Wind forcing of past and future regional sea-level trends in the Indo-Pacific

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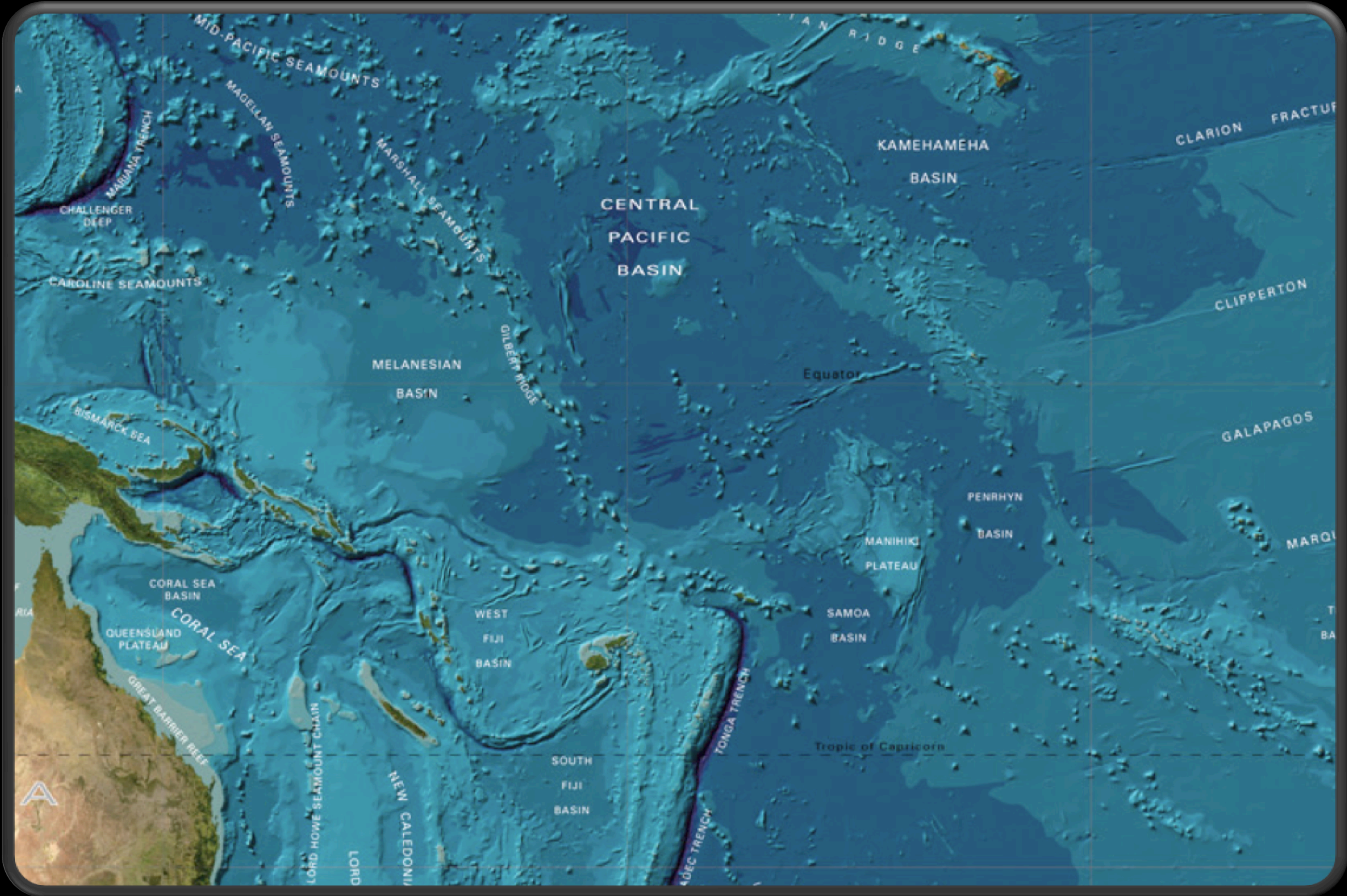
Island Nations

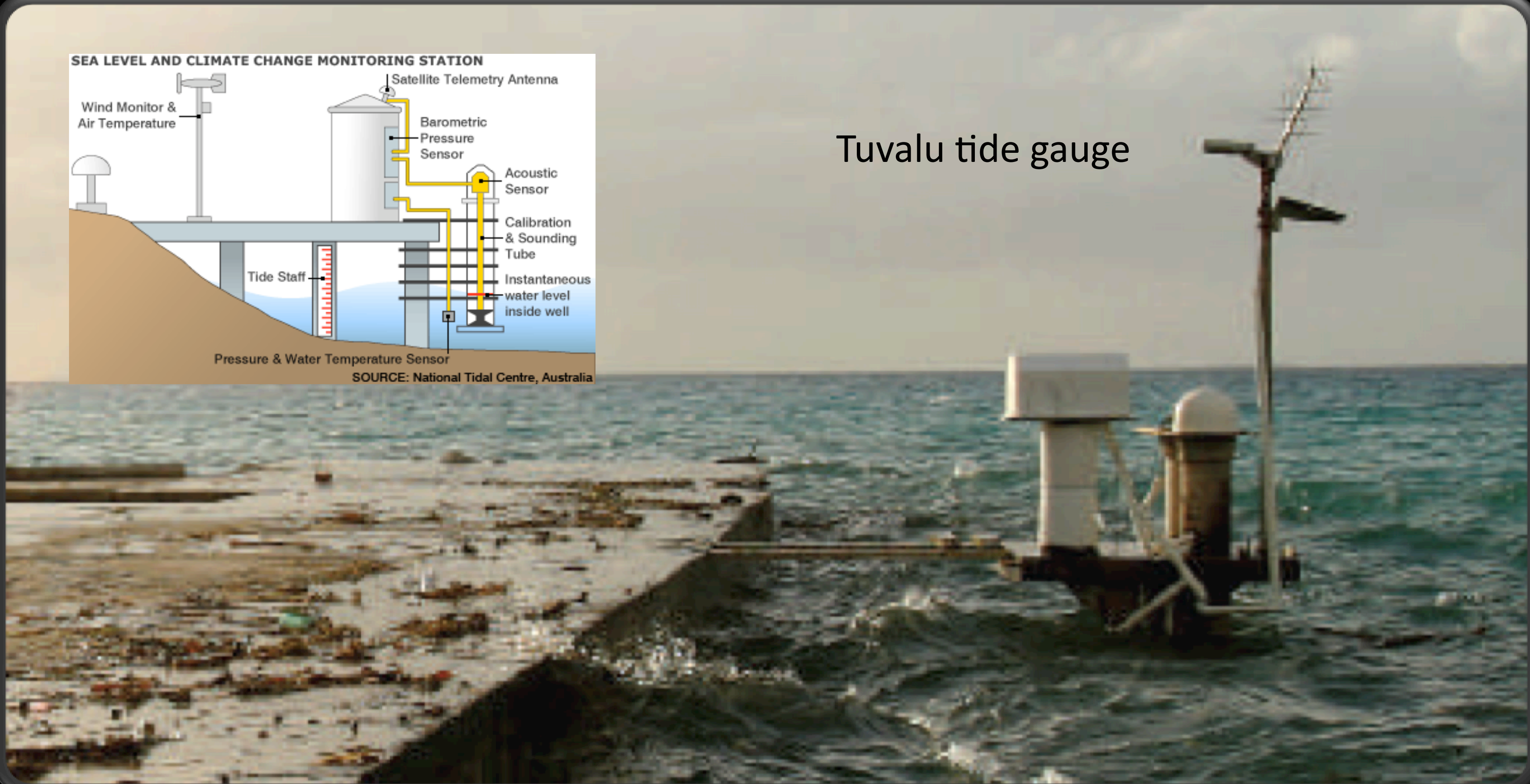
“Sinking Islands”



Tuvalu – the poster child of global warming

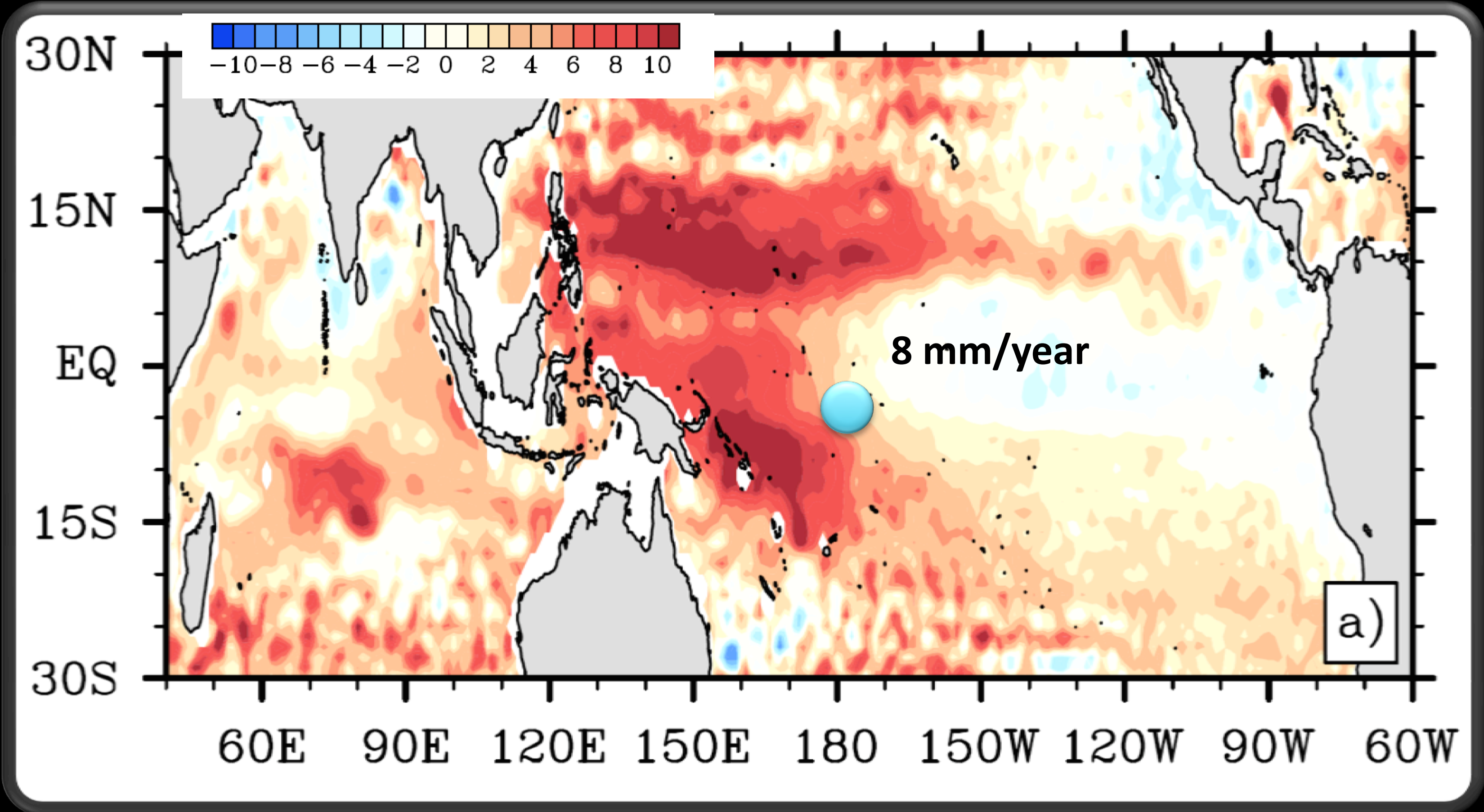
Is it really sinking?

"If corrected for ENSO and tide-gauge sinking, the sea level rise [in Tuvalu] is 1.2 mm/year" (Hunter 2002)

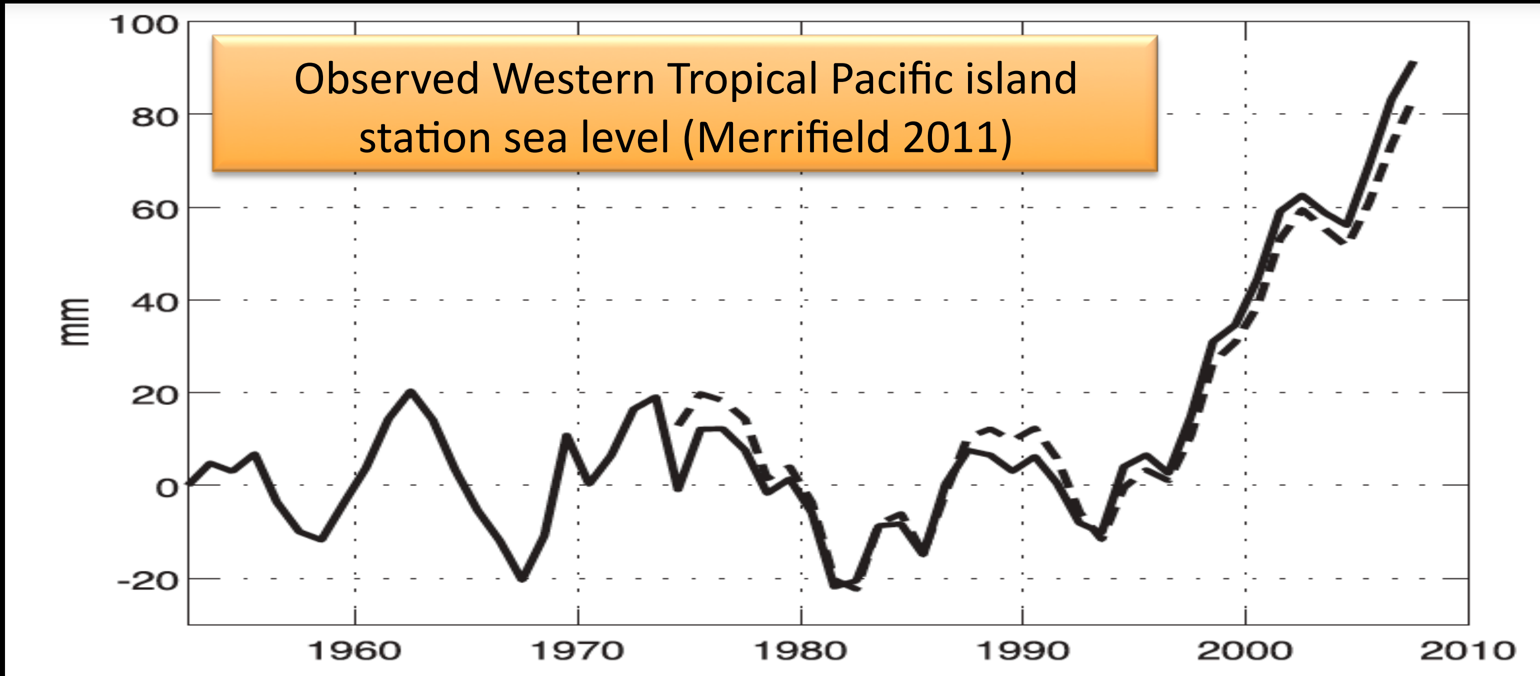


Recent regional sea-level rise

Linear sea surface height trends [mm/year] for the period **1993-2008** in satellite altimeter-data are largely different to the 3mm/year global mean signal (Timmermann et al. 2010). Raises the question: what causes this spatial structure?



Recent WTP sea-level rise



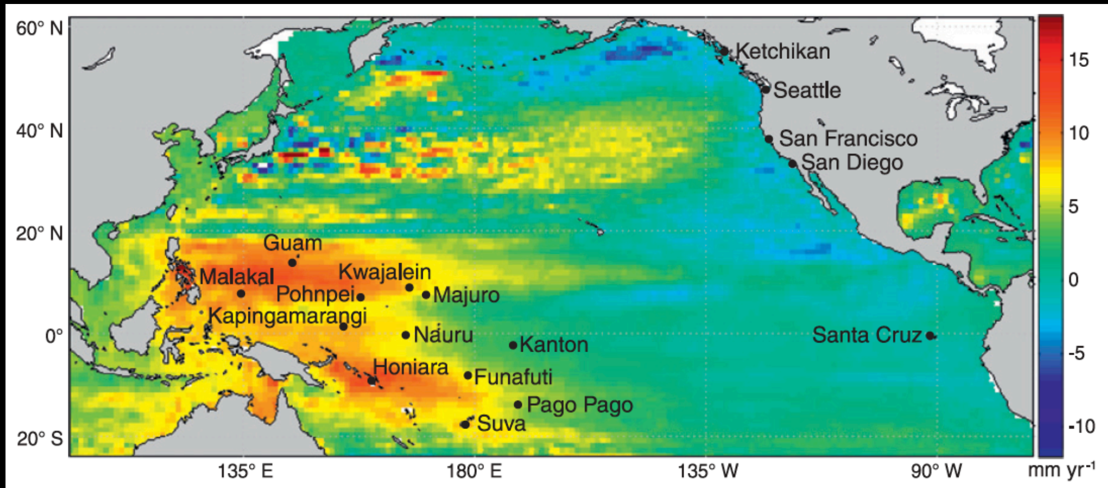
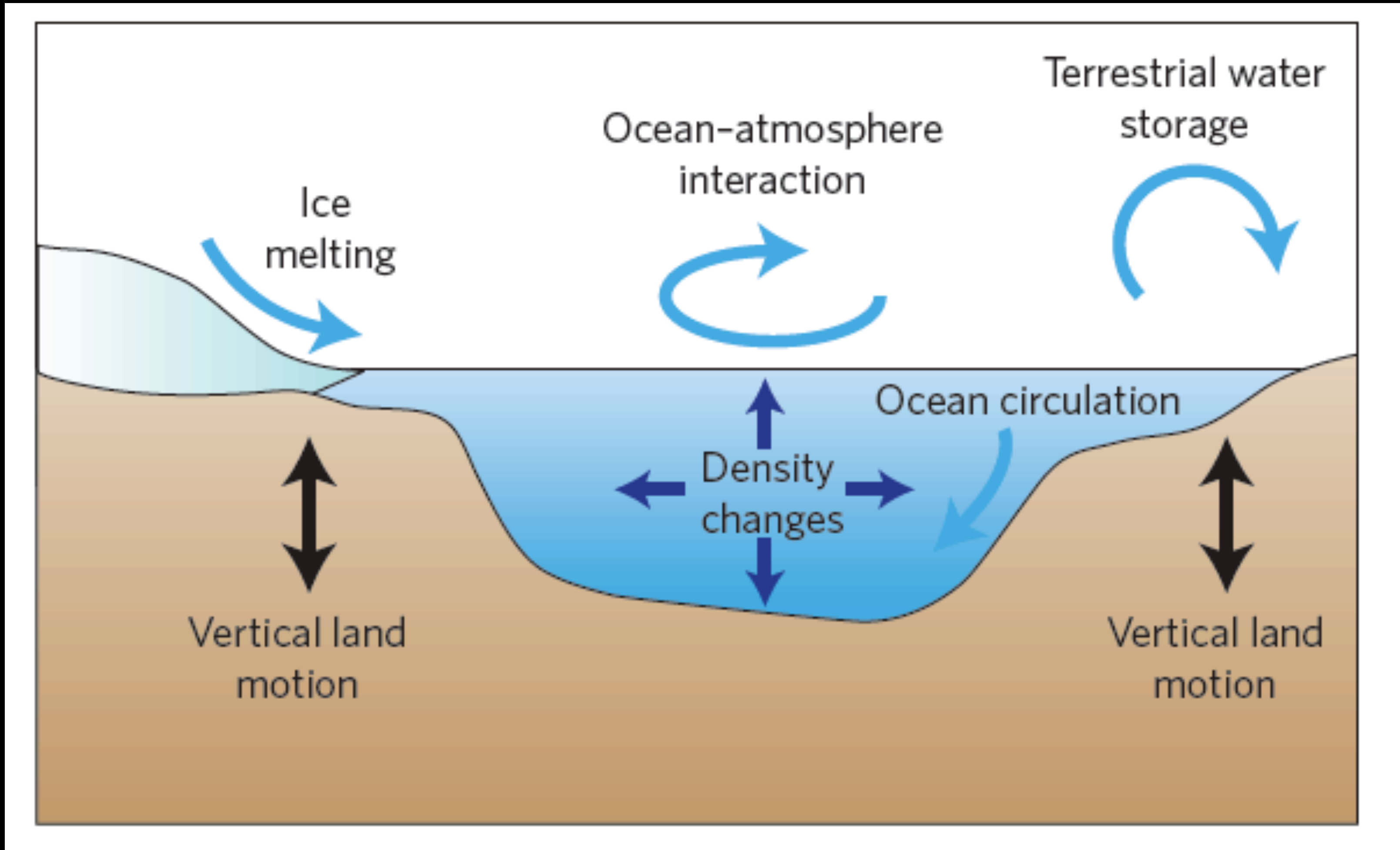


FIG. 3. Map of SSH trends for 1993–2009 with the locations of tide gauge stations.

Factors affecting sea-level rise

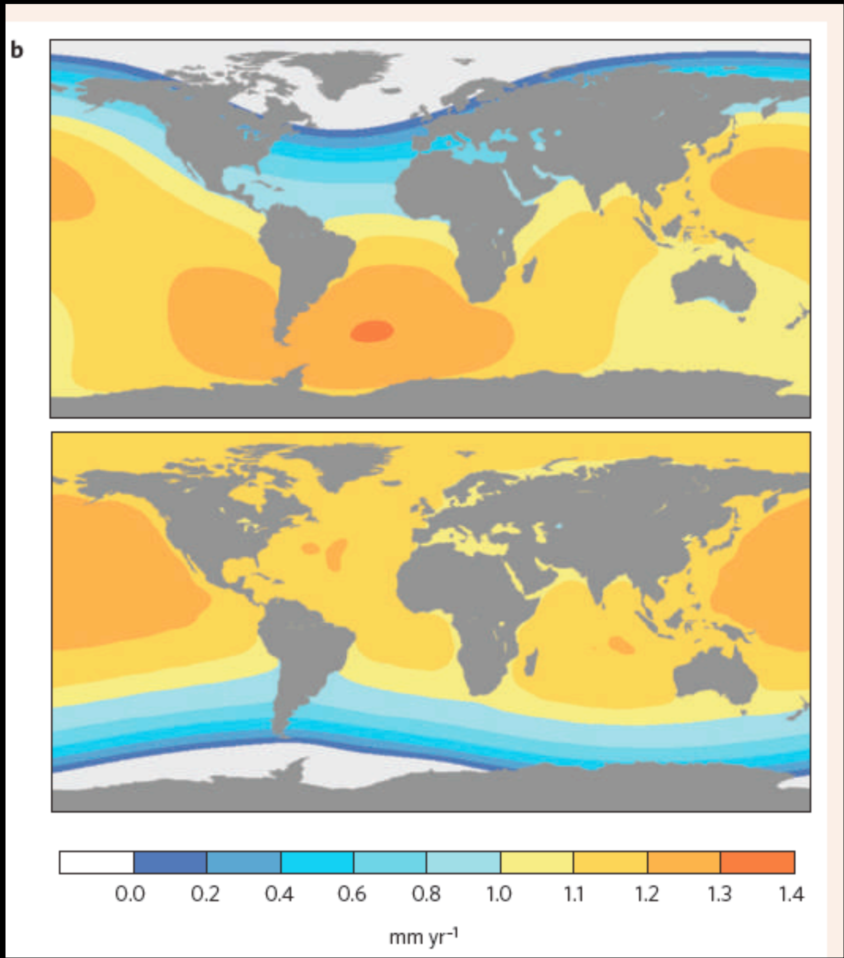


From Milne et al. (2009) Nature Geoscience

Factors affecting sea-level rise

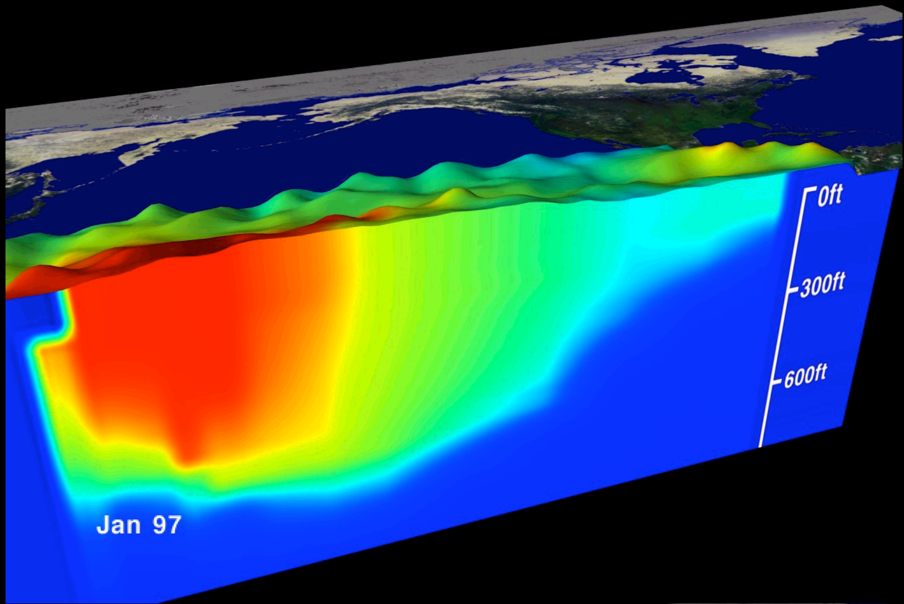
Greenland ice sheet melt (1mm/yr)

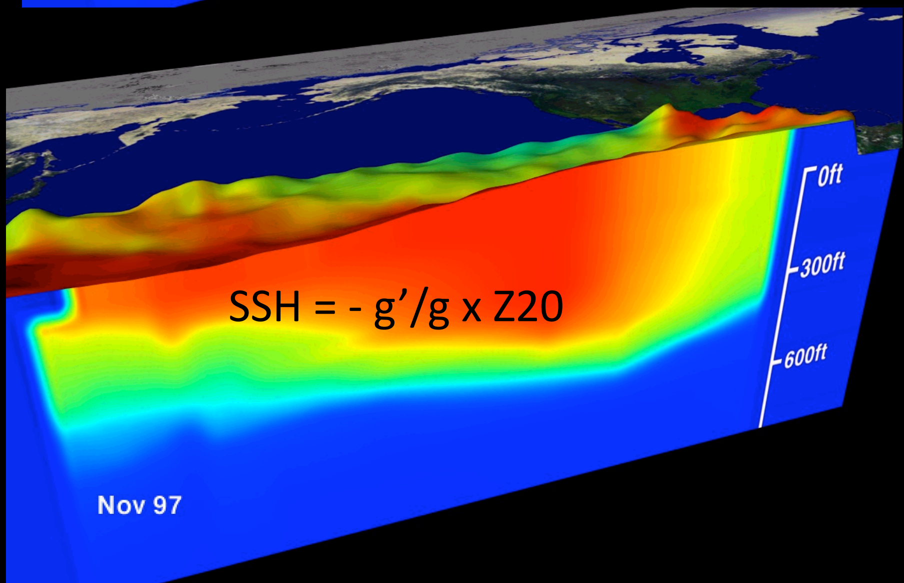
West Antarctic ice sheet melt (1mm/yr)



From Milne et al. (2009) Nature Geoscience

Causes of sea-level change: thermosteric





Equatorial wave dynamics during ENSO

$$\frac{\partial u}{\partial t} - \beta y v = -g' \frac{\partial h}{\partial x} - \epsilon u + \frac{\tau^x}{\rho_0 H}$$

$$\frac{\partial v}{\partial t} + \beta y u = -g' \frac{\partial h}{\partial y} - \epsilon v + \frac{\tau^y}{\rho_0 H}$$

$$\frac{\partial h}{\partial t} + H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = -\epsilon h$$

How much can we explain we simple wind driven ocean dynamics?

Causes of sea-level change: winds

$$\frac{\partial h}{\partial t} - c_R \frac{\partial h}{\partial x} = -\frac{g' \operatorname{curl} \boldsymbol{\tau}}{\rho_o g f} - \varepsilon h,$$

Linear vorticity equation under long-wave approximation

$$h_I(x, y, t) = \frac{g'}{\rho_o g f c_R} \int_{x_e}^{x} \operatorname{curl} \boldsymbol{\tau}\left(x', y, t + \frac{x - x'}{c_R}\right) \times \exp\left[\frac{\varepsilon_I}{c_R}(x - x')\right] dx'.$$

Rossby wave dynamics; long-wave approximation

Thermocline dynamics

Calculation of thermocline depth (h) involves Rossby wave speed (c_R), stratification (g'), wind stress curl, and integration from eastern boundary

SSH = - g'/g h

Relating thermocline dynamics with SSH

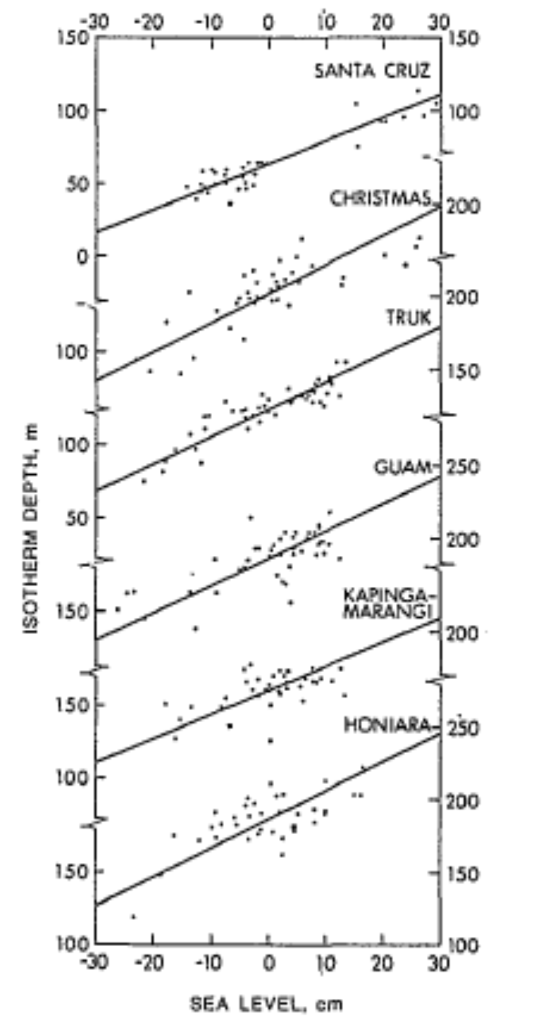


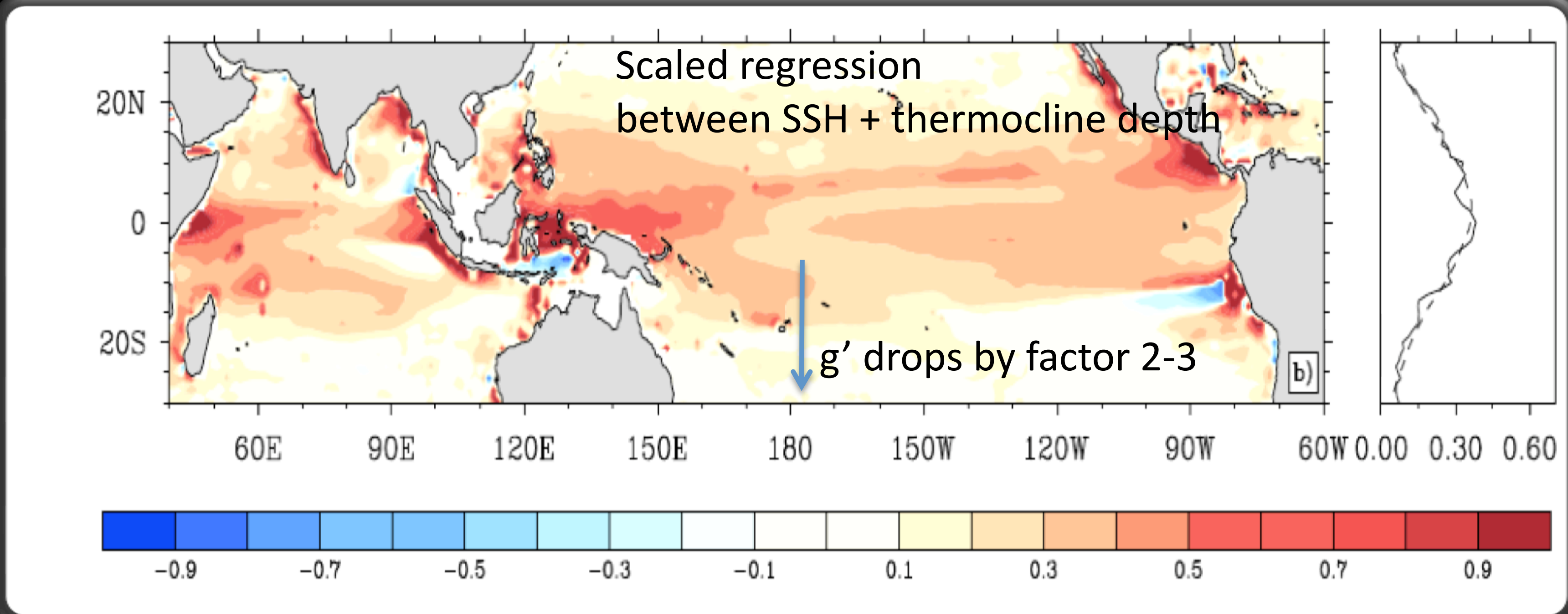
Fig. 3. Relations between monthly means of the depth (m) of the 20°C isotherm and sea level (cm) near six islands in the tropical Pacific.

			Sea Level vs. 20°C Isotherm		
Station	ϕ	n	r	a	$\bar{D}$
Santa Cruz	0	34	0.93	160	64
Truk	7°N	48	0.90	190	125
Christmas	2°N	39	0.80	200	140
Guam	14°N	43	0.73	190	186
Honiara	9°S	40	0.69	200	186
Kapingamarangi	1°N	37	0.56	170	160
Noumea	22°S	29	0.32	350	194
Suva	18°S	34	0.30	300	220
Papeete	18°S	37	0.39	380	232
Honolulu	21°N	132	0.41	220	156

Source: Rebert et al. 1985

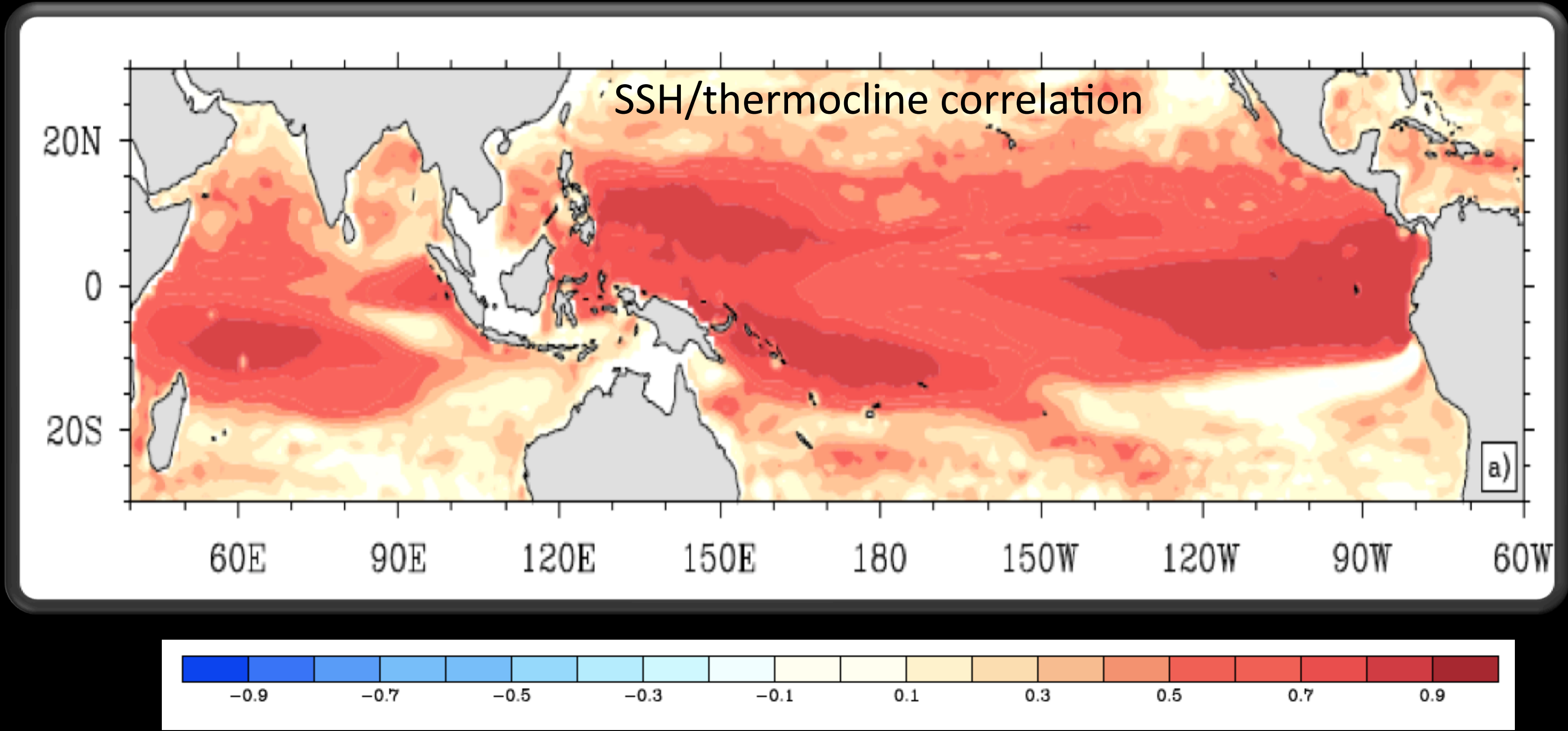
$$SSH = -\,g'/g\;\; Z20$$

Relating thermocline dynamics with SSH



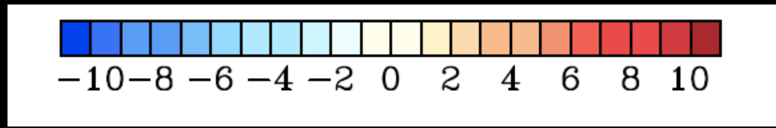
Average scaled regression map between thermocline and sea-level anomalies. The average was obtained from various regression fields that were obtained by **regressing simulated thermocline and simulated sea-level anomalies in the ORA-S3 OGCM reanalysis product, the eddy-resolving OfES model hindcast** and by regressing the **observed sea-level data (AVISO) with the SWM results forced by the ERA40 and NCEP wind-stress data**.

Relating thermocline dynamics with SSH

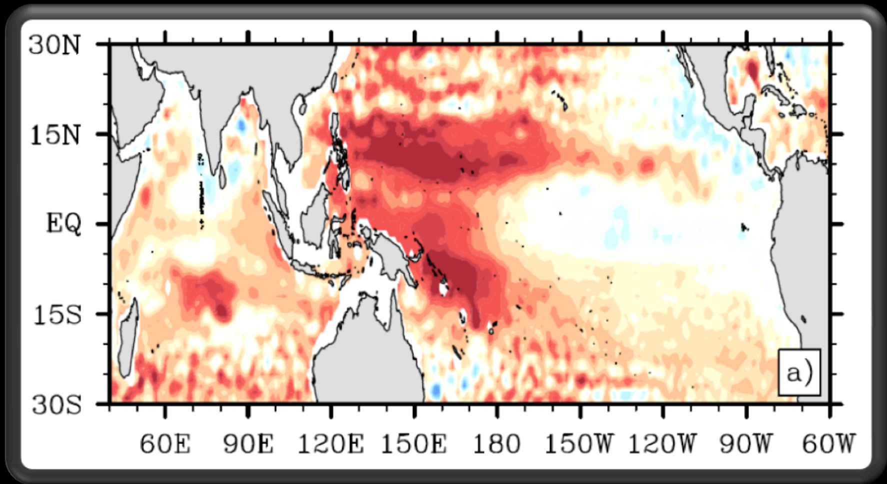


Correlation between observed (detrended) sea-level anomalies for the period 1993-2008 (AVISO) and the model results that were obtained by forcing the shallow water model with the historical wind-stress data for this period obtained from different wind-stress products

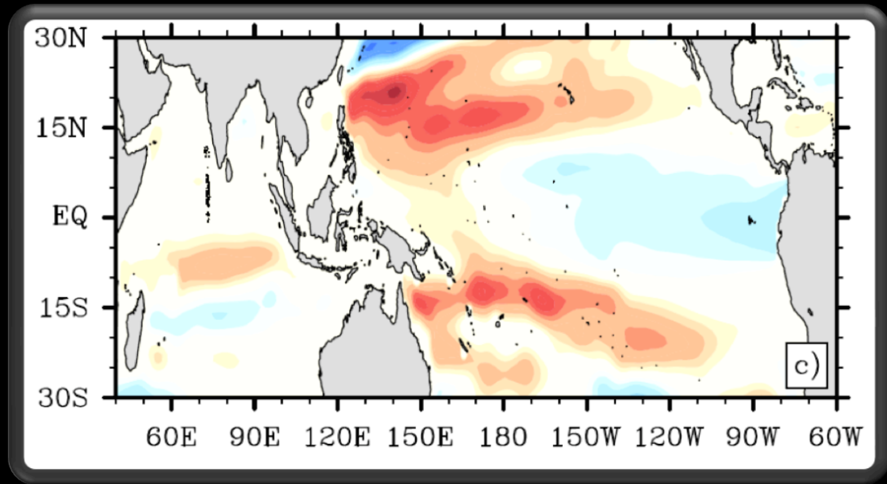
Explaining recent regional sea level trends: 1993-2008



mm/year



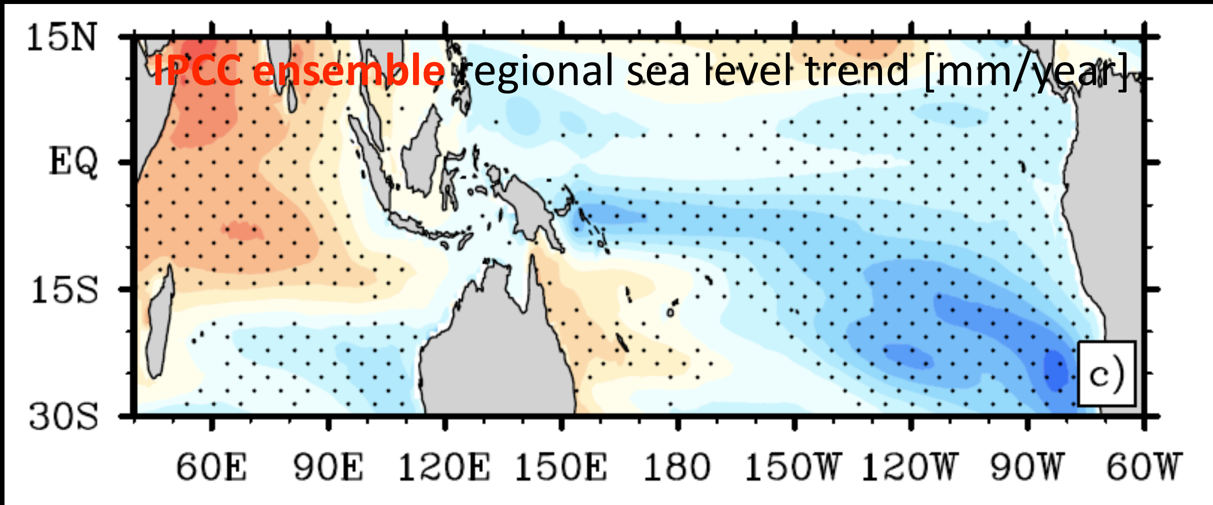
AVISO satellite data : linear trend of SSH



Linear SWM in Cartesian coordinates forced with ECMWF analysis winds

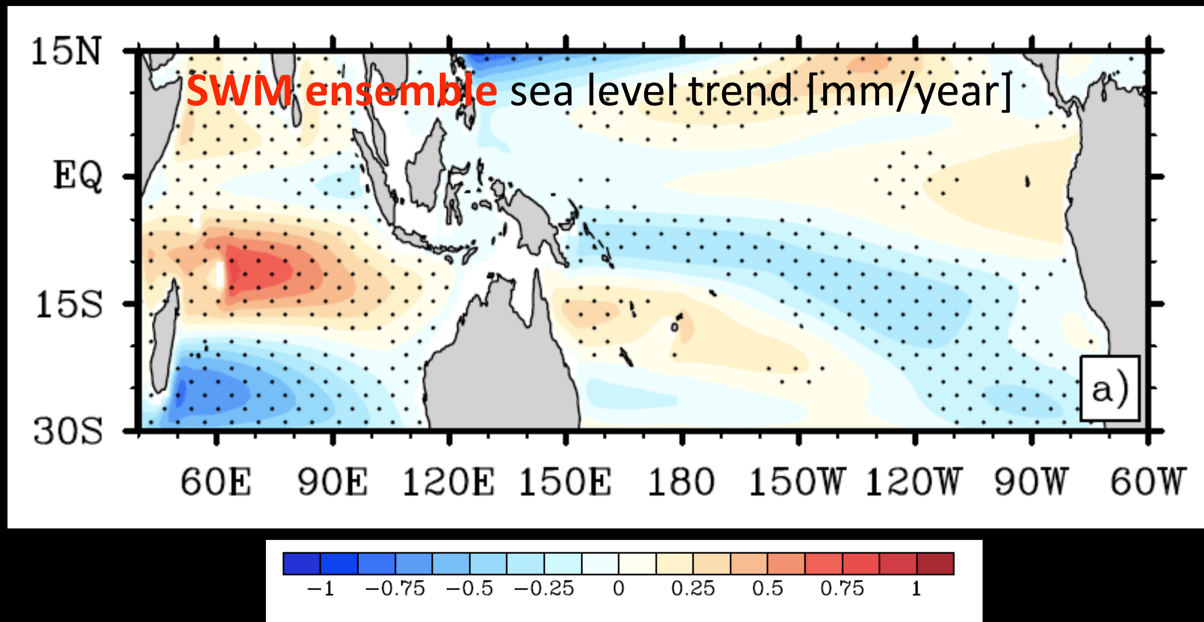
Linear wind-forced SWM reproduces major trend patterns in Indo-Pacific, including Sea-level rise near Philippines and east of PNG

Projected regional sea-level trends: A1B

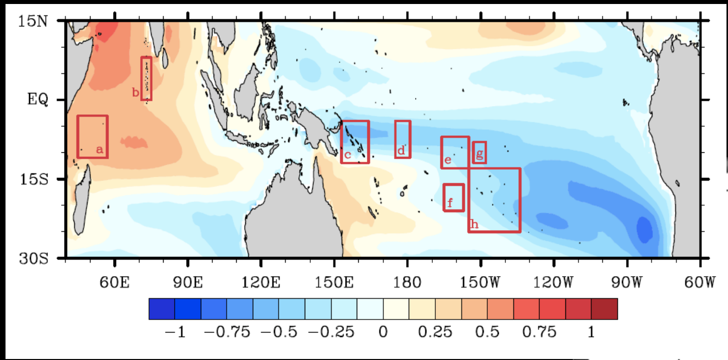


Simulated future sea-level trends (Indo-Pacific spatial average between 30°S-30°N subtracted) obtained from the **multi-model ensemble mean of 10 CGCMs** that were forced from 2001-2100 with the greenhouse gas emission scenarios A1B

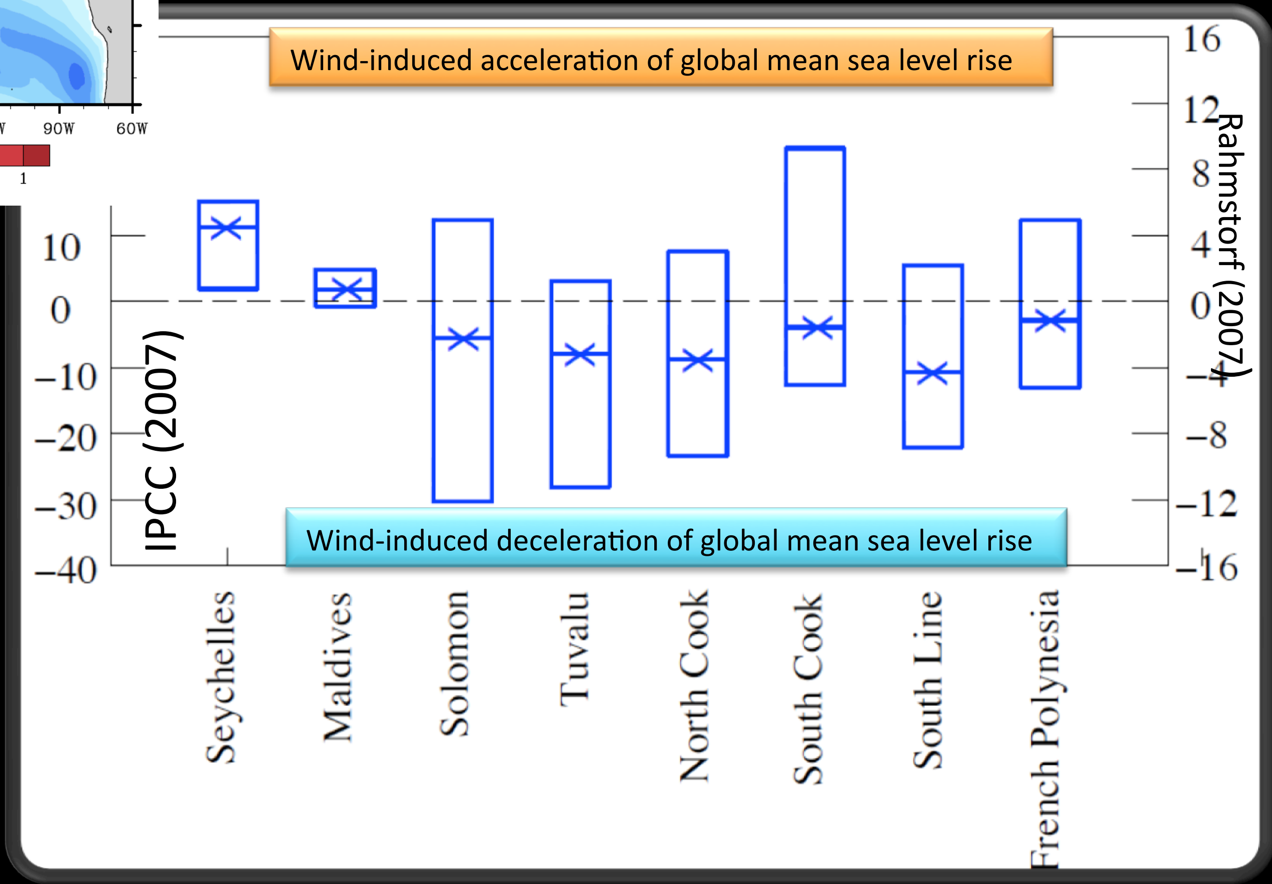
Simulated future sea-level trends [mm/year] derived from the **ensemble mean of 14 shallow water model simulations** that were forced for 100 years with the wind-stress trends obtained from a 14-member ensemble of CGCM A1B greenhouse warming experiments



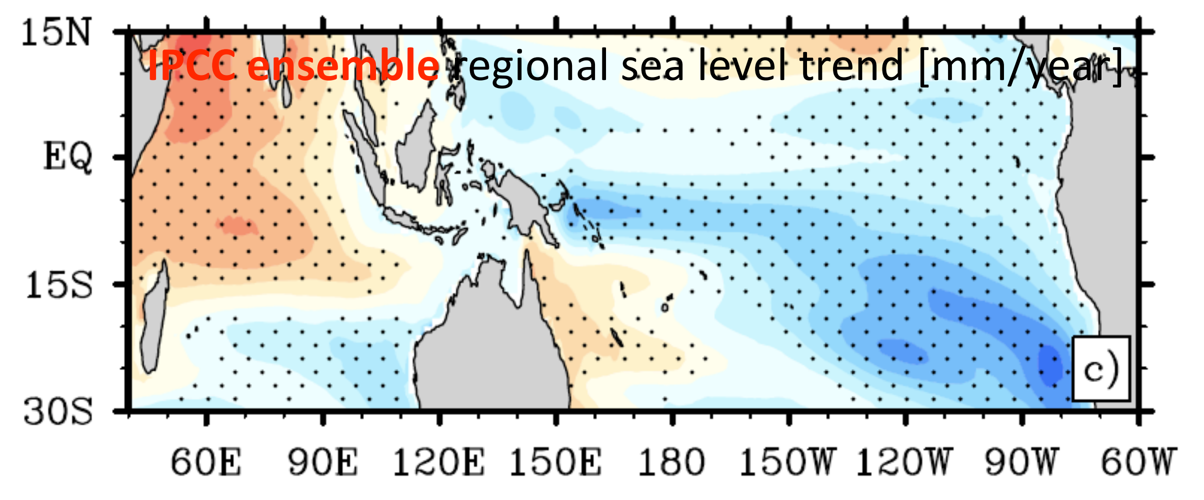
Regional % deviations relative to global mean sea rise (2001-2100)



10% means delay by
1 decade per century



Causes of projected sea level trends: A1B



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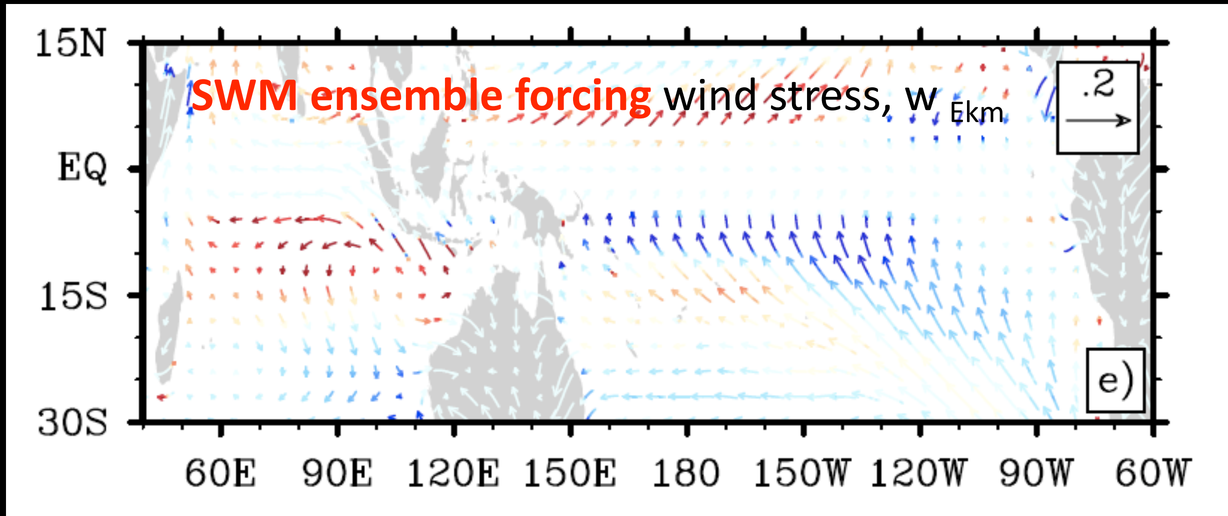
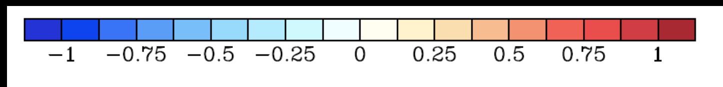
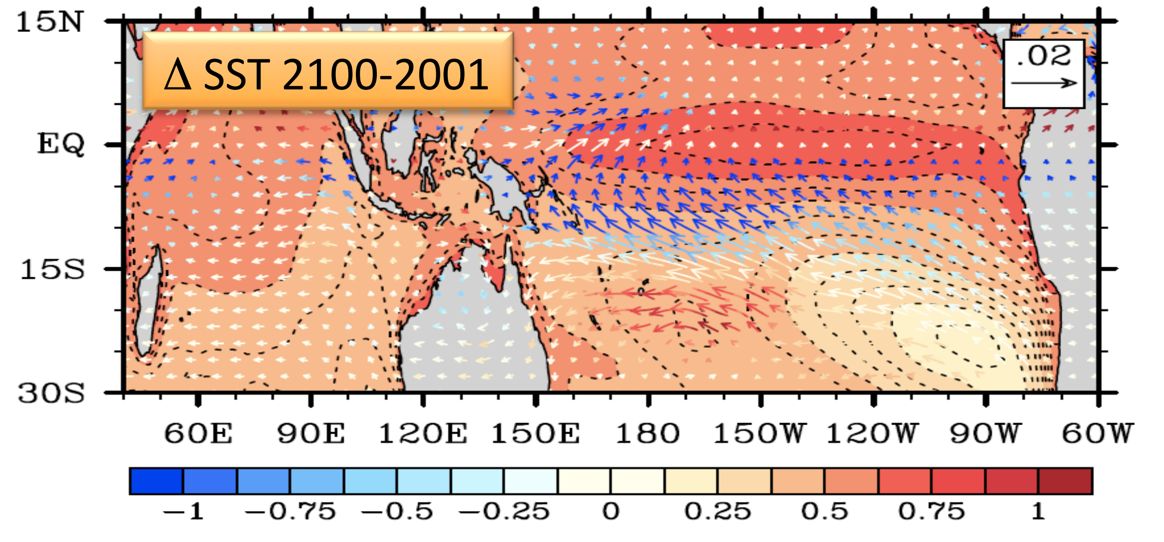
Simulated future wind stress and Ekman velocity obtained from a 14-member ensemble of CGCM A1B greenhouse warming experiments





Causes of Southeasterly Wind-Intensification



$$-\beta y V = -\frac{\partial \Theta}{\partial x} - \varepsilon_a U$$

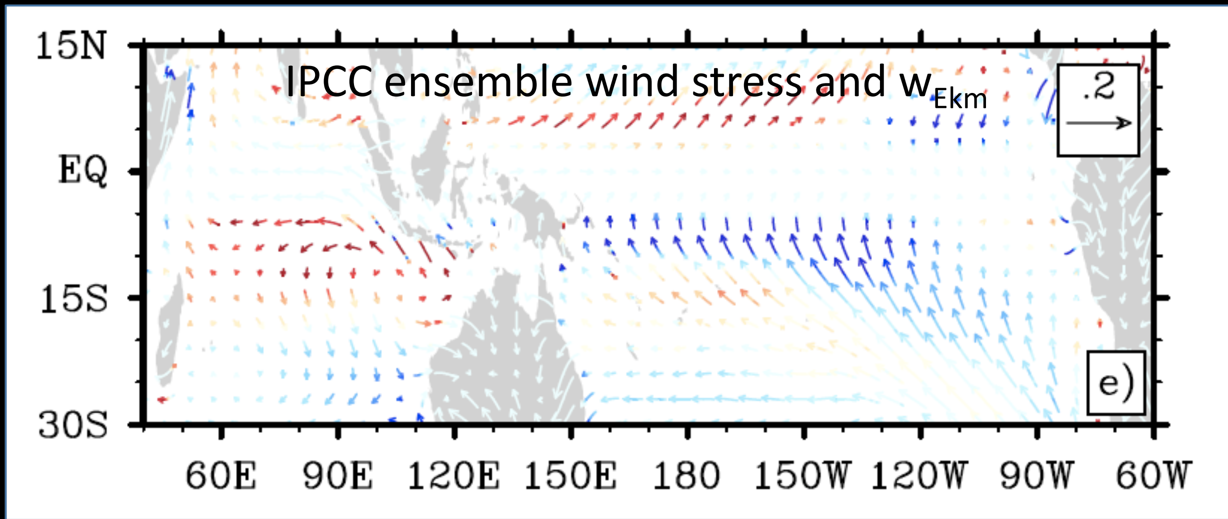
$$+\beta y U = -\frac{\partial \Theta}{\partial y} - \varepsilon_a V$$

$$c_a^2\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right) = -\varepsilon_a \Theta + Q \ ,$$

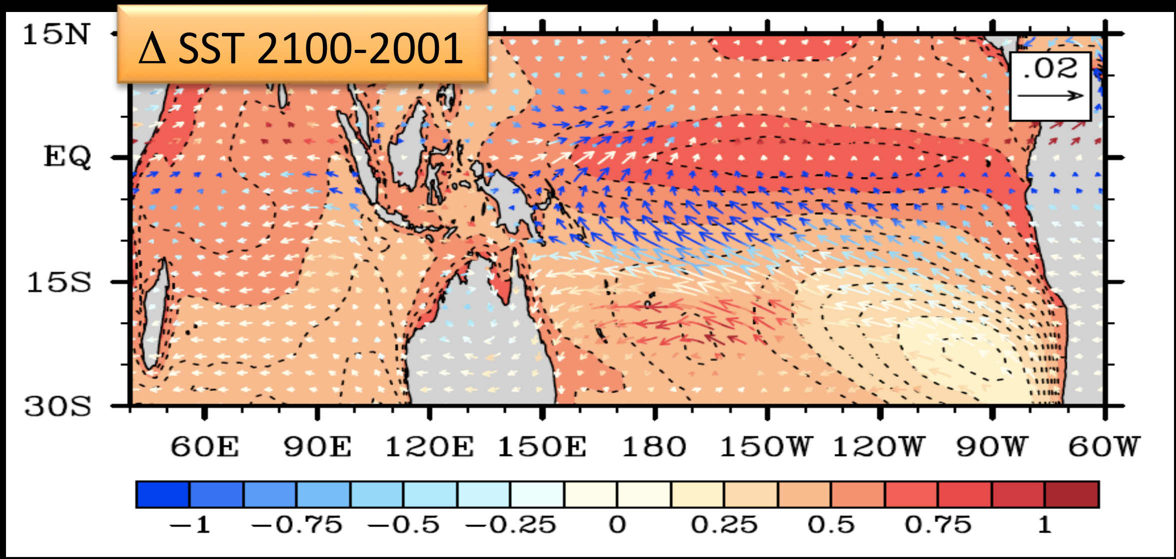
SST response to CO_2 is Characterized by enhanced Equatorial warming

⇒Convergence of trades towards equator

⇒Ekman suction in South-Western Pacific



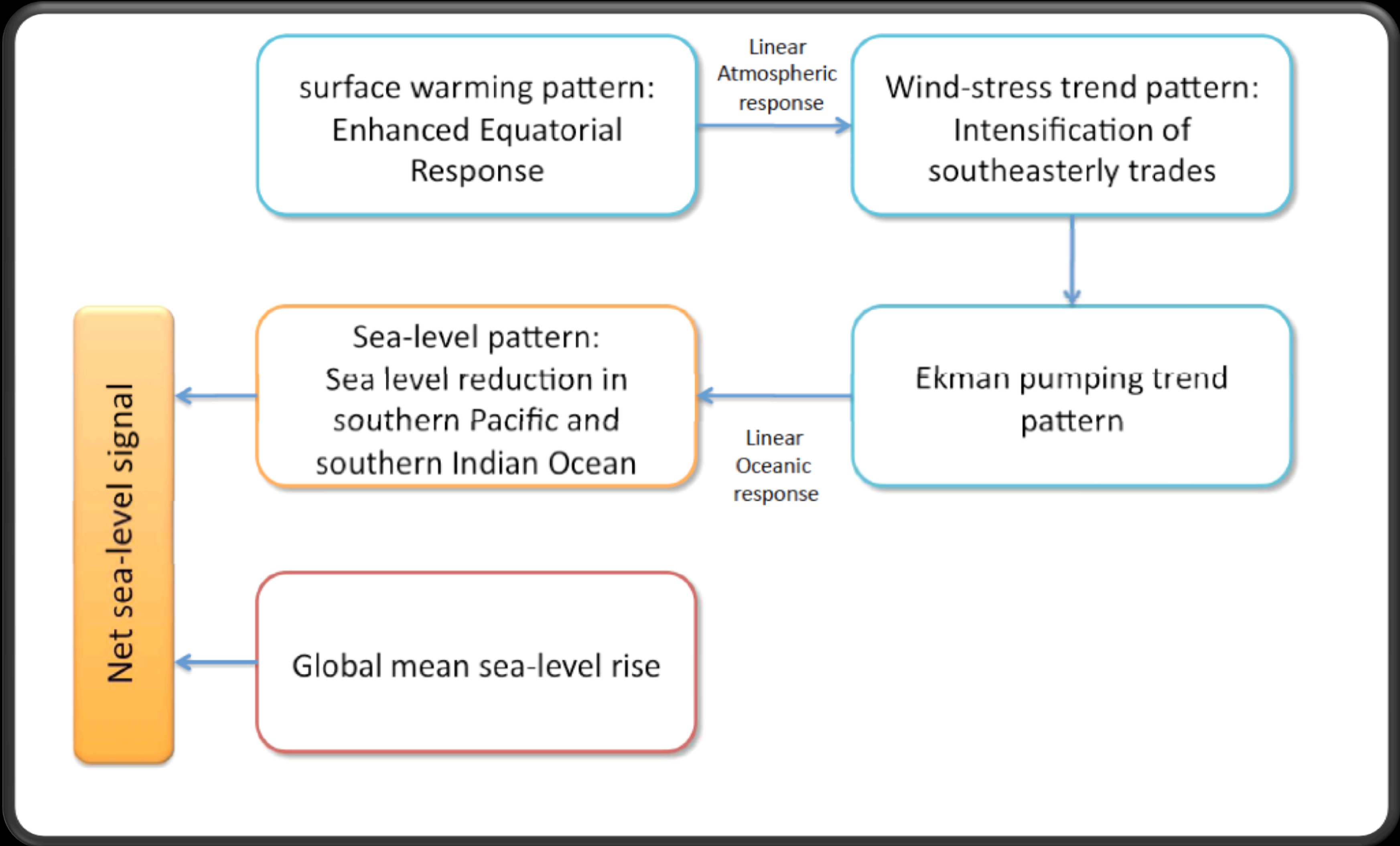
Causes of enhanced equatorial warming



Maximum SST warming results from a reduction of the Newtonian cooling on the equator. This reduced equatorial Newtonian cooling is set by the mean evaporation, which is determined by SST, wind speed and relative humidity.

Furthermore, there is increased latent cooling, due to higher climatological mean winds in off-equatorial regions.

Causes of regional sea-level change



Summary

- Recent regional sea-level trends in Indo-Pacific are largely wind-driven
- There is a robust regional sea-level response pattern to CO_2 doubling which emerges as a response to SST-induced changes in wind-stress curl (Ekman pumping).
- Wind-induced sea-level changes can delay sea-level rise in some regions in the Southwestern Pacific by up to several decades

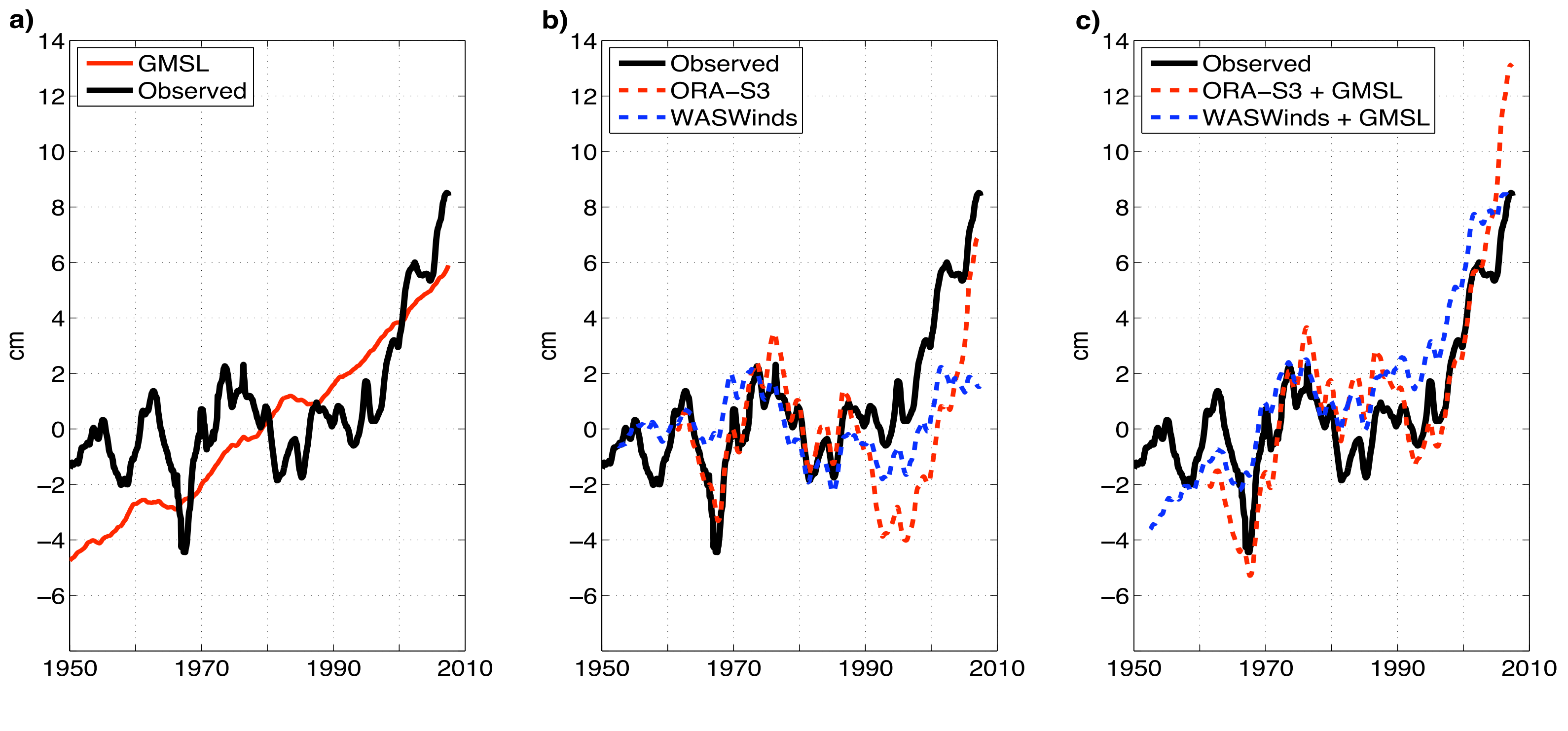
Revisions to IPCC needed

- "The lack of similarity [in the model projected patterns of sea-level rise] means that our confidence in predictions of local sea-level changes is low" (TAR 2001)
- "…large deviations among models make estimates of distributions across the Caribbean, Indian and Pacific Oceans uncertain" (AR4)

Explaining recent WTP sea level trends

Wind stress forced SWM goes a long way to explaining the regional patterns of sea level rise. But, what role does it play in the recent dramatic increase in the total SSH of the WTP?

The addition of the GMSL signal to the wind stress forced SSH of the the WTP acts to reduce the RMSE by 20-30%, making the reproduced signal more accurate (McGregor et al. 2011, submitted to JClim).



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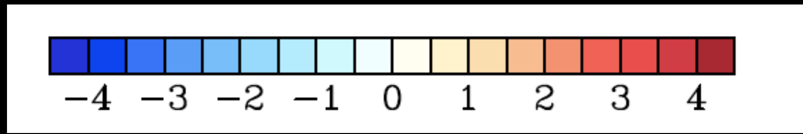
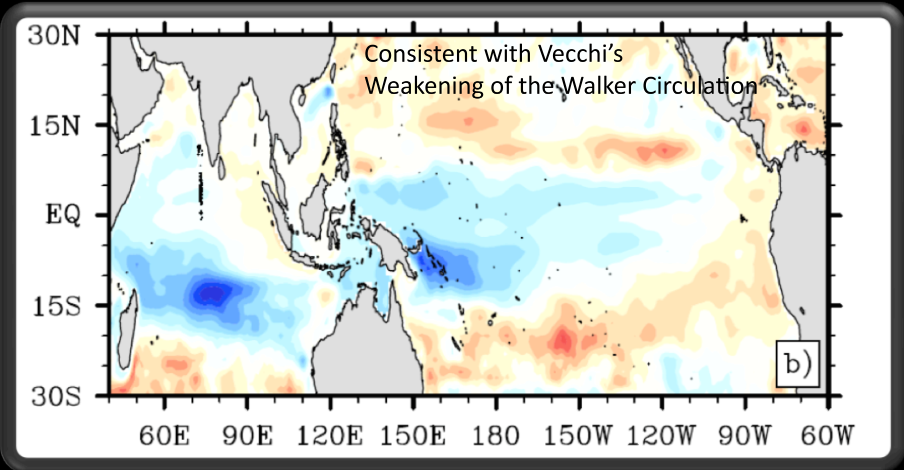
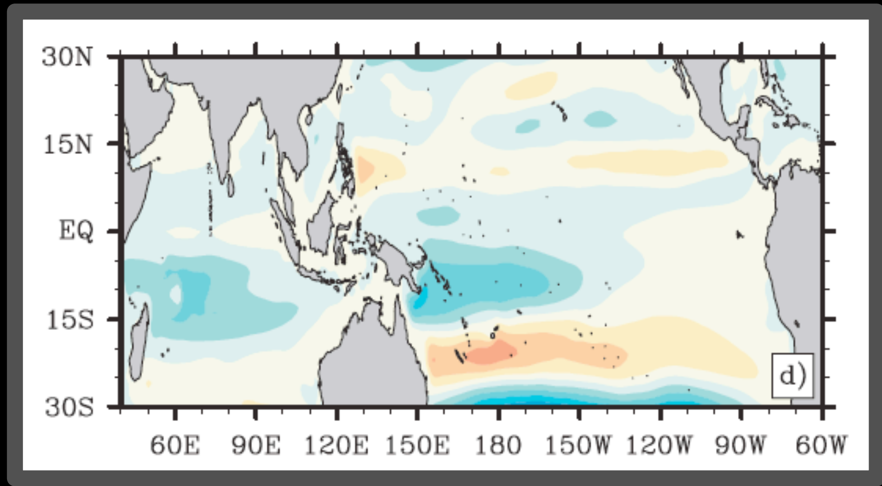
Explaining recent regional sea level trends: 1958-2003



mm/year



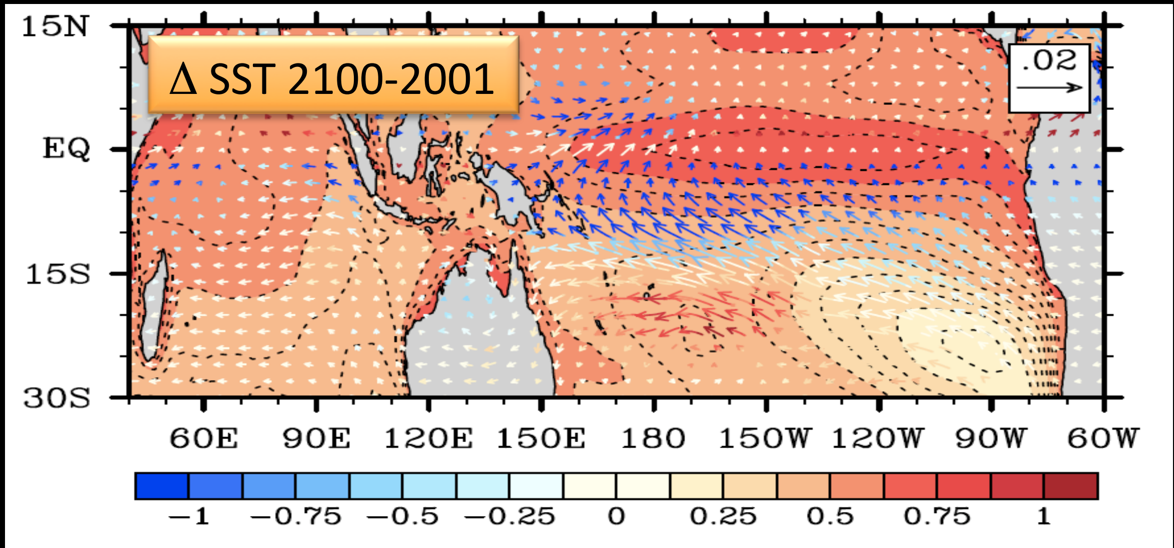


SODA-POP (forced with ERA-40 wind stresses): linear trend of SSH

Linear SWM in Cartesian coordinates forced with ERA40 wind stress

Linear wind-forced SWM reproduces major trend patterns in Indo-Pacific, including Sea-level rise near Philippines and east of PNG

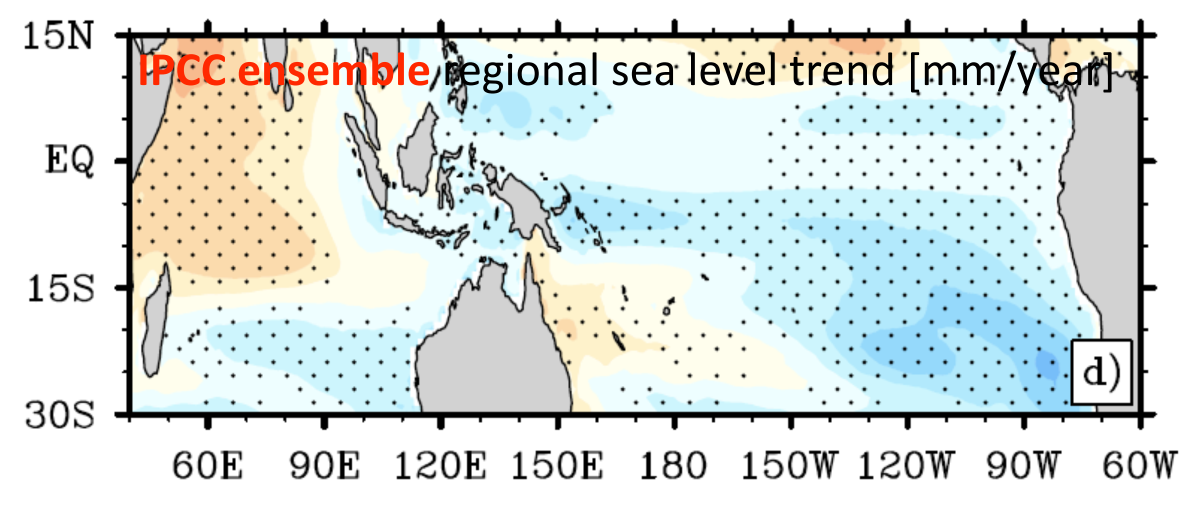
Causes of enhanced equatorial warming



This is **NOT an El Nino-like** warming pattern,
The underlying physics are totally different (Xie et al. 2010)

Maximum SST warming results from a reduction of the Newtonian cooling on the equator. This reduced equatorial Newtonian cooling is set by the mean evaporation, which is determined by SST, wind speed and relative humidity. Furthermore, there is increased latent cooling, due to higher climatological mean winds in off-equatorial regions and CO_2-induced changes in the sea-air specific humidity gradient and increased low-level clouds, due to an increased atmospheric static stability.

Projected regional sea-level trends: B1



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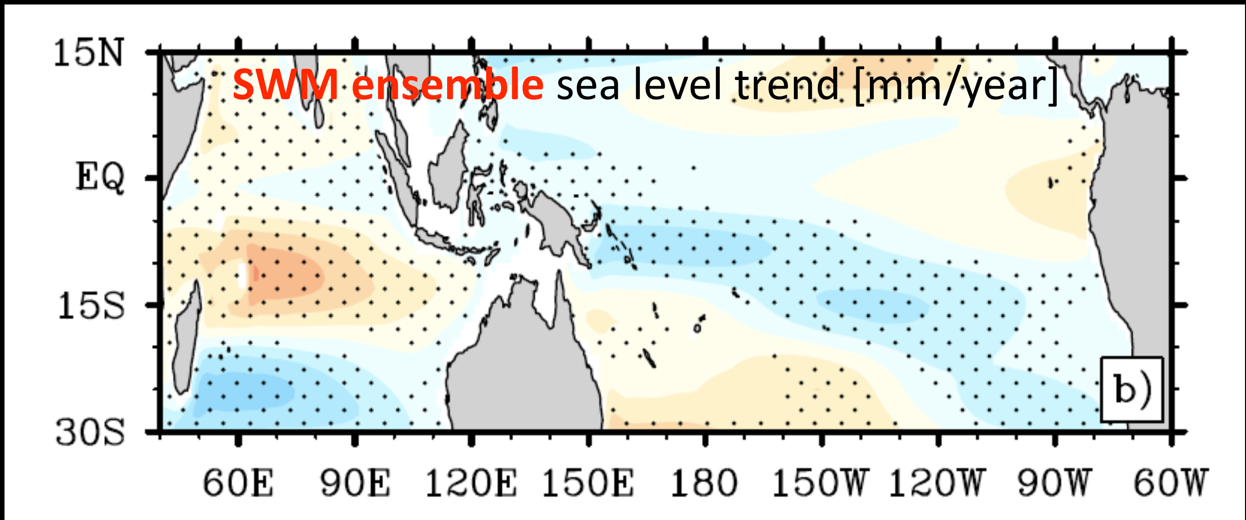
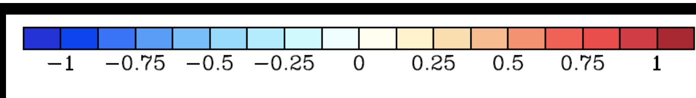
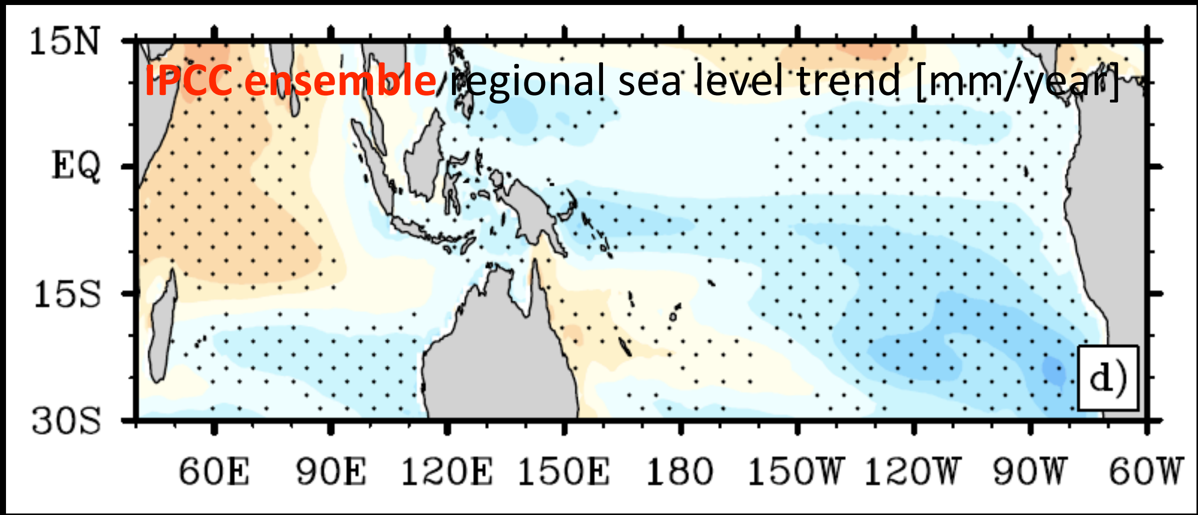
Simulated future sea-level trends [mm/year] derived from the ensemble mean of 14 shallow water model simulations that were forced for 100 years with the wind-stress trends obtained from a 14-member ensemble of CGCM B1 greenhouse warming experiments





Causes of projected sea-level trends: B1



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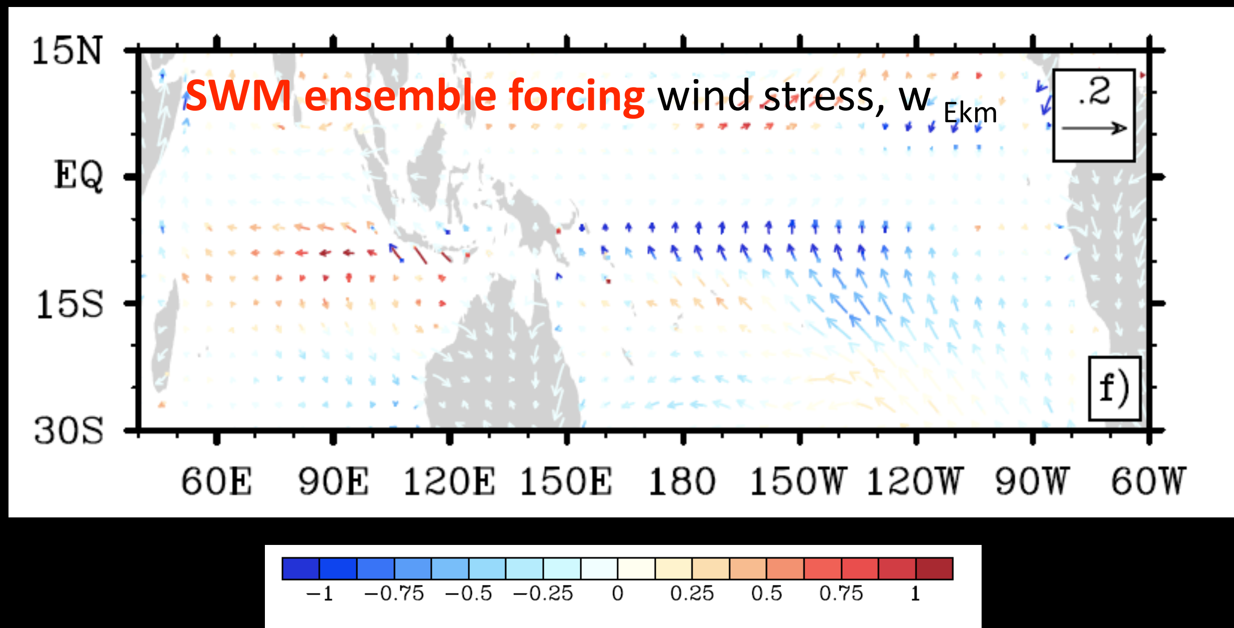
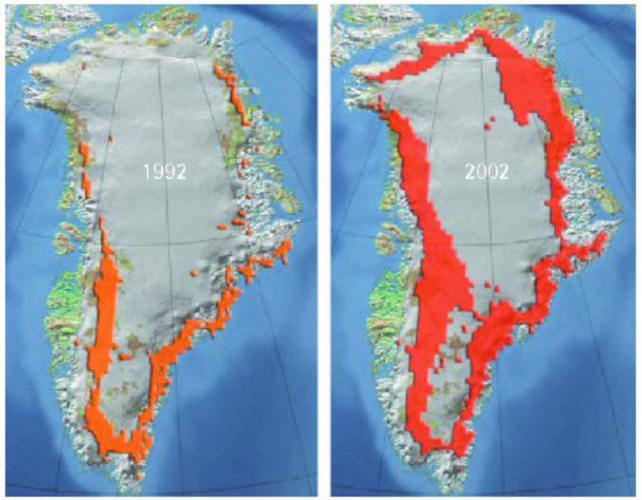


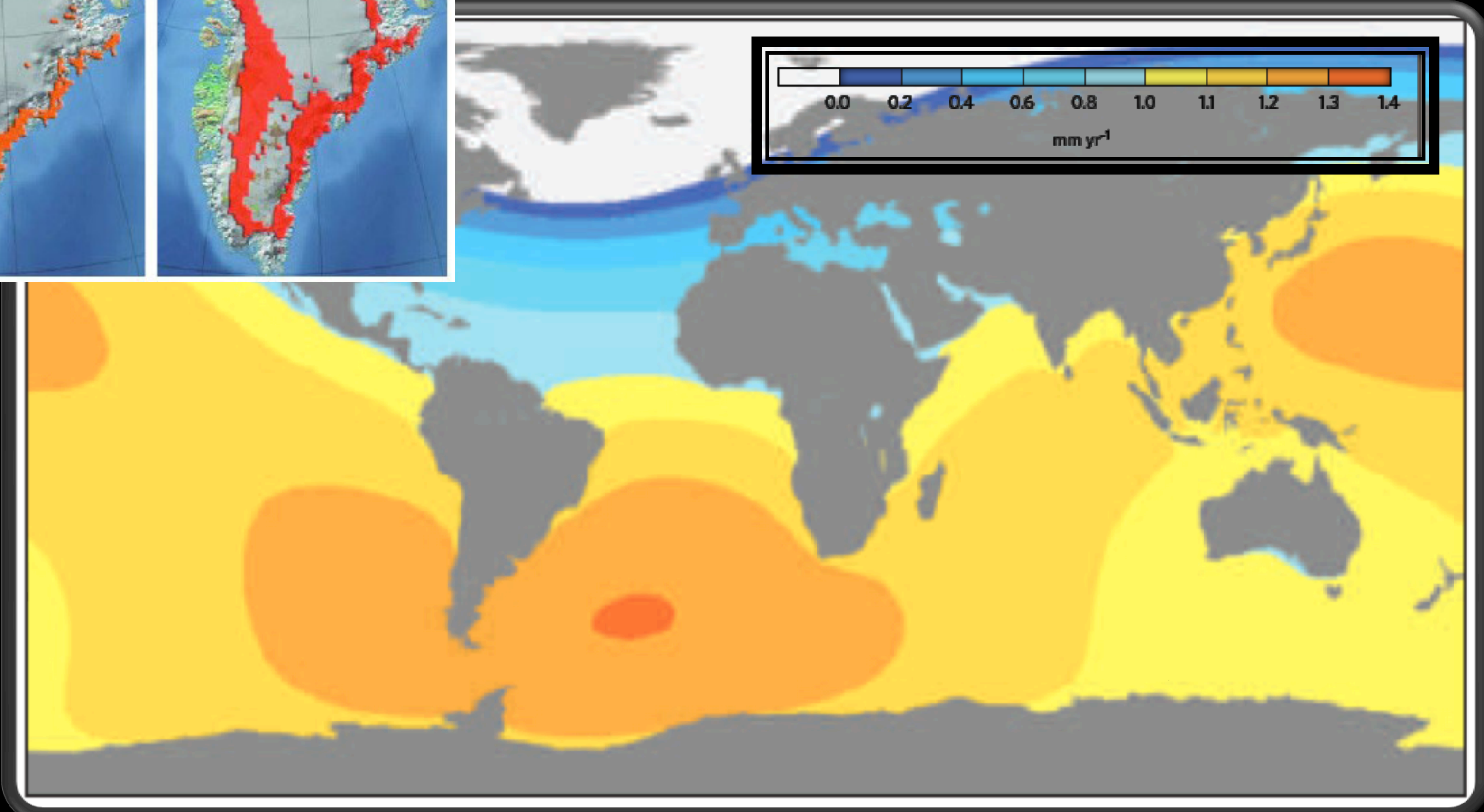
Further research needed

- Future changes in tropical cyclone statistics
- Future changes in ENSO character
- Future changes in wave heights
- Future changes in oceanic eddy statistics
- Assessing the combination of tides, eddies, interannual and anthropogenic sea level change

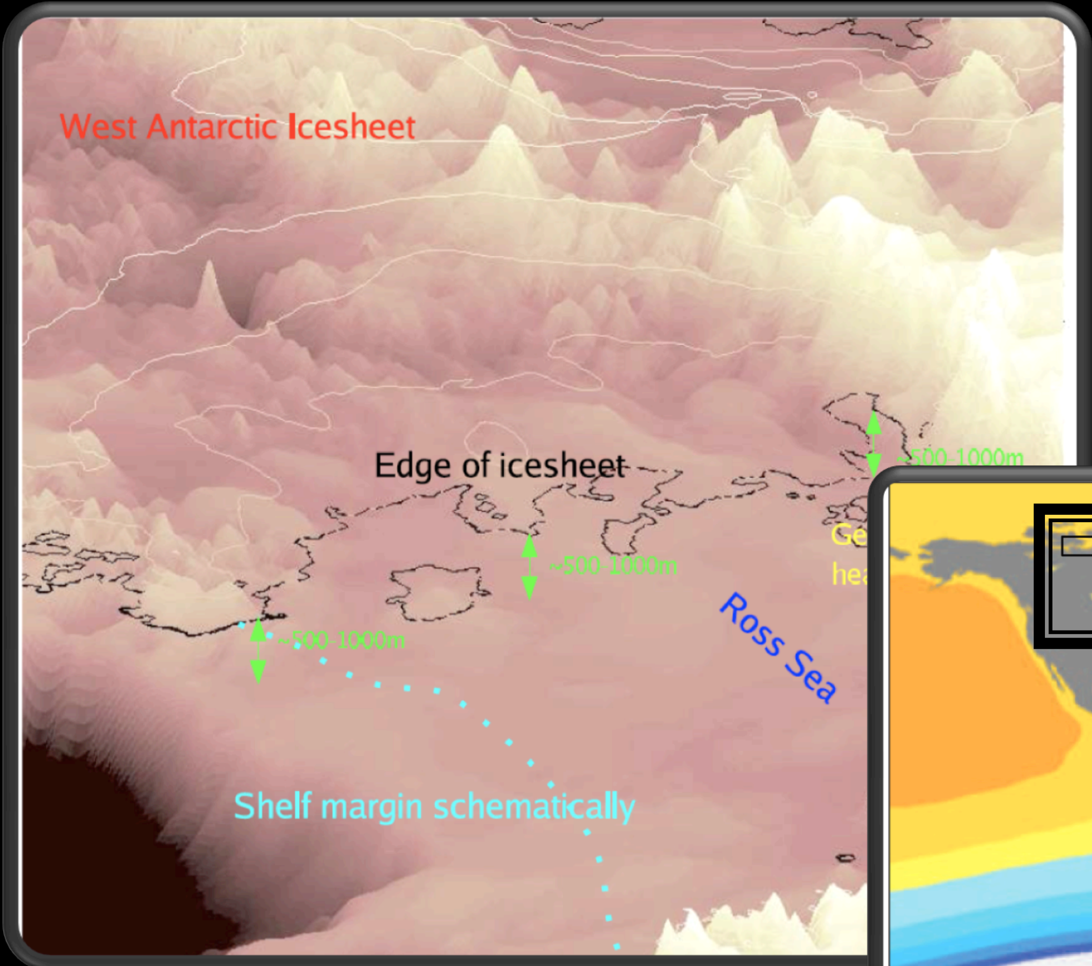
Causes of sea-level change: melting of glaciers and ice-sheets



Melting of Greenland ice-sheet margins during summer
Sea level pattern for 1mm/year
Greenland melting (Milne et al 2009)

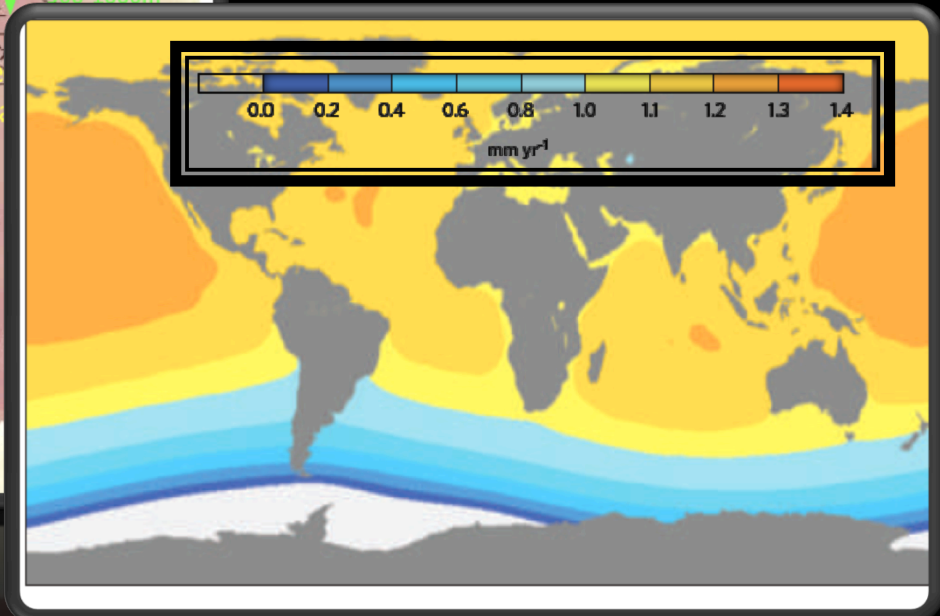


Causes of sea-level change: melting of glaciers and ice-sheets



West Antarctic ice-sheet sensitive to subsurface ocean warming

Isostatic effects due to 1mm/year melting of WAIS

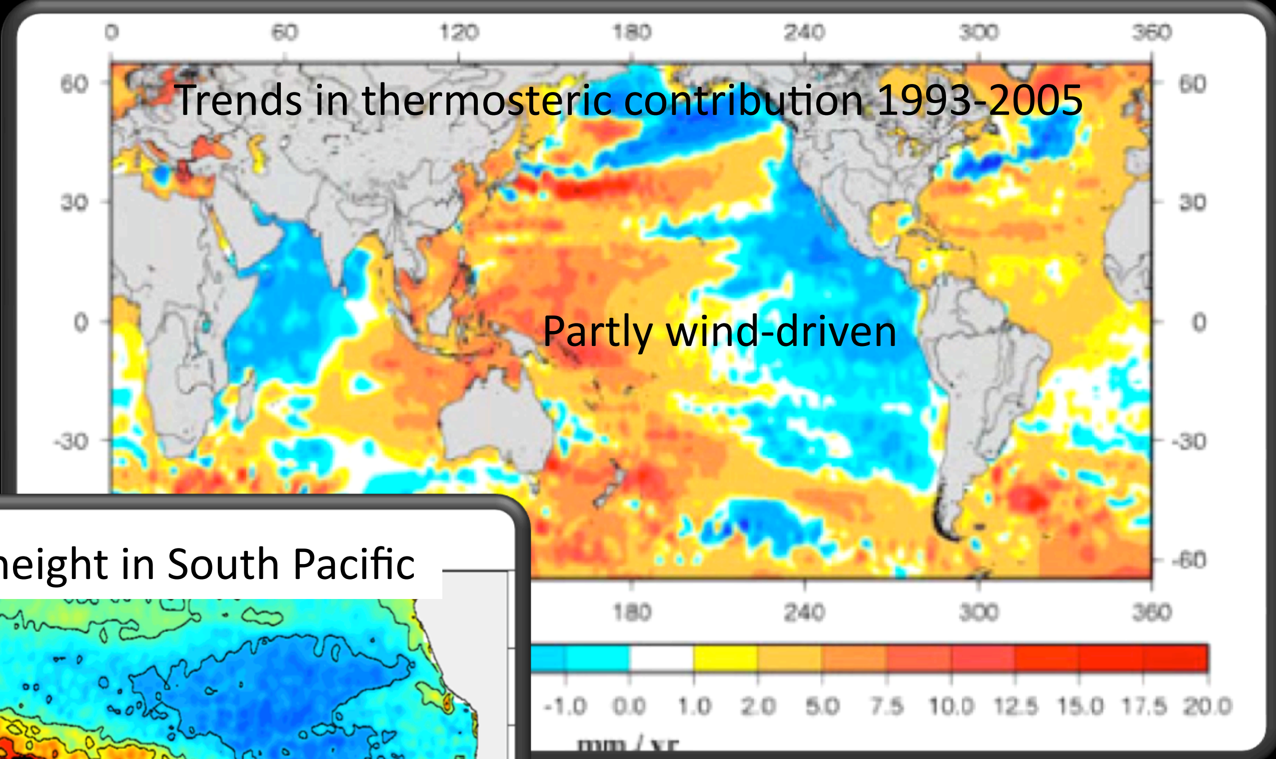


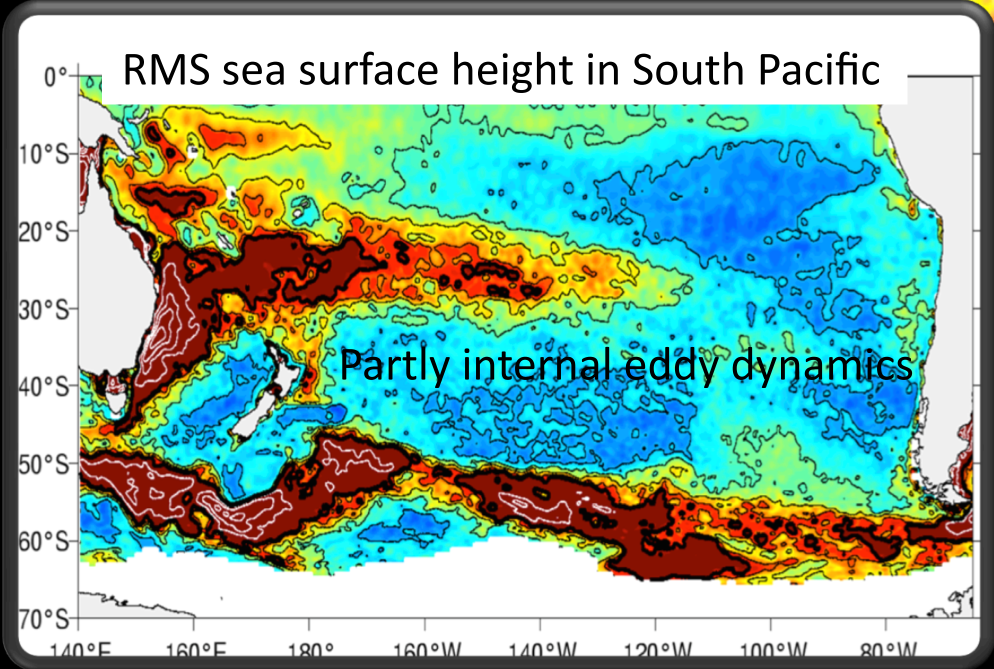
Causes of sea-level change: thermosteric

$$\frac{\partial h_{\mathrm{Ek}}}{\partial t} = -\frac{g' \operatorname{curl} \boldsymbol{\tau}}{\rho_o g f} - \varepsilon_I h_{\mathrm{Ek}},$$

versus

$$\frac{\partial h}{\partial t} - c_R \frac{\partial h}{\partial x} = -\frac{g' \operatorname{curl} \boldsymbol{\tau}}{\rho_o g f} - \varepsilon h,$$



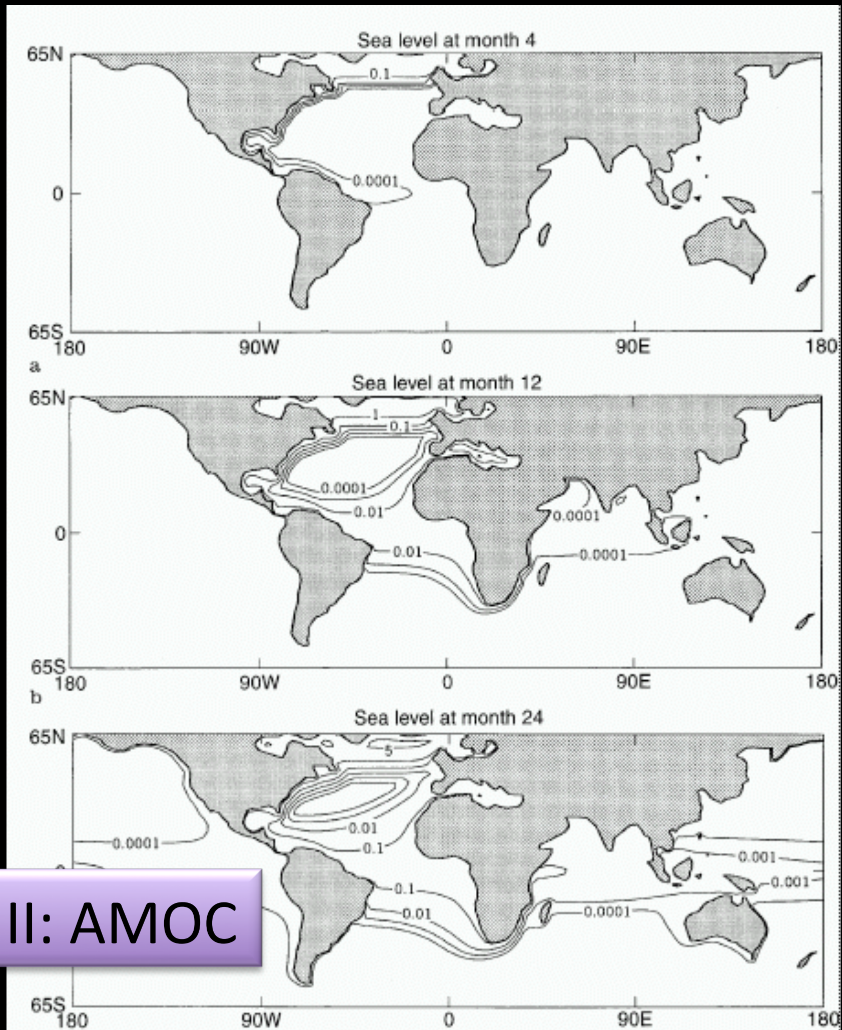


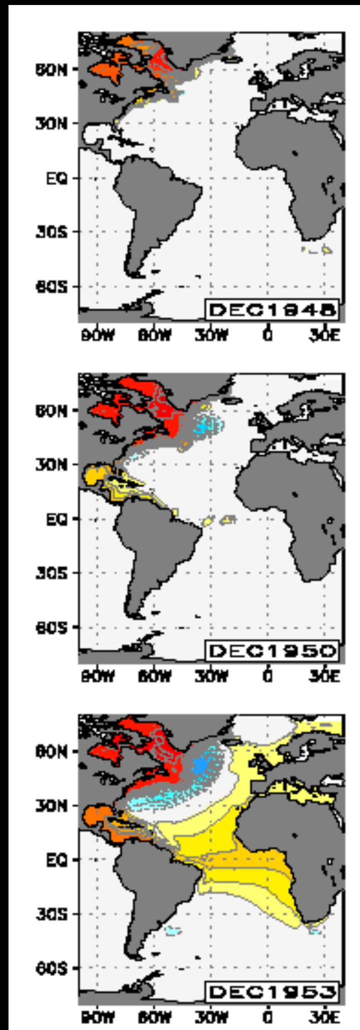
Causes of sea-level change: thermosteric

Large-scale baroclinic response to changes of density in North Atlantic

Reduced Gravity:

Hsieh and Bryan





OGCM:

Stammer (2009)

Example II: AMOC