Projections of tropical heat stress constrained by atmospheric dynamics

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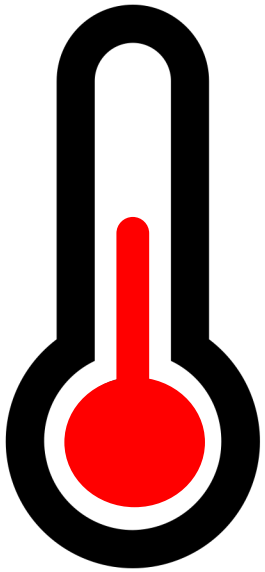
Why wet-bulb temperature (TW)?

$$c_p \mathrm{TW} + L_v q_{\mathrm{sat}}(\mathrm{TW}) = c_p T + L_v q$$

$T_{\mathbf{skin}} = \mathrm{TW}_{\mathrm{env}}$

T_{env}



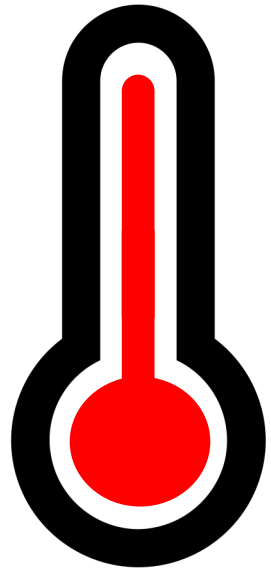
Latent heat flux

$$C \cdot L_v [q_{\mathrm{sat}}(T_{\mathrm{skin}}) - q_{\mathrm{env}}]$$

=

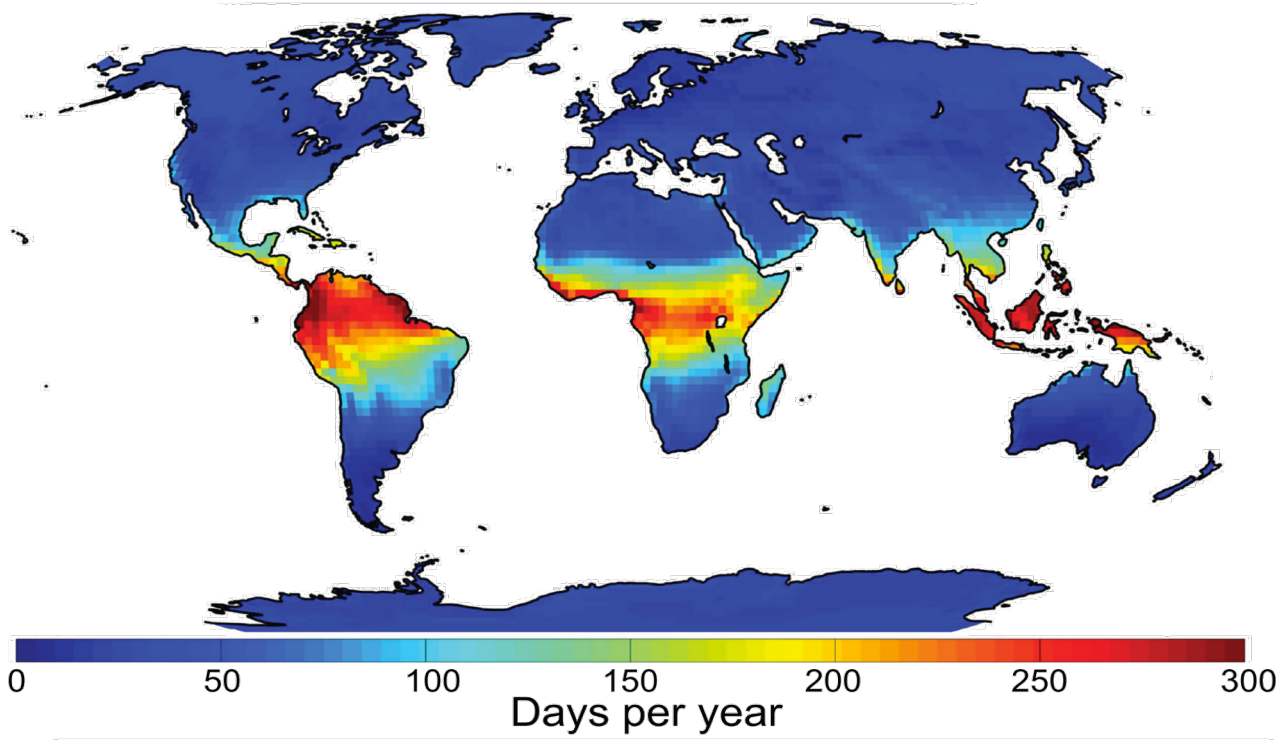
$$C \cdot c_p [T_{\mathrm{env}} - T_{\mathrm{skin}}]$$

Sensible heat flux



Why the tropics?

Survival limit: TW < 35°C
(Sherwood and Huber, 2010)



The number of days per year which exceed the historical (1985–2005) mean annual maximum wet bulb temperature in 2060–2080 (Coffel *et al.* 2018).

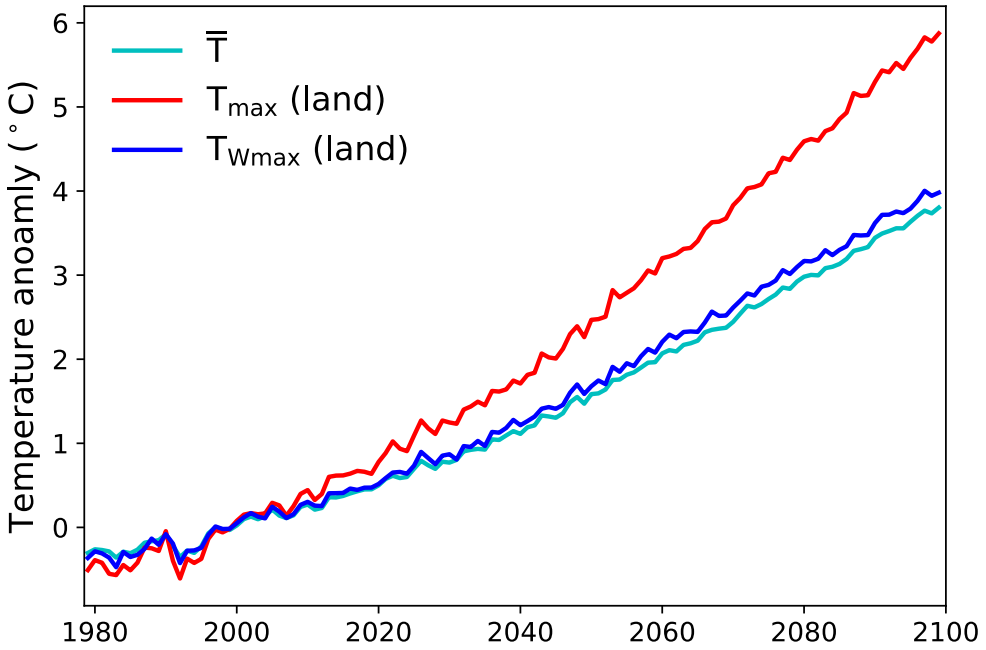
Outline

Part I: 1°C of tropical mean warming leads to 1°C of extreme TW increase
(Zhang, Held, and Fueglistaler, Nat. Geosci., 2021)

Part II: Mechanism controlling extreme TW in the tropics
(Zhang and Fueglistaler, Geophys. Res. Lett., 2020)

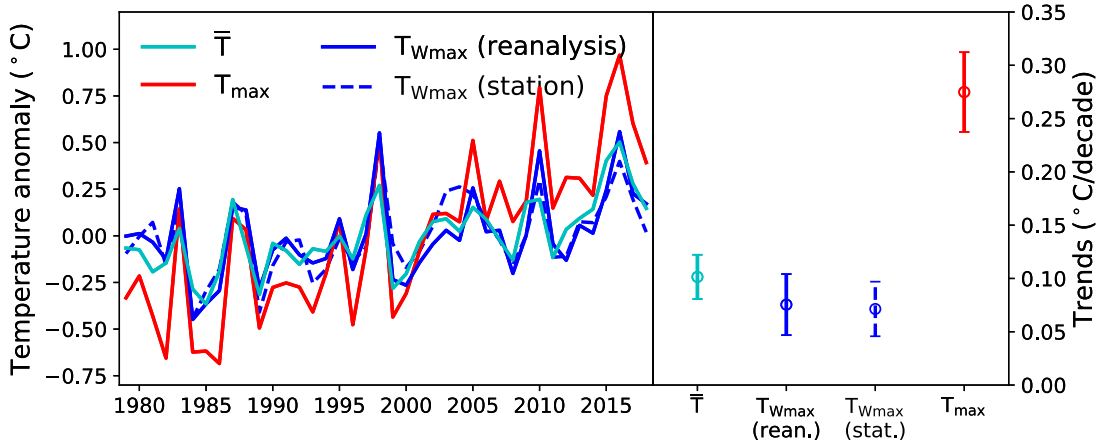
The 1:1 relationship for $T_{W\max}$ and $\bar{T}$ holds for the land mean (20S-20N).

CMIP5 models (RCP 8.5)



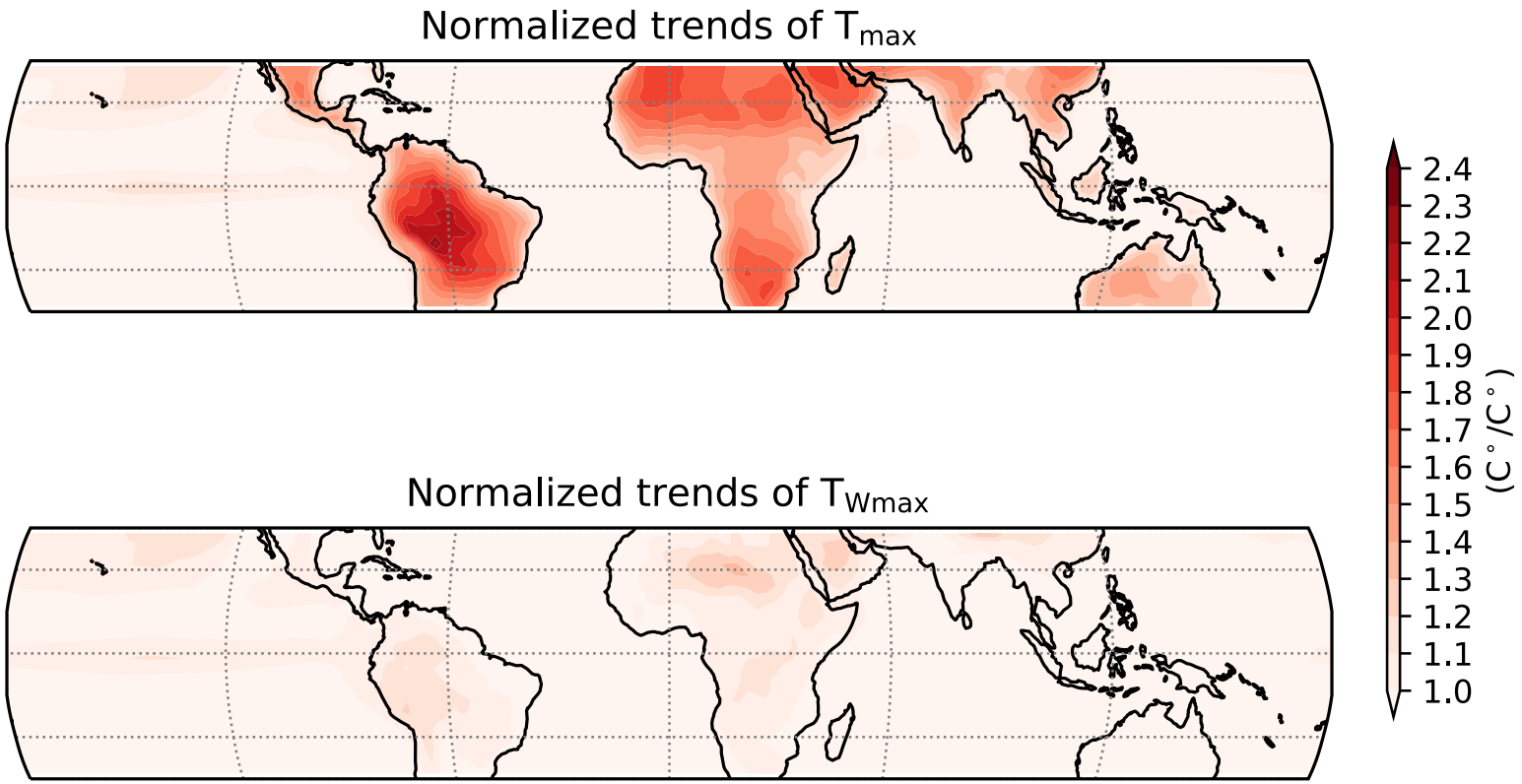
$\{\}_{\max}$ *: Annual maximum of daily mean*

Reanalysis/Station observations



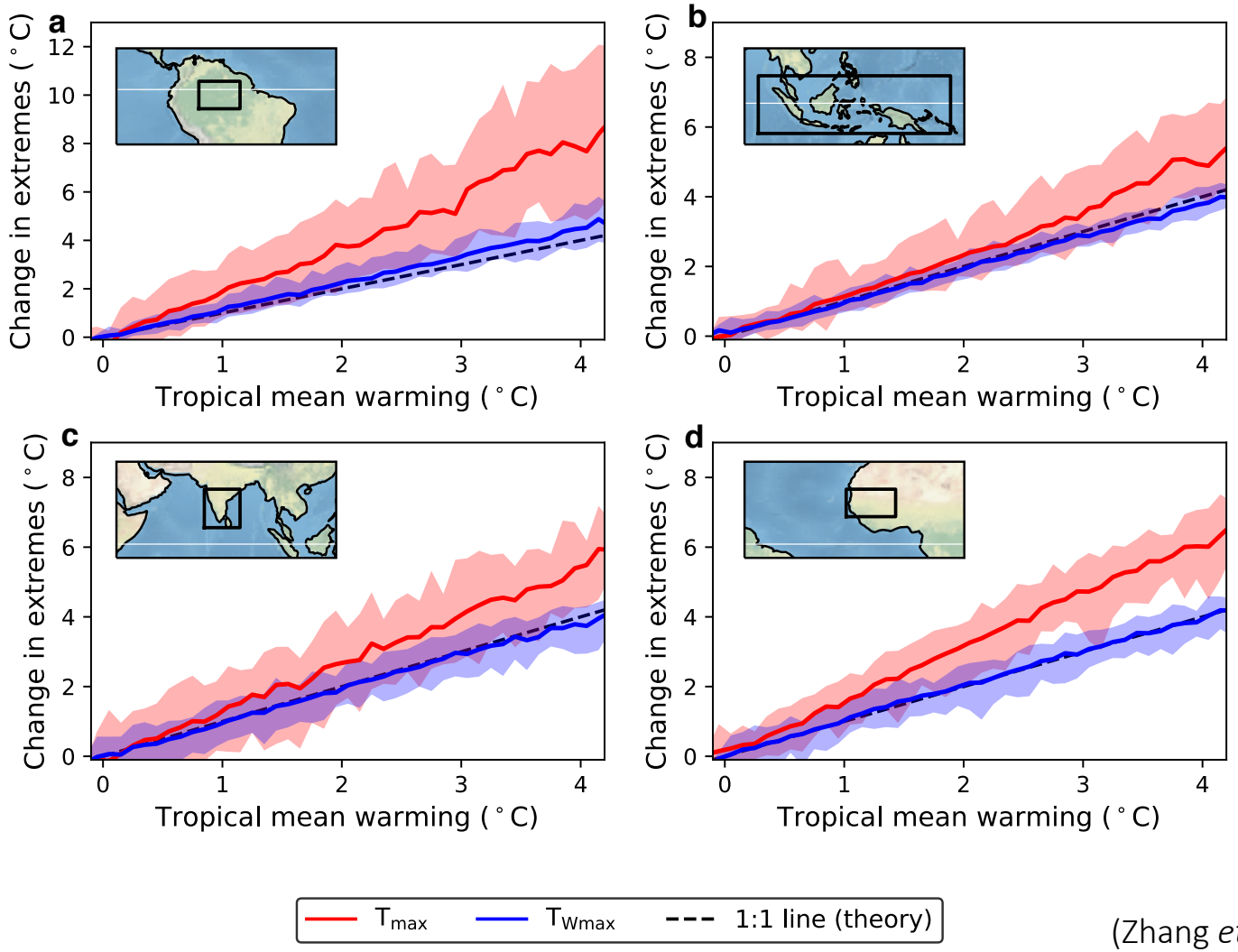
(Zhang *et al.*, 2021)

The 1:1 relationship for $T_{W\max}$ and $\bar{T}$ holds locally in CMIP5 models.



(Zhang *et al.*, 2021)

All 22 models agree well on the 1:1 relationship for $\mathbf{TW_{max}}$ and $\bar{T}$.



(Zhang *et al.*, 2021)

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Moist static energy (MSE)

$$c_p \mathrm{TW} + L_v q_{\mathrm{sat}}(\mathrm{TW}) = c_p T + L_v q = \mathrm{MSE}(z = 0)$$

$$\mathrm{MSE} = c_p T + Lq + gz$$

Temperature Humidity Height

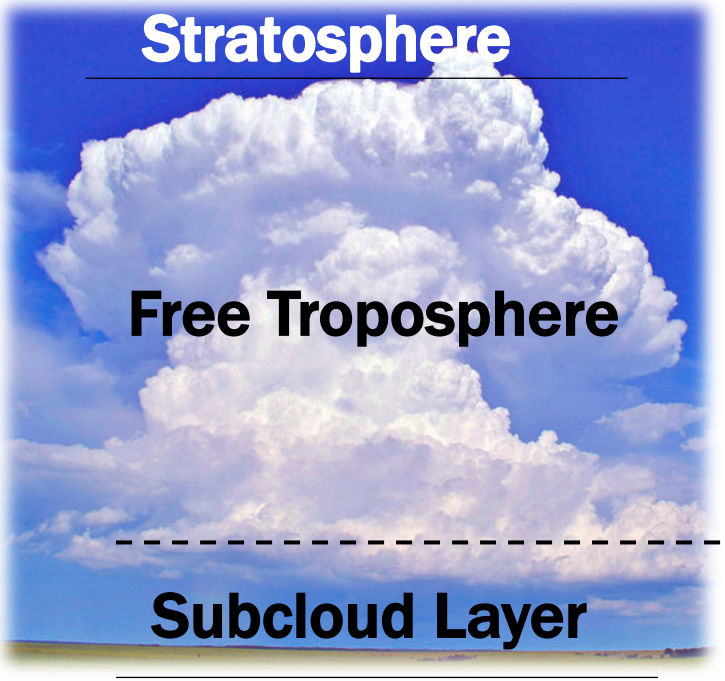
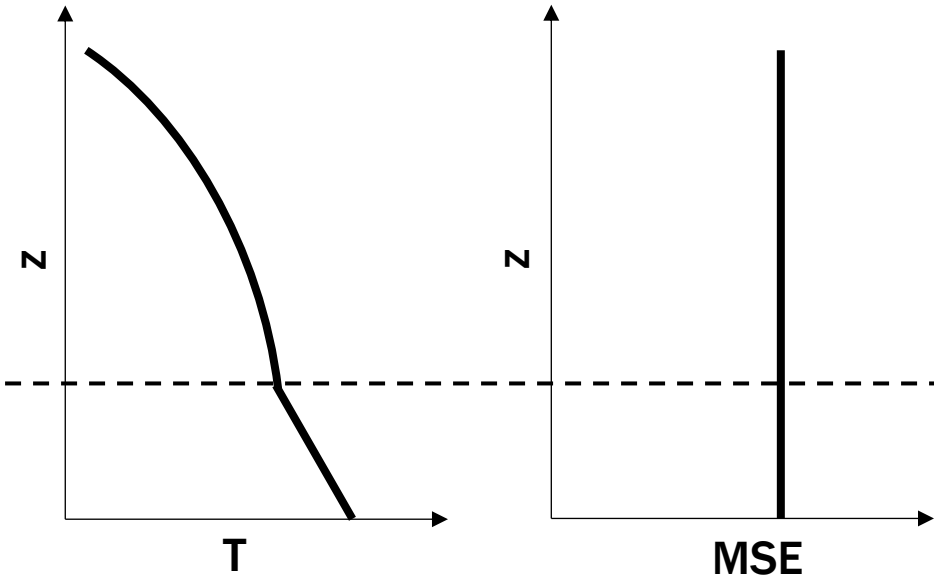
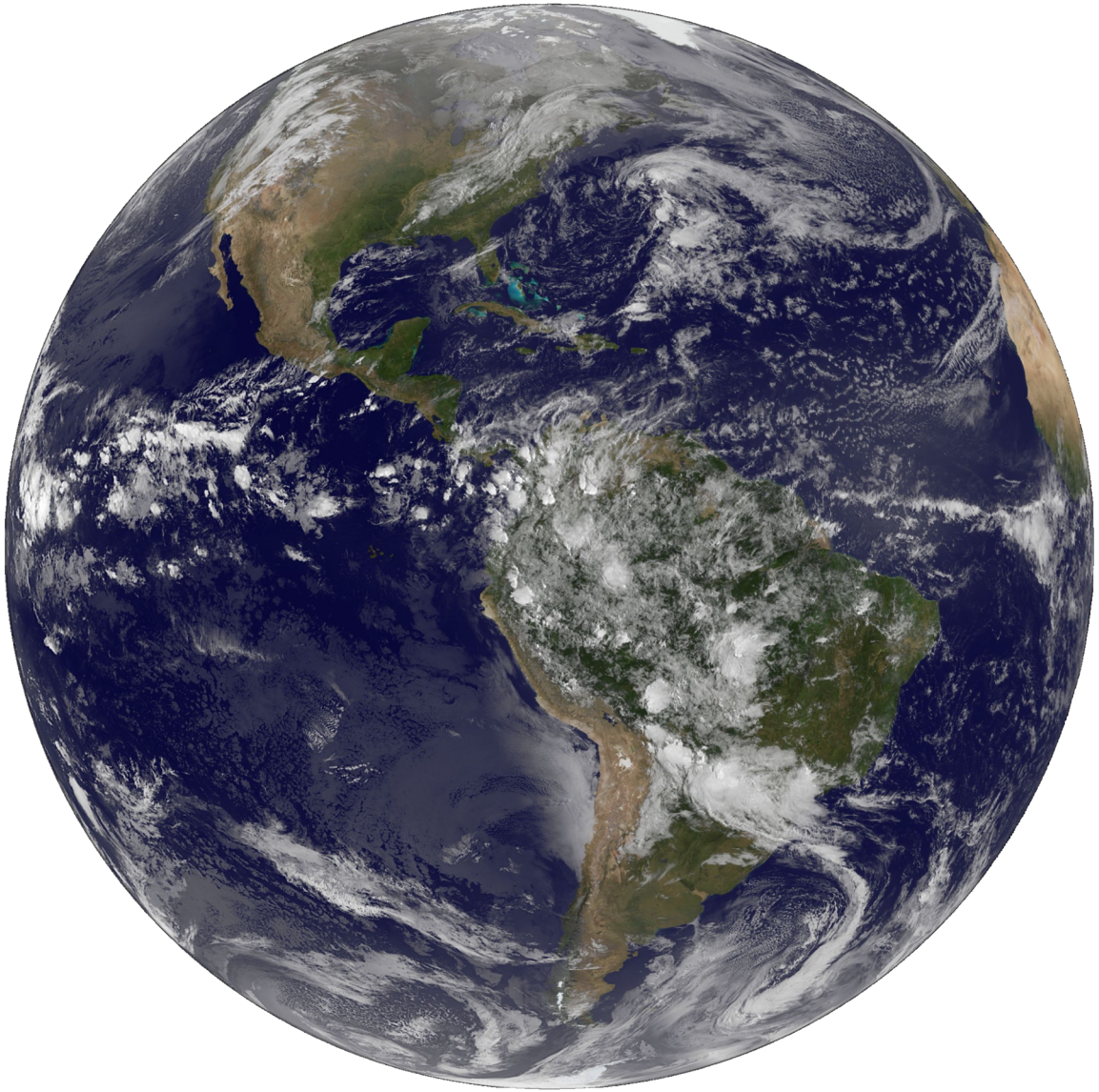


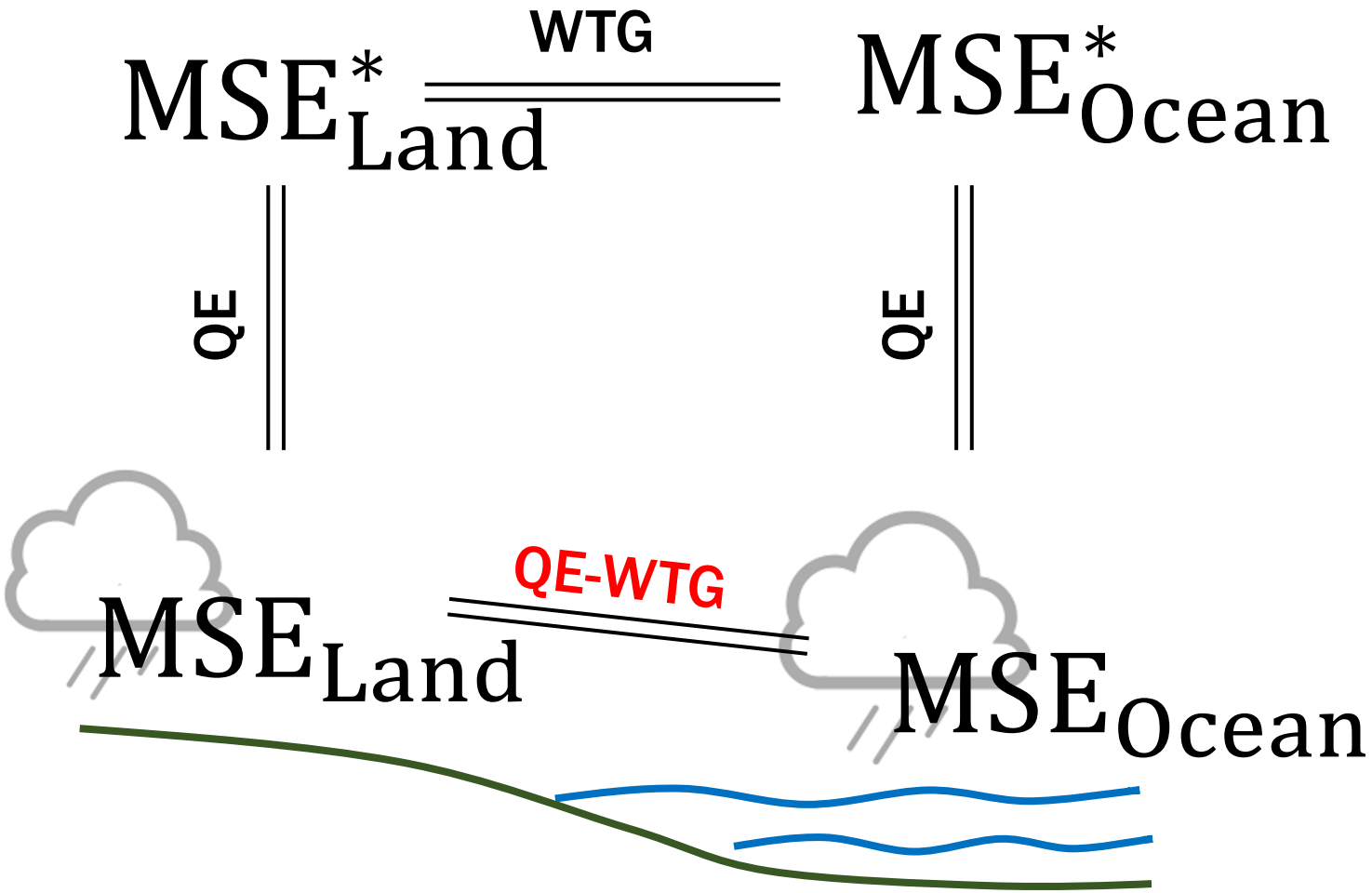
Photo credit: Audie T Photography



How does tropical convection couples land and ocean?



MSE ~ TW

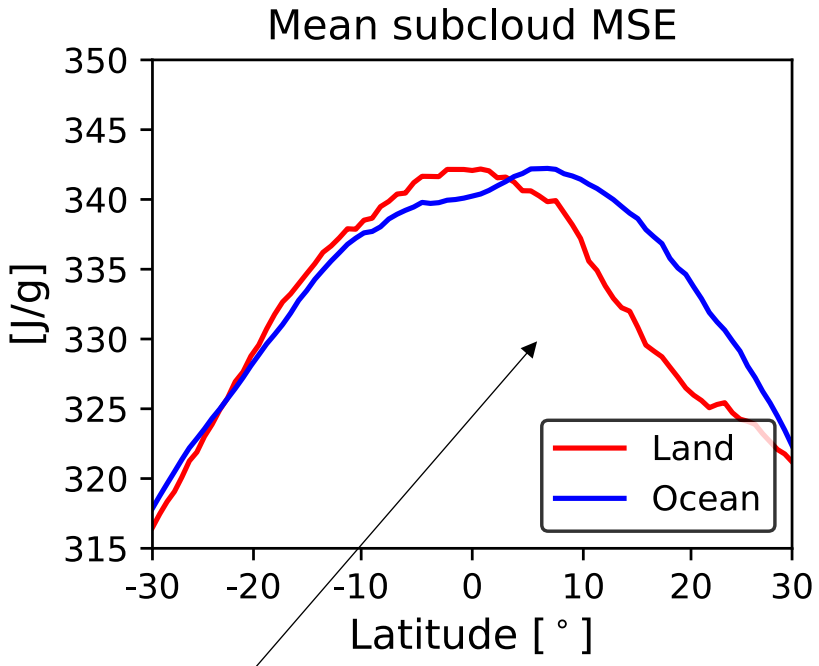


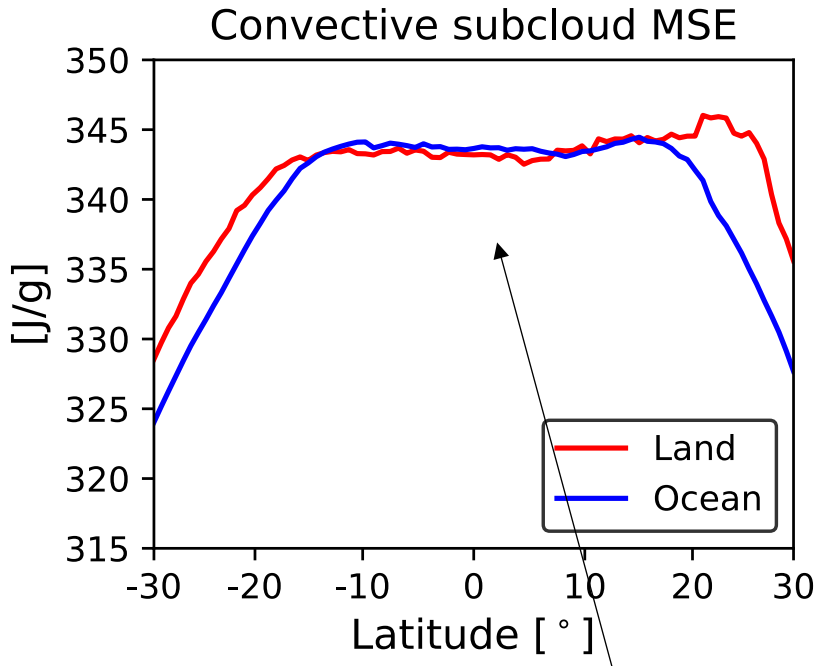
Convective quasi-equilibrium (QE): Moist adiabatic temperature profile in the vertical

Weak temperature gradients (WTG): Uniform free-tropospheric temperature in the horizontal

Convection over land and ocean occurs at very similar subcloud MSE.

(Data shown are from ERA-Interim and TRMM daily 2001-2014)





Byrne and O'Gorman (2013, 2018):

$$\overline{\mathrm{MSE}}_{\mathrm{land}} = \overline{\mathrm{MSE}}_{\mathrm{ocean}}$$

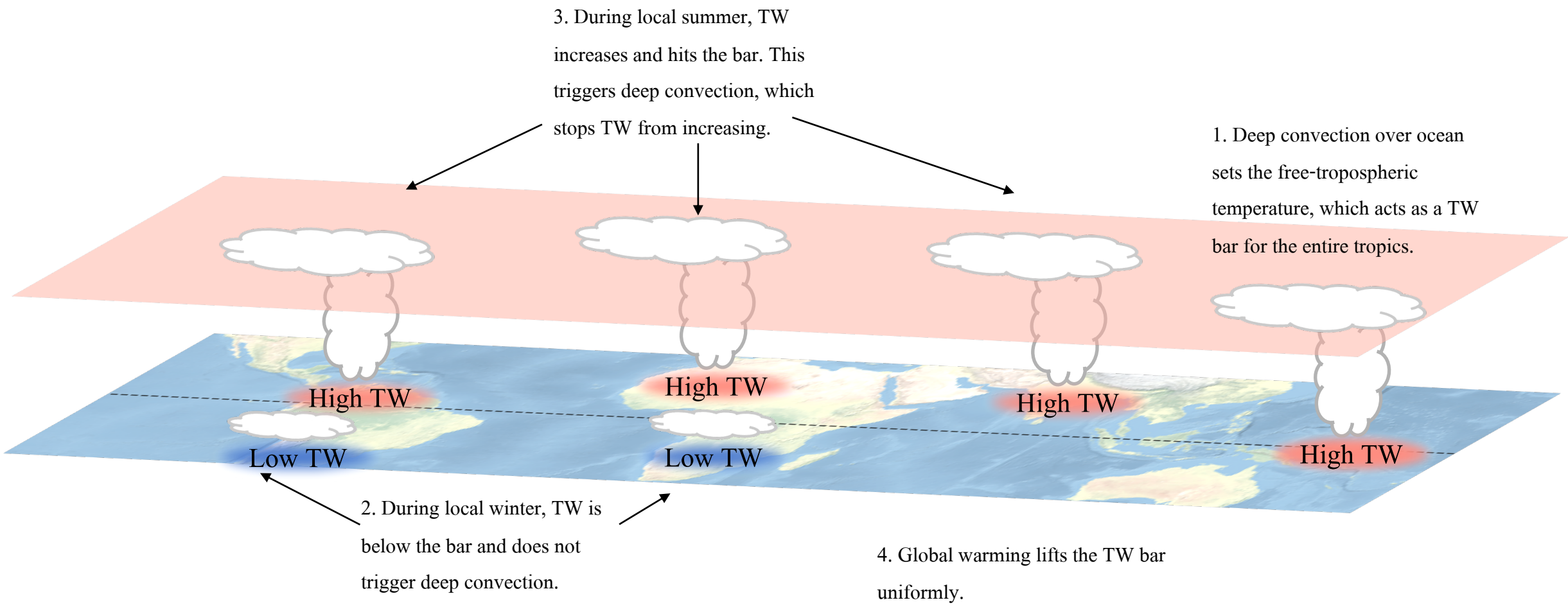
Strict QE-WTG is not accurate for the observations.

Zhang and Fueglistaler (2020):

$$\{\mathrm{MSE}_{\mathrm{land}}\}_{\mathrm{max}} \approx \{\mathrm{MSE}_{\mathrm{ocean}}\}_{\mathrm{max}}$$

Strict QE-WTG is accurate if the observations are examined properly.

Mechanism limiting TW over land $\rightarrow \Delta TW_{max,Land} \approx \Delta TW_{max,Ocean}$



Theoretical projection: 1°C of $\Delta\bar{T}$ ➔ 1°C of ΔTW_{max}

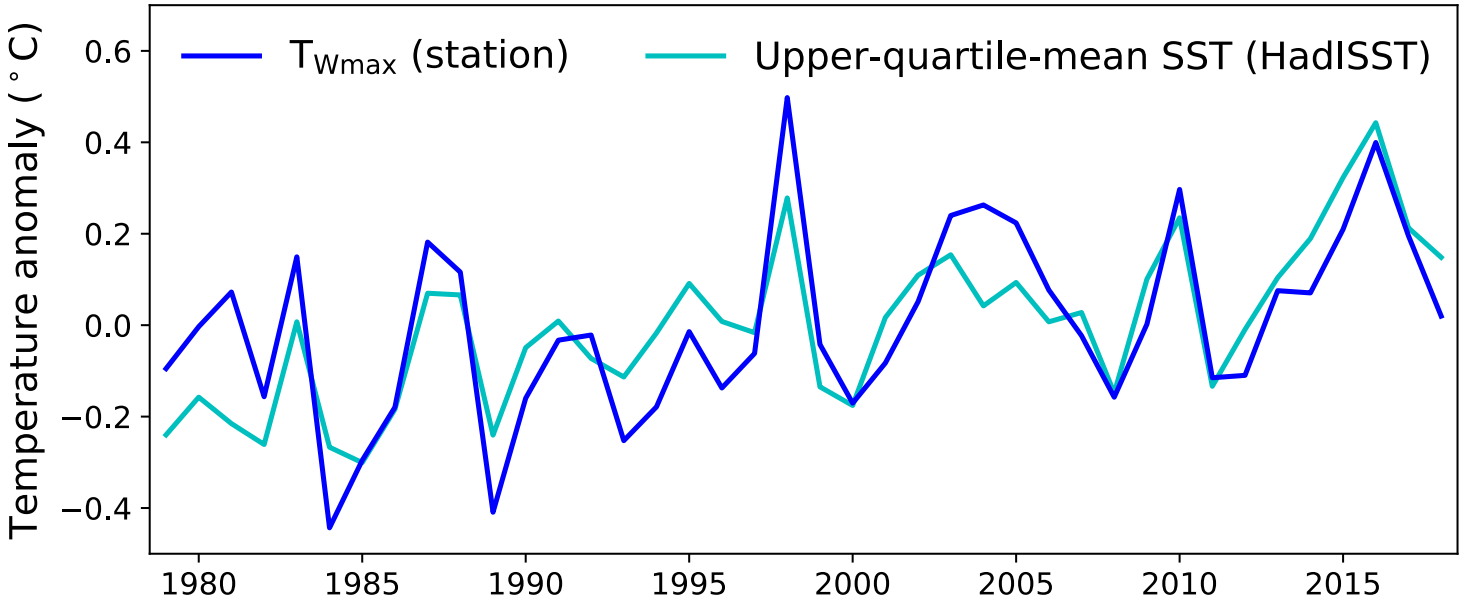
$$\Delta TW_{max,Land} \approx \Delta TW_{max,Ocean}$$

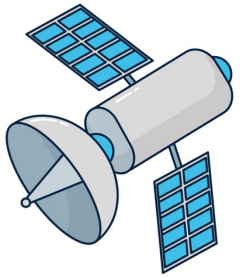
$$\approx \Delta SST_{max}$$ *(Air is near saturation over the ocean surface.)*

$$\approx \Delta\overline{SST}$$ *(SST warming is relatively uniform.)*

$$\approx \Delta\overline{T}$$ *(Ocean covers 80% of the tropical surface area.)*

$\Delta TW_{max,Land} \approx \Delta TW_{max,Ocean}$ -- More evidence from the observations

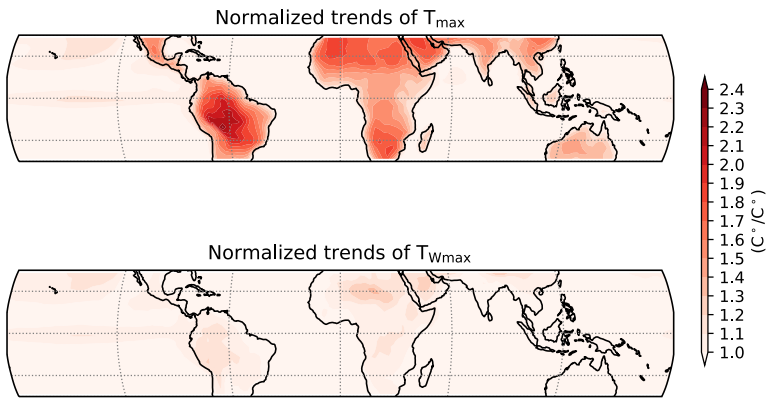




Largely independent observations are highly correlated, which supports the theoretical picture.

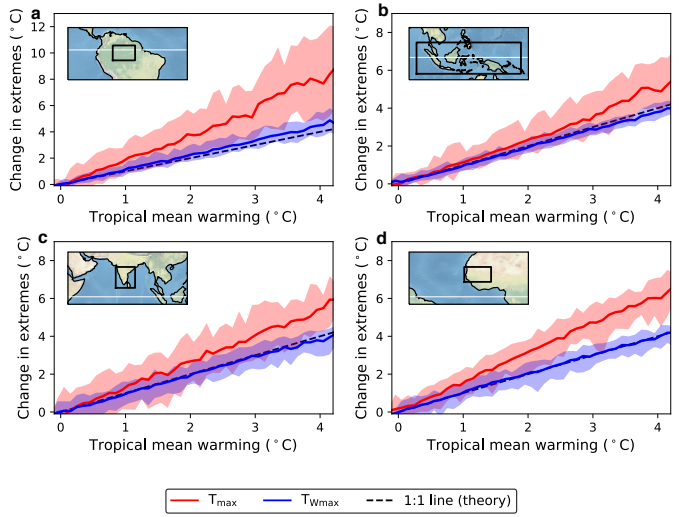
$\Delta TW_{max,Land} \approx \Delta TW_{max,Ocean}$ -- Evidence from the CMIP5 models

The 1:1 relationship for TW_{max} and $\bar{T}$ holds for <u>each location</u>, and for <u>each model</u>.

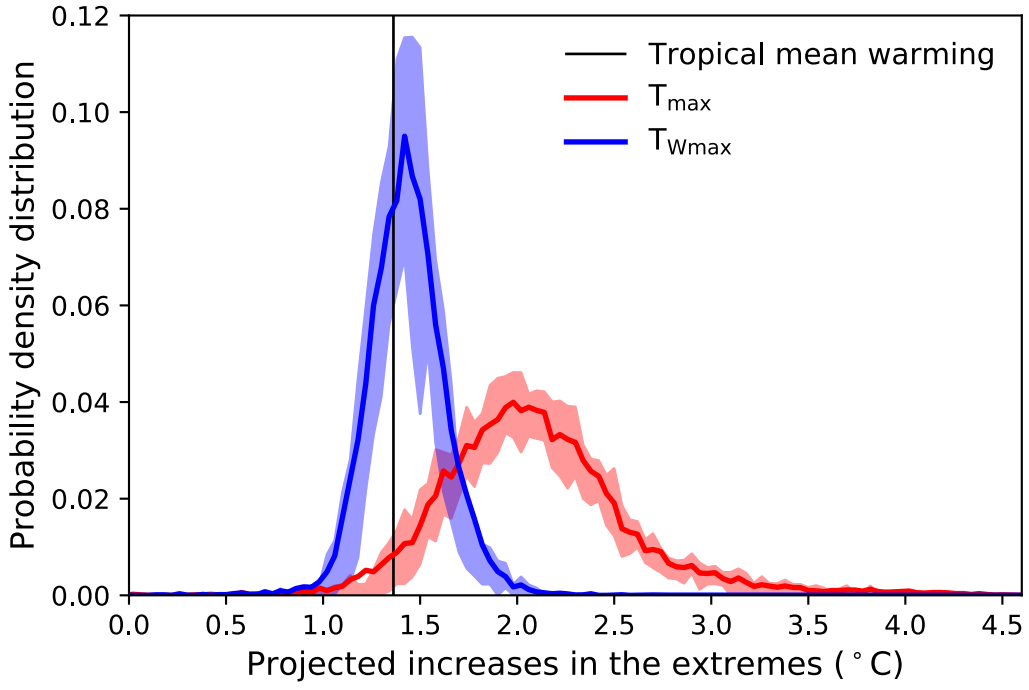


Could only be a non-local constraint
– Uniform free tropospheric temperature

Could only be something independent of model specifics
– Robust atmospheric dynamics



The uncertainty in TW_{max} projection is small.



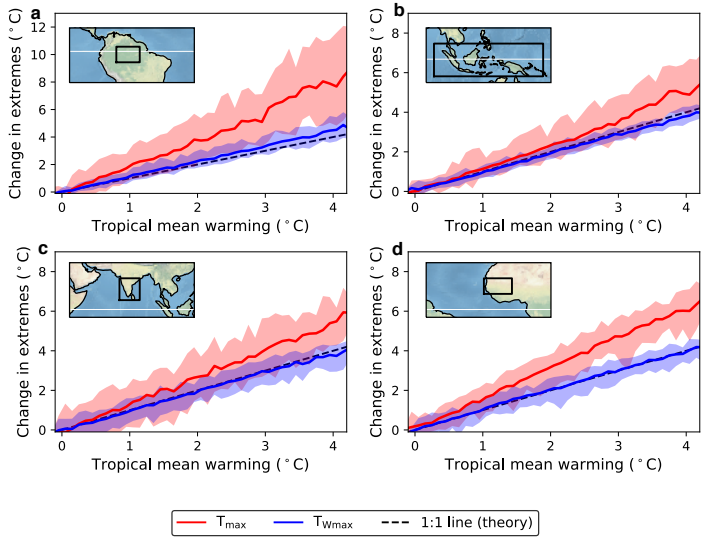
The maximum 3-hourly TW of 99.98% of tropical land area is below 33°C (ERA-Interim).

↪ A 2°C warmer world will exempt most regions from reaching the adaptability limit of 35°C .

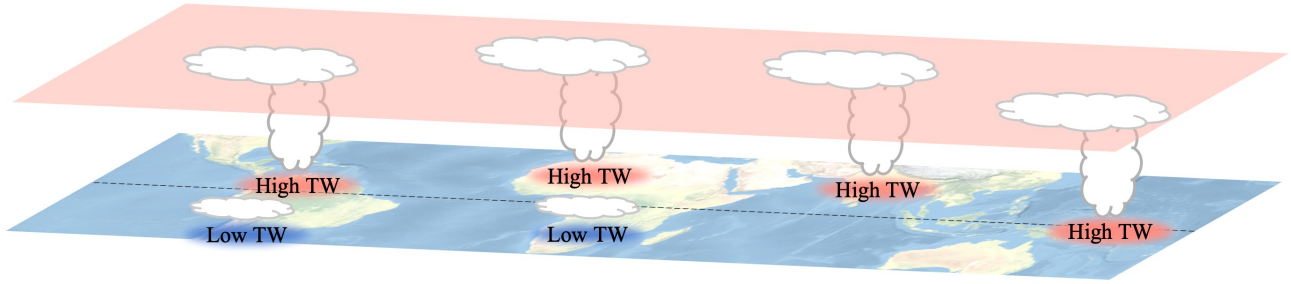
Summary

Part I: 1°C of tropical mean warming leads to 1°C of TW_{max} increase
(Zhang, Held, and Fueglistaler, Nat. Geosci., 2021)

Good news!



Part II: TW_{max} is controlled by a convective instability mechanism
(Zhang and Fueglistaler, Geophys. Res. Lett., 2020)



Reference

- Zhang, Yi, and Stephan Fueglistaler. "How tropical convection couples high moist static energy over land and ocean." *Geophysical Research Letters* (2020).
- Zhang, Yi, Isaac Held, and Stephan Fueglistaler. "Projections of tropical heat stress constrained by atmospheric dynamics." *Nature Geoscience* (2021).

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