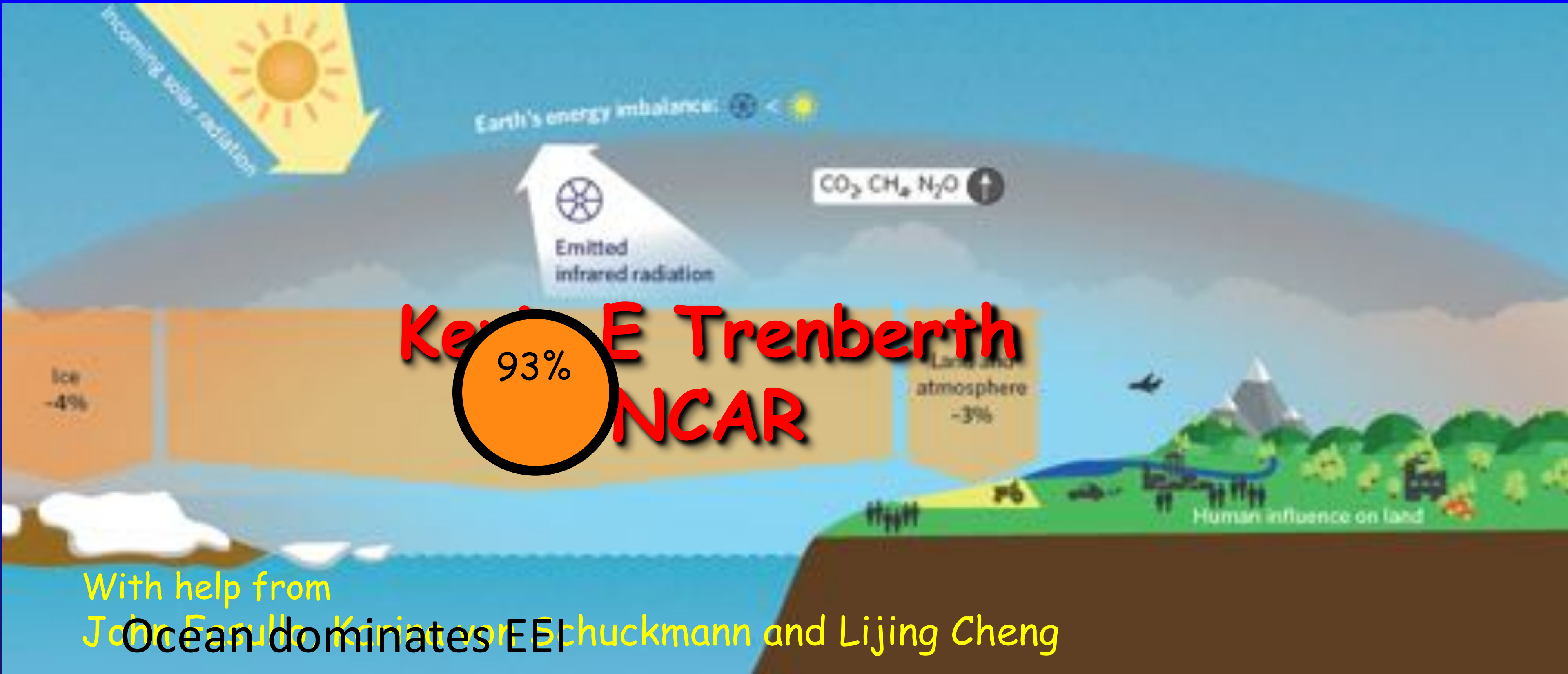
Why tracking Earth's Energy Imbalance is an imperative



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NCAR

With help from
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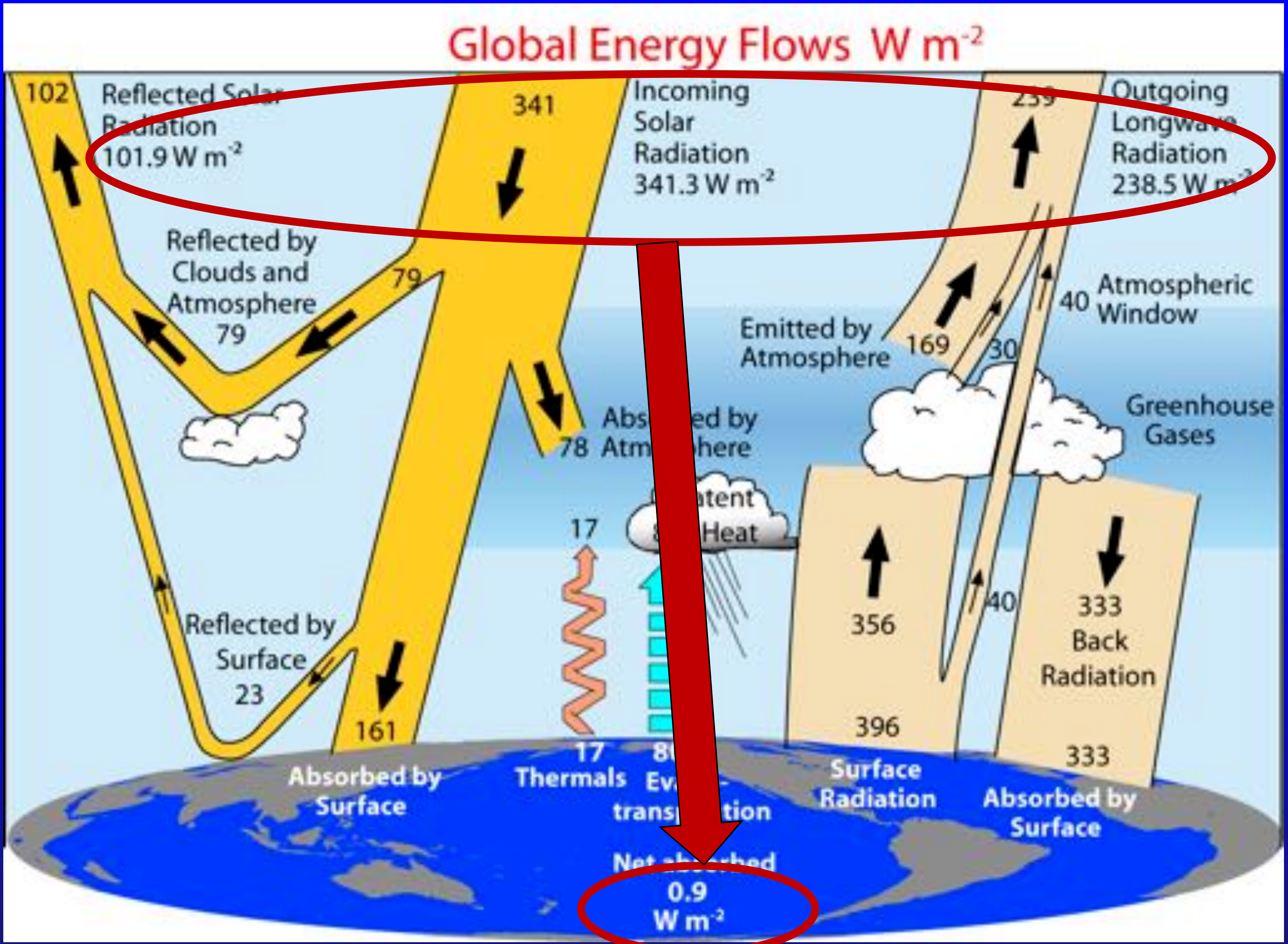
Energy on Earth

The climate is changing from increased GHGs.
We expect an energy imbalance from heat-trapping GHG.
The planet warms until OLR increases to match the ASR.
But there are many feedbacks and complexities.

The most fundamental measure that the climate is changing is the energy imbalance.

GHG: Greenhouse Gases
OLR: Outgoing Longwave Radiation
ASR: Absorbed Solar Radiation

Trenberth et al (2009)



Earth's Energy Imbalance
How do we measure it?

1. Direct measurements from space of ASR, OLR, Net
2. Take inventory of where all the energy has gone
3. Use climate models with specified forcings
4. Use atmospheric reanalyses
5. Use surface fluxes (assume no atmospheric heat capacity)

1. Not accurate enough; good for relative changes after 2000
2. Only viable option: requires derivative. Not consistent over time.
3. Depends on how good the model and the forcings are.
4. Do not conserve energy, do not have accurate forcings.
5. Large systematic errors.

Earth's Energy Imbalance
(net effect after all feedbacks included)

1 W m^{-2}

This is small at any time compared to natural flow of energy:

240 W m^{-2}.

So this is NOT how climate change is experienced.

Instead it has to accumulate, which it does under some circumstances, since it is always in the same direction.

Earth's Energy Imbalance
(net effect after all feedbacks included)

Varies over time but is now about:

$1\ W\ m^{-2}$.

1 Christmas tree light is about 0.4 W.

Hence the heating is about 500 TW.

[vs U.S. in 2014 electricity consumption was about 43×10^{10}W
Germany 6.5×10^{10} W: Total order 1 TW: Factor of 500 less.]

The direct effects of humans is small:
except locally in cities.
It is mainly through interference with natural flows of energy that matters

Global warming means more heat:

Where does the heat go?

1. Warms land and atmosphere

>90%

2. Heat storage in the ocean (raises sea level)
3. Melts land ice (raises sea level)
4. Melts sea ice and warms melted water
5. Evaporates moisture ⇒ rain storms, cloud
   ⇒ possibly reflection to space

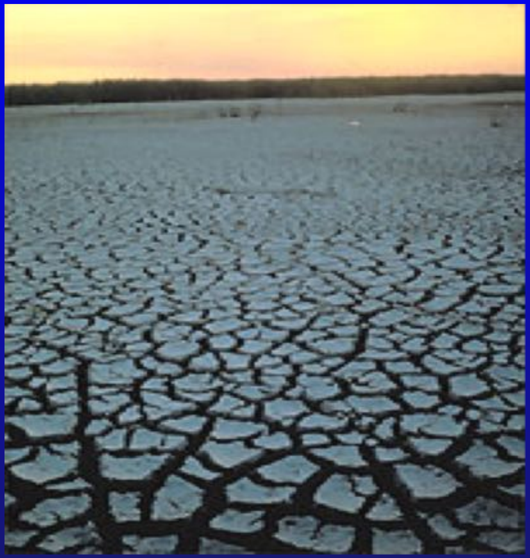
Controlling Heat

Human body: sweats

Homes: Evaporative coolers (swamp coolers)

Planet Earth: Evaporation (if moisture available)

e.g., When sun comes out after showers,



the first thing that happens is that the puddles dry up:
before the temperature increases.

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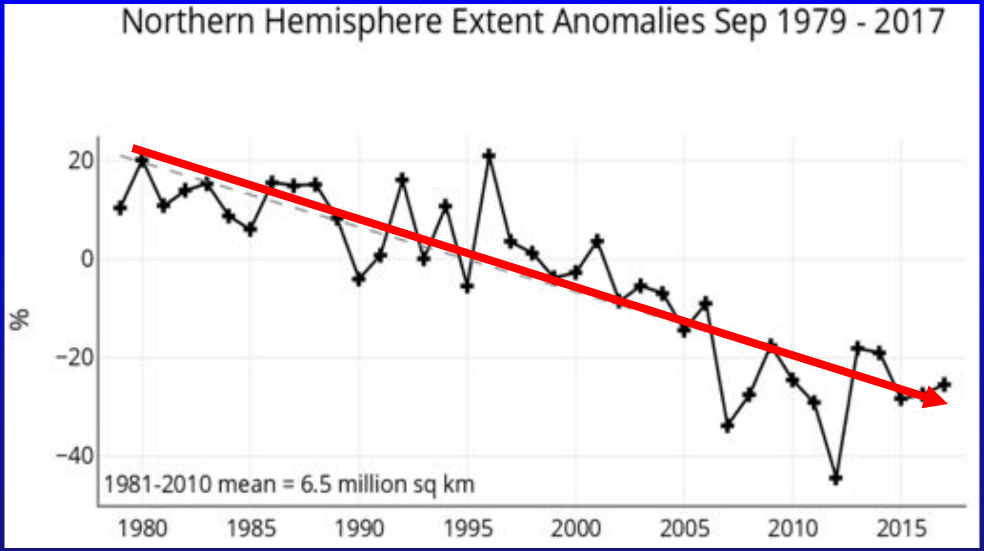
Effects accumulate in melted ice

Increased Glacier retreat since the early 1990s

Muir Glacier, Alaska

Arctic sea ice loss: over 40% in summer



Accumulation on land?

If land is wet: heat goes into evaporation.
But in a drought, the heat accumulates.

- Drying
- Heating

1 W m^{-2} over a month, if accumulated, is equivalent to 720 W m^{-2} over 1 hour.

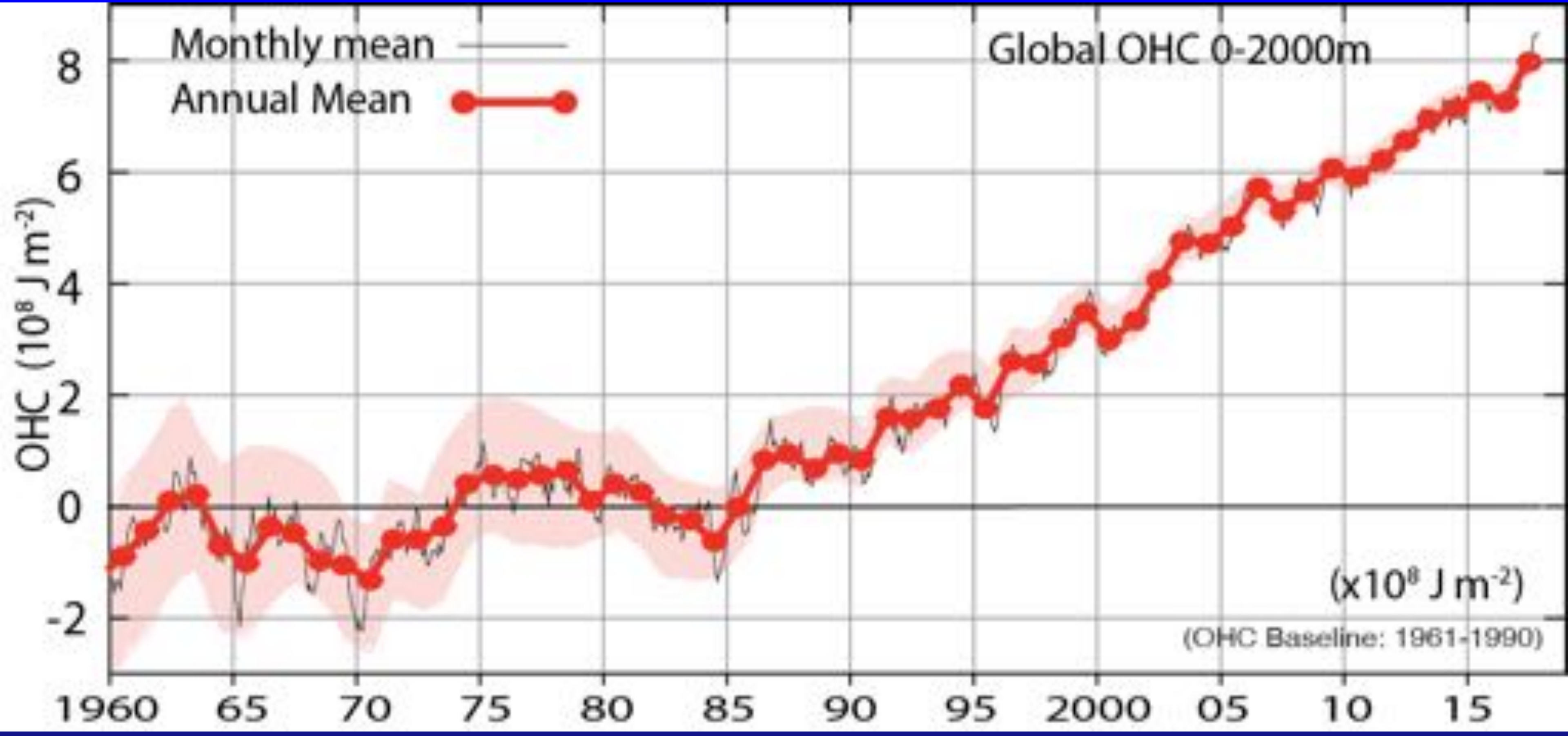
720 W is equivalent to full power in a small microwave oven.
1 m^2 is 10 sq ft

=> 1 microwave oven at full power every square foot for 6 minutes:

No wonder things catch on fire!

Ocean Heat Content

Updated from Cheng et al 2017



Through 2017

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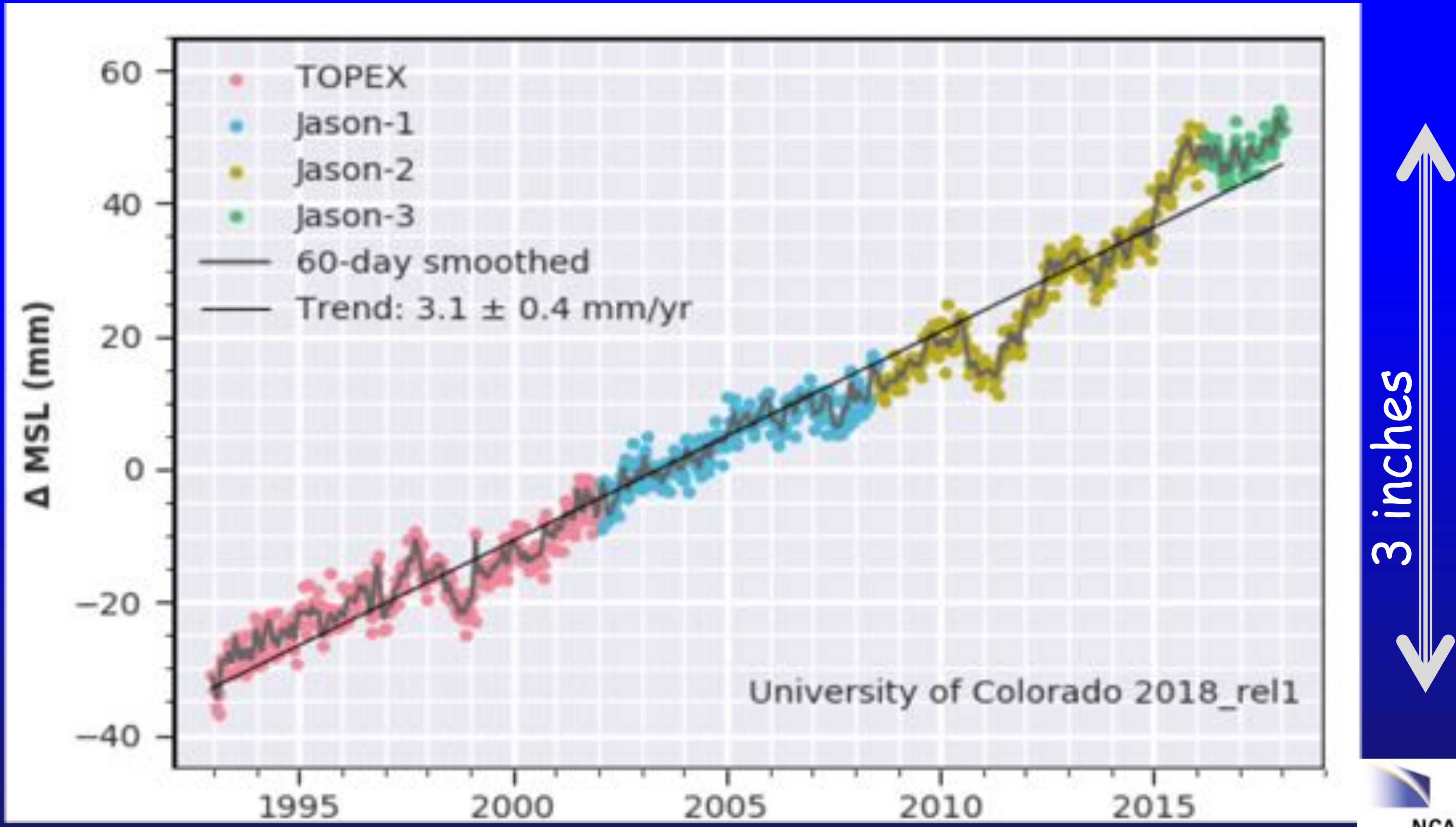
A consequence of glacier melt and ocean heating: Sea Level Rise



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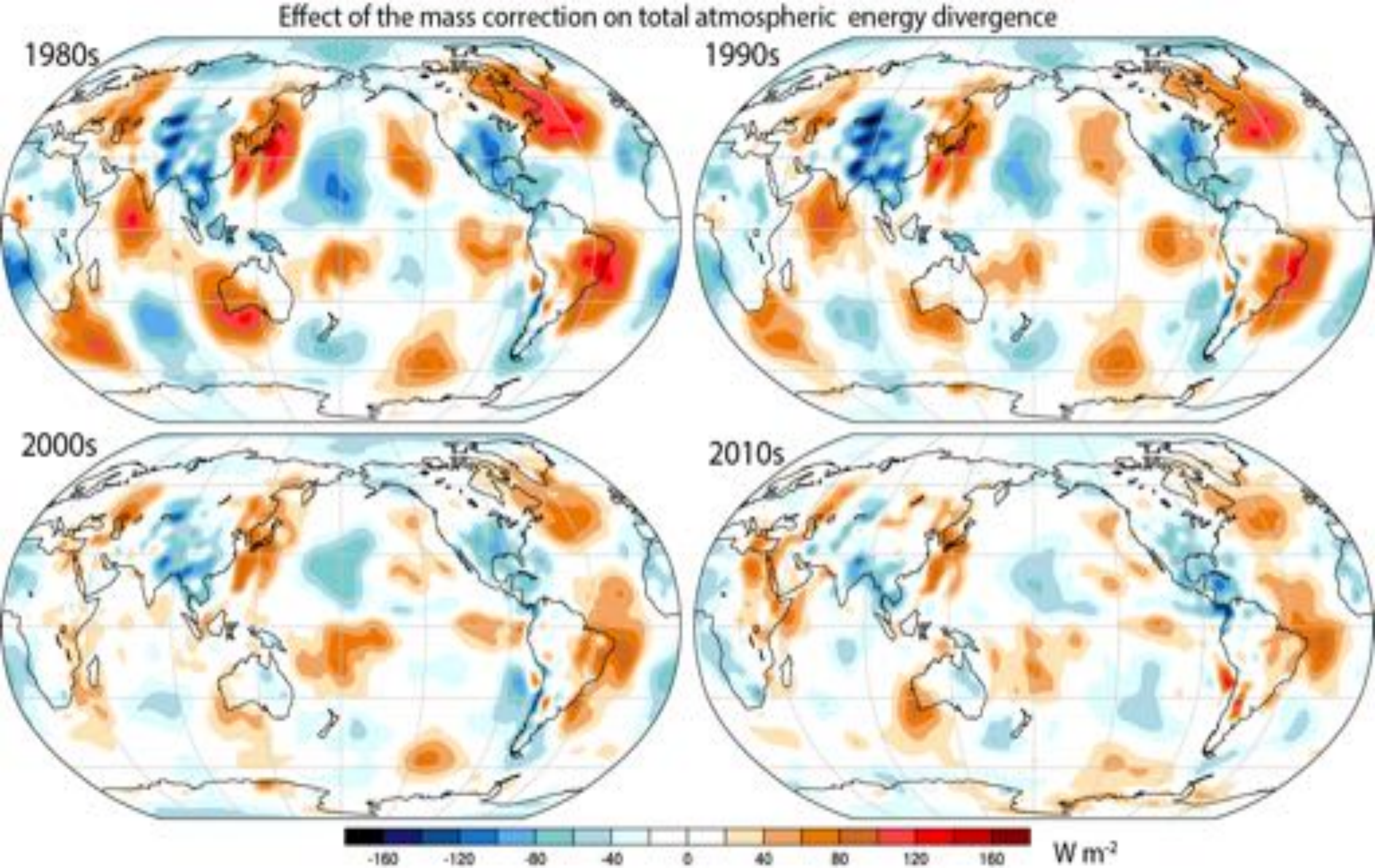
Can we balance the energy budget locally?

Mass imbalances

- In reanalyses, the mass is not balanced. Even a small spurious imbalance can imply a large energy flux.
- *It is essential to balance mass budgets before doing energy budgets.*
- There is a real mass imbalance in atmosphere associated with precipitation
- *Previously we used a barotropic adjustment*
- *Instead it should be weighted by the moisture profile*



The difference between making no mass correction versus with, on the total atmospheric energy divergence: **ERA-I**

Mass equations

Need to consistently account for mass and enthalpy associated with precipitation!

…ntinuity in pressure coordinates is

$$\frac{\partial \omega}{\partial p} \ldots = e - c$$

…re equation in flux form:

$$\frac{\partial q\omega}{\partial p} = e - c$$

- Here $q = q_v$ (w… …apor) – ignores liquid and ice
- RHS relates to precipita… …ion = $-\frac{\partial q_l}{\partial t}$,
- Or vertically integrated = $E - P$

Gives rise to a term not previously considered:
The enthalpy of precipitation

Energy Equations

The total dry energy equation in advective form

- $$\frac{\partial}{\partial t}\left(c_p T + k\right) + \mathrm{v}.\nabla(s+k) + \omega\frac{\partial}{\partial p}(s+k) = Q_1 - Q_f$$
  - $s = c_p T + gz$ is the dry static energy. OR
  - $s = c_p(T - T_0) + gz$ using a reference temperature.
- the flux form of this equation: add *(s+k)* × eq conty;
- $$\frac{\partial}{\partial t}\left(c_p(T - T_0) + k\right) + \nabla.(s+k)\mathrm{v} + \frac{\partial}{\partial p}(s+k)\omega = Q_1 - Q_f + (s+k)(e-c)$$

The extra term relates to the enthalpy of precipitation

Integrated mass equations

The mass of dry air is conserved, so that

- $\frac{\partial m_d}{\partial t} + \nabla . \frac{1}{g} \int_0^{p_s} (1 - q) \mathrm{v} \, dp = 0$ **(8)**

while for water vapor

- $\frac{\partial w}{\partial t} + \nabla . \frac{1}{g} \int_0^{p_s} q \mathrm{v} \, dp = E - P$

Combining these gives

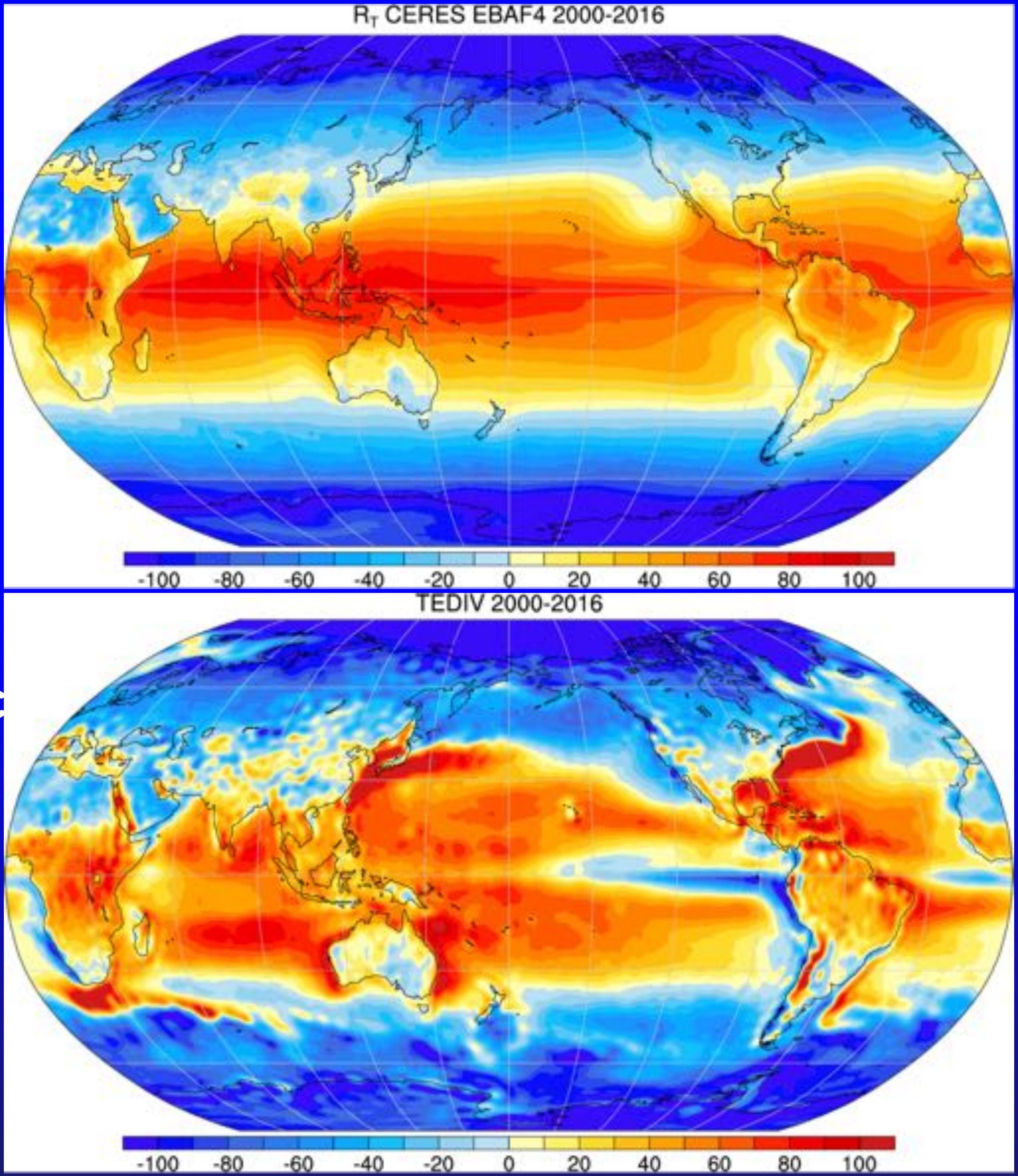
- $\frac{1}{g} \frac{\partial p_s}{\partial t} + \nabla . \frac{1}{g} \int_0^{p_s} \mathrm{v} \, dp = E - P$

For steady state

- $\nabla . \int_0^{p_s} \mathrm{v} \, dp = \nabla . \int_0^{p_s} q \mathrm{v} \, dp.$

The mass imbalance is associated with the moisture convergence

Net Radiation TOA R_T



CERES

Difference due to ocean transports (net surface flux)

ERA-I

Dgce of atmospheric energy =

Total heating $Q_1 - Q_2$

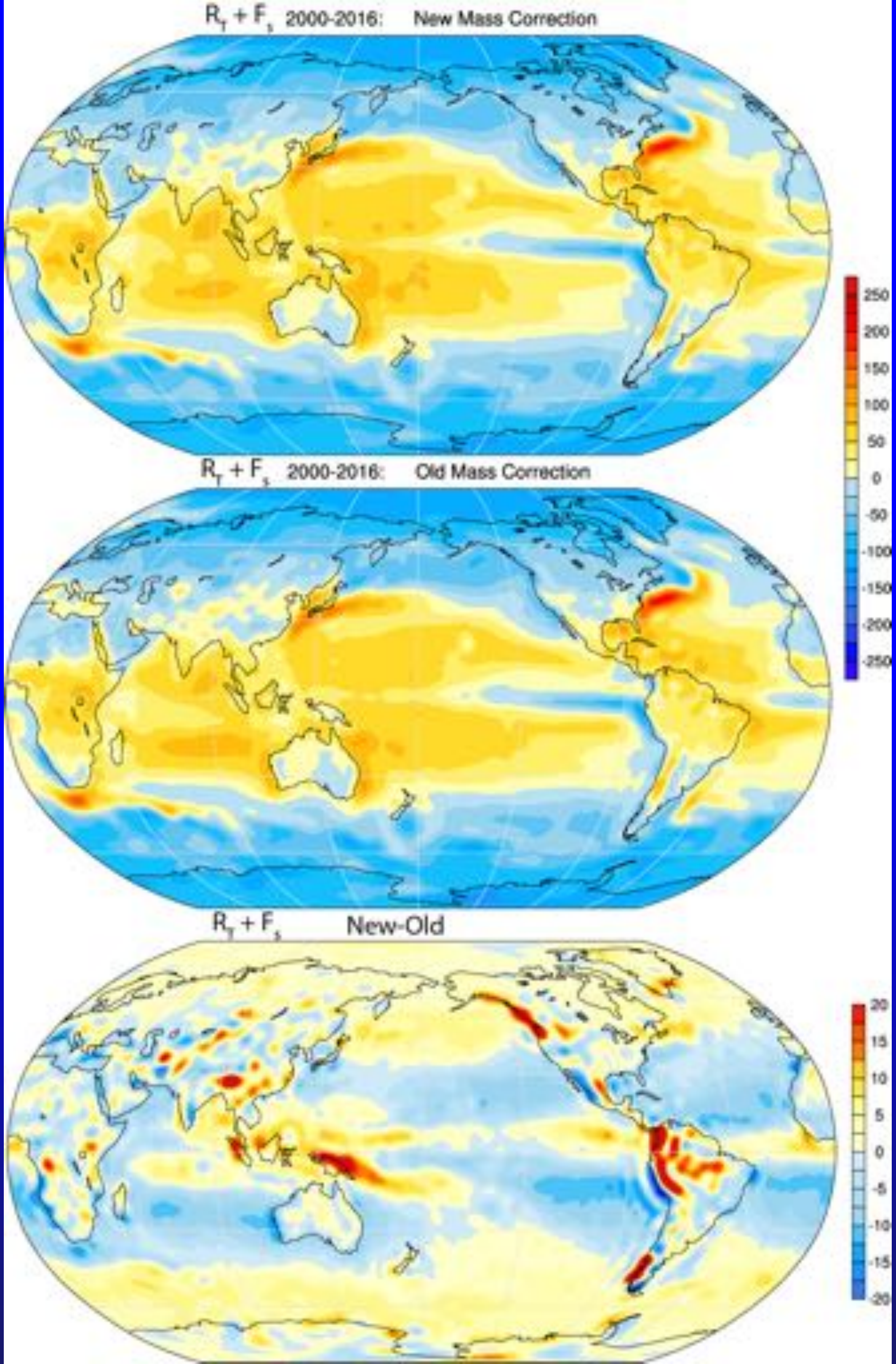
$= R_T + F_s$

Total atmospheric energy divergence

New

Old

Difference

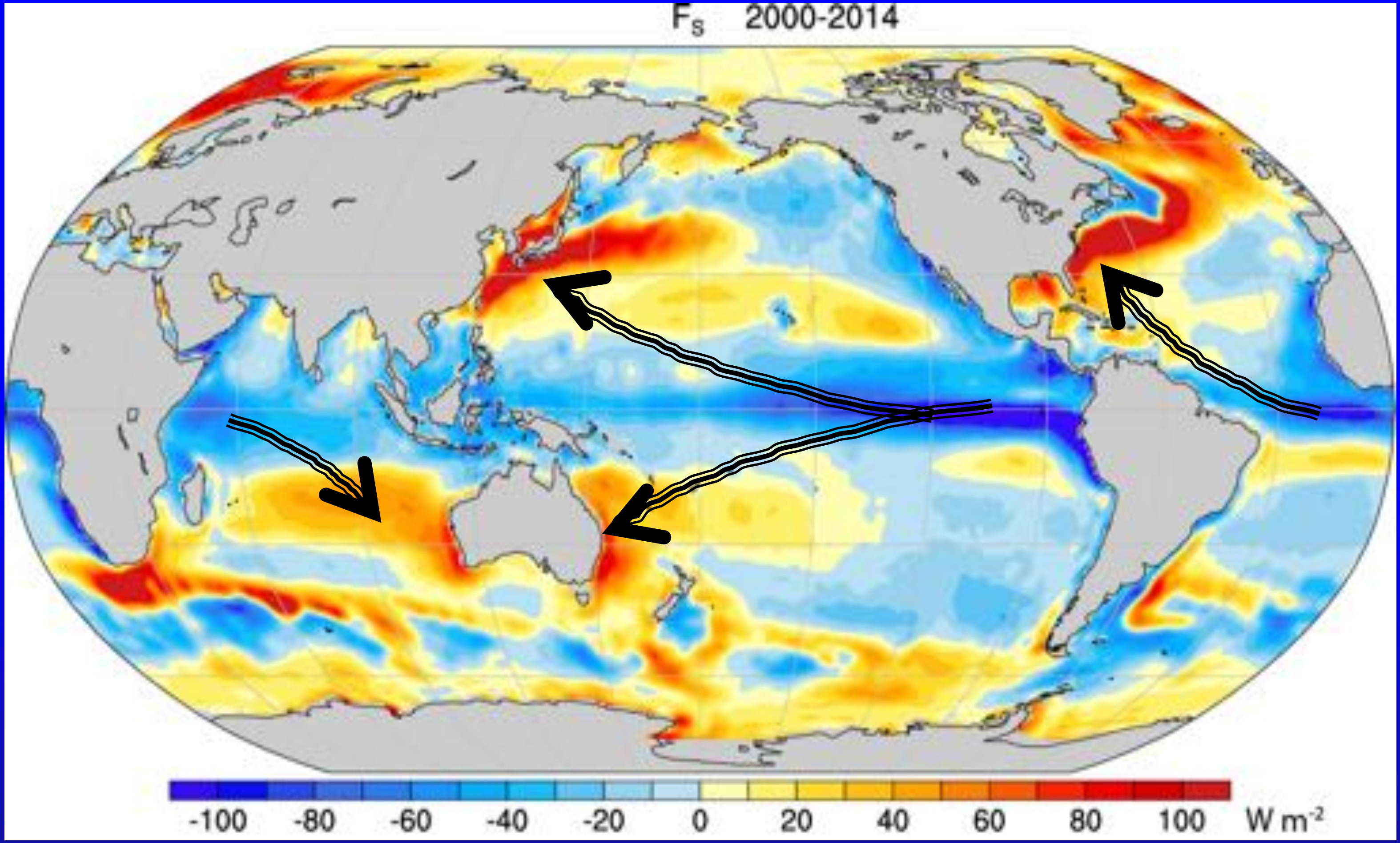


$= R_T + F_s$

$= Q_1 - Q_f - Q_2 + F_s^2$

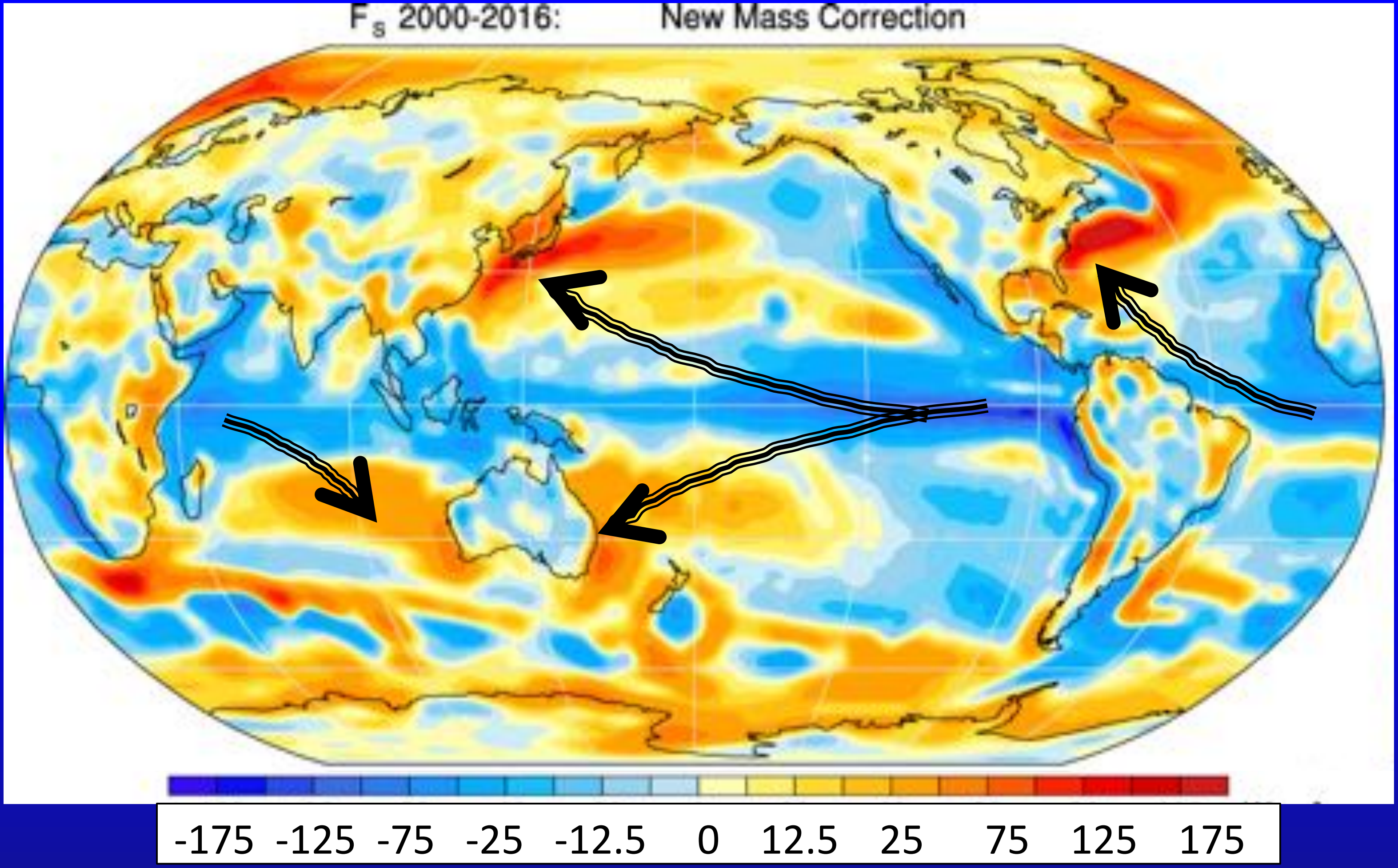
Difference relates to E-P

Annual mean surface flux



Trenberth and Fasullo (2017)

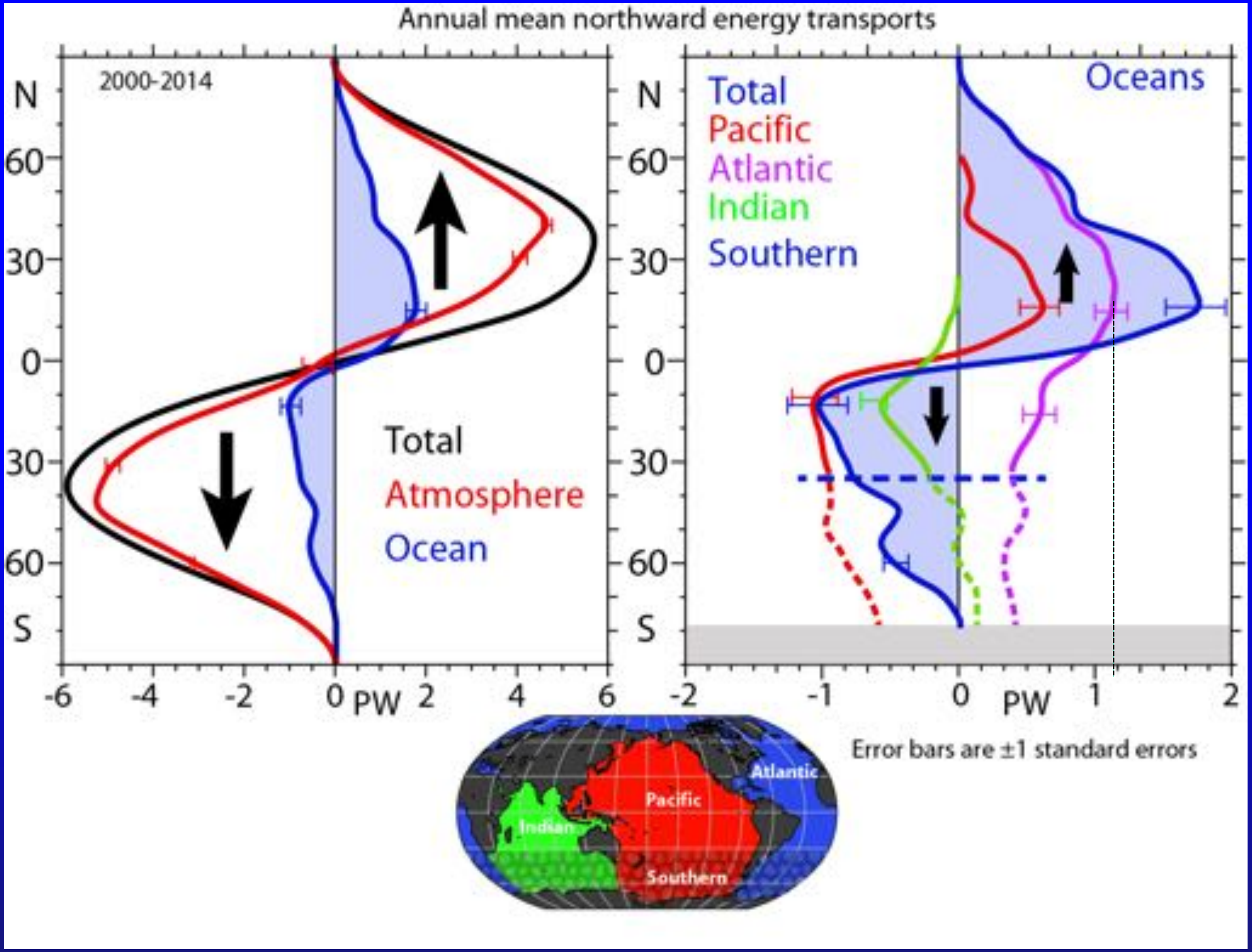
Annual mean surface flux



Updated with land included

Rms land: 13, N Am 10; Eurasia 11; S Am 17 Wm^{-2}
Africa 15; Antarctica 17.

Energy transports

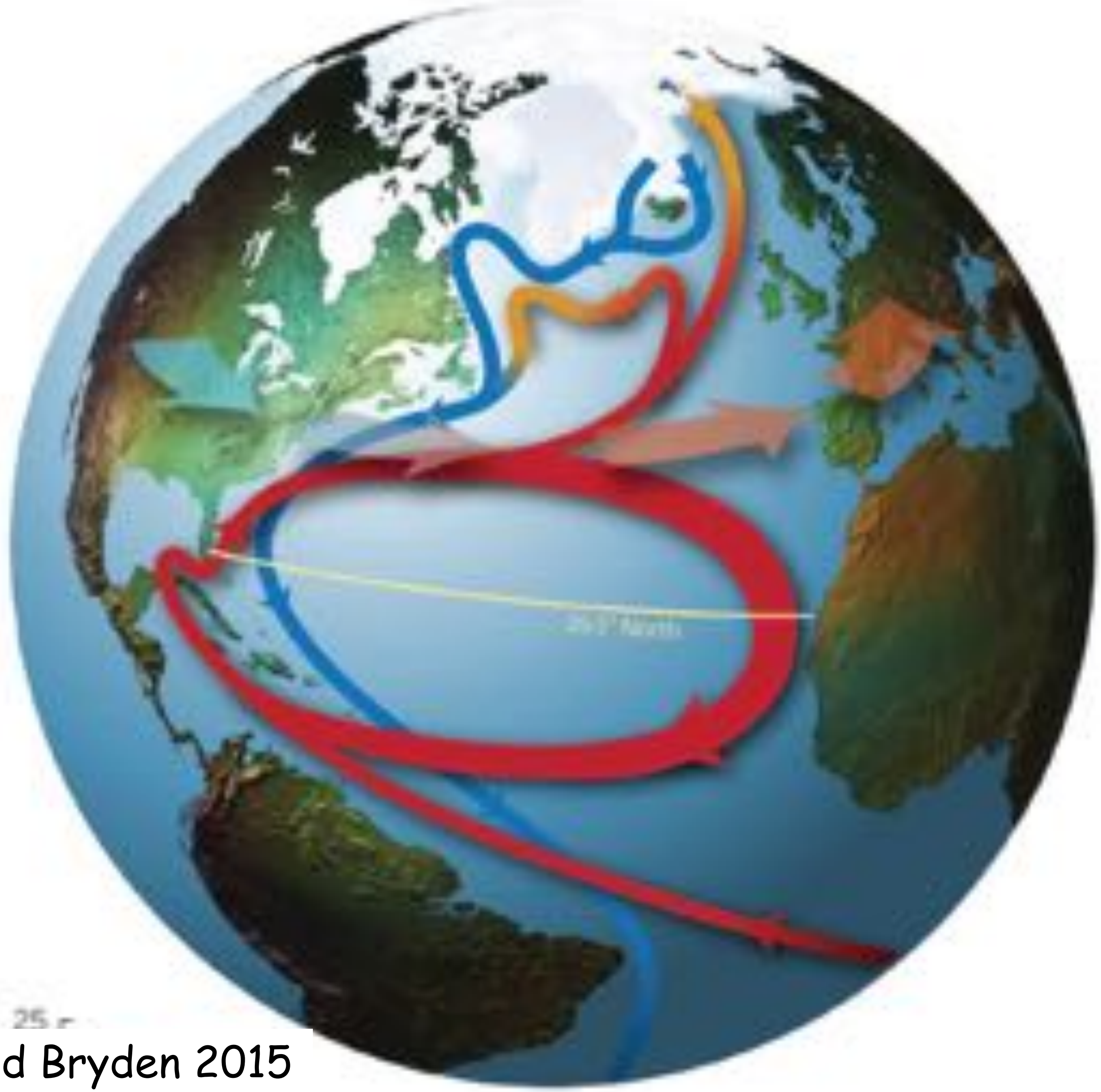


Atlantic:
1.1 PW
Peak
at 15°N

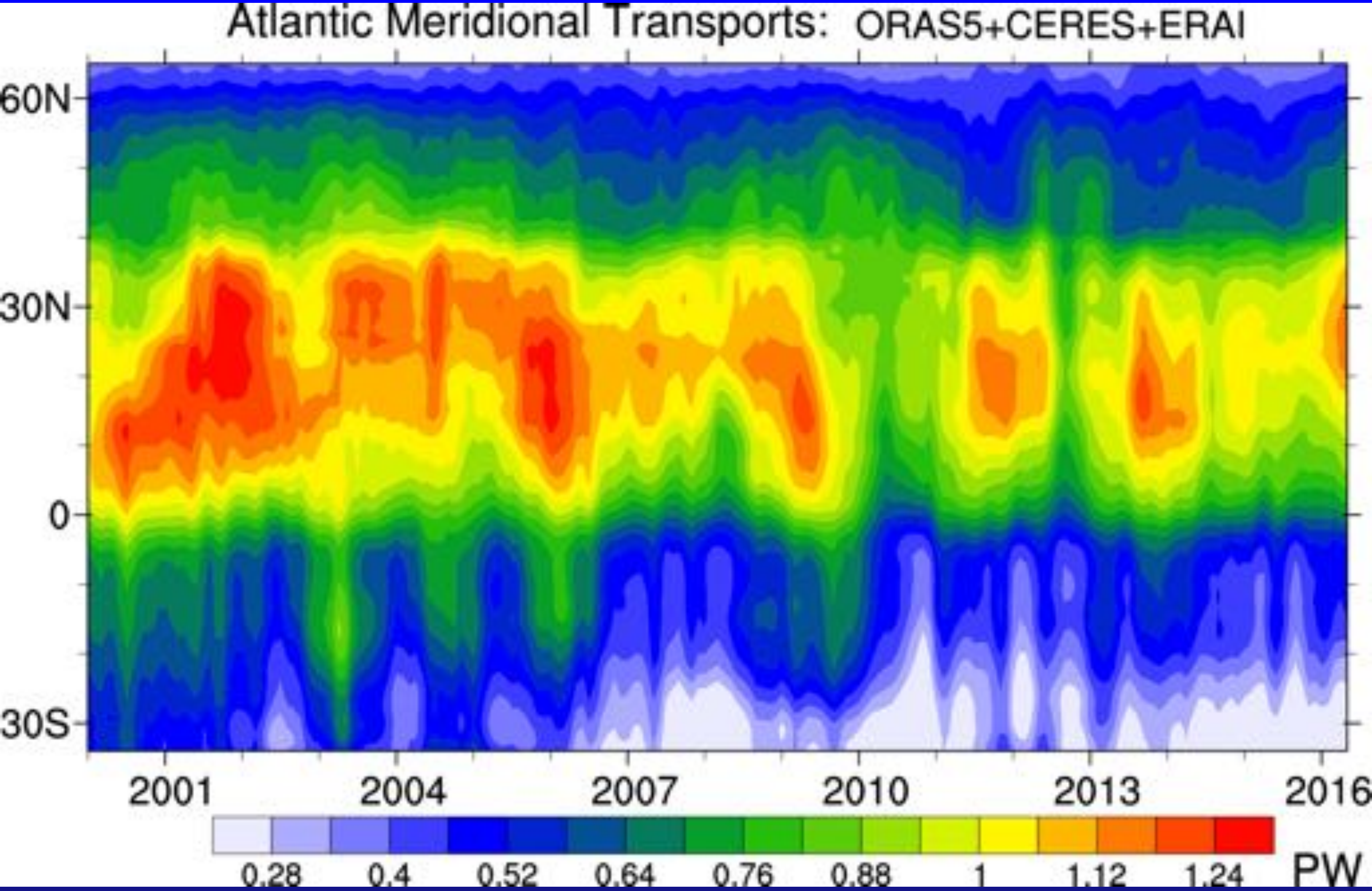
The Atlantic

AMOC

Atlantic Meridional Overturning Circulation



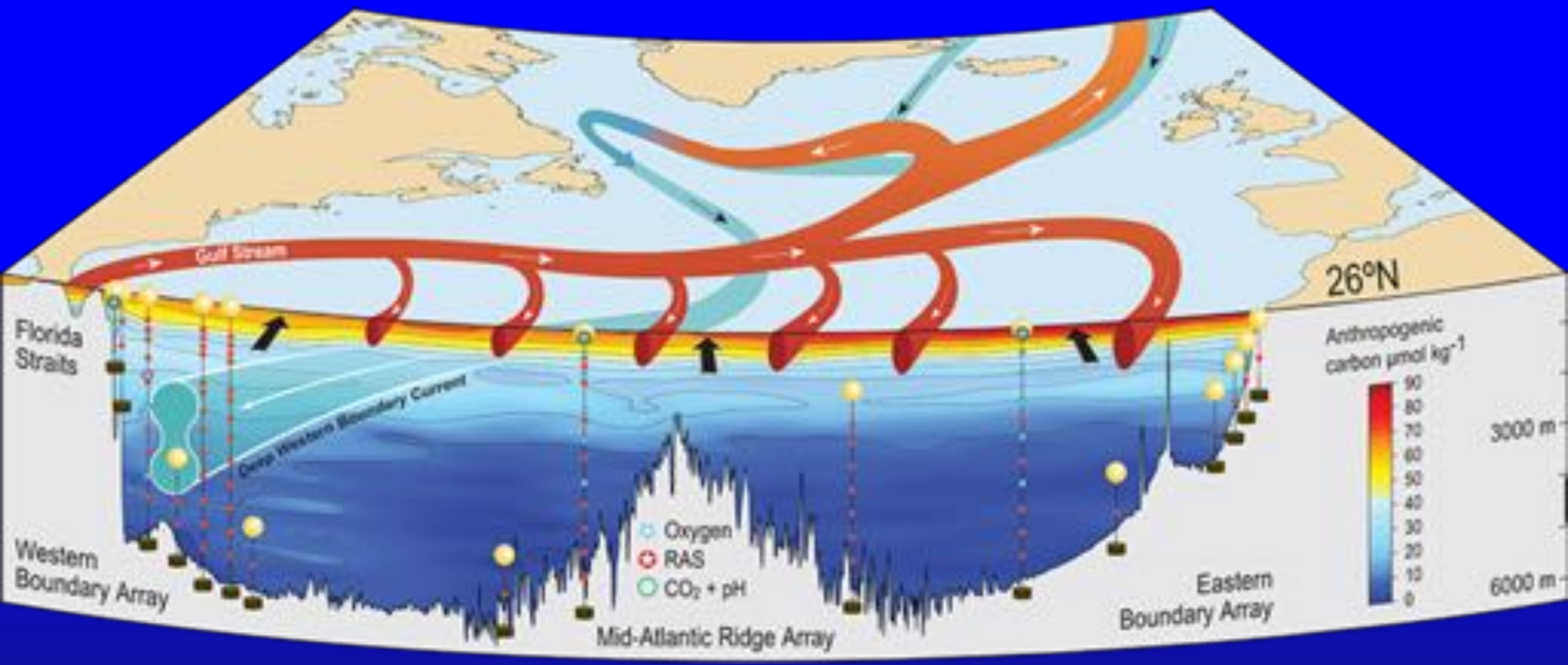
Srokosz and Bryden 2015



Revised

12-month running means

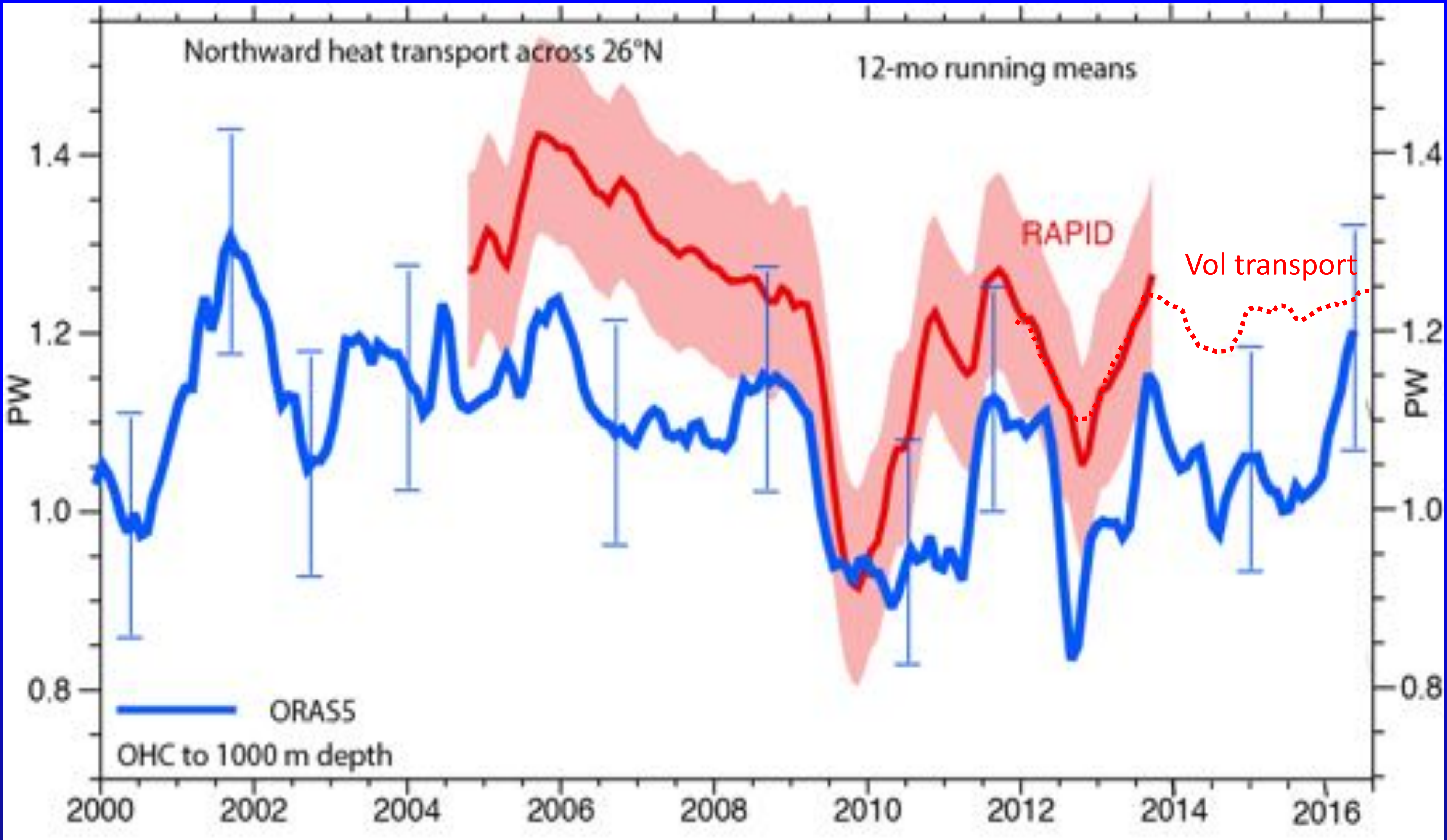
RAPID-MOCHA ARRAY
24 to 28°N: nominally 26.5°N



RAPID Climate Change Programme plus the Meridional Overturning Circulation and Heat Flux Array (MOCHA)

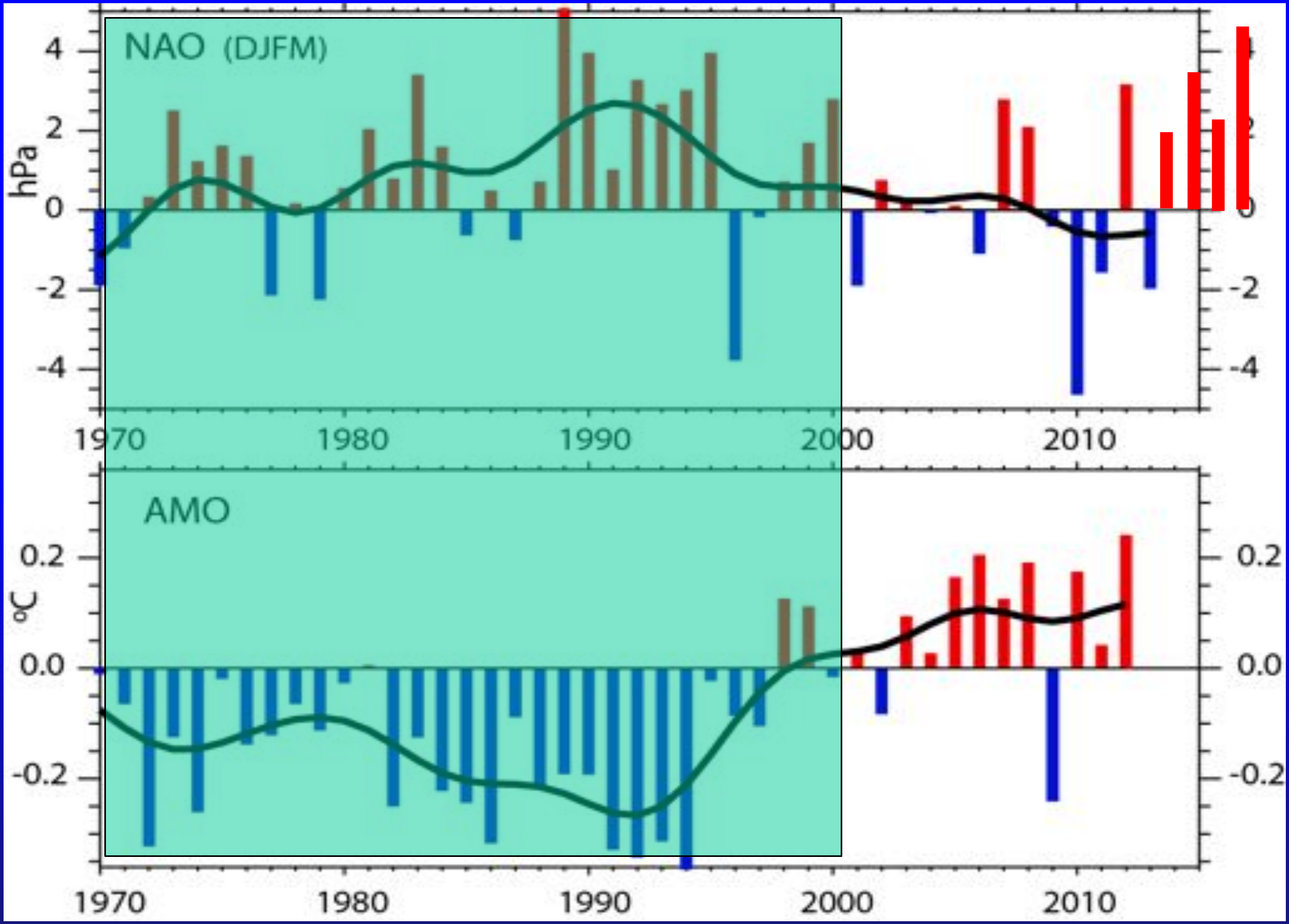
Canth 2011

North Atlantic meridional heat transport 26 N



ORAS5 is operational and high resolution.

NAO



DJFM for year of D

Ways forward

There are deficiencies/assumptions in these methods

- Need to balance the mass budgets, and this has had some approximations that can be improved
- Need to account for liquid (and solid) water
- Need to account for the enthalpy associated with precipitation
- Small effects: snow, assumptions about L and c_p dependence on T, etc.

- We can also bring in all of the surface flux estimates
- Ocean reanalyses

EEI has implications for the future

- These methods bring in new information
- Indeed, there is a lot of information in the **coupled** system not being utilized in many analyses.
- Constrains many datasets

  --- and models

WCRP workshop

"The Earth's Energy Imbalance and its implications"

- 13 – 16 November 2018, Toulouse, France