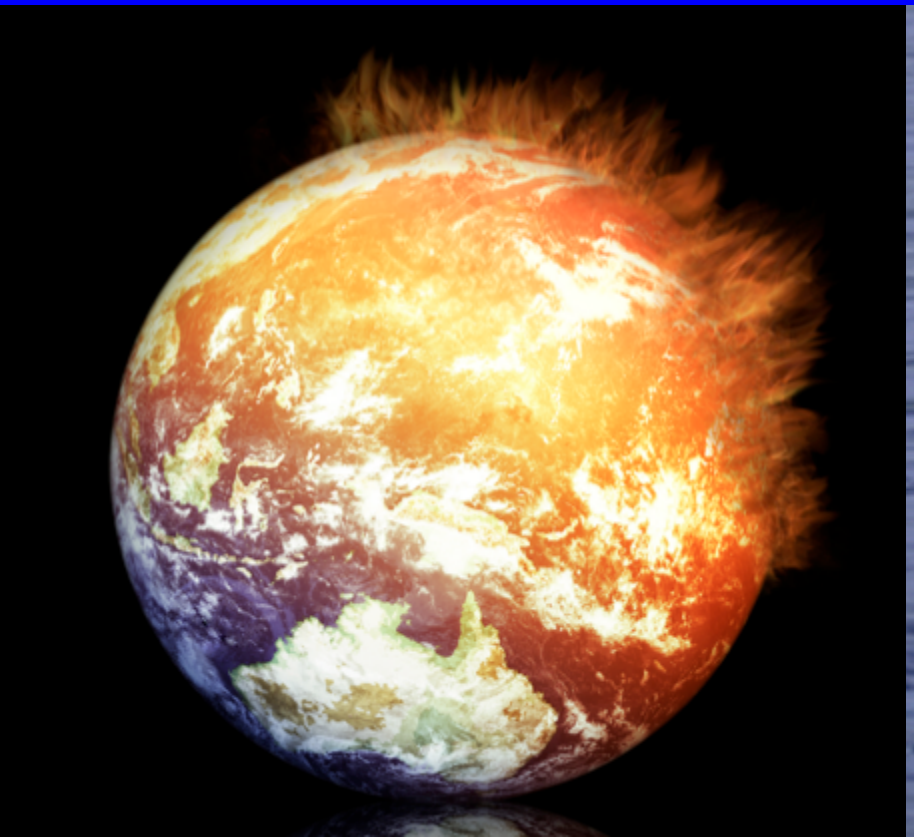
Changes in Extremes with Climate Change

Kevin E Trenberth
NCAR



Climate change is happening:
It is due to humans

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

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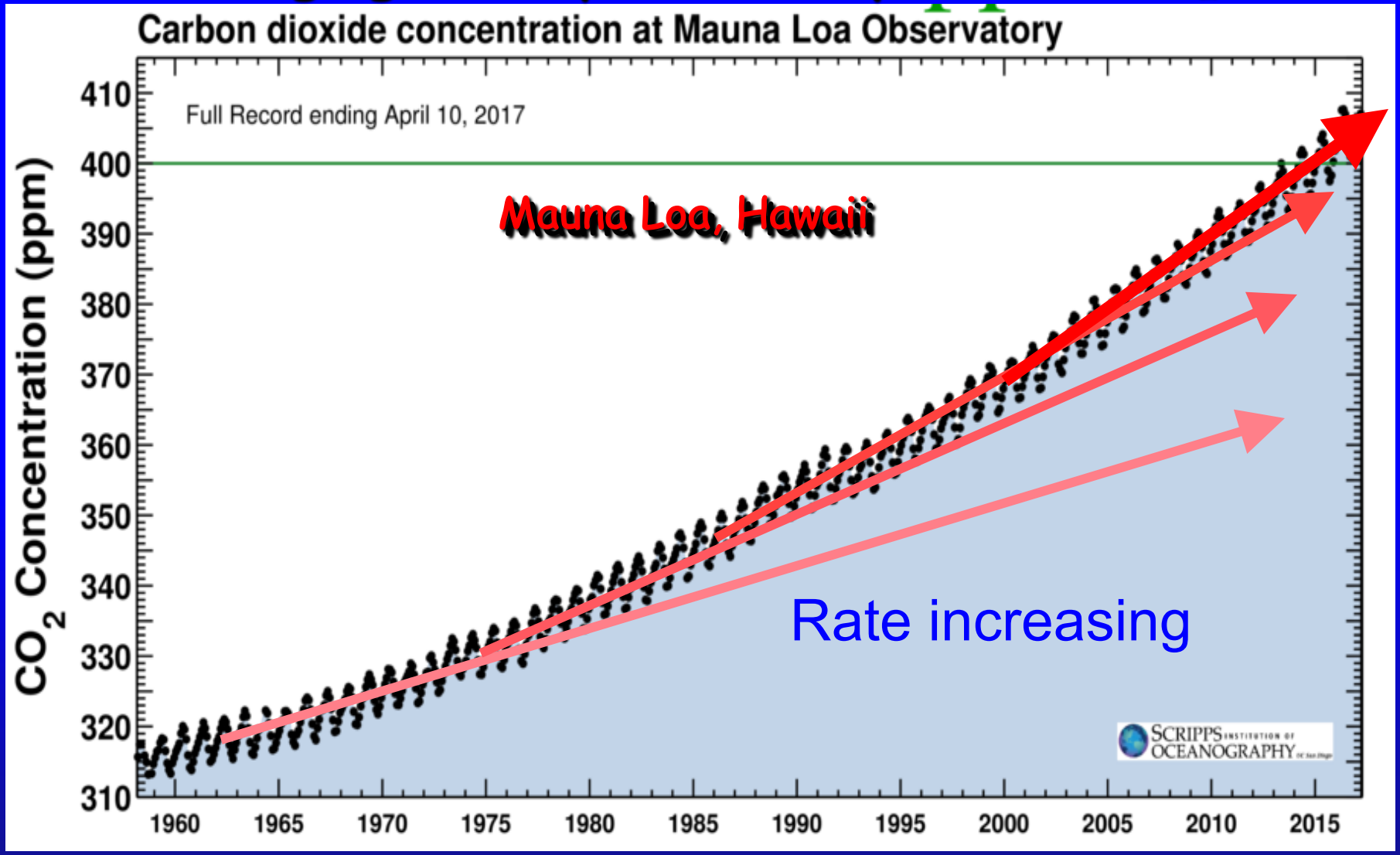
Changing atmospheric composition: CO_2



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

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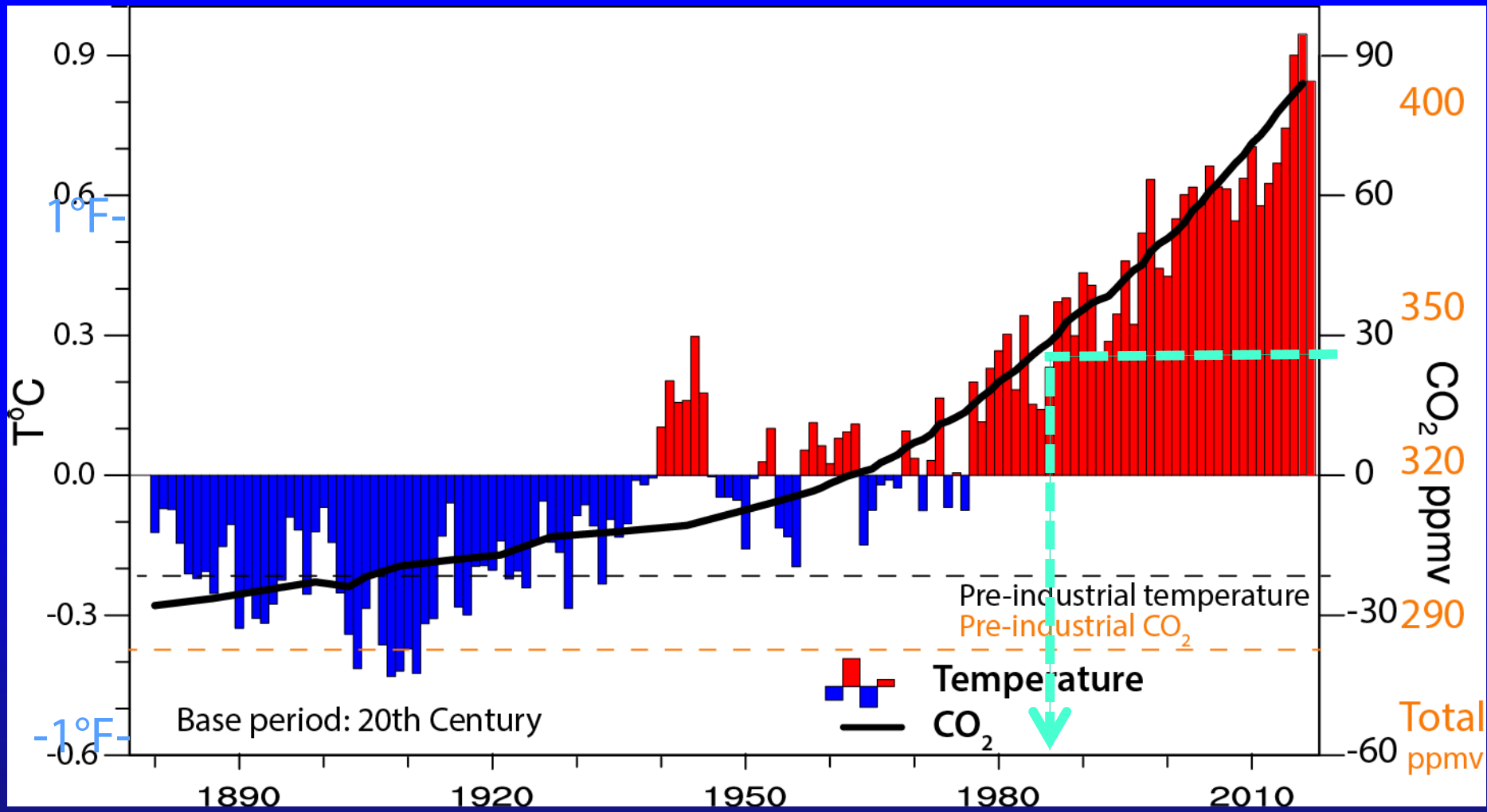
Global temperature and carbon dioxide: anomalies through 2017



Base period 1900-99; data from NOAA

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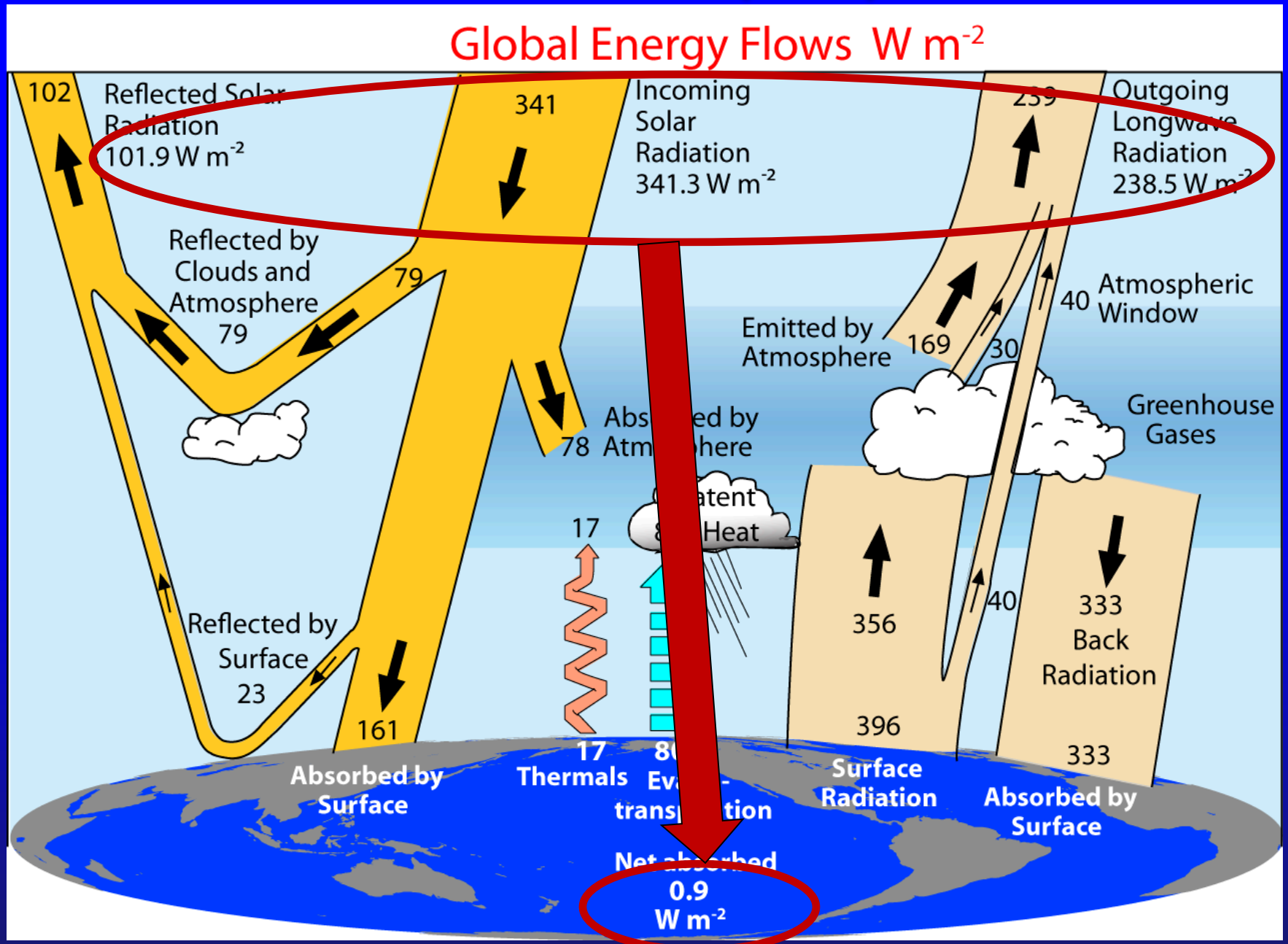
Energy on Earth

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
(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.

This is over 5.1×10^{14} m^2 (area of Earth).

Hence the heating is about 0.5 PW (=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

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.

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 ⇒ rain storms, cloud
   ⇒ possibly reflection of sun's rays to space

>90%

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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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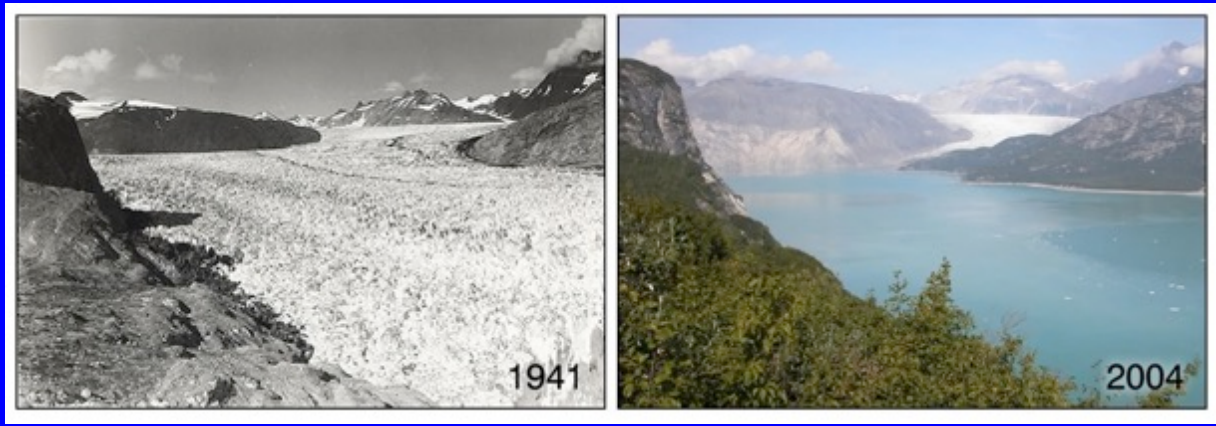
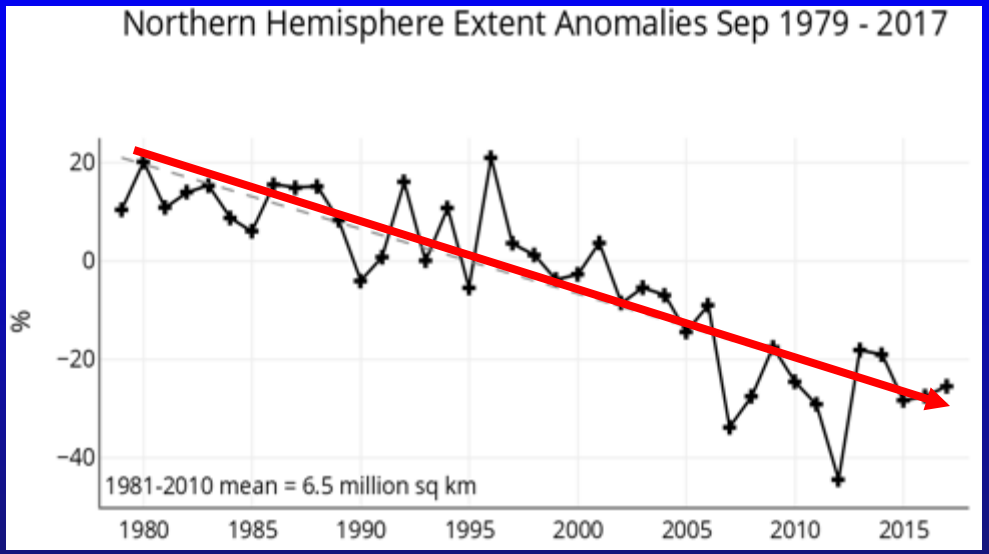
Effects accumulate in melted ice

Increased Glacier retreat since the early 1990s



Muir Glacier, Alaska

Arctic sea ice loss: over 40% in summer



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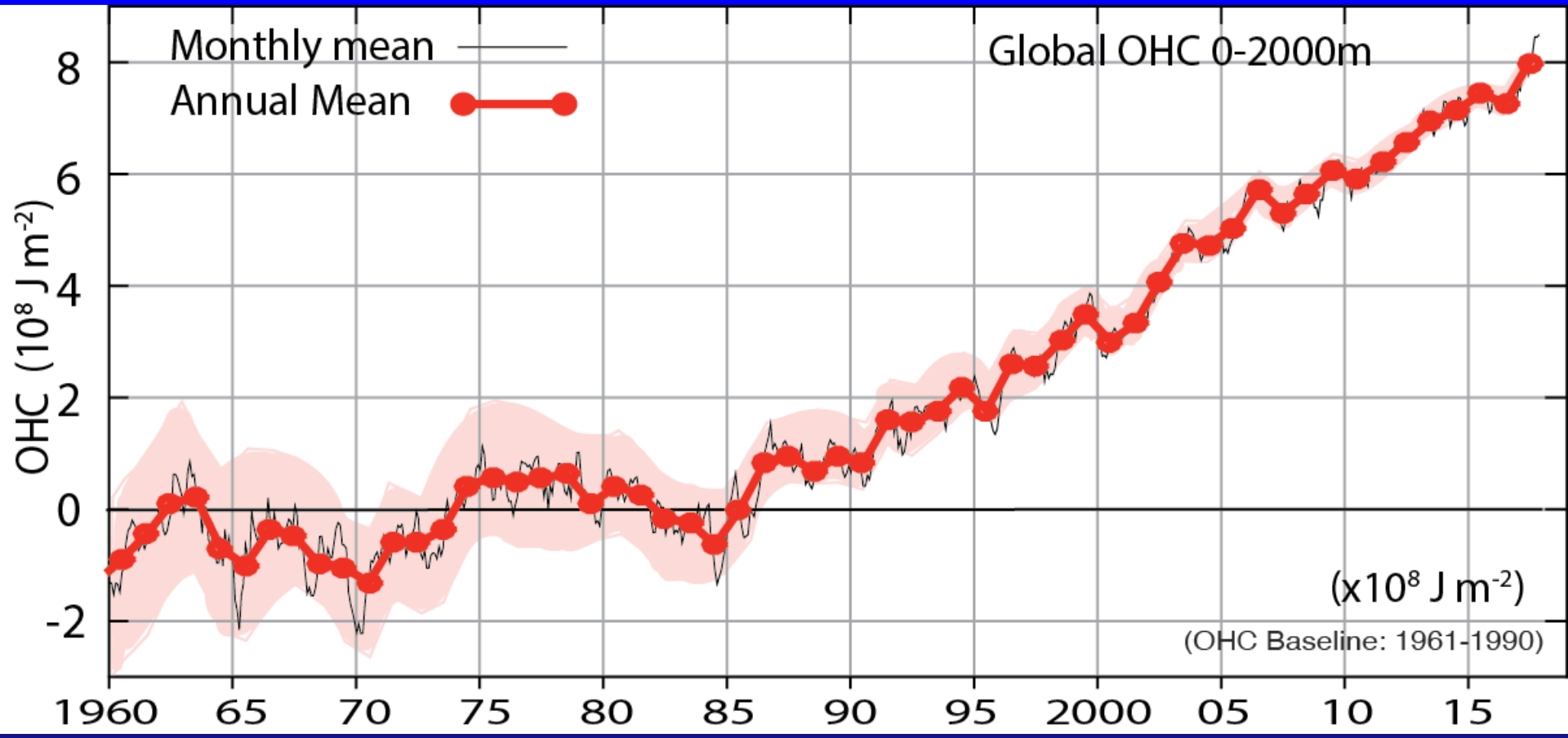
Ocean Heat Content

Updated from Cheng et al 2017





Through 2017

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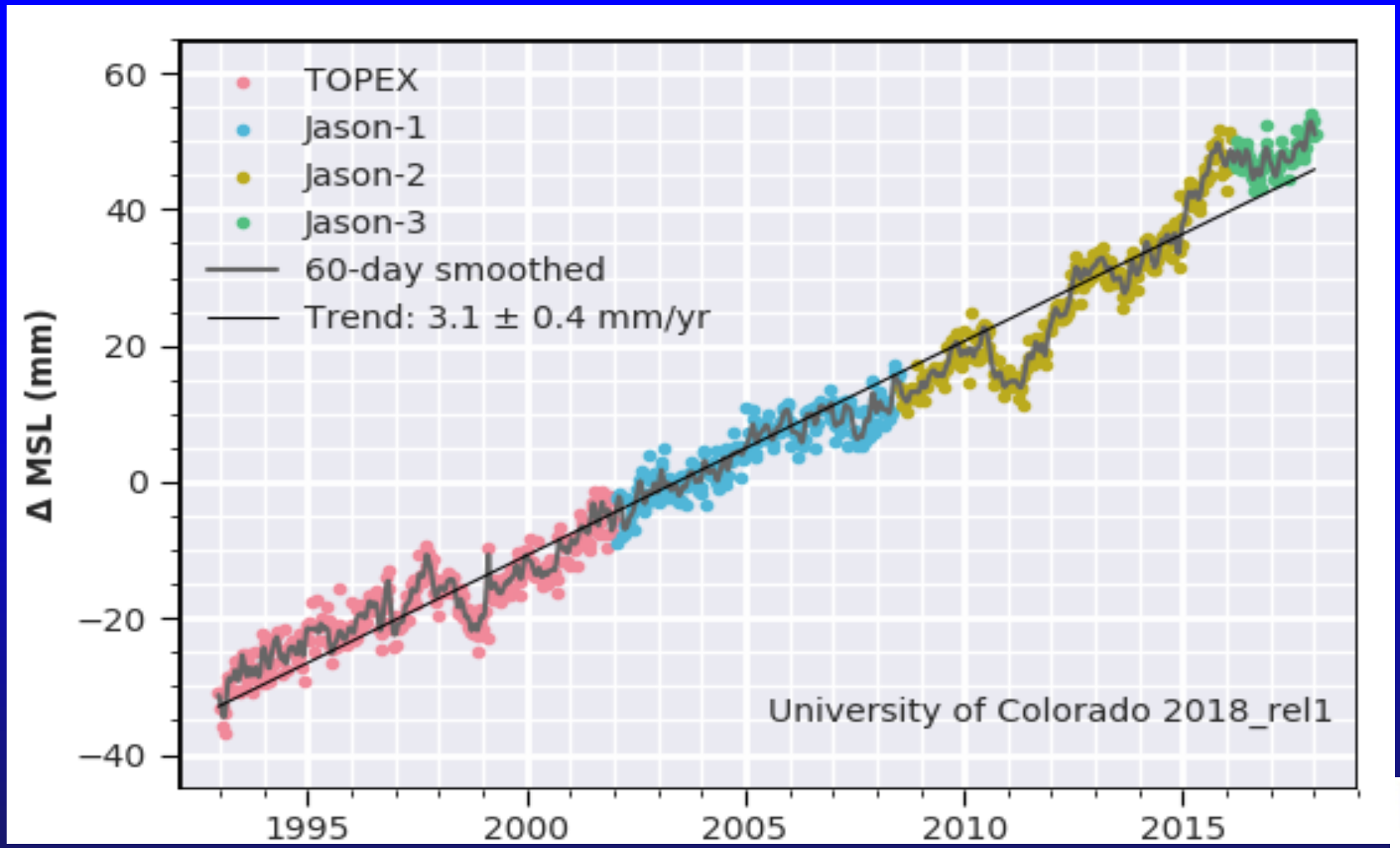
A consequence of glacier melt and ocean heating: Sea Level Rise



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What about land?

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

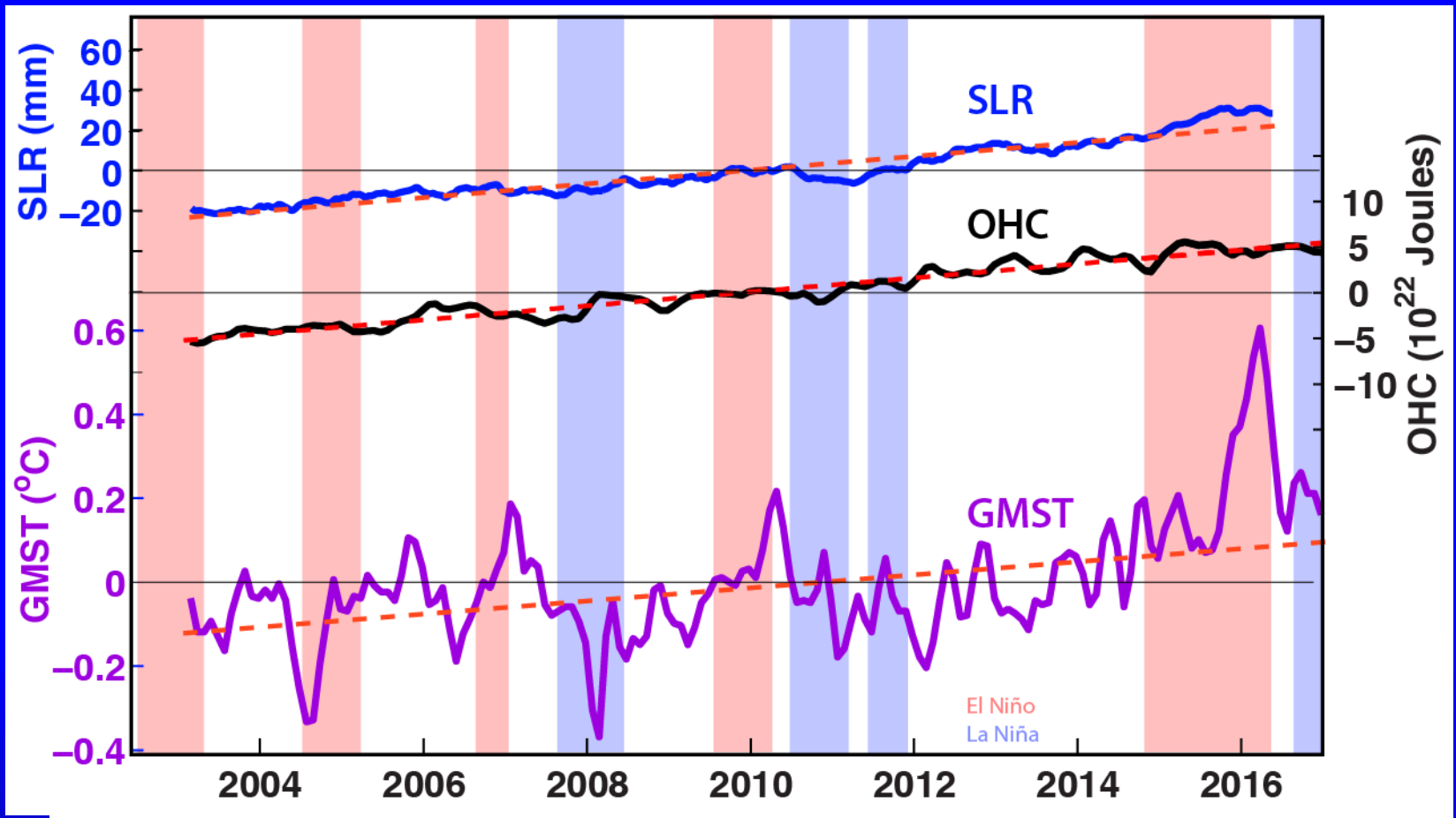
- Drying
- Heating

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!



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 σ	S/N (yr^{-1})	Time
GMST	0.016±0.005 °C/yr	0.110 °C	0.14	27 yr
OHC	0.79±0.03×10^{22} J/yr	0.77×10^{22} J	1.03	3.9 yr
SL	3.38±0.10 mm/yr	3.90 mm	0.87	4.6 yr

Cheng et al. 2018,

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- Is it global warming?
- Is it natural variability?

These are **not** the right questions: do not have answers.

Instead it is always a combination of both.

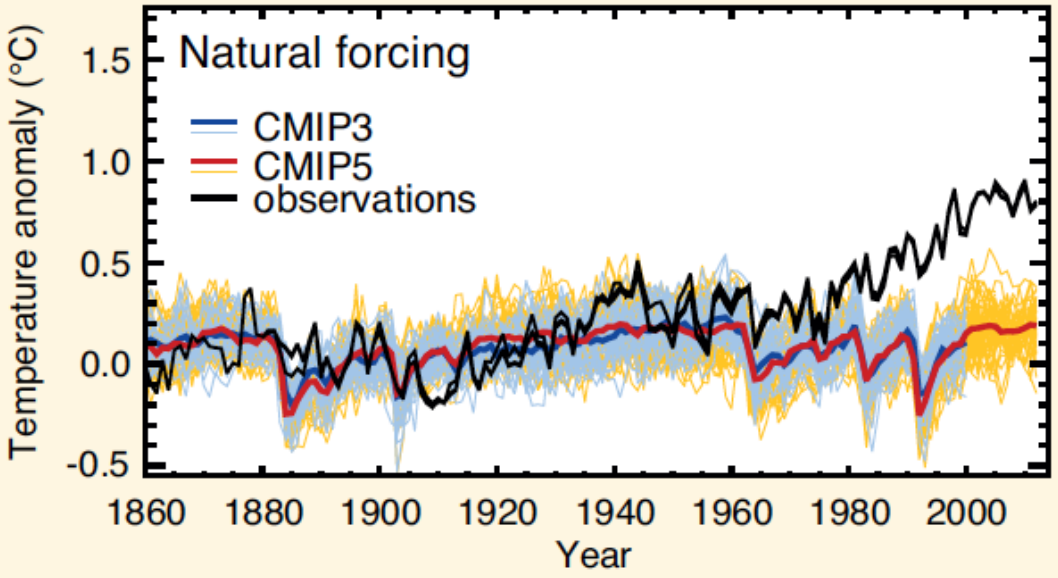
Attribution of climate change

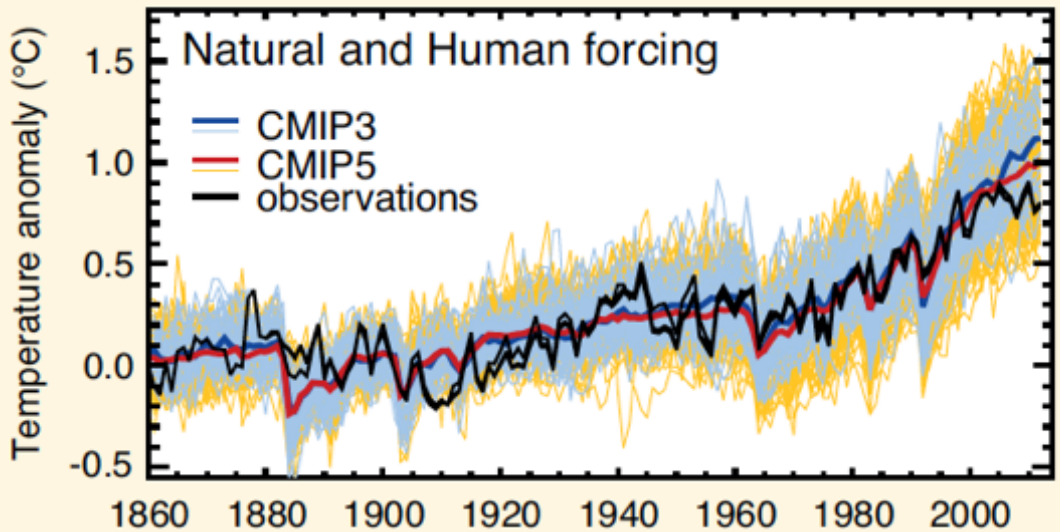
With climate models, scientists can play "God".

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

Global surface temperature

IPCC 2013





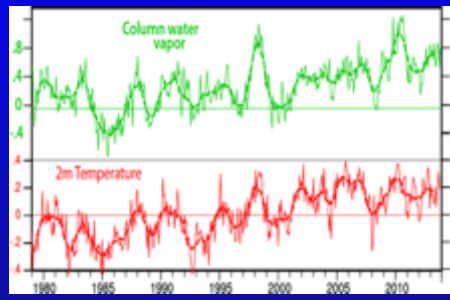
Dynamics vs thermodynamics

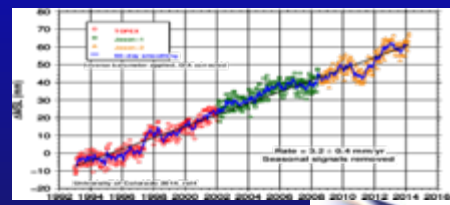
Phenomena:
Movement
Development
Chaotic (unpredictable)
Unique

Environment:
Temperature
Water vapor
Sea level
Robust (predictable)

The environment for all storms has changed:

- Warmer by >1°F,
- Moister by 5-10%
- Ocean Heat Content is much higher
- Sea level is higher by 19 cm





Supported by the huge memory and thermal inertia of the oceans:
Ocean Heat Content

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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

Take a parcel of air:

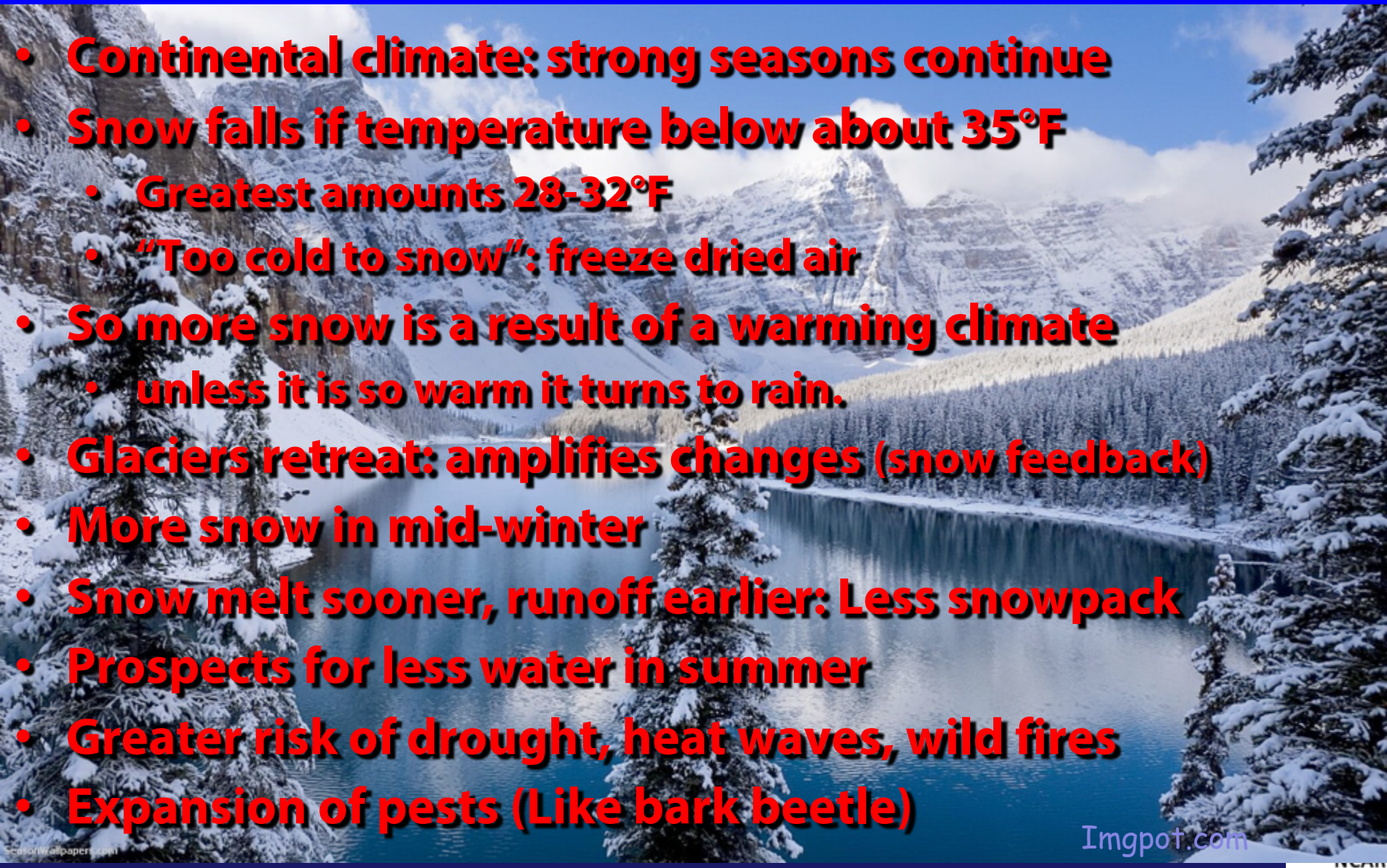
When it rises
(for whatever reason),
it expands and cools,
and any moisture in it condenses
and forms a cloud,
and then it rains the moisture out.

Most precipitation comes from moisture convergence by weather systems

Low level winds bring in moisture from afar

More moisture means heavier rains

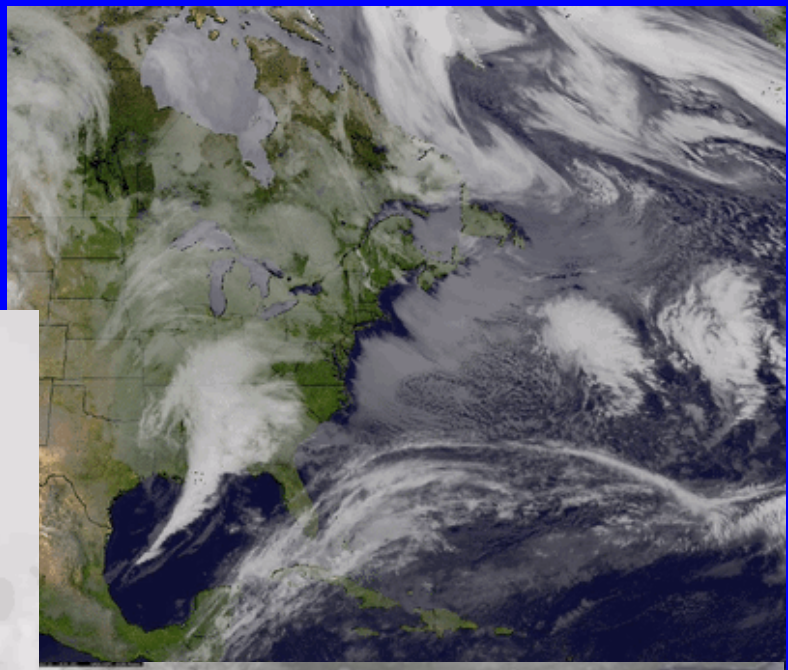
Mountains and climate change



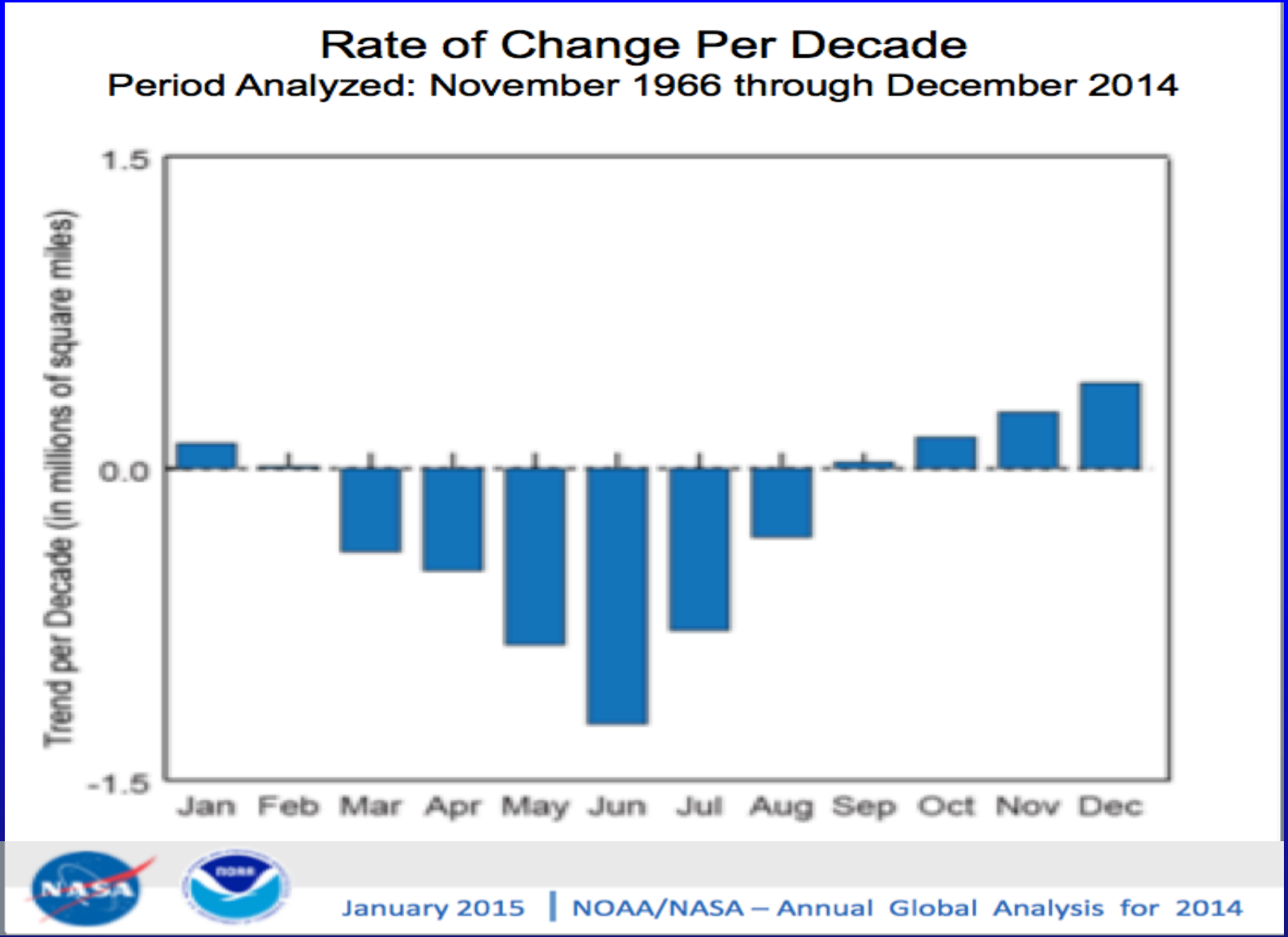
- Continental climate: strong seasons continue
- Snow falls if temperature below about 35°F
  - Greatest amounts 28-32°F
  - "Too cold to snow": freeze dried air
- So more snow is a result of a warming climate
  - unless it is so warm it turns to rain.
- Glaciers retreat: amplifies changes (snow feedback)
- 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)

Jonas: East coast snow storm

Jan 22-23 2016



Northern Hemisphere snow cover extent



US 48 contiguous States

Temperature: annual

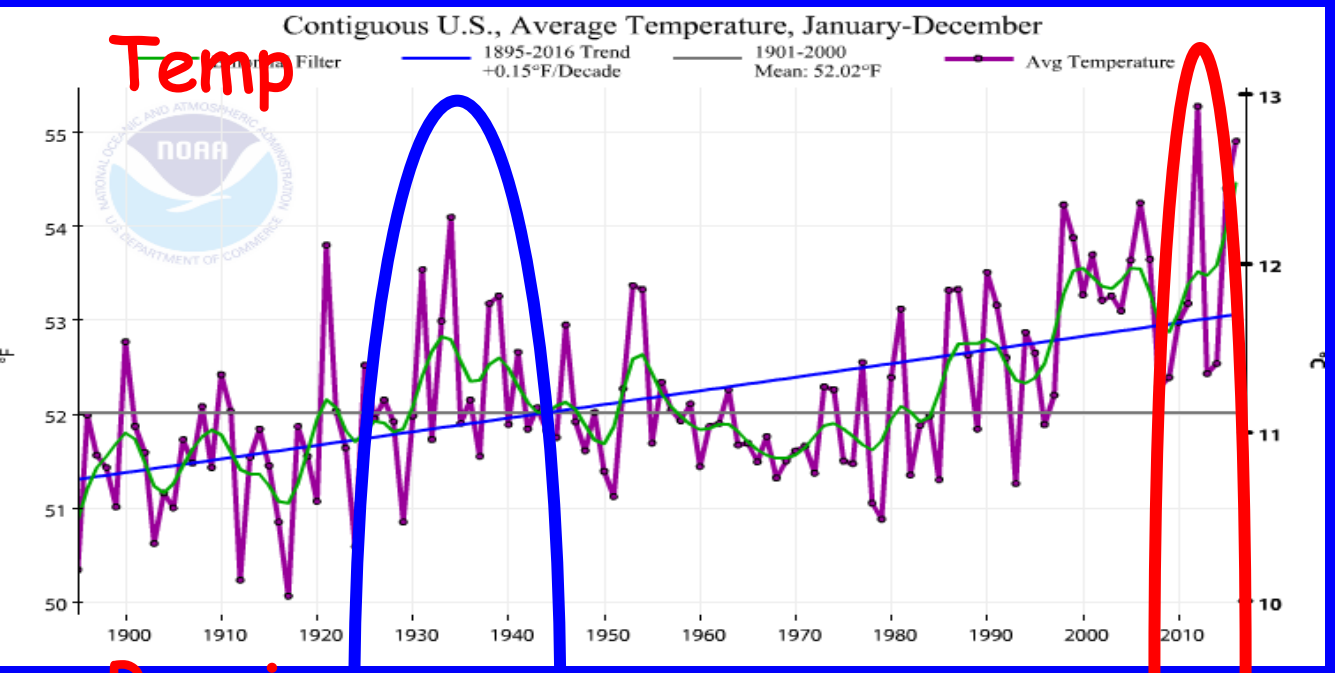
Precipitation: Annual

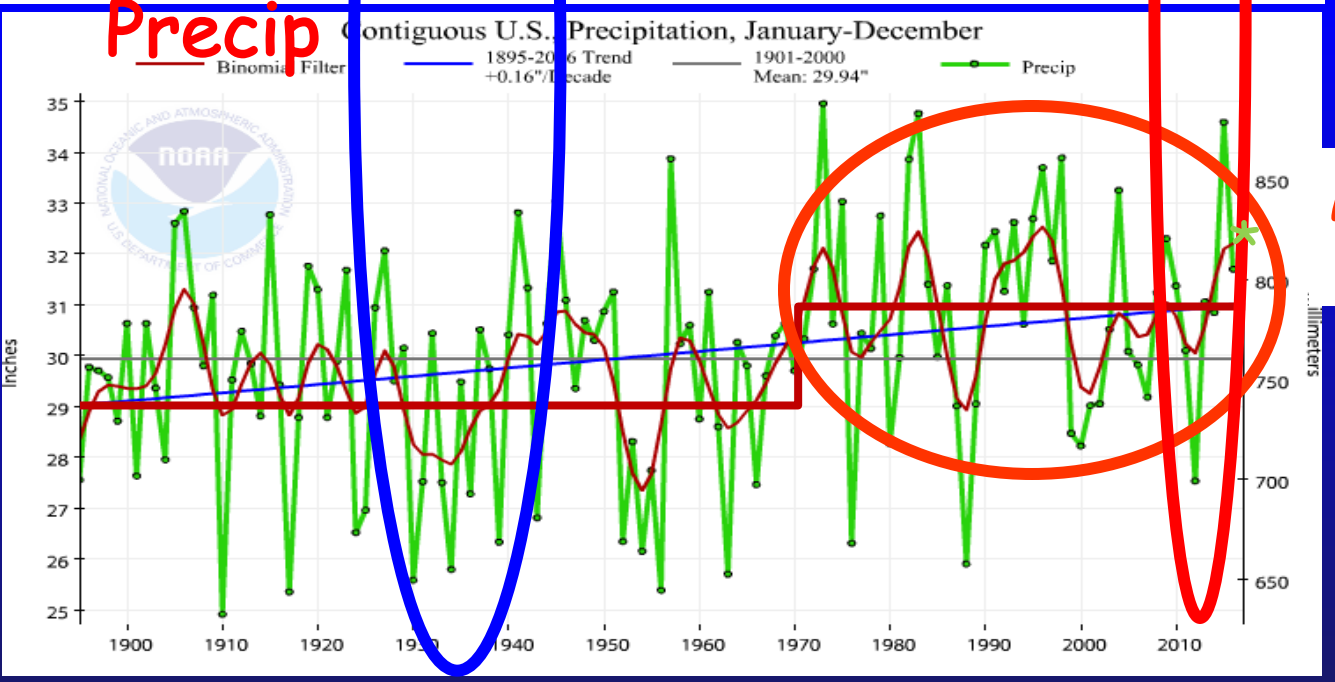
Thru 2016,

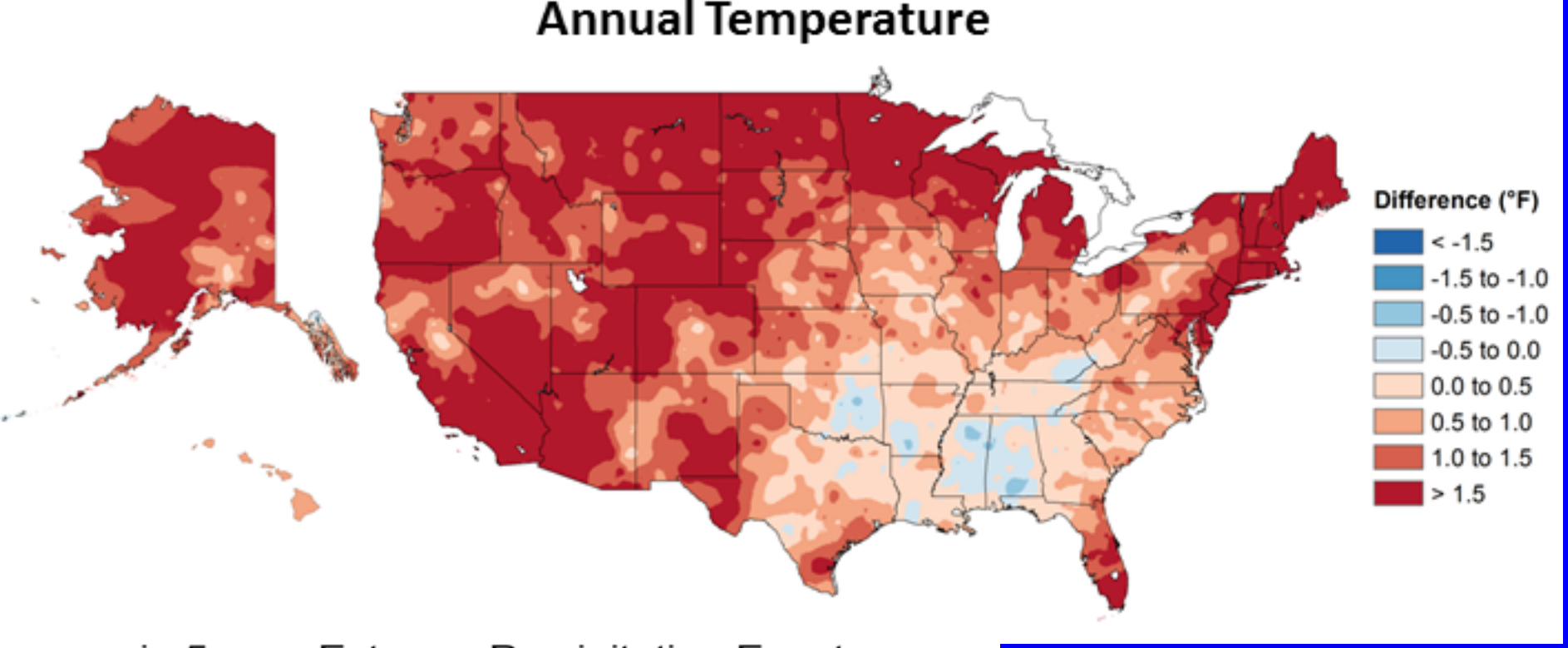
Much wetter

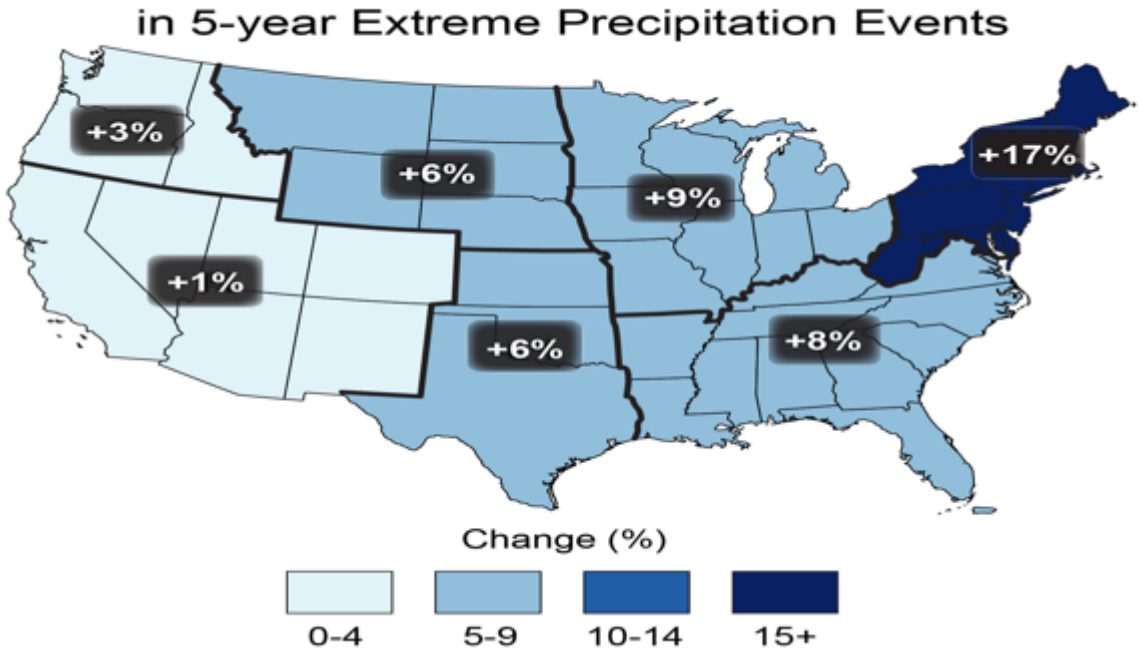
2012:
V hot and dry

1930s:
Hot and dry
"Dust Bowl"









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

% diff in top 20% of daily precipitation

National assessment
USGCRP 2017

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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

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Recent extremes in Colorado

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Colorado on Fire: June 2012

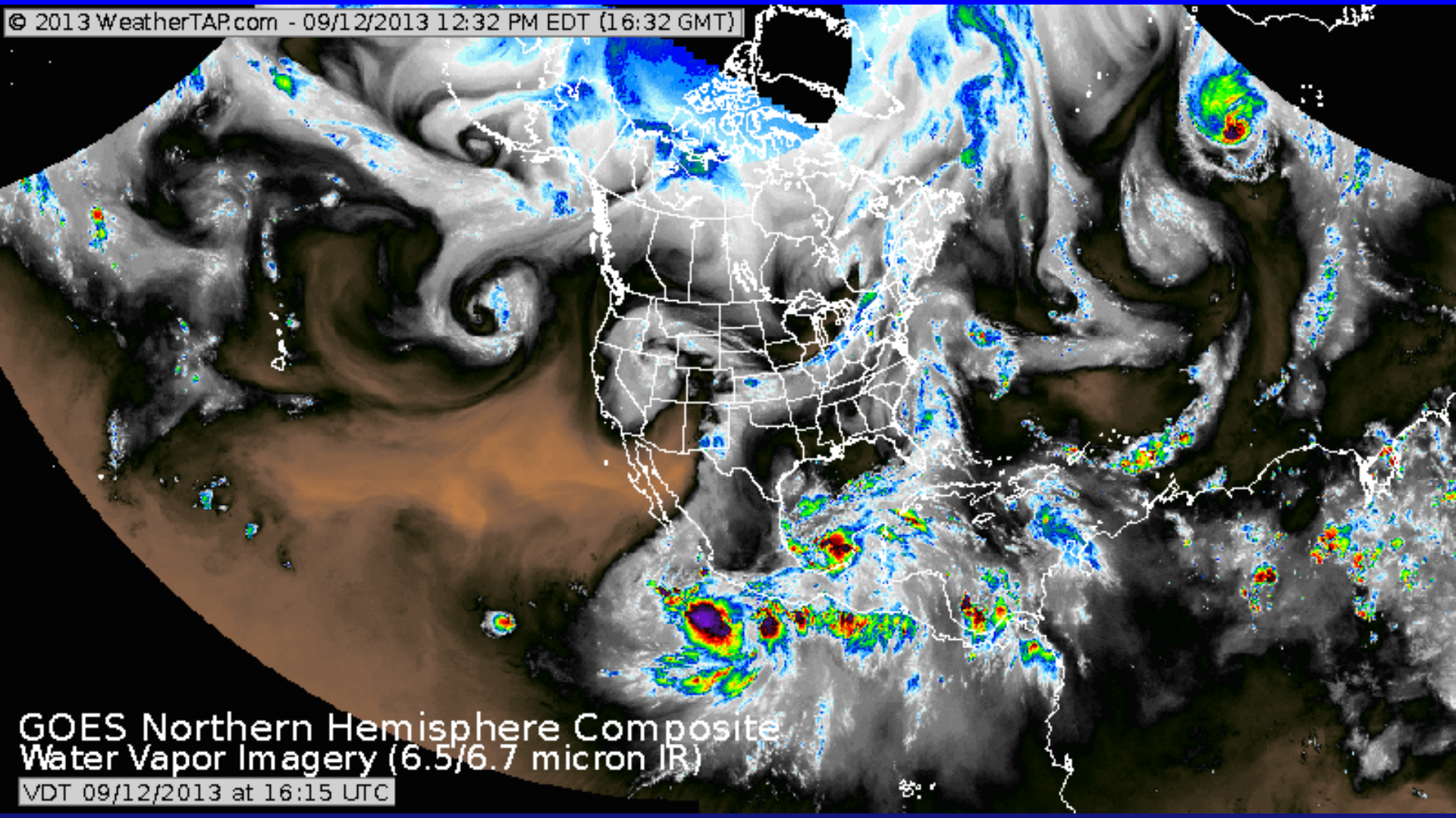
Flagstaff fire: above NCAR, circled.
High Park fire 259 houses, 1 death

Waldo Canyon fire
346 homes…

Boulder Flooding September 2013


Broadway

Composite satellite imagery



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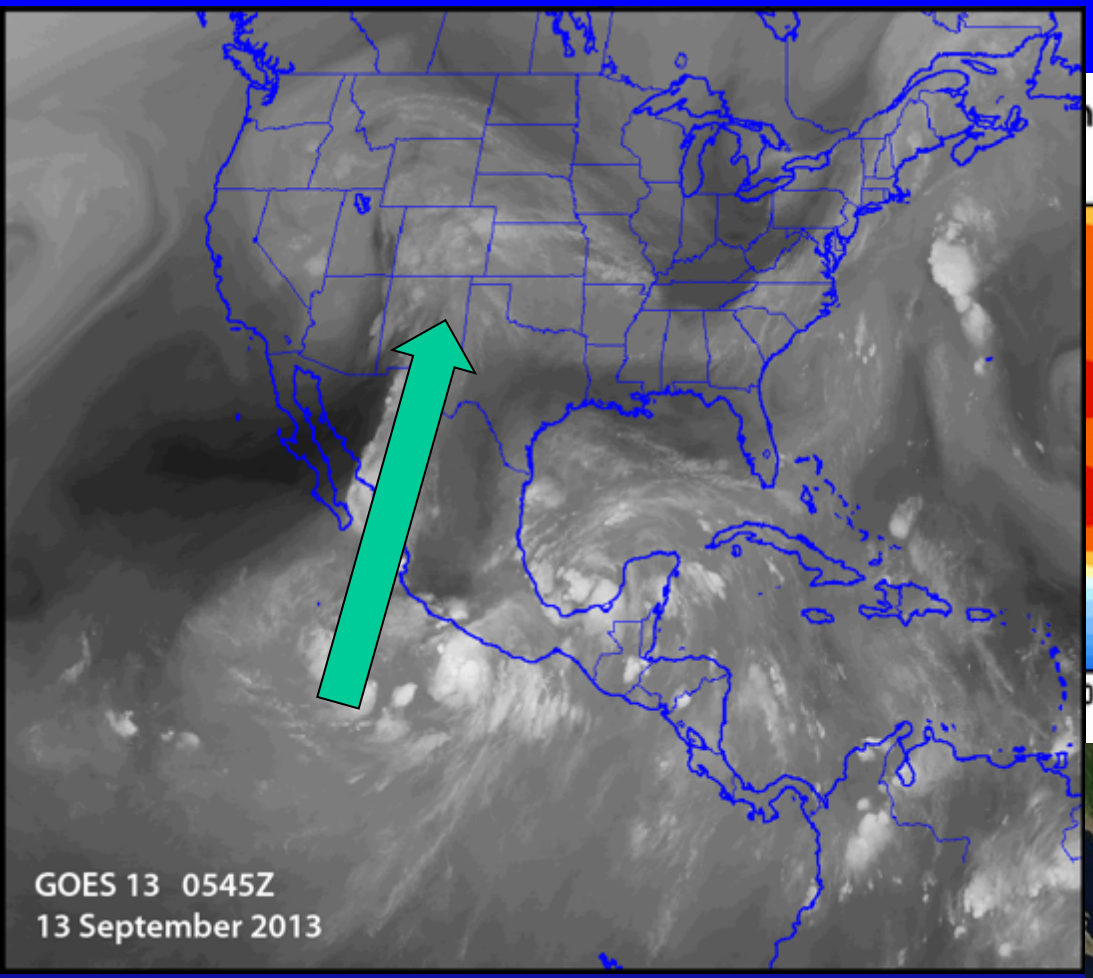
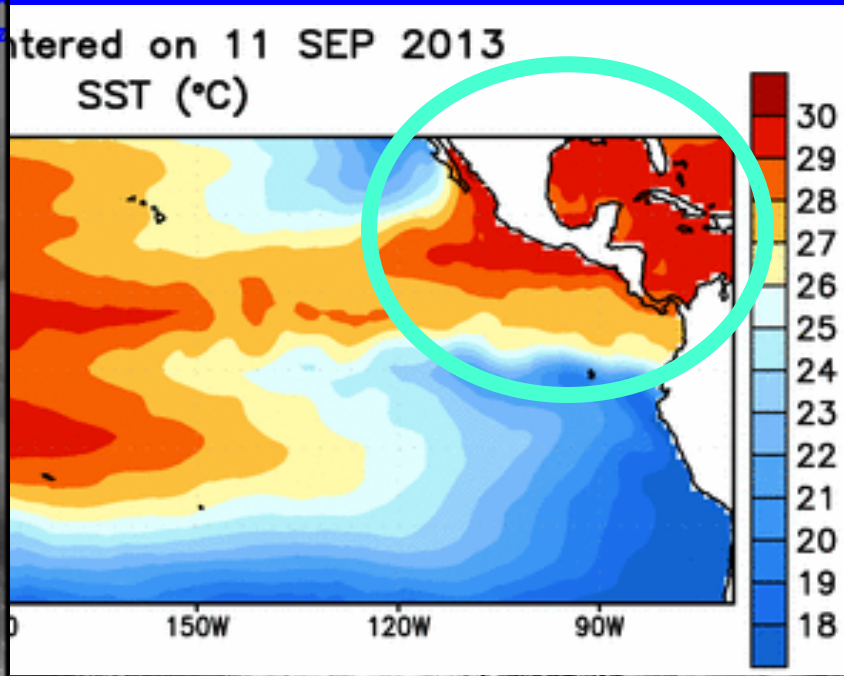
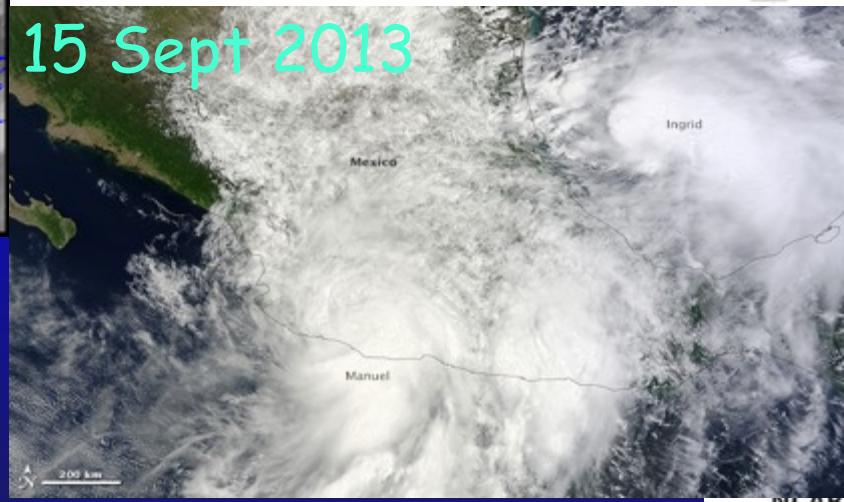
Atmospheric river into CO



6.5 micron water vapor channel NOAA/NESDIS

Very high above normal SSTs





2017

110 wild fires in West 4 Sept 2017

NASA

Canyon fire: Carona CA
Sep 25 2017
Threatens 300 homes

Devastating wild fires in California: wine country 10-15 Sept 2017

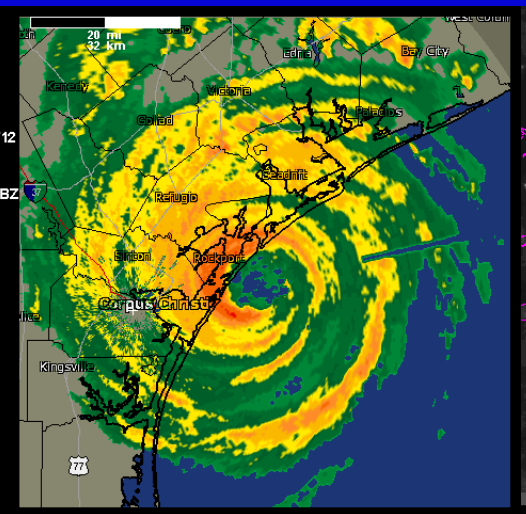
Fires Ravage Northern California's wine country have left 41 dead, 90 missing and over 6,700 homes and businesses destroyed, making this week's fires among the worst on record in the state in terms of lives and property lost.

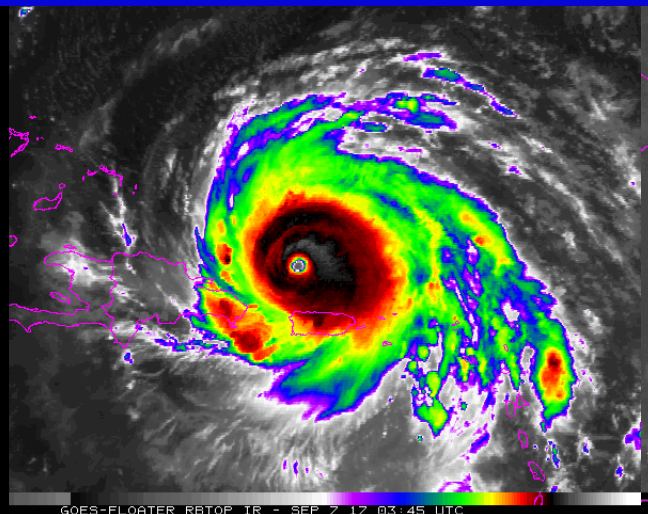
(Shades of 1964?)

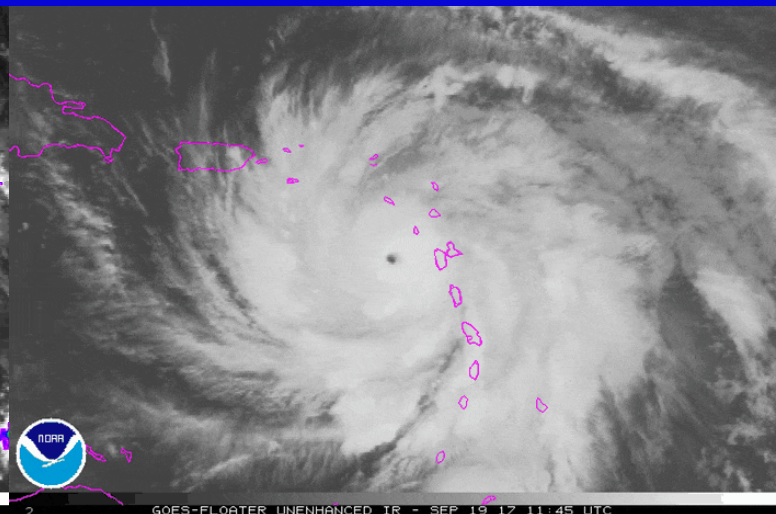
Are recent hurricane (Harvey, Irma, Maria) disasters natural?

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

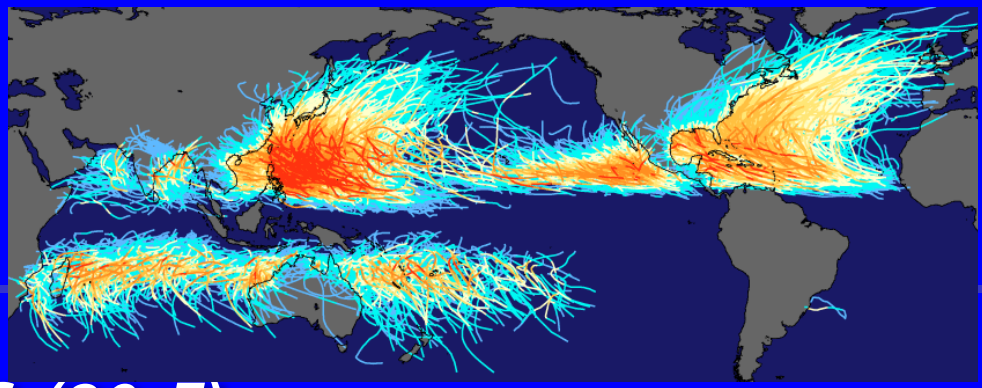
Harvey: Aug 26 Irma: Sep 7 Maria Sep 19







Hurricanes:



- *Depend on SSTs > 26°C (80°F)*
- *High water vapor content*
- *Weak wind shear (or vortex comes apart)*
- *Weak static stability*
- *Pre-existing disturbance*

With climate change:

- *More intense hurricanes*
- *Bigger hurricanes*
- *Longer-lasting hurricanes*
- *More flooding rains*

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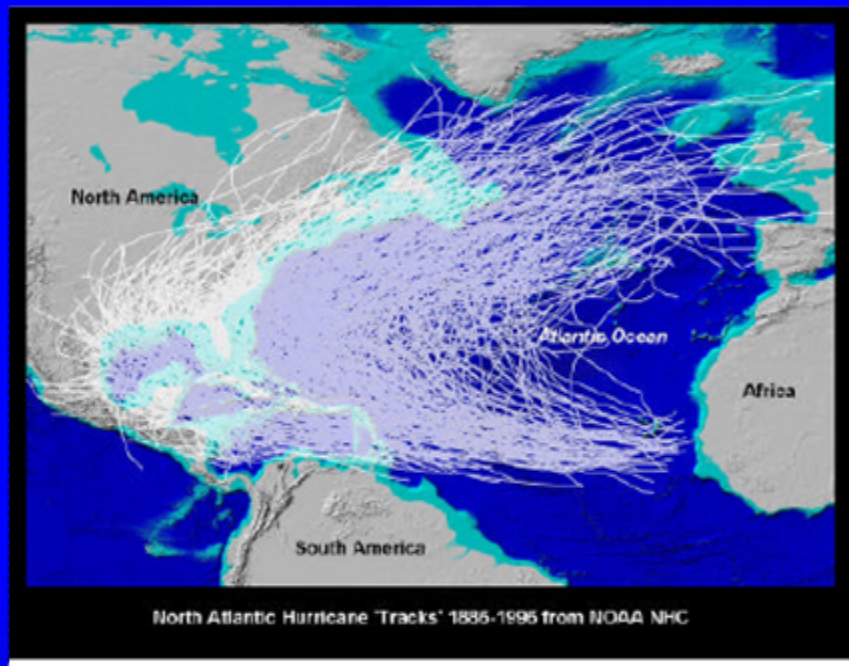
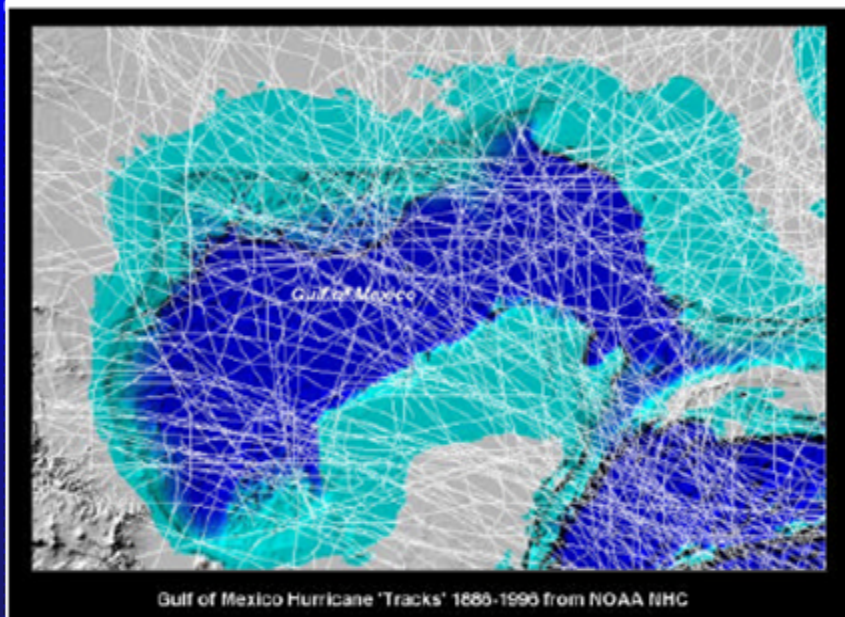
Climate change and hurricanes

- 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



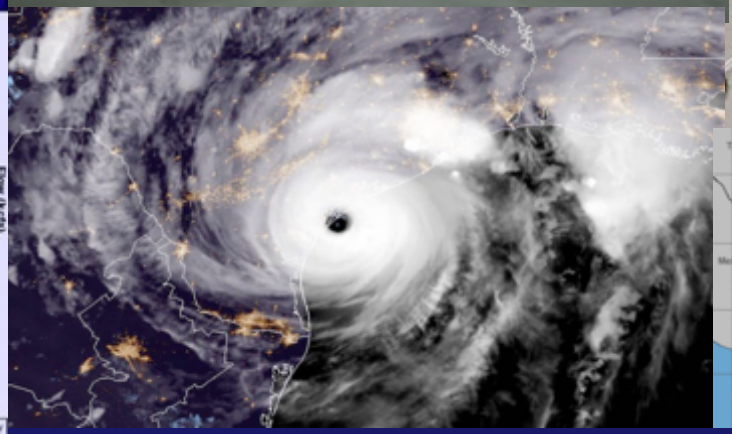
North Atlantic Hurricane 'Tracks' 1886-1996 from NOAA NHC



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

Harvey

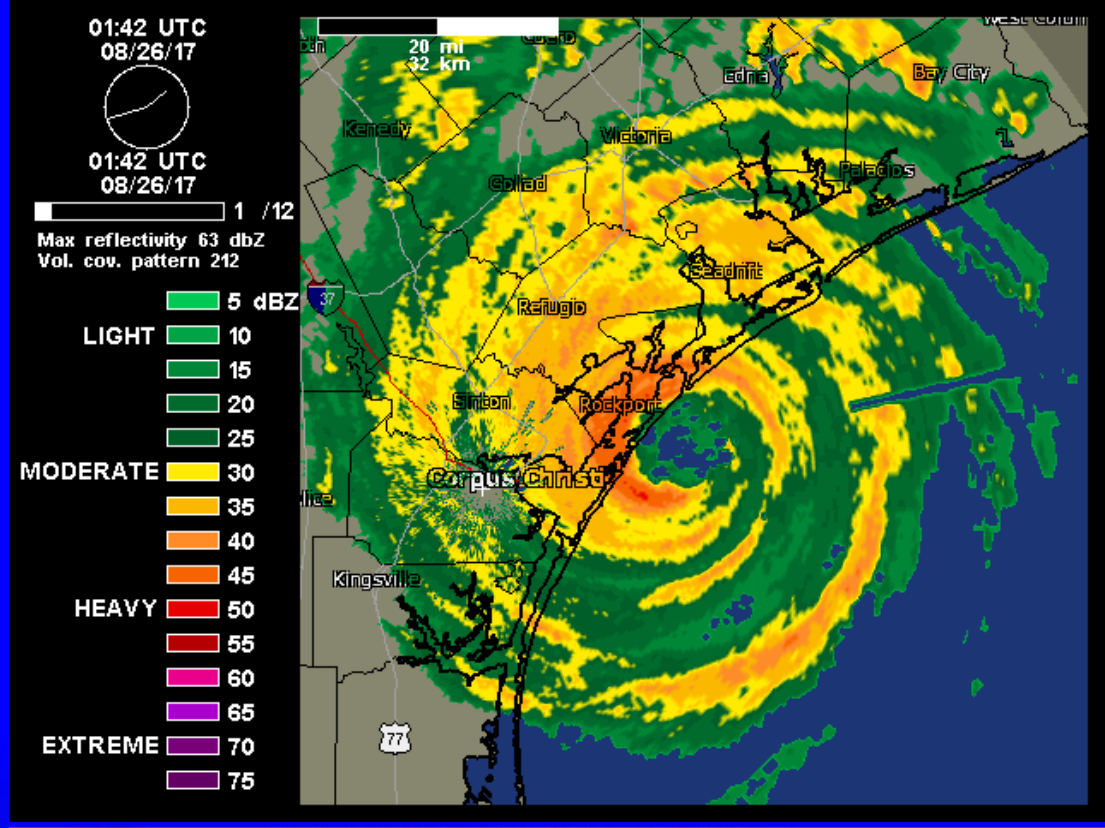

BUFFALO BAYOU AT SHEPHERD DRIVE
Universal Time (UTC)
Latest observed value: 25.14 ft at 1:30 PM CDT 30-Aug-2017. Flood Stage is 28 ft
28.78 ft
25.7 ft
Major: 32.0'
Moderate: 29.5'
Minor: 28.0'
Stage (ft)
Flow (kcfs)
Site Time (CDT)
Graph Created (2:21PM Aug 30, 2017)
Observed
Forecast (issued 2:01PM Aug 30)
Observations courtesy of US Geological Survey

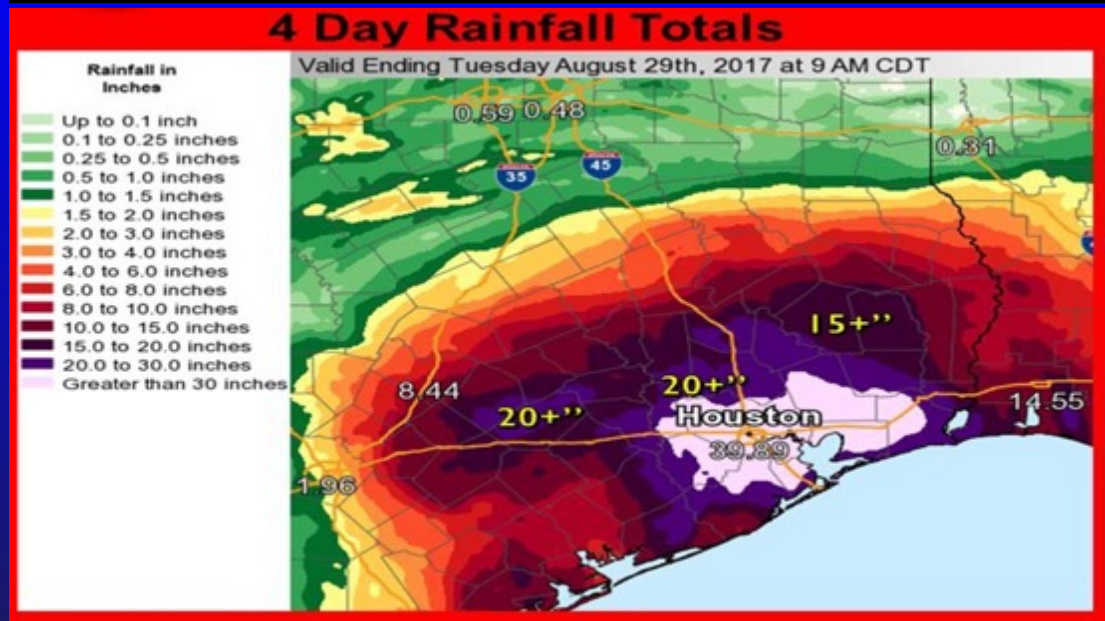


Harvey

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…





Attribution of extremes

While we can not say that these events were due to global warming (poorly posed question),

it is **highly likely** that they would not have had such extreme impacts without global warming!

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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!

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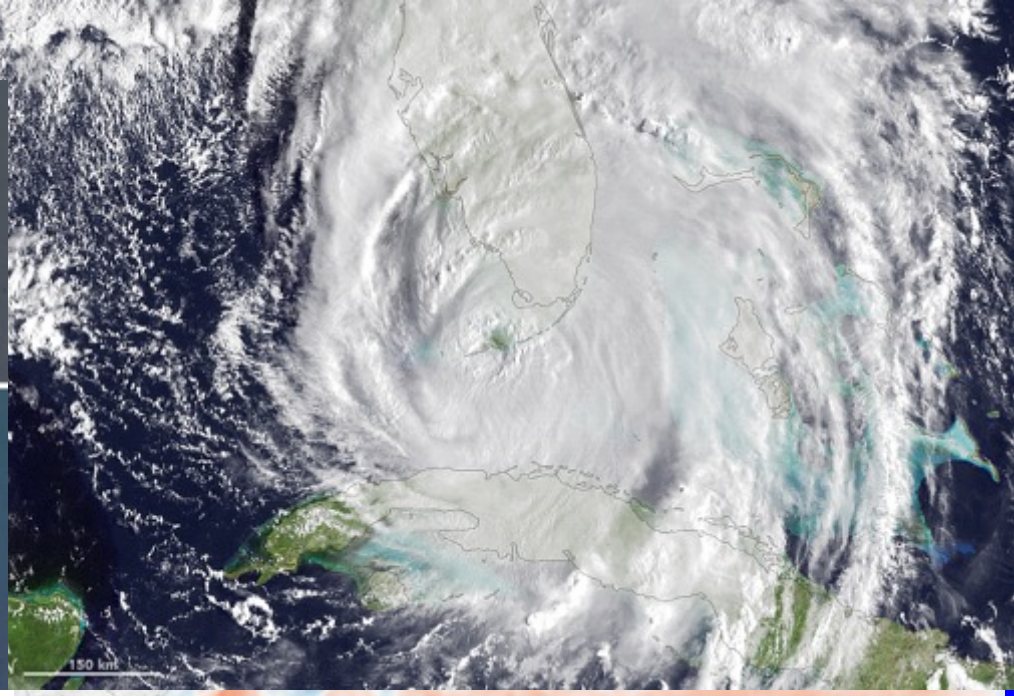
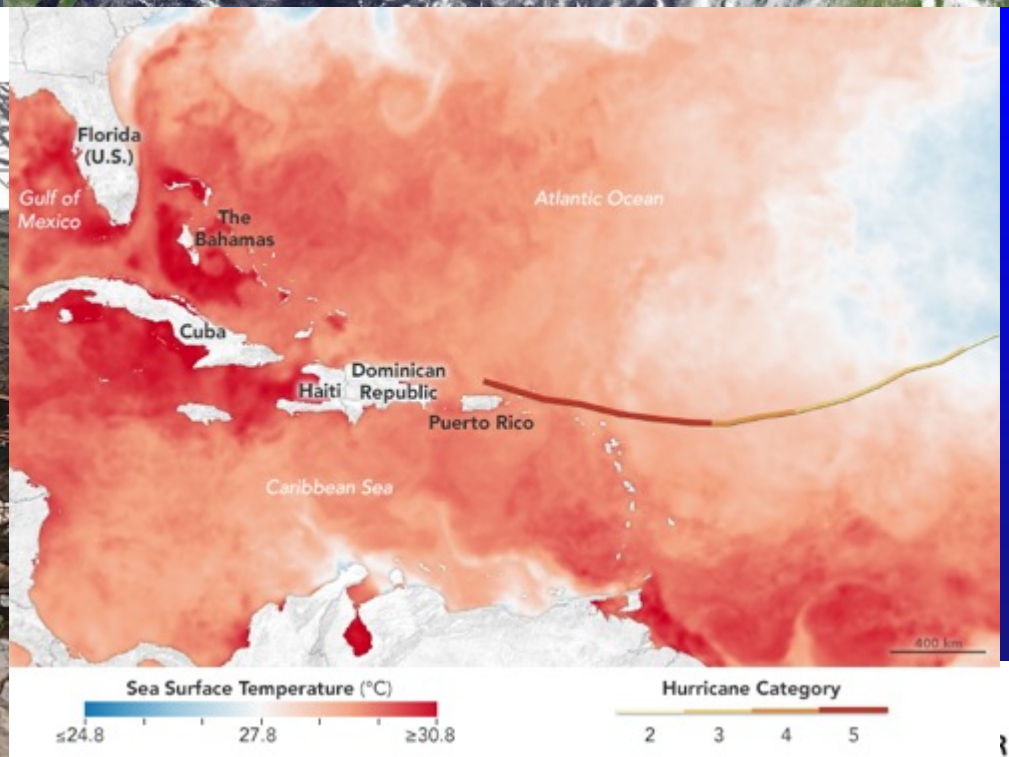
Irma 7-10 Sept 2017





Irma 7 Sept 2017
102+ deaths

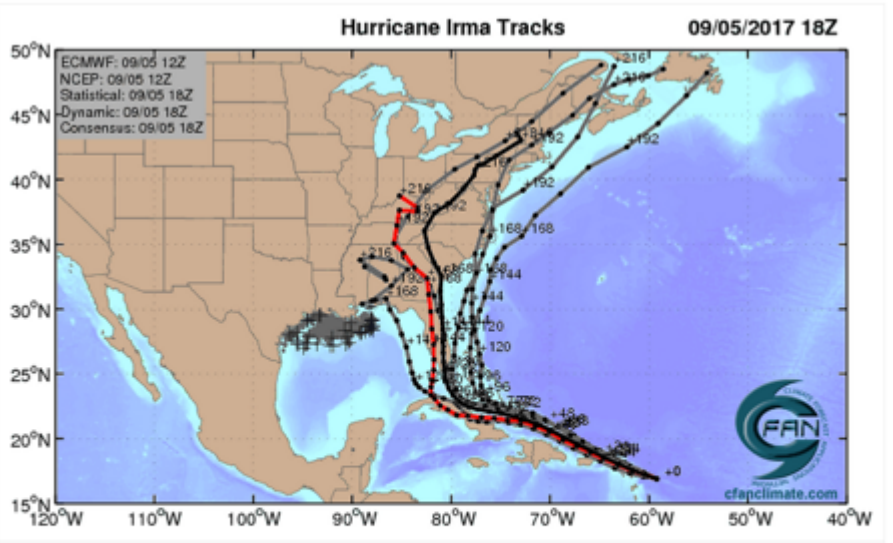
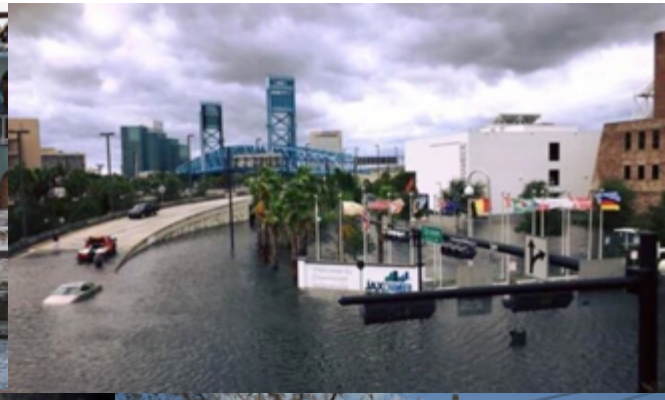


Figure 7. The 12Z September 5, 2017, track forecast by the operational European model for Irma (red line, adjusted by CFAN using a proprietary technique that accounts for storm movement since 12Z), along with the track of the average of the 50 members of the European model ensemble (heavy black line), 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

Costs of Climate Change

- Climate change is happening
- It is caused by human activities

- For many events we can estimate that the difference from climate change is 5 to 15%.
- But this means records are broken
- Thresholds are crossed
- Things break/flood/burn
    - EXTREME NON-LINEARITY

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

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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

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Contact information

Kevin Trenberth
Distinguished Senior Scientist
Email: trenbert@ucar.edu

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