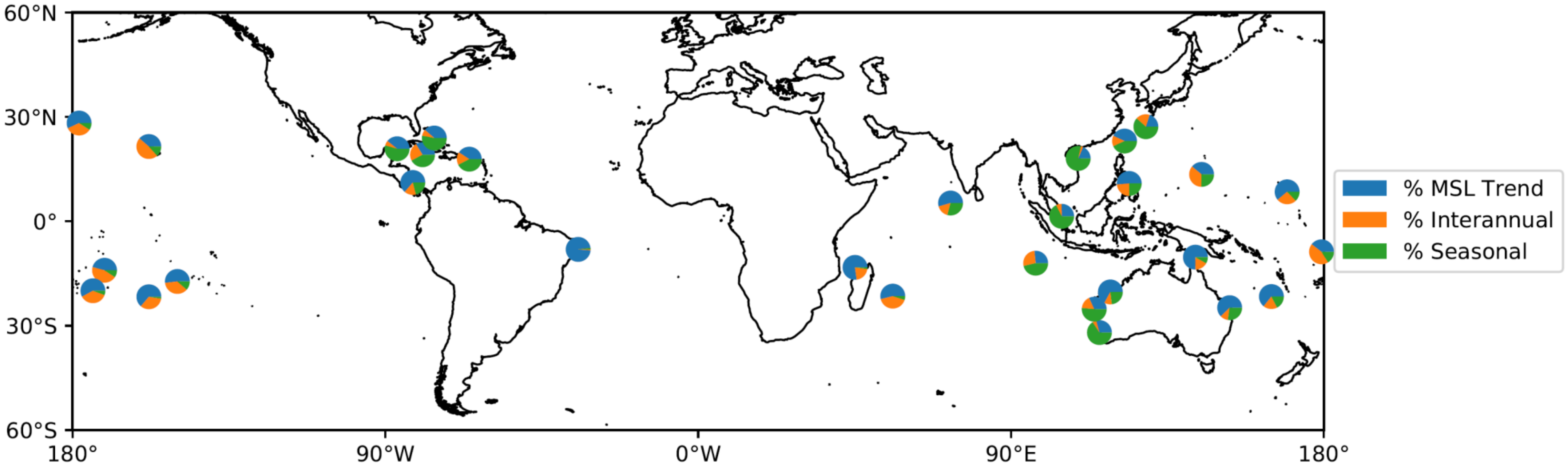


- Tides generally only determine the time of day when extremes occur -> not the periods (days to years) when ESL events are more likely to occur

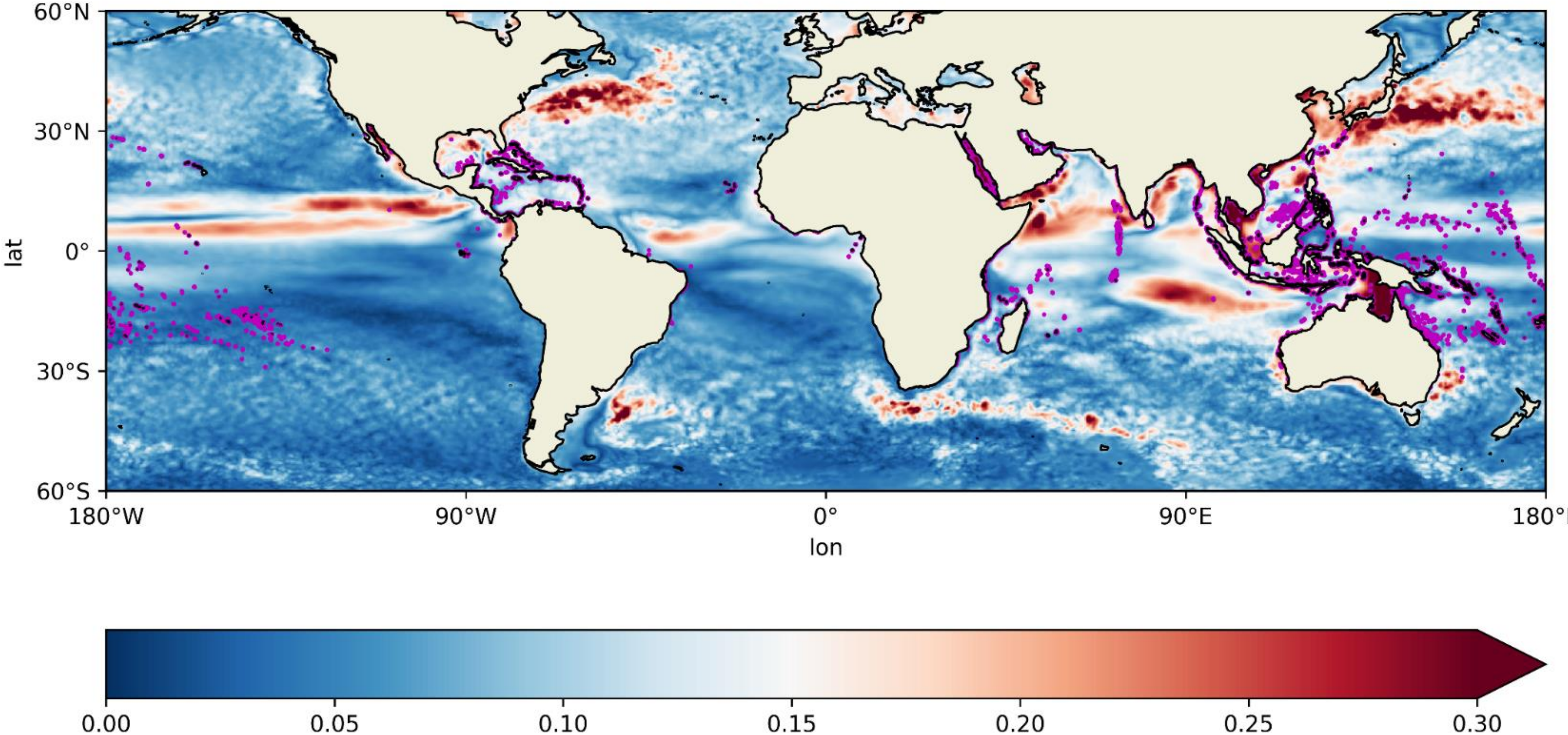
Global drivers of extreme sea level events

Long term (inter-annual to decadal) contributions to extremes

- Regional patterns evident where MSL rise, inter-annual and seasonal drivers are dominant



Seasonal range (max-min) in still water level

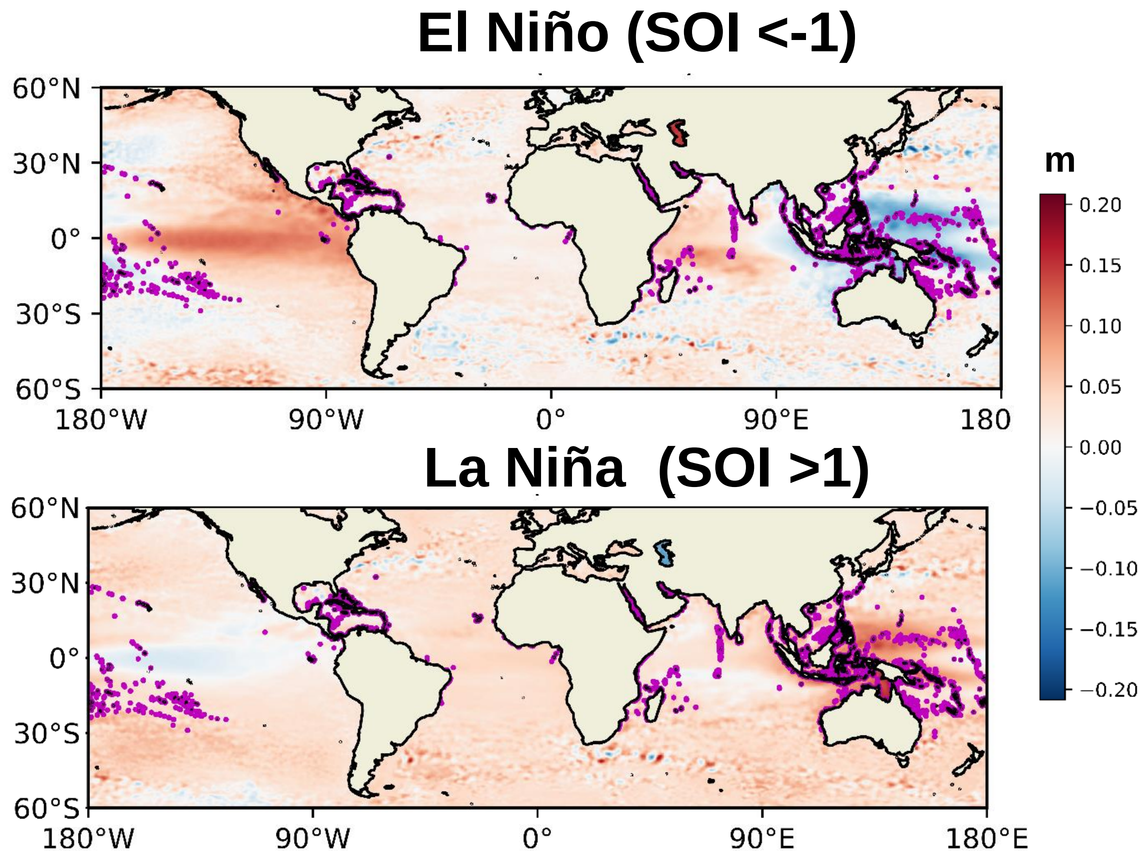


meters

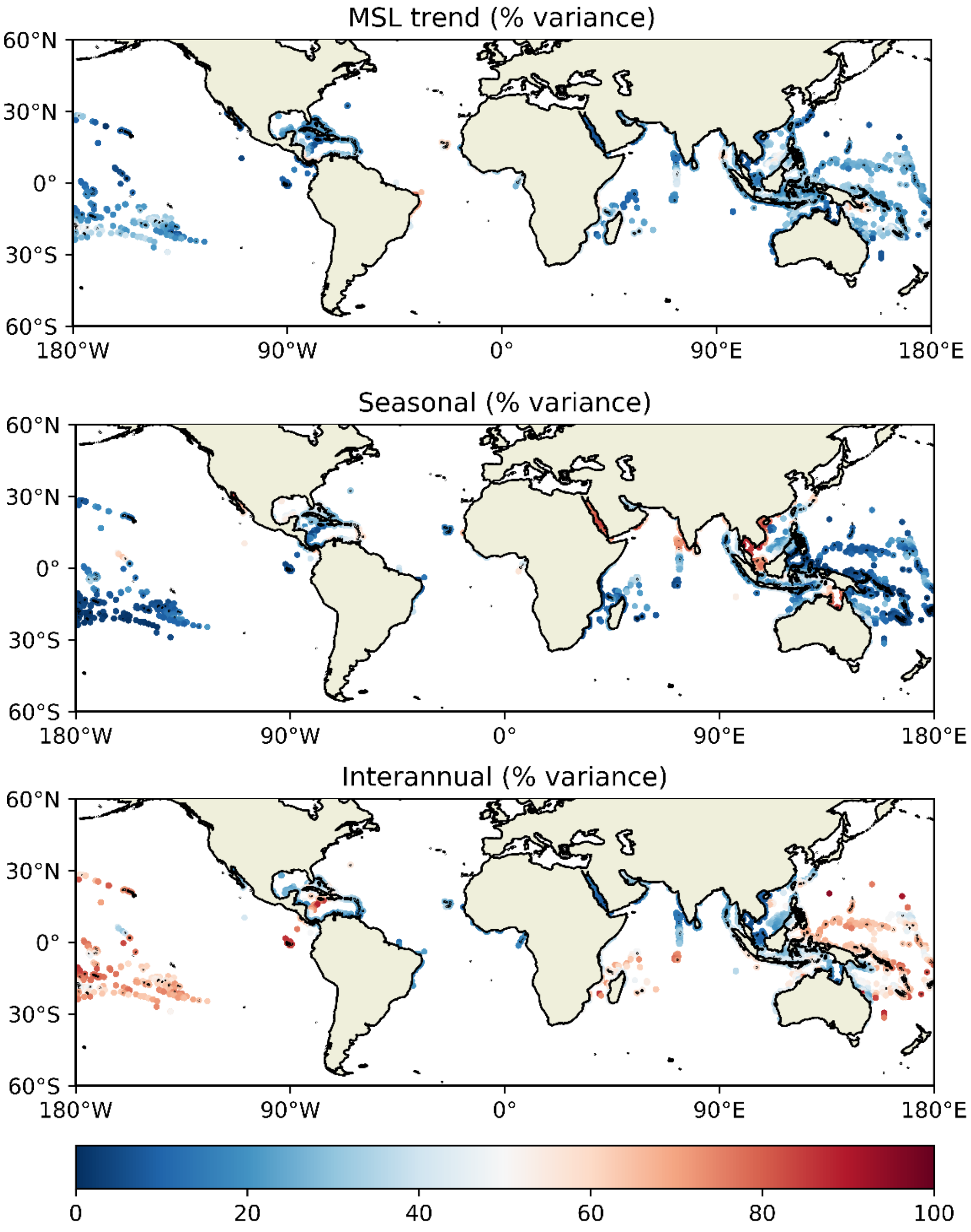
Values capped at 0.3 m

Inter-annual variability (role of ENSO)

- Strong inter-annual variations in water levels, particularly in the tropics
- Largest variations in the Western Pacific / Coral Triangle / N. Australia region
- Up to 40 cm difference between El Niño and La Niña periods



Low frequency (>1 month) contributions to sea level variability at reef coastlines



e.g., reefs with major interannual contributions more vulnerable to ENSO

Summary and conclusions

- There are strong regional variations in the mechanisms that drive extreme sea level events -> how these individual mechanisms change will determine the future of reef coastlines

- In many (or most) cases these regional variations overwhelm the responses to details of reef morphology (weak sensitivity of wave setup to reef profile)

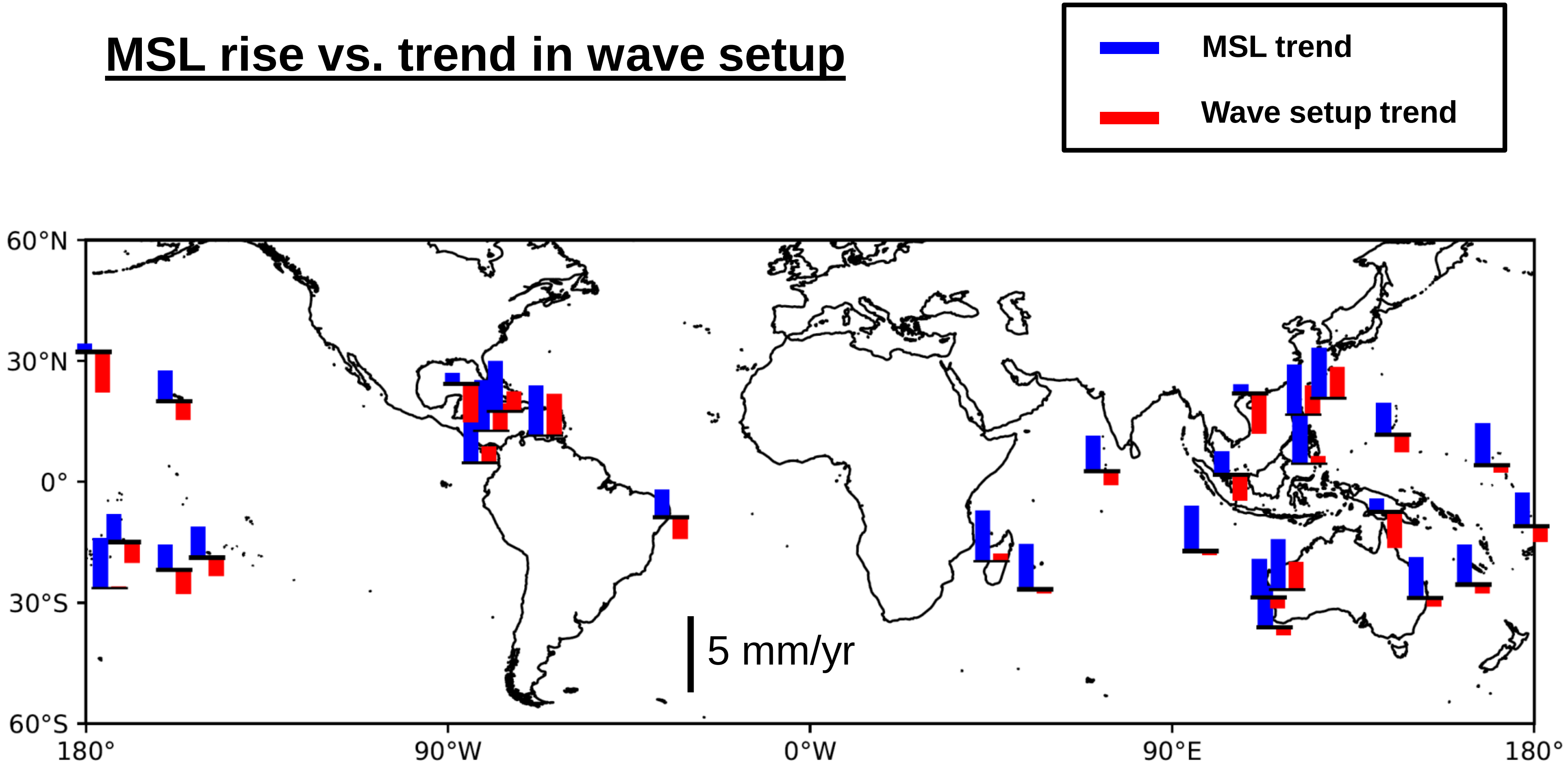
- Mean sea level rise increasing the frequency and severity of flooding events

- Well-defined regions where both seasonal and inter-annual variations are a major cause of reef flooding

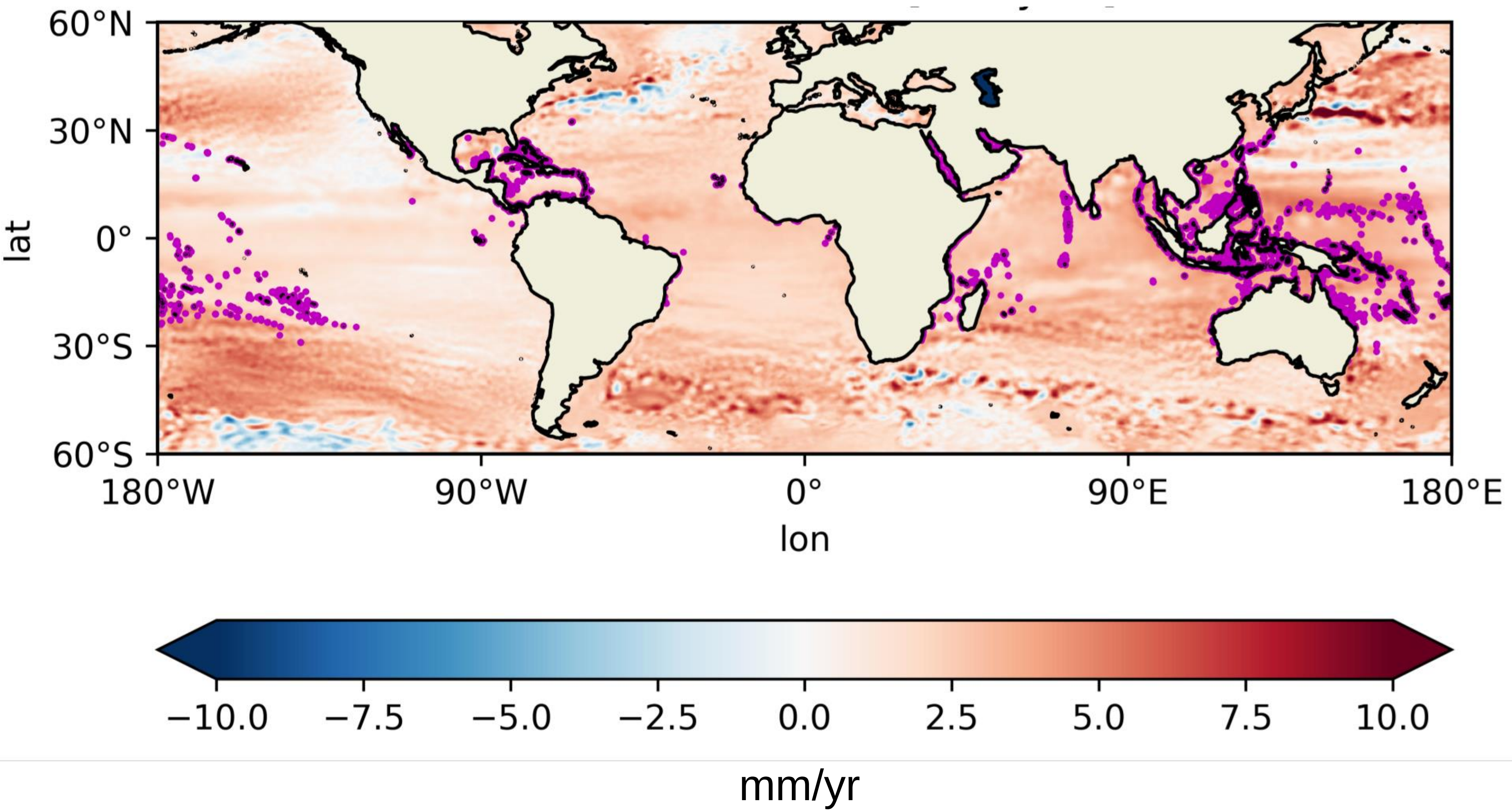
- Inter-annual variability is strongly coupled global climate cycles (e.g. ENSO) across the Indo-Pacific -> ranges (up to 40 cm) are comparable to multi-decadal scenarios of sea level rise

Long term trends in mean water levels (1992-2018)

MSL rise vs. trend in wave setup

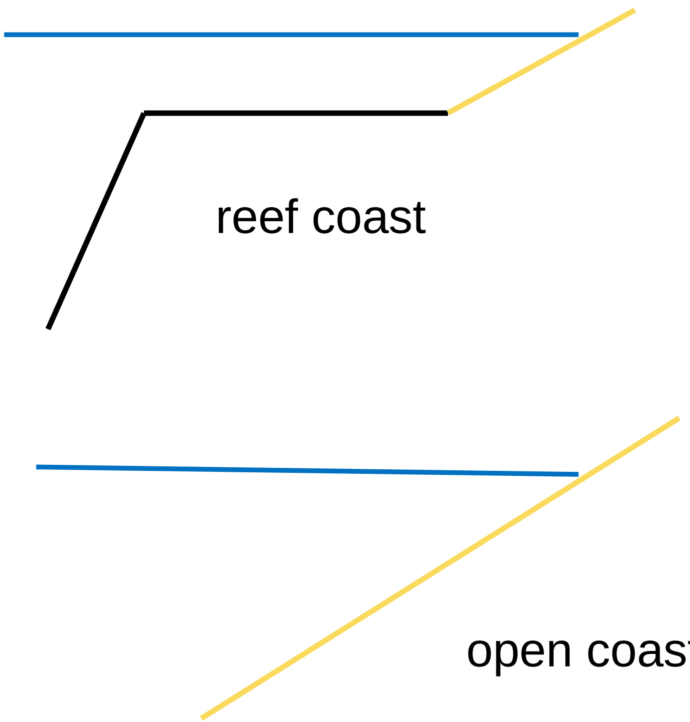


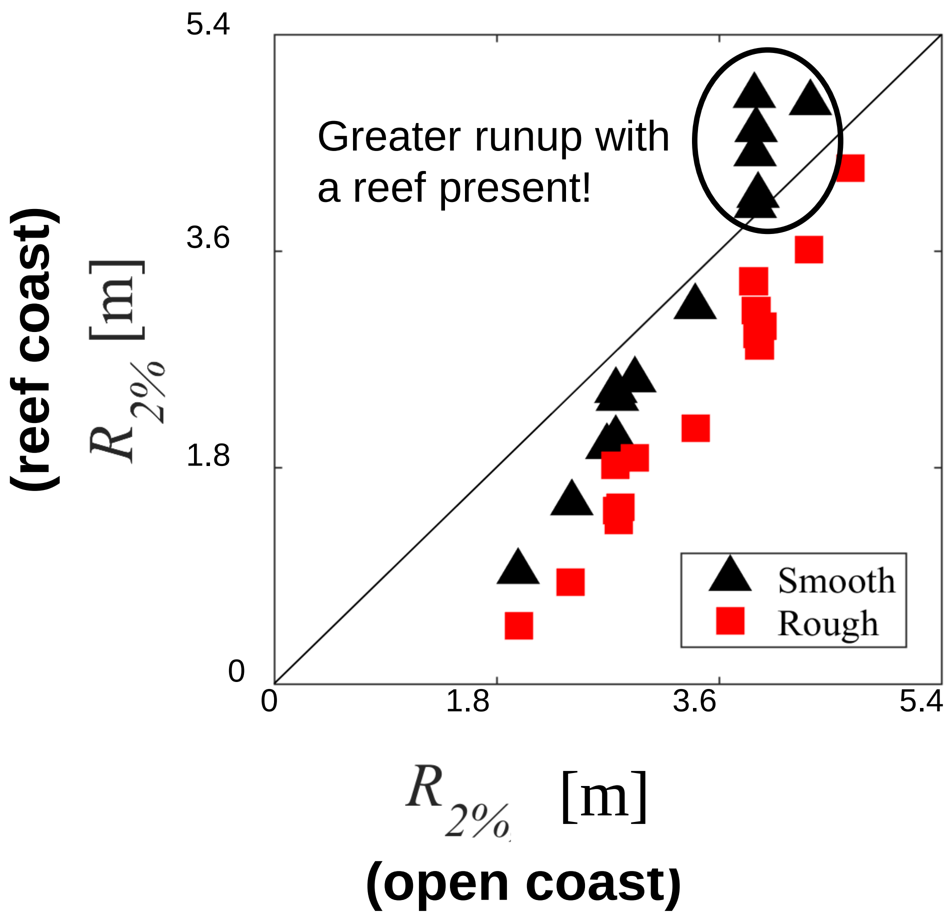
Long-term trends in still water level (1993-2018)



Modification of wave runup by fringing reefs

- Example of $R_{2\%}$ at a 1:12 beach with and without a reef -> note this is for just one particular reef morphology
- Refer to Mark Buckley talk in the afternoon…





Understanding and predicting coastal hazards

- Low-lying reef coastlines are particularly vulnerable to flooding during Extreme Sea Level (ESL) events
- General drivers of coastal flooding and erosion
  - ✓ Variations in **wave conditions** (e.g. seasonal and storms)
  - ✓ Variations in **mean sea level** (over weeks to years)