

# ***Extreme weather and the changing climate***

***Kevin E Trenberth***

***NCAR***



# Running a fever: Seeing the doctor



- **Symptoms:** the planet's temperature and carbon dioxide are increasing
- **Diagnosis:** human activities are causal
- **Prognosis:** the outlook is for more warming at rates that can be disruptive and will cause strife
- **Treatment:** mitigation (reduce emissions) and adaptation (plan consequences)



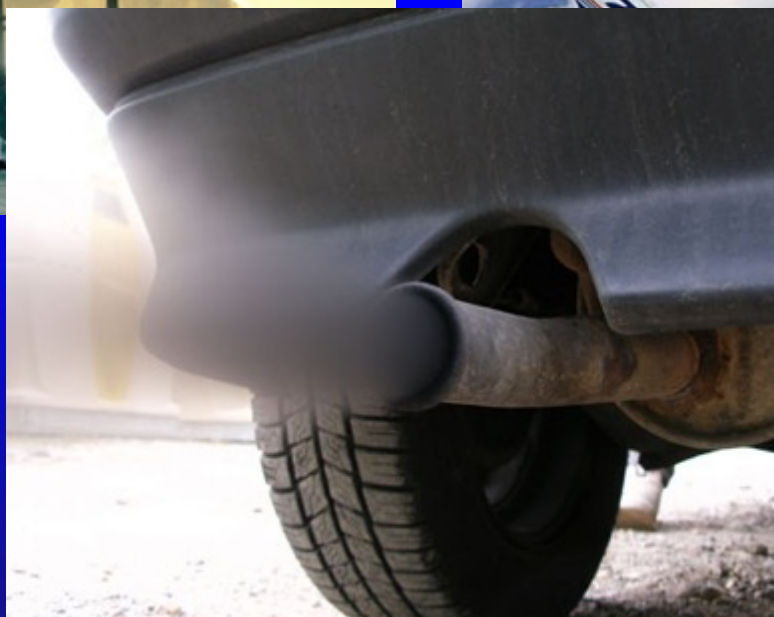
# Climate change is happening: It is due to humans

97% of scientists agree.

The data are of mixed quality and length, but together they tell a compelling story leaving no doubt about the human role in climate change.

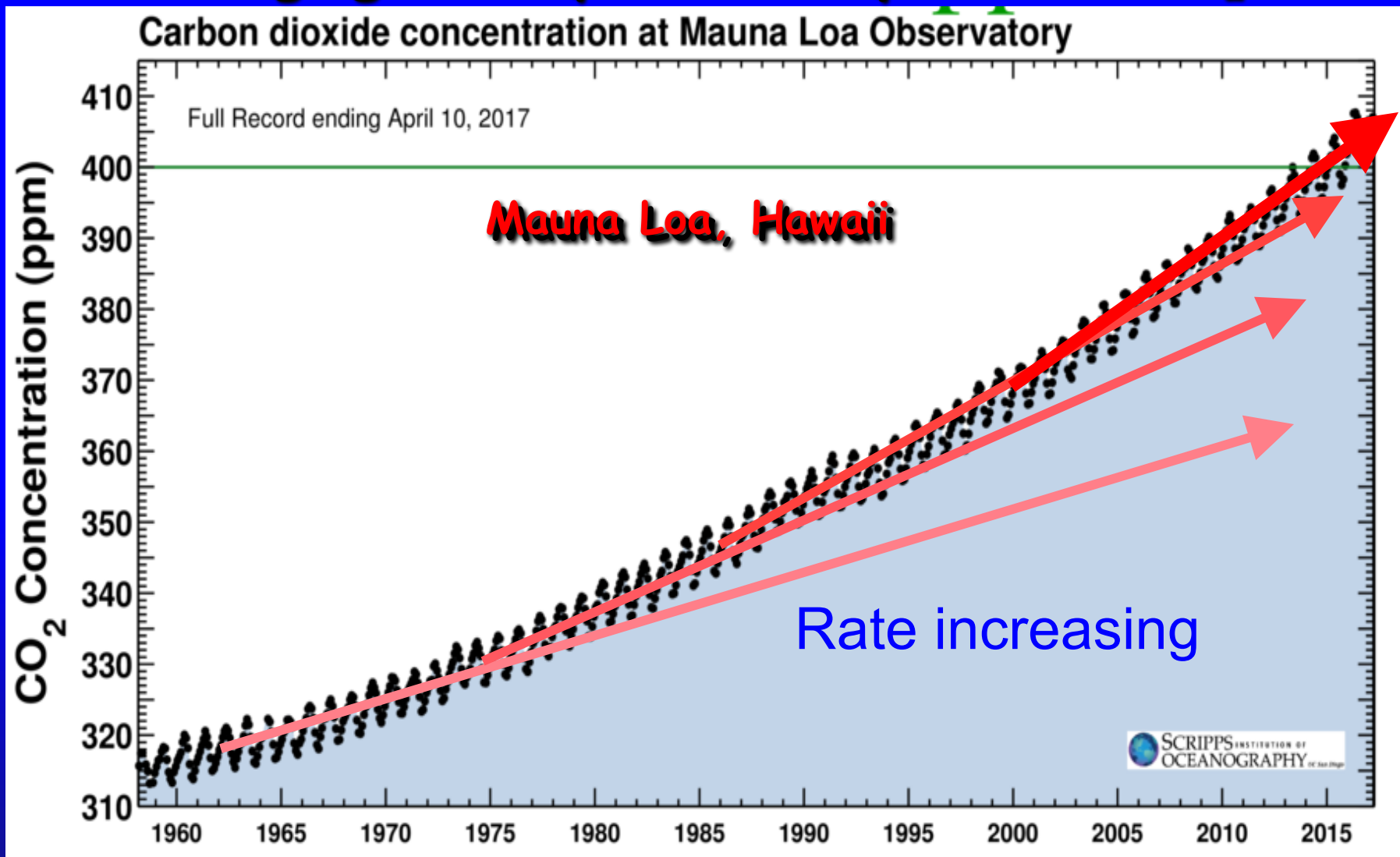
What we do about this problem involves value systems and politics!

# What Is Causing Warming?



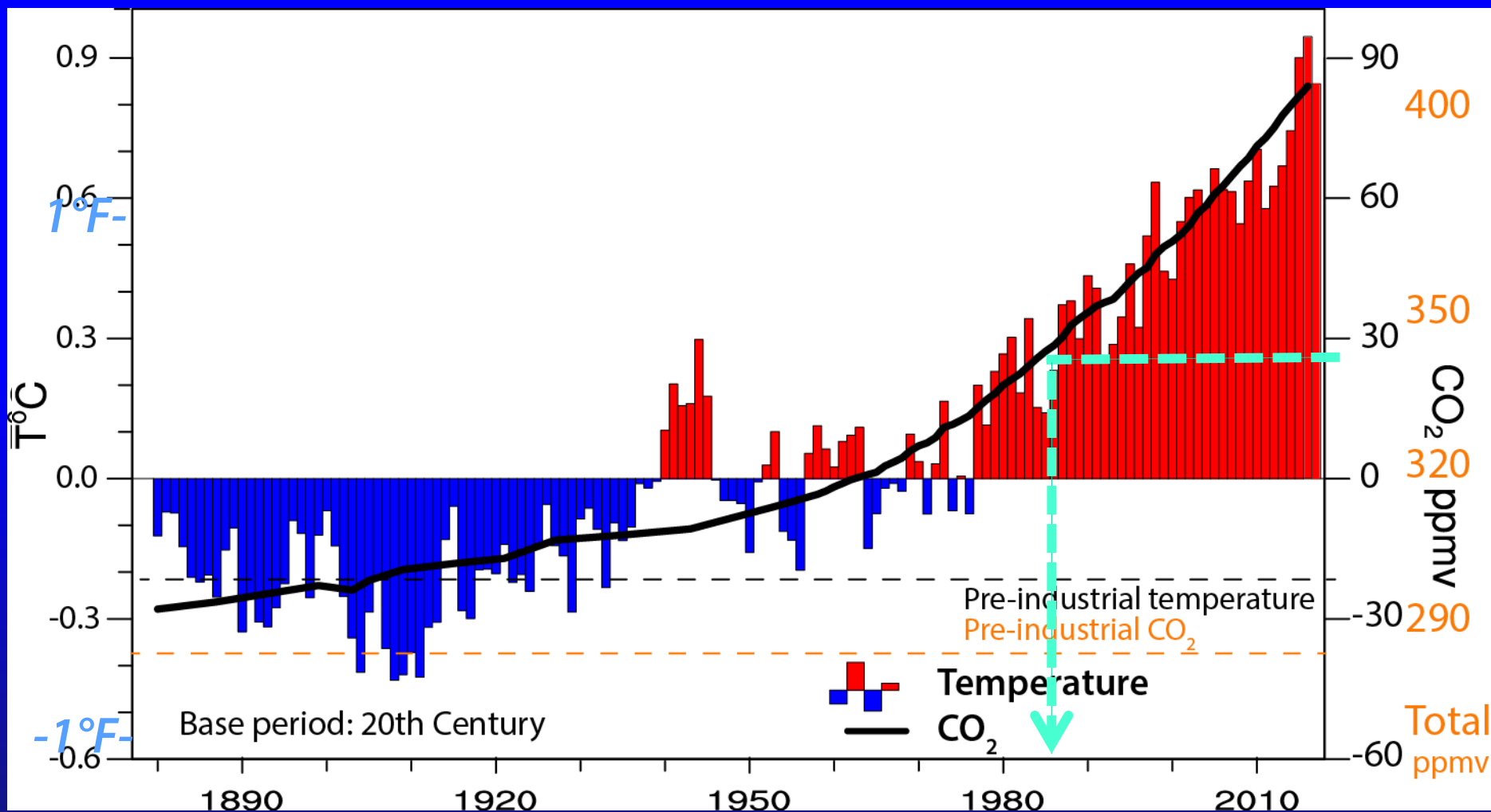
Emissions of carbon dioxide pollution

# Changing atmospheric composition: CO<sub>2</sub>



Data from Climate Monitoring and Diagnostics Lab., NOAA. Data prior to 1974 from C. Keeling, Scripps Inst. Oceanogr.

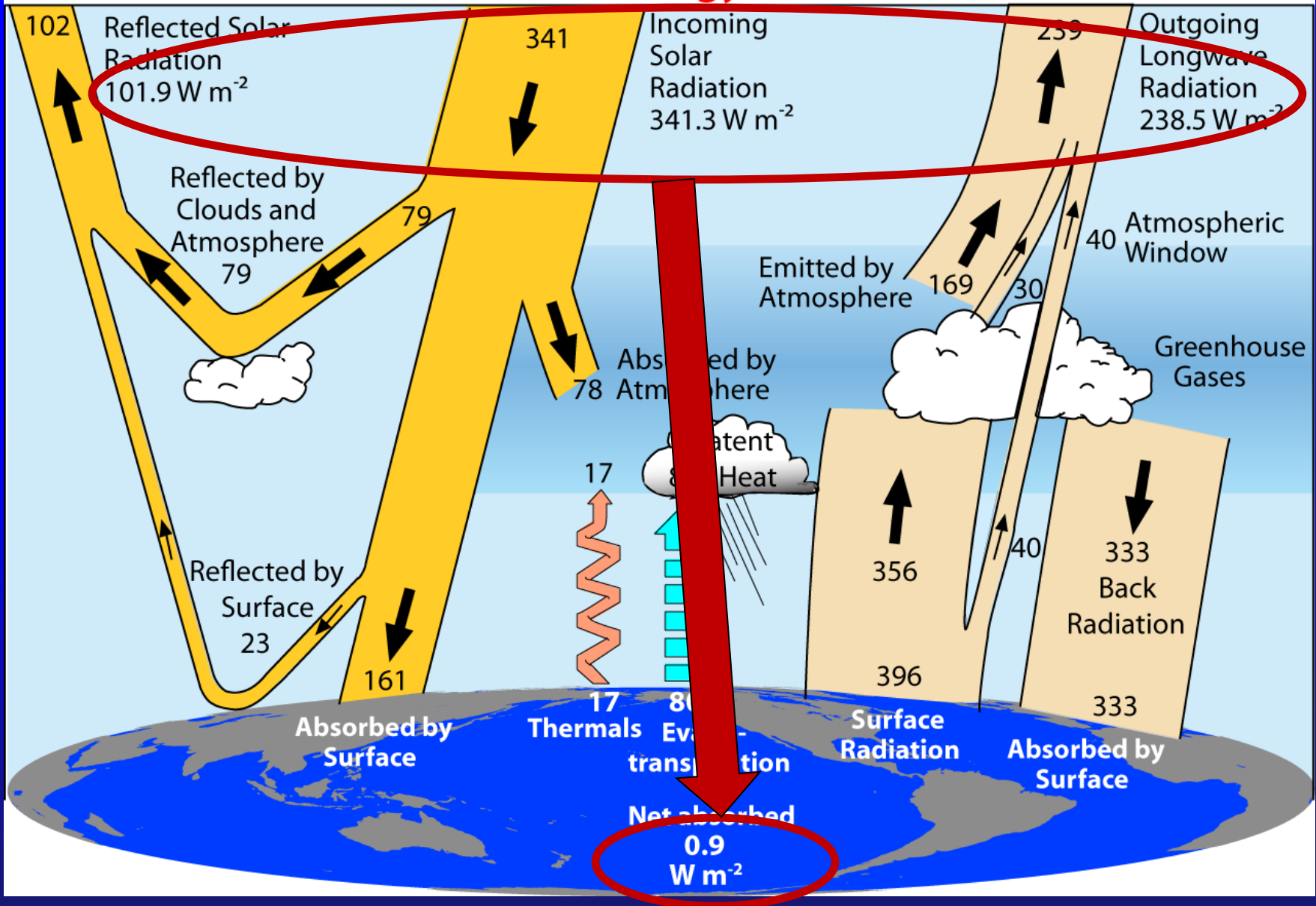
# Global temperature and carbon dioxide: anomalies through 2017



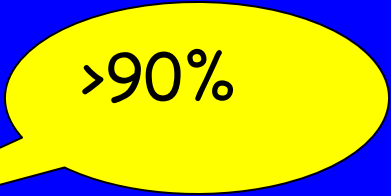
Base period 1900-99; data from NOAA

# Trenberth et al (2009)

## Global Energy Flows $W m^{-2}$



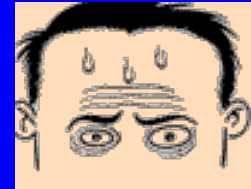
# Global warming means more heat: Where does the heat go?

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  $\Rightarrow$  rain storms, cloud  
 $\Rightarrow$  possibly reflection of sun's rays 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.***



# Evidence for reality of climate change

## Glaciers melting



1909



Toboggan  
Glacier  
Alaska

2000



1941



2004

Muir Glacier, Alaska



A. Circa 1900  
Photo Source: Munich Society for Environmental Research



B. Recent

1900

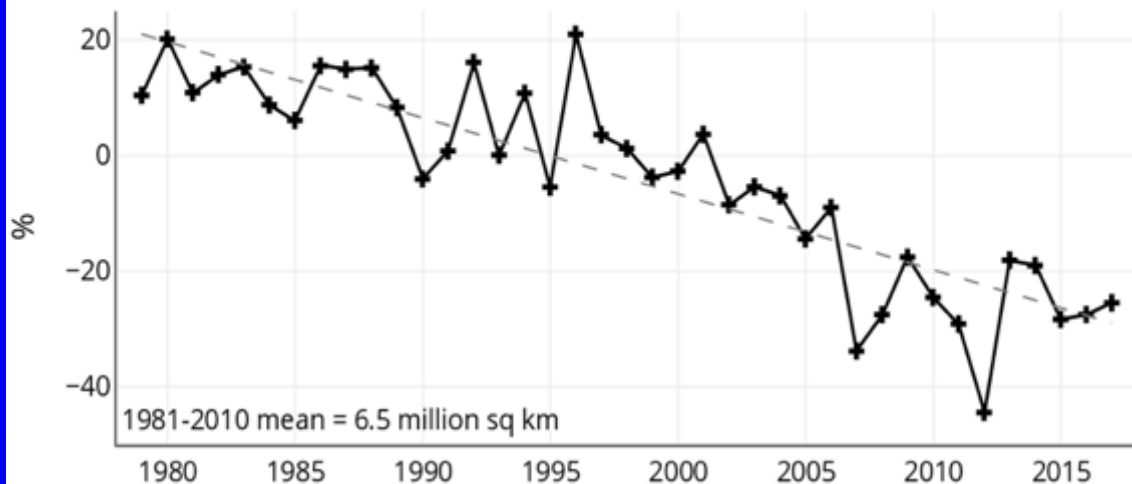
2003

Alpine glacier, Austria

Increased Glacier retreat  
since the early 1990s

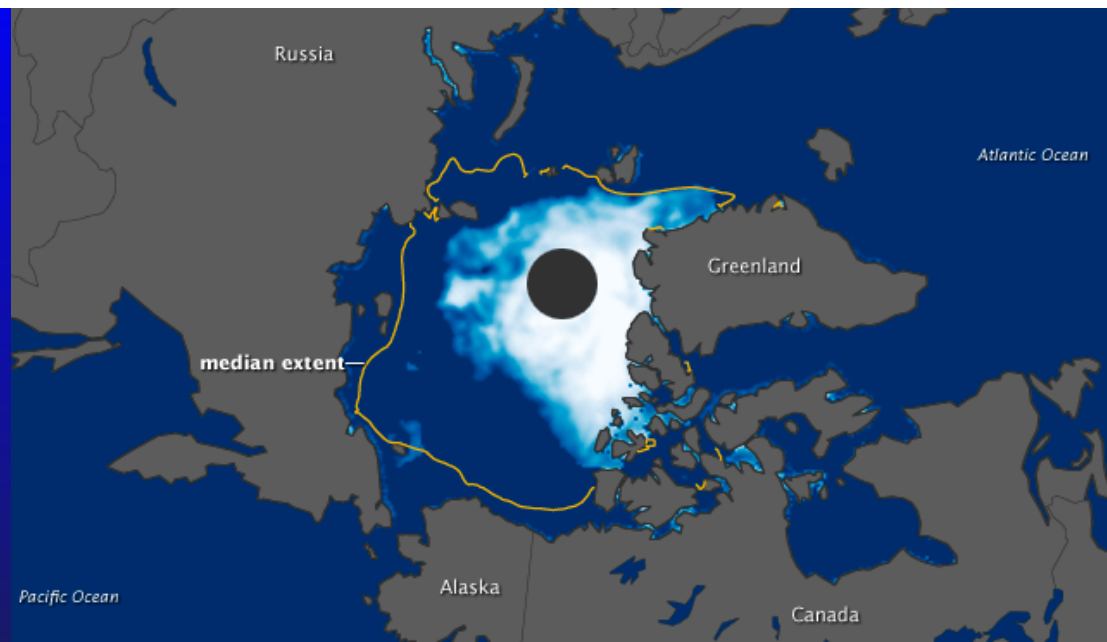
# Snow cover and Arctic sea ice are decreasing

Northern Hemisphere Extent Anomalies Sep 1979 - 2017



Arctic sea ice area decreased by 40% in summer

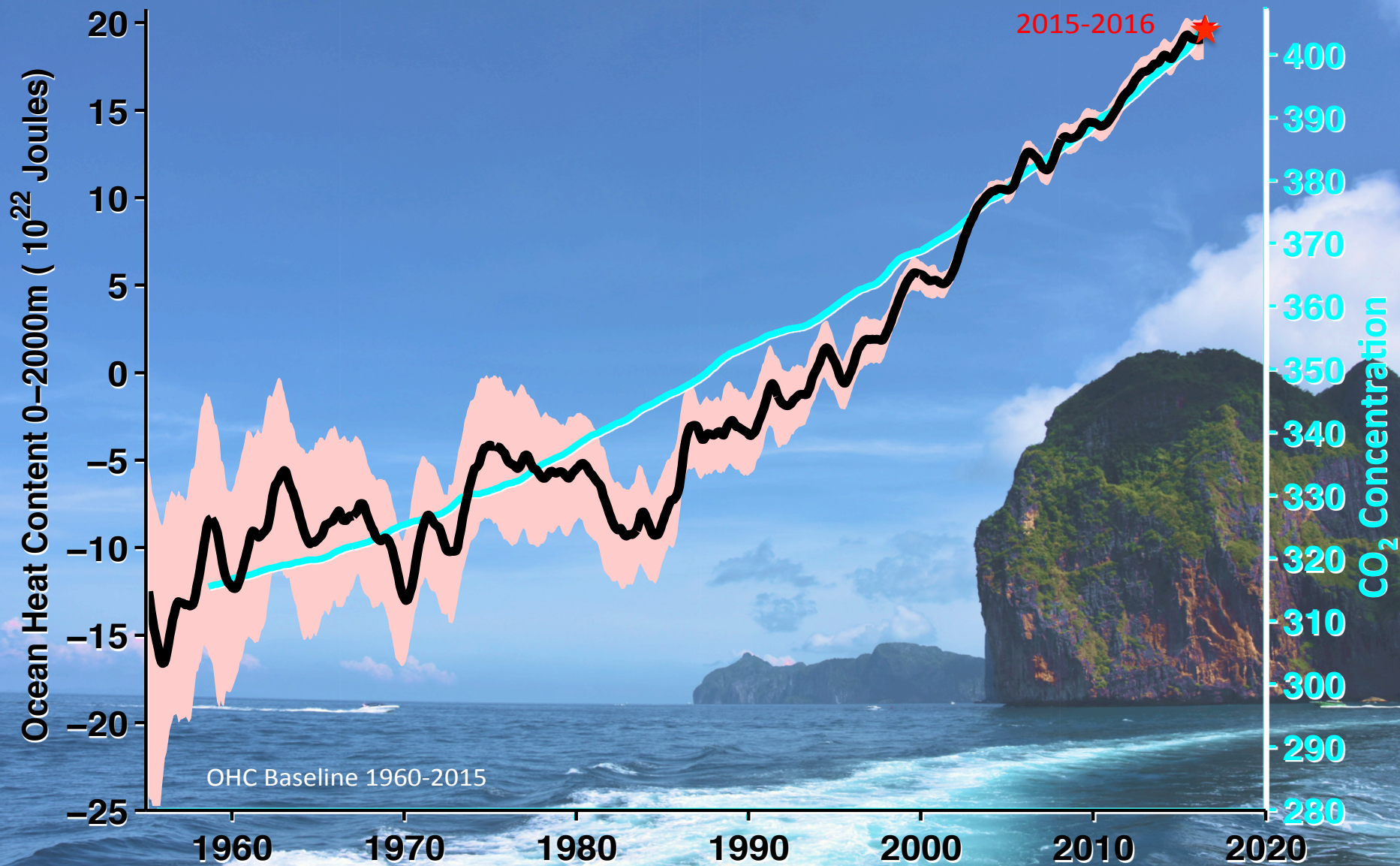
2012 lowest on record



Late August 2012

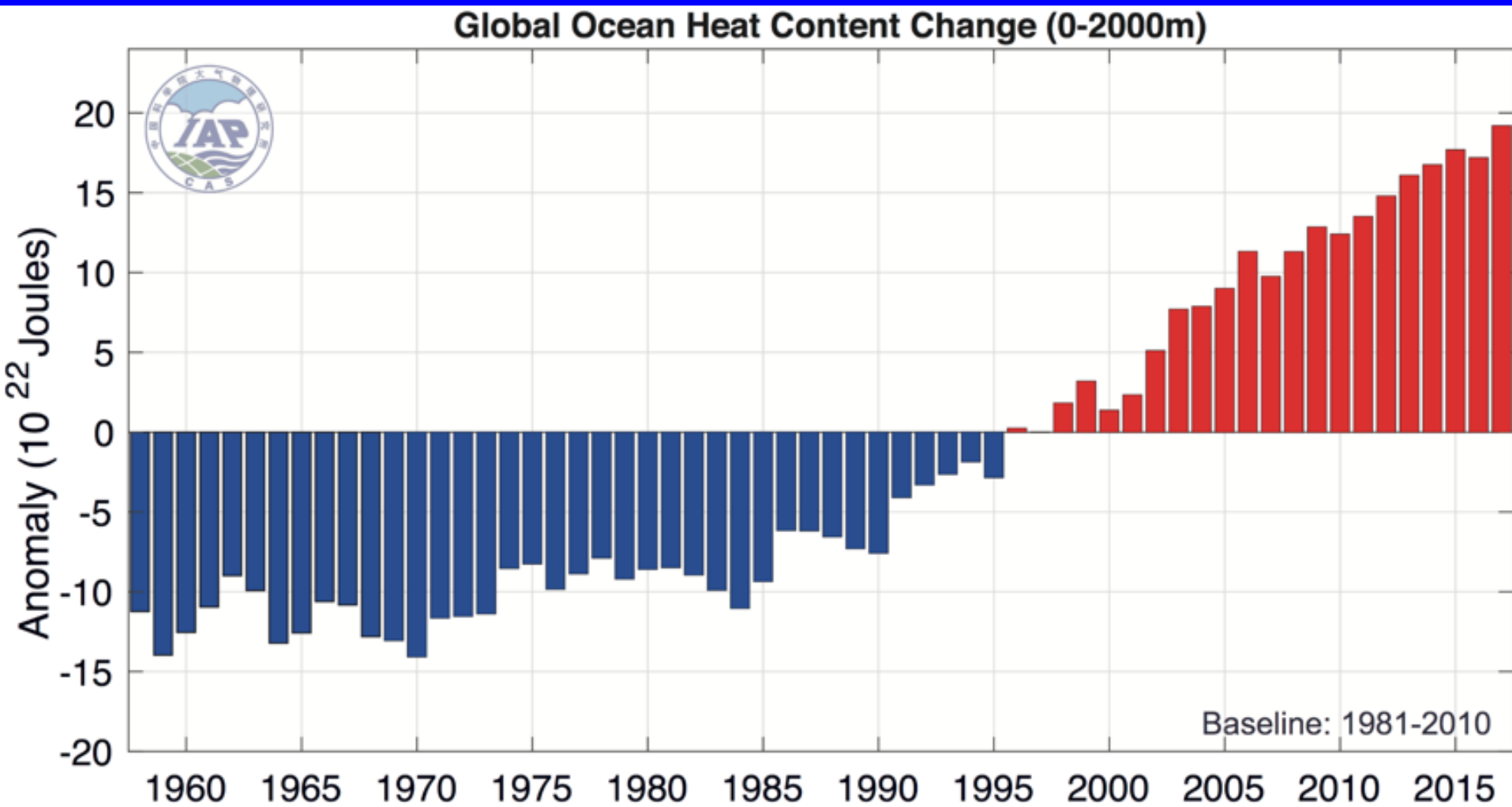
# Ocean Heat Content

Cheng et al  
2017



# Ocean Heat Content

Cheng

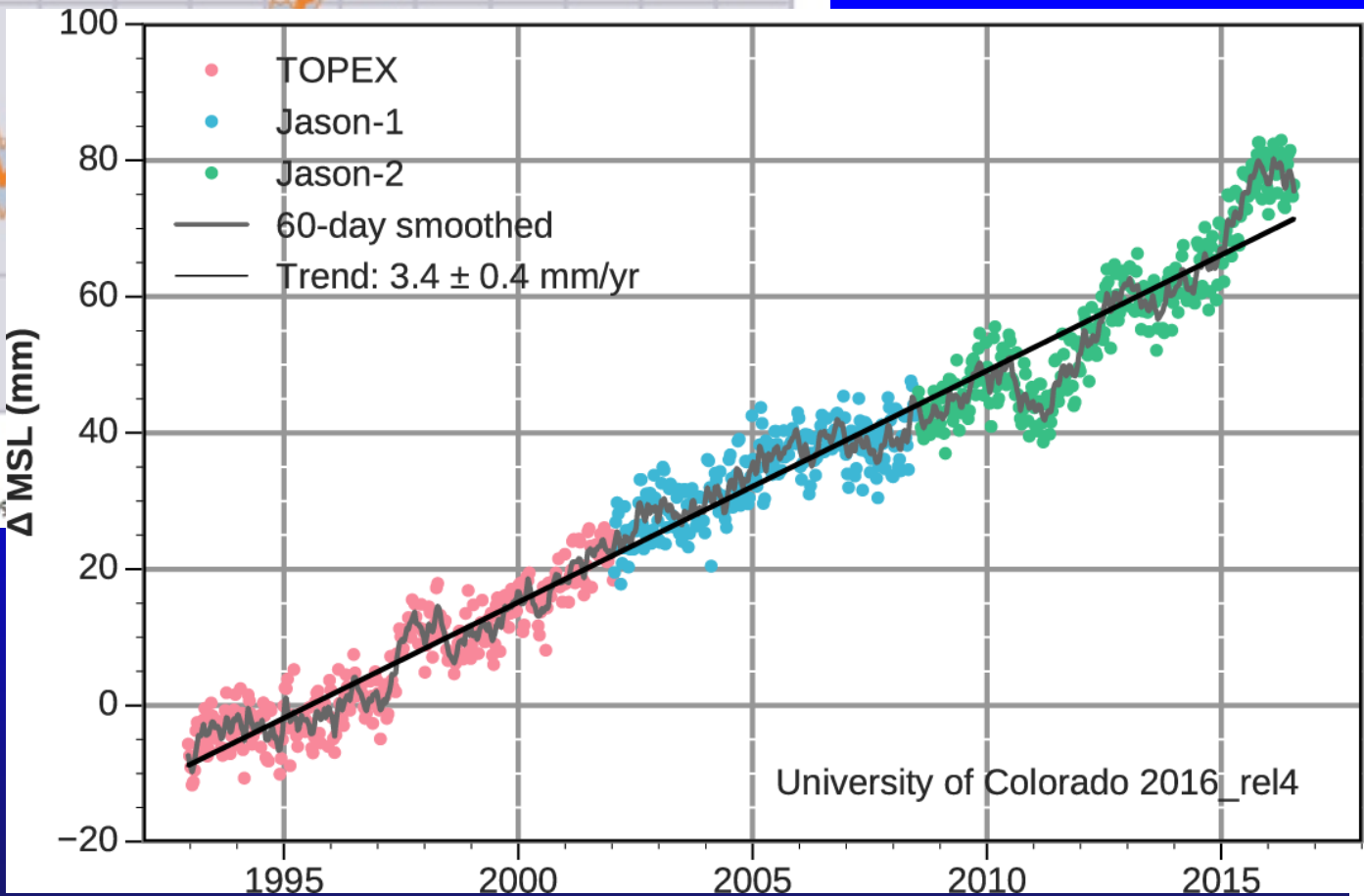


Through 2017

# Trends in Global Average Absolute Sea Level

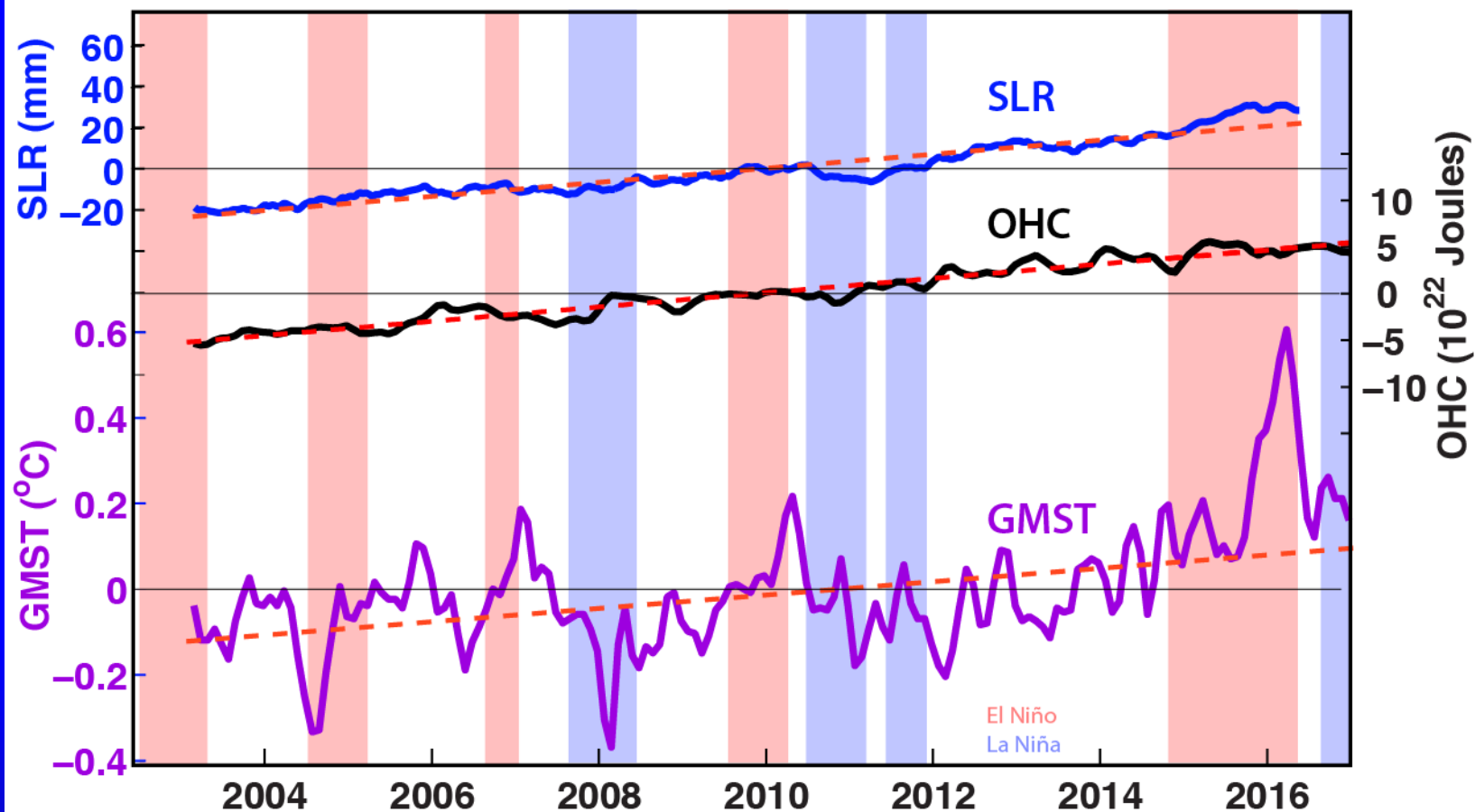


# Sea Level Rise



3 inches

University of Colorado 2016\_rel4



The linear trend, noise, signal-to-noise ratio (S/N), and the time required for detection of trends (linear trend exceeds 4 times the inter-annual standard deviation) for 2004-15.

	Linear trend	detrended $\sigma$	S/N ( $\text{yr}^{-1}$ )	Time
GMST	$0.016 \pm 0.005$ °C/yr	$0.110$ °C	0.14	27 yr
OHC	$0.79 \pm 0.03 \times 10^{22}$ J/yr	$0.77 \times 10^{22}$ J	1.03	3.9 yr
SL	$3.38 \pm 0.10$ mm/yr	3.90 mm	0.87	4.6 yr

# Warmer air holds more moisture

4% per °F



Global warming=

More heat



More drying



More evaporation



More moisture

More rain

More drought





# Take a parcel of air:

When it rises  
(for whatever reason),  
it expands and cools,  
and any moisture in it condenses  
and forms a cloud,  
and then it rains the moisture out.





# Most precipitation comes from moisture convergence by weather systems

Low level winds bring in moisture from afar



More moisture means heavier rains

# Mountains and climate change

- **Continental climate: strong seasons continue**
- **Snow falls if temperature below about 35°F**
  - **Greatest amounts 28-32°F**
  - **“Too cold to snow”: freeze dried air**
- **So more snow is a result of a warming climate**
  - **unless it is so warm it turns to rain.**
- **Glaciers retreat: amplifies changes (snow feedback)**
- **More snow in mid-winter**
- **Snow melt sooner, runoff earlier: Less snowpack**
- **Prospects for less water in summer**
- **Greater risk of drought, heat waves, wild fires**
- **Expansion of pests (Like bark beetle)**

What about all the snow?

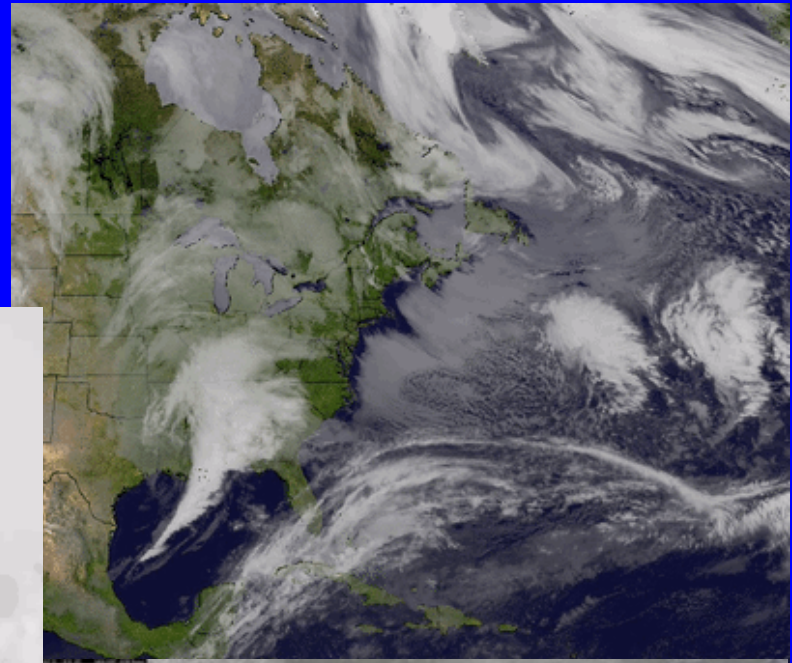
# Senator James Inhofe stunt on snow and climate change in Senate



26 Feb 2015

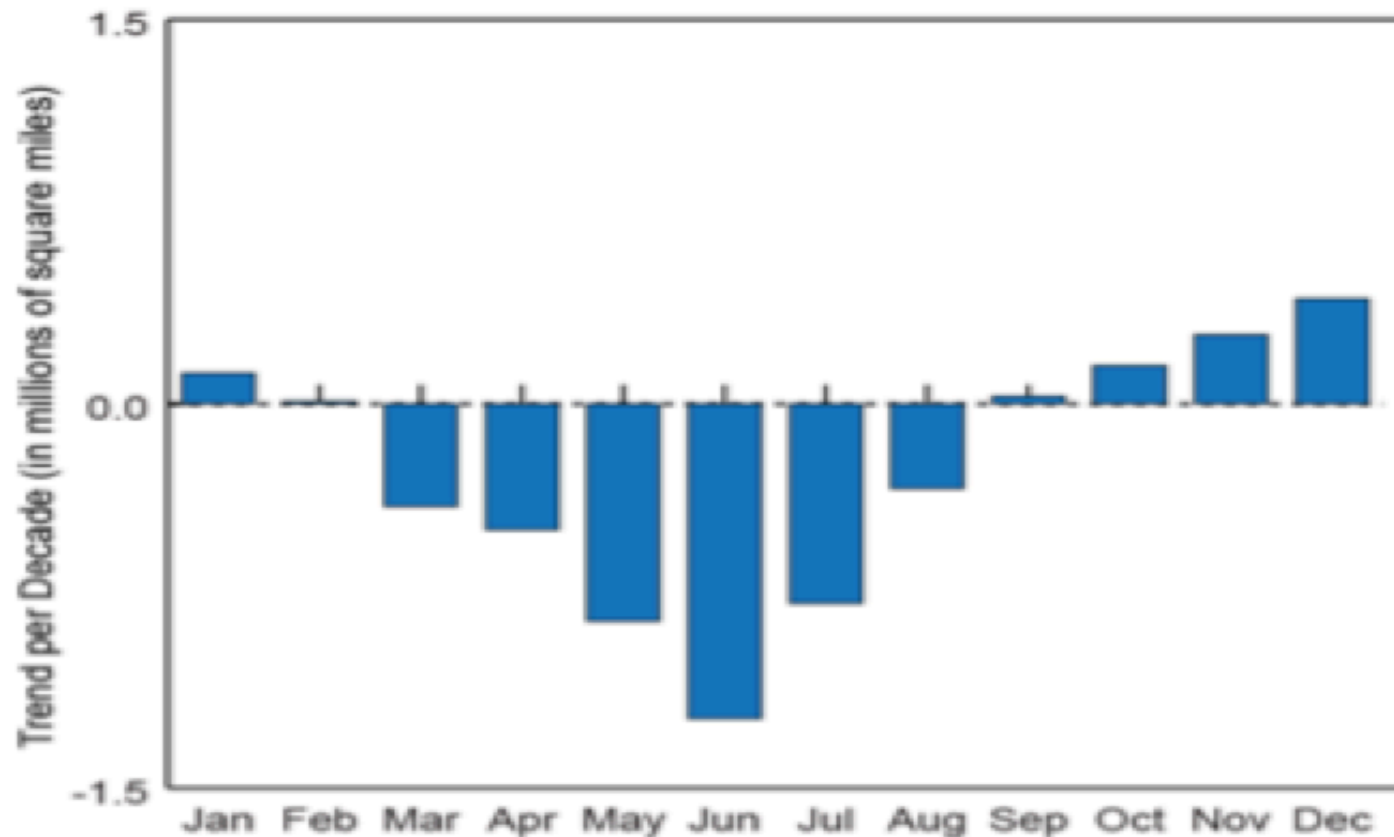
# *Jonas: East coast snow storm*

*Jan 22-23 2016*



# Northern Hemisphere snow cover extent

Rate of Change Per Decade  
Period Analyzed: November 1966 through December 2014



January 2015 | NOAA/NASA – Annual Global Analysis for 2014

27 Jan 2015 NOAA



# US 48 contiguous States

Temperature:  
annual

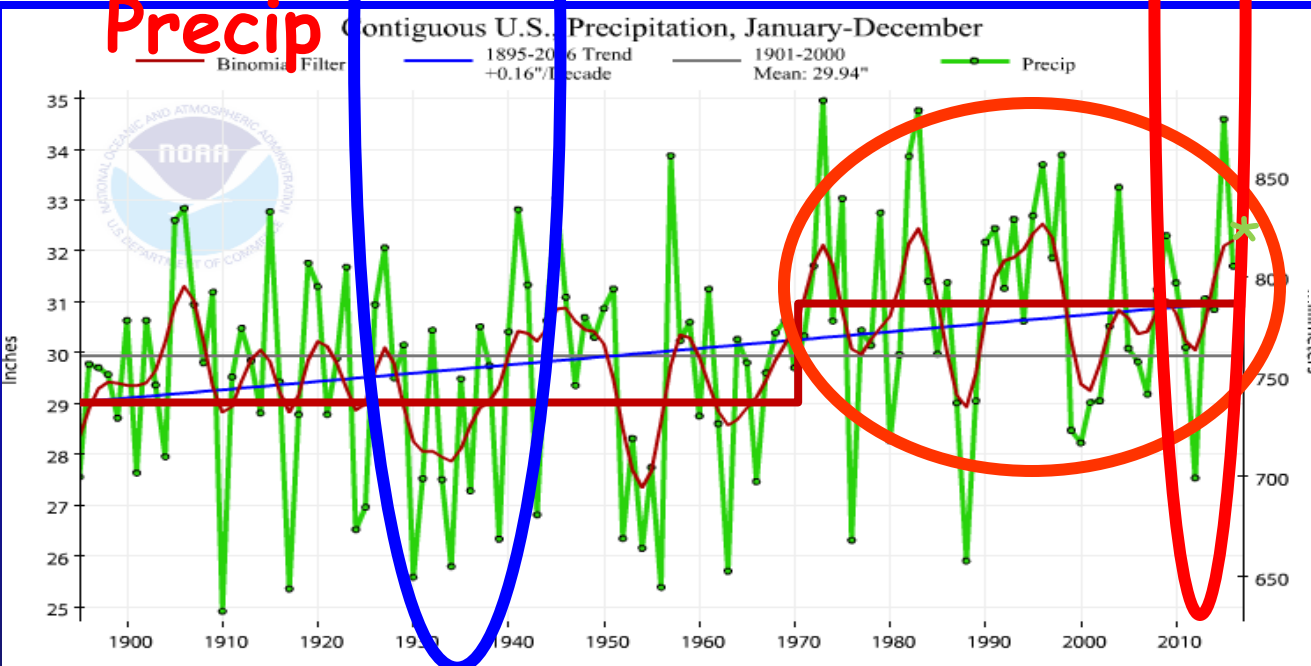
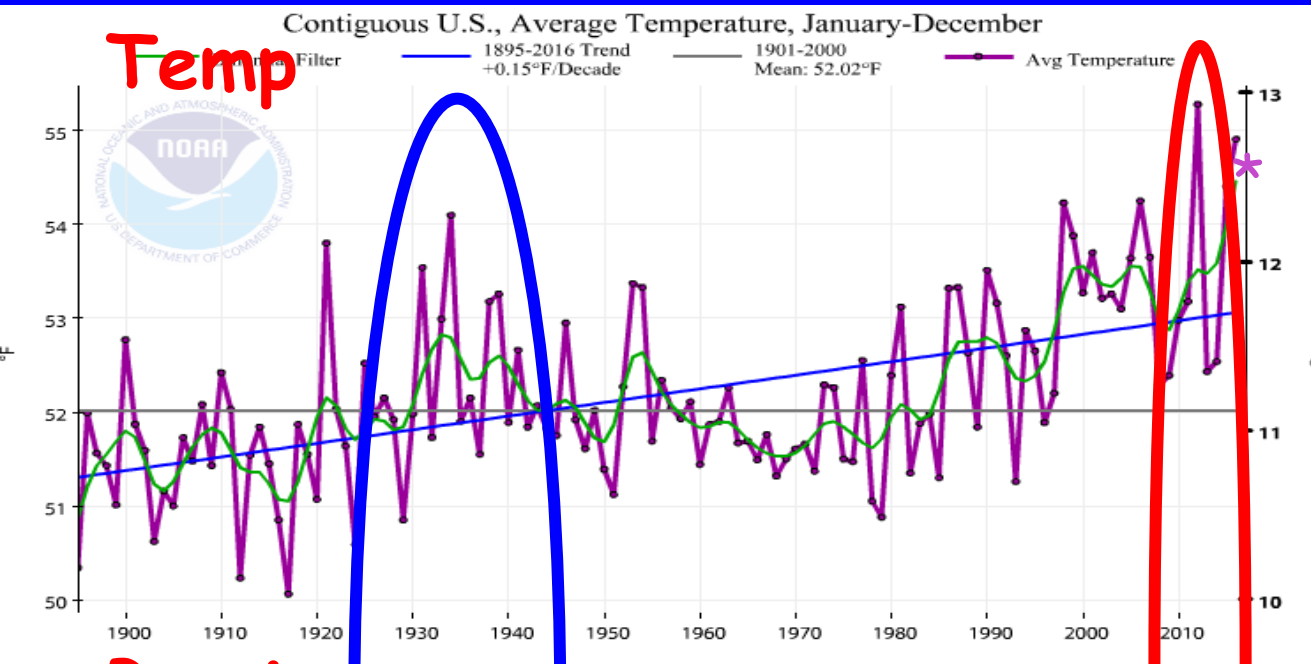
Precipitation:  
Annual

Thru 2016, \*2017

Much wetter

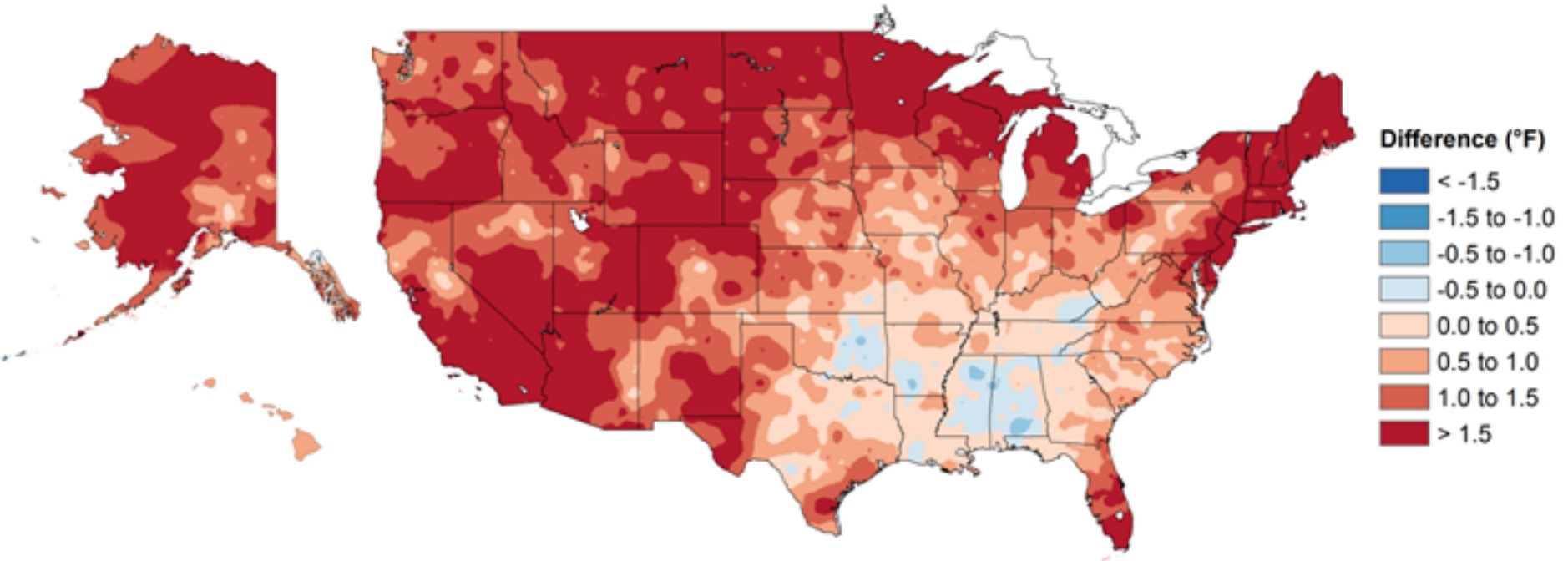
2012:  
V hot and dry

1930s:  
Hot and dry  
"Dust Bowl"

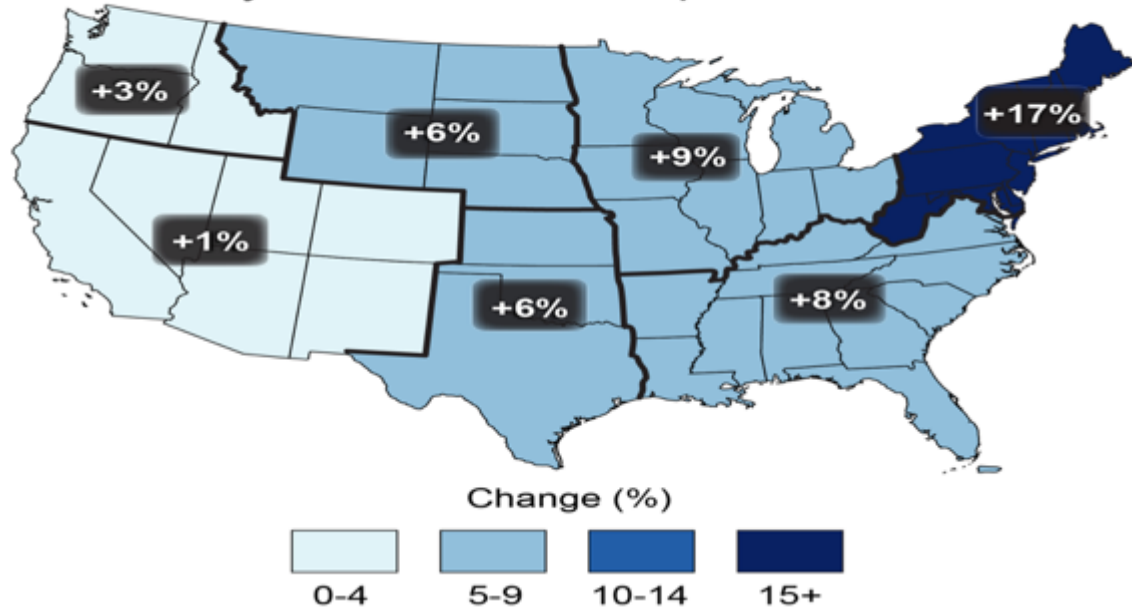




# Annual Temperature



## in 5-year Extreme Precipitation Events



**1981-2015 vs 1901-60**  
Or 1925-1960 Alaska

% diff in top 20% of daily precipitation

USGCRP 2017

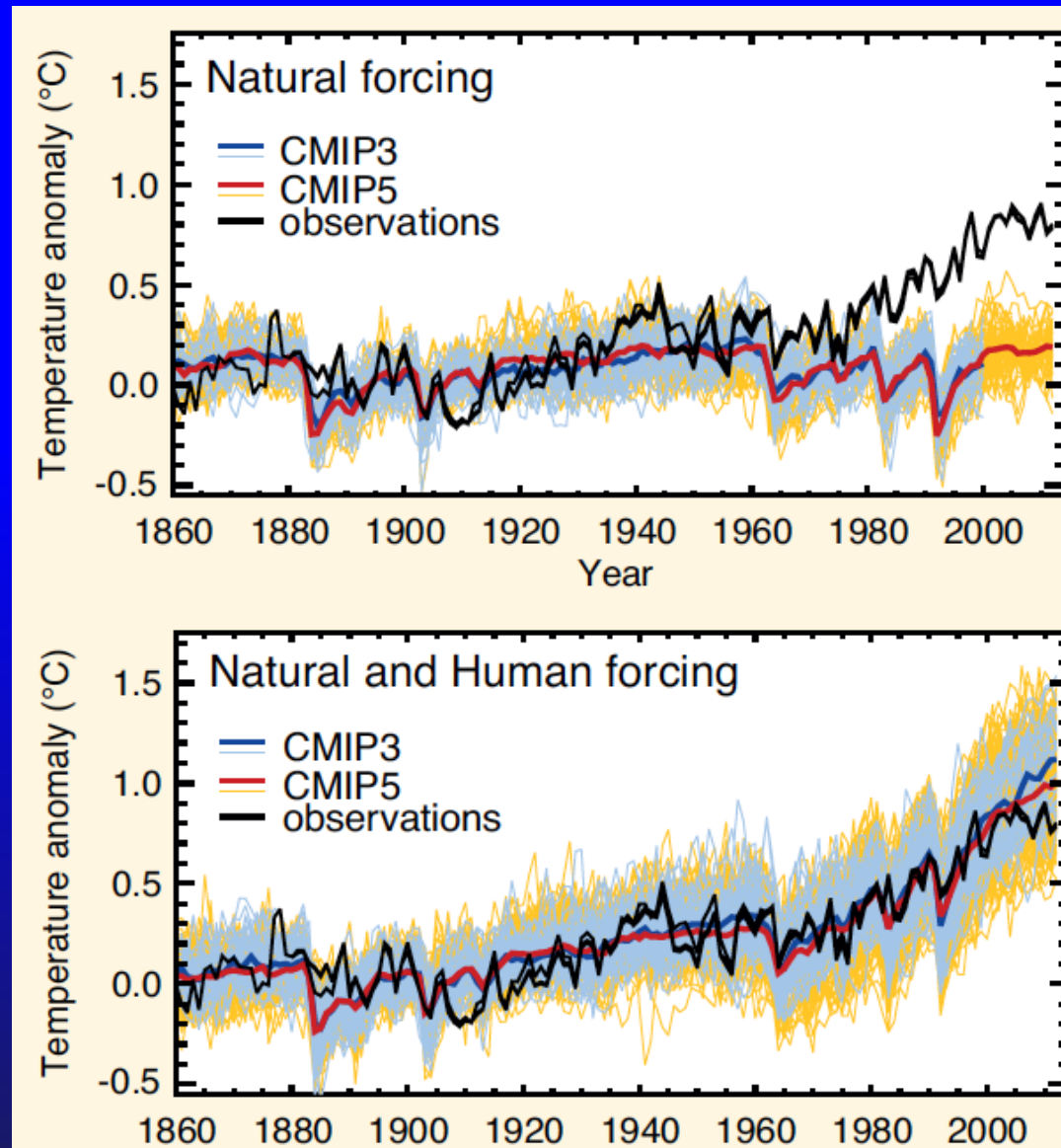
# Attribution of climate change

With climate models, scientists can play "God".

We can run models with and without human influences and see what the difference is.

Global surface temperature

IPCC 2013

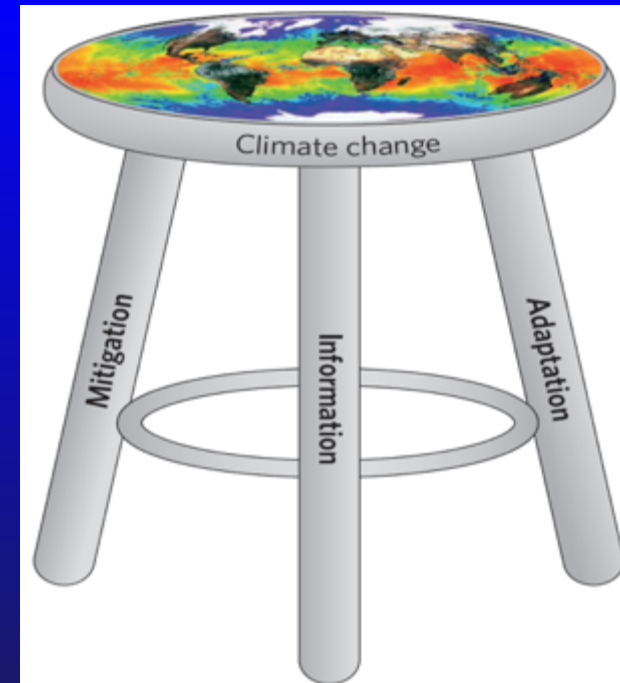


# New National Climate Assessment: CSSR

Climate Science Special Report

Nov 3, 2017

*“This assessment concludes, based on extensive evidence, that it is extremely likely that human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence.”*



# Changes in extremes

Matter most for society and human health

With a warming climate:

- More high temperatures, heat waves
- Wild fires and other consequences
- Fewer cold extremes.
- More extremes in hydrological cycle:
  - More intense precipitation
  - Longer dry spells
- Increased risk of flooding and drought
- More intense storms, hurricanes, tornadoes



Major challenges for a water manager

# More Than 1,000 Died in South Asia

## Floods Summer 2017 41 million people affected

Jeffrey Gettleman NY Times

330 mm rain in Mumbai 29 Aug



← Nepal  
India



Bangladesh ↓

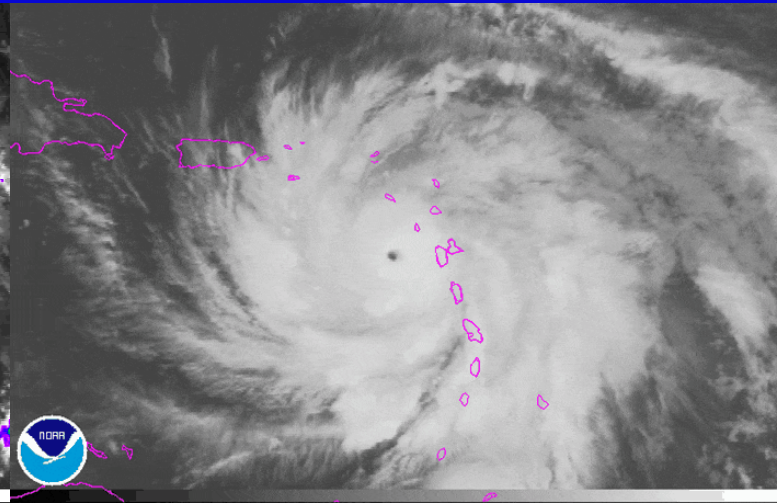
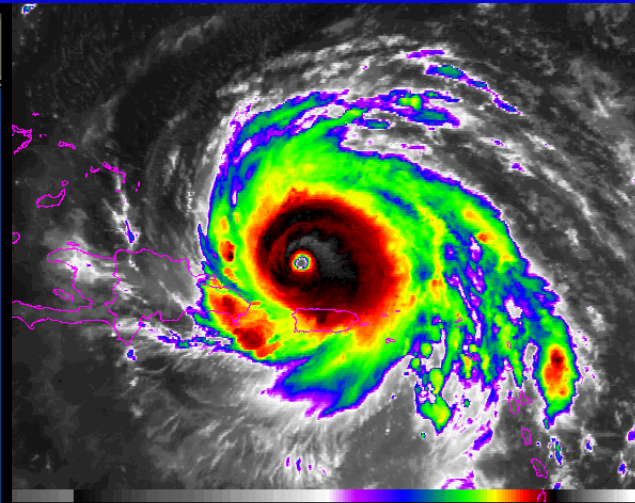
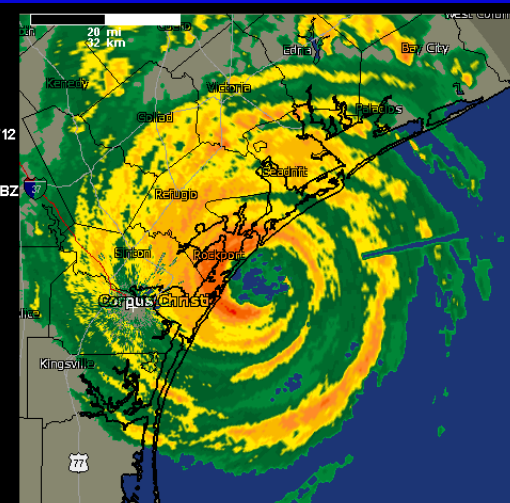


# Are recent hurricane (Harvey, Irma, Maria) disasters natural?

Harvey  
Aug 26

Irma  
Sep 7

Maria  
Sep 19

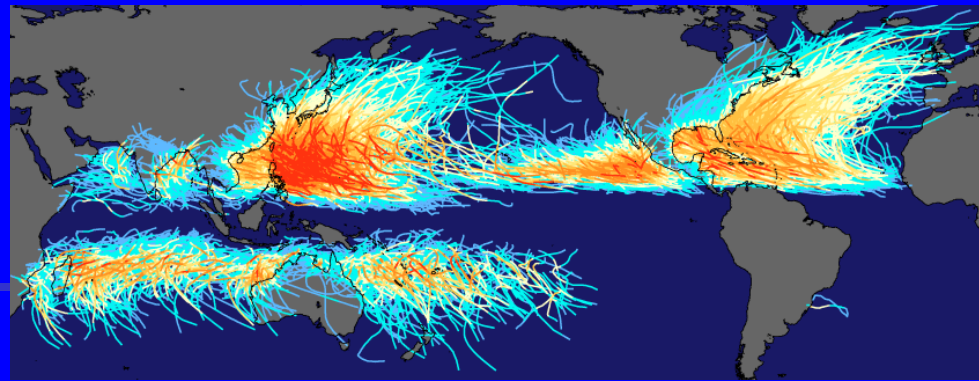


# ***Are recent hurricane (Harvey, Irma, Maria) disasters natural?***

***Yes, and no!***

- Yes: hurricanes are natural***
- No: they were supersized***
- These events would not have occurred without human-induced climate change.***
- And they were further exacerbated by poor preparedness***

# Hurricanes:



- ☺ Depend on SSTs  $> 26^{\circ}\text{C}$  ( $80^{\circ}\text{F}$ )
- ☺ High water vapor content
- ☺ Weak wind shear (or vortex comes apart)
- ☺ Weak static stability
- ☺ Pre-existing disturbance

**Large variability year to year in individual basins.**

El Niño means more action in Pacific, suppression in Atlantic

Large decadal variability in Atlantic

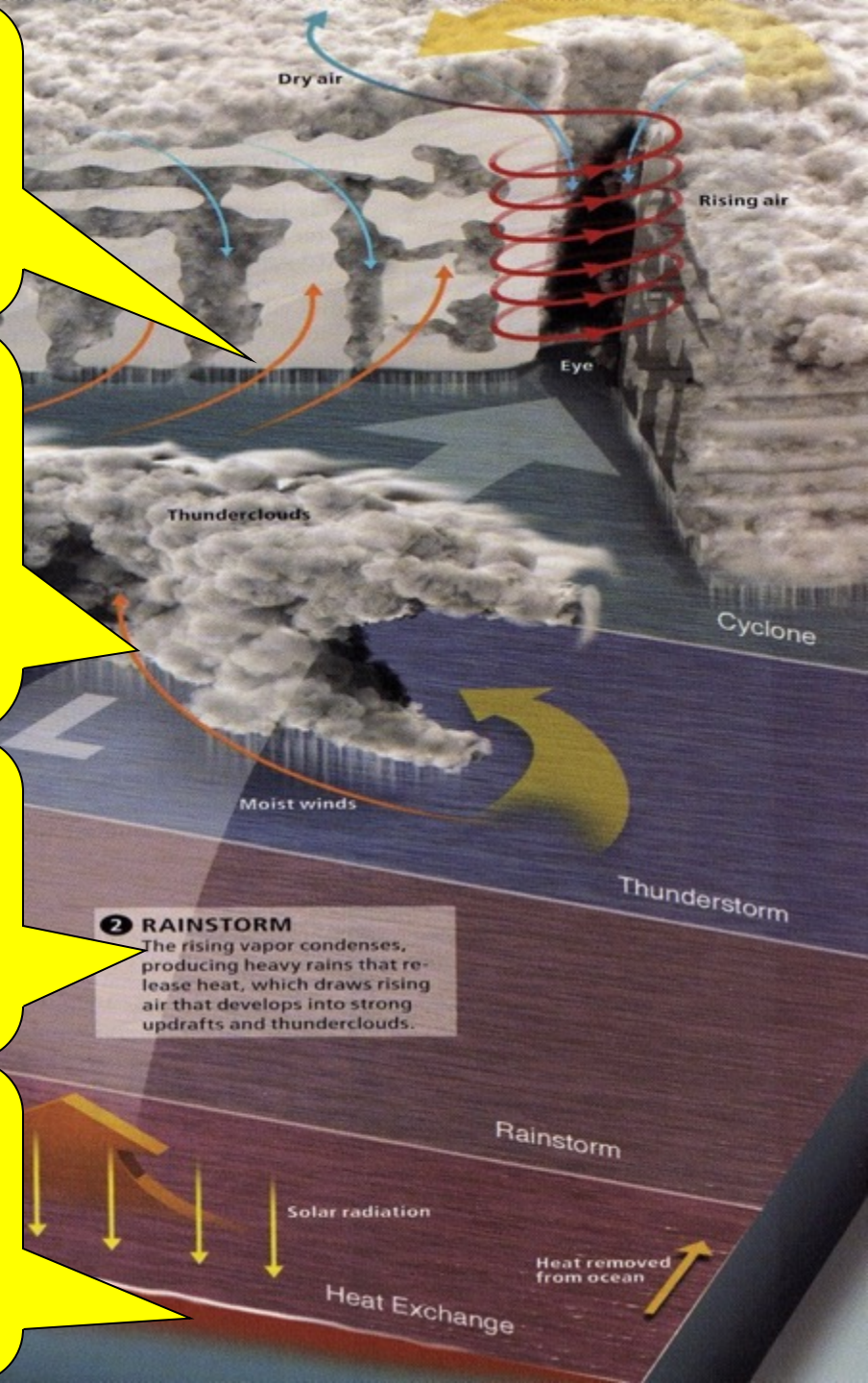


4) The storm strengthens and strong surface winds increase evaporation, rainfall and energy in the storm.

3) A disturbance (from Africa) organizes the thunderstorms and starts them swirling: air spirals in at the bottom and out at the top

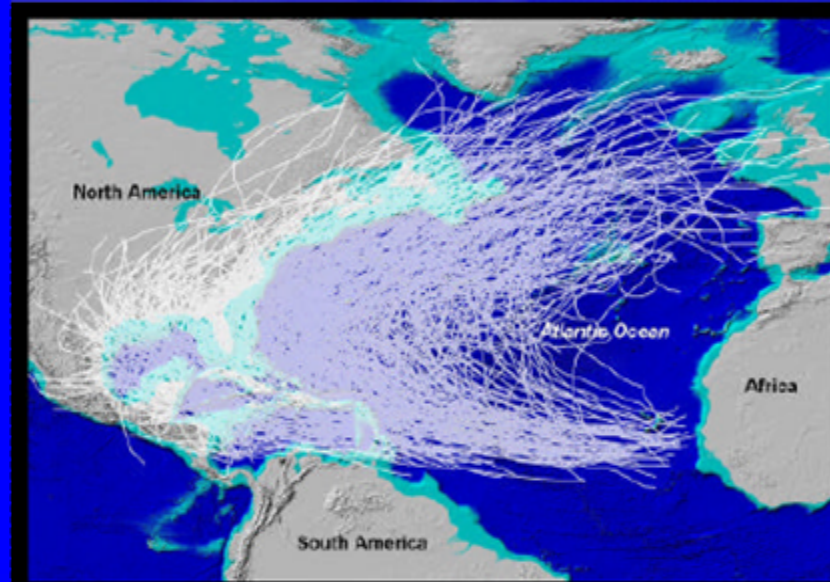
2) Rising air condenses the water vapor producing latent heat and strong updrafts, drawing in more air

1) The sun shines down and warms the ocean: evaporative cooling keeps the balance, but creates warm moist air

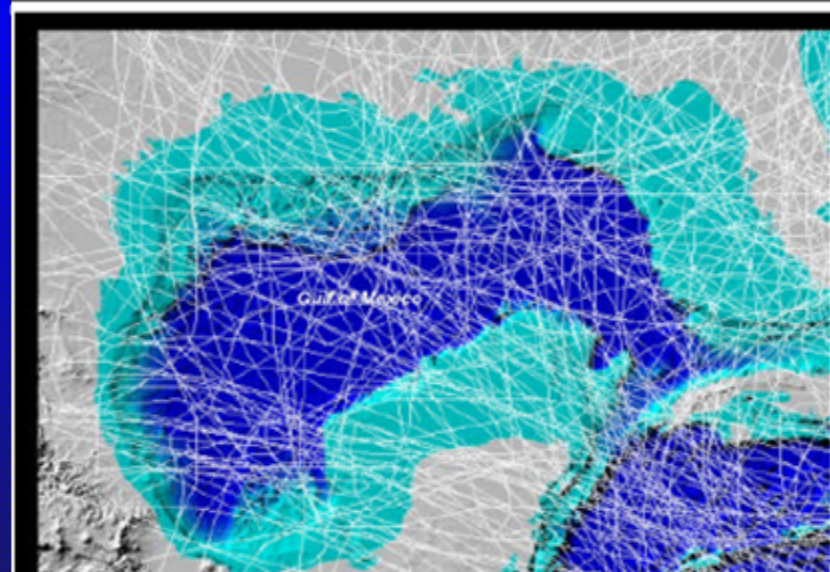


# Climate change and hurricanes

- Hurricanes act as a relief valve for the ocean
- They mix and cool the ocean (evaporative cooling)
- They moisten the atmosphere
- Heavy rains result, releasing latent heat
- The heat is redistributed by winds, and
- Can then radiate to space
- They leave a cold wake behind
- Hurricanes thus do not track on same track



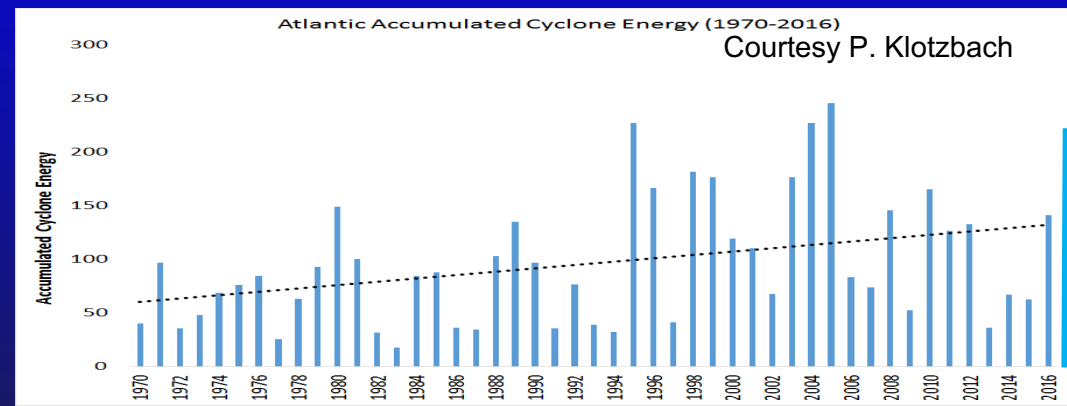
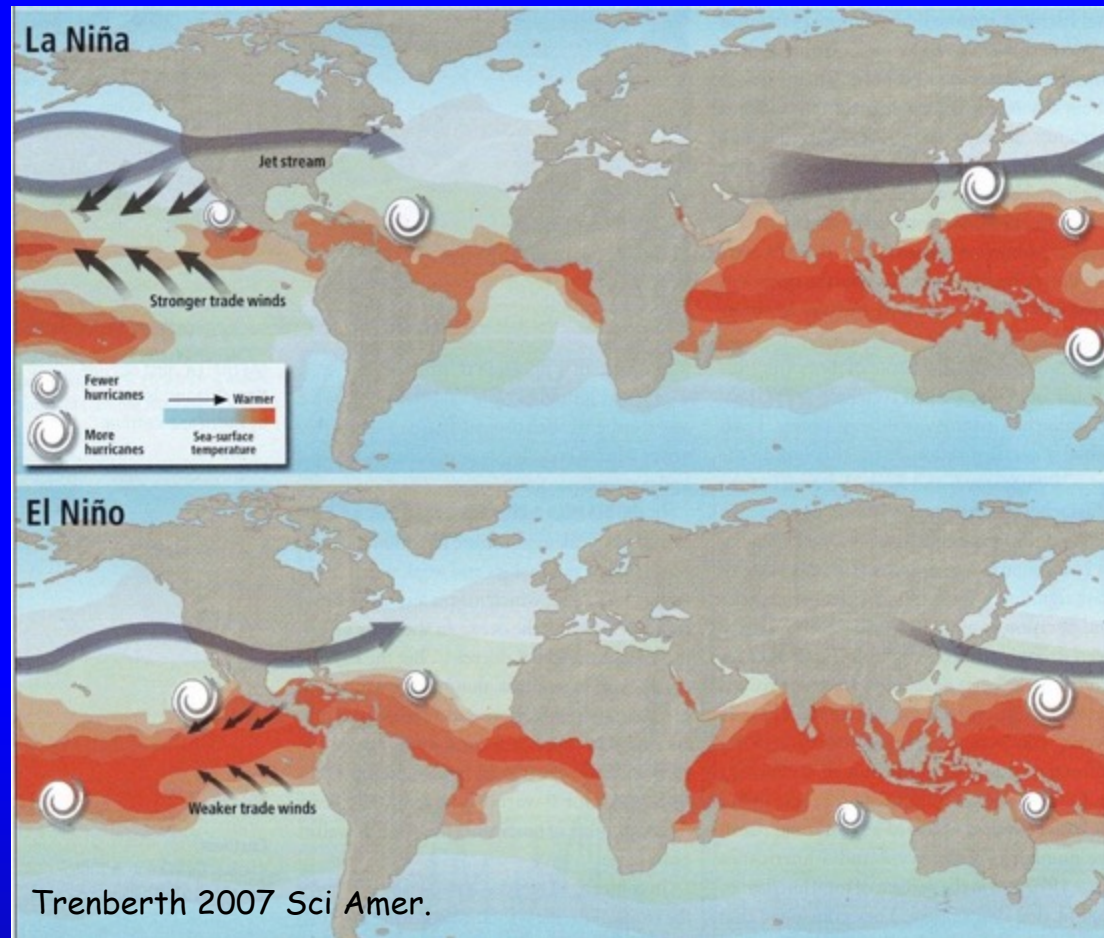
North Atlantic Hurricane 'Tracks' 1886-1996 from NOAA NHC



Gulf of Mexico Hurricane 'Tracks' 1886-1996 from NOAA NHC

# Hurricane variability

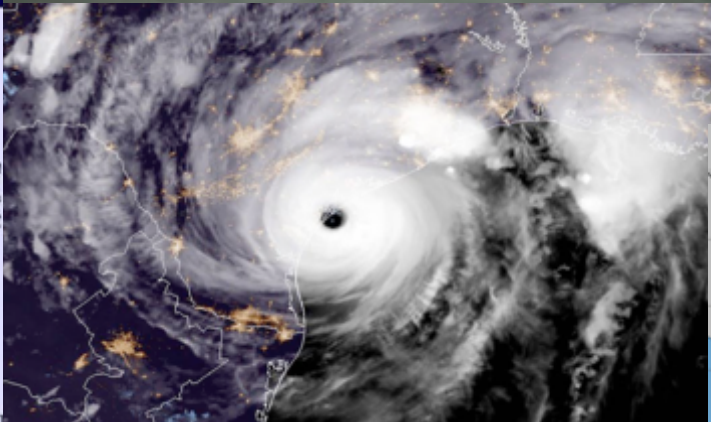
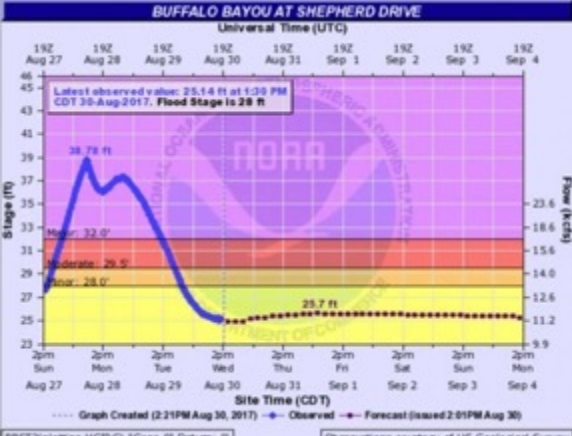
- Hurricanes have large natural variability
- Competition among basins
- El Niño has profound effects
- Records are poor prior to satellite era (1970)
- September 2017: 40 "hurricane days" highest on record
- 2017:
  - 17 (12) named,
  - 10 (6) hurricanes;
  - 6 major



# Climate change and hurricanes

- The memory of past climate change is the ocean heat content (OHC) and sea level rise
- The air above the ocean is warmer and moister as a result by 5 to 15% vs prior to 1970
- The moisture evaporating from the oceans is the fuel for hurricanes
- Evaporative cooling of ocean plus mixing ocean leaves a cold wake
- When natural variability is in the same direction, records can be broken:
  - More intense hurricanes
  - Bigger hurricanes
  - Longer-lasting hurricanes
  - More flooding rains

# Harvey



# 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 without  
power

185,000 homes damaged

**1 in 6 had flood insurance**

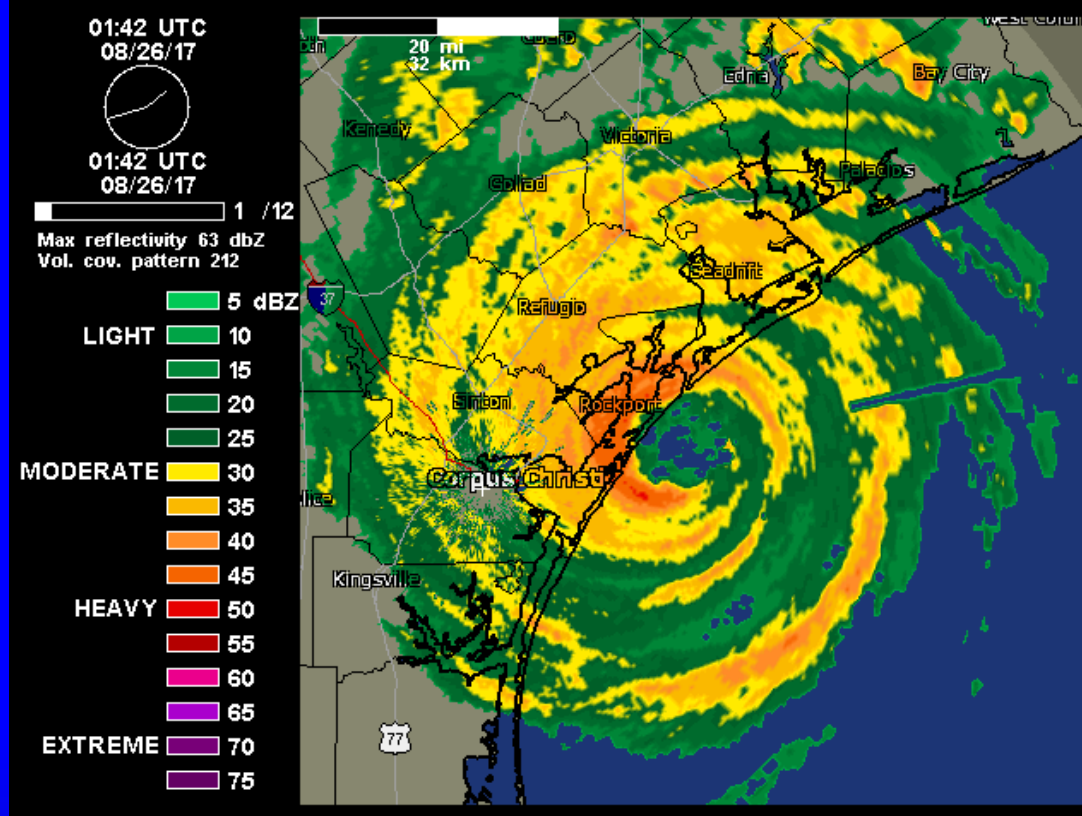
440,000 registered with

FEMA for aid as of Sep 1.

64.58" of rainfall at Nederland

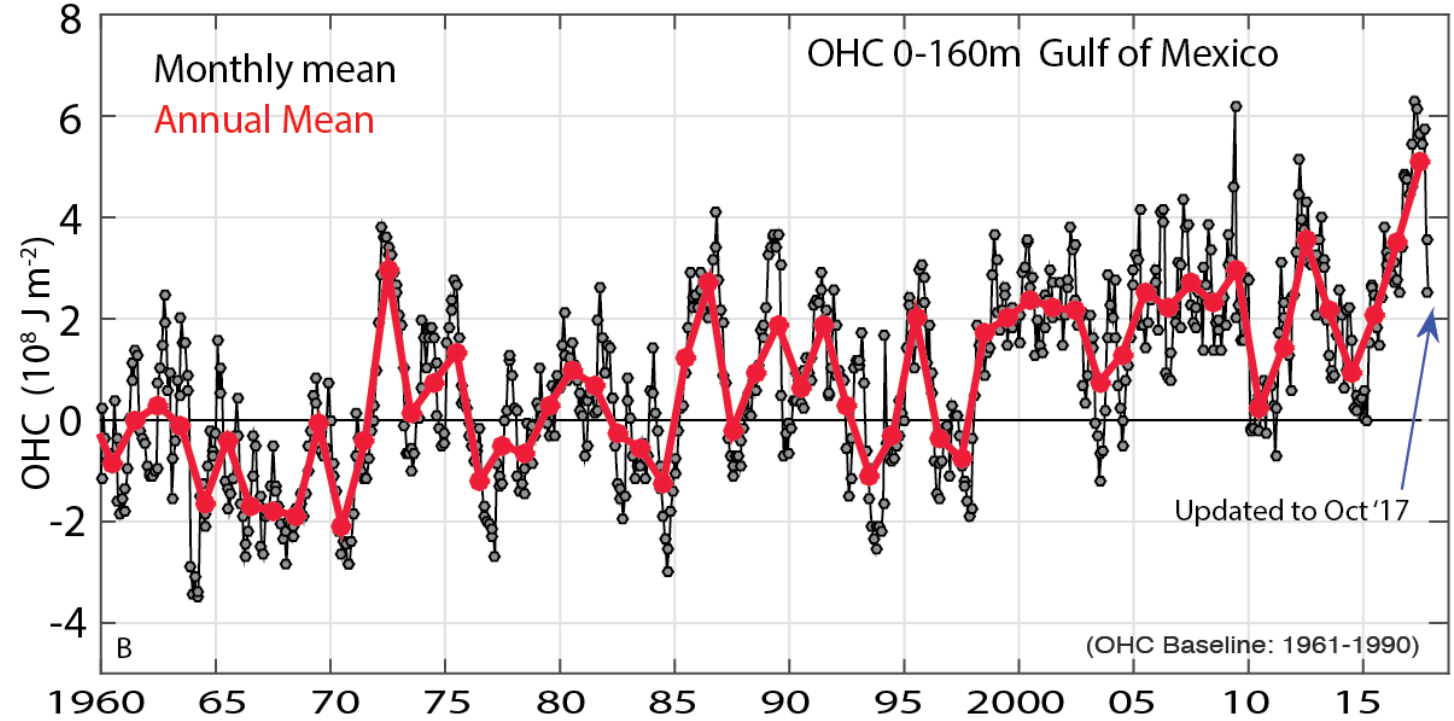
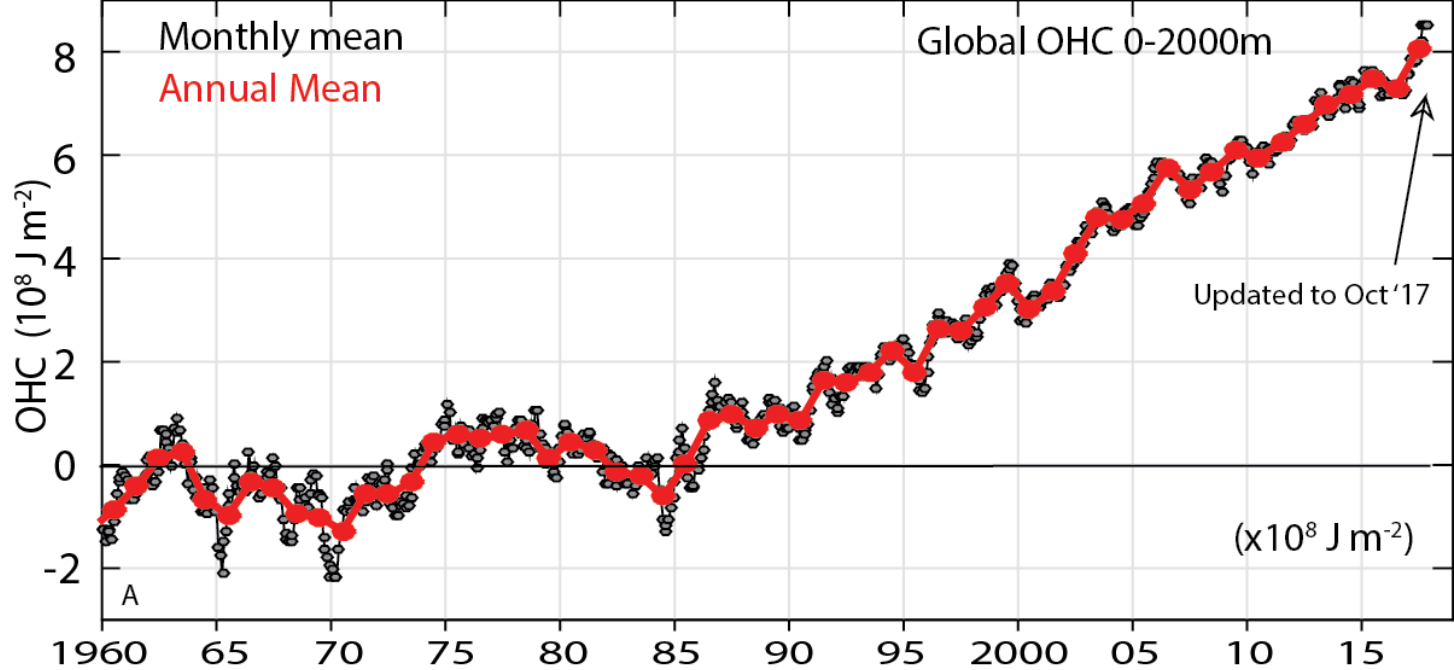
TX: highest anywhere in US

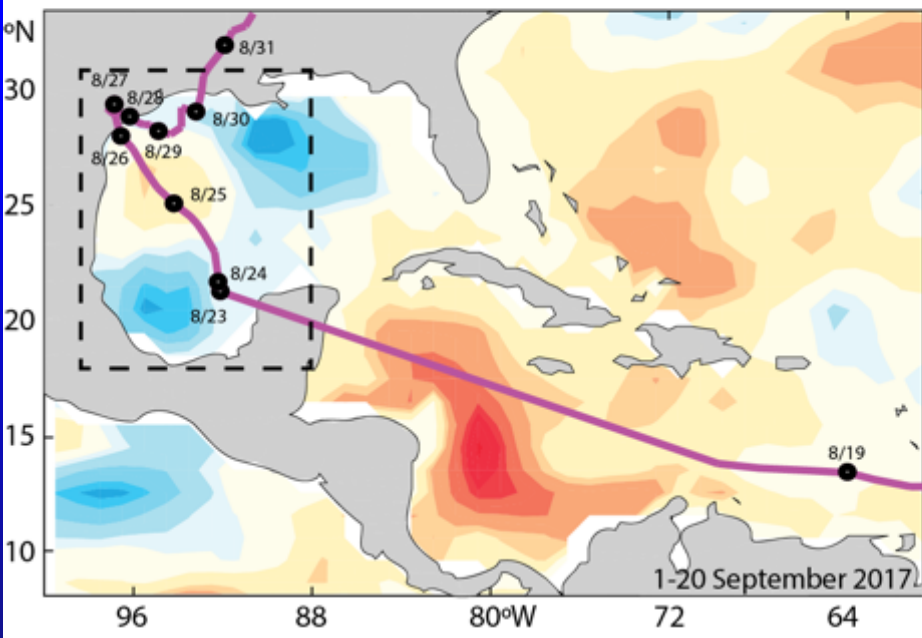
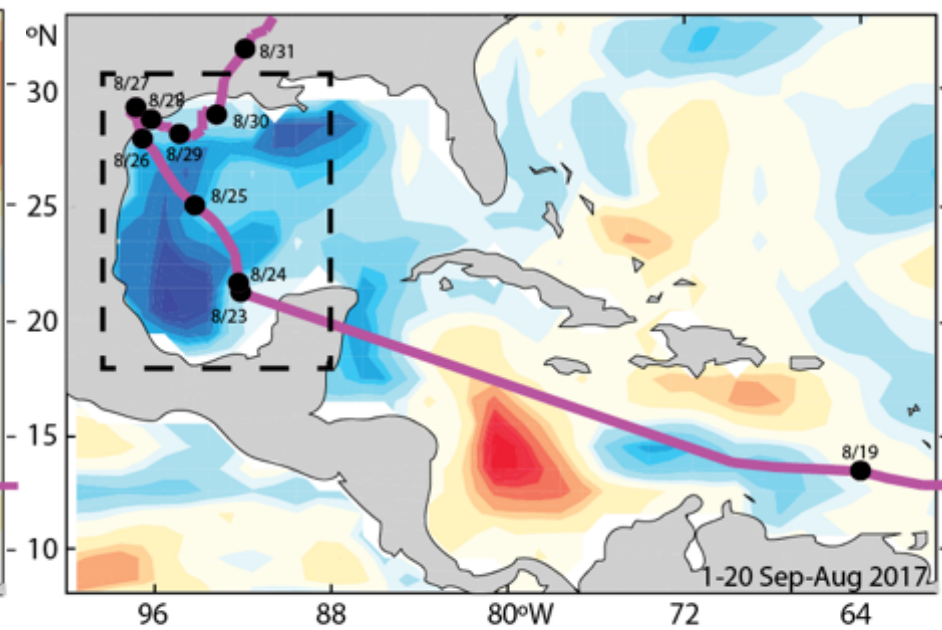
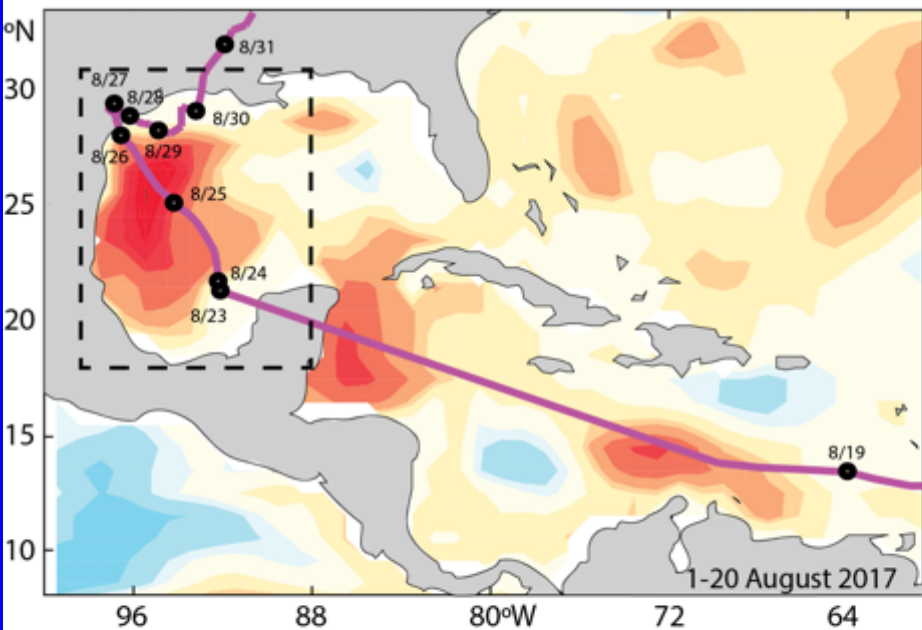
60.54" at Lake Charles...



# Ocean Heat Content

Updated from Cheng et al 2017



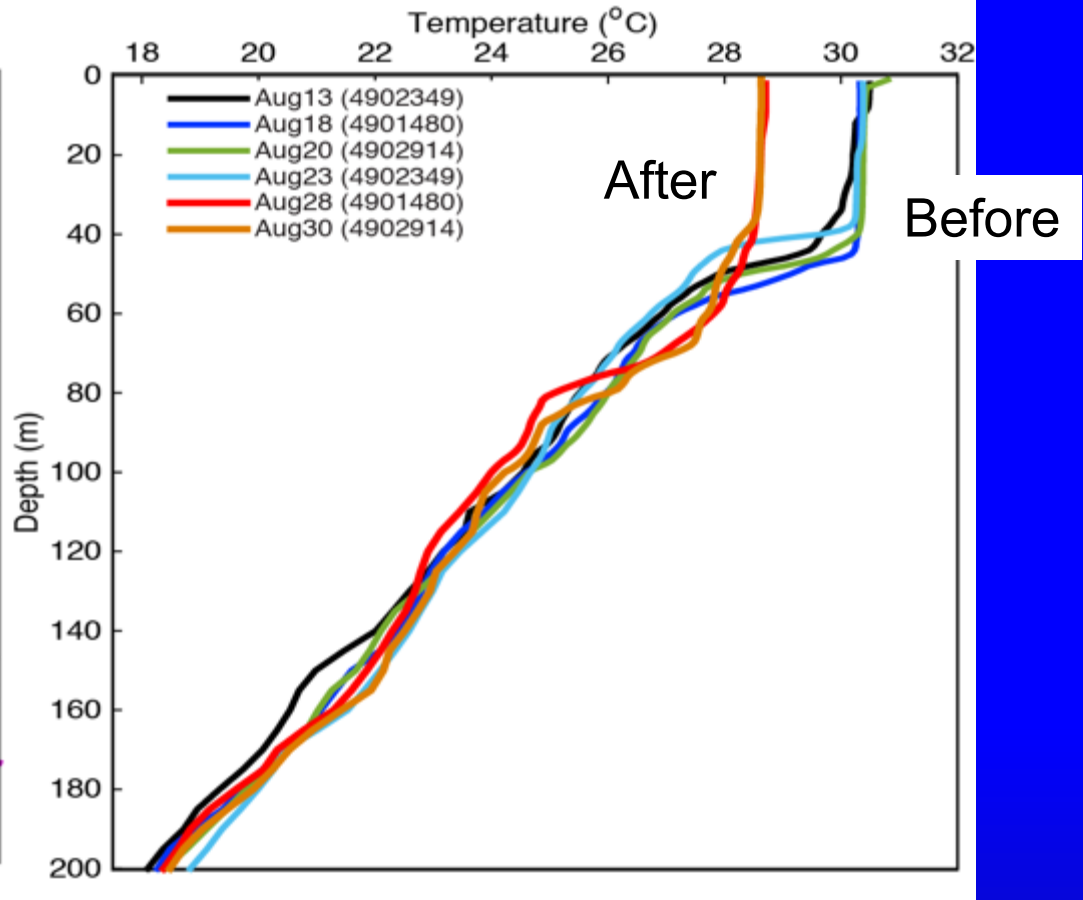
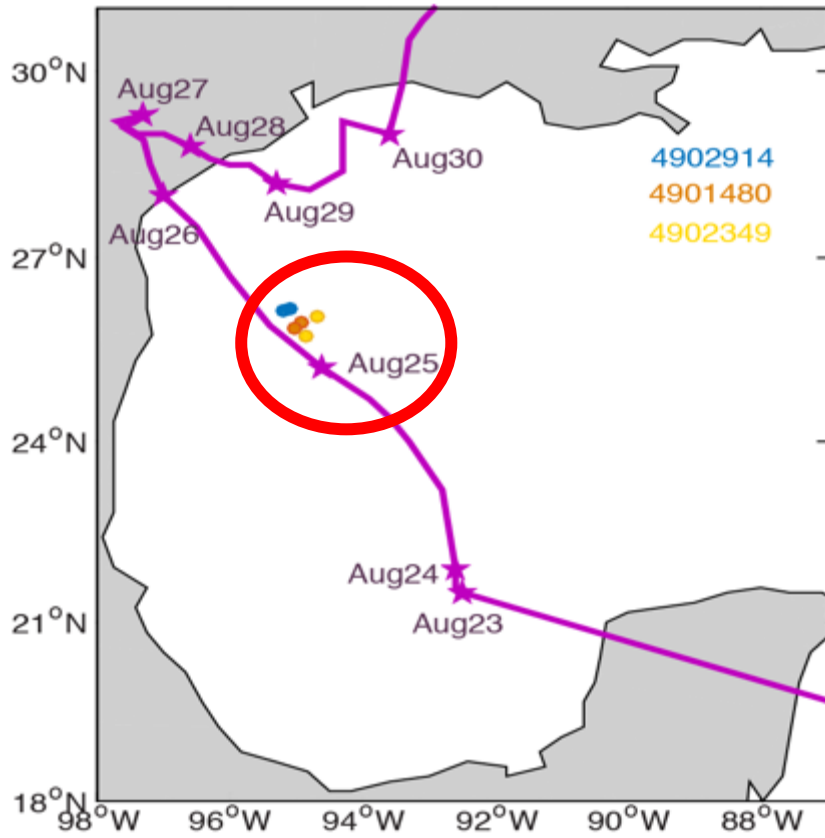


Base period 1961-90

**OHC loss in Gulf**  
 $4.7 \times 10^{20} \text{ J}$   $\sim 0.18 \text{ PW}$



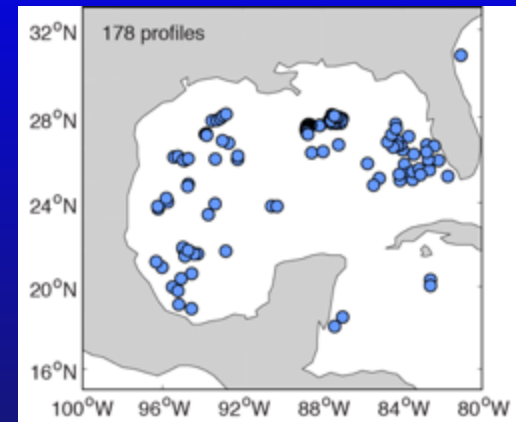
### Harvey: August 2017



### Argo observations under Harvey.

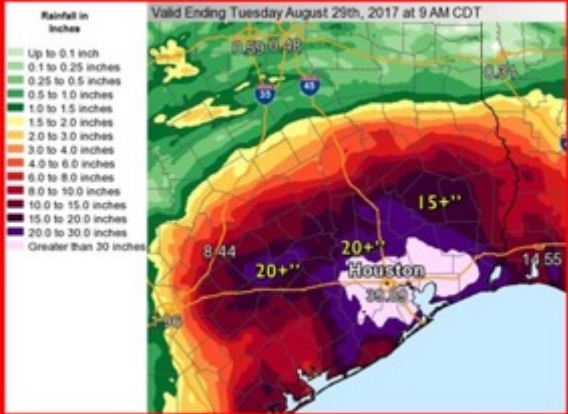
The numbers are the Argo series.

Right: temperature profiles observed by 3 Argo floats **before** (observation dates: 13, 18, 20, 23 August) and **after** Harvey (observation dates: 28 and 30 August)



Argo floats Aug 2017

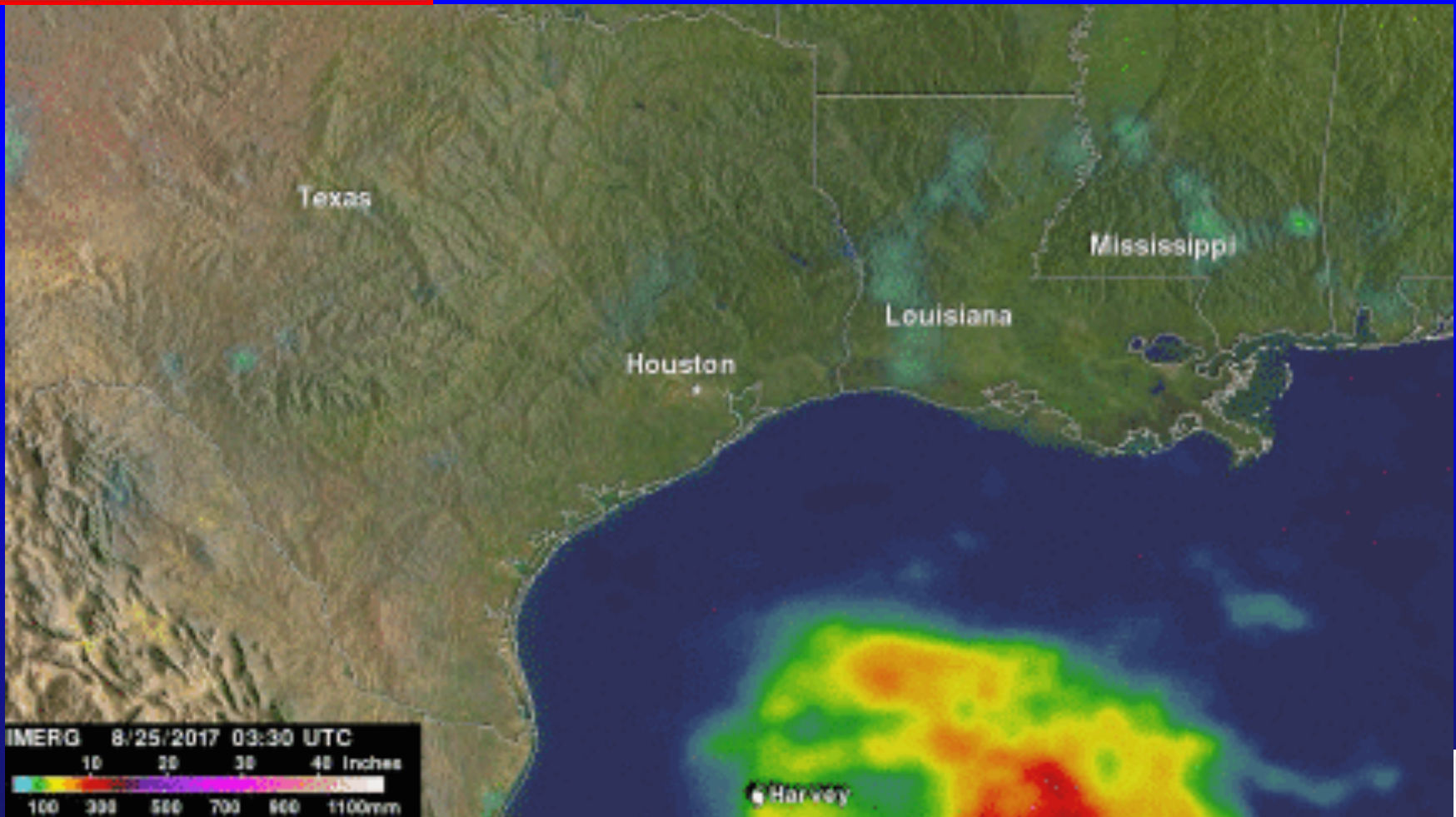
### 4 Day Rainfall Totals



# Harvey

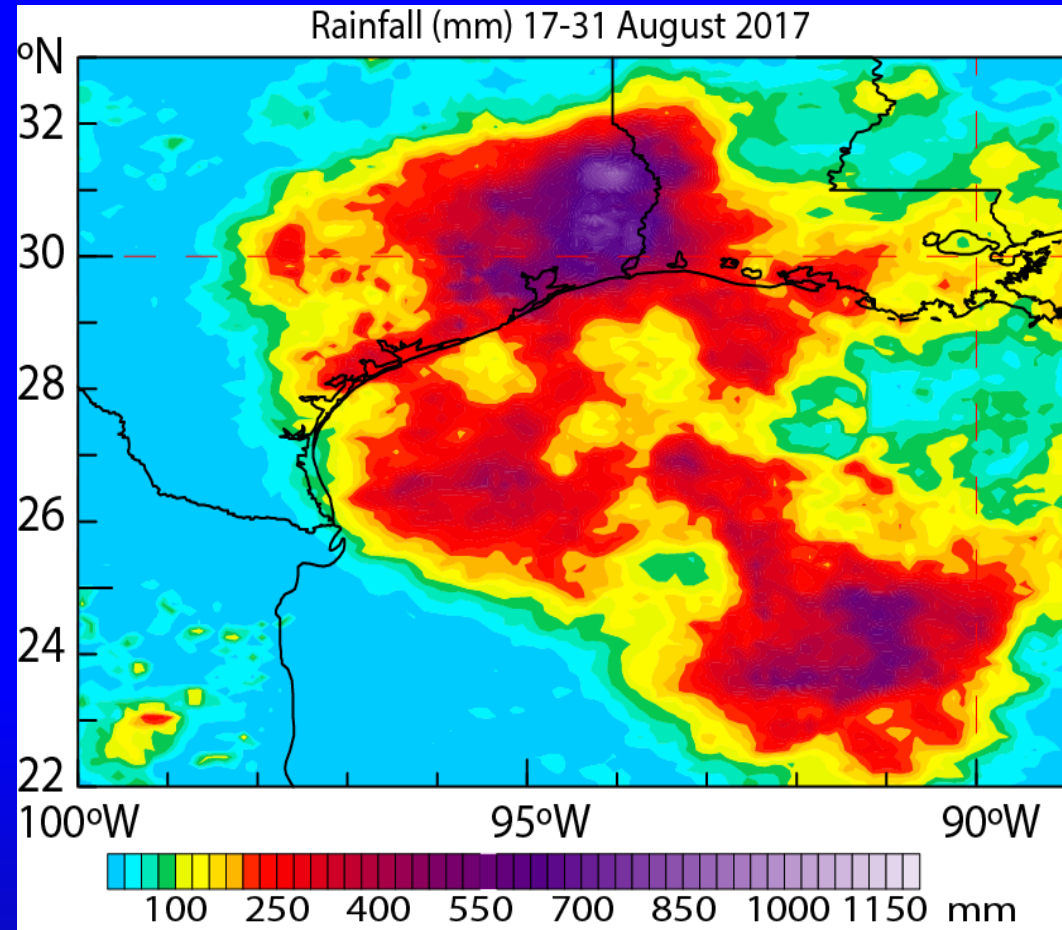
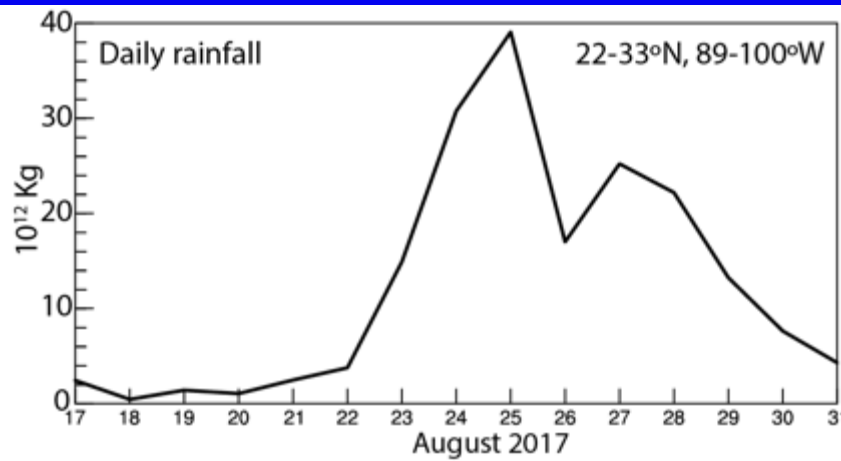
Max: 64.6 inches: Nederland  
highest anywhere in US

NASA: Eric Niiler: Wired 8:29:17



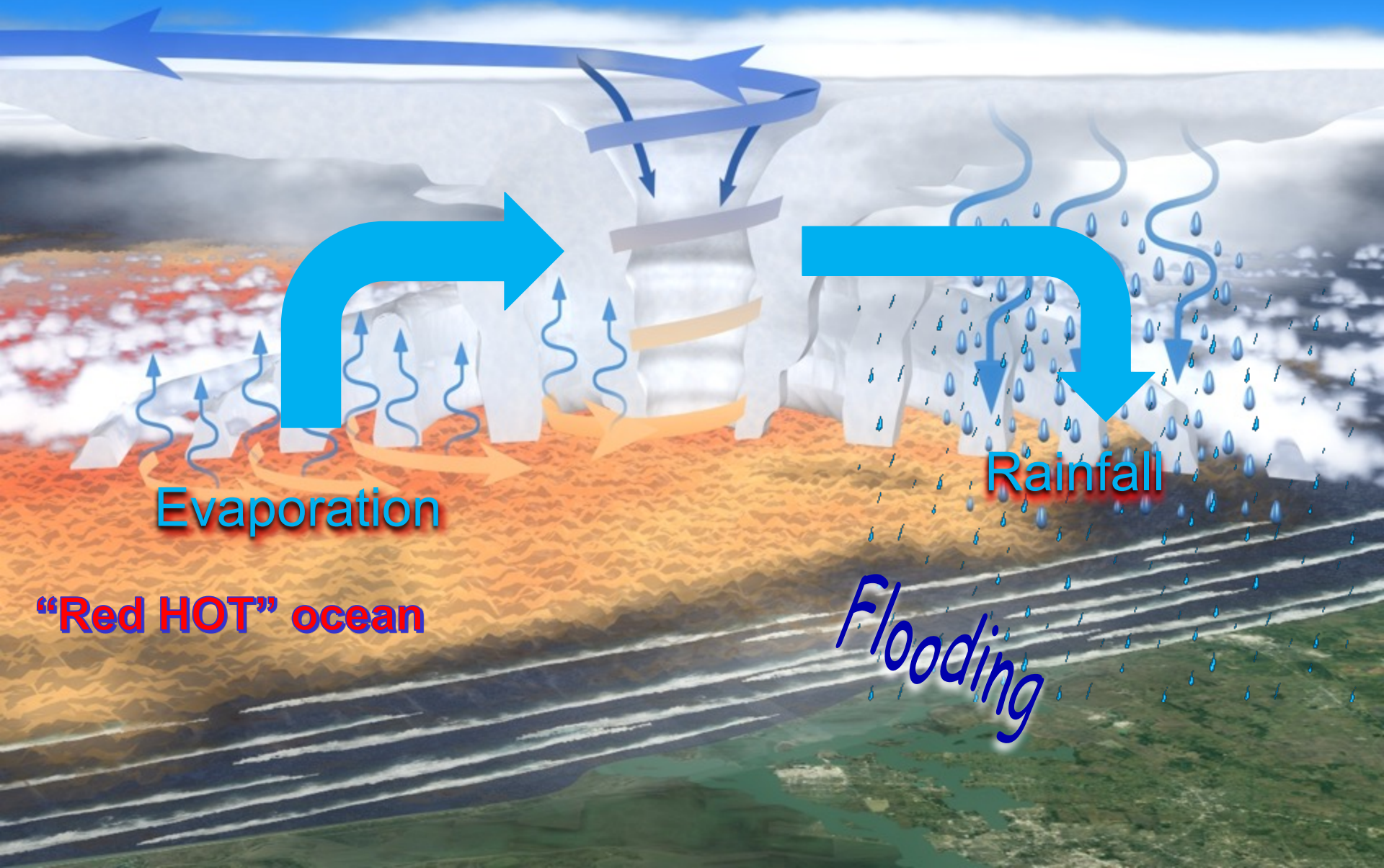
# Harvey

Total rainfall 22 to 33°N 89-100°W  
17-31 August was 140.7 mm,  
or  $4.65 \times 10^{20}$  J  
of latent energy in rainfall:  
**Matches OHC loss.**



Hence, if OHC had been less,  
rainfall would have been less.

Large moisture fluxes from a “red hot” ocean fuel the hurricane and its heavy rains



Evaporation

“Red HOT” ocean

Rainfall

Flooding

# Damage from hurricanes comes from 3 main sources

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 all the way from Gulf Coast to Canada

# How well prepared were people for Harvey?

Major flooding in Houston area is not uncommon:

Major flooding event in April 2016

⇒

Yet only 1 in 6 had flood insurance!



In the wake of Hurricane Ike, which claimed 113 lives in Galveston Bay in 2008, proposals for large-scale flood-control projects were rebuffed. Houston's residents have 3 times voted **not** to enact a zoning code.

**They voted to suffer the consequences!**

Houston: pro-business,  
low taxes,  
little government.

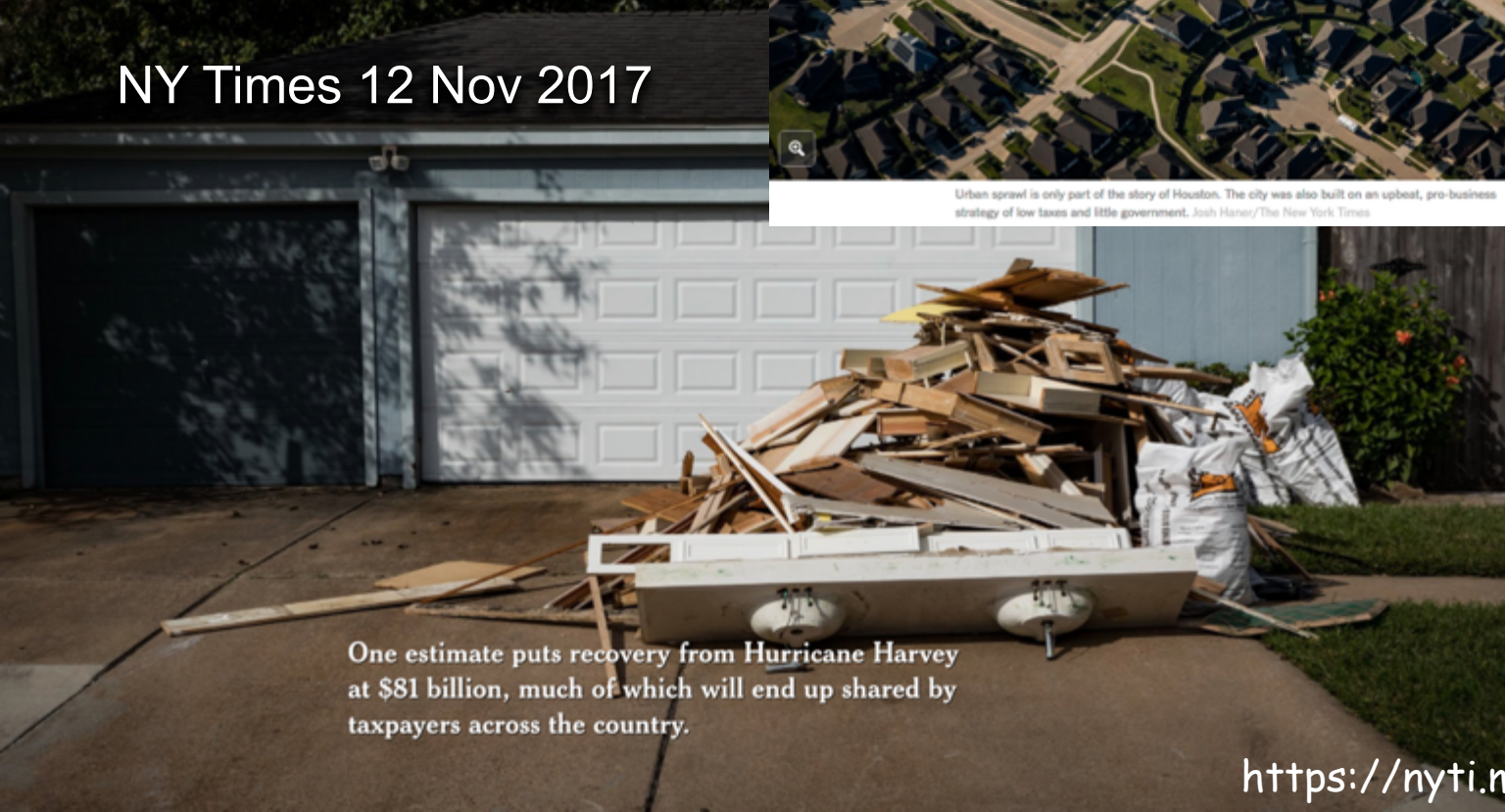
Expenses shared by  
taxpayers across the  
country!

NY Times 12 Nov 2017



Urban sprawl

Urban sprawl is only part of the story of Houston. The city was also built on an upbeat, pro-business strategy of low taxes and little government. Josh Haner/The New York Times



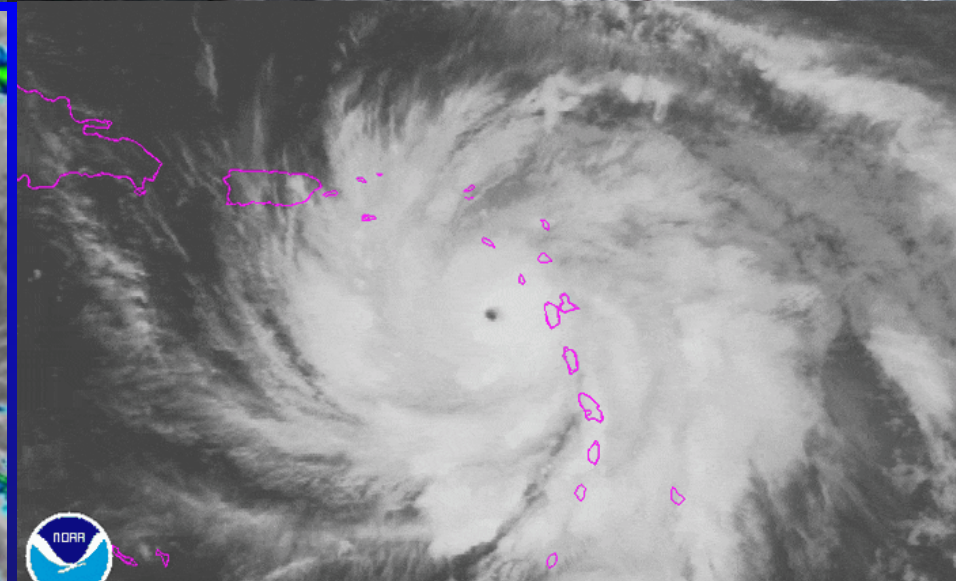
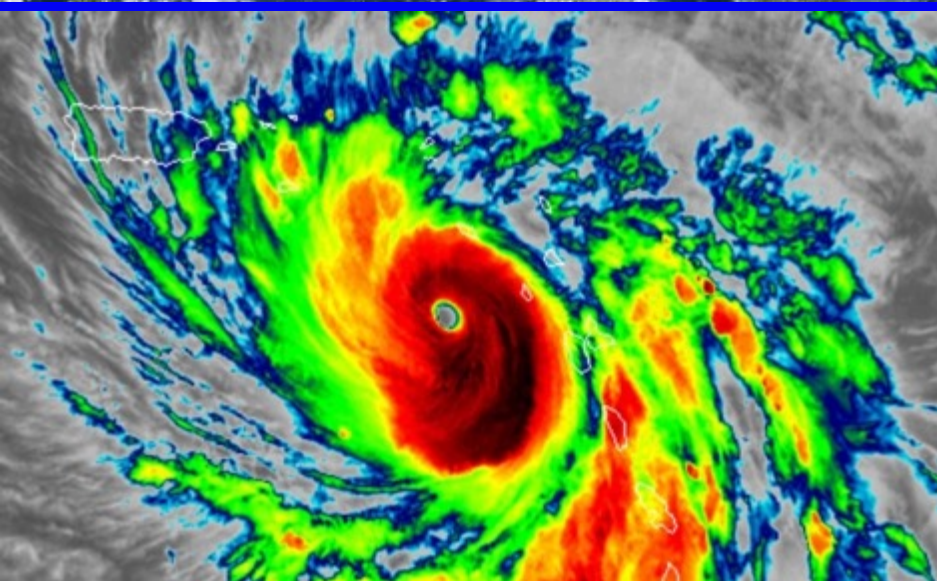
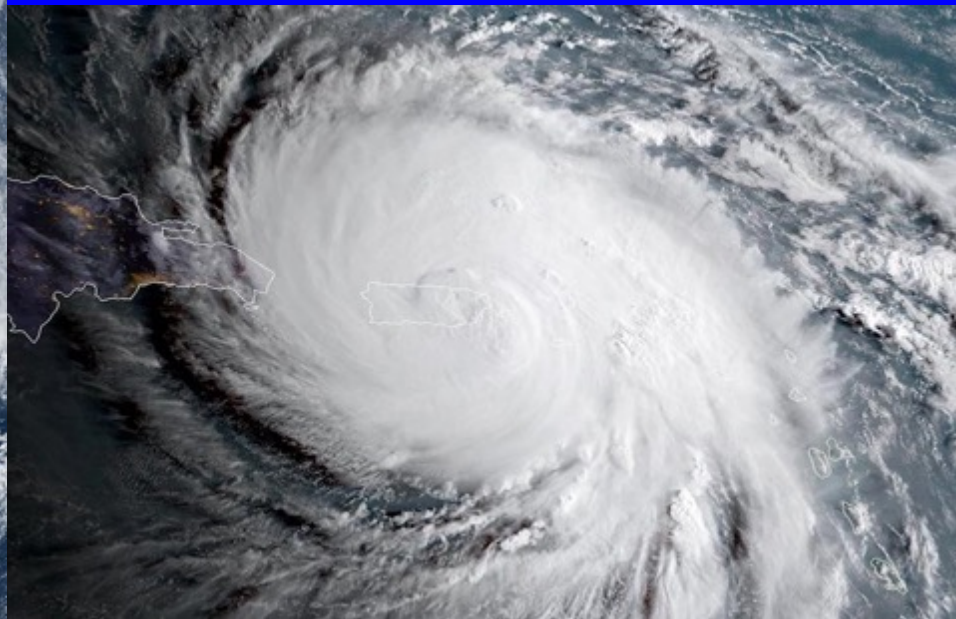
One estimate puts recovery from Hurricane Harvey at \$81 billion, much of which will end up shared by taxpayers across the country.

<https://nyti.ms/2hqXvd5>



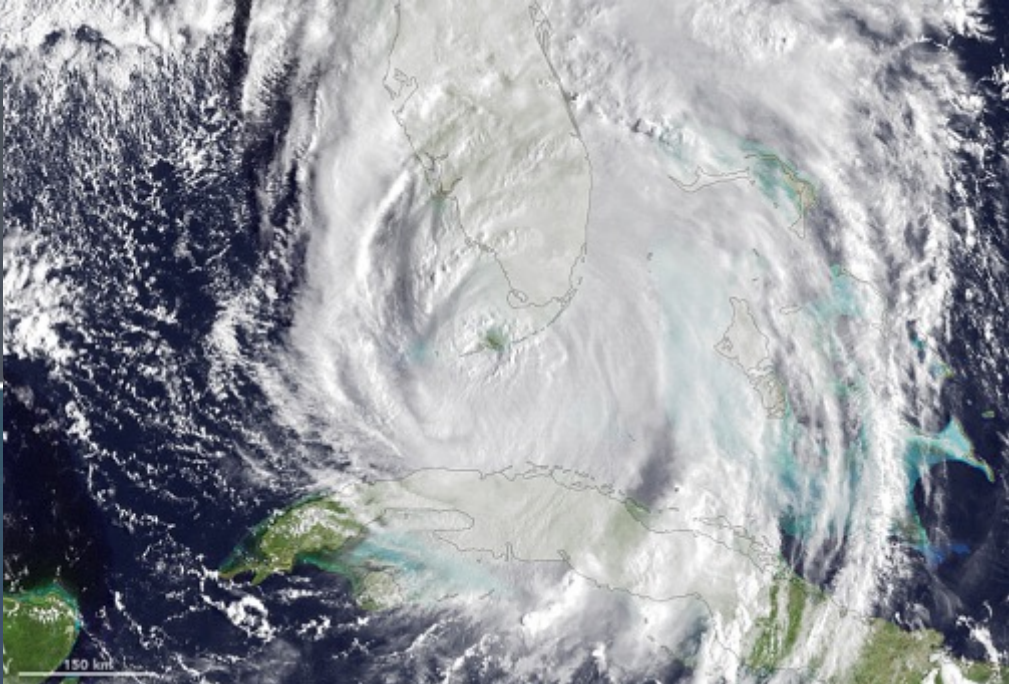
Jose, Maria 18-20 Sept 2017

NASA

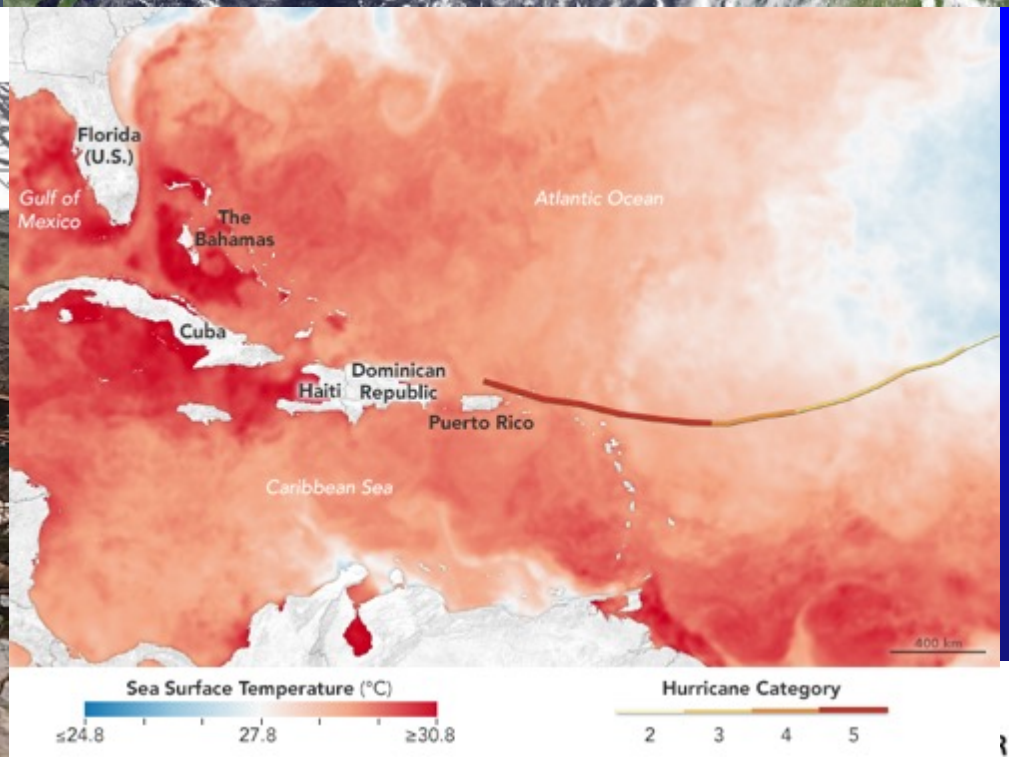




# Irma 7-10 Sept 2017



 **richardbranson**   
Necker Island [Follow](#) 



# Irma 7 Sept 2017 102+ deaths

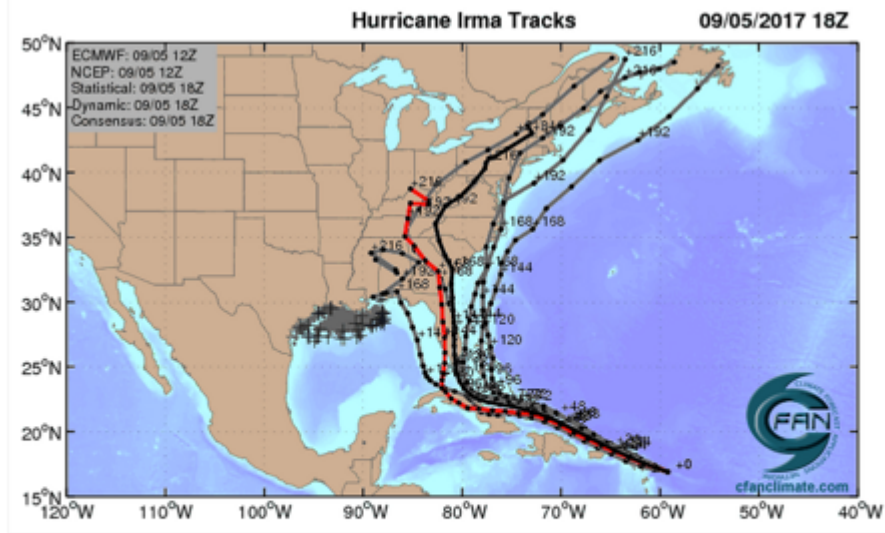


Figure 7. The 12Z September 5, 2017, track forecast by the operational European model for Irma (red line, adjusted by CFAN using a proprietary technique that accounts for storm movement since 12Z), along with the track of the average of the 50 members of the European model ensemble (heavy black line), and the track forecasts from the "high probability cluster" (grey lines)—the four European model ensemble members that have performed best with Irma thus far. Image credit: CFAN.



# Puerto Rico: Maria 18-20 Sept 2017





## Before and After Maria:

Rio Grande  
de Manati  
in Jaguas  
Ventana,  
Puerto Rico

## Puerto Rico: Maria 18-20 Sept 2017

### 1 week later:

- 34 dead\*
- 11,437 in shelters (was 12,500)
- 80% loss of agriculture (bananas), coffee etc
- 11 out of 69 hospitals with power or fuel
- 44% without water
- 2,400 miles of transmission wires wiped out
- 91% of cell towers out
- 1 dam about to fail: 11 billion gallons of water



Where are the feds? No mobilization.

Where is solar power?

No resilience.

\* Official total is 62 but NYT estimates 1,052

# Puerto Rico: Maria 18-20 Sept 2017

**Trump:**

"We're doing a tremendous job in Puerto Rico, getting great ratings". "This is an island, surrounded by water. Big water. Ocean water,"



**Bernie Sanders** ✓  
@SenSanders

 Follow

What world does Trump live in where it's acceptable to attack the mayor of San Juan while he plays golf with his billionaire friends? [twitter.com/realDonaldTrump...](https://twitter.com/realDonaldTrump...)

8:40 AM - Oct 1, 2017

 3,207  33,034  97,152



# Climate Change

- Climate change is happening
- It is caused by human activities
- It already costs tens of billions \$\$\$ per year in damages

We can:

- **Mitigate** it: (stop or reduce emissions)
- **Adapt** to it: (plan for the consequences, build resiliency)
- **Do nothing**: suffer the consequences

- Stop building in flood plains, stop unbridled growth
- Adhere to strict building codes: "Harden" infrastructure
- Manage drainage systems and water
- Plan evacuation routes
- Plan for emergency shelters and power
- Utilize flood insurance

**Are hurricanes changing with  
global warming?**





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