Oceans and climate

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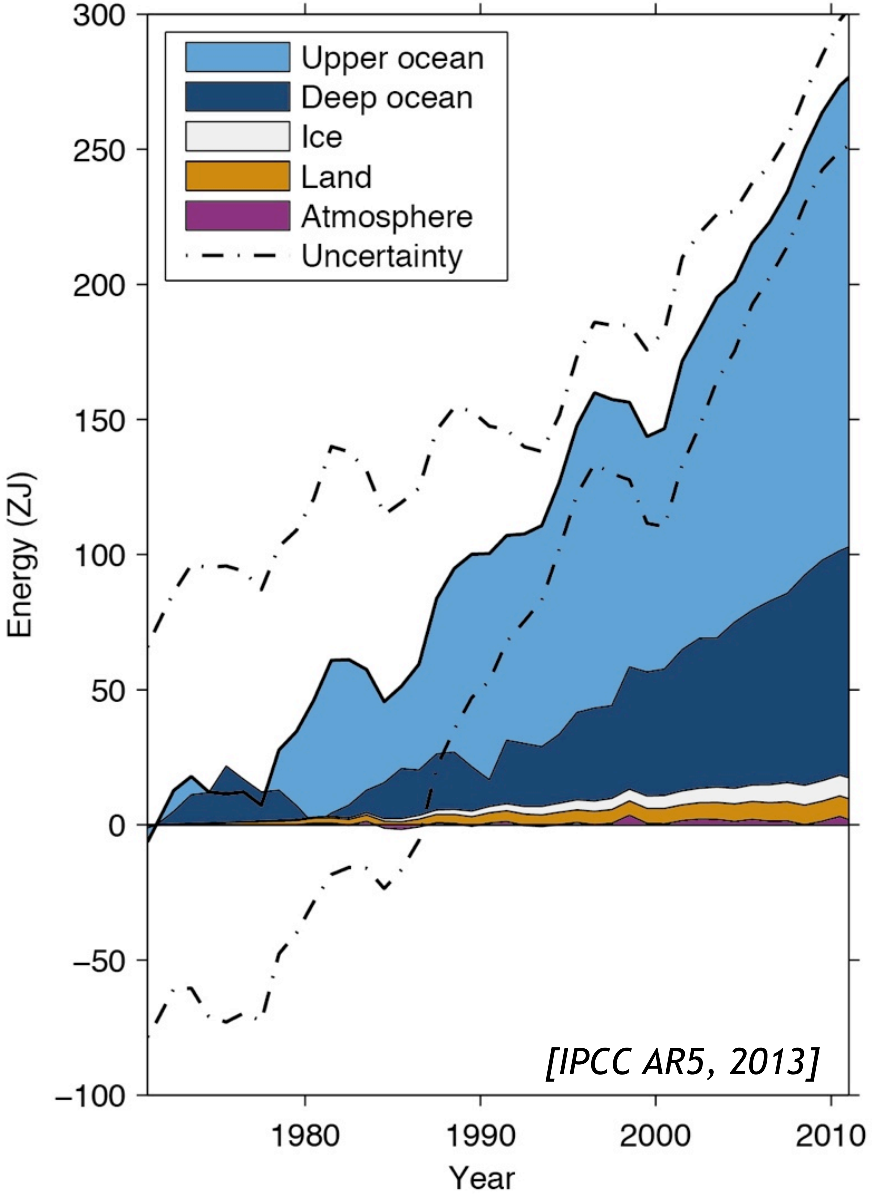
Global heat content change

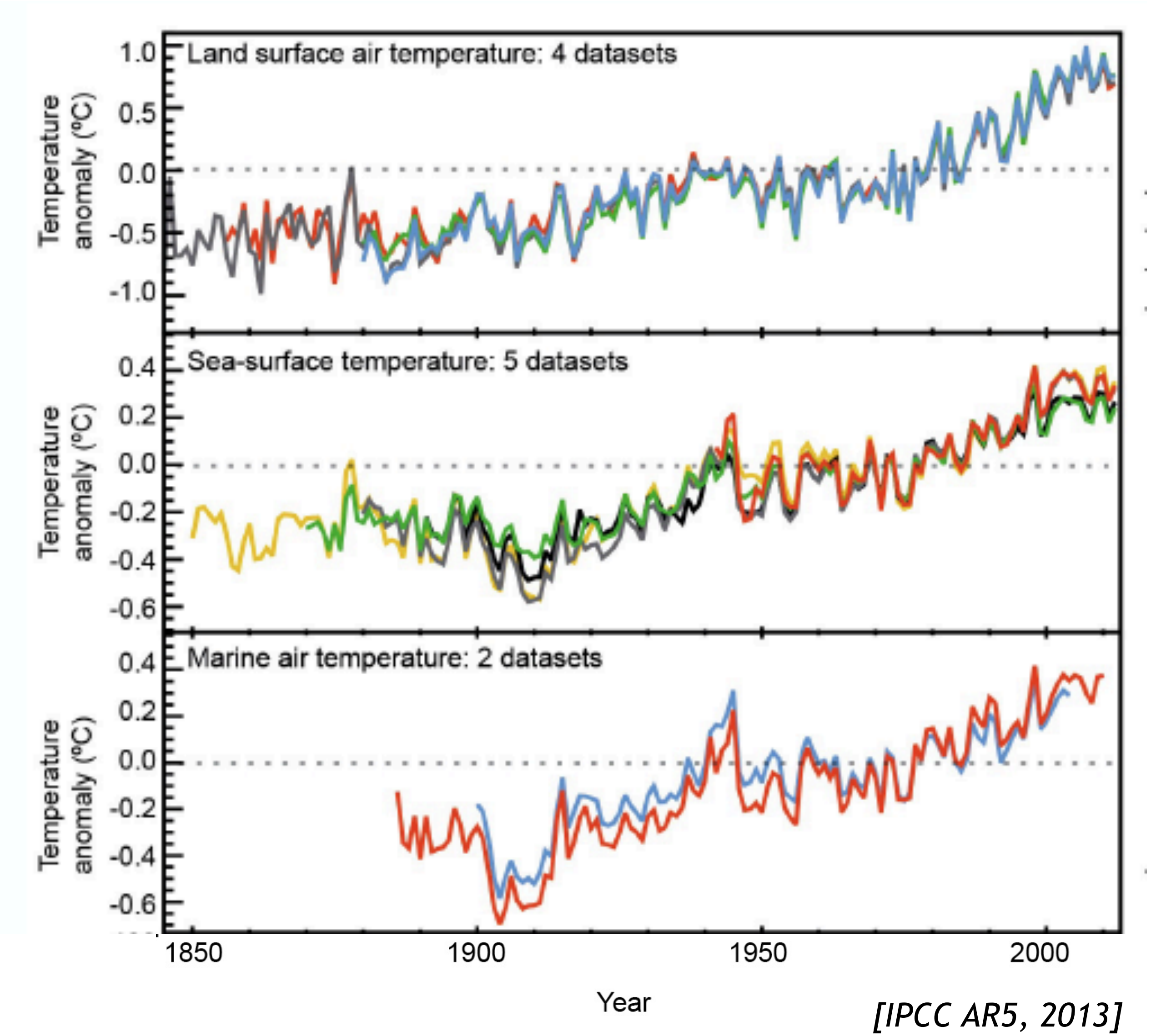


[IPCC AR5, 2013]

Over the last 50 years:

Ocean heat content has changed much more than land and atmosphere heat content.

Temperature change



[IPCC AR5, 2013]

Land surface air temperature has increased by about 1°C.

Sea surface temperature has increased by about 0.5°C.

Heat capacity of land and oceans

Oceans have LARGE EFFECTIVE HEAT CAPACITY compared to land.

$$mc\Delta T = Q$$

$$\frac{dT}{dt} = \frac{\dot{Q}}{mc} = \frac{\dot{Q}}{\rho V c} = \frac{F}{\rho h c} = \frac{F}{C}$$

$$\frac{\text{HEAT FLUX}}{\text{EFFECTIVE HEAT CAPACITY}}$$

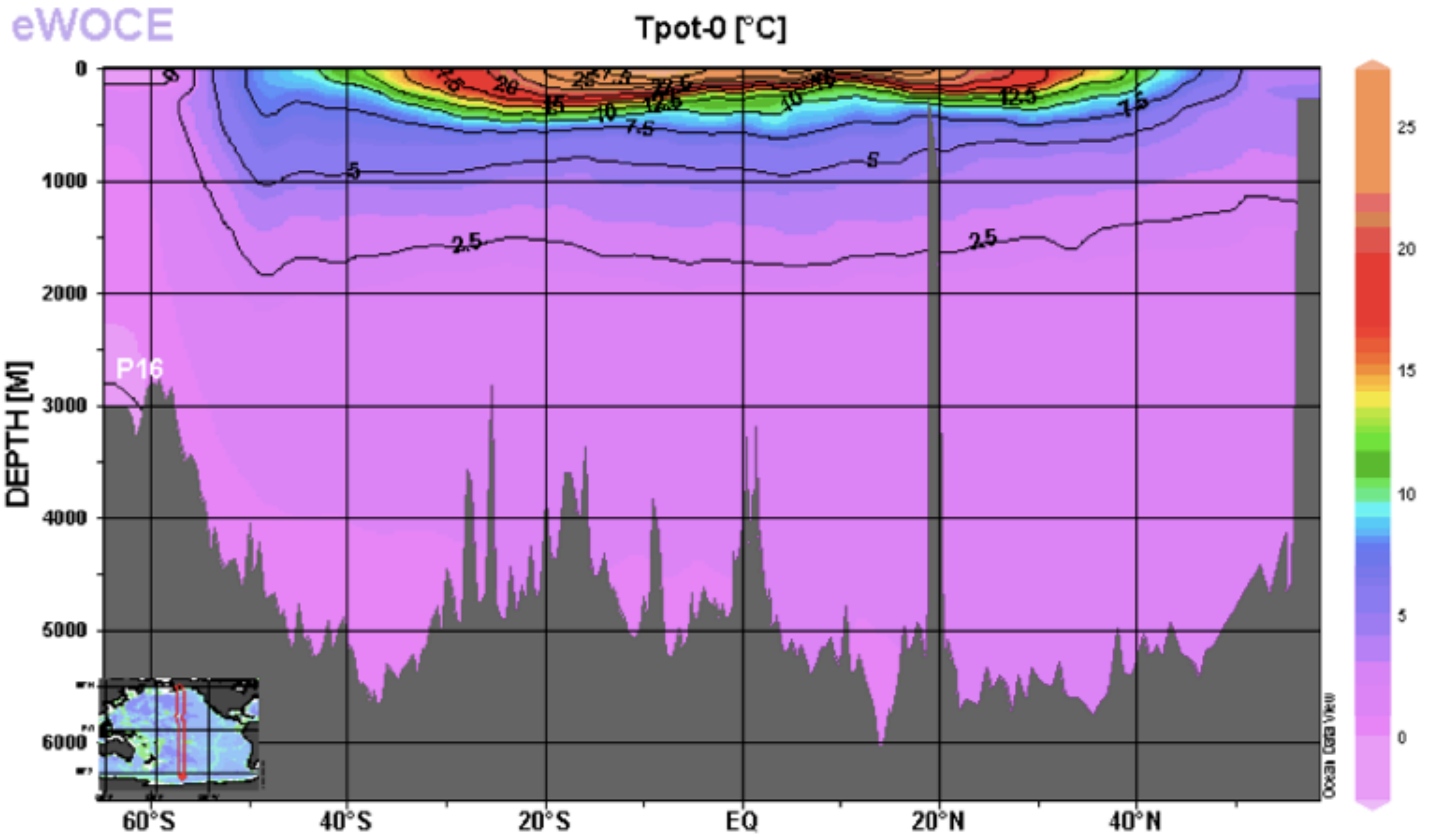
Q	heat exchanged	m	mass	ρ	density	$F = \dot{Q}/A$	heat flux
$\dot{Q}$	heating rate	c	heat capacity	$V = Ah$	volume	$C = \rho\ h\ c$	effective heat capacity

$$C_{\text{land}} = (\rho h c)_{\text{land}} \sim 3000\ \text{kg m}^{-3}\ 1\ \text{m}\ 1000\ \text{J kg}^{-1}\text{K}^{-1} \sim 3 \cdot 10^6\ \text{J m}^{-2}\text{K}^{-1}$$

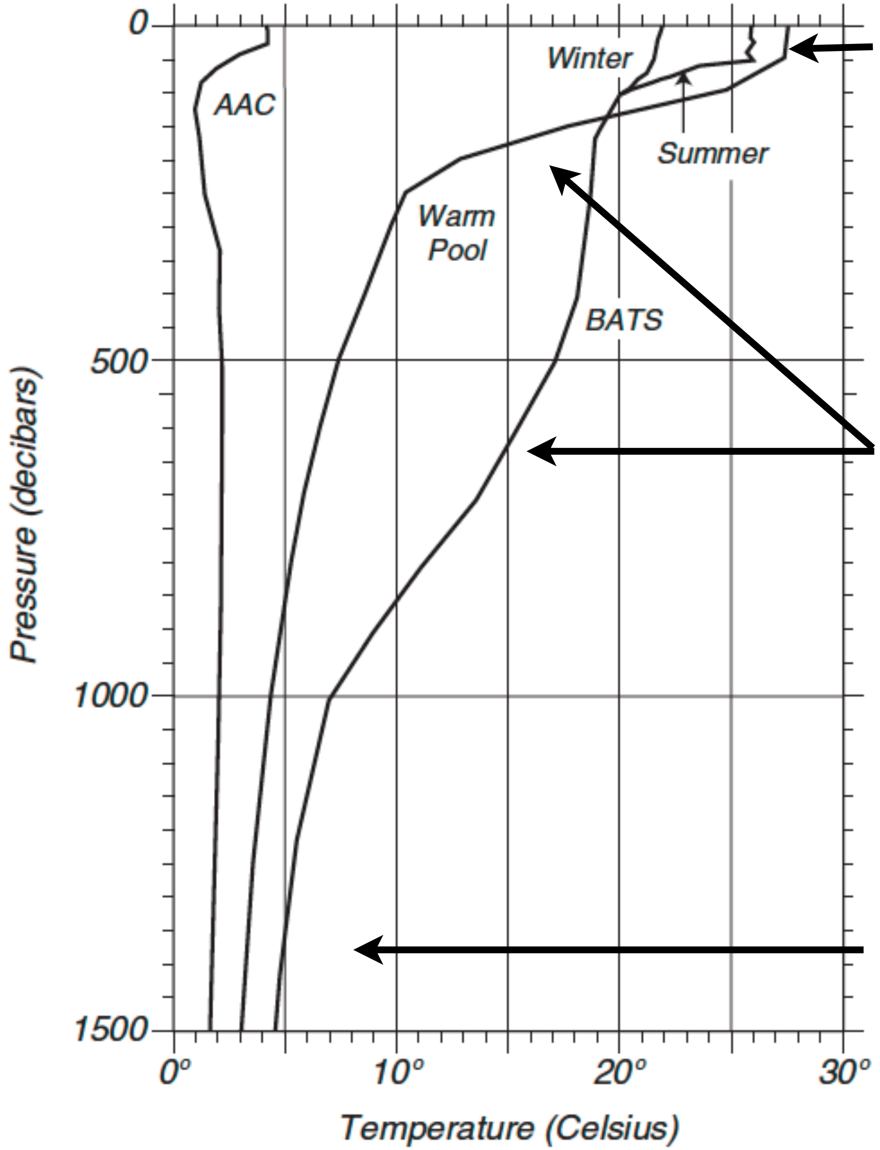
$$C_{\text{ocean}} = (\rho h c)_{\text{ocean}} \sim 1000\ \text{kg m}^{-3}\ [20\text{-}200]\ \text{m}\ 4000\ \text{J kg}^{-1}\text{K}^{-1} \sim [8 \cdot 10^7 - 8 \cdot 10^8]\ \text{J m}^{-2}\text{K}^{-1}$$

For the same heat flux, the rate of warming for land is 100 times larger than for the ocean.

Ocean temperature



Thermal stratification



Surface mixed layer (top 100 meters)

Thermocline

Deep ocean

Response to periodic forcing

evolution of temperature *anomaly* T

$$C\frac{dT}{dt} = \overset{\text{heating}}{S} - \overset{\text{cooling}}{\lambda T}$$

$$S = S(t) = S_0\cos(\omega t) = \Re(S_0 e^{i\omega t})$$

$$T = \Re(T_0 e^{i\omega t})$$

$$T = S_0\frac{\lambda\cos(\omega t) + \omega C\sin(\omega t)}{\lambda^2 + \omega^2 C^2}$$

Response to periodic forcing

evolution of temperature *anomaly* T

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$$S = S(t) = S_0\cos(\omega t) = \Re(S_0 e^{i\omega t}) \qquad T = \Re(T_0 e^{i\omega t})$$

$$T = S_0\frac{\lambda\cos(\omega t) + \omega C\sin(\omega t)}{\lambda^2 + \omega^2 C^2}$$

$$\omega C \ll \lambda \qquad T = S_0\frac{\lambda\cos(\omega t) + \omega C\sin(\omega t)}{\lambda^2 + \omega^2 C^2}$$

larger amplitude,
in phase with heating

$$\omega C \gg \lambda \qquad T = S_0\frac{\lambda\cos(\omega t) + \omega C\sin(\omega t)}{\lambda^2 + \omega^2 C^2}$$

smaller amplitude,
out of phase with heating

Heat storage in the ocean mitigates (high frequency) climate variability (and climate change)

Boreal vs Austral hemispheres

Hemisphere surface
covered by ocean:

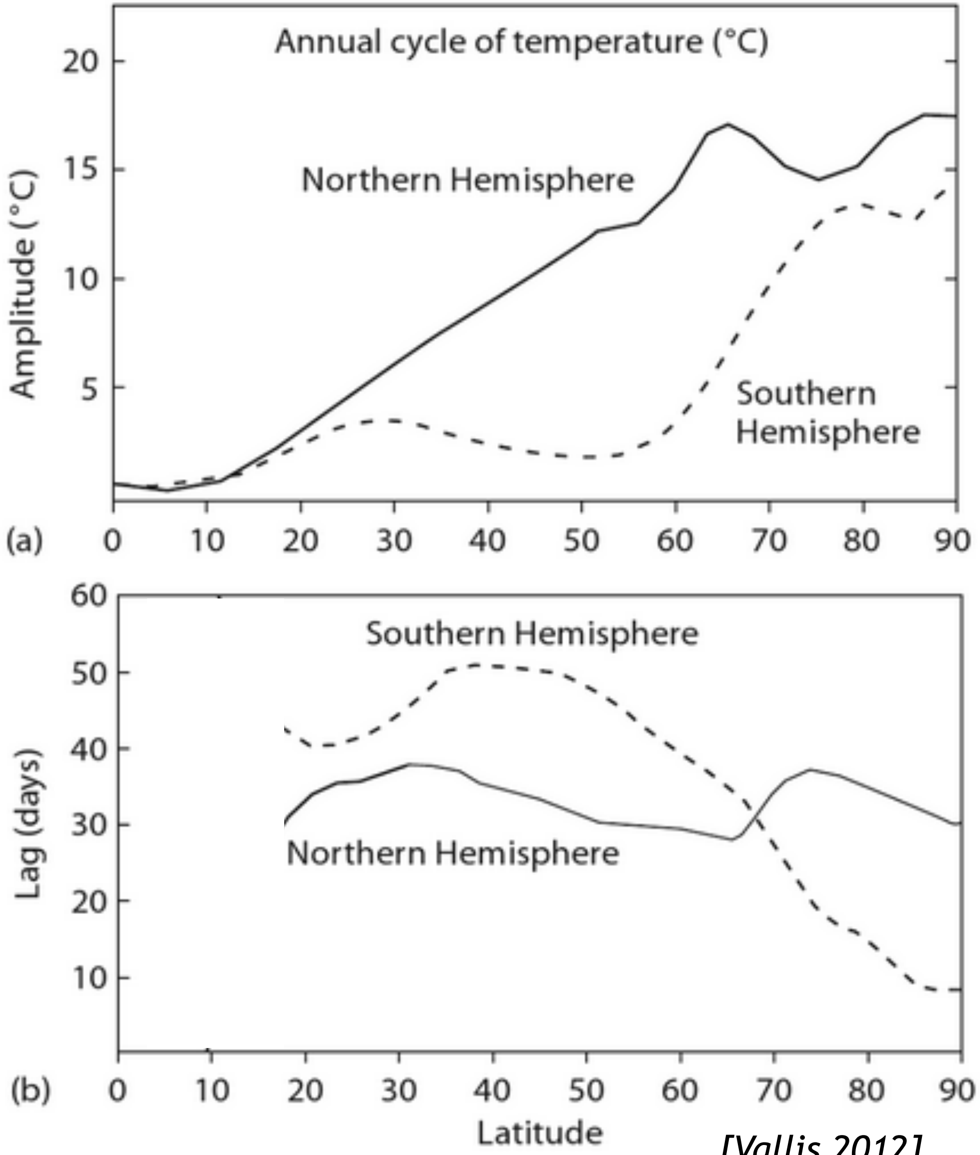
60% Northern

80% Southern

High latitude regions:

land (ice) in the Southern hemisphere

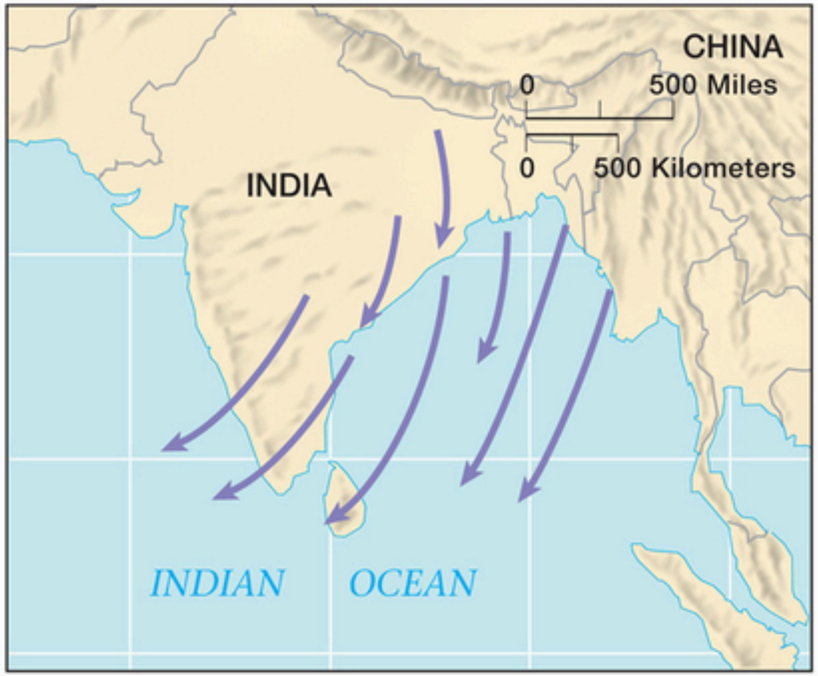
ocean in the Northern hemisphere



[Vallis 2012]

Monsoons

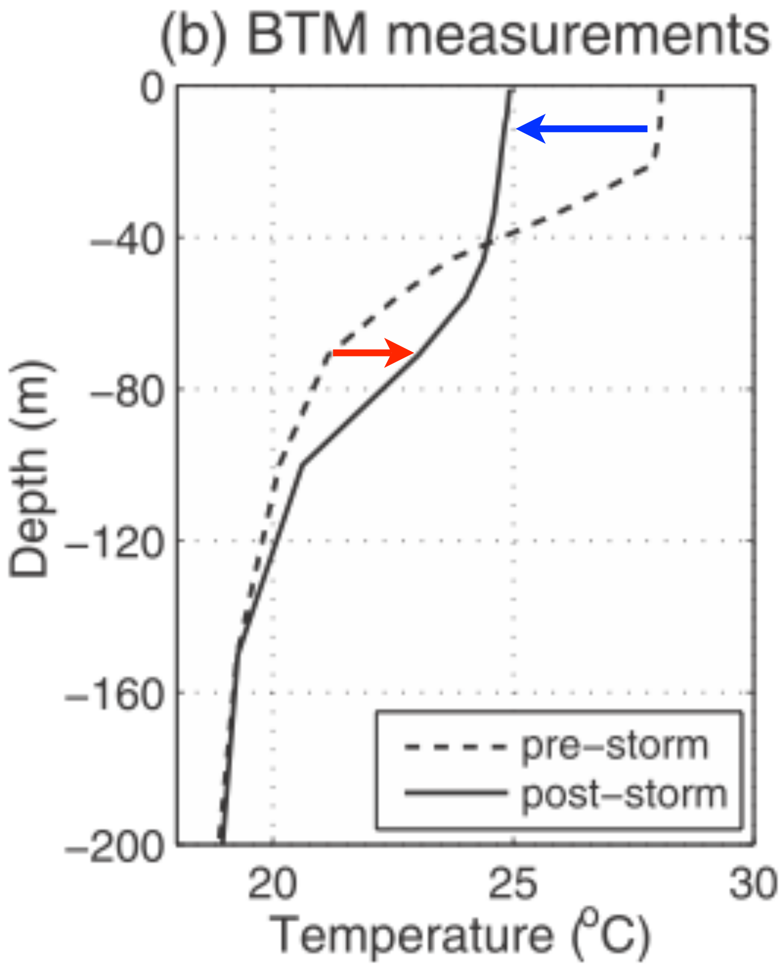
Summer



Winter

The role of intense winds

Effective ocean heat capacity depends on mixed layer depth, h, whose value is a nonlinear function of wind speed.



Winds input kinetic energy into the ocean, which can erode stratification and induce mixing (shear instability).

Wind induced vertical mixing cools the surface and warms part of the thermocline.

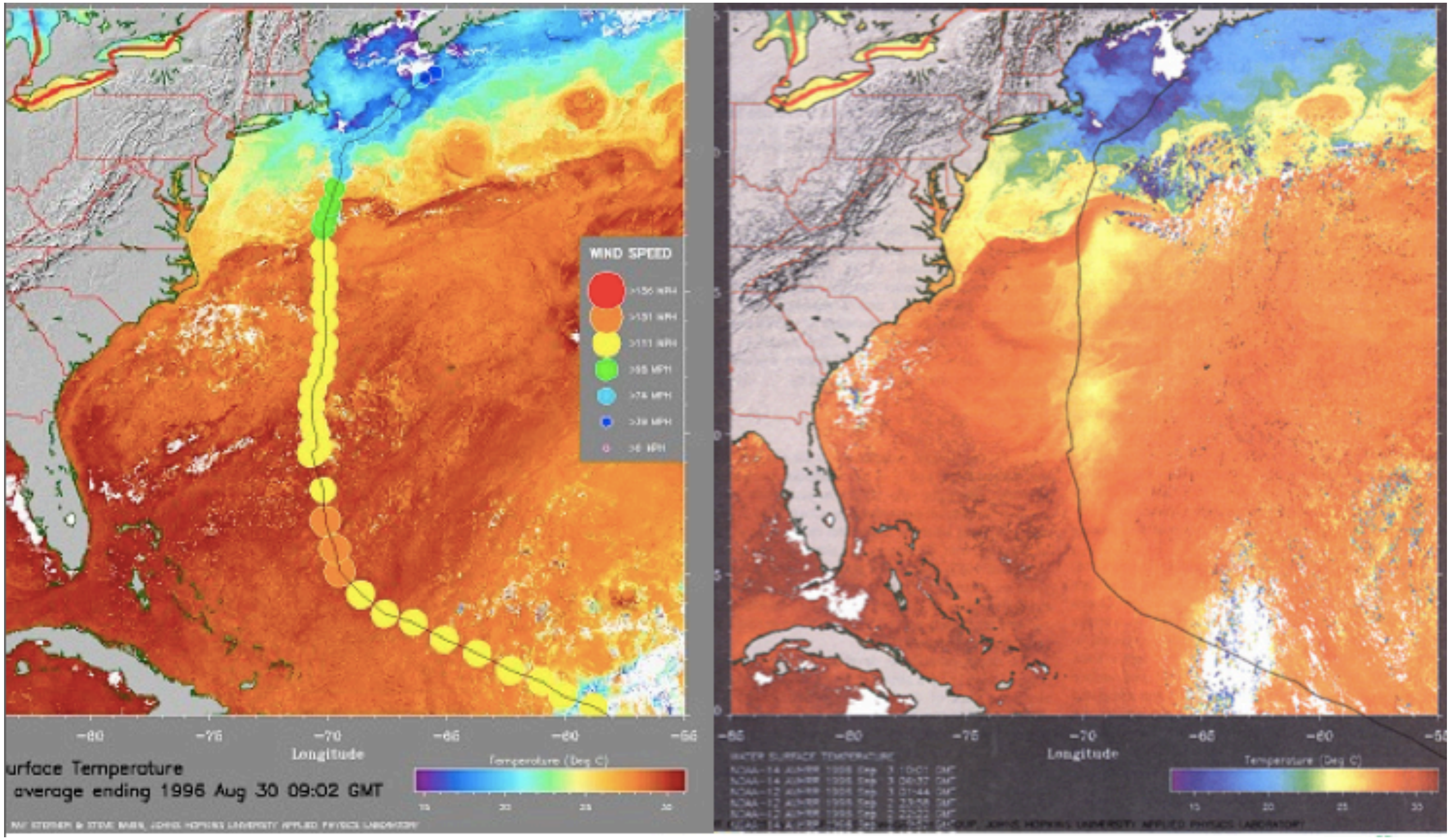
Hurricane Fabian 2003

[Wei and Pasquero JPO 2012]

Cold wake

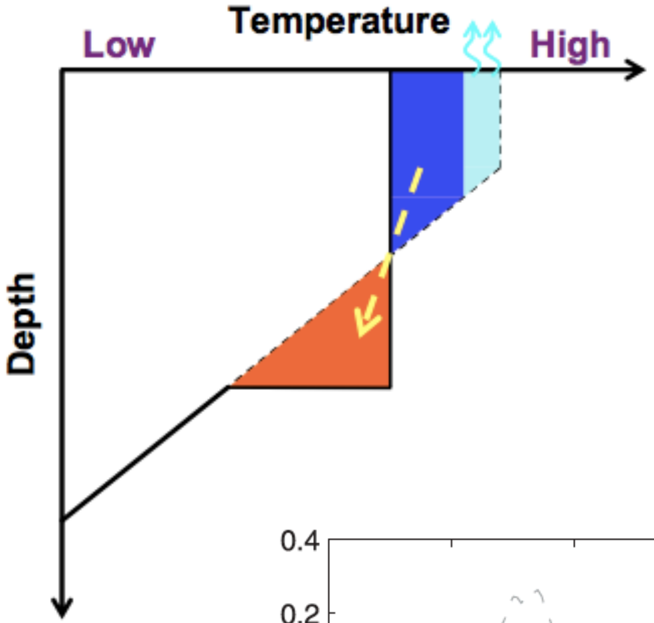
Cold wakes left by intense winds have SST anomalies up to -10°C. **[Chiang et al. JPO 2011]**

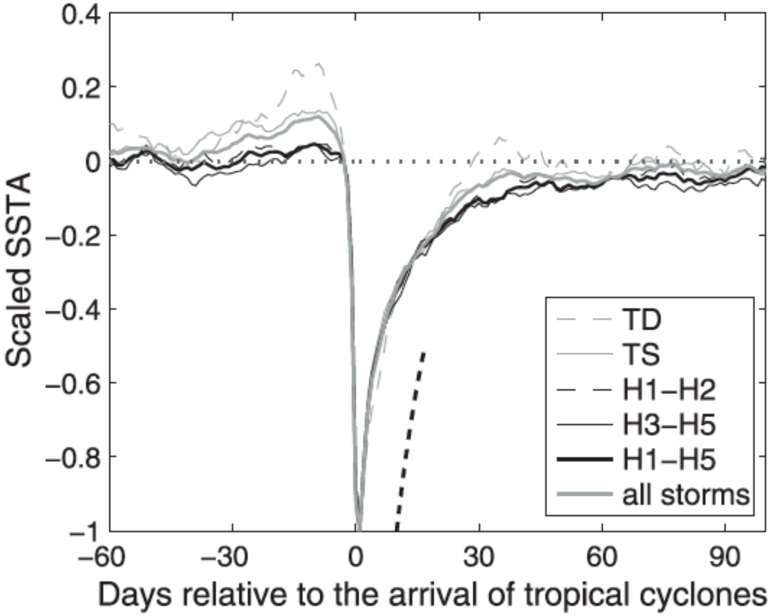
Sea Surface Temperature

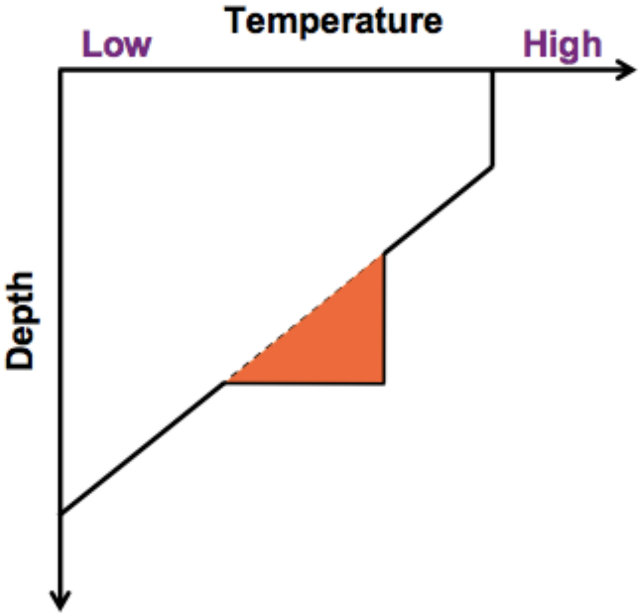


Hurricane Edouard, 1996 (30 august and 3 september)

Wake recovery







Within a month the surface cold anomaly has disappeared.

What happens to the subsurface warm anomaly?

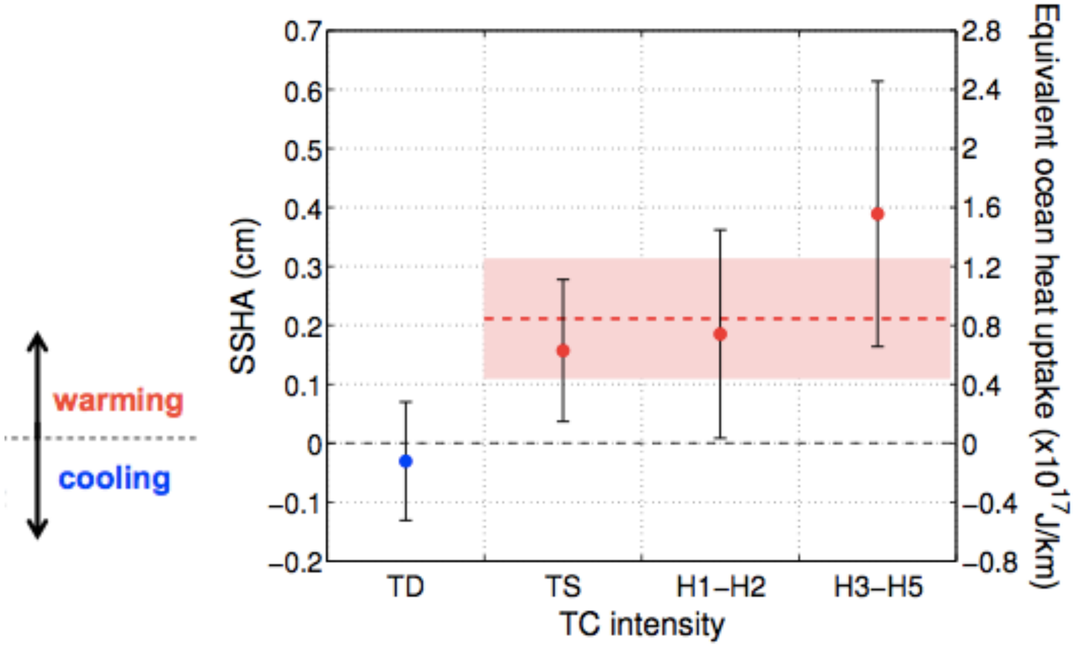
[Wei and Pasquero, J. Climate 2013]

Measuring the warming of the ocean due to TC

Sea surface height (SSH) records thermal expansion of water.

By studying the temporal evolution of SSH anomalies after the passage of TC, the warming effect of TC is estimated.

The effect is visible several months after the TC season.



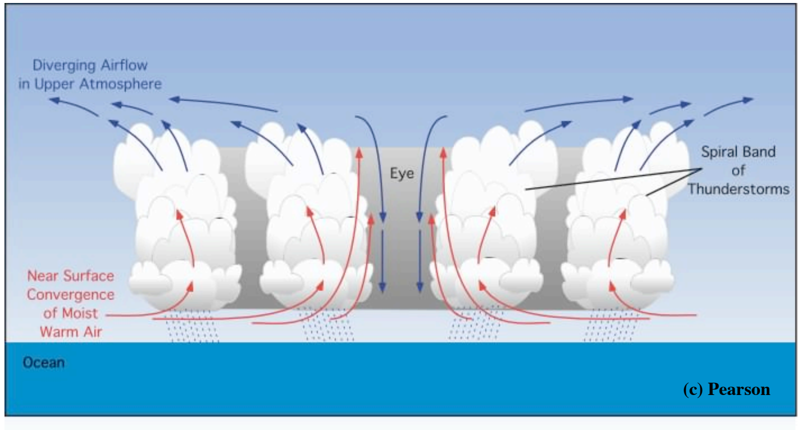
[Mei, Pasquero et al. PNAS *2013*]

Today, TCs have a global long term warming effect on the ocean of 0.32 ± 0.15 PW

Global wind energy dissipation rate over the oceans is about 1TW.

Does subsurface heat affect the atmosphere?
Yes, even suddenly, such as in tropical cyclones

Tropical cyclones: mechanism



(c) Pearson

1. Warm and moist air at the surface is uplifted by convection.

2. Expansion cooling induces condensation and release of latent heat, which increases the buoyancy of the air parcel, up to the tropopause.

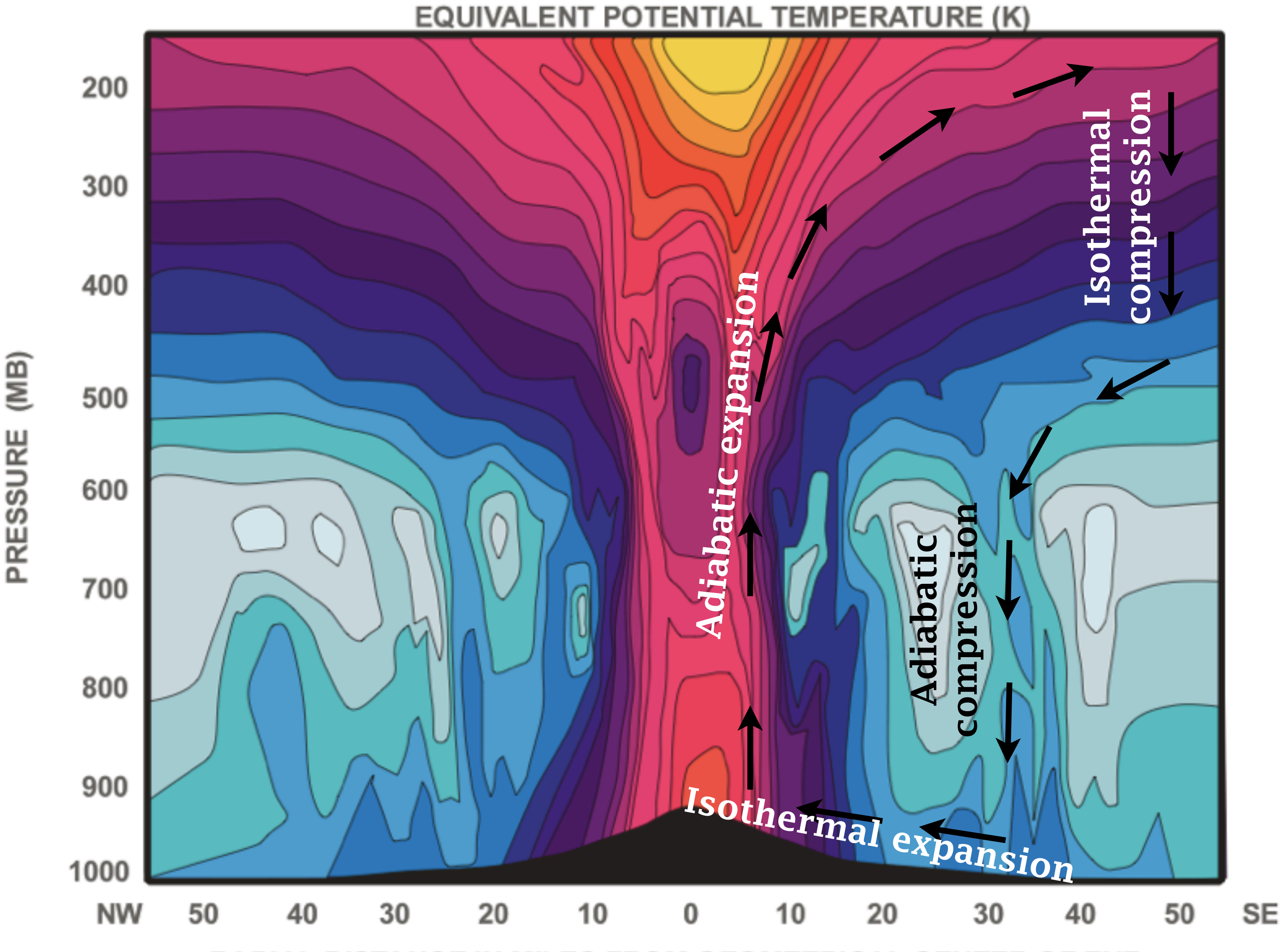
3. Air accumulating in the tropopause generates divergence and reduction of total mass in the air column. Low pressure at the surface.

4. Low pressure center drives convergence at the surface. Earth rotation deviates the inward flow, causing an intense spiraling motion.

5. Strong winds at the surface drive large enthalpy fluxes at the air-sea interface, which intensify convection.

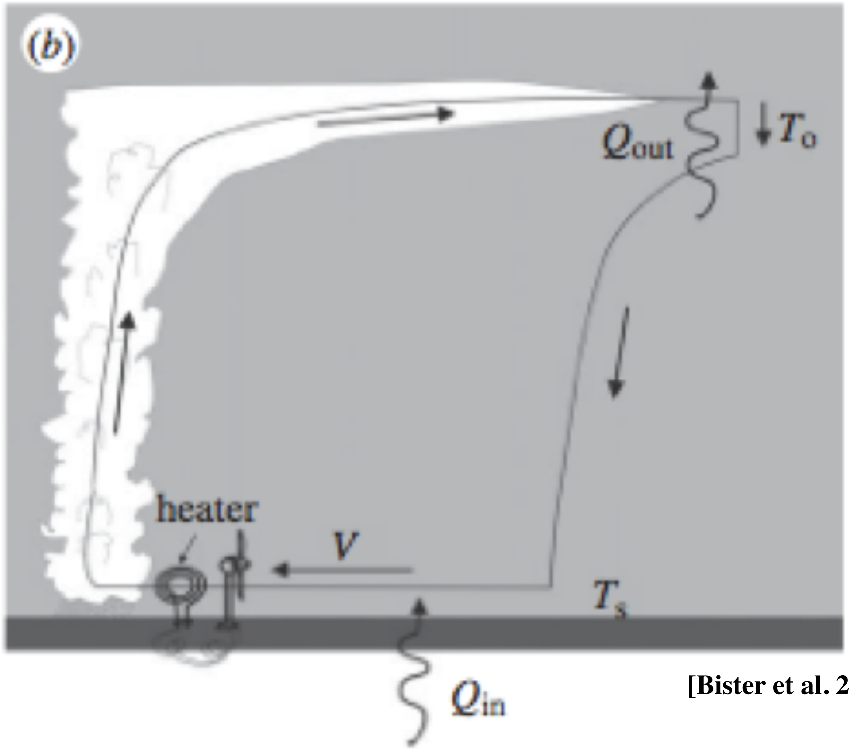
Isabel, 2003

Tropical cyclones as Carnot cycles



Data from Hurricane Inez 1966, redrawn by Emanuel [2003]

Potential intensity



[Bister et al. 2011]

C_k	air/sea heat exchange coefficient
C_D	air/sea momentum exchange coefficient
T_s	Sea Surface Temperature
T_O	tropopause temperature
h	moist static energy of air in the boundary layer
h_s^*	moist static energy of saturated air at T_s

$$F_k = C_k \rho |V| (h_s^* - h)$$

air-sea flux of enthalpy

$$D = C_D \rho |V|^3$$

energy extracted through friction and recycled to heat the boundary layer

$$\frac{Q_{in}}{T_s} - \frac{Q_{out}}{T_0} + \frac{\rho C_D V^3}{T_S} = 0$$

$$Q_{in} = Q_{out} = F_k$$

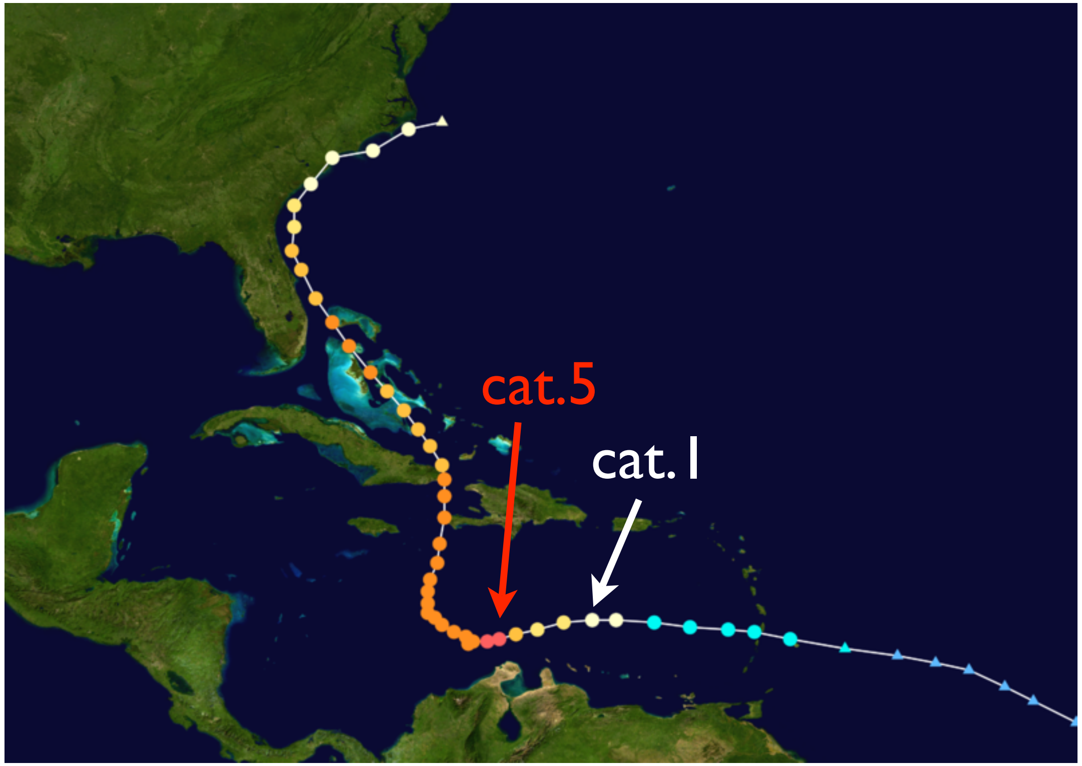
$$\boxed{V^2 = \frac{C_k}{C_D} \frac{T_s - T_o}{T_o} (h_s^* - h)}$$

Weak sensitivity of V to SST (1 m/s per 1°C)

Rapid intensification

Hurricane Matthew (october 2016):

from 130 km/hr (cat.1) to 260 Km/hr (cat.5) in 24 hours



more than
1600 casualties,
mainly in Haiti

Rapid intensification

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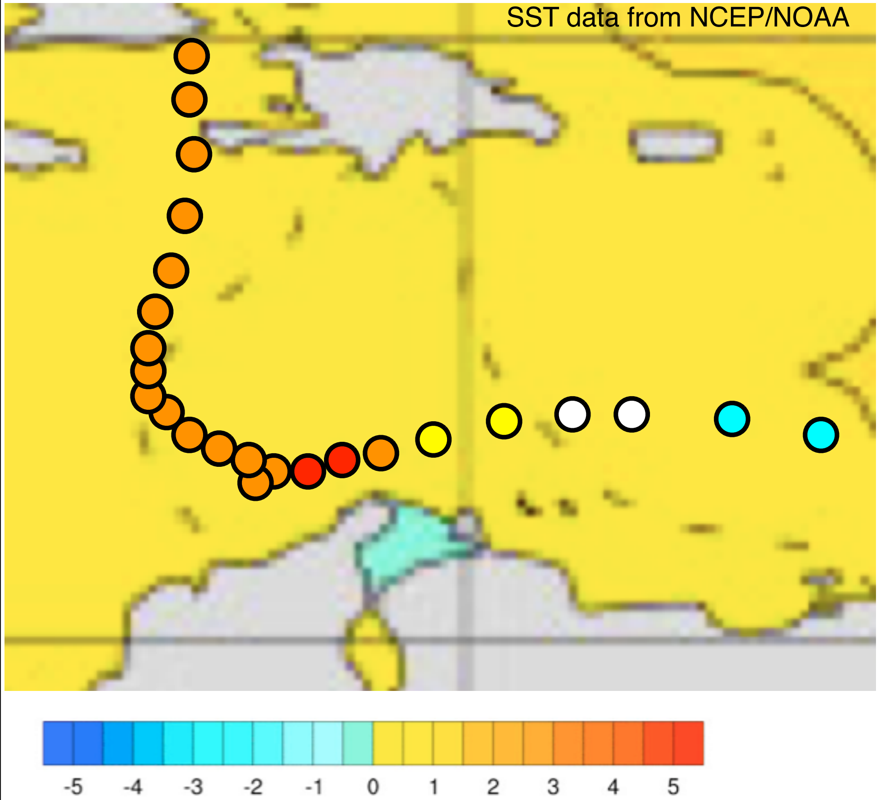
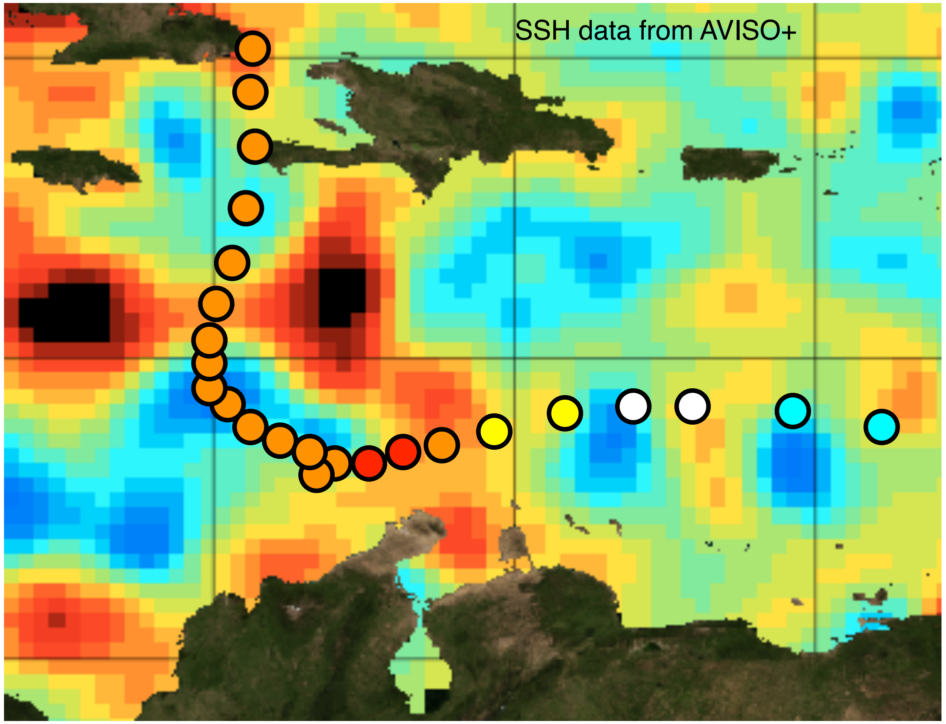
SEA SURFACE TEMPERATURE ANOMALY (°C)



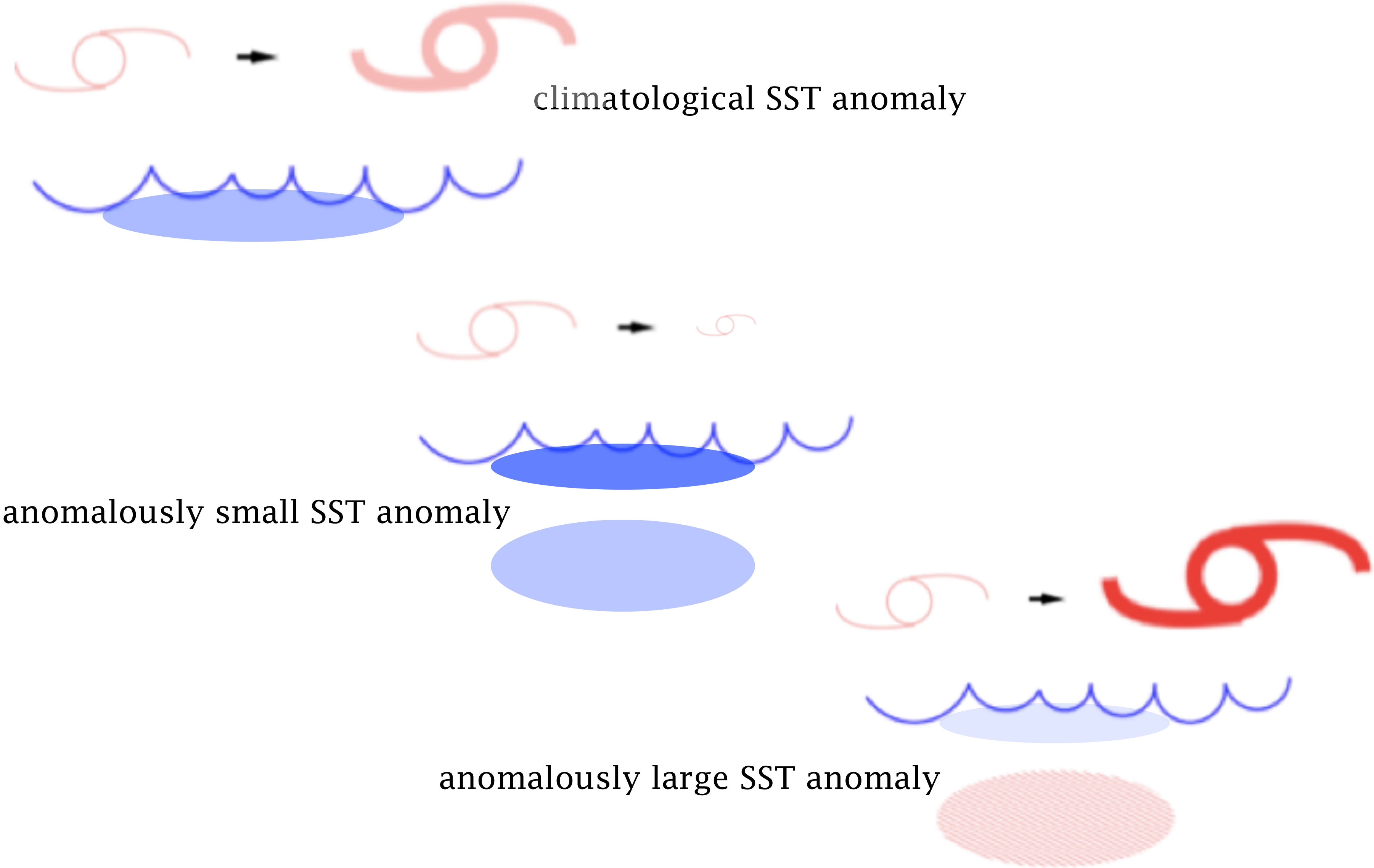
SST data from NCEP/NOAA

SEA SURFACE HEIGHT
(proxy for upper ocean heat content)



SSH data from AVISO+

Negative feedback



climatological SST anomaly

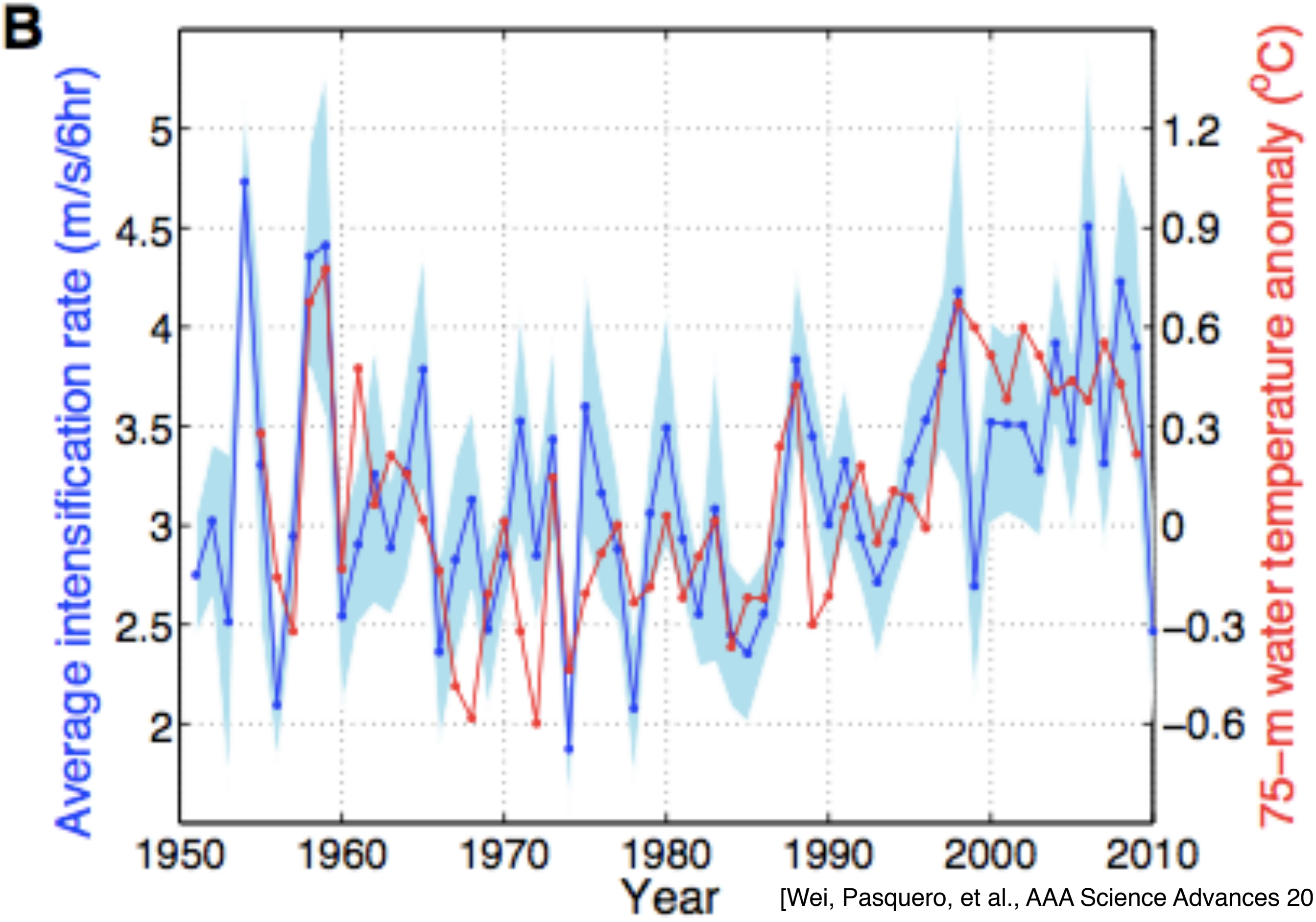
anomalously small SST anomaly

anomalously large SST anomaly

Climatological correlation

North Western Tropical Pacific typhoons

Annual mean intensification rate has a significant correlation (R=0.6) with subsurface temperature.



[Wei, Pasquero, et al., AAA Science Advances 2015]

Conclusions

Large effective heat capacity of ocean is associated to depth of the mixed layer.

Mixed layer depth (and ocean heat content) depend nonnlinearly on wind speed.

Intense winds have a long term warming effect on the ocean. Heating is two orders of magnitude larger than the input of kinetic energy.

Thermal energy stored in the ocean can suddenly be released in the atmosphere.
Example: strong sensitivity of hurricane intensity on subsurface ocean temperatures.