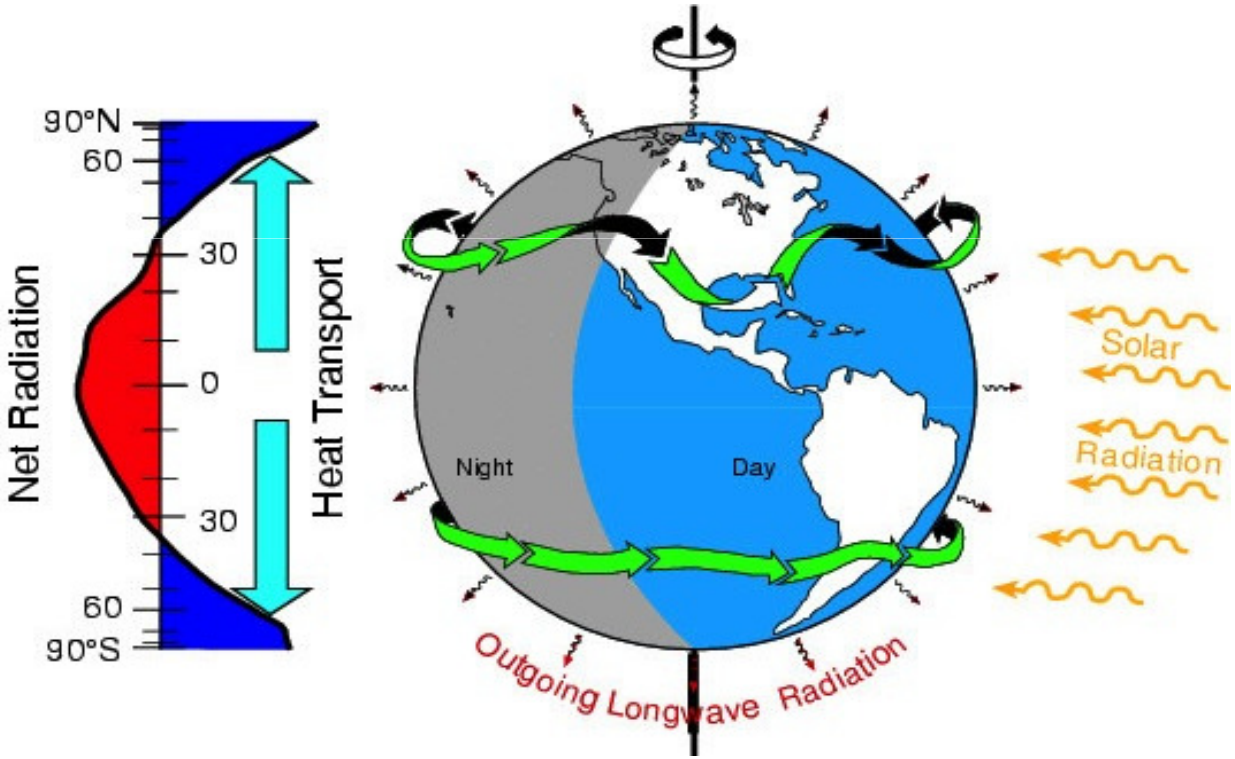
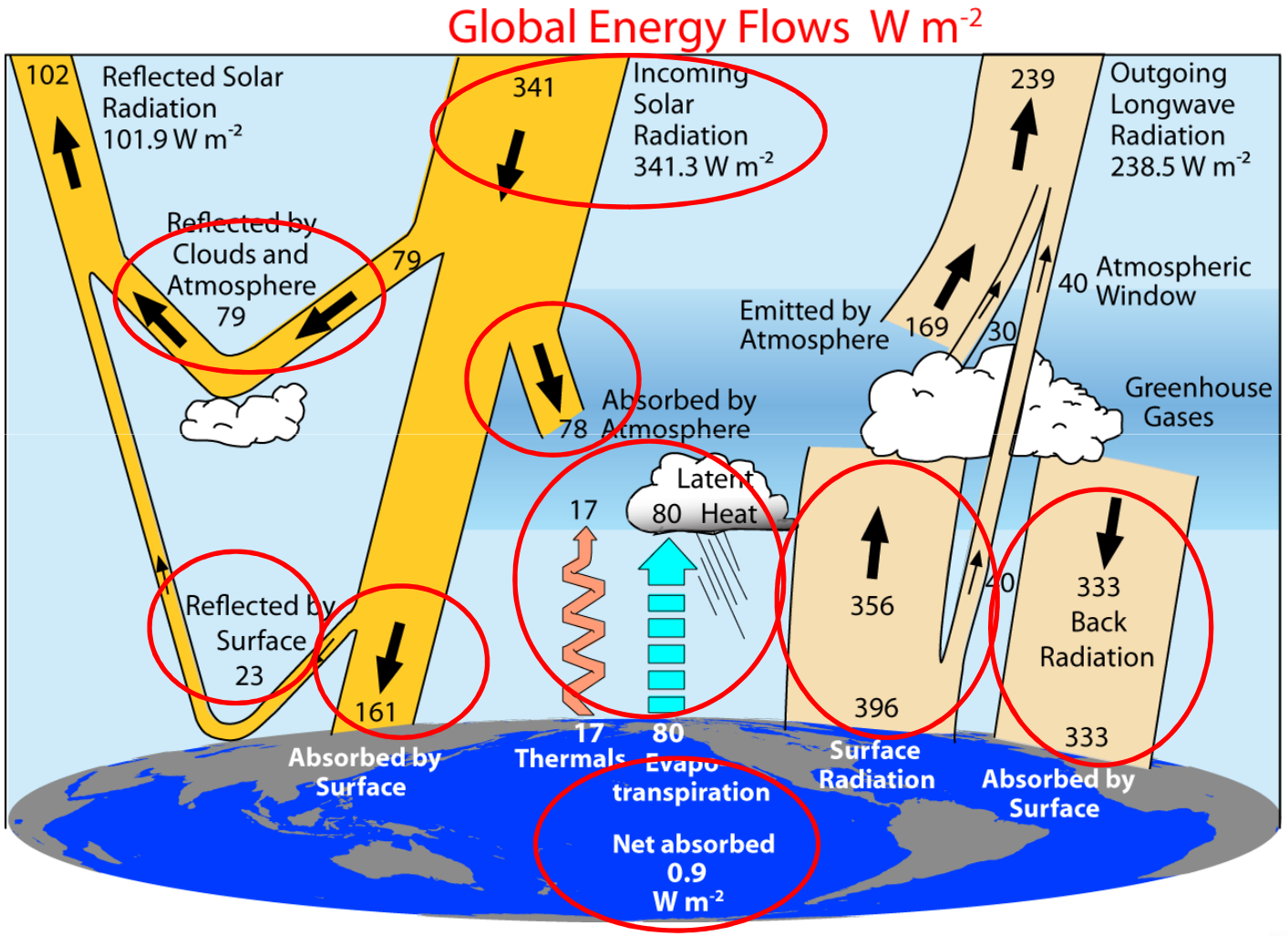
Closing the Earth's Energy Imbalance

J.P. Abraham, B.D. Plourde, University of St. Thomas
K. E. Trenberth, NCAR Earth Systems Laboratory
S. A. Mandia, Suffolk County Community College



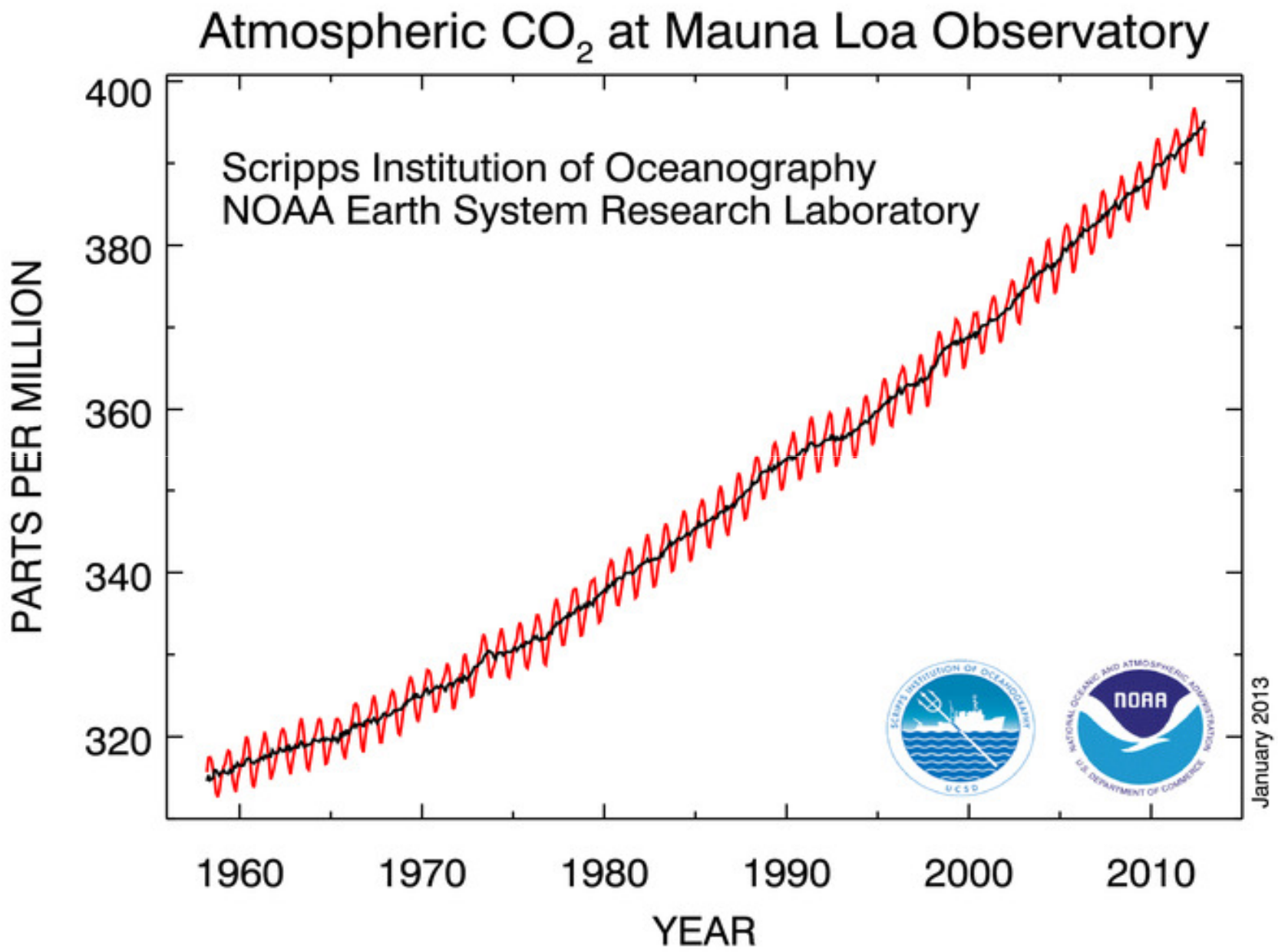
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Quantifying Energy Flow

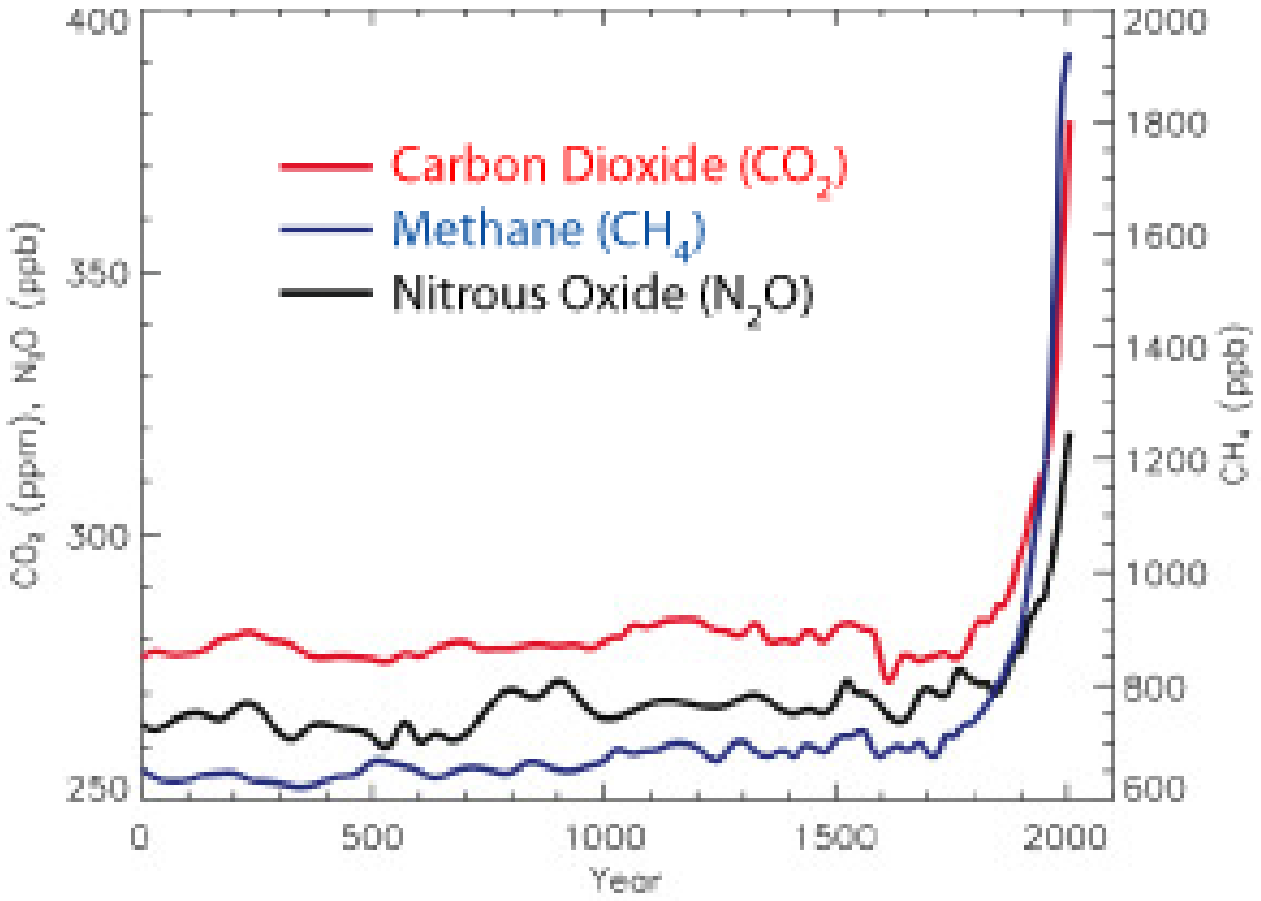


Trenberth, 2009

University of St. Thomas Minnesota


Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
PARTS PER MILLION
400
380
360
340
320
1960
1970
1980
1990
2000
2010
YEAR
January 2013

History of Greenhouse Gases



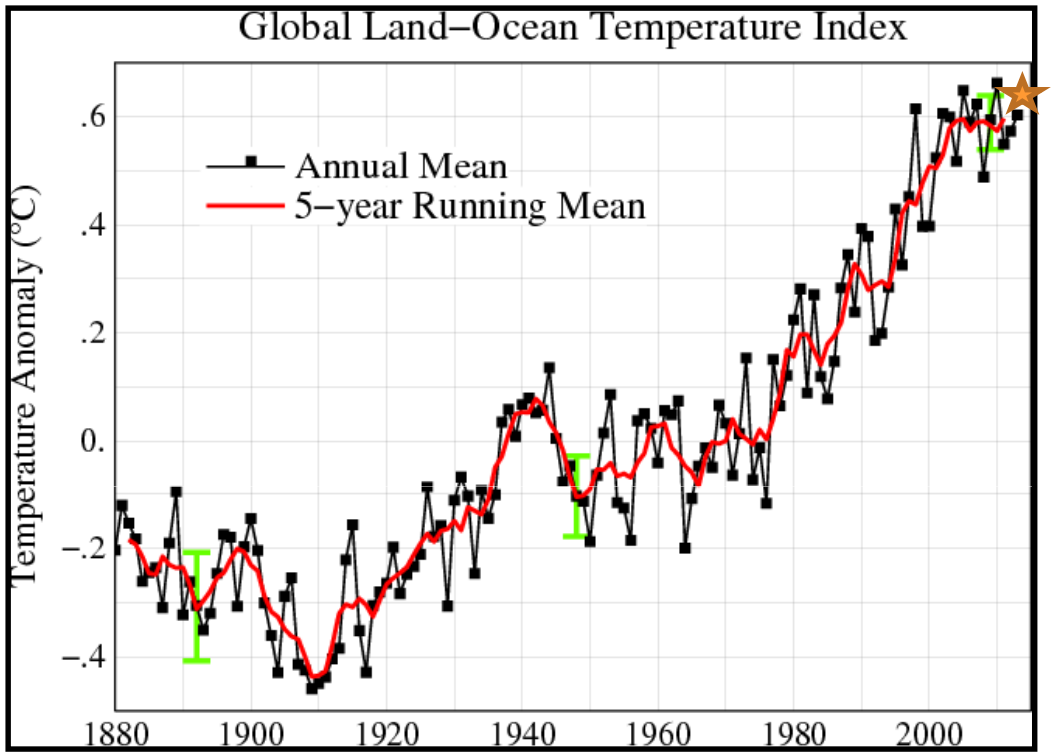
IPCC, 2007

This increase in CO_2 is also accompanied by increases in other greenhouse gases.

- Methane is ~20 times more potent than CO_2 over a 100 year period.
- Nitrous Oxide is 300 times more potent than CO_2 over a 100 year period.

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A History of Measuring Devices

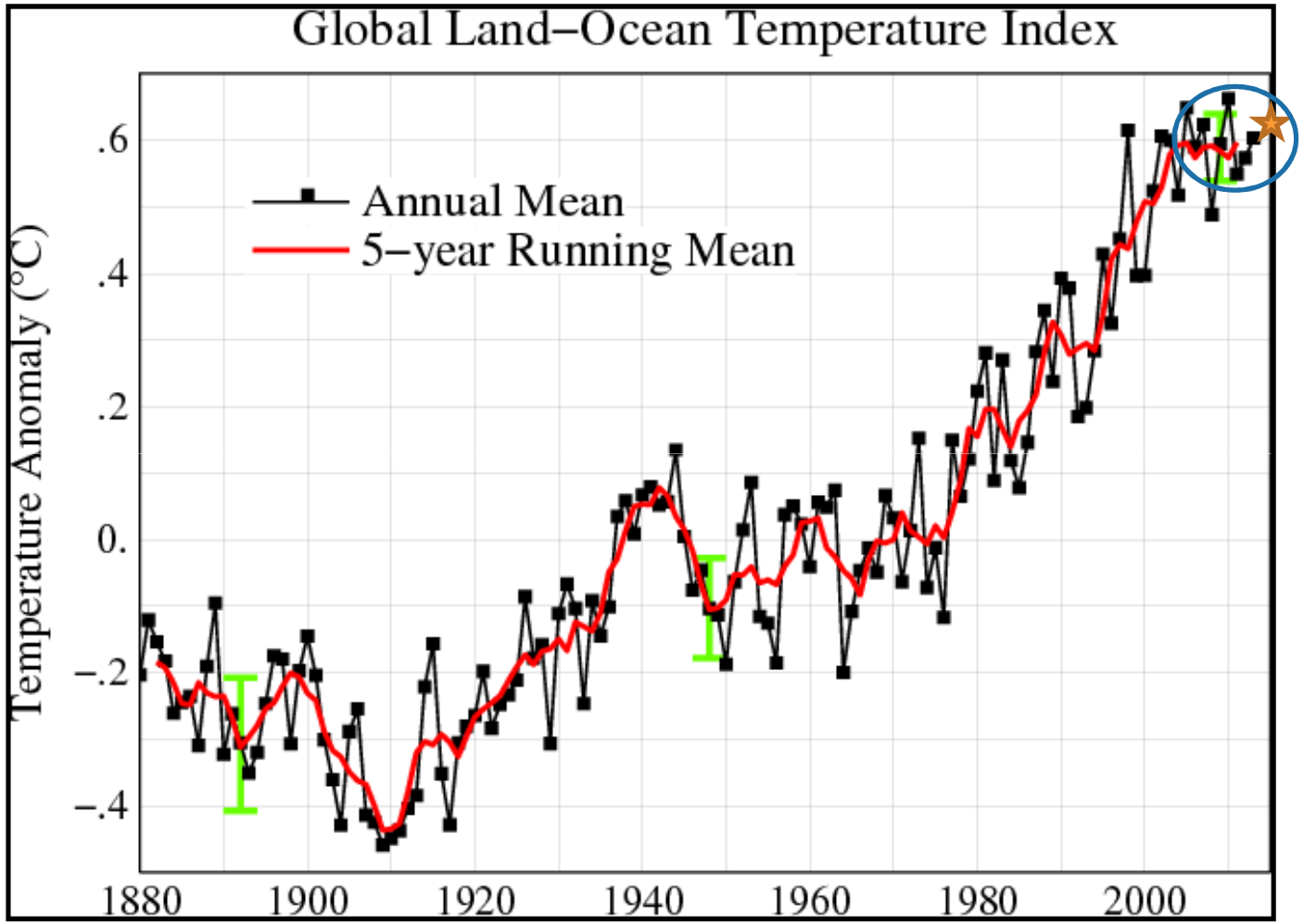


Hottest Years on Record

1. **2010**
2. **2005**
3. **2007** ★ 2014?
4. **2002**
5. **1998**
6. **2013**
7. **2003**
8. **2009**
9. **2006**
10. **2012**

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A Hiatus?



Has global warming stopped?

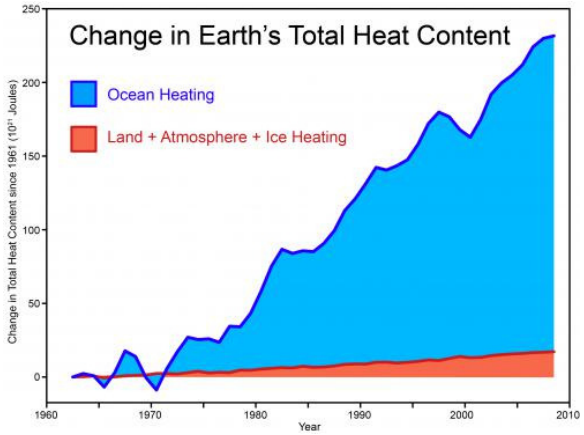
How is Earth's Energy Imbalance Measured?

1. Direct measurements from space, absorbed solar radiation, outgoing long wavelength radiation, net radiant flux.
   - Measurements are not absolutely accurate but can measure changes in time.

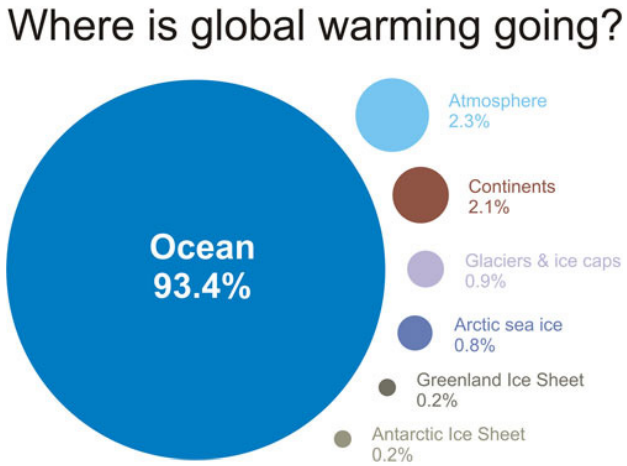
2. Measure energy storage on Earth.
   - A challenge to make adequate measurements of thermal reservoirs (oceans).

3. Climate models with specified forcings.

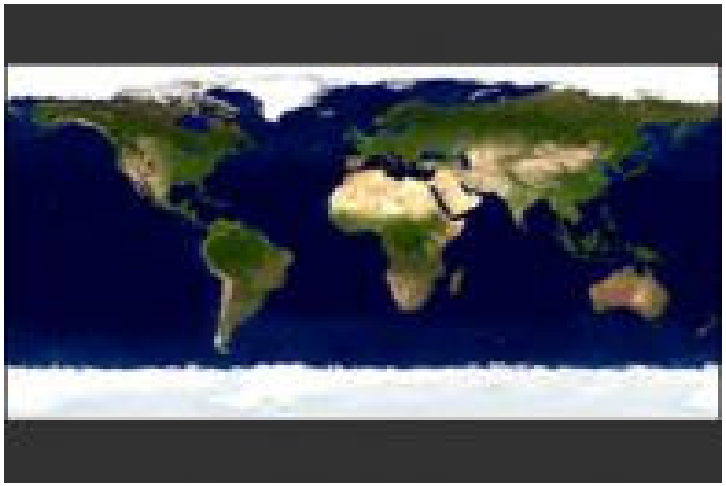
The Difficult Challenge – Measuring the Oceans



Nuccitelli et al, 2012

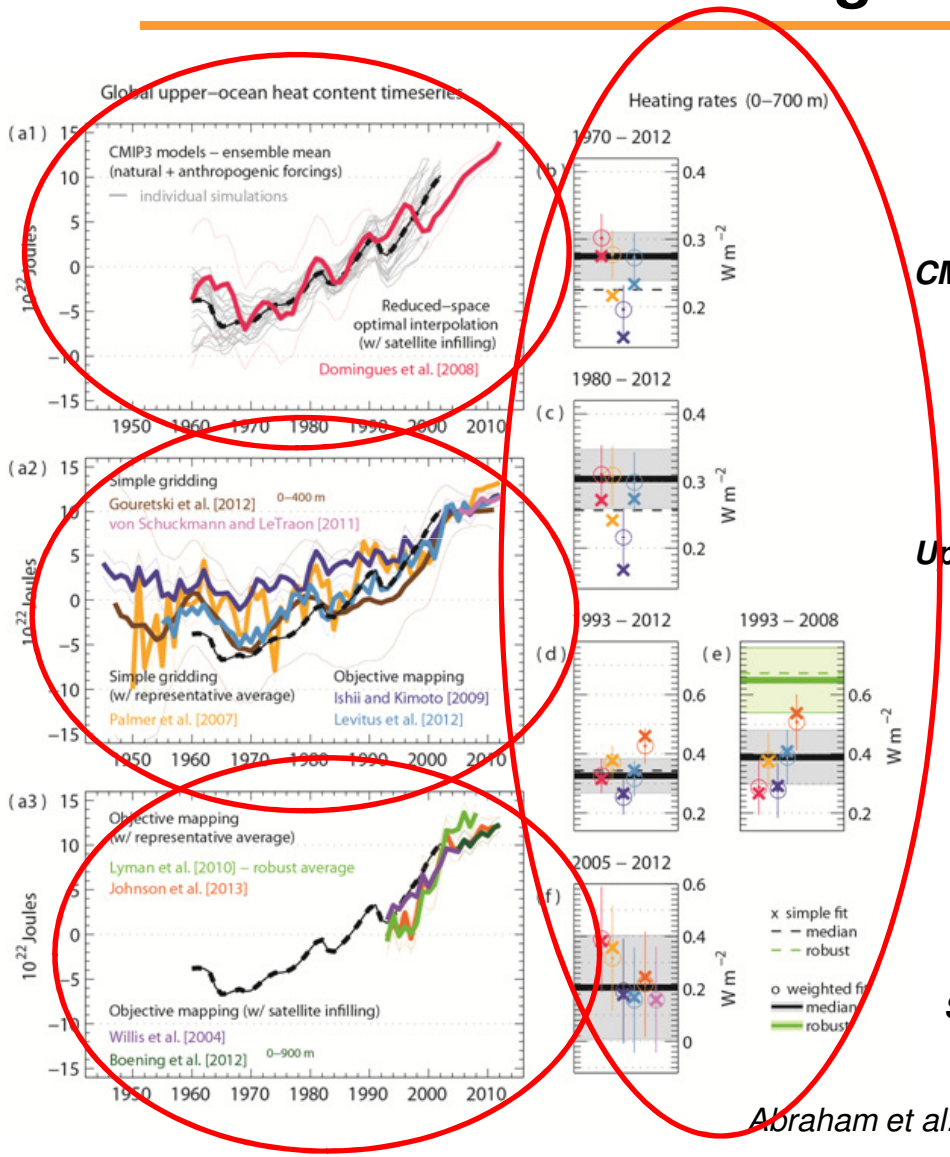


SKS, 2014



NASA, 2014

Measuring Ocean Heating



CMIP3 models and Domingues, 2008 estimates

Upper Oceans – various estimates, simple gridding

Upper Oceans – various estimates, mapping

Slopes, past four decades

Abraham et al., 2013

Progress on Closing the Earth Energy Budget

ORAS4 – A new **O**cean **R**e**A**nalysis **S**ystem, based on the European Center for Medium-Range Weather Forecasts (ECMWF) model.

Reanalysis spans 1958-current.

Improves fit of models to observations including interannual variability and seasonal predictions.

Data are assimilated using XBT, CTD, Mooring, etc. measurements.

Forcings from ERA-40 (prior to 1989), ERA-Interim (1989-2009), and ECMWF analysis from 2010-present.

M. Balmaseda, K. Mogensen and A. Weaver, Evaluation of the ECMWF Ocean Reanalysis System ORAS4, Quarterly Journal of the Royal Meteorological Society, Vol. 139, pp. 1132-1161, 2013.

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What is Reanalysis?

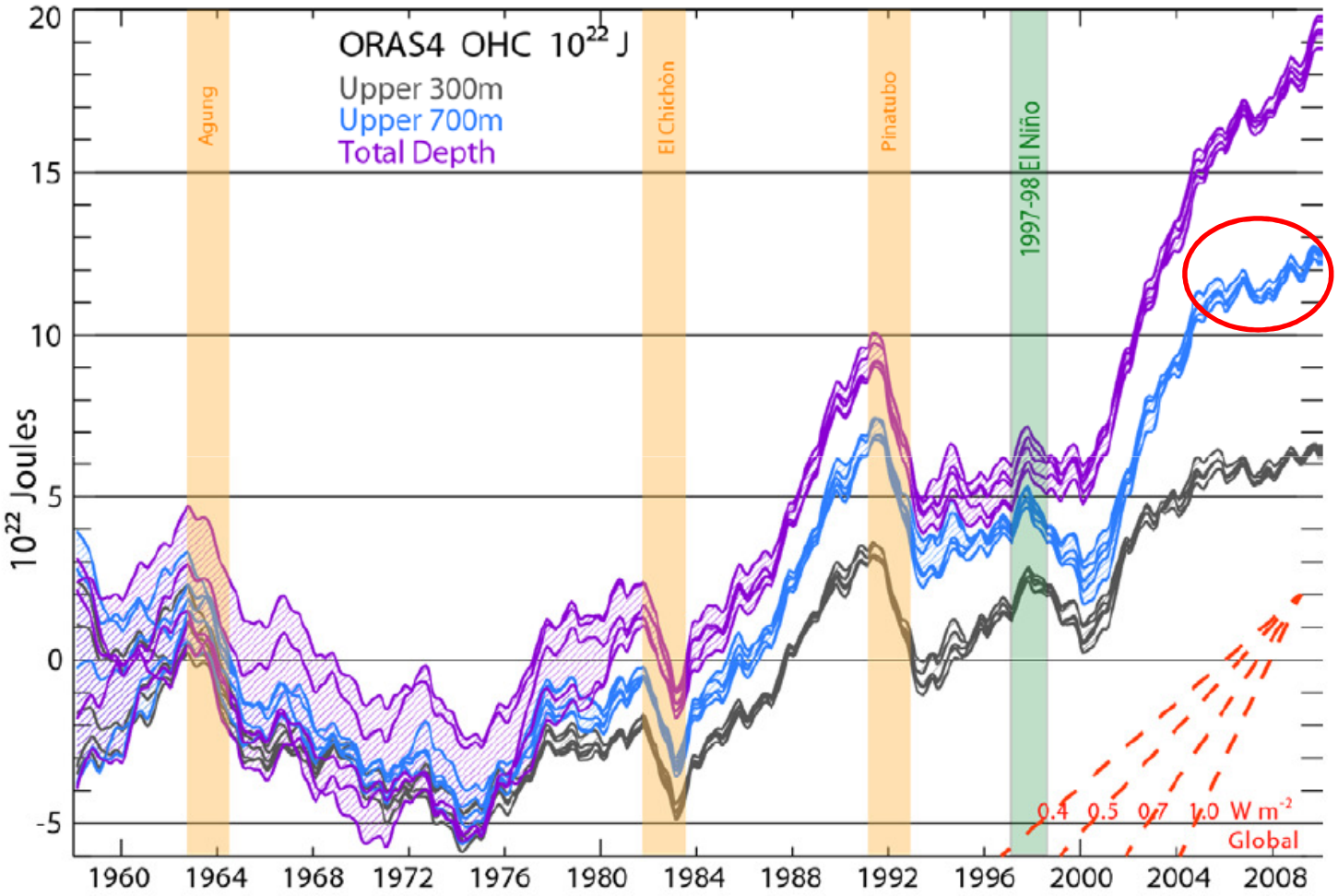
From ECMWF (http://www.ecmwf.int/en/research/data-assimilation)

> "*To make a forecast, we need to know the current state of the Earth's surface (land and oceans). The weather forecasts produced at ECMWF use data assimilation to estimate local conditions for the forecast model from meteorological observations.*"

Models are run forward in time, new observations are continually used to update the simulation.

The models are run as ensembles – multiple simulations including small perturbations in the initial conditions.

Ocean Warming



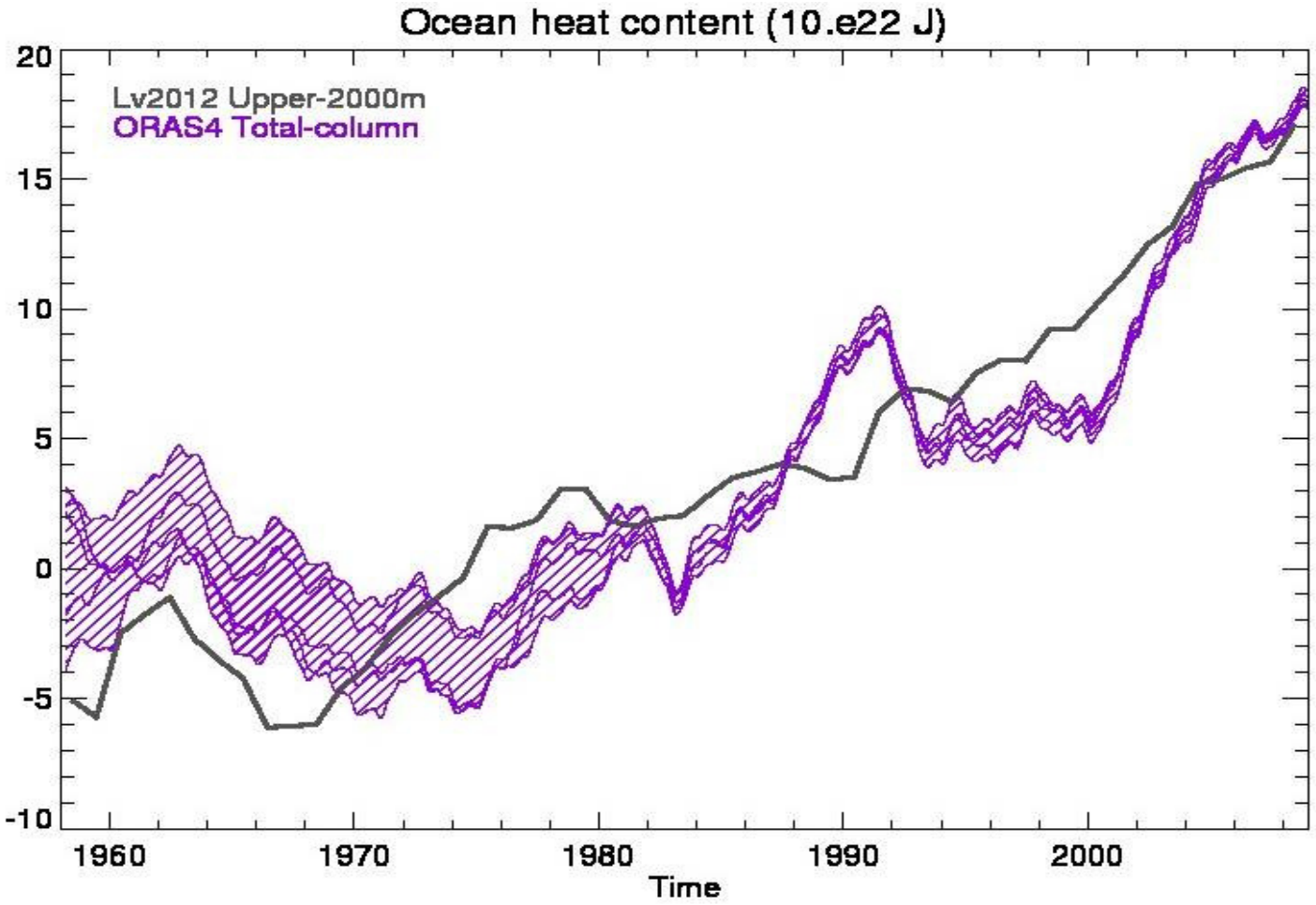
Has global warming stopped?

Which slope Matches OHC?

Balmaseda et al., 2013

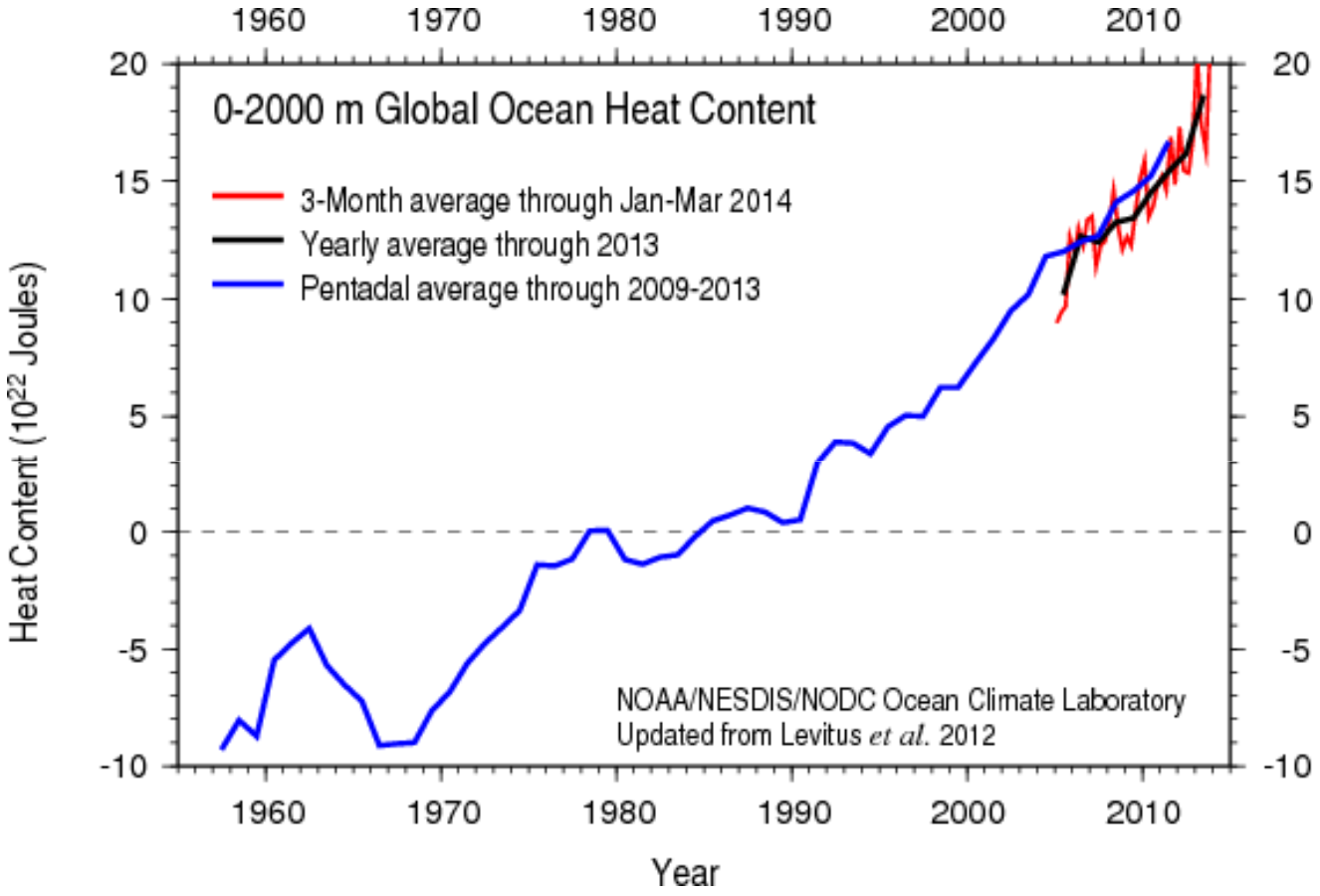
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Measurements vs. Reanalysis

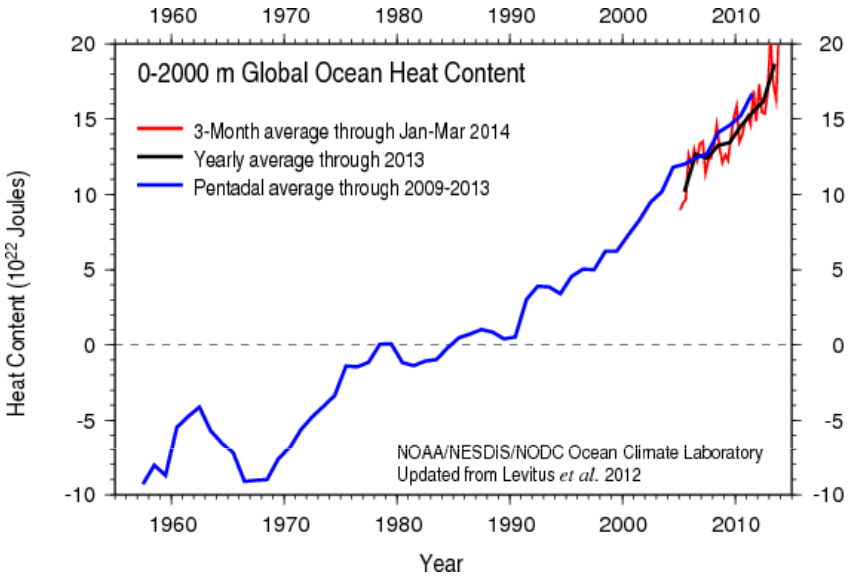


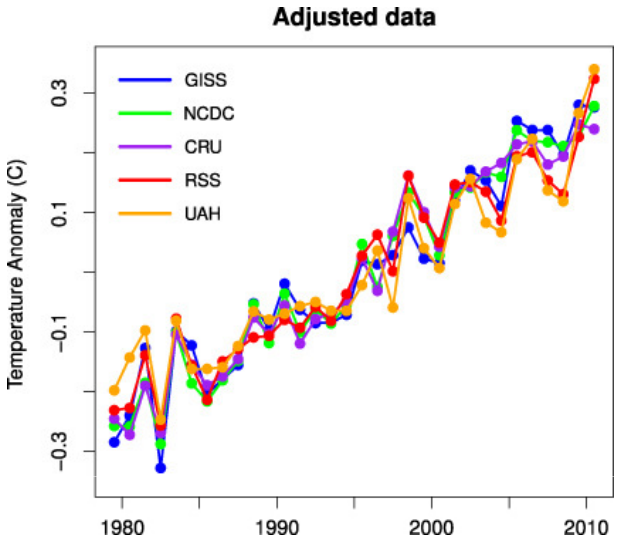
Trenberth, 2013

Most Recent Ocean Warming



Long-Term Continued Warming



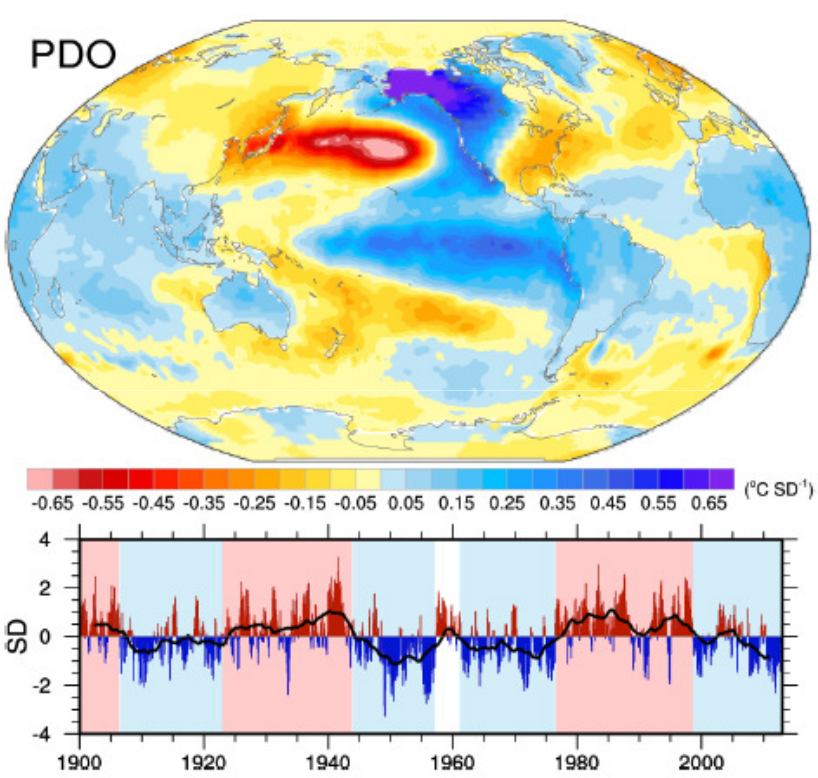


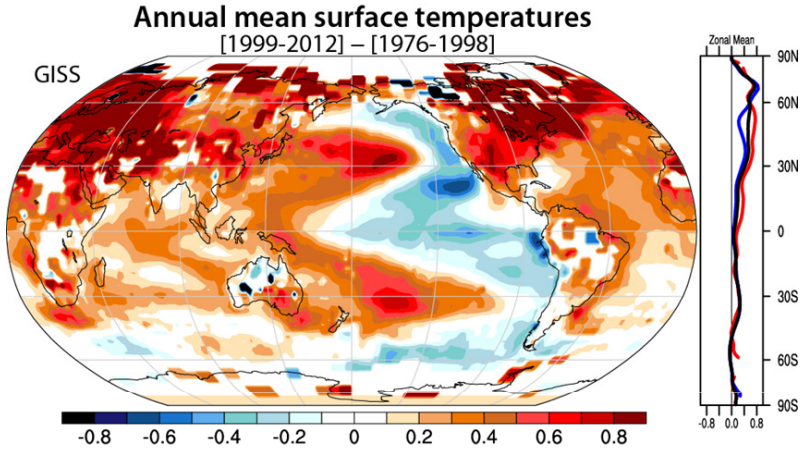
Foster and Rahmstorf, 2011

When account is made for volcanoes and ENSO, and when the entire ocean is measured, the “hiatus’ becomes hard to find.

Why Has Deep-Ocean Heat Storage Increased?

Temperature difference per st. dev. PDO

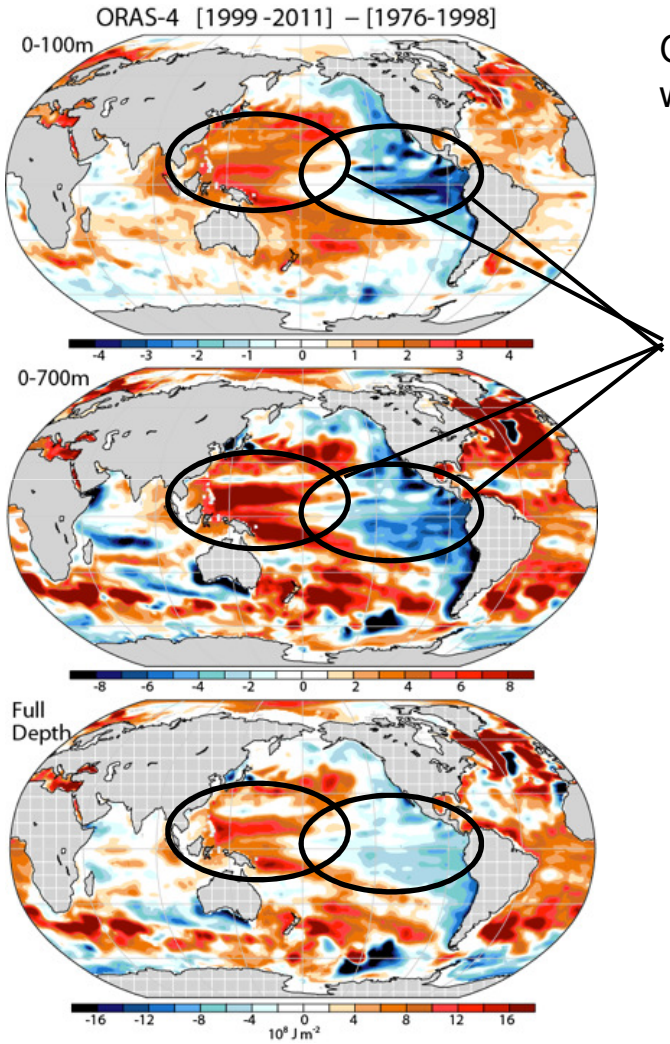




Trenberth et al., 2014

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Why Has Deep-Ocean Heat Storage Increased?

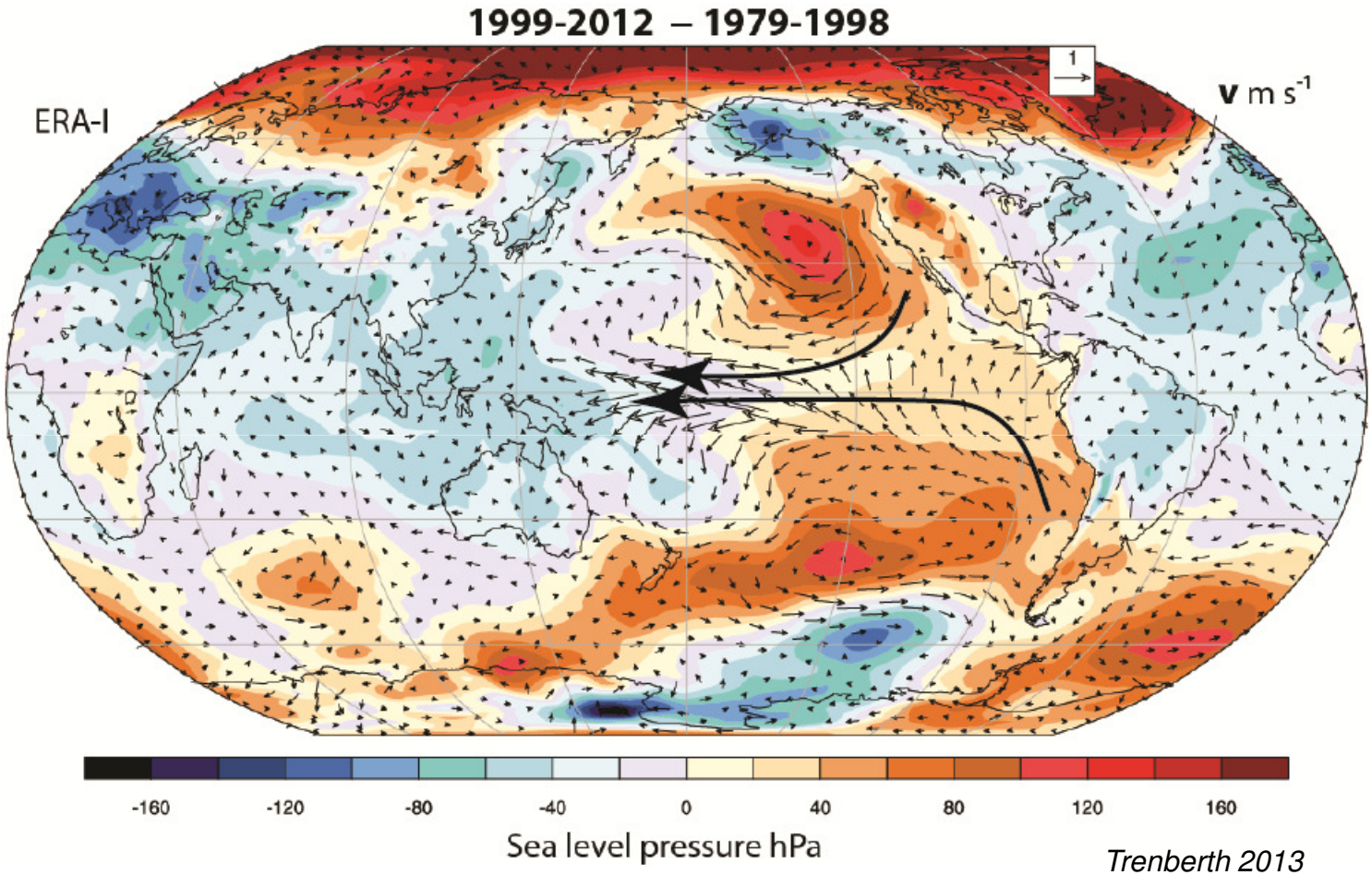


Comparison of ocean heat content for different water layers.

Waters in the Eastern Pacific have gotten colder

Waters in the Western Pacific have gotten warmer

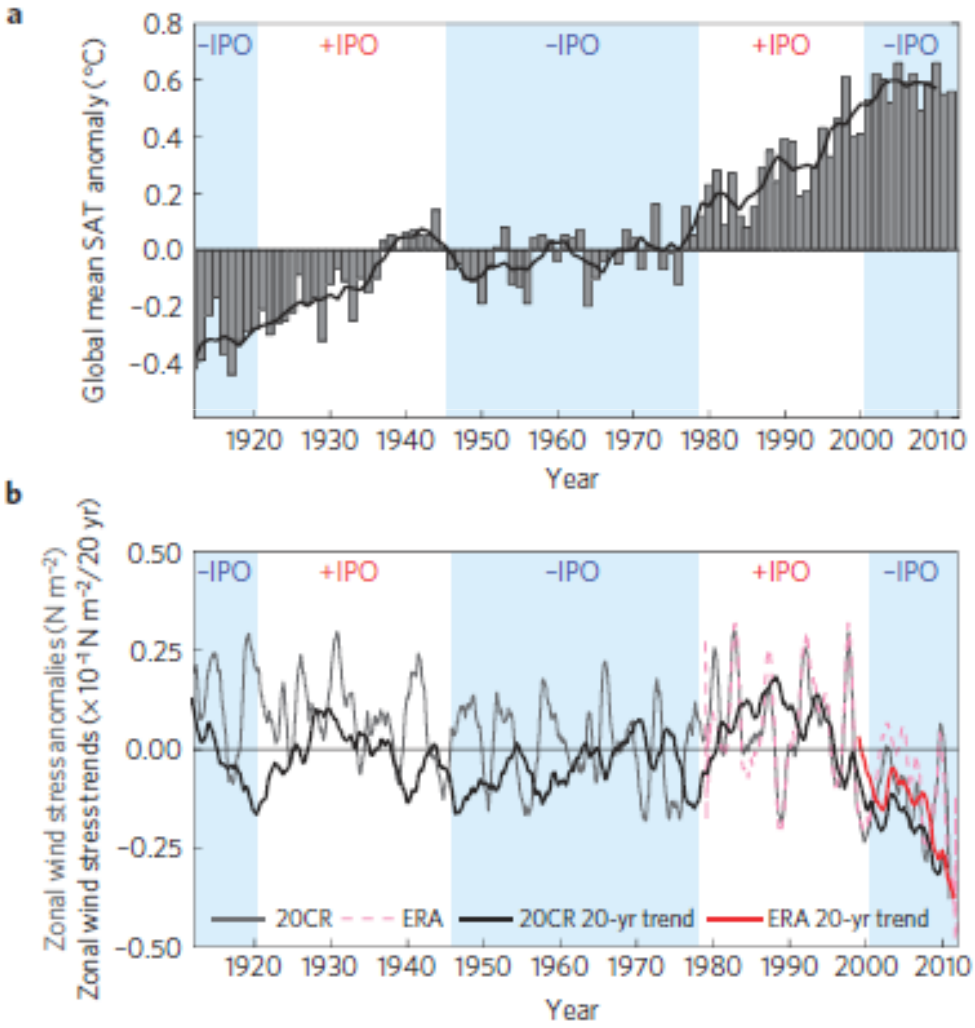
Pacific Pressure and Winds



Trenberth 2013

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Pacific Oscillation, Temperatures, and Winds

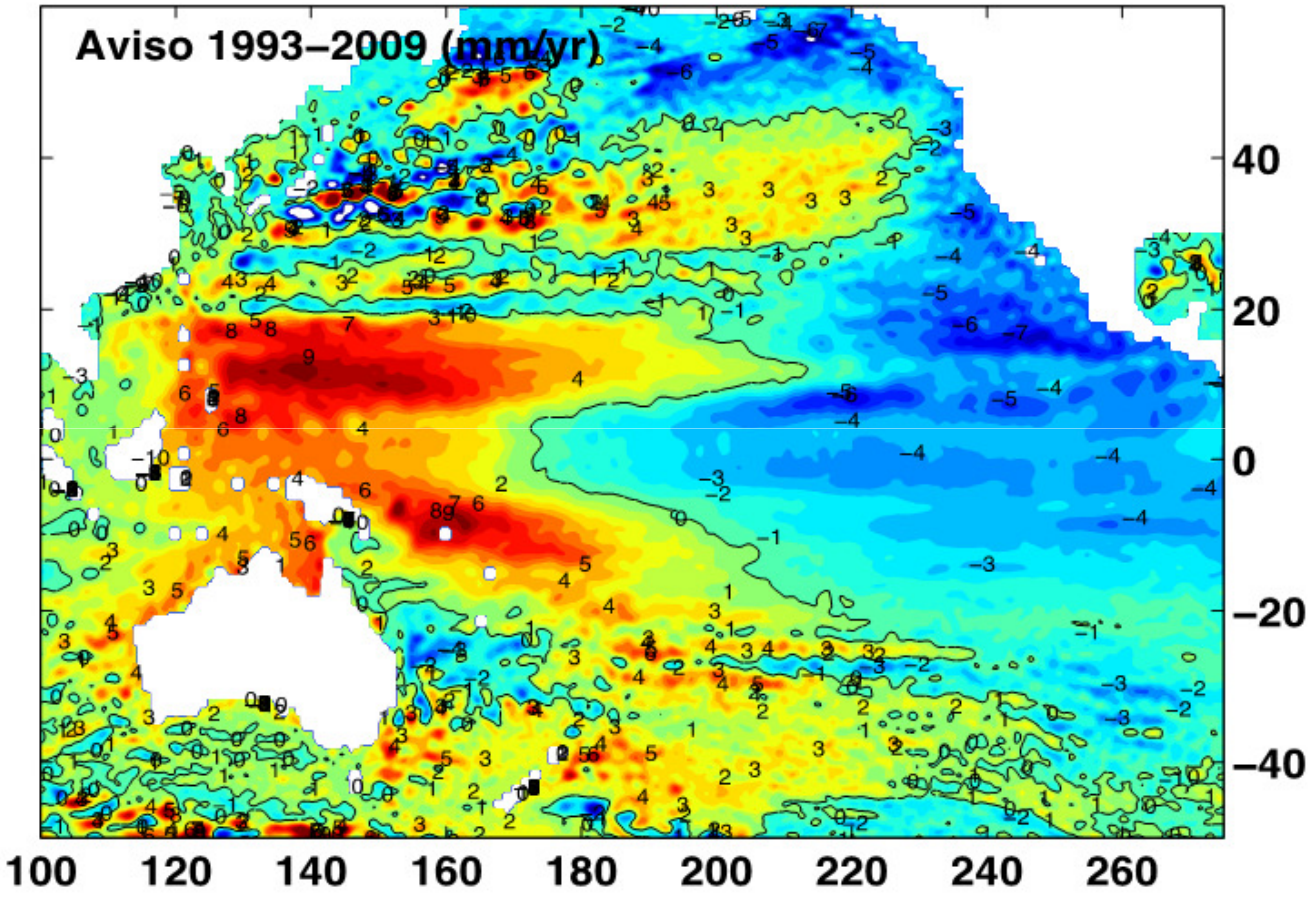


Is this natural internal variability? Is it partly caused by human-induced climate change?

England et al., 2014

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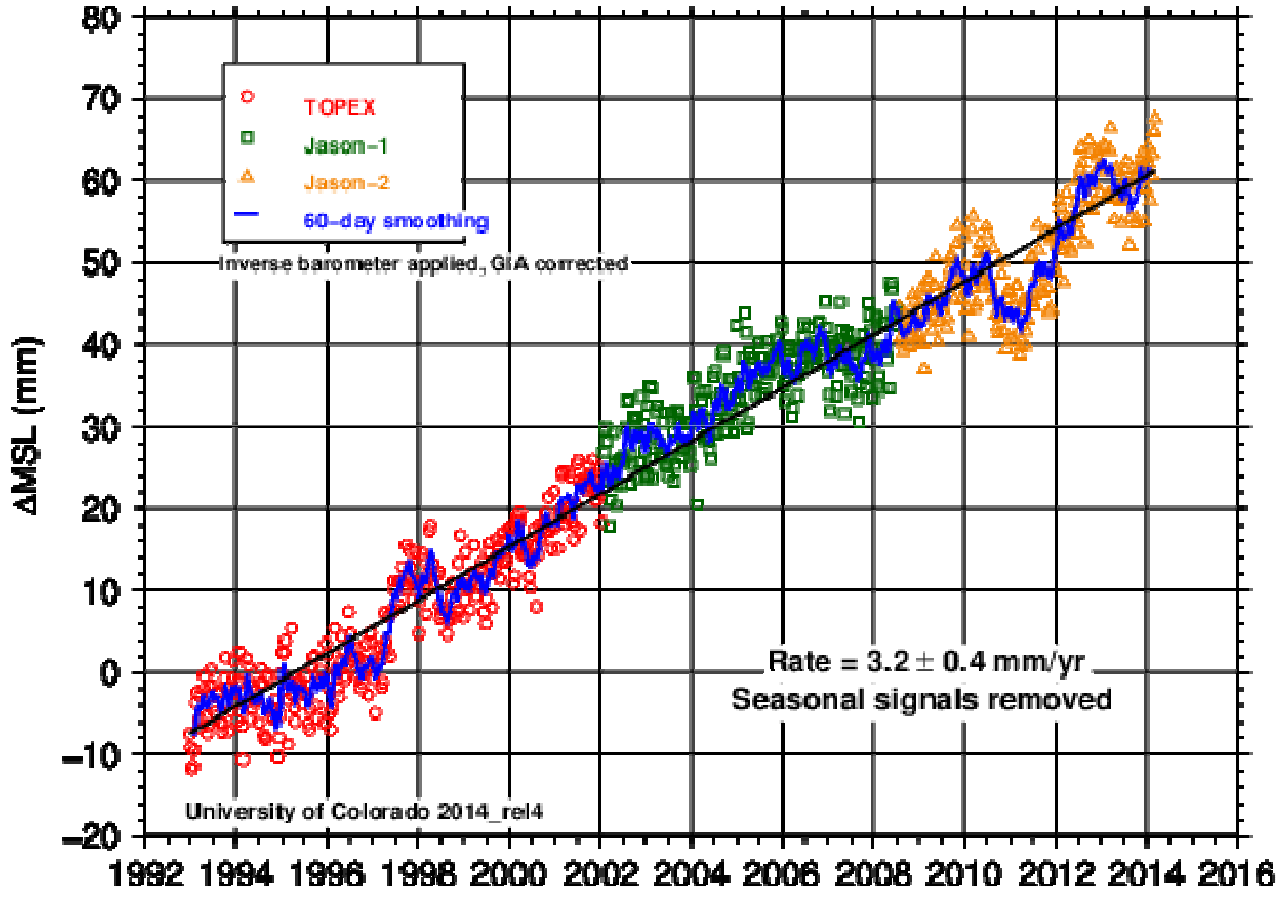
Impact on Regional Sea Level – 3mm/yr removed



Lagerloef, 2013

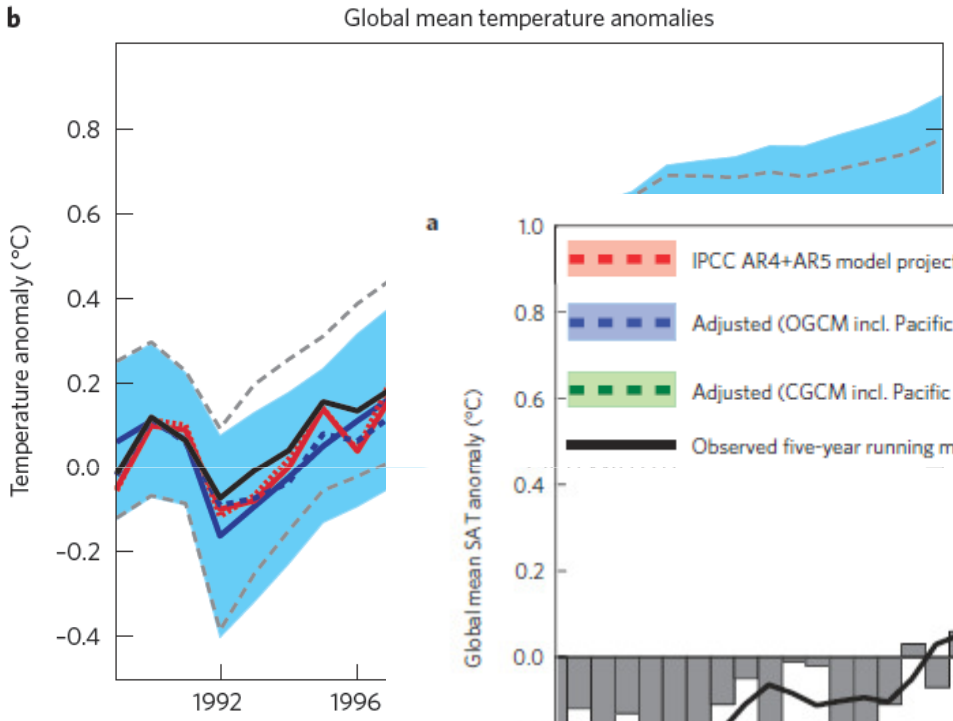
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Global Sea Level – Also no Hiatus

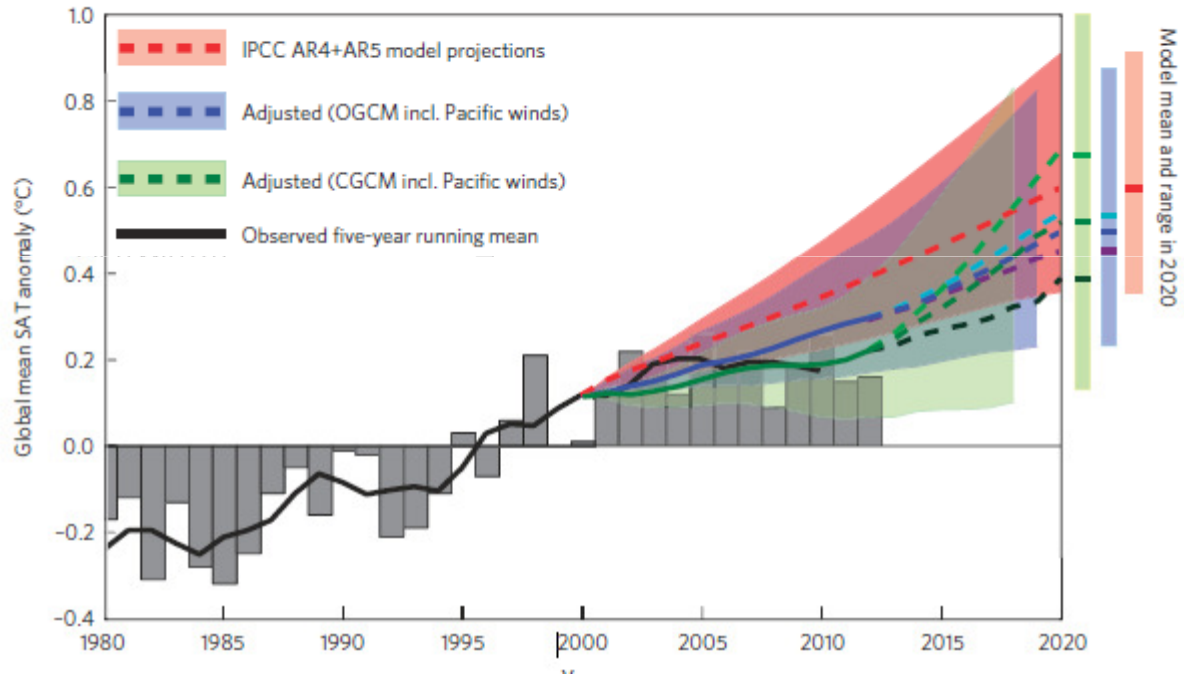


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Where Does This Leave Us?



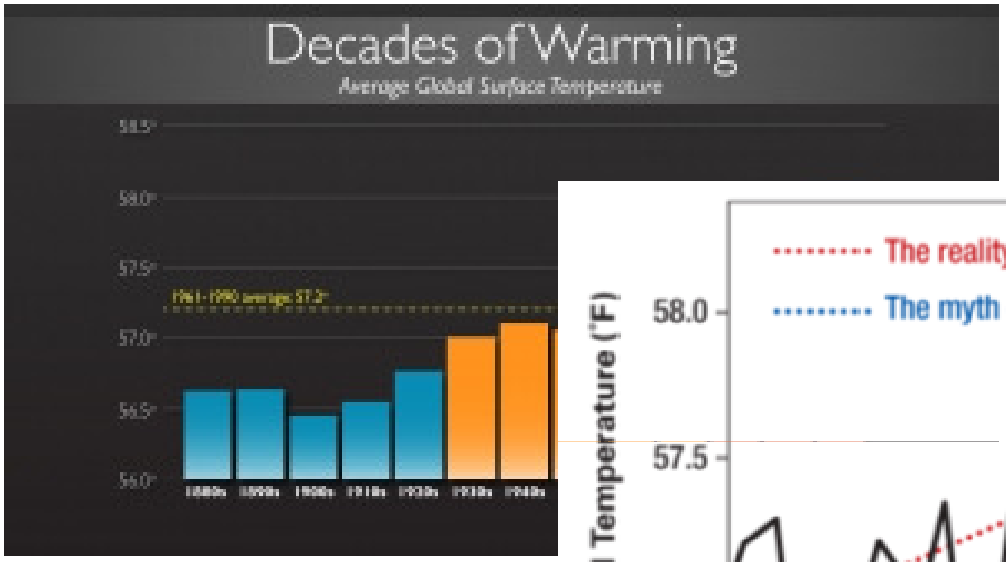
Schmidt et al., 2014

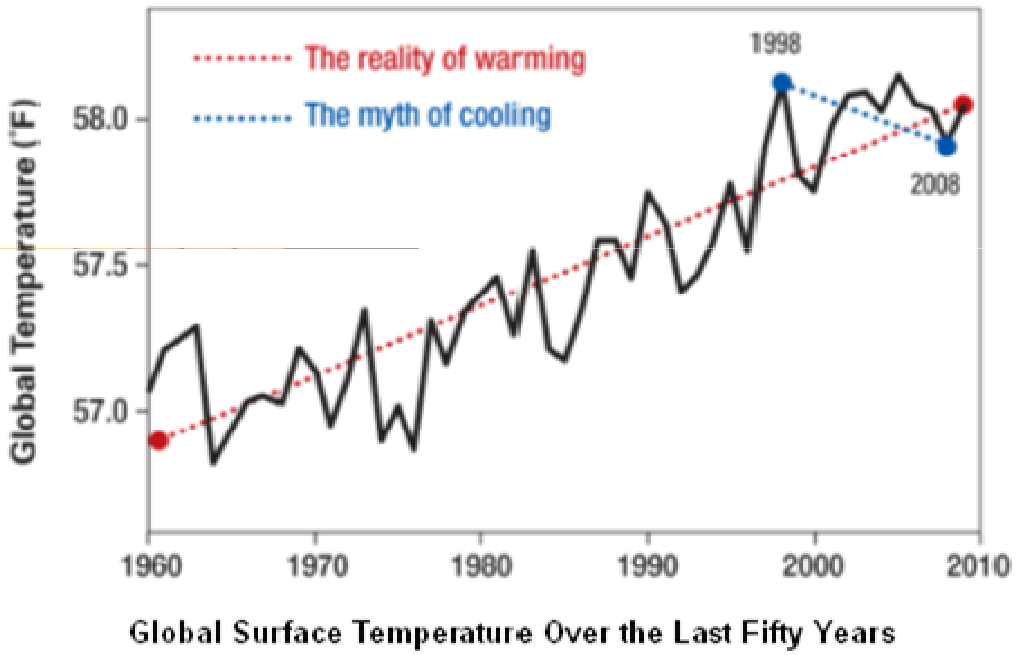


England et al., 2014

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Where is the Hiatus?





Global Surface Temperature Over the Last Fifty Years

UCS, K. Hayhoe

University of St. Thomas
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Thank you….

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