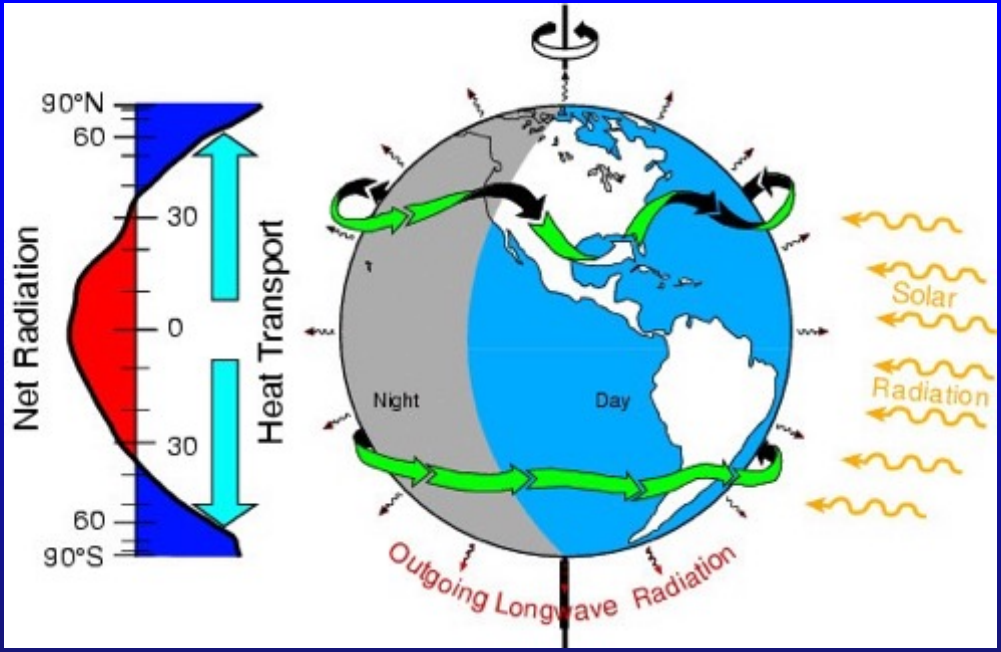
The changing flow of energy through the climate system

Kevin E Trenberth

NCAR and U. Auckland



The main external influence on Earth is from radiation.

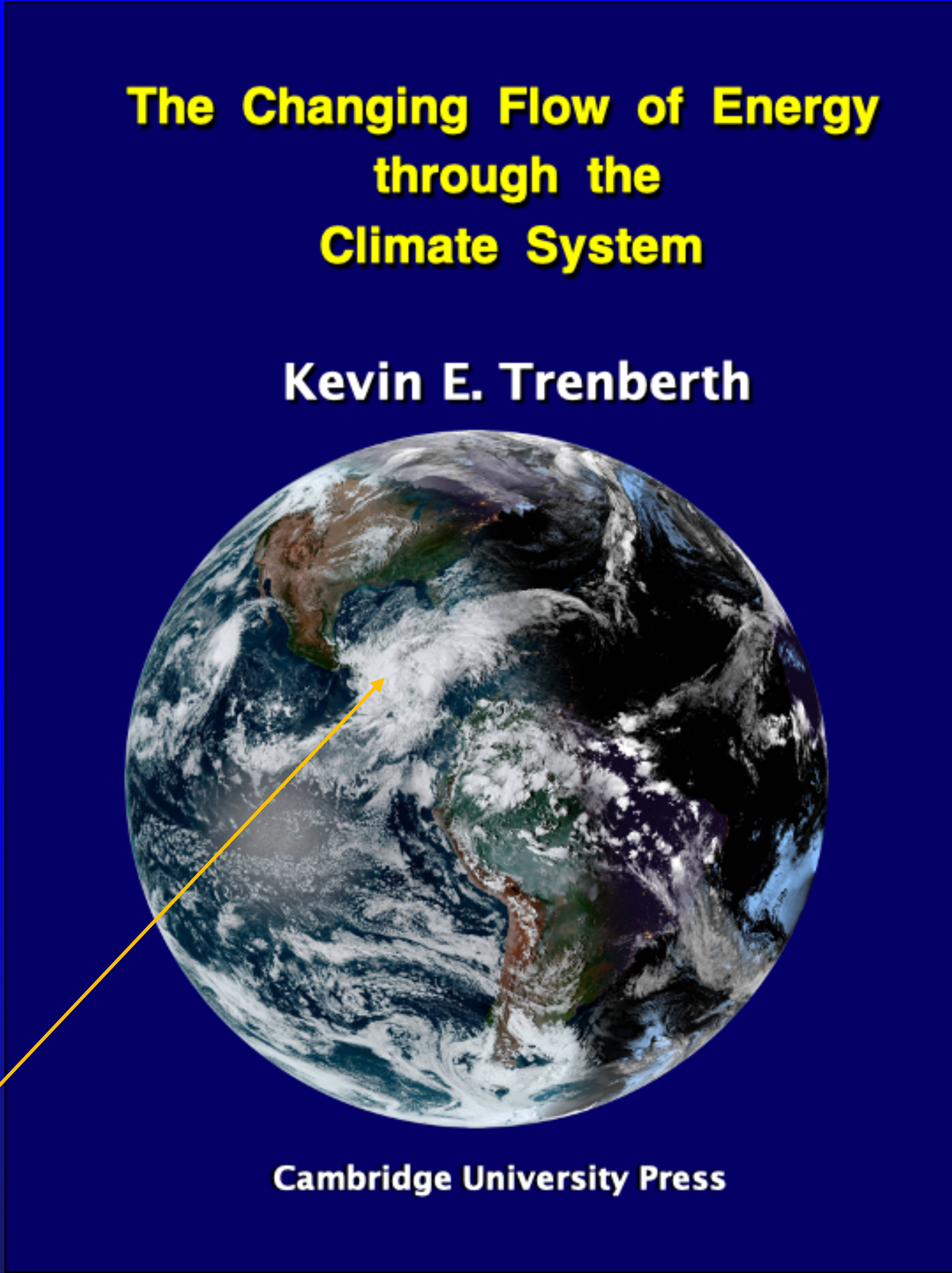
Incoming solar shortwave radiation is uneven owing to geometry and rotation of Earth.

Outgoing long-wave radiation is more uniform.

My new book,
Submitted Nov 5 with the satellite imagery from Nov 5, 2020

Has
- 18 Chapters,
- 128 Figures
- 100K words

Topic of today's talk is mostly Chapters 9 & 14.



Hurricane Eta
Nov 5, 2019

Energy on Earth

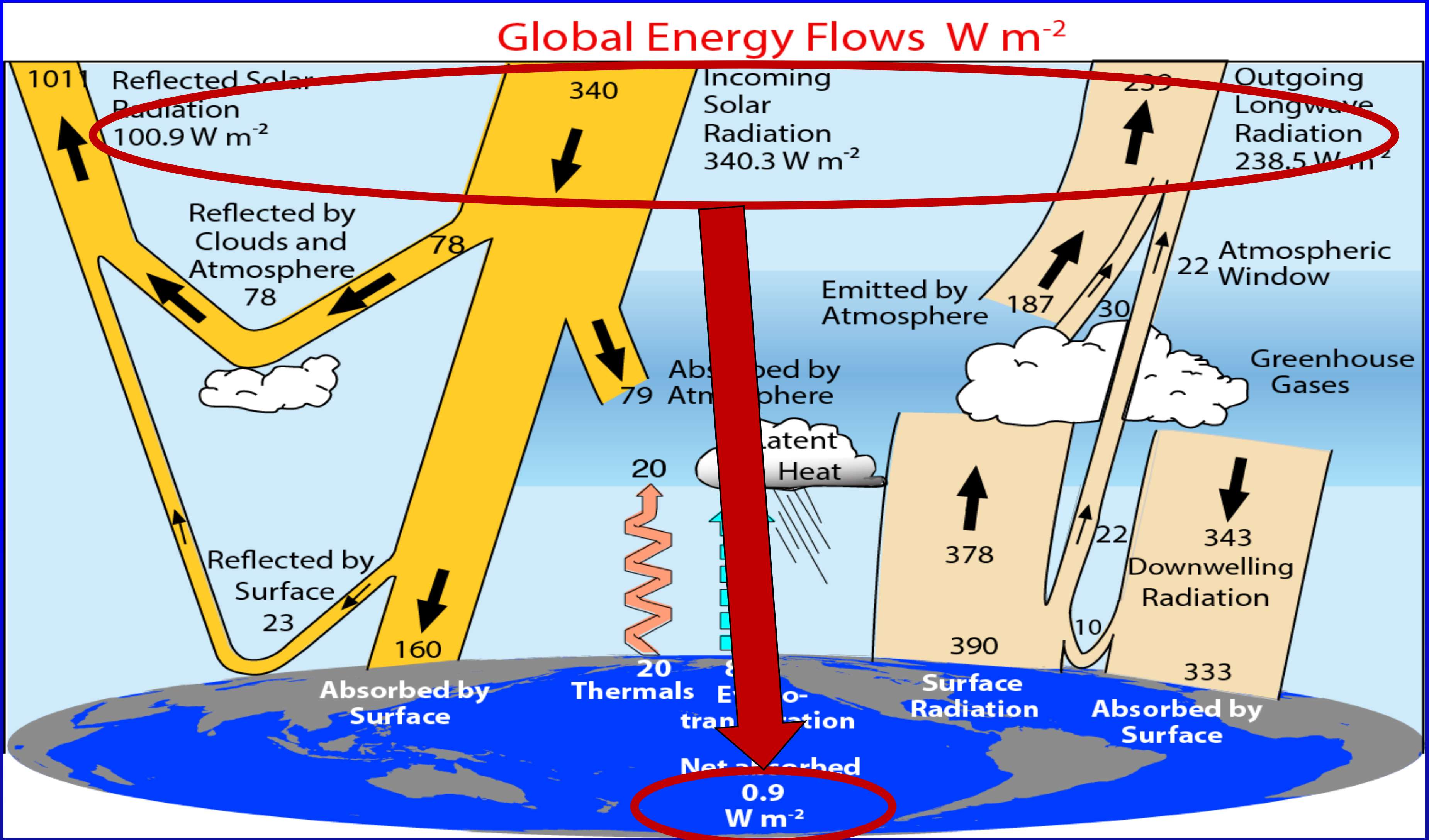
The climate is changing from increased GHGs that create an energy imbalance.
The planet warms until OLR increases to match the ASR.
But there are many feedbacks and complexities.

The most fundamental measure that the climate is changing is Earth's Energy Imbalance.

Major advantage: it is the **net** result of all complicated feedbacks.

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

Trenberth et al (2009) updated



The EEI is the net effect after all of the complicated feedbacks (from clouds, aerosols, water vapor etc) have operated.

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

Varies over time but is now about:

$0.9\ \mathrm{W\ m^{-2}}$.

Globally this is about 500 TeraWatts

= 500,000,000,000,000 Watts.

In 2018 global electricity generation was about 5.7 TeraWatts

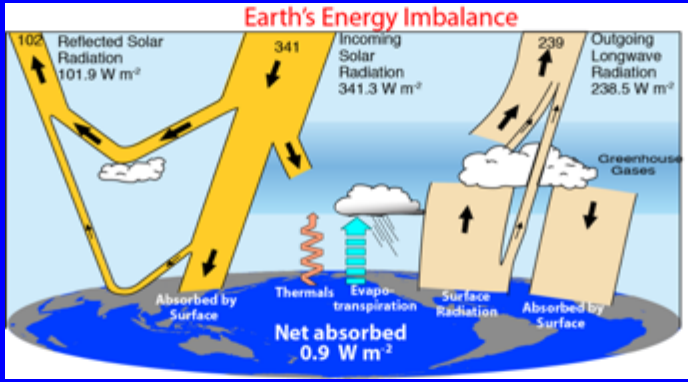
Factor of 90 less

1 Christmas tree light is about 0.4 W.

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

Earth's Energy Imbalance

(net effect after all feedbacks included)



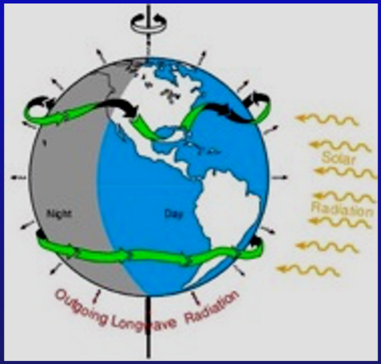
$0.9\ W\ m^{-2}$

small 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.



Global warming means more heat:

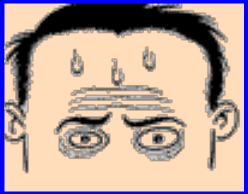
Where does the heat go?

>90%

1. Warms land and atmosphere
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



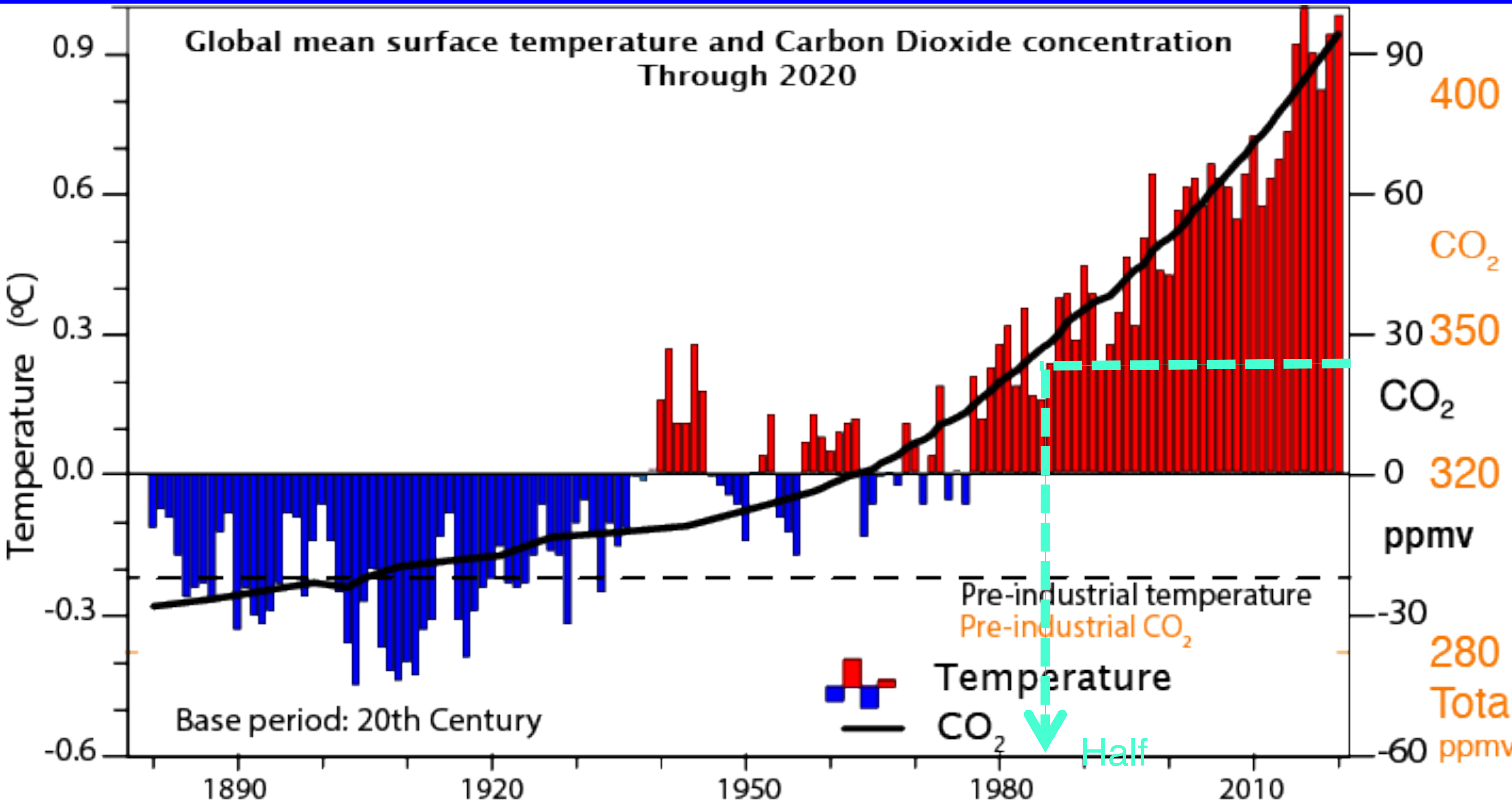
Homes: Evaporative coolers (swamp coolers)

Planet Earth: Evaporation (if moisture available)

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

the first thing that h[illegible]s is that the puddles dry up:
before the temperature increases.

Global temperature and carbon dioxide: anomalies through 2020



Base period 1900-99; data from NOAA

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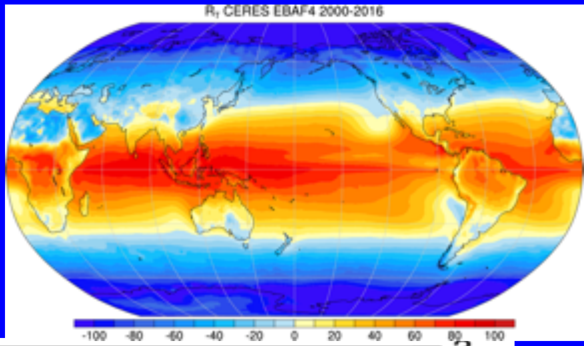
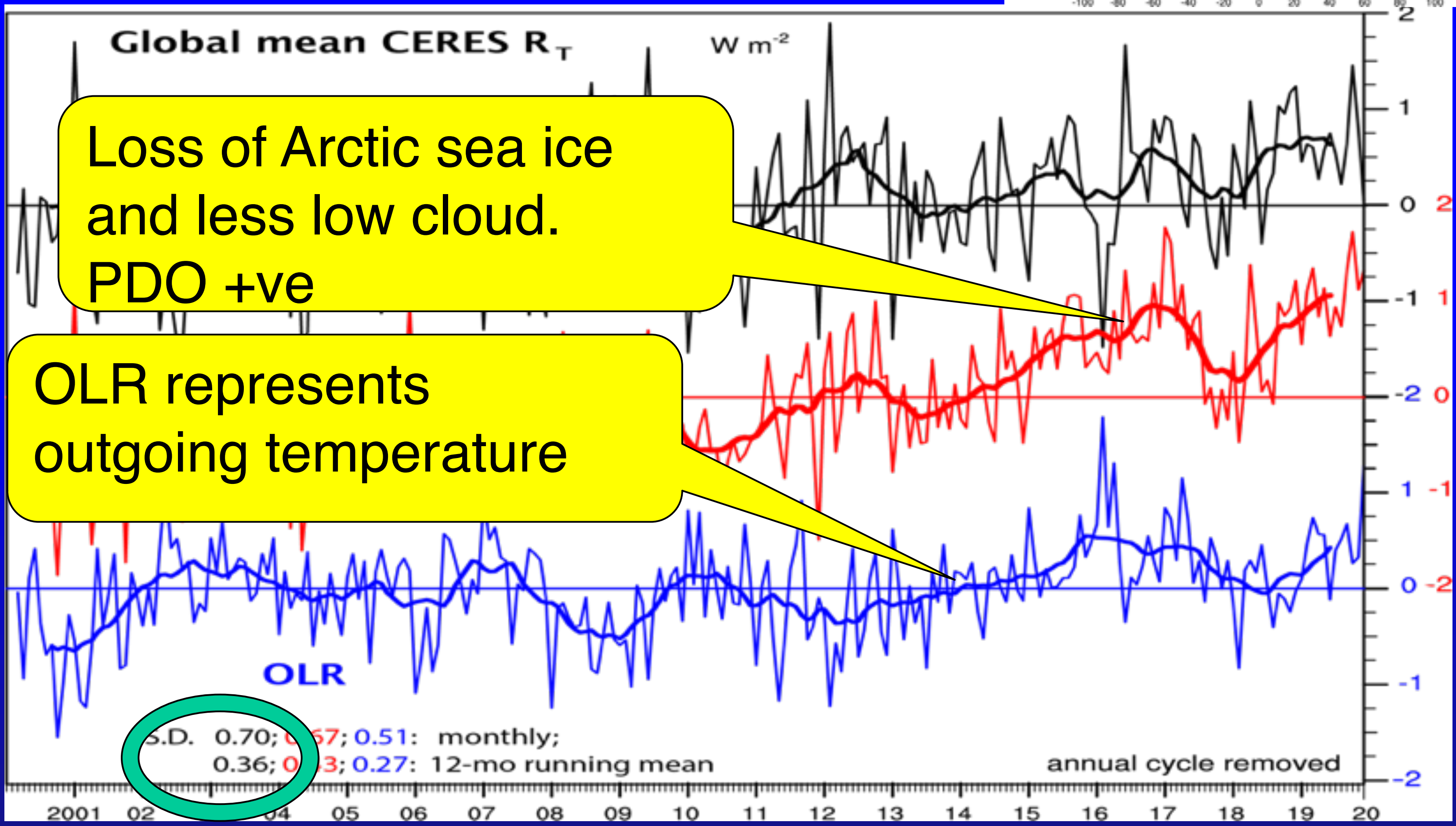
Earth's Energy Imbalance

TOA radiation



Mean
0.7
W m^{-2}



Monthly anomalies and 12-month running mean

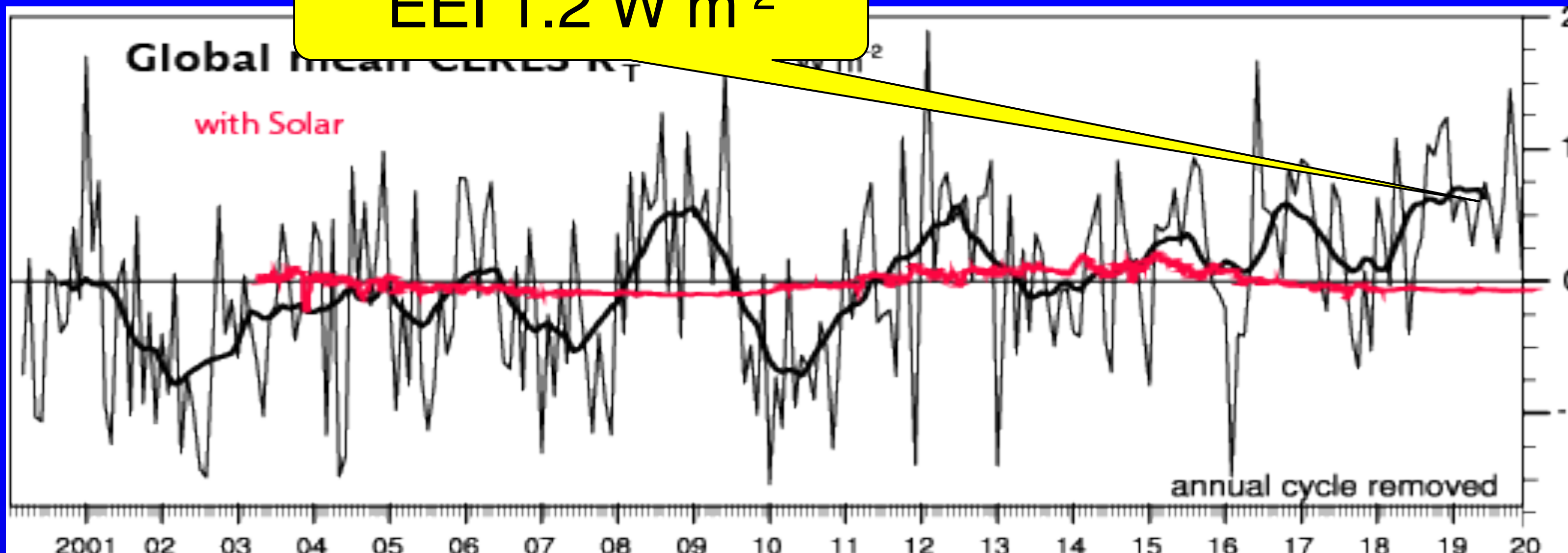
0.36 W m^{-2}=> 184 TW

Earth's Energy Imbalance

TOA radiation

EEI 1.2 W m^{-2}

Mean 0.7 W m^{-2}



Total solar irradiance contributions

Monthly anomalies and 12-month running mean

What about the atmosphere?

Warmer air holds more moisture

7% per °C =4% per °F

Global warming=

More heat

⇓

More drying

⇓

More evaporation

⇓

More moisture

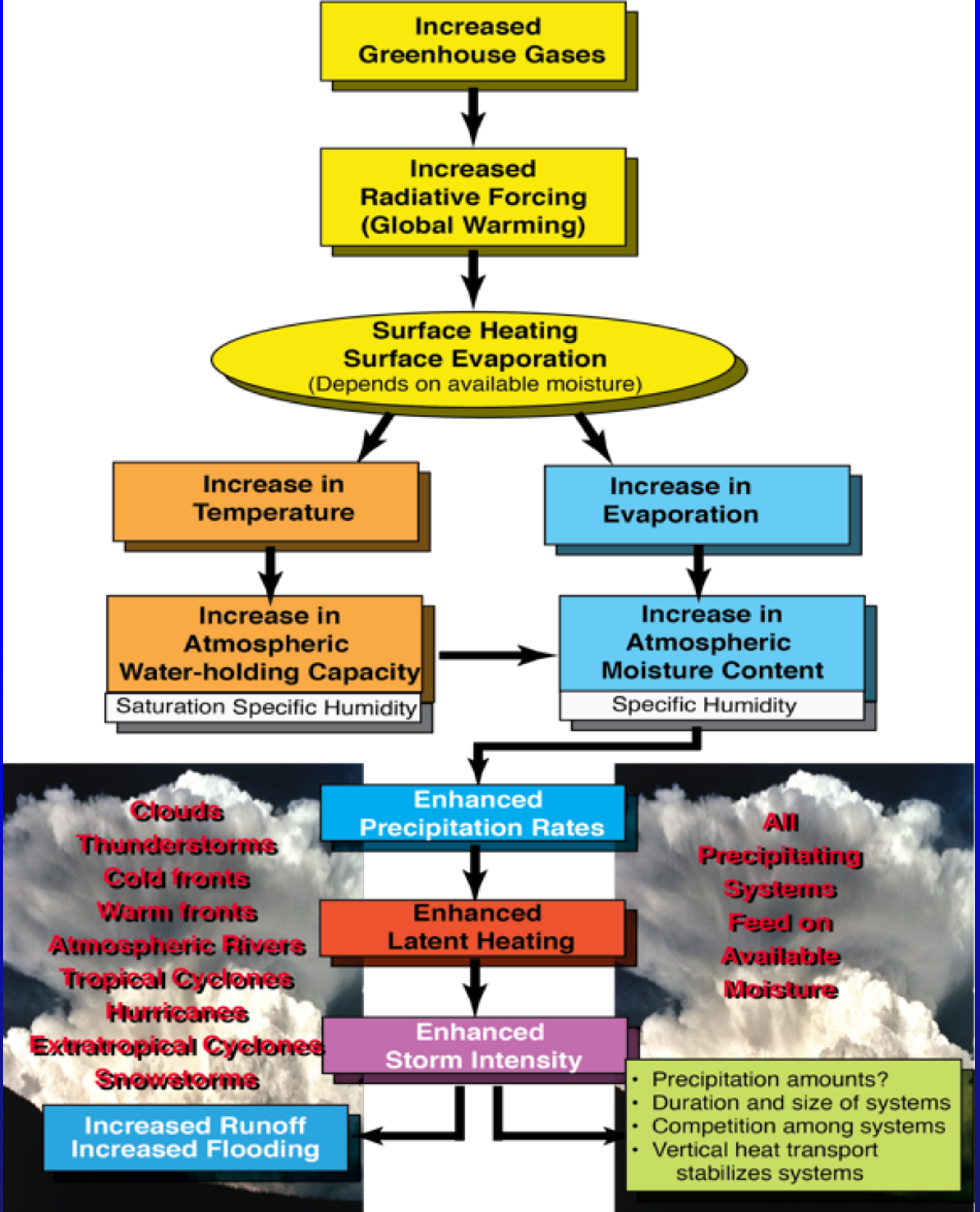
More rain

More drought

Most precipitation comes from moisture convergence by weather systems

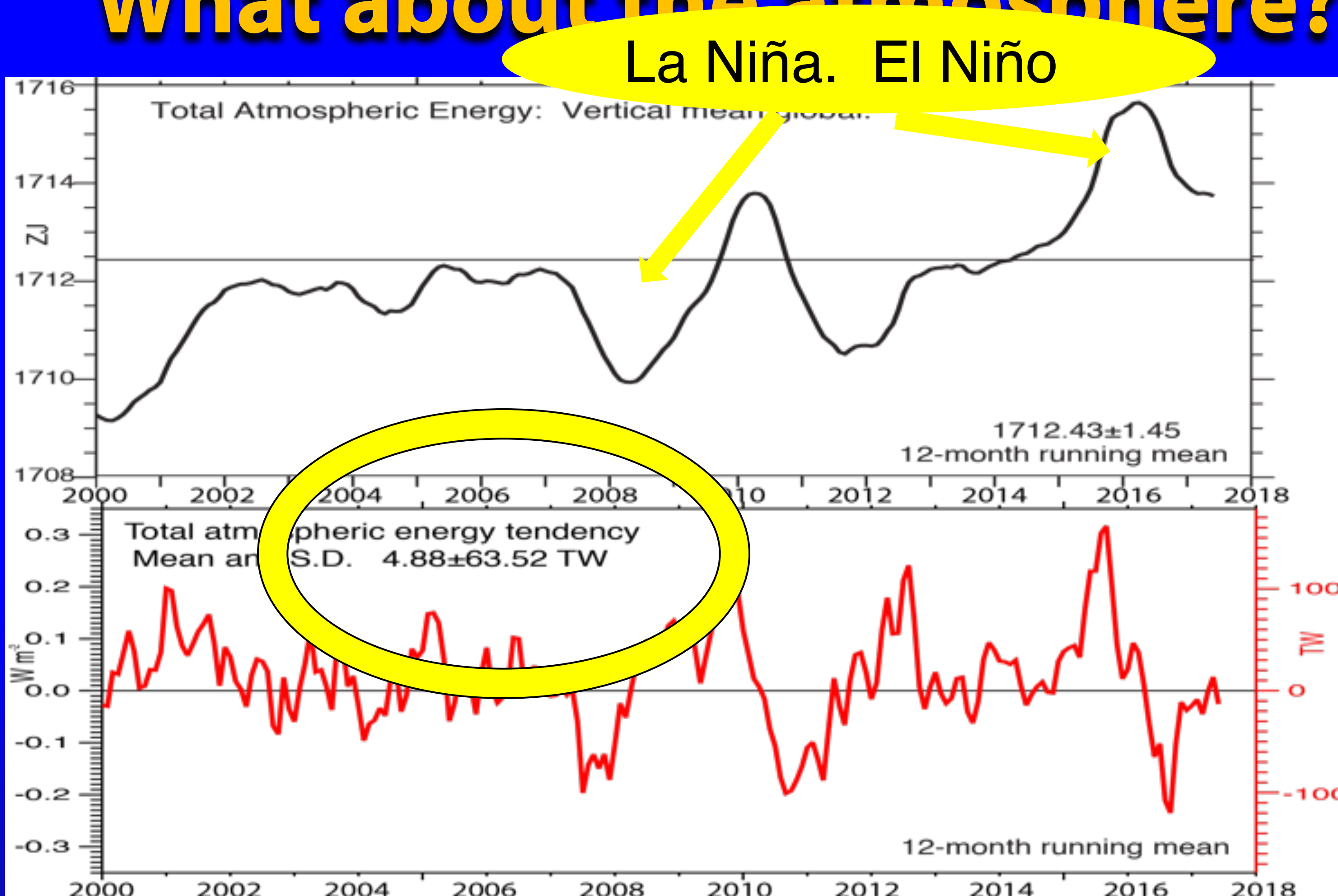
Low level winds bring in moisture from afar

More moisture means heavier rains



Adapted from
Trenberth 1999

What about the atmosphere?



ERA-Interim

1 W m^{-2} (globally) is 510 TW.

64 TW (0.12 W m^{-2}) accounts for 35% of EEI variability s.d.

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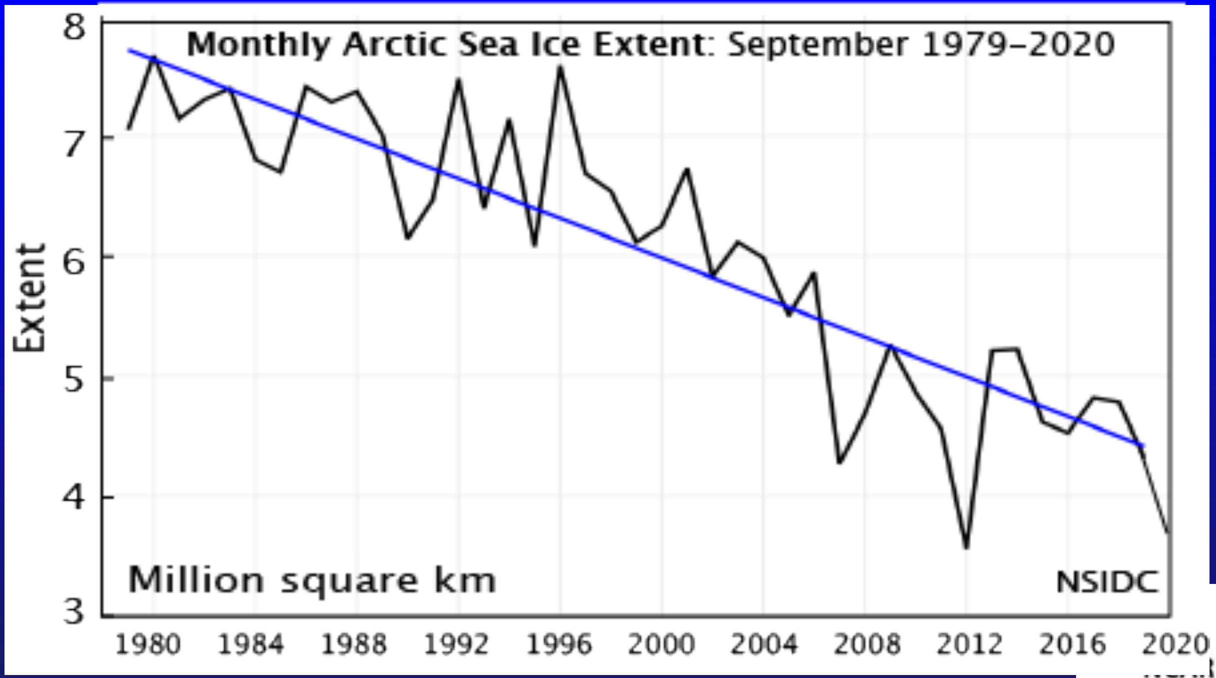
Effects accumulate in melted ice

Increased Glacier retreat since the early 1990s

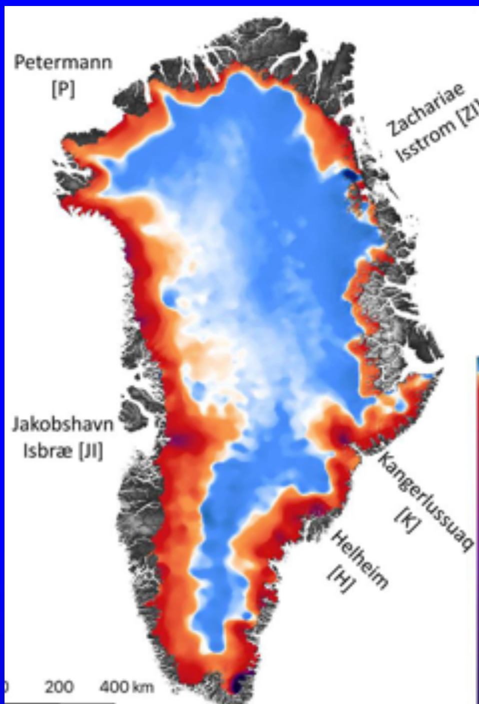
Muir Glacier, Alaska

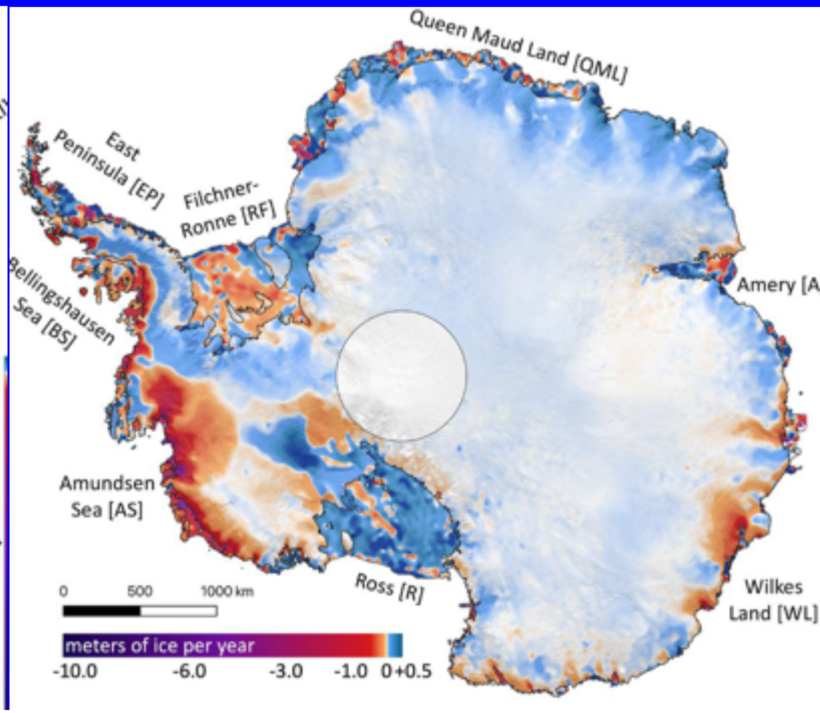
Arctic sea ice loss: over 40% in summer



This is extent, not volume

Ice sheets





Greenland and Antarctica ice melt in terms of energy is about -2.6 and -1.1 TW $\cong$ 0.007 W m^{-2}

	dM/dt (Gt a^{-1})				
	Floating	Grounded	TW	SLR potential (m)	Total SLE 2003–2019 (mm)
Greenland	N/A	−200 ± 12	-2	7.4	8.9
EAIS	106 ± 29	90 ± 21	2	51.1	−4.0
WAIS	−76 ± 49	−169 ± 10	-2.5	5.6	7.5
AP	−14 ± 28	−39 ± 5	-0.5	0.5	1.7
Antarctica	15 ± 65	−118 ± 24	-1	57.2	5.2

Smith et al. 2019 Science

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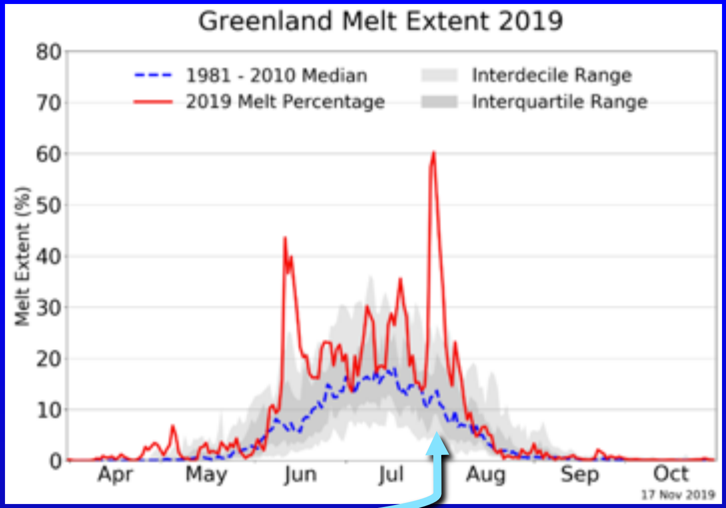
Effects accumulate in melted ice

Greenland melting has increased



Early August 2019

Courtesy NSIDC

Global ice melt in terms of energy is about 11 TW $\cong$ 0.03 W m^{-2}

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What about land?

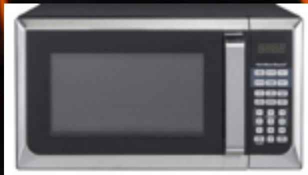
If land is wet: heat goes into evaporation.
But in a drought, the heat <u>accumulates</u>.

- **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 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!

What about land?

Land use and land cover change from clearing for agriculture and pasture, and wood harvest is about 1/3 of human CO_2 emissions.

It also changes energy fluxes via albedo, hydrology, and vegetation; and via irrigation.

Desert crop circles

Forest increased 7% globally 1982 to 2016

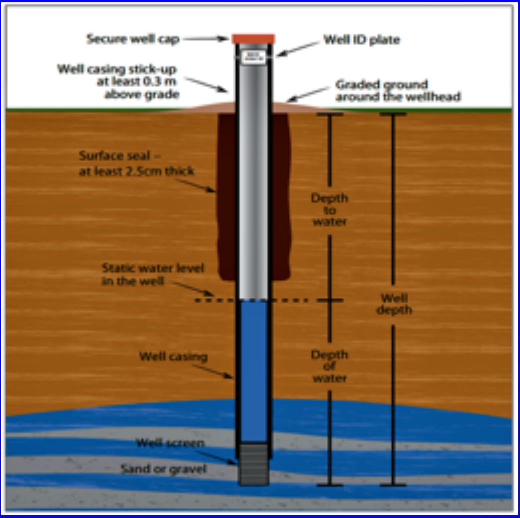
loss in tropics vs increase in extratropics

Bare ground increased 3%.

Surface signal takes ~ 50 years to penetrate to 50 m depth.
Varies spatially, especially where water plays a role.

What about land?

Borehole temperature changes: rate of land warming after 1950 is ~ 6 - 7 TW, increasing after 2000 to ~10 -12 TW.



Inland waters cover 2.6% of continental area. Artificial reservoirs have increased global lake volume by 3.2%: modestly since 2005. Since 2005, the mean trend in global lake, river and reservoir heat uptake is ~ 0.4 TW and energy in increased mass of waters in reservoirs is about 0.9 TW.

vanderkelen et al. 2020: GRL

A **borehole** may be constructed for: extraction of water, oil or natural gas; a geotechnical investigation to assess ground properties (e.g., for construction purposes); environmental site assessment; mineral exploration; as a pilot hole for installing piers or underground utilities; geothermal installations, or underground storage of unwanted substances.

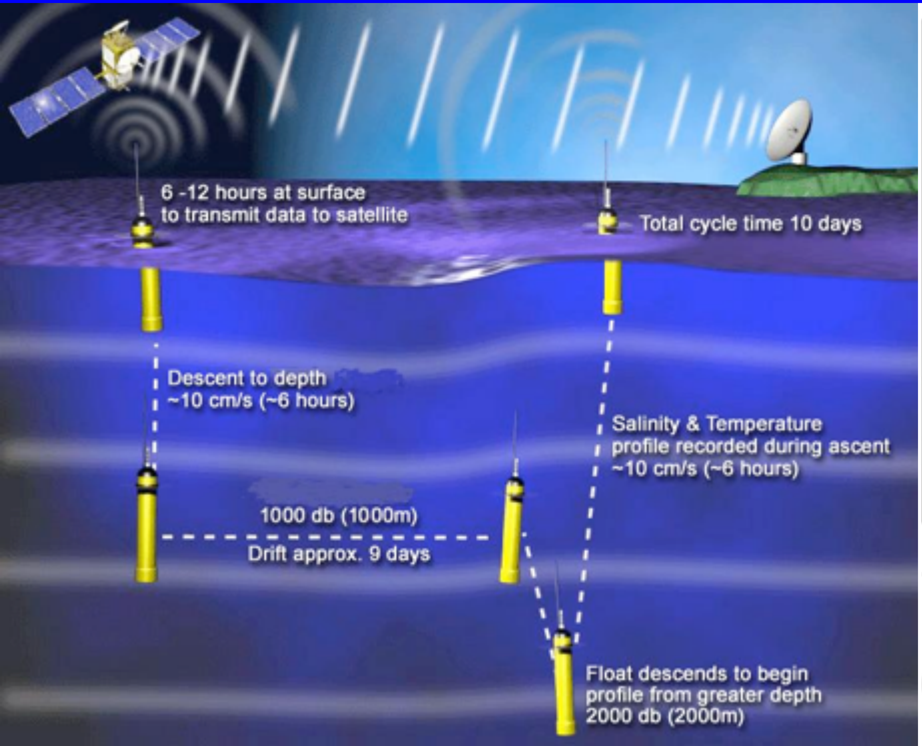
Most boreholes are drilled for other purposes, and are therefore heavily biased as to where they are located.

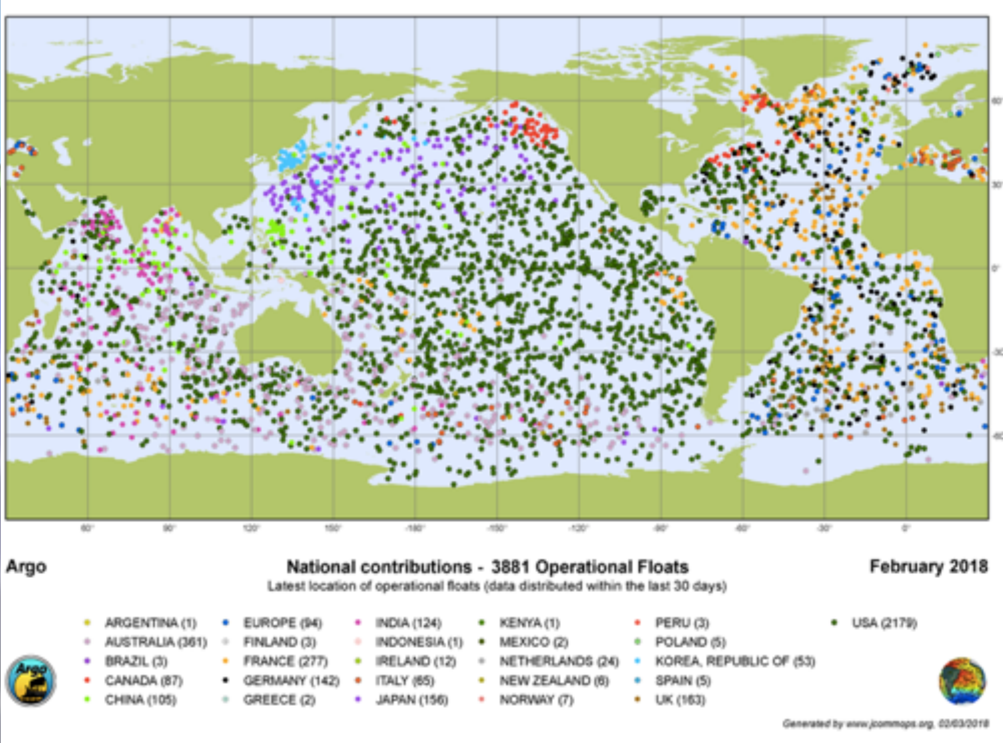
What about the oceans?

OHC

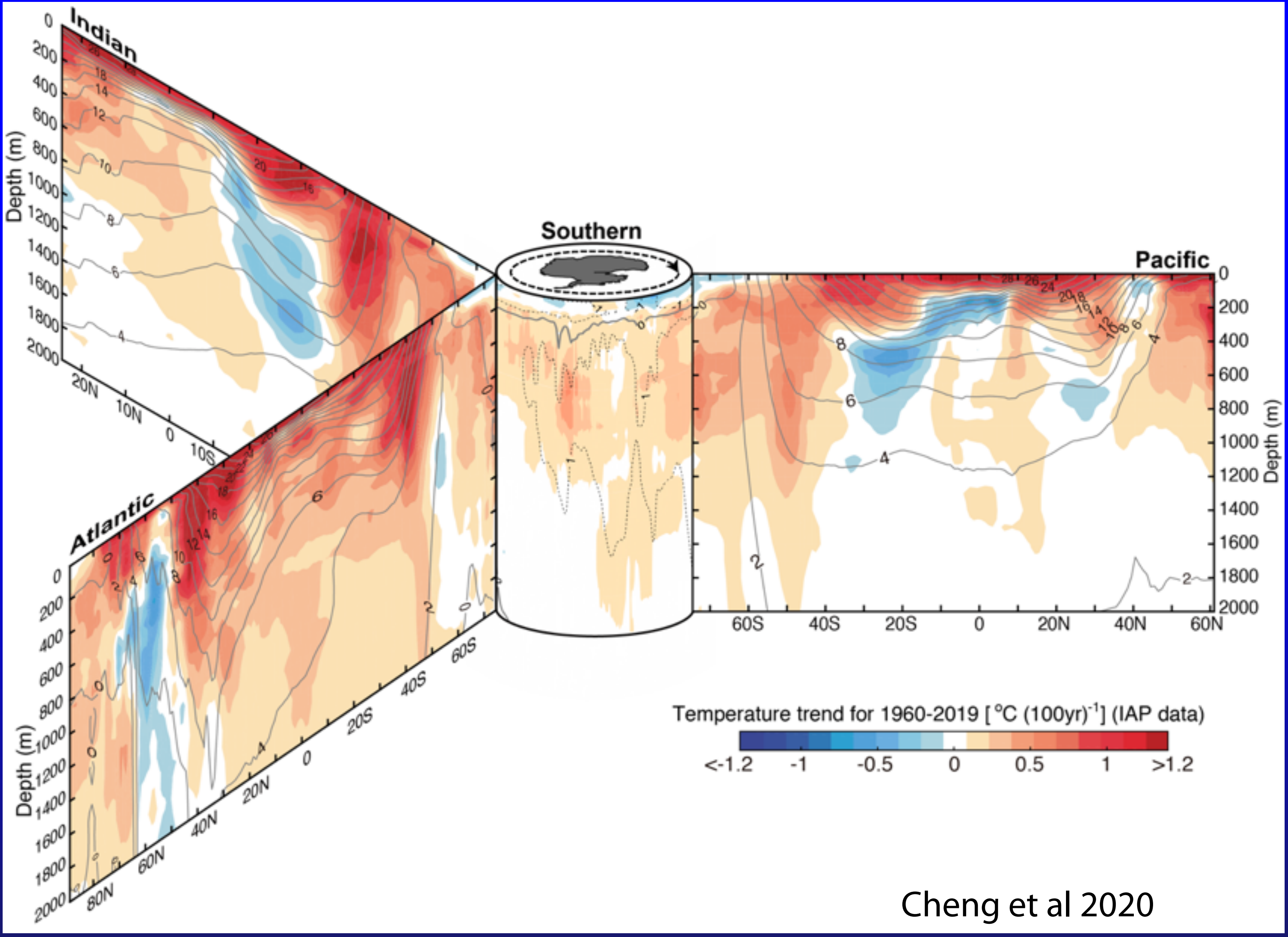
Ocean Heat Content

New observations: Argo floats, since about 2005



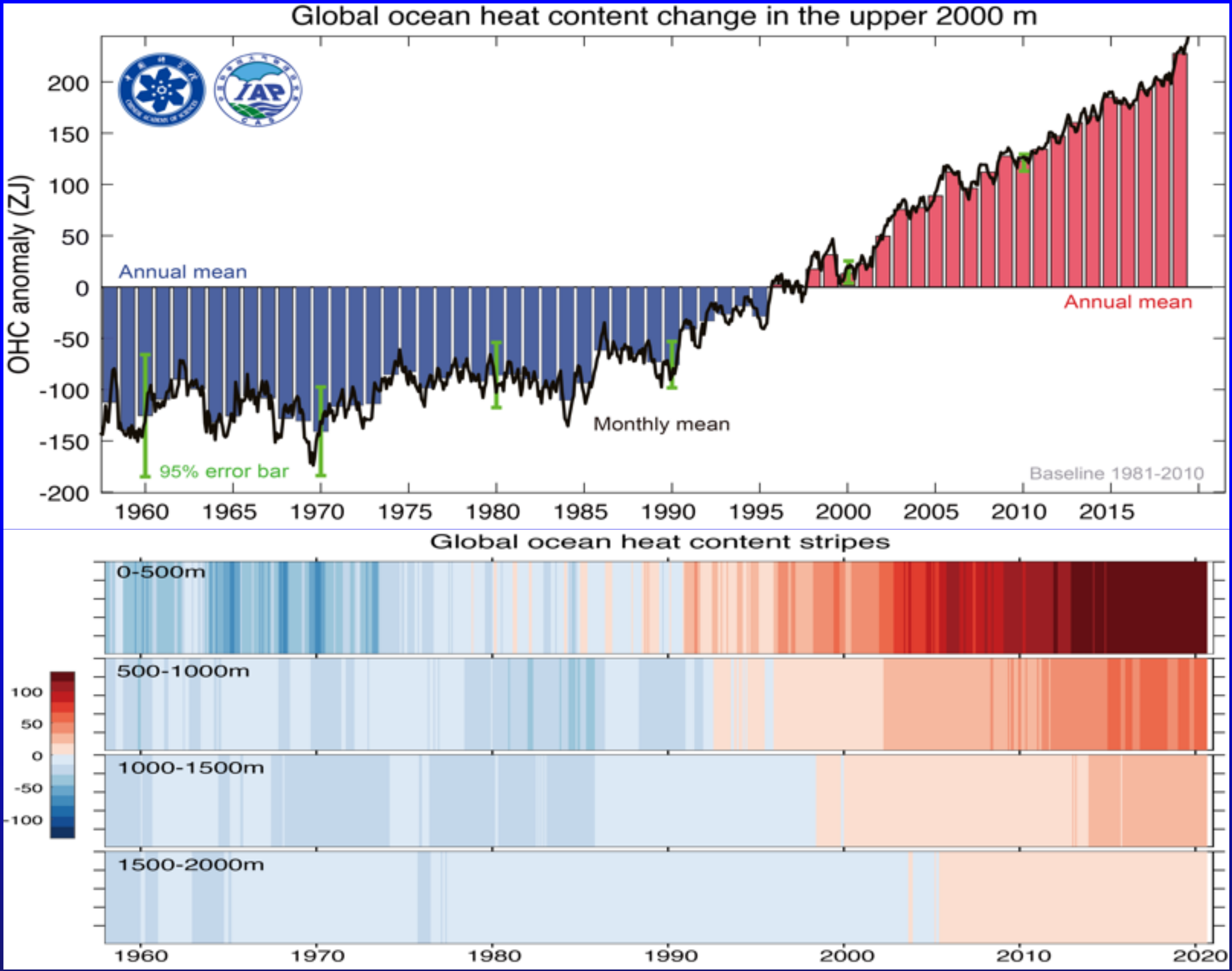


Trend in ocean heat 1960 to 2019



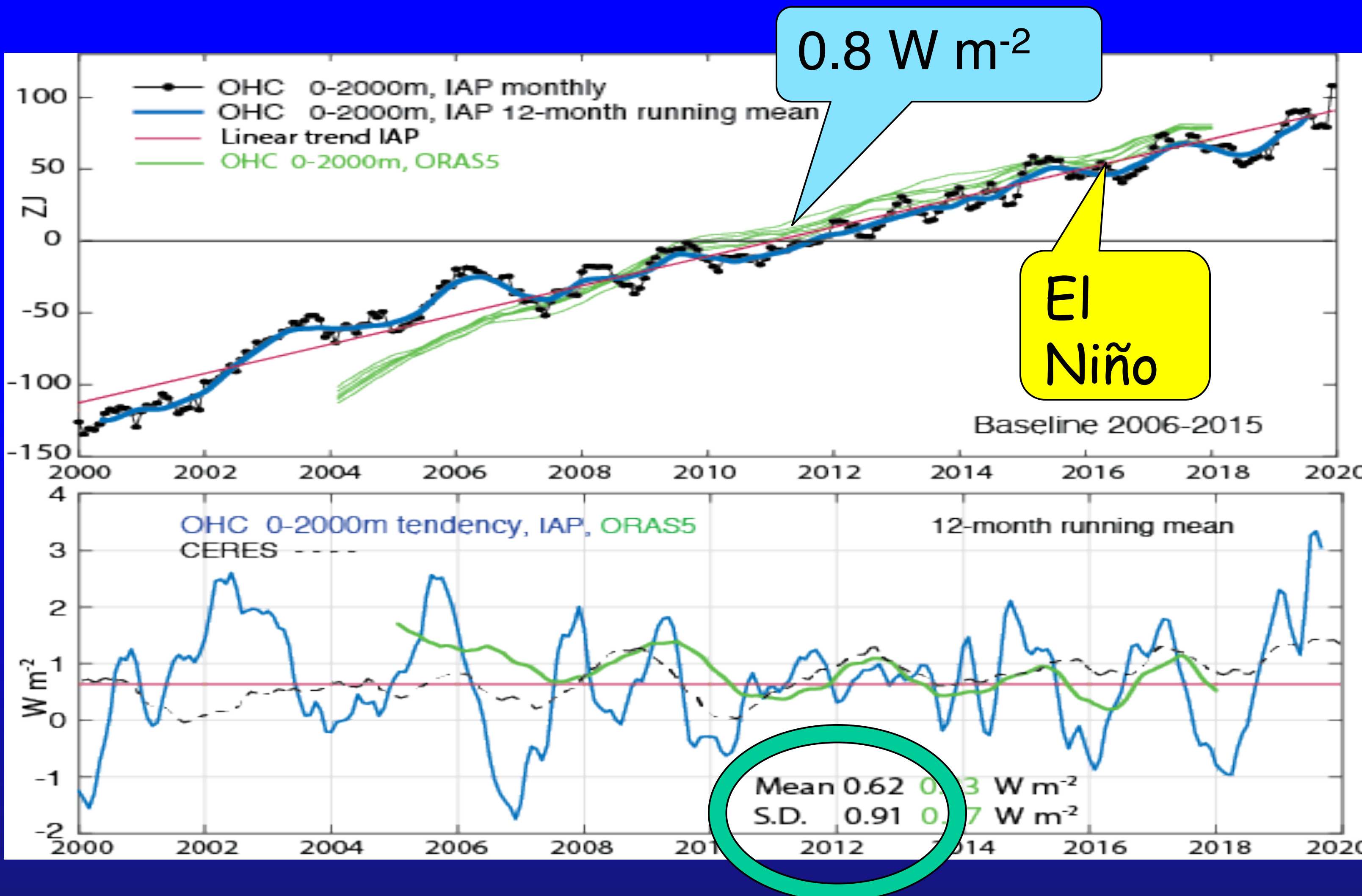
Cheng et al 2020

OHC: 2020

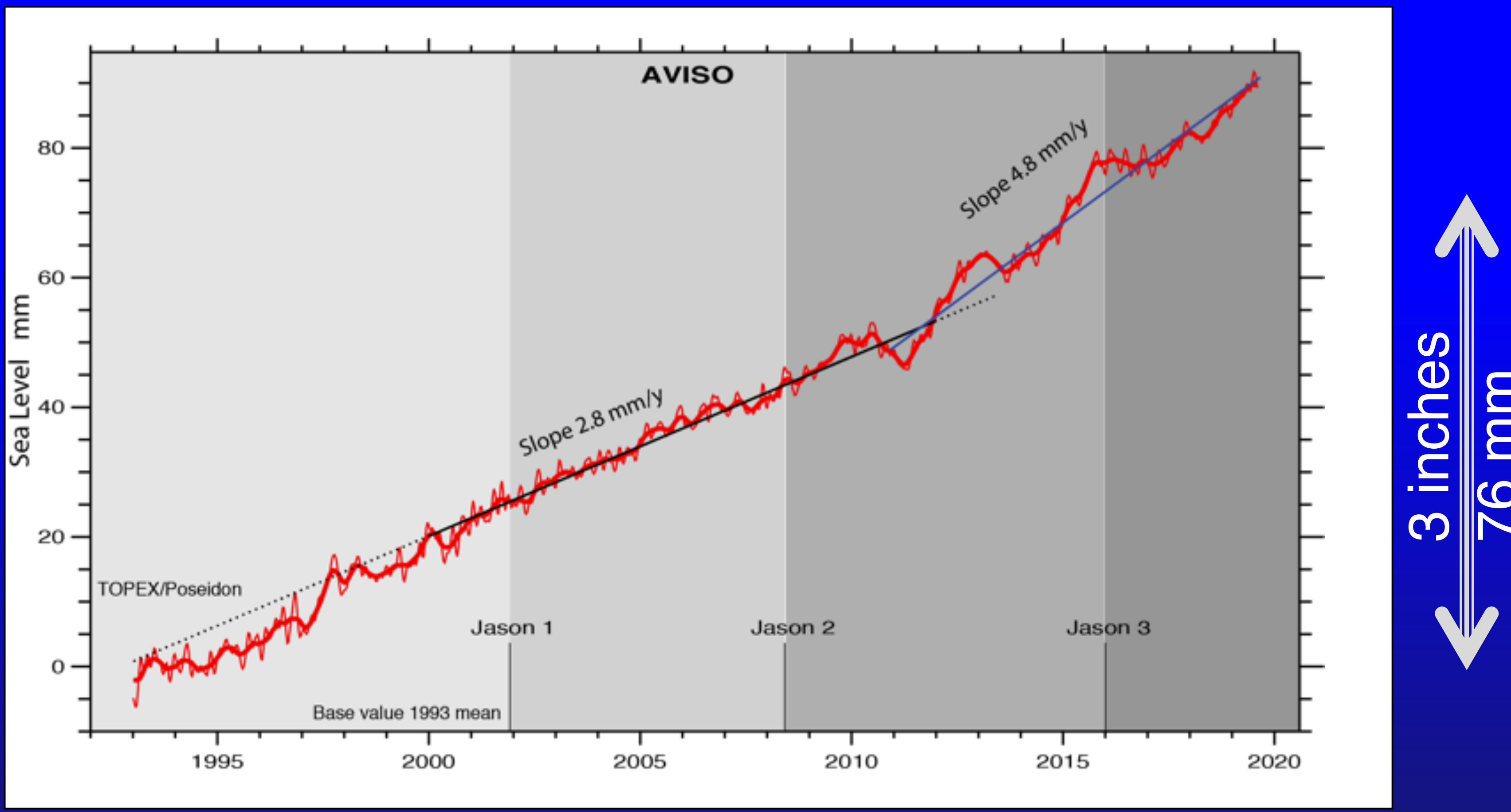


Cheng et al. 2021

OHC and rates of change



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



380 ZJ ocean warming since 1960 corresponds to ~47 mm global SLR (thermosteric)

Synthesis: 2005-19

Atmosphere	3.4 TW
Thawing permafrost:	2 TW
Land warming	14 TW
Arctic Sea ice	3.8 TW
Greenland	2.6 TW
Antarctica	1.2 TW
Glaciers	3.4 TW
Ice Total	**11 TW**

Non-ocean	**30 TW (7% total)**
vs Ocean*	**430±70 TW**

EEI: 0.9±0.15 W m^{-2} since 2005

* Includes contribution from below 2000m depth.

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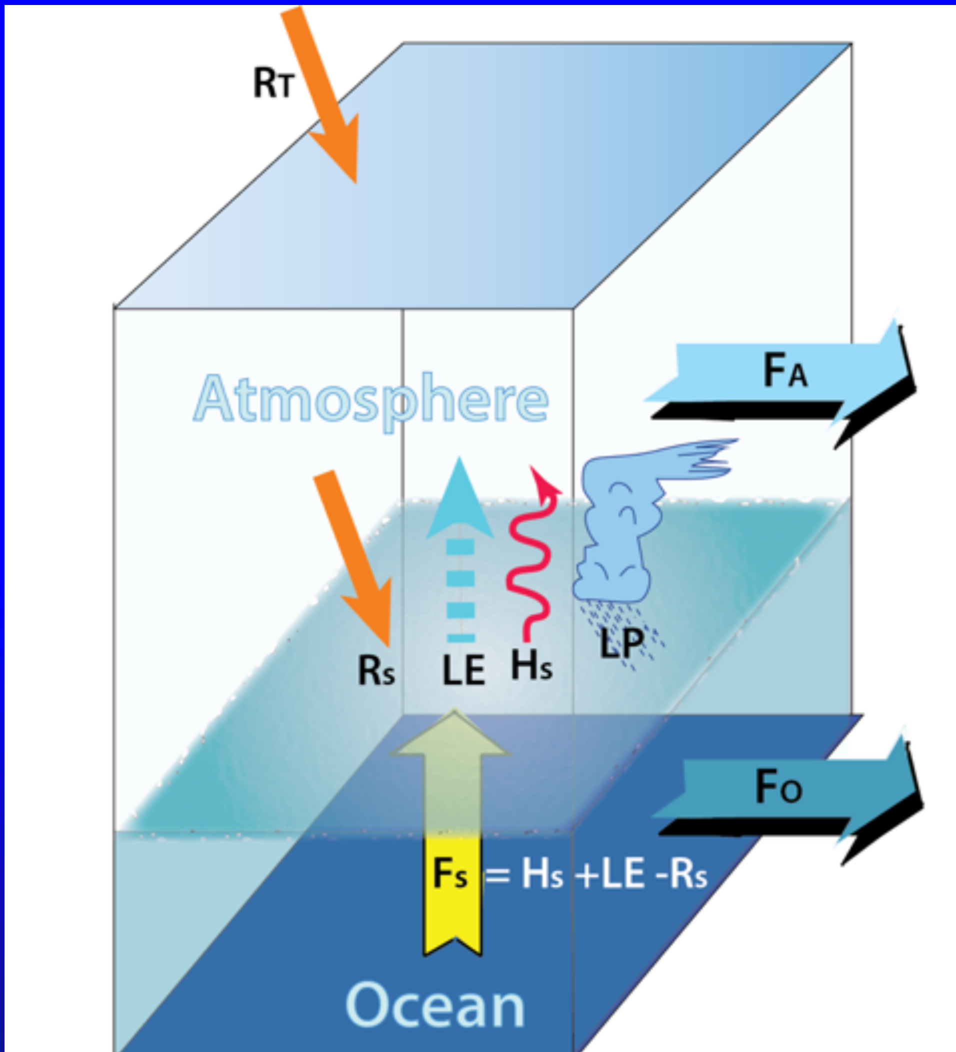
Regional manifestations

Vertically integrated energy budgets

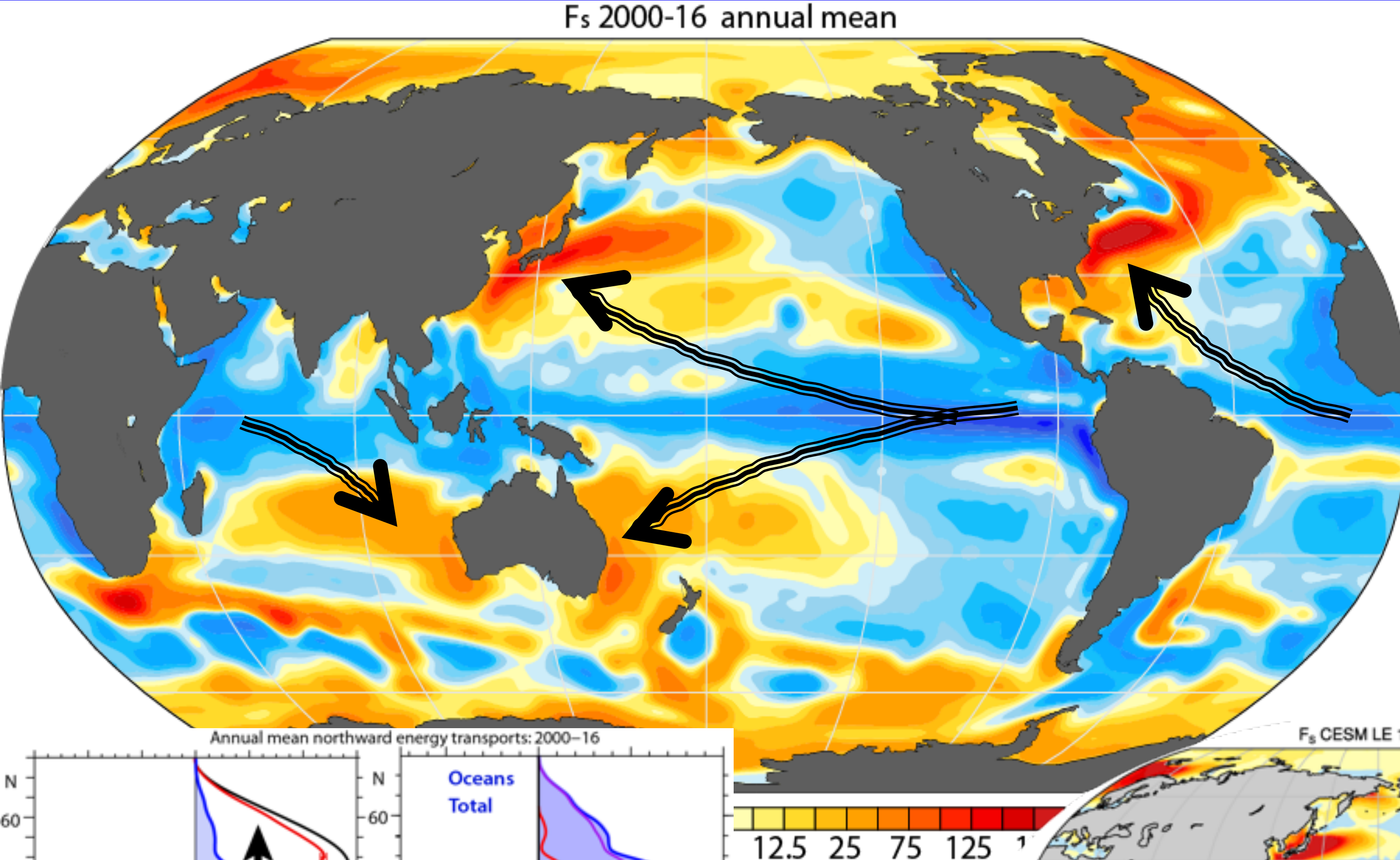


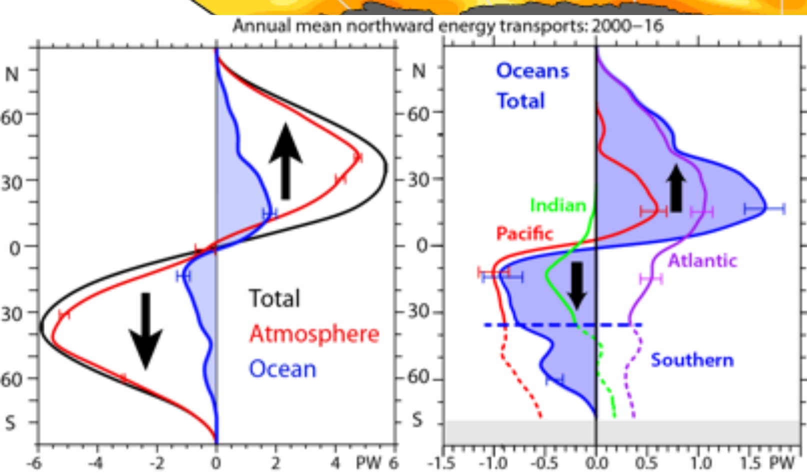
$$\nabla \cdot F_A = Q_1 - Q_2 = R_T + F_s$$

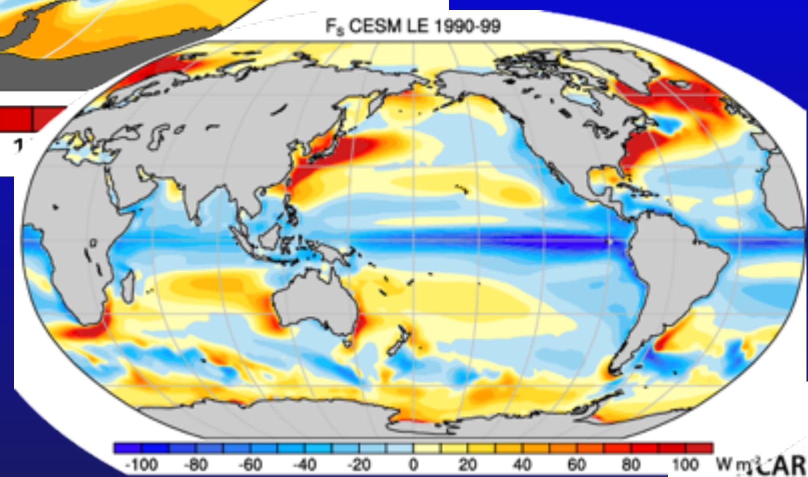
$$\nabla \cdot F_O = - dOHC/dt - F_s$$

The divergence of the energy transport has to match the sources and sinks, and any change in storage.

Balancing the energy budget locally:
Annual mean surface flux





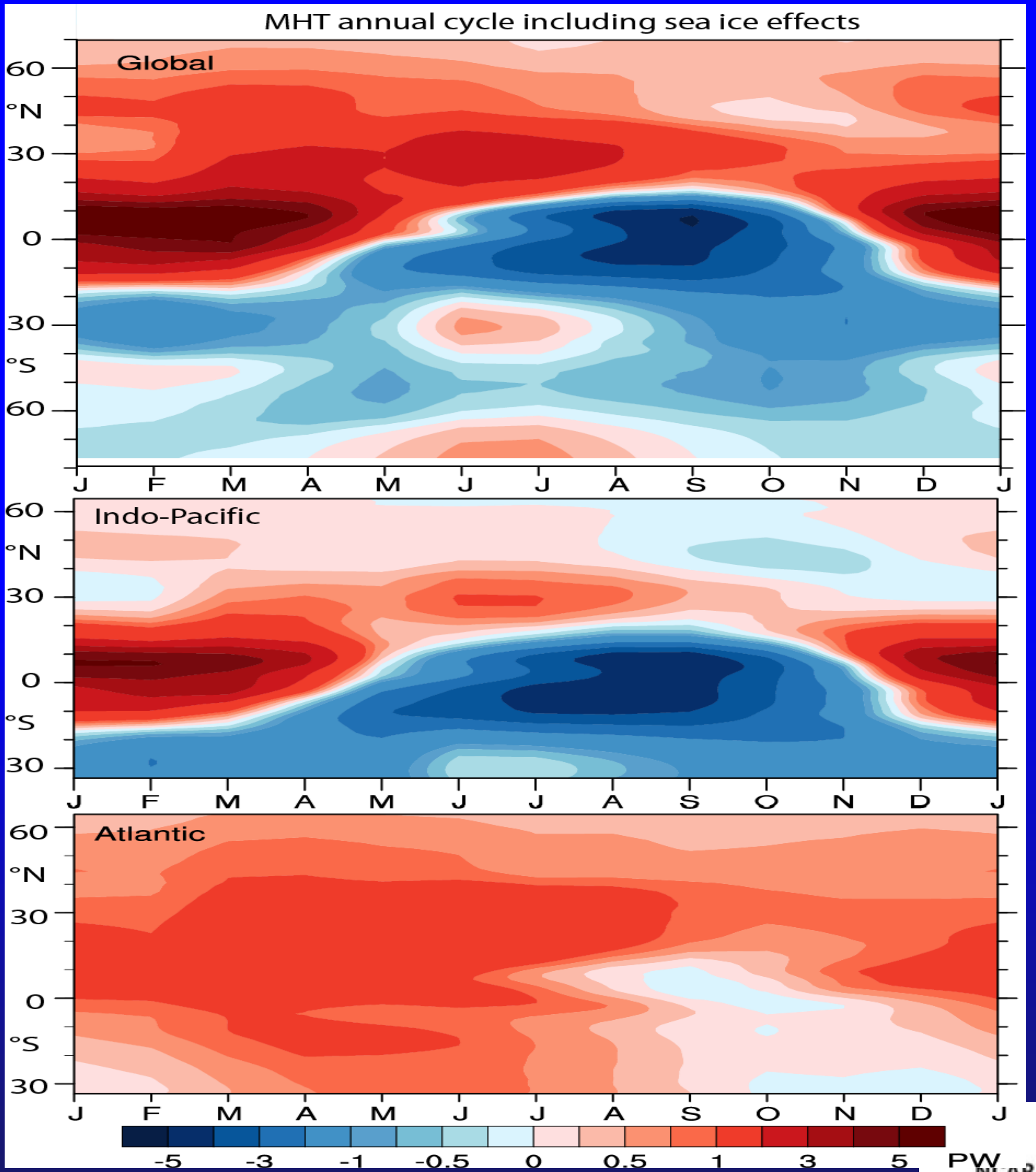


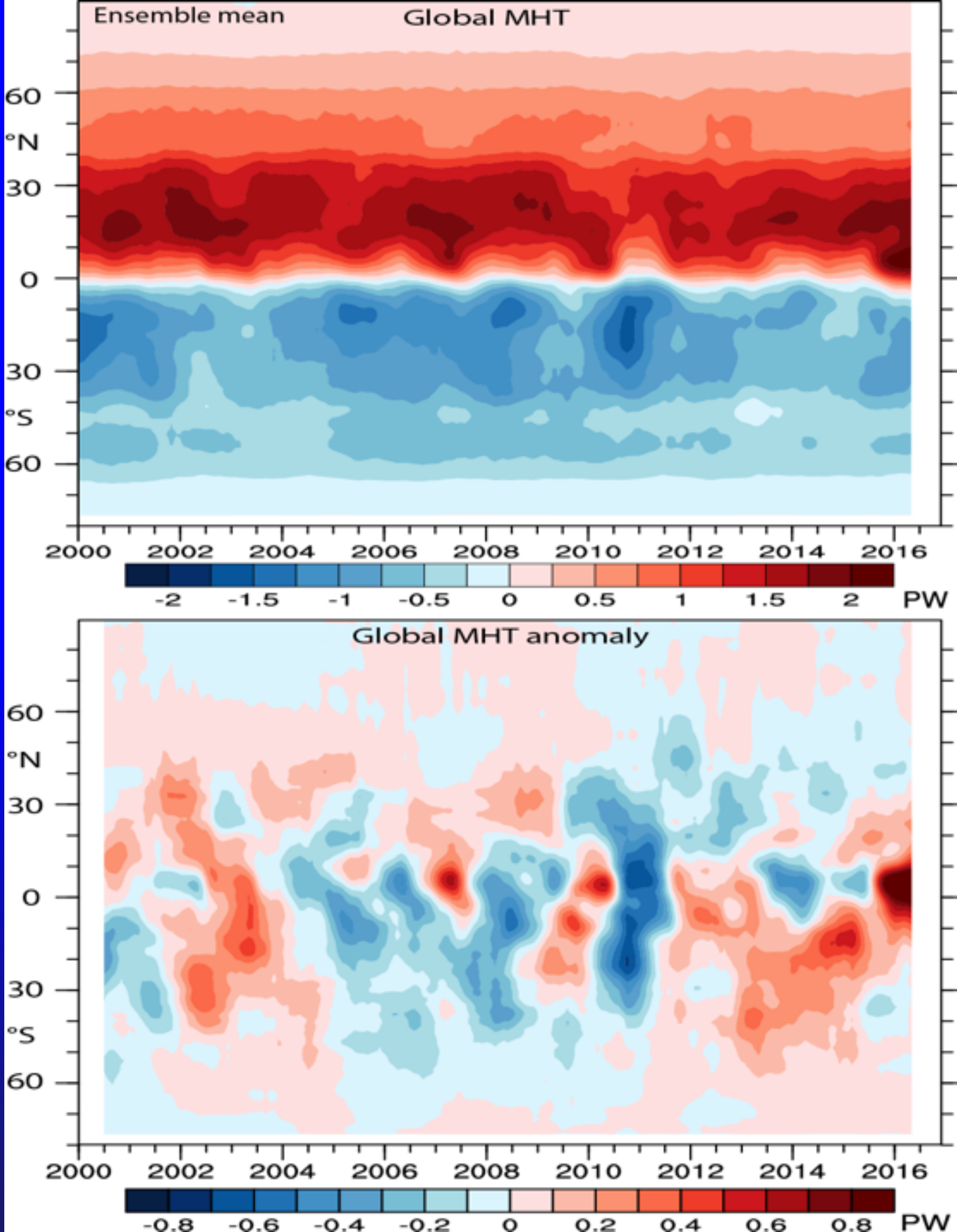
Meridional Energy Transports

Ocean

Mean annual cycle

Ensemble mean.
Sea-ice formation/melt included



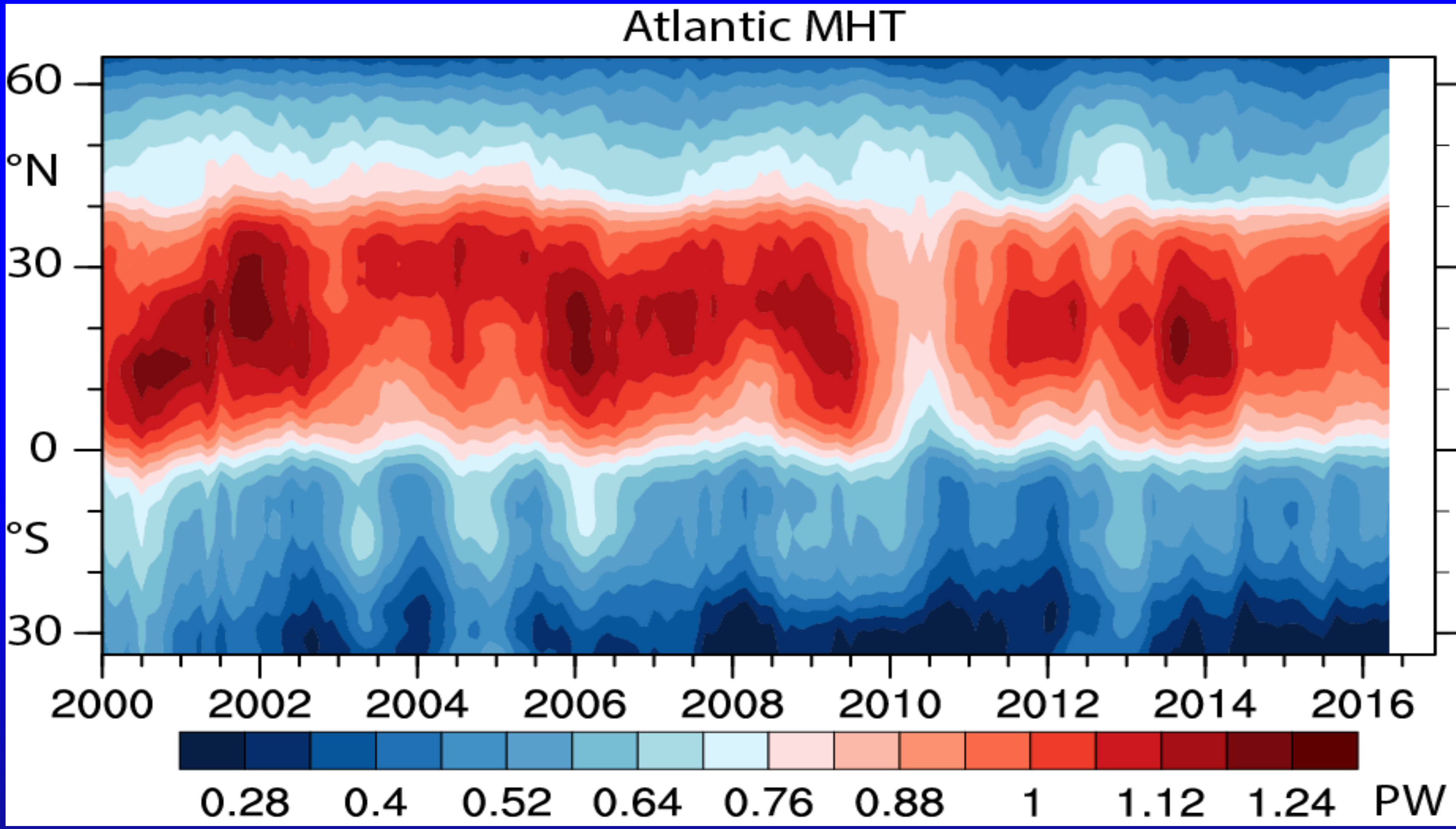


Meridional Heat Transports **(MHT)** variability

adjusted to satisfy global constraints.

Ensemble mean
March 2000 to March 2018
12-mo running means.

Atlantic



Ensemble mean

Top 2000m

12-mo running mean

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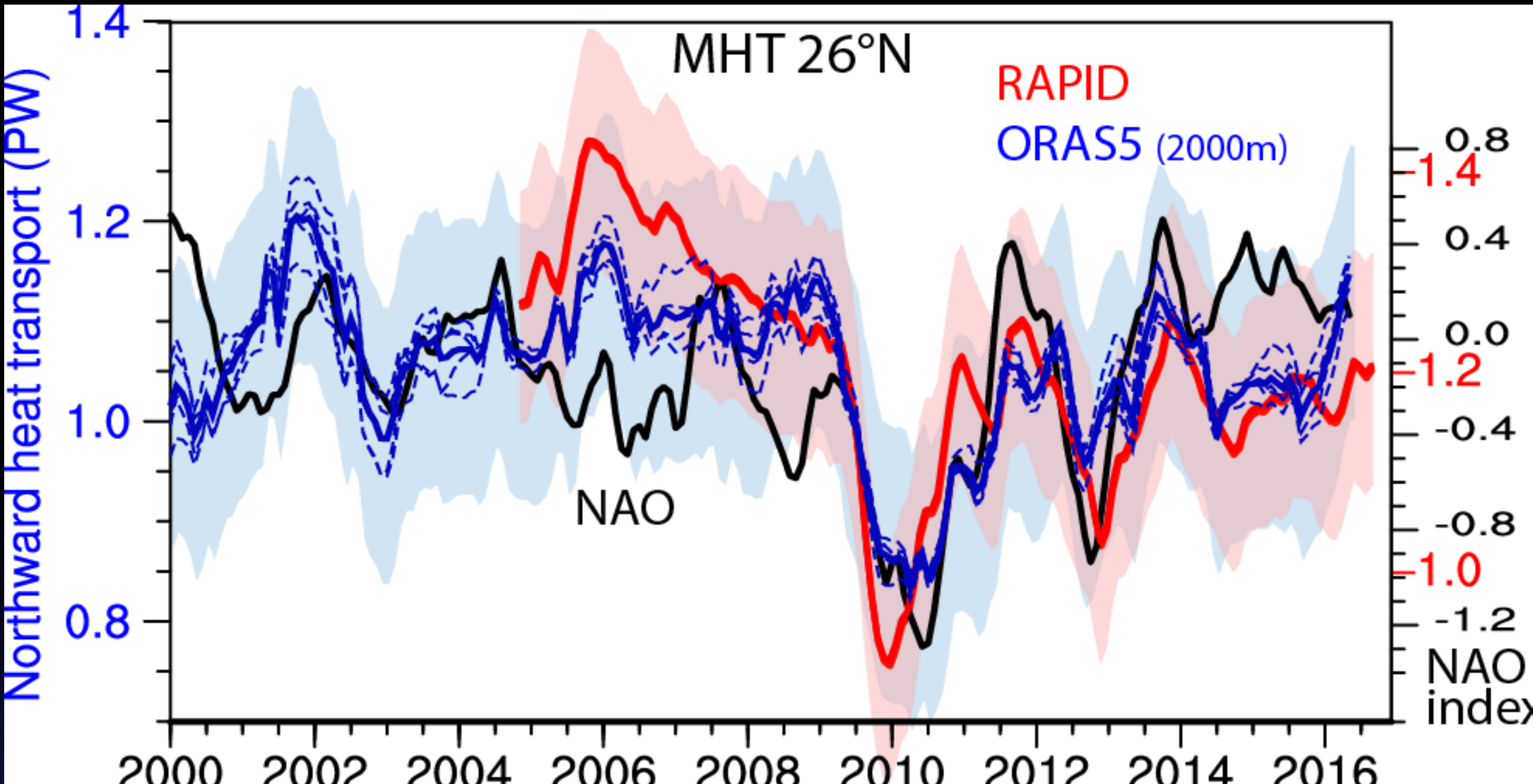
North Atlantic meridional heat transport 26 ºN



RAPID/MOCHA is an ocean moored array across about 26°N

0.15 PW offset

12 month running means

ORAS5 is operational and high resolution (2000m).

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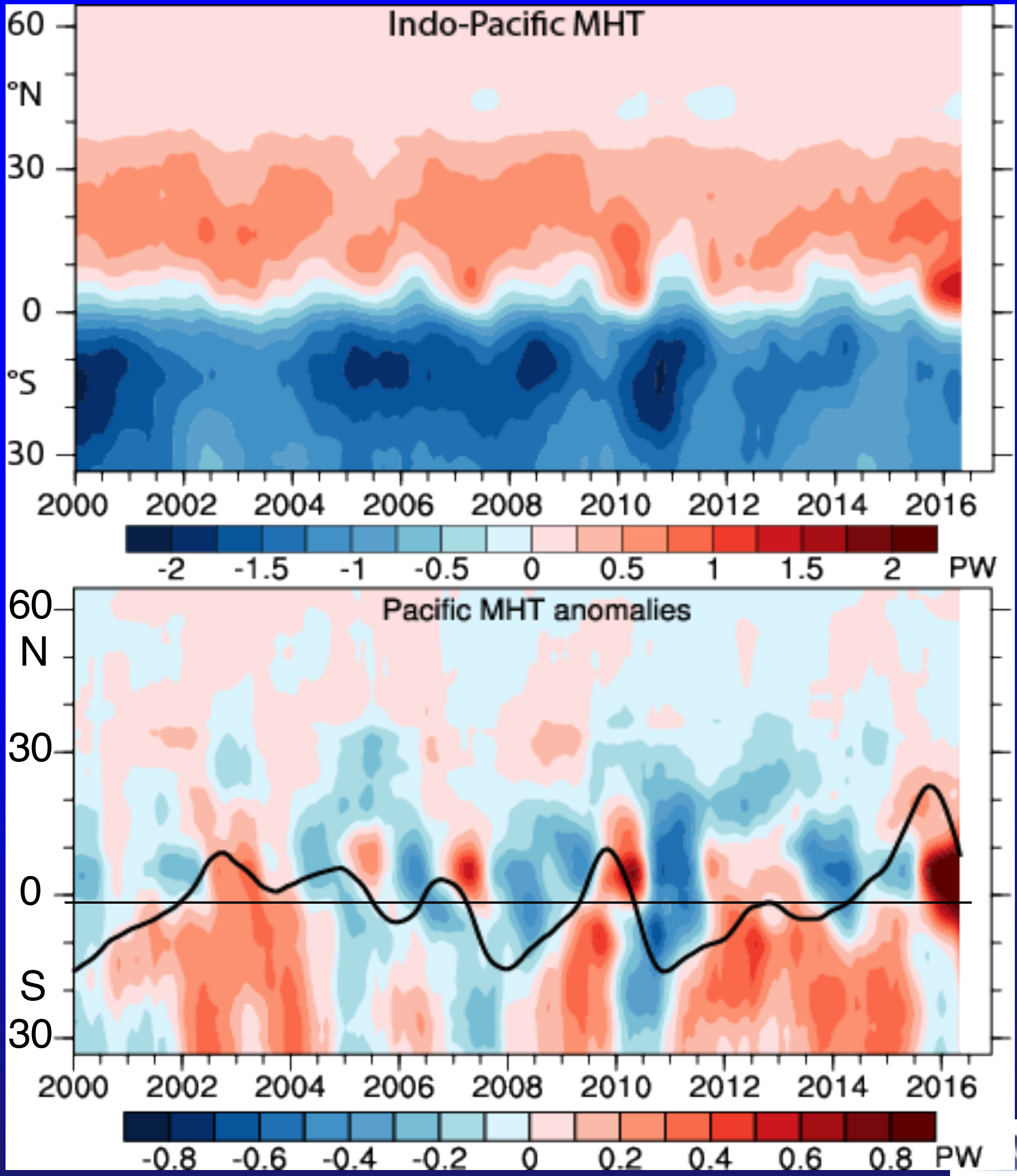
Meridional Heat Transport
0-2000m

12-mo running mean

Pacific

Niño 3.4



Trenberth and Zhang 2019

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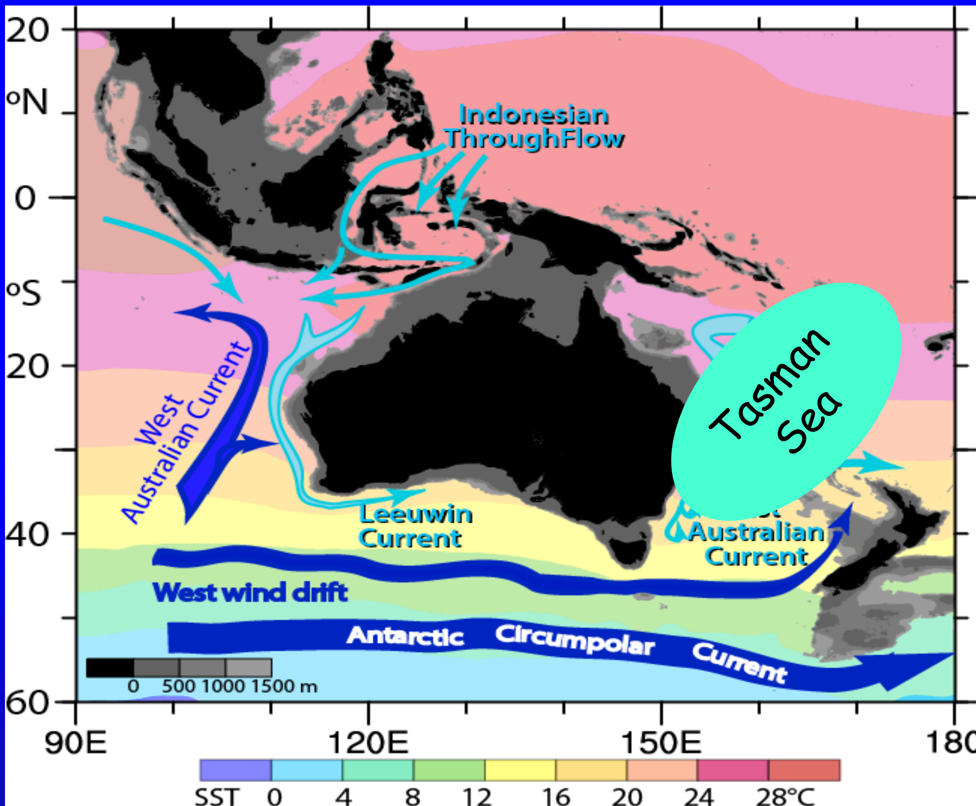
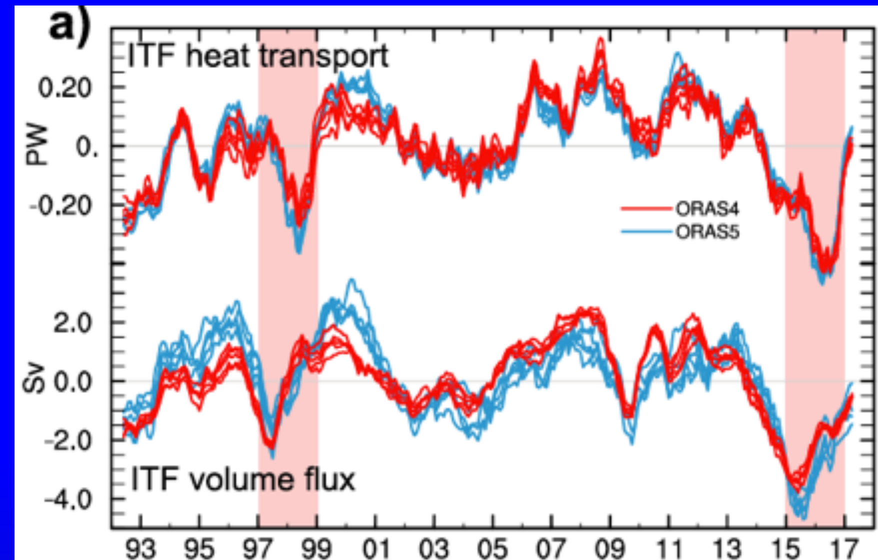
Indonesian ThroughFlow (ITF)





- ITF component (from model with ITF open vs closed)
- Results from ORAS (Meyer et al 2018) below

Trenberth and Zhang 2019

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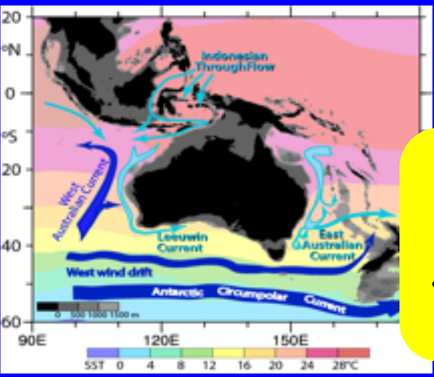
Unprecedented 2015/16 Tasman Sea marine heatwave



- Oliver et al (2017; *N Comms*): most intense heatwave ever in Tasman Sea in 2015/16

2.9 C

he

.

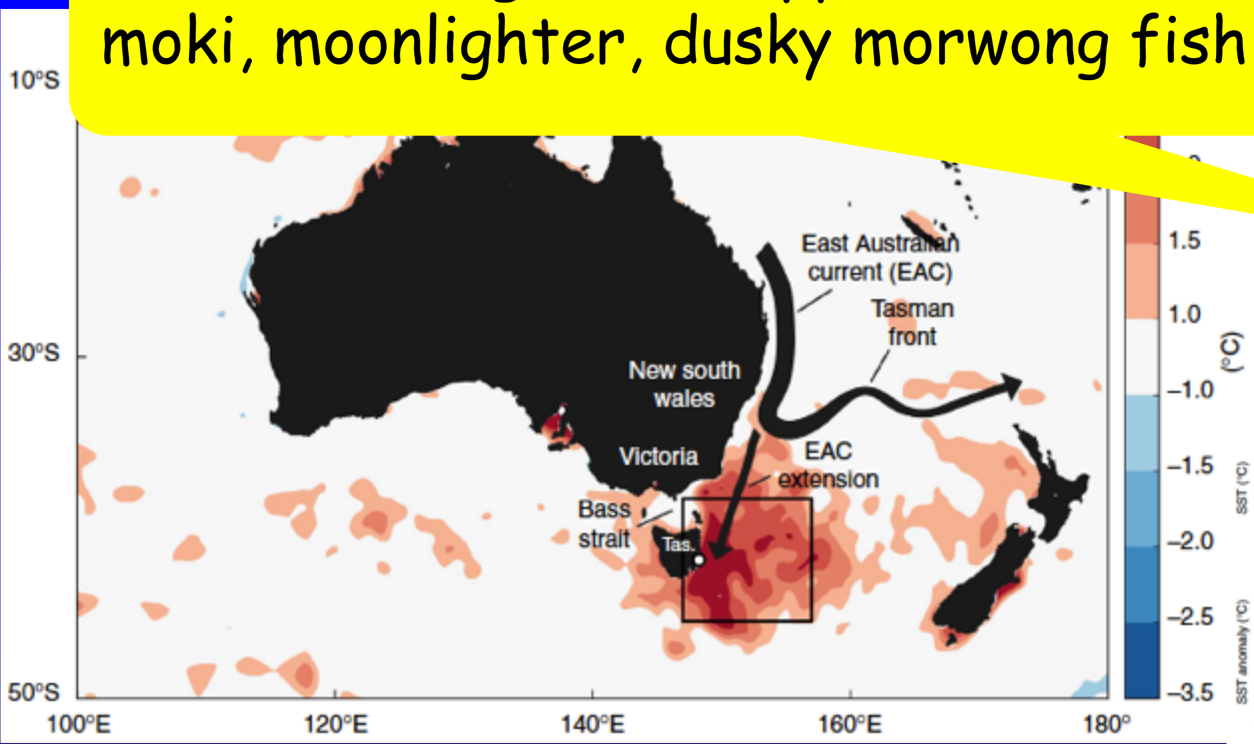
system impacts:

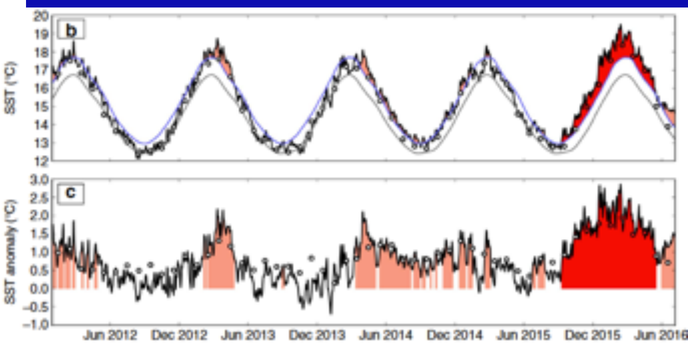
disease

ou eaks in farmed shell ish, mortality of wild molluscs and out-of-range species observations.

Mass mortality of abalone, oysters, salmon, giant kelp. Surfers affected…

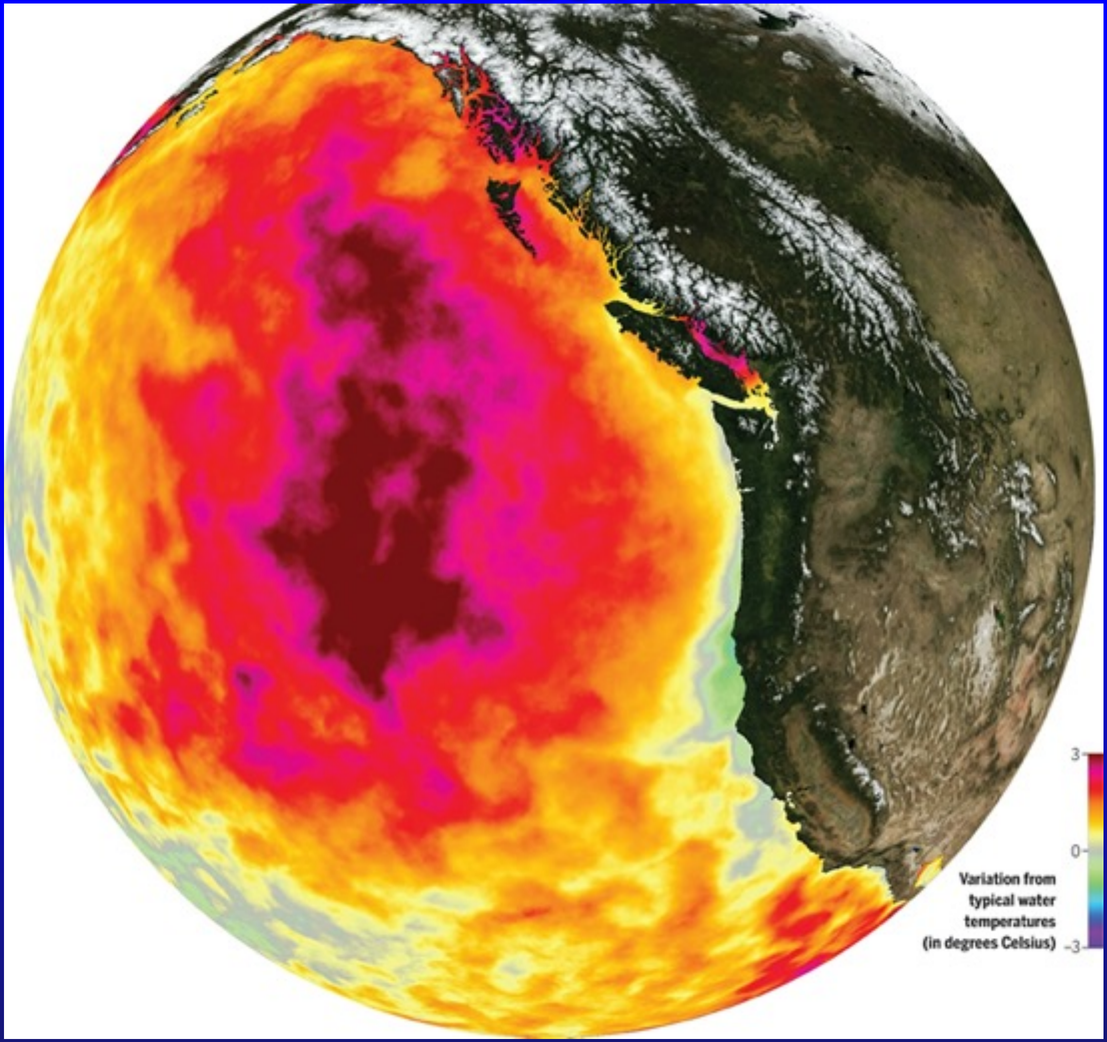
Yellowtail kingfish, snapper, mahi mahi, moki, moonlighter, dusky morwong fish





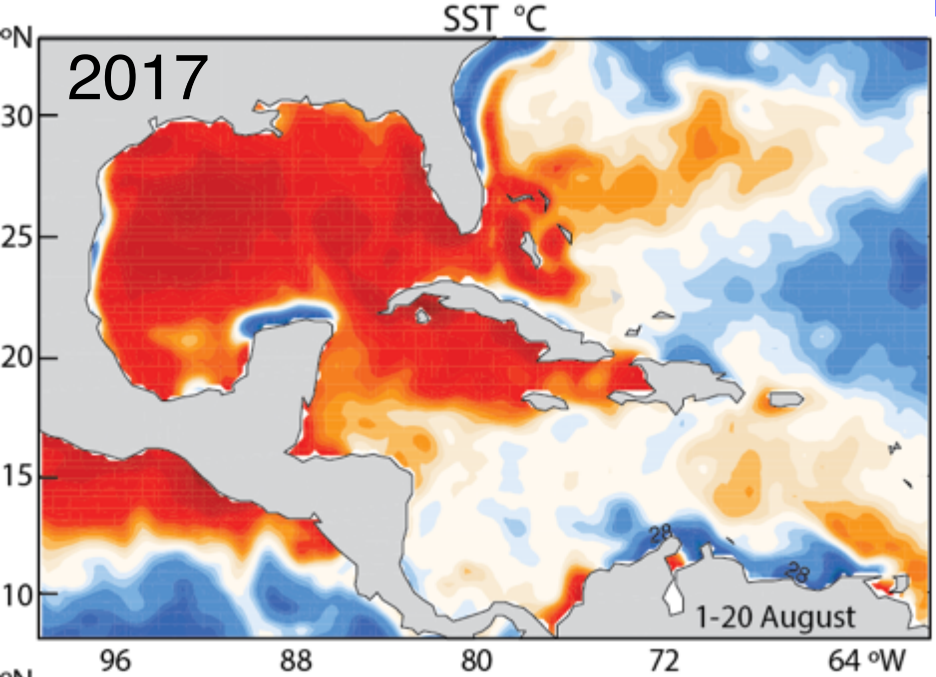
Other regional marine consequences

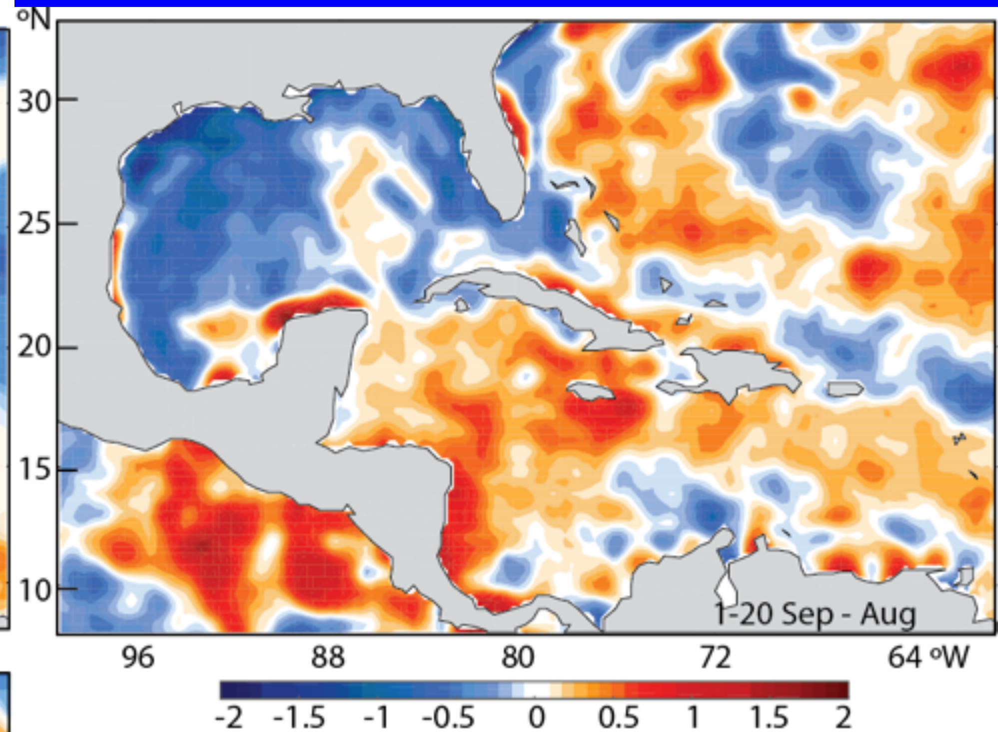
Marine heat wave
“The Blob”
2014–2016

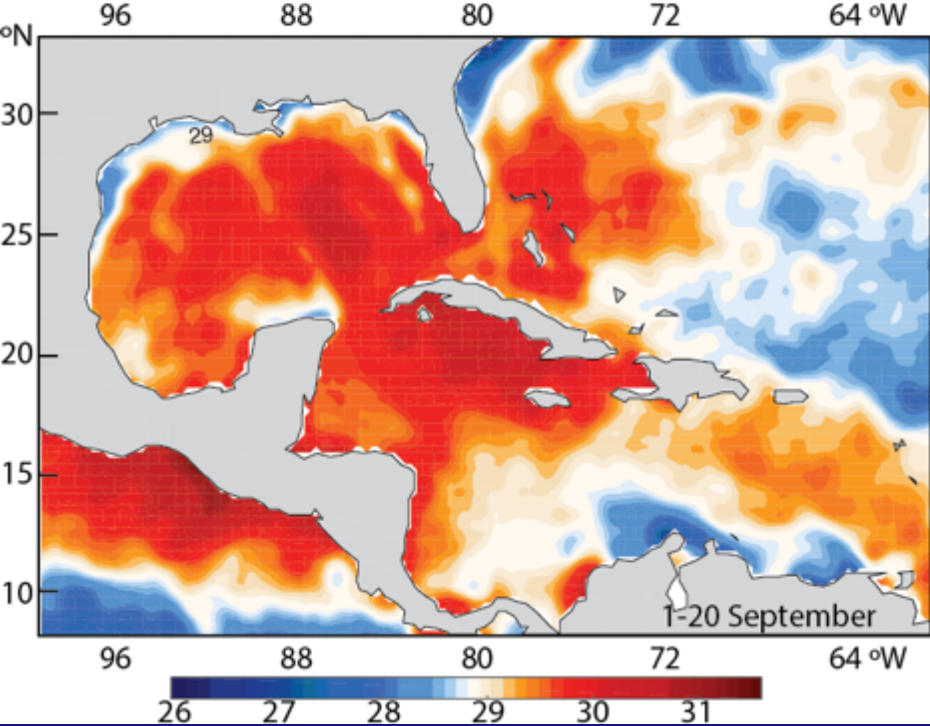


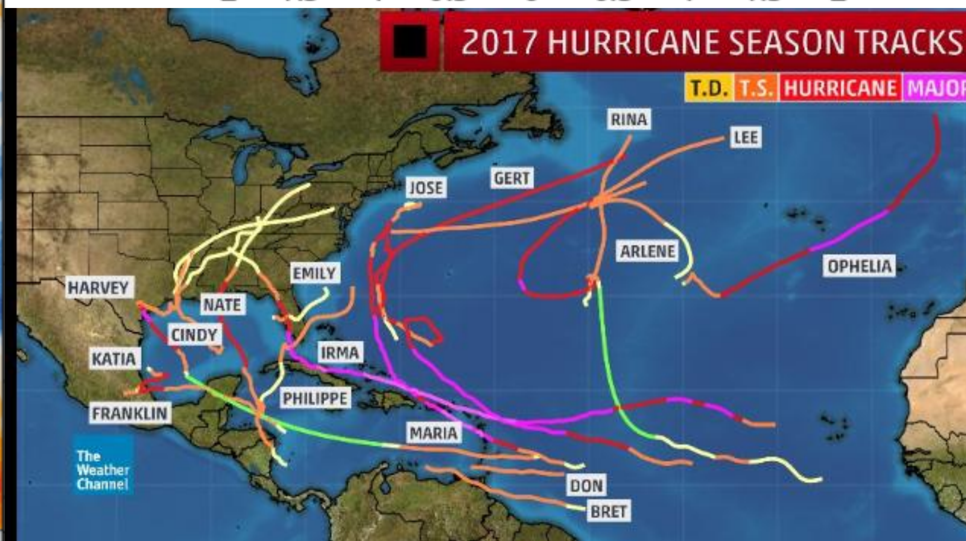
The whole food web was decimated:
Phytoplankton
Zooplankton
Krill
Swarms of small fish
Birds–auklets, murres
half a million
Cod 100 million
Humpback whales
hundreds
disappeared by 2017

Cornwall: 1 Feb Science 2019









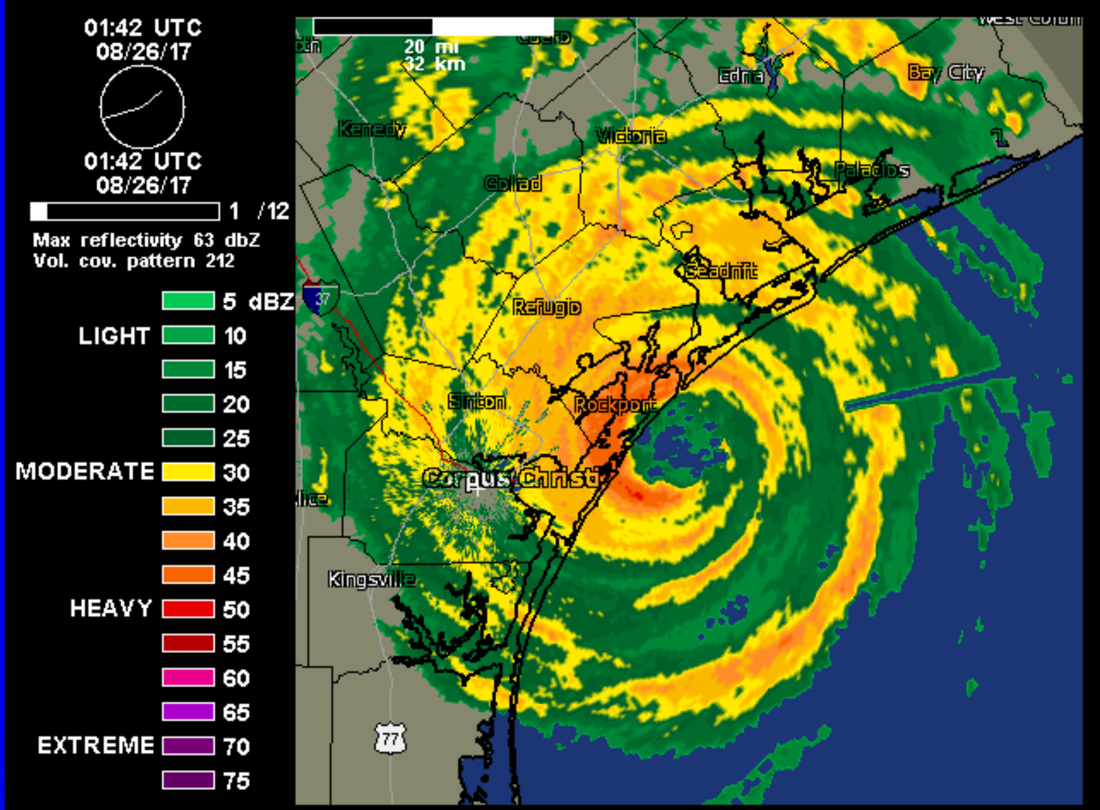
SST and changes

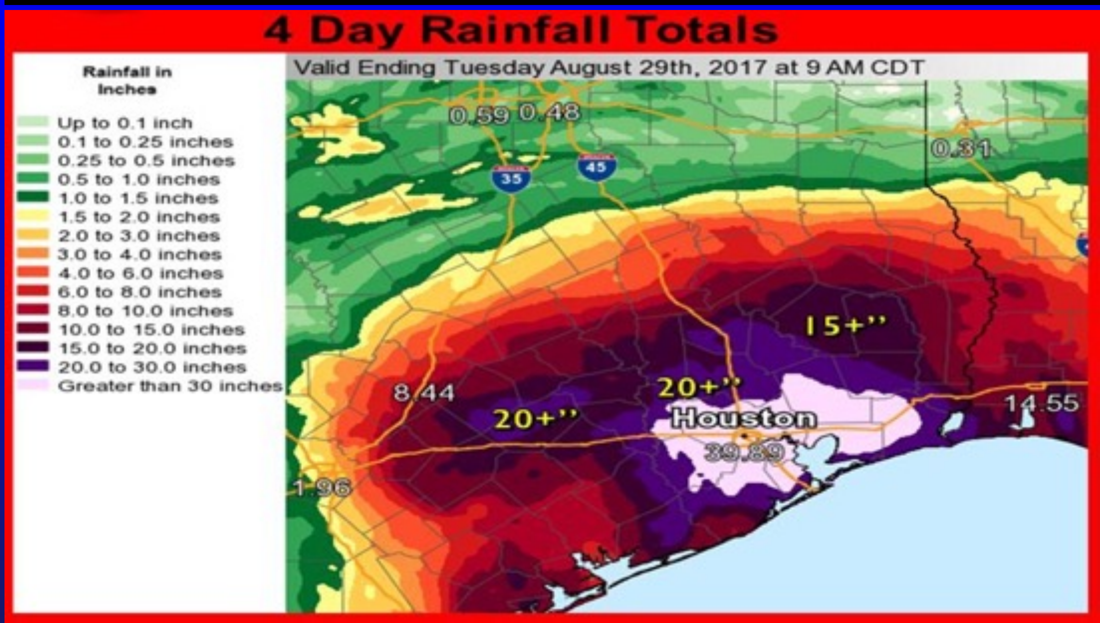
Harvey

Harvey 24-26 Aug 2017
Developed into cat 4
before Landfall

83 dead
Displaced more than 1,000,000
Damages $150 to $180B
(Reuters)
Landfall Aug 25 cat 4
Peak 300,000 homes no power
185,000 homes damaged
1 in 6 had flood insurance
440,000 registered with FEMA
for aid as of Sep 1.

64.58” of rainfall at Nederland
TX: highest anywhere in US
60.54” at Lake Charles…

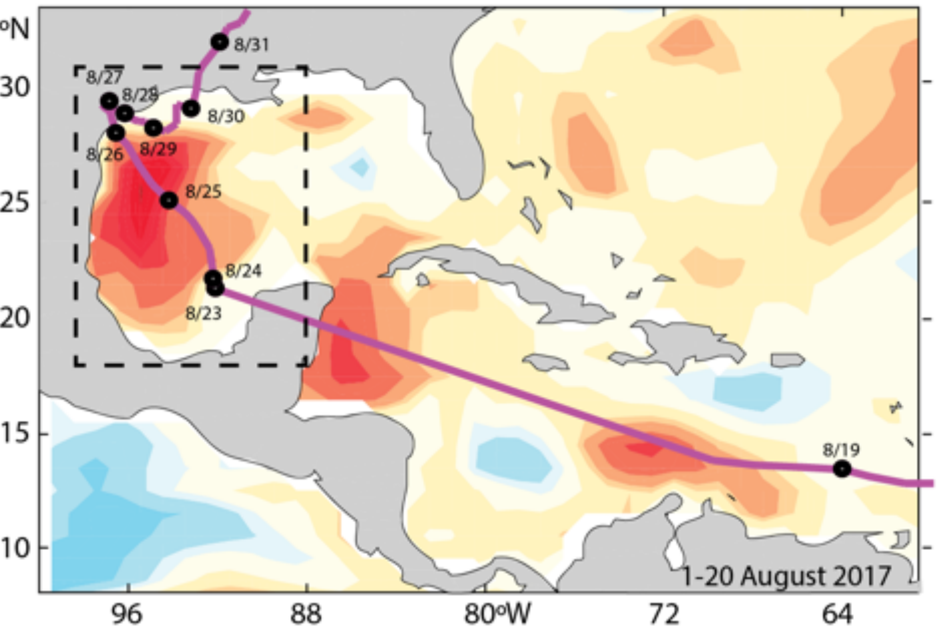


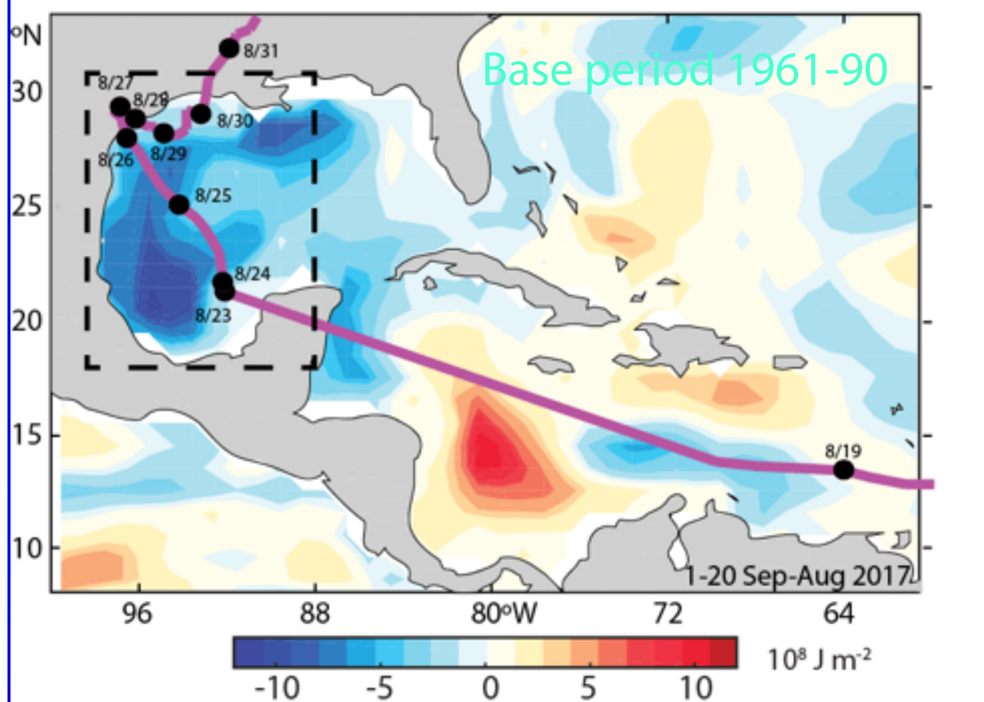


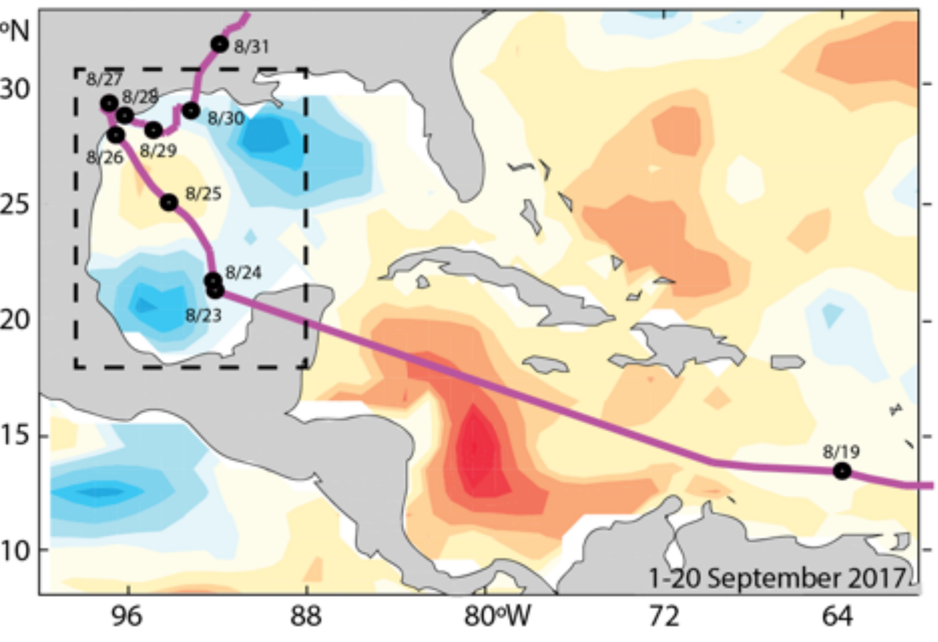
OHC changes: Harvey

OHC loss: 5.9x10^{20} J

Rain LH: 6.0x10^{20} J







Other Consequences

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Some recent Floods, heatwaves, wildfires

More Than 1,000 Died in South Asia Floods Summer 2017

41 million people affected

330 mm rain in Mumbai 29 Aug

India flooding Sep 2019

UK flooding Oct 2019

Venice Nov 2019

Flooding Japan: July 2-9 2018
Heaviest rainfall in 35 years
death toll >200;
>7000 homeless
Also Oct 2019

Heatwaves Japan 26 July, 18:
>80 deaths; >22,600 with heat stroke in hospitals
Kumagaya: 41.1°C (106°F): highest ever in Japan.
Tokyo: temperatures 40°C.

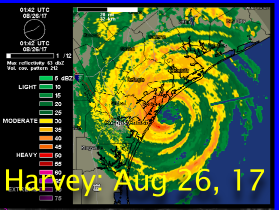
California wildfires
Nov 2018 Camp Fire: Deadliest, most destructive ever.
77 dead+ 12,637 houses burned
3,800 other structures
152,000 acres
>8000 blazes, very poor air quality

Oct-Nov 2019: Kincade: blackouts; 180K evacuated

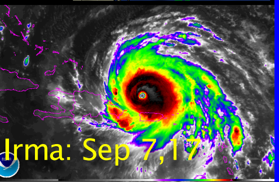
Brazil (Amazon) wildfires
Aug 2019

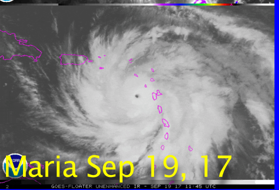
Are recent typhoon/ hurricane disasters natural?

(Hurricanes Harvey, Irma, Maria, Florence, Michael, Dorian Cyclones Idai, Kenneth, Fani; Typhoons Mangkhut, Hagibis)



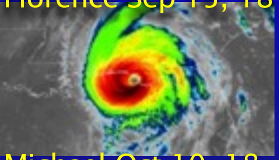
Harvey: Aug 26, 17


Irma: Sep 7, 17


Maria Sep 19, 17


Mangkhut Sep 14, 18

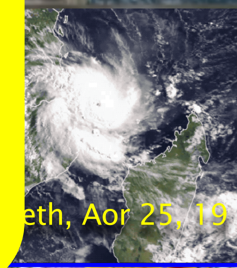

Florence Sep 15, 18

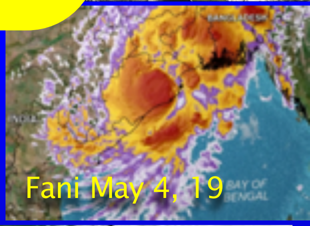

Michael Oct 10, 18

- ***Yes: hurrican***
- ***No: they are s***
  These events
  without huma
- ***And they have***
  poor preparedness

With climate change:
- *More intense hurricanes*
- *Bigger hurricanes*
- *Longer-lasting hurricanes*
- *More flooding rains*

Mar 10, 19


eth, Aor 25, 19



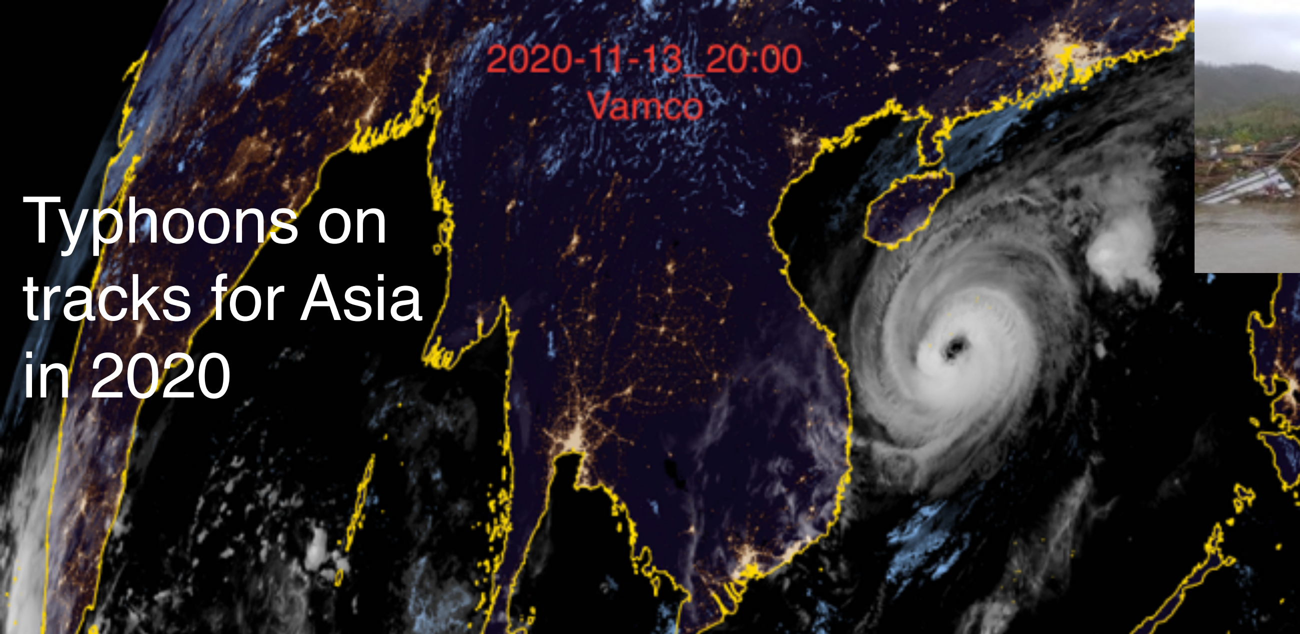
Fani May 4, 19


Dorian, Sep 7, 19

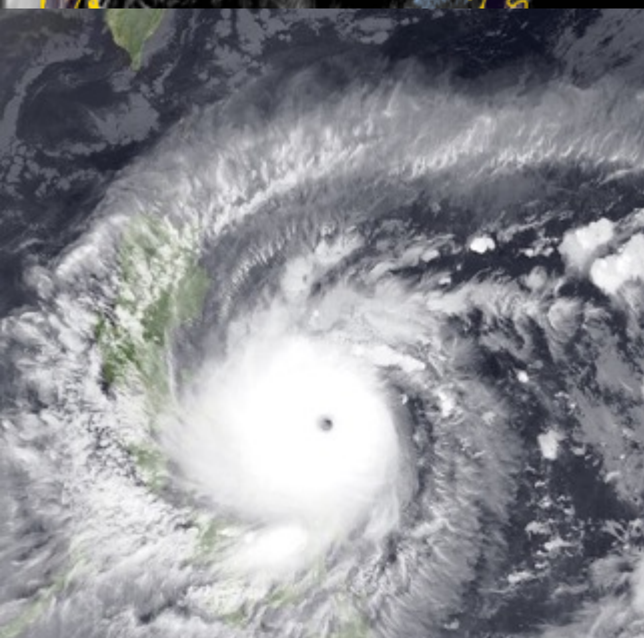

Hagabis, Oct 19, 19

1. **Wind related damage as the storm comes ashore**
   Consequences: flying debris, falling trees, power outages
2. **Coastal storm surge**
   Much worse if landfall occurs at high tide
   Mainly coastal: worse if no wetlands or buffer
   Worsens as sea level rises
3. **Heavy rains and flooding**
   Can extend far inland

Typhoons on tracks for Asia in 2020



Molave Oct. 28, 2020

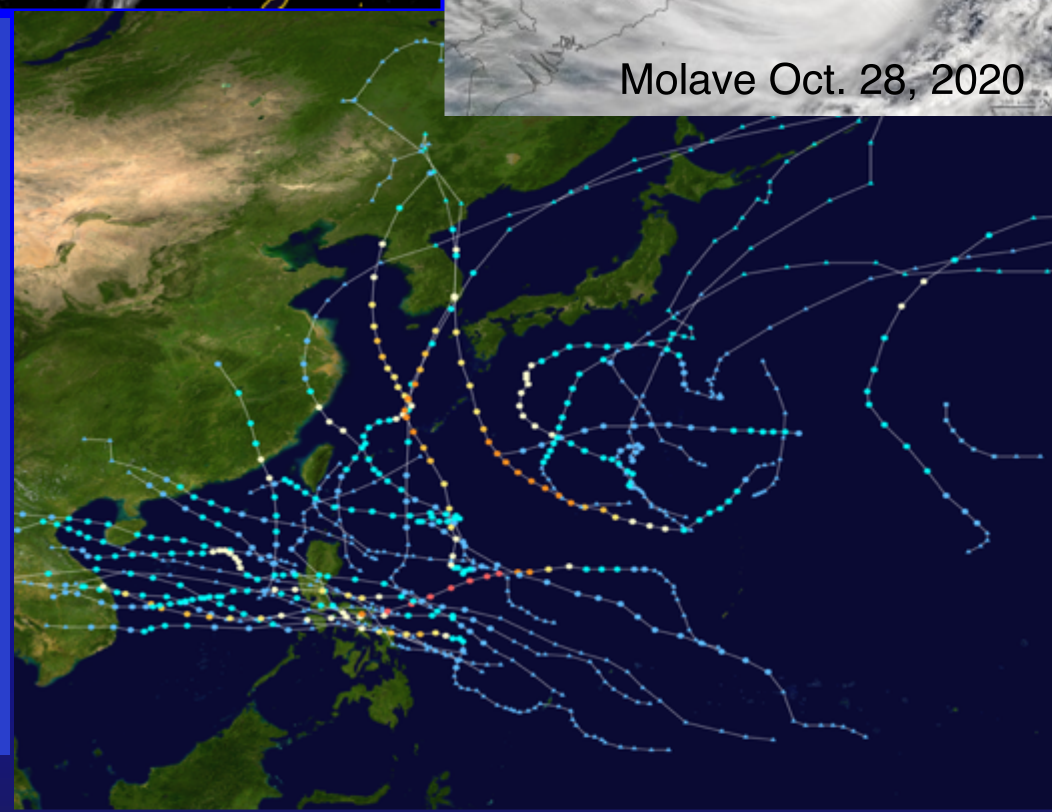


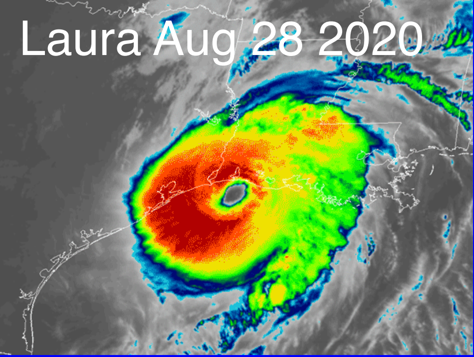
Goni
31 Oct 20

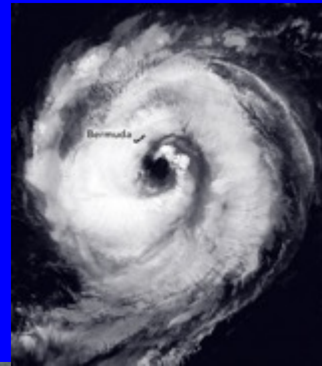
TYPHOON PARADE:

Vamco
7th to hit Vietnam:

>100 died.
400,000 homes destroyed in Oct

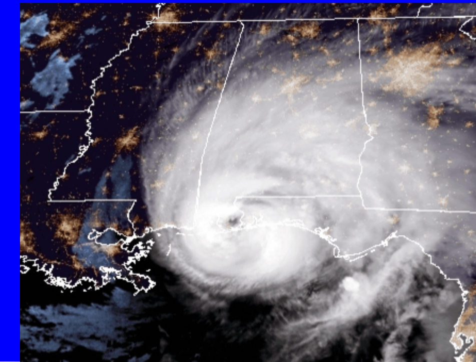


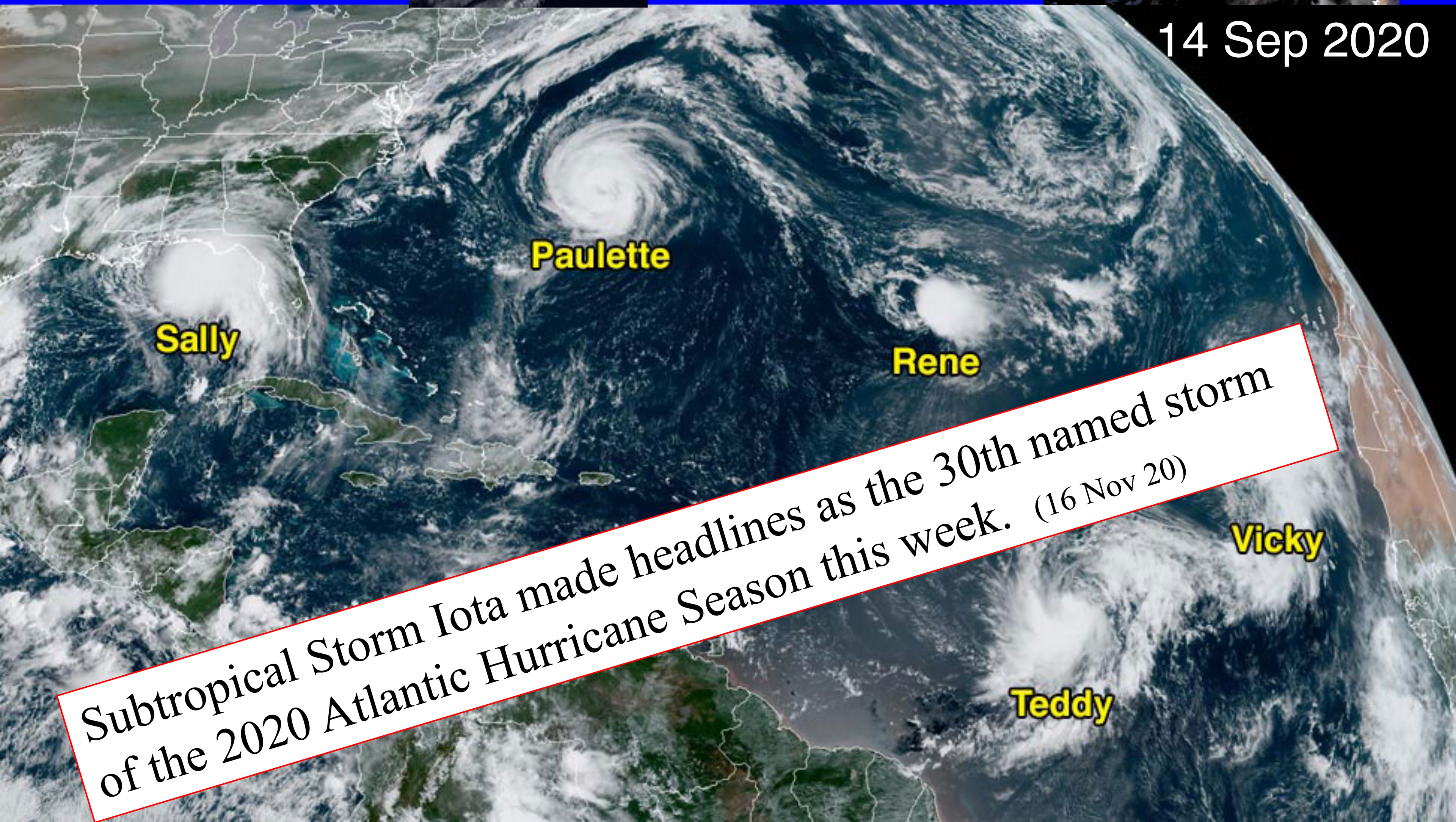




Paulette over Bermuda

Sally over Gulf coast

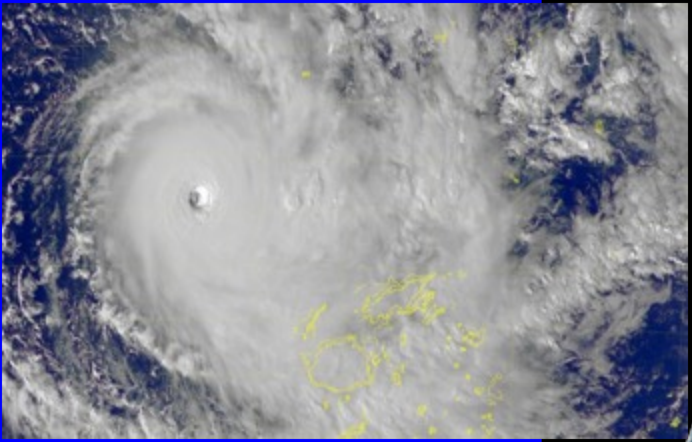




Subtropical Storm Iota made headlines as the 30th named storm of the 2020 Atlantic Hurricane Season this week. (16 Nov 20)

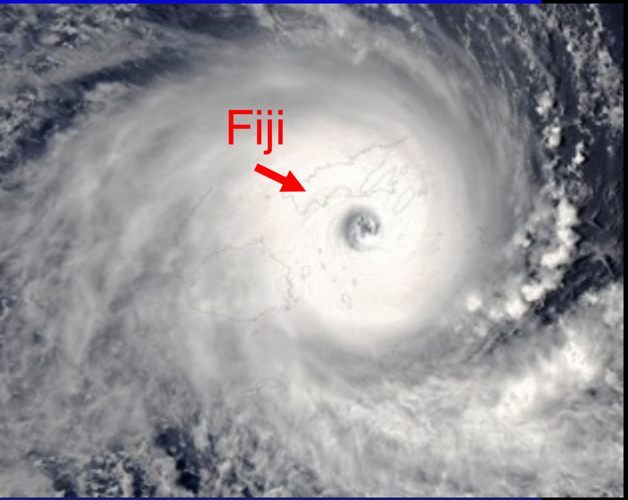
Yasa Dec 17, 2020

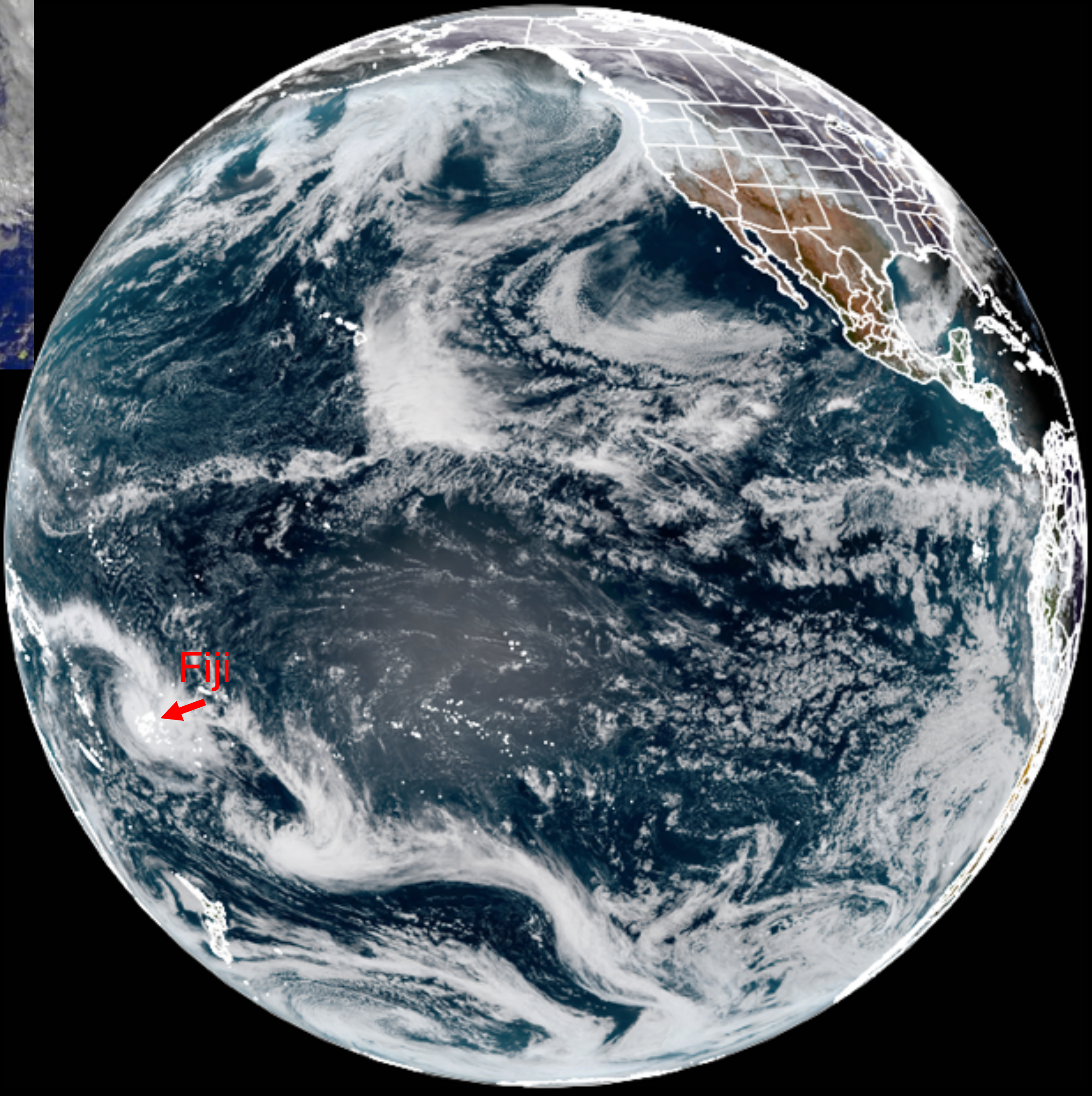
Cat. 5 devastated Fiji

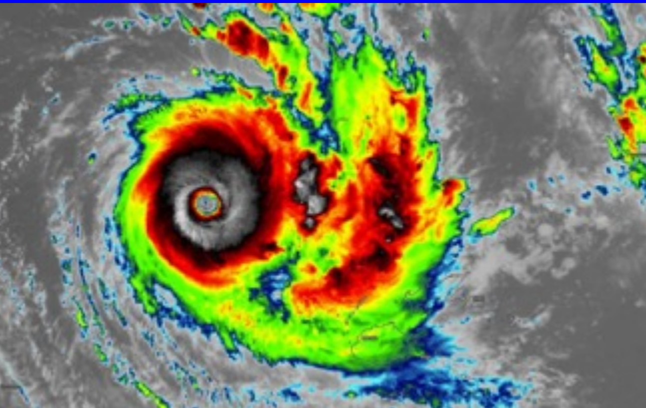


16th

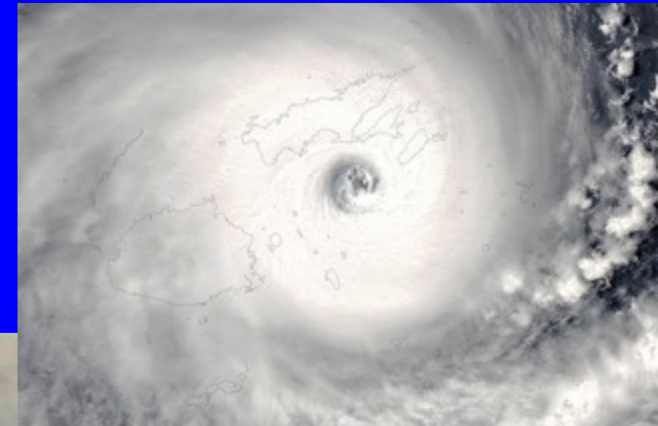
17th



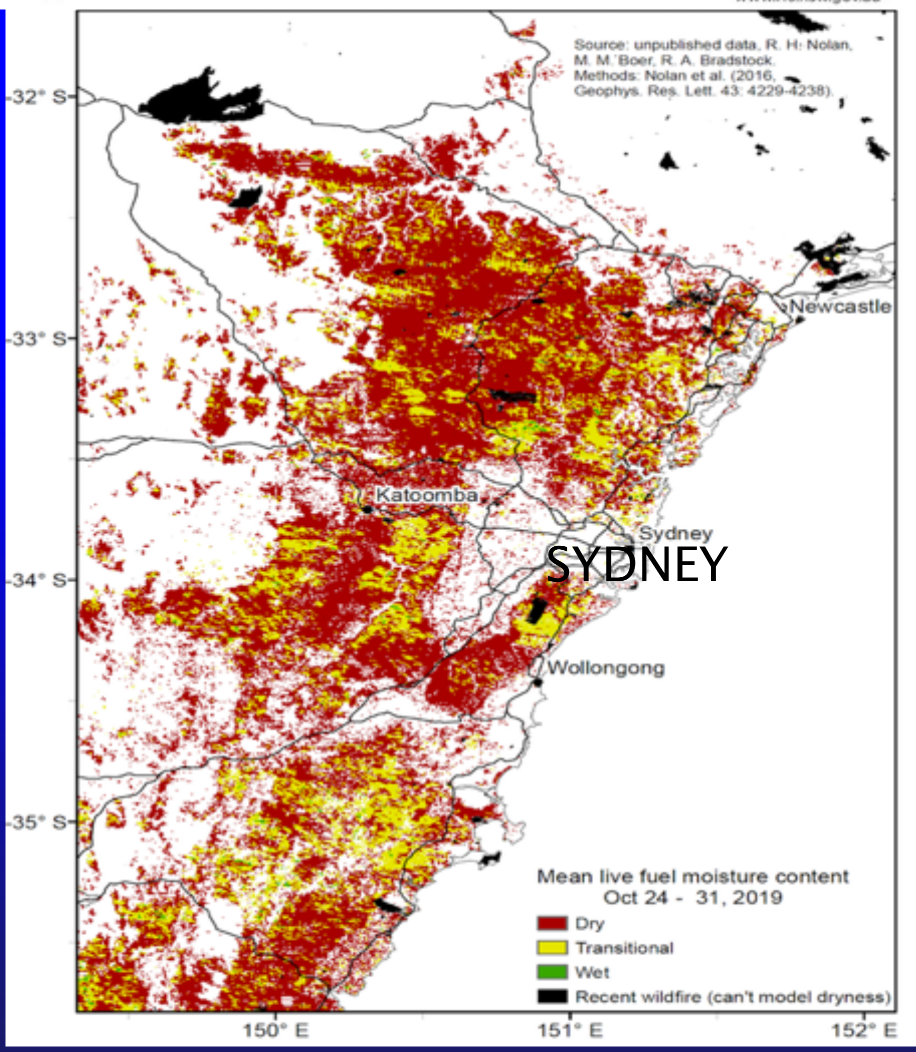




Yasa
19 Dec 2020




CATASTROPHIC
FIRE DANGER
Greater Sydney
Greater Hunter
Illawarra/Shoalhaven
Tuesday 12 November 2019
NSW RURAL FIRE SERVICE
BUSH FIRE INFORMATION LINE
1800 NSW RFS
1800 679 737
www.rfs.nsw.gov.au

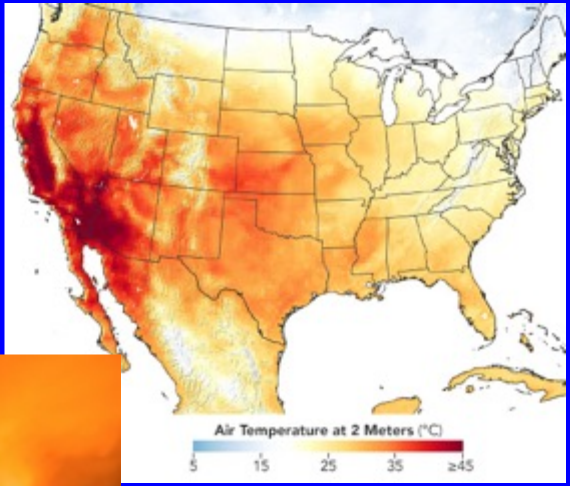

Source: unpublished data, R. H. Nolan, M. M. Boer, R. A. Bradstock.
Methods: Nolan et al. (2016, Geophys. Res. Lett. 43: 4229-4238).
-32° S
-33° S
-34° S
-35° S
Newcastle
Katoomba
Sydney
SYDNEY
Wollongong
Mean live fuel moisture content
Oct 24 - 31, 2019
Dry
Transitional
Wet
Recent wildfire (can't model dryness)
150° E
151° E
152° E

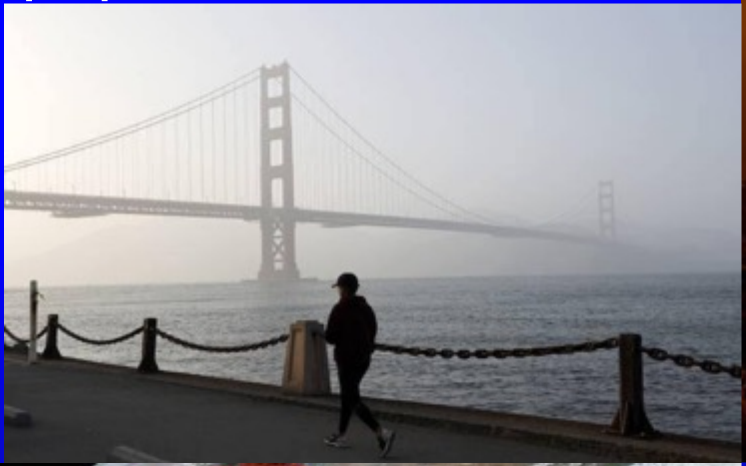

Byron Bay
Coffs Harbour
Port Macquarie
Newcastle
Sydney
NASA

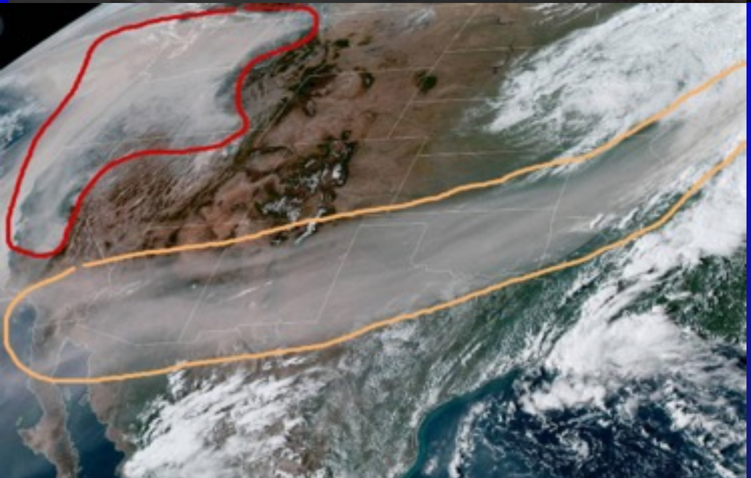
California wildfires 2020

2020 exceeded 2018 as worst on record.

17 Sep:
More than 3.3 million acres have burned so far this season in California, double the record set in 2018.
The blazes destroyed over **4,200 structures and killed 25 people.**







Fires in California through mid-September burned enough forest to put about **91 million metric tons** of CO_2 into the air: 3x more than total CO_2 emissions for providing power to the entire state.

Costs of Climate Change

- Climate chang
- It is caused b

“The straw that breaks the camel’s back” syndrome

- F
  from
- But
- T
  sed
- Things break/flood/burn; people die!
  - **EXTREME NON-LINEARITY**

- So instead of US$1B in damage, the damage is $100B
- **The real cost of climate change is grossly underestimated by economists.**

EEI has implications for the future

- We can now balance the energy budget locally
- We can link these variations to heat waves which have profound consequences in both hemispheres.
- These methods bring in new information
  - there is a lot of information in the **coupled** system not being utilized in many analyses.
- Constrains many datasets --- and models

Some Recommendations

- EEI varies esp. with clouds, and ENSO
- It is not well known
  - OHC can and must be done much better as a coupled problem, not an ocean one.
  - Land is largely unknown
  - Ice is poorly known: various syntheses do not overlap
  - Surface fluxes can be useful but only in a coupled context
- Analyzing land and ice in this framework would greatly improve knowledge about each component and set the stage for initialized Earth system prediction
- Models must improve, and using this framework provides a way.

Contact information

Kevin Trenberth
Distinguished Scholar
NCAR
Phone: +64 27 771 4868
Email: trenbert@ucar.edu

http://www.cgd.ucar.edu/staff/trenbert/