Warming of the Upper Equatorial Indian Ocean and Changes in the Heat Budget (1960-2000)

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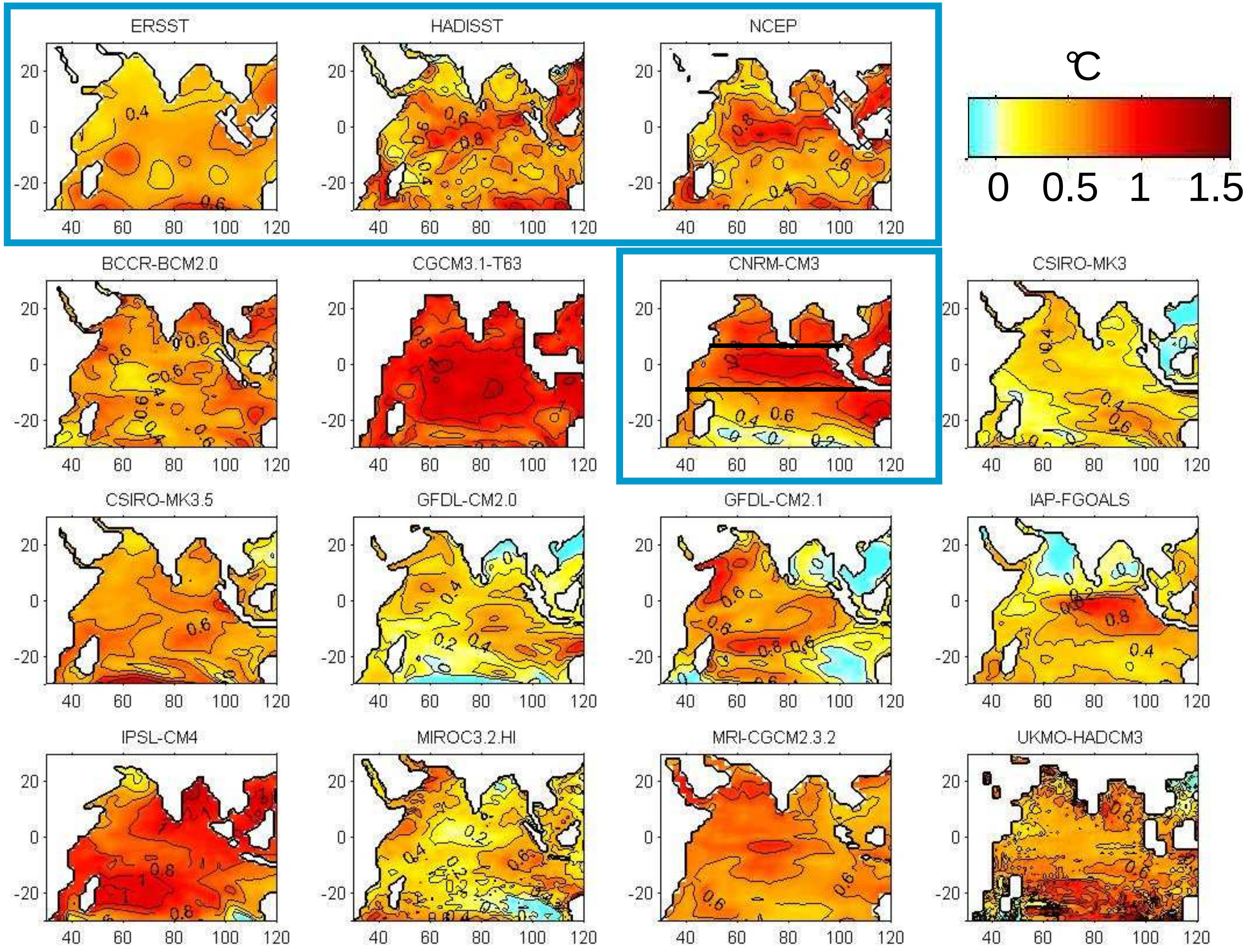
Outline

- Strong surface warming of the equatorial Indian Ocean observed over the last 4 decades
- Can climate change models reproduce this warming and other observed long-term changes?
- Can we estimate from models long term changes in the heat budget, and identify mechanisms responsible for the observed warming?

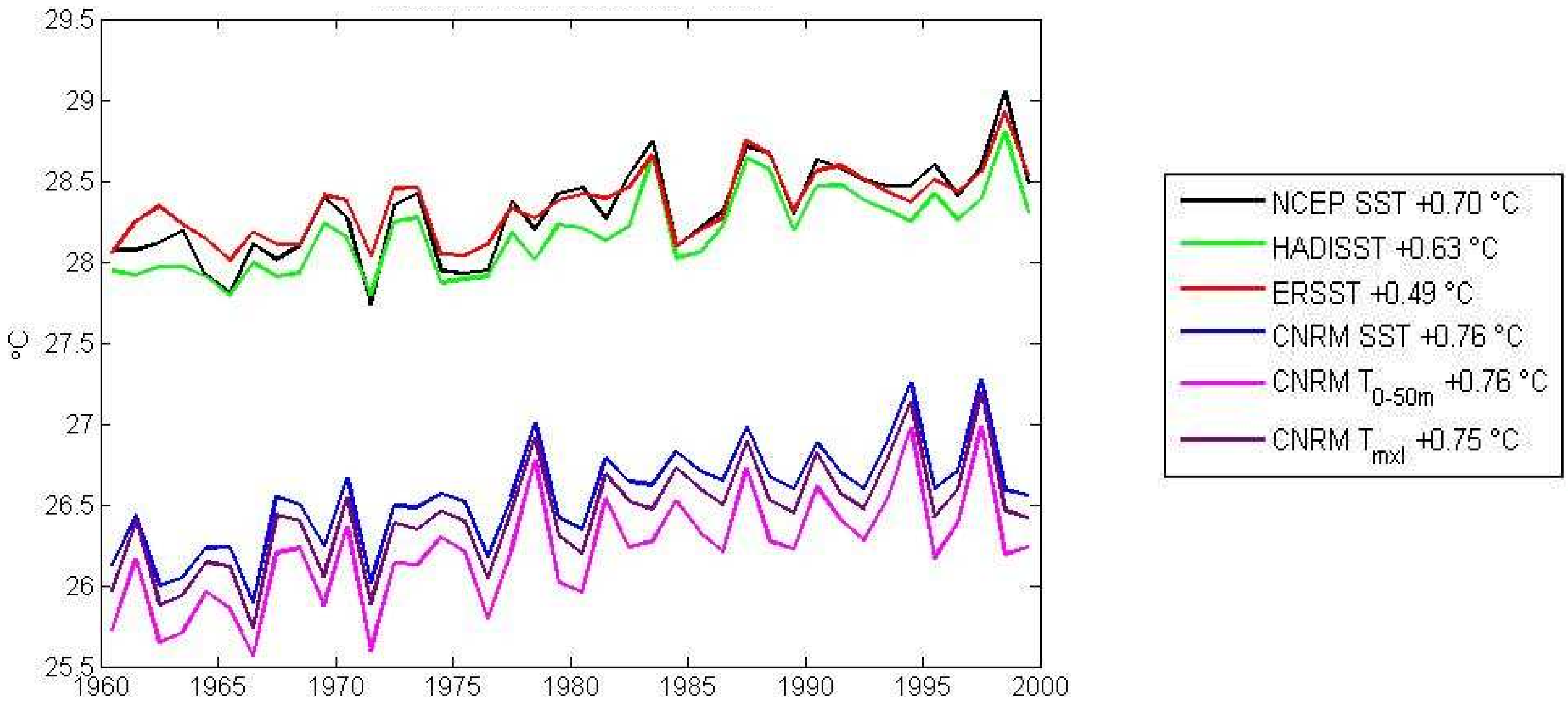
Sea Surface Temperature trend 1960-1999

Observations

IPCC models

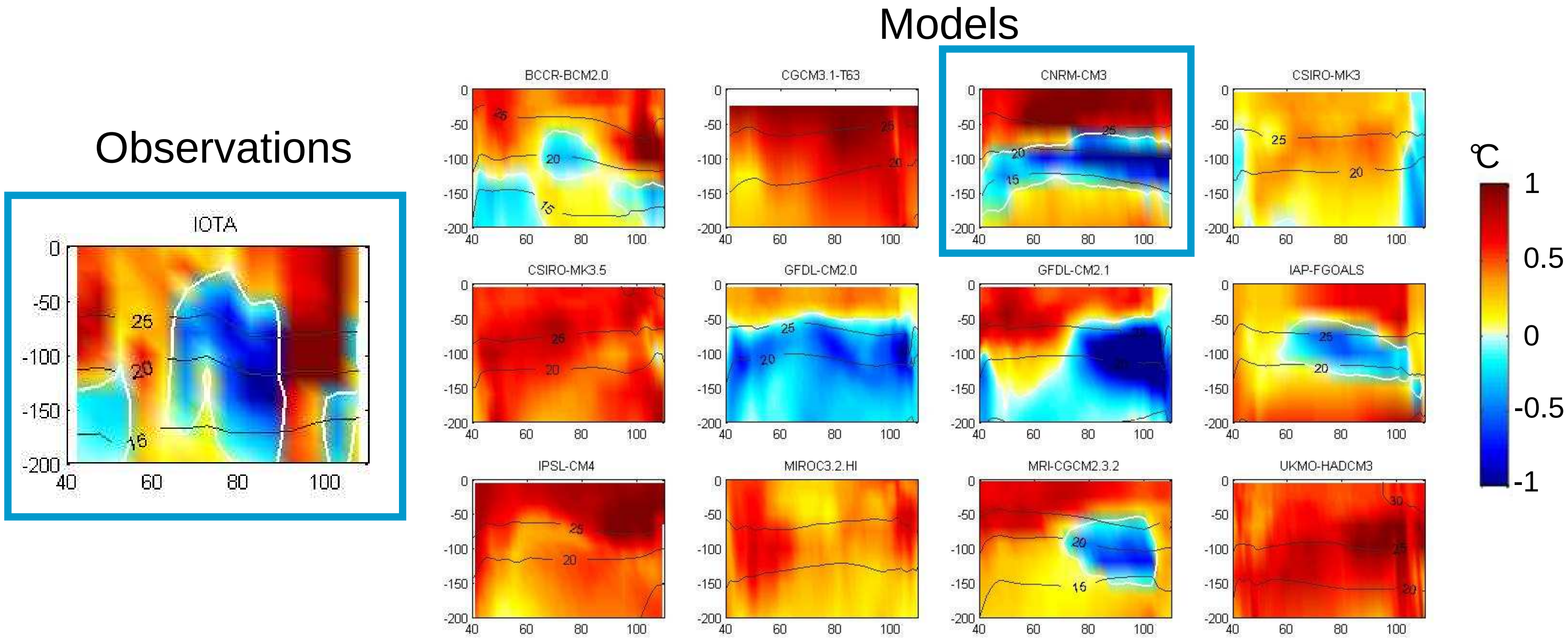


Equatorial Indian Ocean SST trend



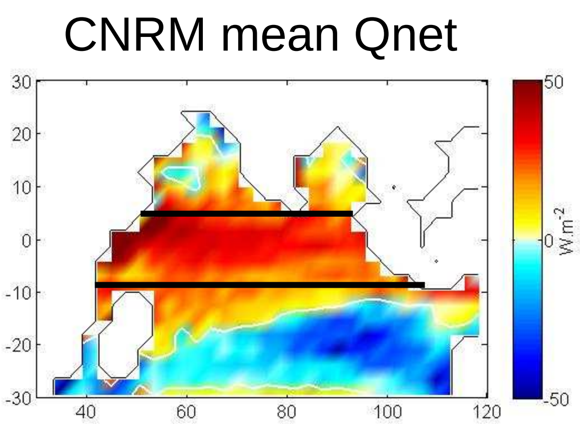
- CNRM-CM3 SST trend in the upper range of observations
- Cold bias in mean state (2℃)
- Similar trends in SST, $T_{0\text{-}50m}$, T_{mxl}

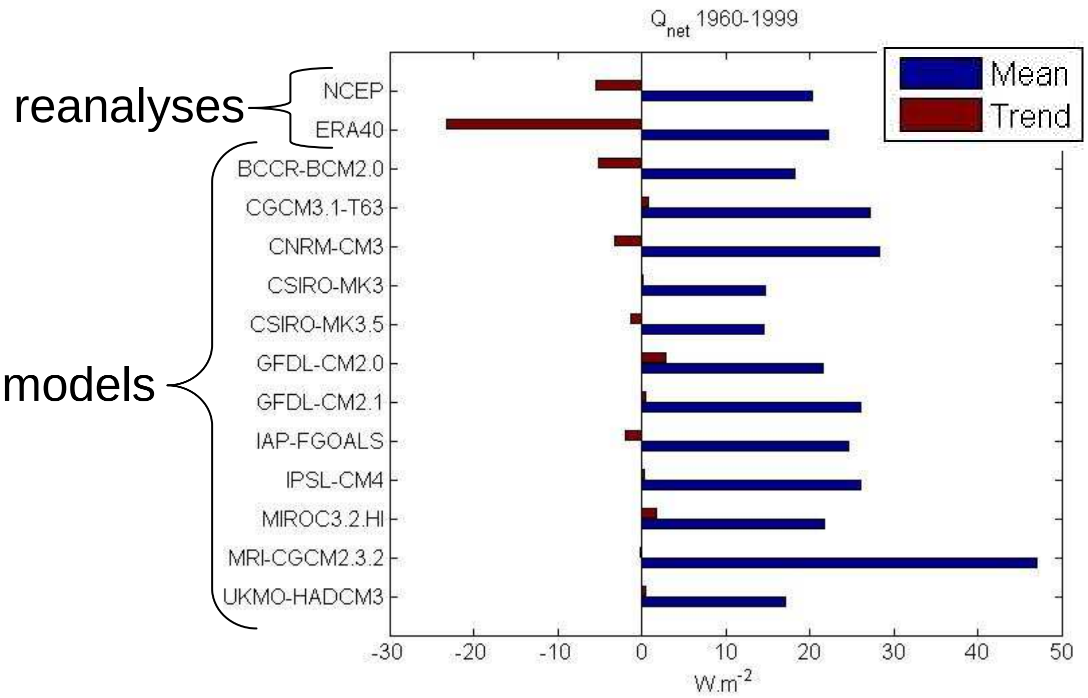
Subsurface Temperature trend (9°S-6°N)



- Observed cooling trend around the 20°C isotherm: sh allowing of the thermocline due to weakening of Walker circulation (*Alory et al., 2007; Vecchi et al., 2007*)
- Reproduced by only half of the models (CNRM-CM3)

Net Heat Flux trend





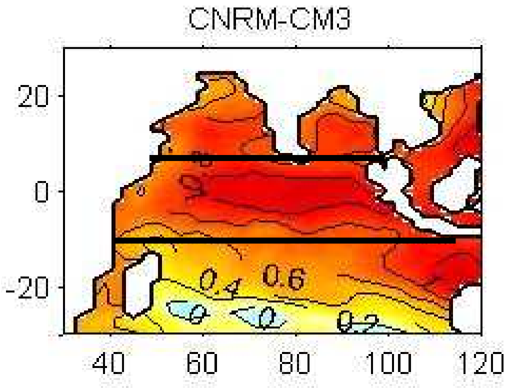
- Decreasing heat flux towards ocean in atmospheric reanalysis products, and a few models (CNRM-CM3)
- Most consistent trend in reanalyses: increase in Qlat (evaporation)
- SST warming due to an oceanic mechanism?

Model evaluation

- In the equatorial Indian Ocean, over 1960-2000, CNRM-CM3 reproduces key observed features:
  - equatorial tongue of SST warming
  - cooling in the thermocline
  - decrease in net heat flux
- Simulation of interannual variability of the tropical Indian Ocean (IOD, ENSO): CNRM-CM3 ranked among the best (*Saji et al., 2006*)

→ **We select CNRM-CM3 to investigate changes in the long-term heat budget of the equatorial Indian Ocean**

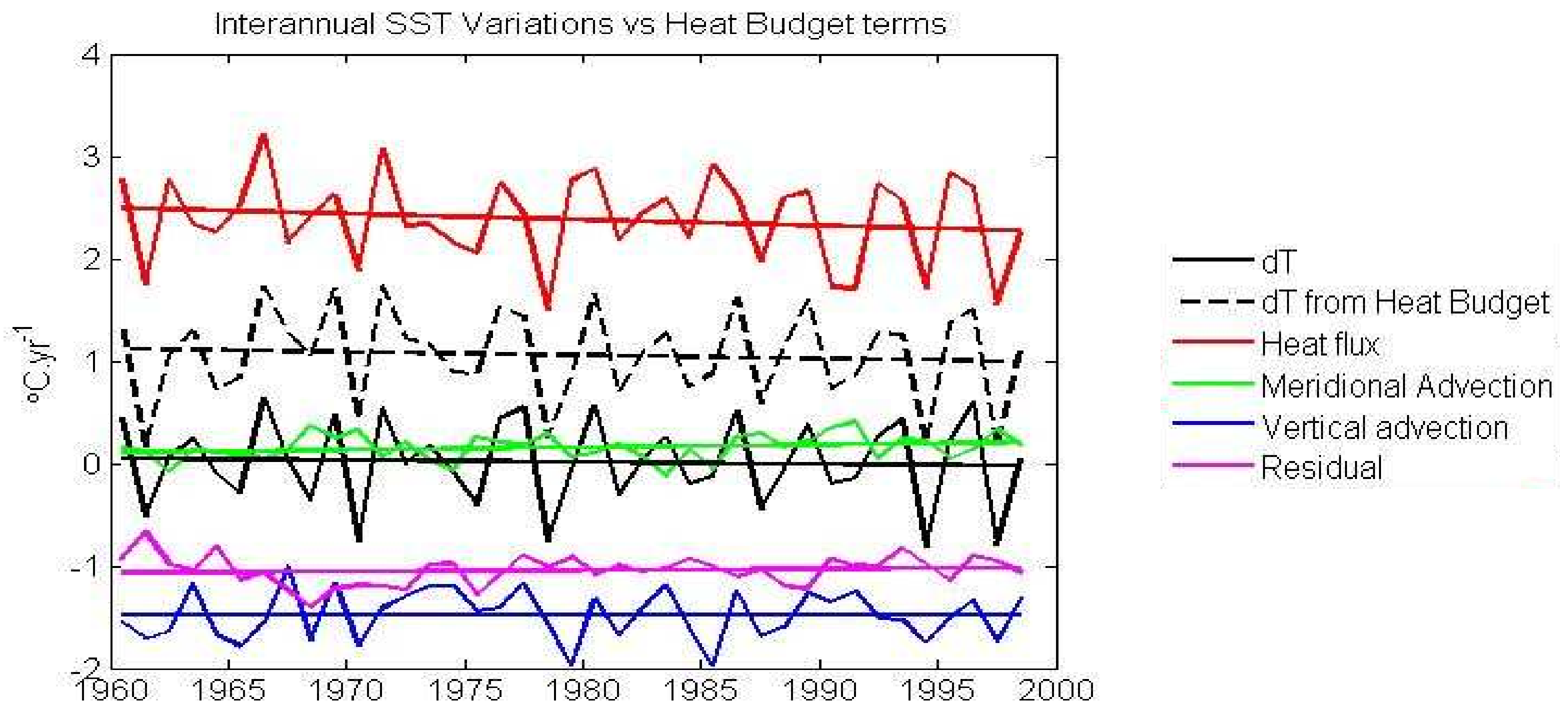
Heat Budget in the 0-50m layer: Formulation



$$\frac{\partial T_{box}}{\partial t} = \frac{1}{v_{box}}\left(\iint \frac{Q_0 - Q_h}{\rho C_p} dxdy + \iint V(T - T_{box}) dxdz + \iint W_h (T_h - T_{box}) dxdy + res \right)$$

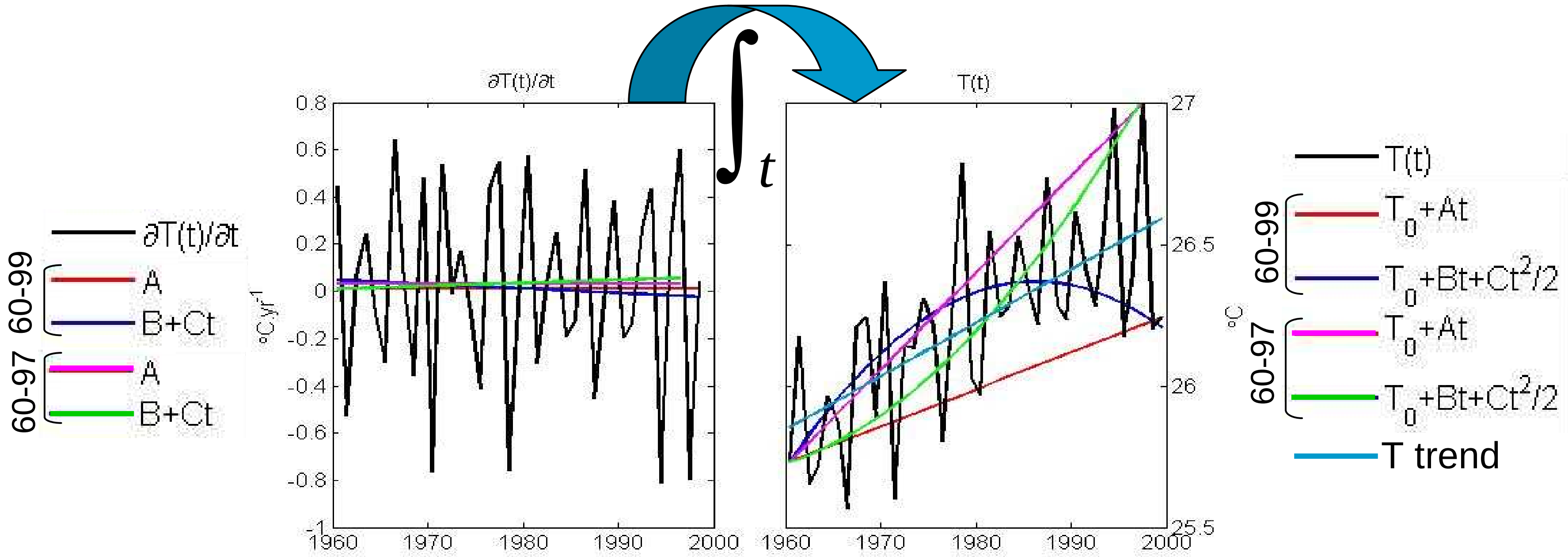
- Different terms:
  - Heat fluxes (penetration below 50 m = 5% Q_{sw})
  - Meridional advection (Arabian sea, Bay of Bengal, South)
  - Vertical advection (upwelling)
  - Residual term: diffusion/eddy processes
- Fixed bottom → no entrainment term
- Original grid outputs to reduce interpolation errors
- Monthly means of Q, V, W, T

Heat Budget in the 0-50m layer: Balance



- Mean warming by heat fluxes, cooling by vertical advection
- Explicit resolution of interannual variability (*r*=0.95)
- 1℃/yr residual term = diffusion/eddy processes (w eak variability)

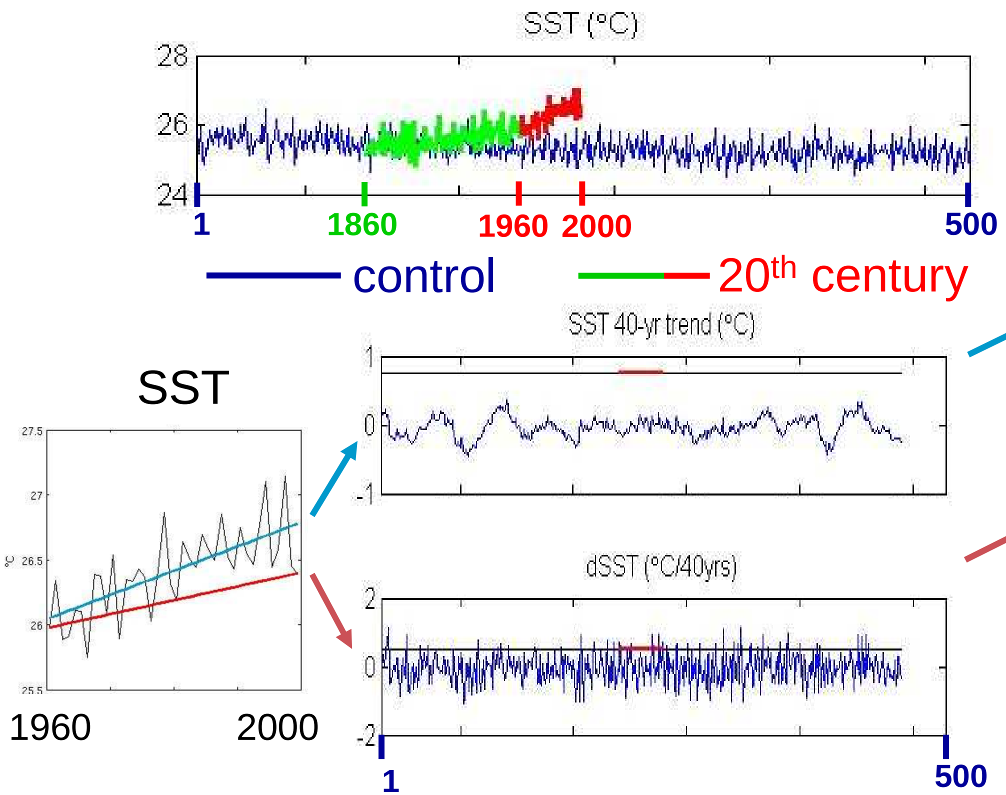
From Heat Budget to SST trend

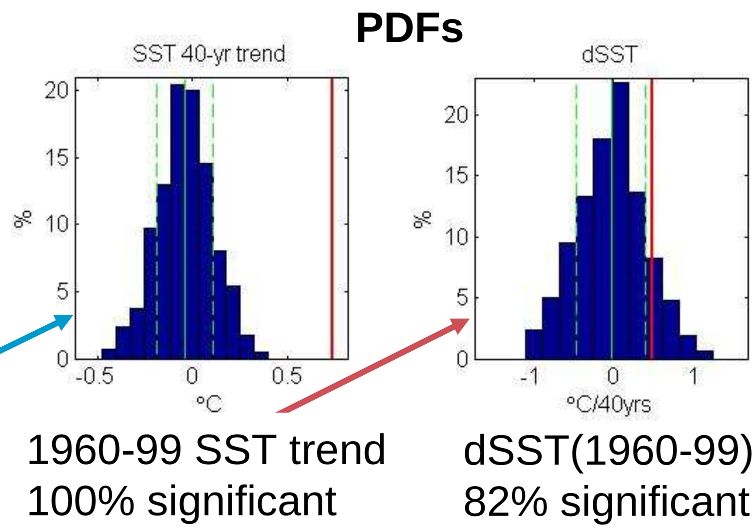


- Long-term mean of dT/dt over 1960-1999 ↔ T(1999)-T(1960)
- Linear trend of dT/dt ↔ quadratic fit of T(t)
  - decreasing trend in dT/dt not inconsistent with increasing SST!
  - only a secondary term, very sensitive to interannual variability
- T(1999)-T(1960) underestimates warming trend due to interannual variability

Heat Budget: 20th Century vs. Preindustrial

- Preindustrial control run: natural coupled variability
- 20th century run: natural coupled variability
  + radiative forcing (solar, volcanic, aerosols, ozone, greenhouse gases)

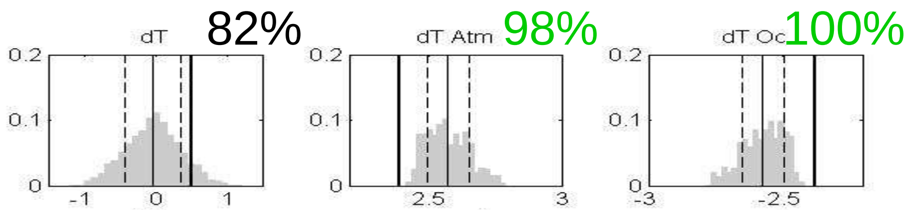




- SST trend outside the range of natural variability→ related to climate change (GHGs)

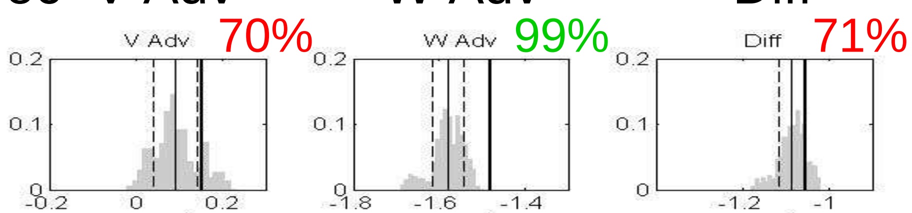
Heat Budget: changes in heat terms

dT = dTatm + dToc



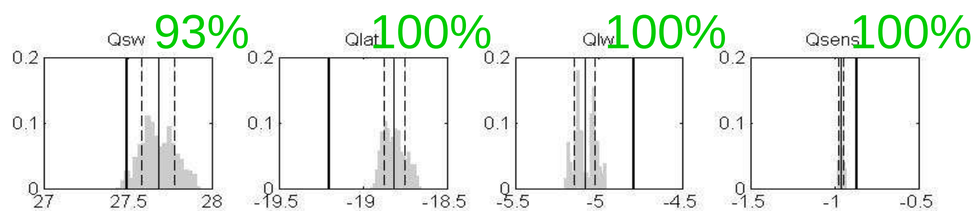
CTL: -0.03℃ +2.57℃/yr -2.57℃ /yr
20C: +0.51℃ +2.39℃/yr -2.38℃/ yr
DIFF: +0.54℃ -0.18℃/yr +0.19℃/ yr

dToc=V Adv + W Adv + Diff



DIFF: +0.07℃/yr +0.10℃/yr +0.04 °/yr

dTatm= Qsw+ Qlat + Qlw + Qsens



DIFF: -0.19℃/yr -0.39℃/yr +0.29°/yr +0.0 9℃/yr

- Very significant changes in the heat budget
- Decrease in atmospheric warming overcompensated by decrease in oceanic cooling: ocean rules!
- Oceanic changes mostly due to vertical advection, less significant contribution of meridional advection, diffusion
- Decrease in Qnet mostly due to Qlat (evaporation), Qsw also contributes, Qlw and Qsens are damping terms

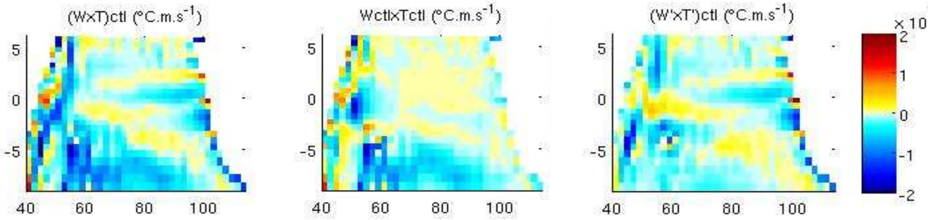
Changes in vertical advection

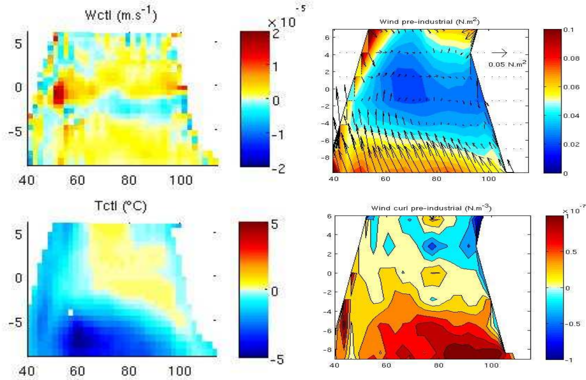
$$T = \overline{T} + T'$$
$$\Delta T = \overline{T}^{20C} - \overline{T}^{CTL}$$

Advective terms — W, T at 50m — wind/w-curl

CTL

$$\overline{WT} = \overline{W}\,\overline{T} + \overline{W'T'}$$

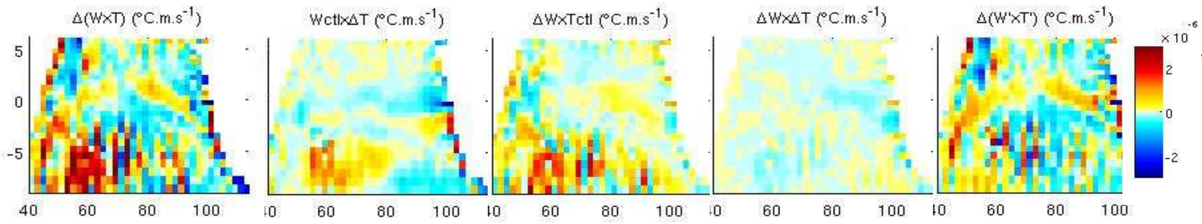


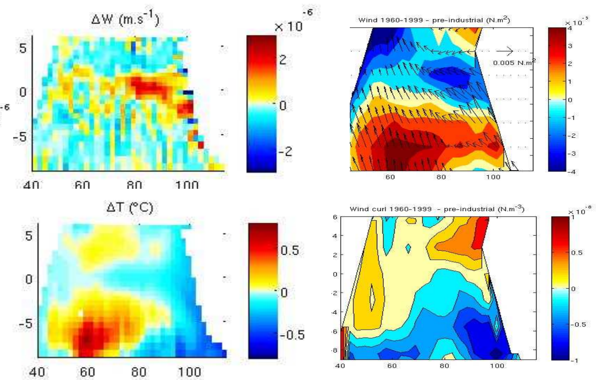


$\int_{x,y}$ → -1.57 = -0.80 -0.77 (°C/yr)

20C-CTL

$$\Delta(WT) = \overline{W}\Delta T + \Delta W\overline{T} + \Delta W\Delta T + \Delta(W'T')$$

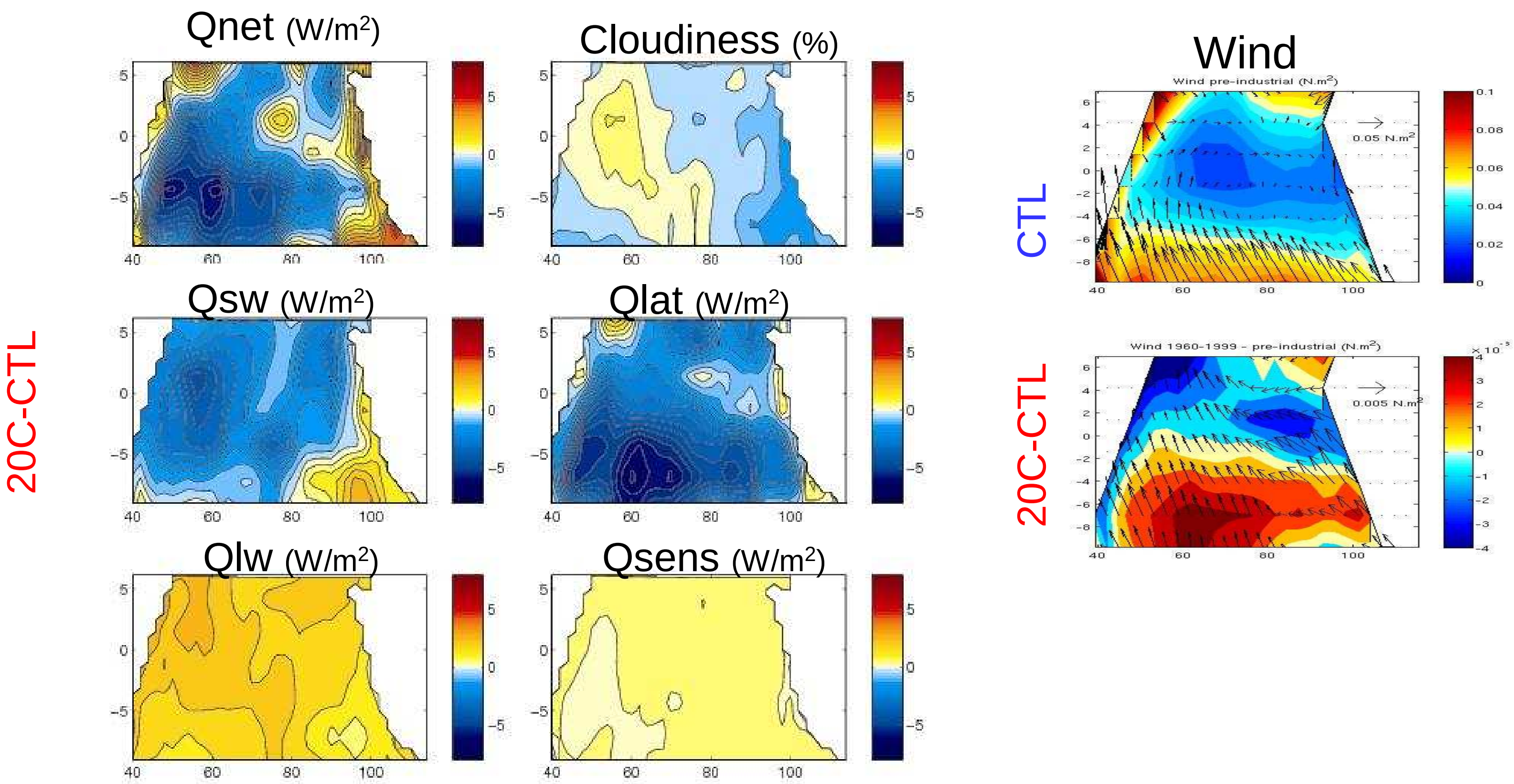




$\int_{x,y}$ → +0.094 = +0.001 **+0.106** -0.013 -0.0002 (°C/yr)

- In the south, upwelling-favorable wind curl decreased -> ΔW<0, ΔT>0
- In the thermocline dome, both ΔW.T and W.ΔT increase vertical advection but ΔW.T > W.ΔT and W.ΔT ~0 on spatial mean

Changes in Heat Fluxes



- Changes in evaporation(Qlat) strongly correlated to changes in wind speed
- Evaporation further enhanced by increase in SST
- Increase in cloudiness downstream of max(ΔQlat) due to more moisture → decrease in Qsw and increase in Qlw due to cloud filtering

Conclusion (1/2)

- New methodology to identify long term shifts in heat budget related to climate change by comparing post/pre-industrial IPCC simulations

- SST warming of the equatorial Indian Ocean due to global changes in radiative forcing (GHGs) but regionally driven by ocean rather than atmosphere (dynamics rather than thermodynamics)

- Regional coupled mechanisms identified

Conclusion (2/2)

- Main process: weakening (ΔW.T) of thermocline dome upwelling, consistent with decrease in Southern overturning Cell (*Lee & McPhaden, 2008*)
- Driven by decrease in southern wind curl
- Strengthening of southern trade winds consistent with Gill-atmosphere response to SST increase (North-South gradient)
- Increasing wind speed and warming SST enhance evaporation which drives the decrease in downward heat flux
- The decrease in heat flux is a negative feedback to warming SST