



Climate Change & Increasing Severe Weather



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Vermont Emergency Preparation Program
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Outline

- **Climate change and severe weather**
 - **Global and local aspects**
 - **Oceans storing Earth's heat imbalance**
 - *Hurricanes*
 - **Quasi-stationary mid-latitude wave patterns increasing local floods/heat waves, droughts and fires**
 - **Warming & melting Arctic**
 - **Tight coupling of processes**
 - **Snow, temperature, cloud, cloud water, precip**

Discussion

Fundamentals

- ***Burning fossil fuels: transforming climate***
 - ***Many water cycle amplifying feedbacks***
 - ***Water vapor greenhouse 3x CO₂; loss of reflective ice***
 - ***Evaporation, precip and instability increase rapidly with Temp***
 - ***93% Earth's energy imbalance stored in oceans***
 - ***Decadal to centennial - long timescales***
 - ***Heading for high CO₂ "hot-house climate"***
 - ***Climate extremes increasing; circulation changing***
 - ***Severe weather costs increasing***
- **Global impact of technology/consumer society**
 - **Waste streams on climate/Earth's ecosystems**
 - **Fixable by changing system guidelines**
 - **Create efficient society, based on renewable energy**

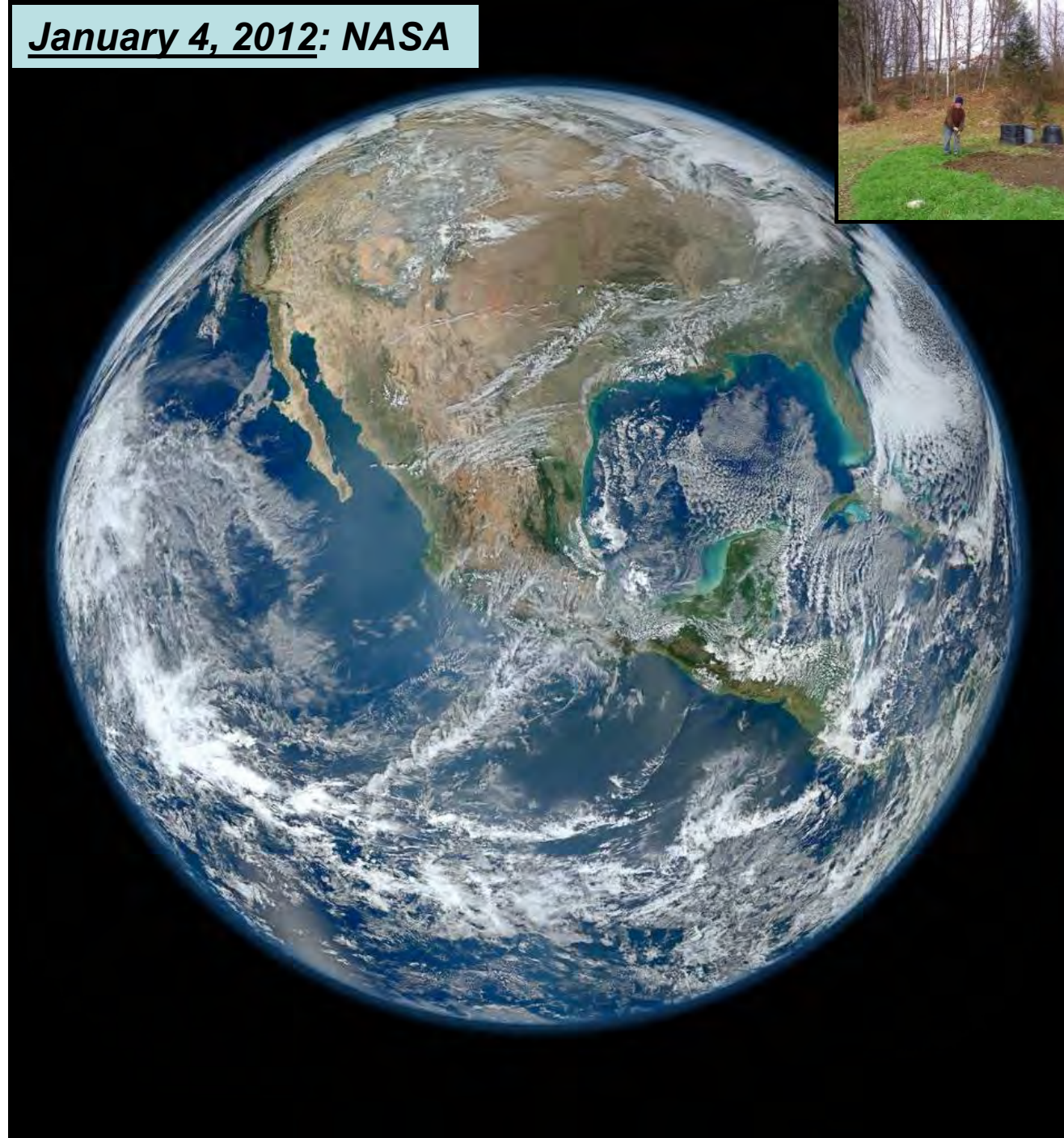
Water, Snow & Ice Give Positive Radiative Feedbacks

- As Earth warms, evaporation and water vapor increase and this is 3X amplifier on CO₂ rise
- As Earth warms, snow & ice decrease and reduced SW reflection amplifies warming in Arctic in summer and mid-latitudes in winter
- Doubling CO₂ will warm globe about 5°F (3°C)
 - Much more in the cold regions and over land, which responds faster than oceans
 - Change the global circulation

January 4, 2012: NASA

Earth's climate sustains life

- Increasing greenhouse gases reduces cooling to space
- **Climate is warming: ice is melting, extreme weather is increasing**
- Water plays crucial amplifying role



Hurricane seasons

- Earth is warming as greenhouse gases increase and reflective ice cover falls
- Oceans are storing 93% of heat
 - Warmer Atlantic, Caribbean, Gulf of Mexico and Gulf Stream means stronger hurricanes; when vertical shear is low
- *2017: Harvey, Irma, (Jose), Maria*
- *2018: Florence*
- *2019: Barry, Dorian*



Major Hurricane Harvey - August 25-29, 2017

Weather.gov > Corpus Christi, TX > Major Hurricane Harvey - August 25-29, 2017

Corpus Christi, TX
Weather Forecast Office

[Current Hazards](#) [Current Conditions](#) [Radar](#) [Forecasts](#) [Rivers and Lakes](#) [Climate and Past Weather](#) [Local Programs](#)

Category 4 Hurricane Harvey: South Texas Landfall & Impacts from August 25th to 29th, 2017

[Overview](#) [Stats](#) [Radar](#) [Satellite](#) [Winds](#) [Storm Surge](#) [Rainfall](#) [Rivers](#) [Seadrift](#) [Tornado](#) [Storm Reports](#) [Photos](#) [One Year Later](#)

[Hurricane Harvey Summary PDF](#)

...Hurricane Harvey is the first major hurricane to make landfall along the Middle TX Coast since Celia in 1970...

...Hurricane Harvey is the first Category 4 hurricane to make landfall along the TX Coast since Carla in 1961...



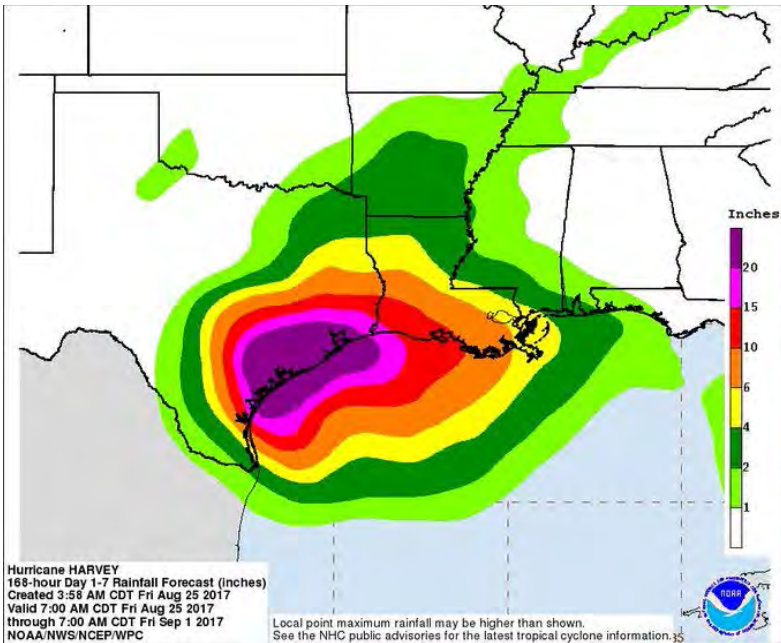
NHC Final Best Track of Harvey (Click points above to view additional information.)

Why was Harvey so Damaging?

- **Huge evaporation off warm ocean**
- **Category 4 hurricane** developed fast
- **Very heavy rain-rate: 10-12 inches per day**
- **Two stationary high pressure systems** to the north **trapped** Harvey for 4 days over Houston
- **Result 40+ inches** of rain & massive flooding



Challenged Forecast & Emergency Services



8/25/17: >20ins (6days)

– Unprecedented; hoped
FX is wrong!

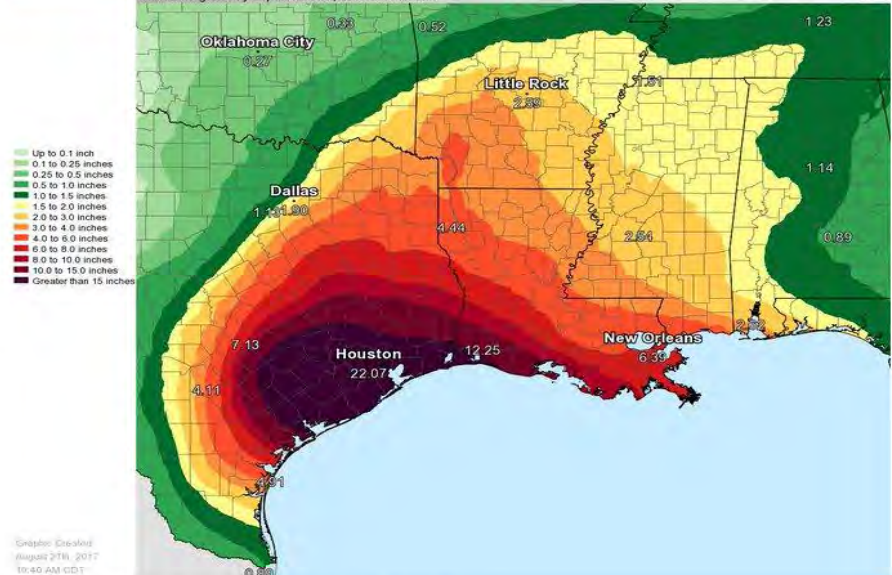


National Weather Service
@NWS

This event is unprecedented & all impacts are unknown & beyond anything experienced. Follow orders from officials to ensure safety. #Harvey

Forecast Precipitation

Valid Ending Sunday September 3rd, 2017 at 7 AM CDT

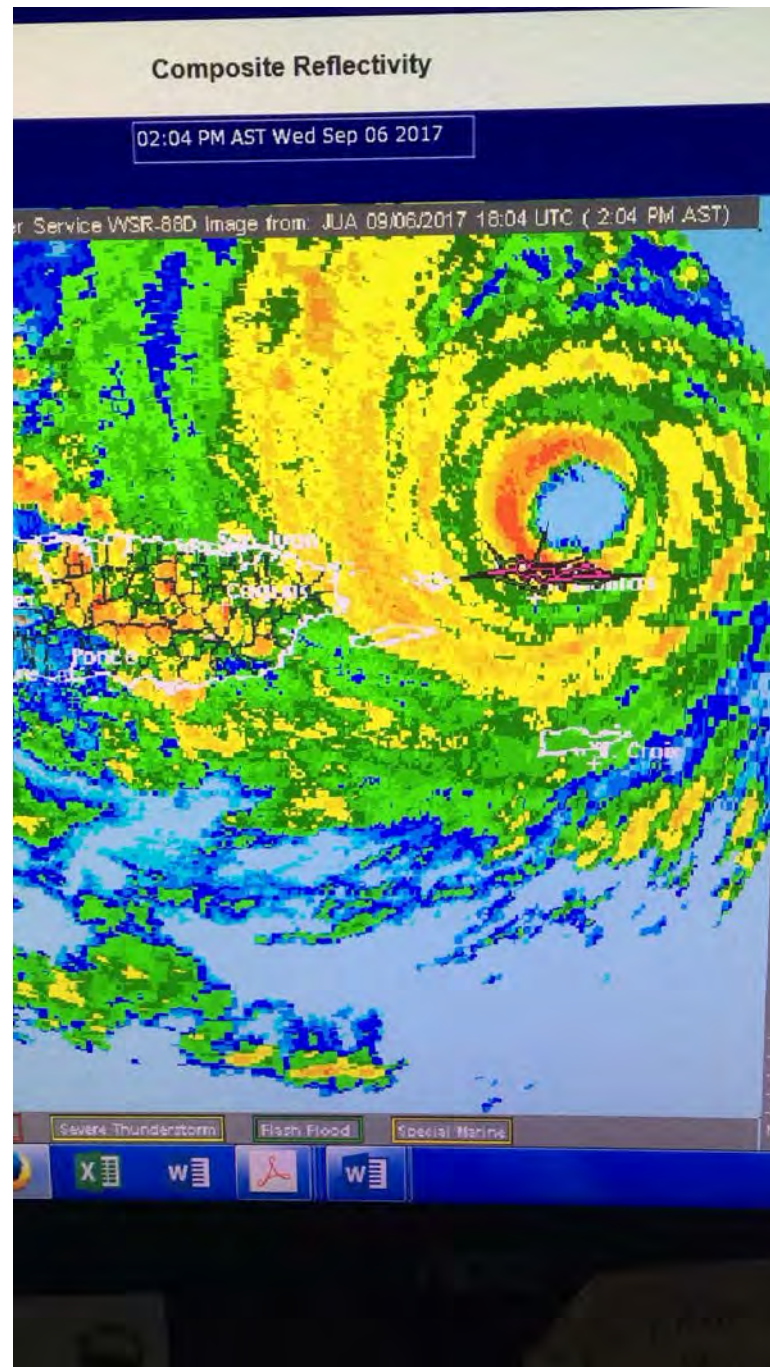


21.8K 11:44 AM - Aug 27, 2017

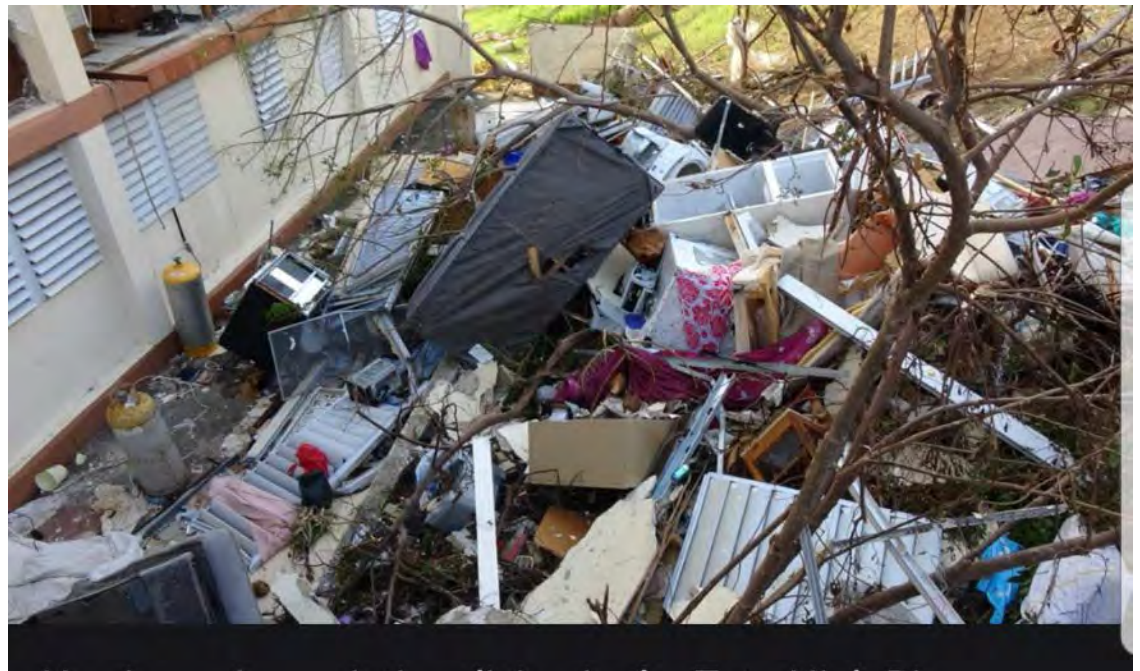
8/27/17: 36 hrs after landfall
Forecast >15 ins more

2pm Sept. 6
Category 5*
IRMA
grazing
St Thomas

***Cat 5 >155mph**
IRMA >180mph



Irma(Cat.5)
Sept. 6
St Thomas



Irma and Jose: Sept 7



After Jose passed; Catamaran to Puerto Rico on Sept 11

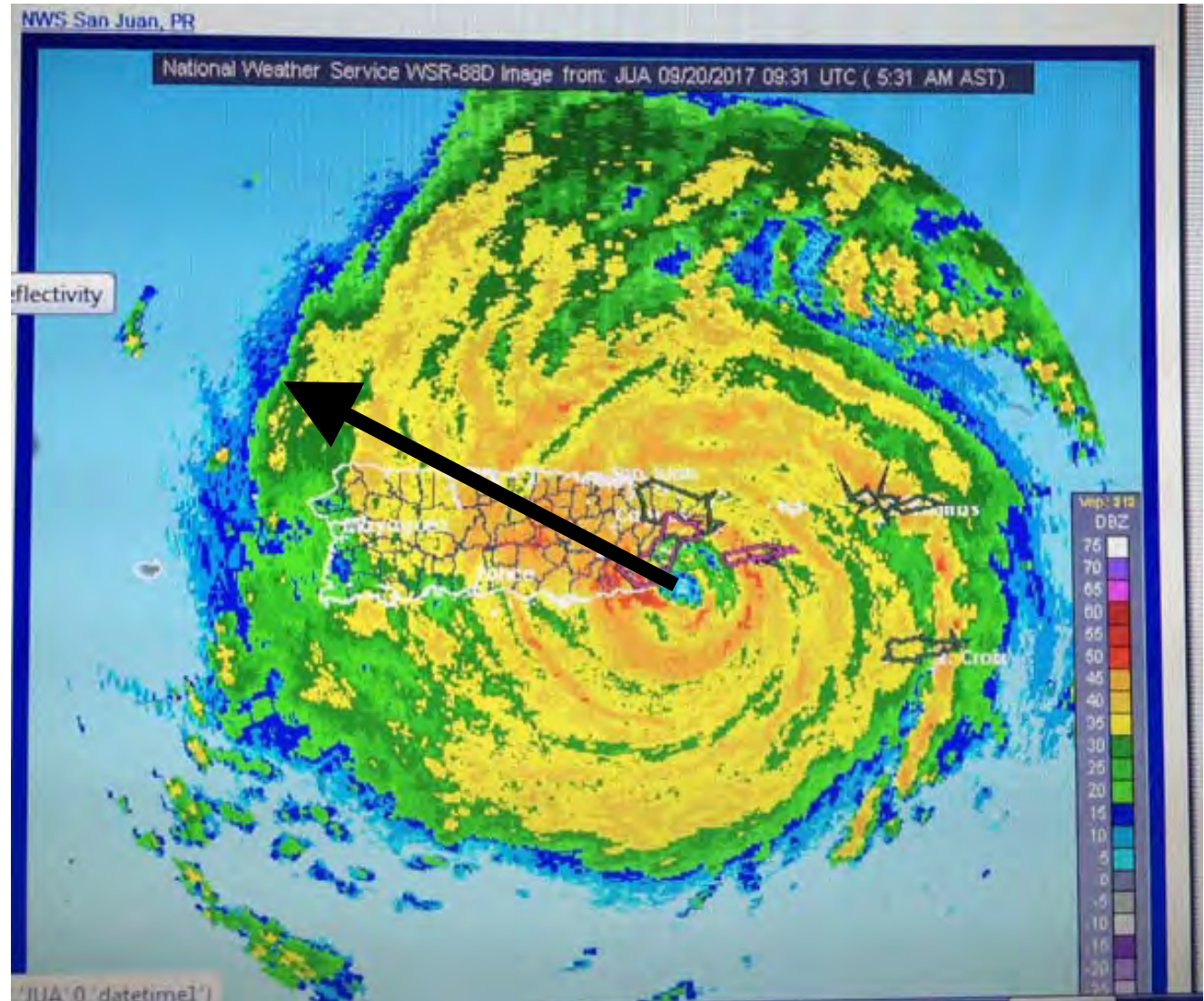
Maria: 5:30am Sept. 20

Category 4 hits Puerto Rico

Cat 4
>130mph
Maria
>150mph

**Wiped cell
towers and
power grid
(90% back
after 6 mos!)**

**Narratives:
alanbetts.com**



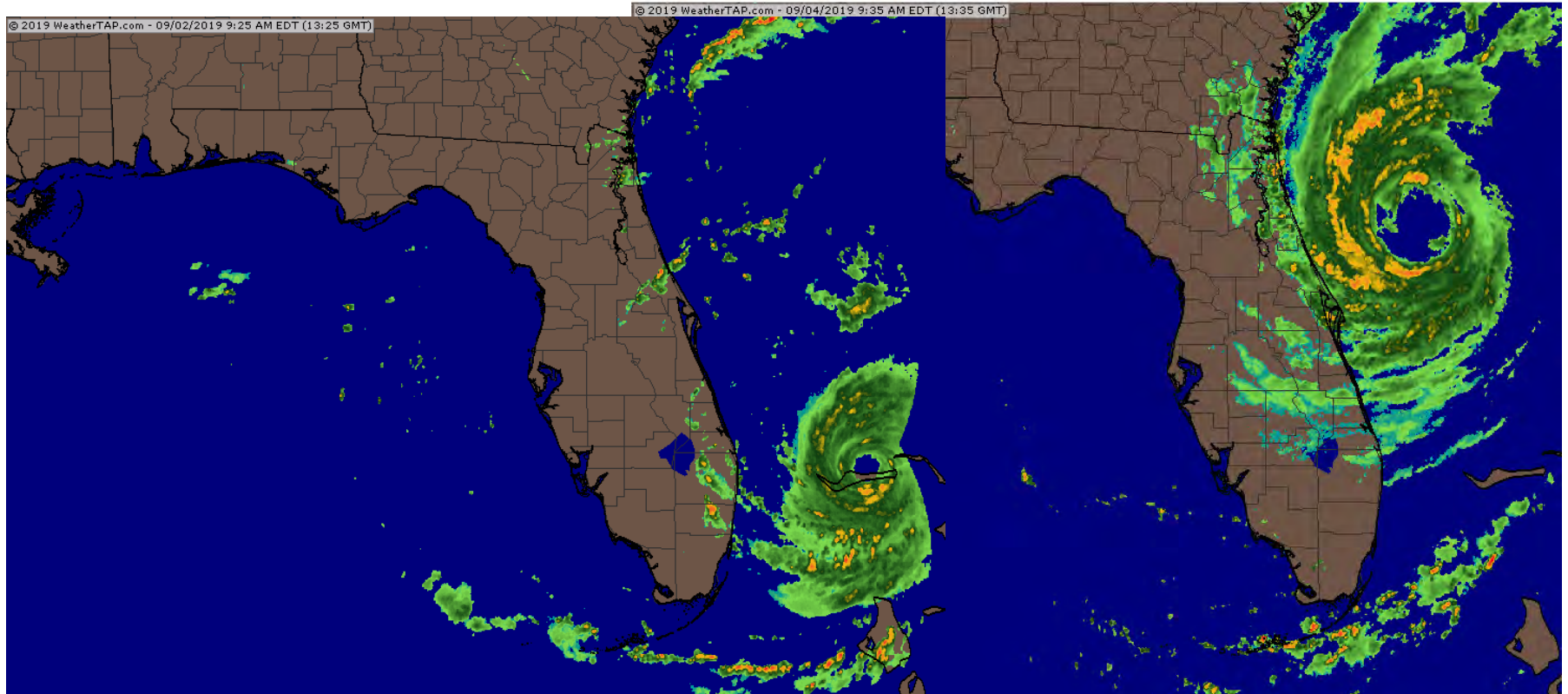
July 2019: track of Barry



Started as band of thunderstorms in Kansas, traveled in slow circle, intensified over warm water of Gulf to weak hurricane, rained on wet Louisiana [Cost: \$1 billion]

Dorian: Cat 5

Cat 2/3

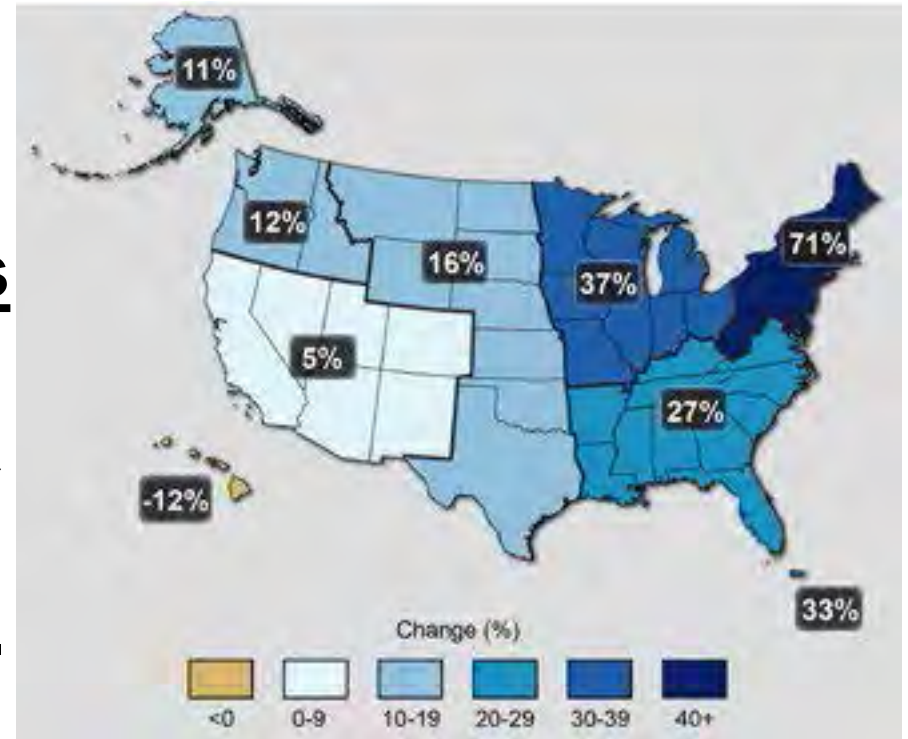


**Sept 2, 2019
Stationary over
Grand Bahama**

**Sept 4, 2019
Off Florida
Coast**

Very Heavy Precipitation Is Increasing

- **Precipitation Extremes**
- **Most of the observed precipitation increase during the last 50 years has come from the increasing frequency & intensity of heavy downpours (upper 1%).**



(Walsh et al., 2014)

- **71% increase in Northeast**

TS Irene

*Rte 131,
Cavendish
Sept, 2011*

Roads in valleys

Massive damage

**Some roads took
months to repair**

Wake-up call



TS Irene: 2011



Brattleboro, VT, Courtesy of Caleb Clark, CNN



Brattleboro, M. Reston



Wilmington, J. Cantore



**Mouth of Connecticut River from Irene
2011**



Lake Champlain, Spring 2011, Courtesy LCBP

2011 Classic Flood Situations

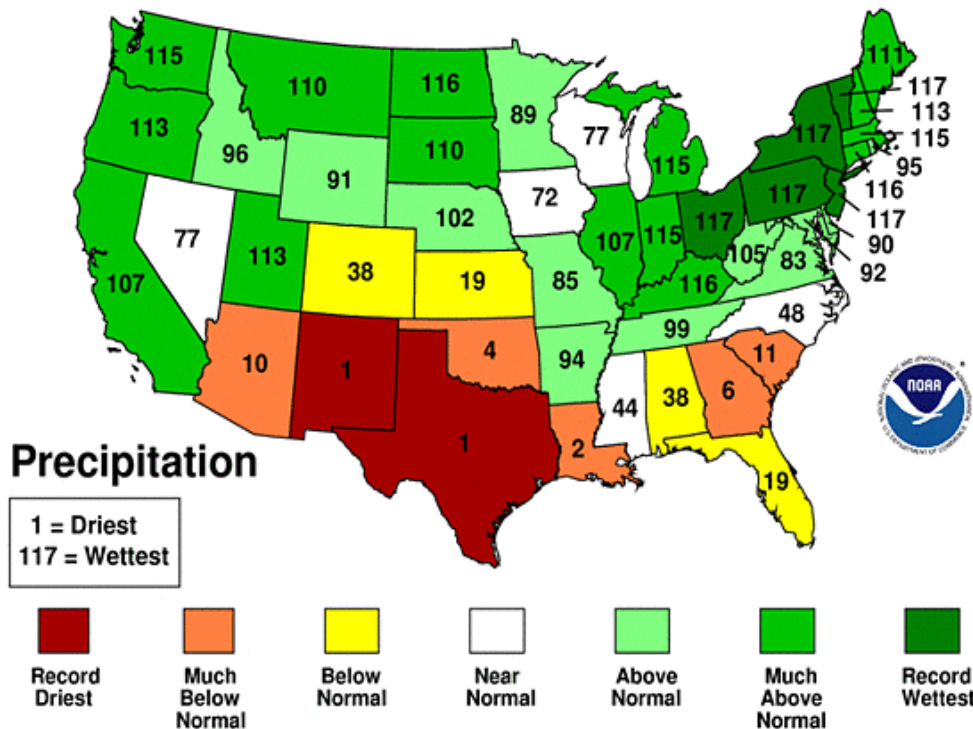
- **Spring flood:** heavy rain and warm weather, melting large snowpack from 2010-11 winter
 - 70F (April 11) and 80F(May 27) + heavy rain
 - record April, May rainfall: 3X at BTV
 - Severe floods on Winooski and Adirondack rivers
 - Lake Champlain record flood stage of 103ft
- **Irene flood: tropical storm** moved up east of Green Mountains and Catskills
 - dumped 6-10 ins rain on wet ground
 - Extreme flooding

2011 Floods: VT and NY

- Record spring flood: Lake Champlain
- Record flood with Tropical Storm Irene

March-August 2011 Statewide Ranks

National Climatic Data Center/NESDIS/NOAA



March-August, 2011

- Record wet : OH to VT
- Record drought: TX & NM
- Pattern nearly stationary

Value of Flood Plains



- **Otter Creek after Irene on August 30, 2011**
 - **River rose ten feet on flood plain saved Middlebury**

Historic Floods on the Otter Creek



W. Creek Rd

***Flood height relative to Irene (2011) on rock;
Estimate flood plain depth in Pittsford***

Year	Height relative to Irene	Flood plain depth
1811	+0'1"	10'1" ± 6"
1913	-3'1"	6'11" ± 6"
1927	+2'4"	12'4" ± 6"
1938	-1'4"	8'8" ± 6"
2011 (Irene)	0	10'0" ± 6"

Recommend we collect height of other floods around VT

Irene: Resilience

- 13 towns cut off overnight
- State emergency systems flooded
- FEMA: no road access
- Communities reorganized overnight
- Those with equipment stepped in
 - “Can fix this in 72 hrs”: will need engineer to check bridge (Brandon)
 - “We worked 120hrs last week...” (Wardsboro)
 - Social networks collected supplies; and rescue services across mountains
 - Communication networks critical

Flooding Issues

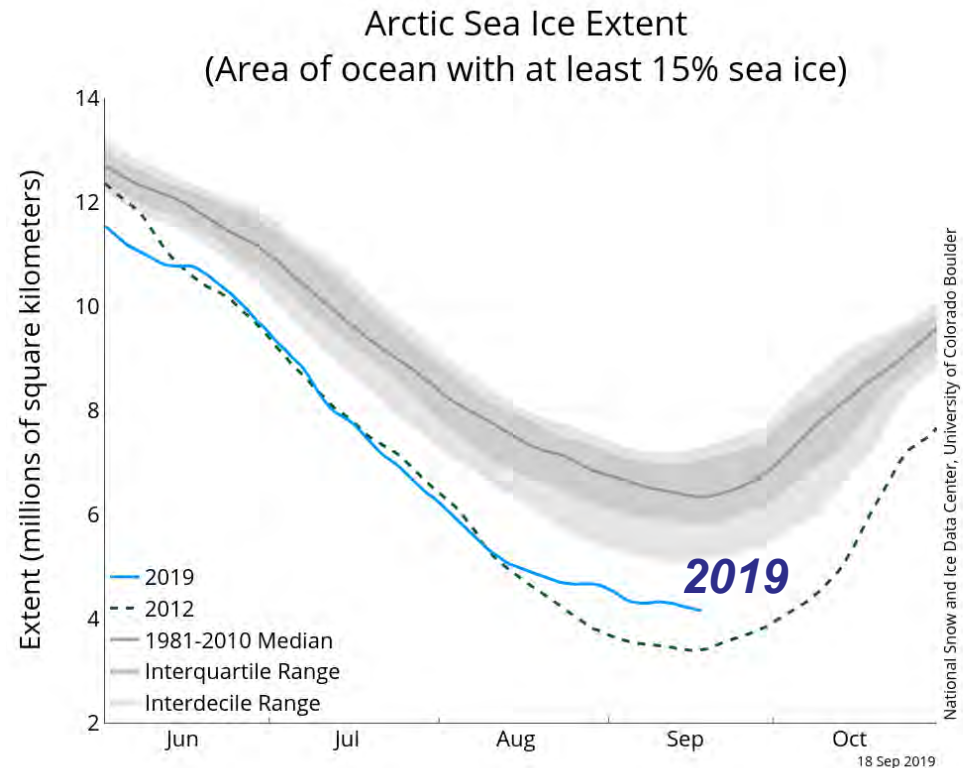
- **Maintain mountain forest cover**
 - Devastating floods in 1920's, 30's with reduced forest cover
- **Manage water/pollutants on landscape**
 - Maximize infiltration: urban and on farms
 - Don't wall-in rivers
- **Preserve flood plains**
 - Saves downstream towns (Middlebury)
 - Stop building houses and trailer parks in flood plains

Winters are changing

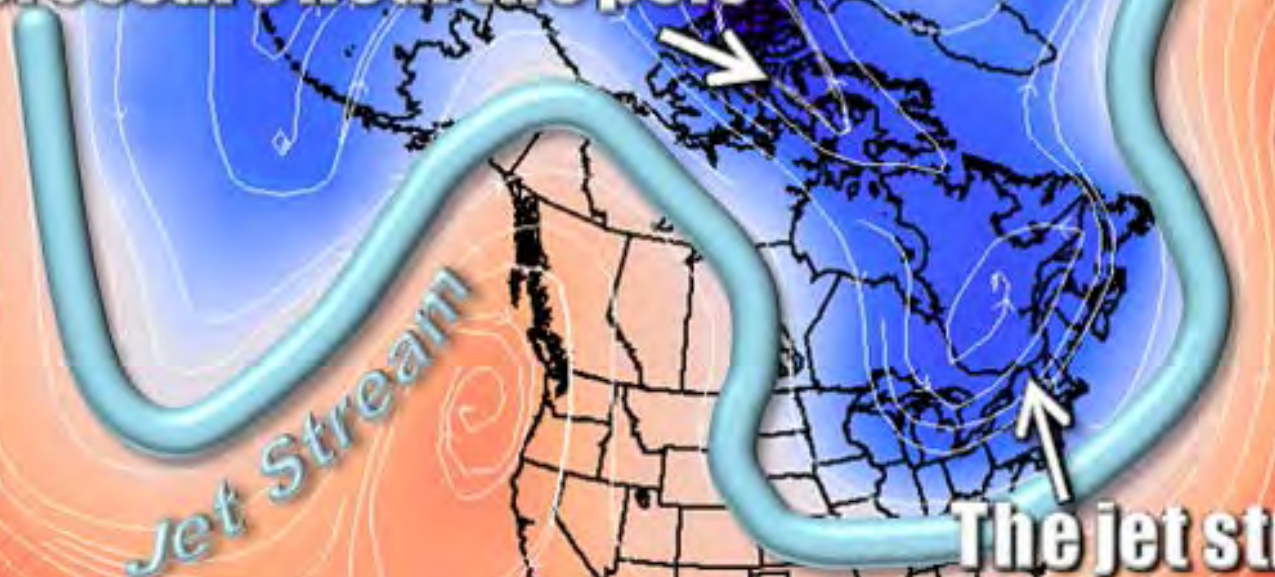
- as Arctic warms and melts

- **Sea-ice minimum mid-September**

- **Winter sea-ice coverage falling**
- **Sea-ice thinning**
- **Polar vortex weakening**



**“Polar Vortex”:
Cold air and low
pressure near the pole**



**The jet stream
and cold air surge
south into the U.S.**

- **Half the Arctic Sea Ice Melted in 2012**
- **Open water in Oct. Nov. gives warmer Fall in Northeast**

- *Positive feedbacks:*
- *Less ice, less reflection of sunlight*
- *More evaporation, larger vapor greenhouse effect*
- *Same feedbacks as in our winters*





January 2, 2012



March 11, 2012



October 2011– March 2012

- **Warmest 6 months on record**
- **My garden frozen only 67 days**

• **January 15, 2013**



February 5, 2016

(Digging in Feb. first time ever)



March 3, 2017



January 10 and 12, 2018



January 10, 2018

**After cold snowy period
 T_{\min} down to -10 to -20F**

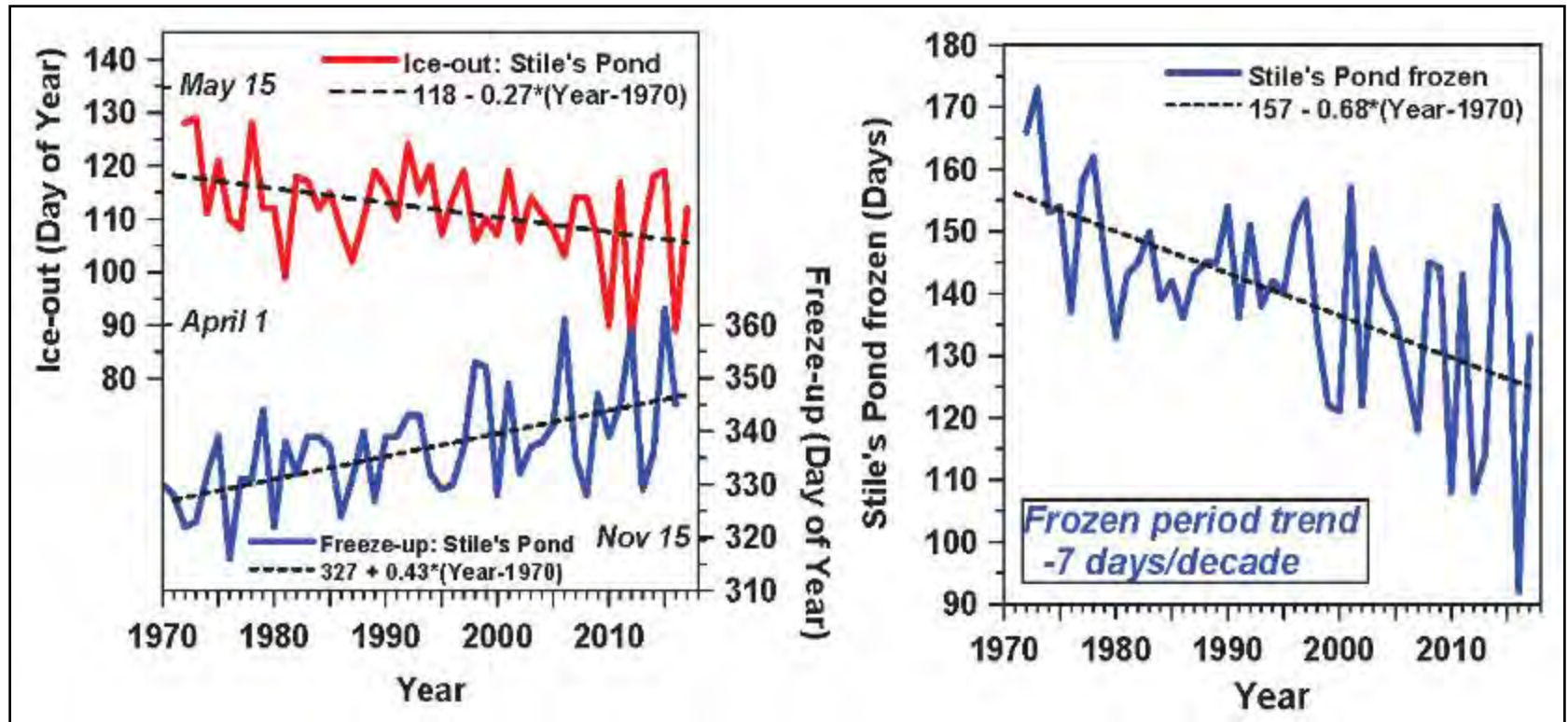


January 12, 2018

After T_{\max} up to 50F

Marker: Lake Freeze-up & Ice-out

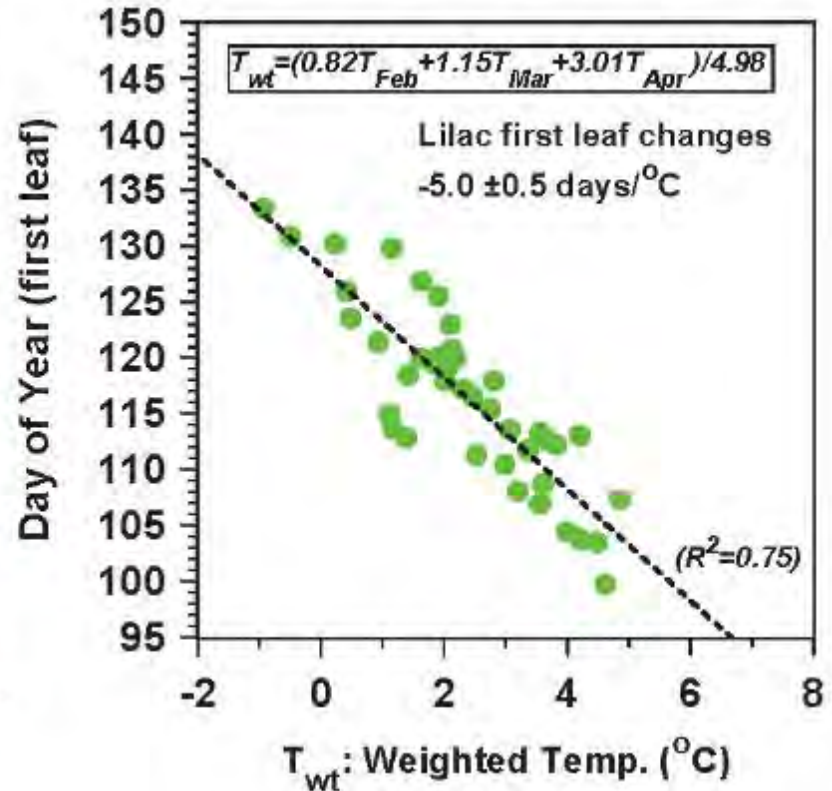
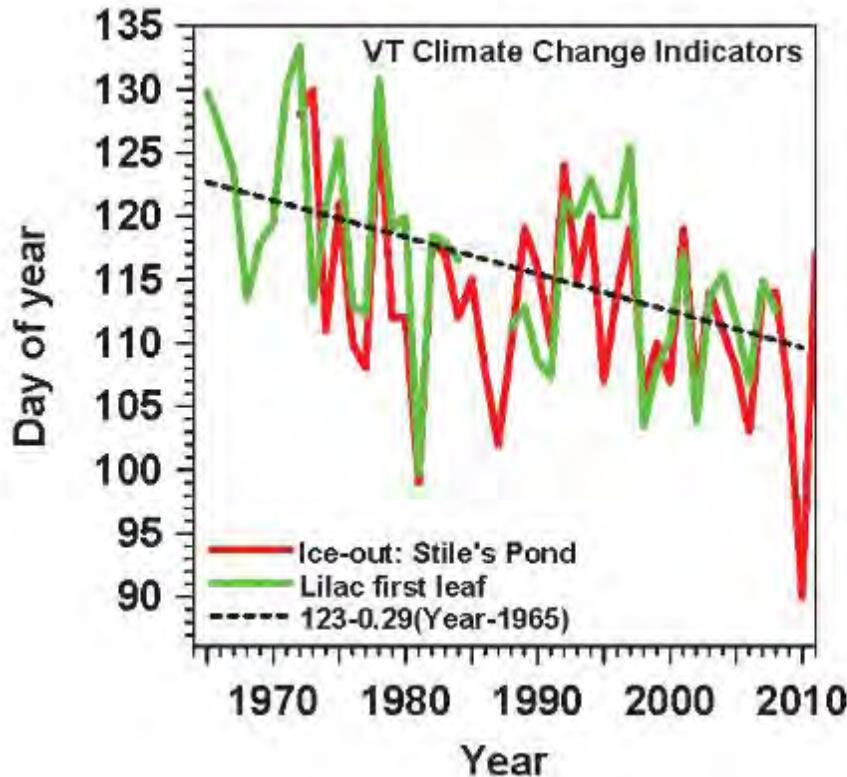
Frozen Period Shrinking: variability huge



- Freeze-up later by **+4 days / decade**
- Ice-out earlier by **-3 days / decade**
- Lake frozen period trend **-7 days/decade**
- *Interannual variability \approx 40 yr trend*

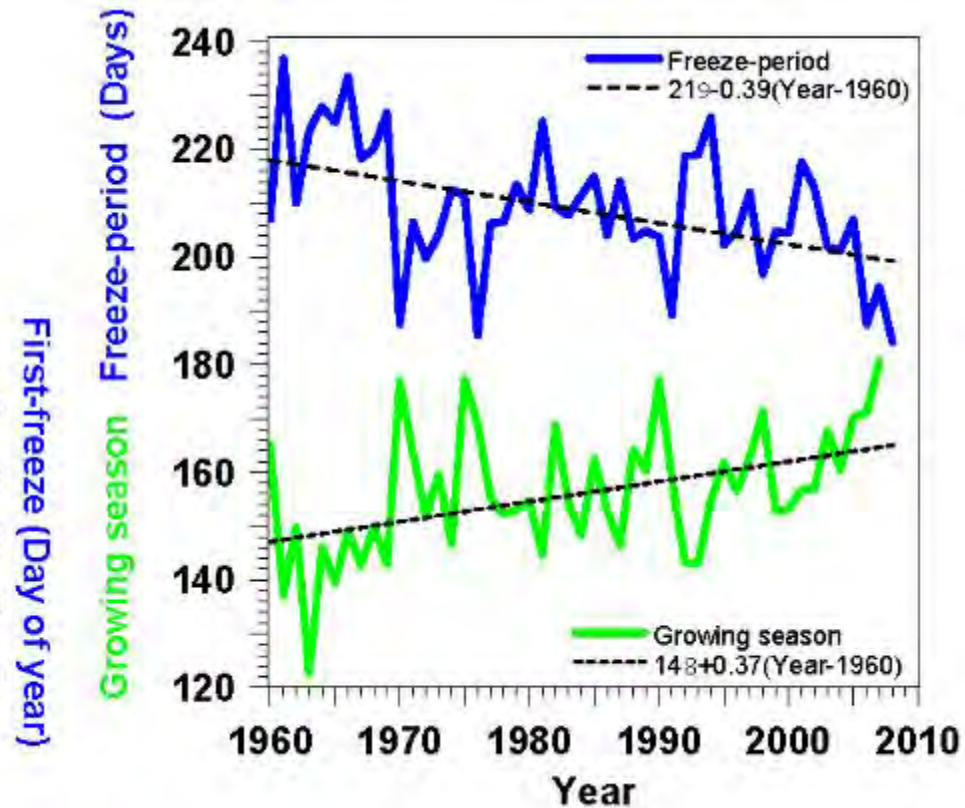
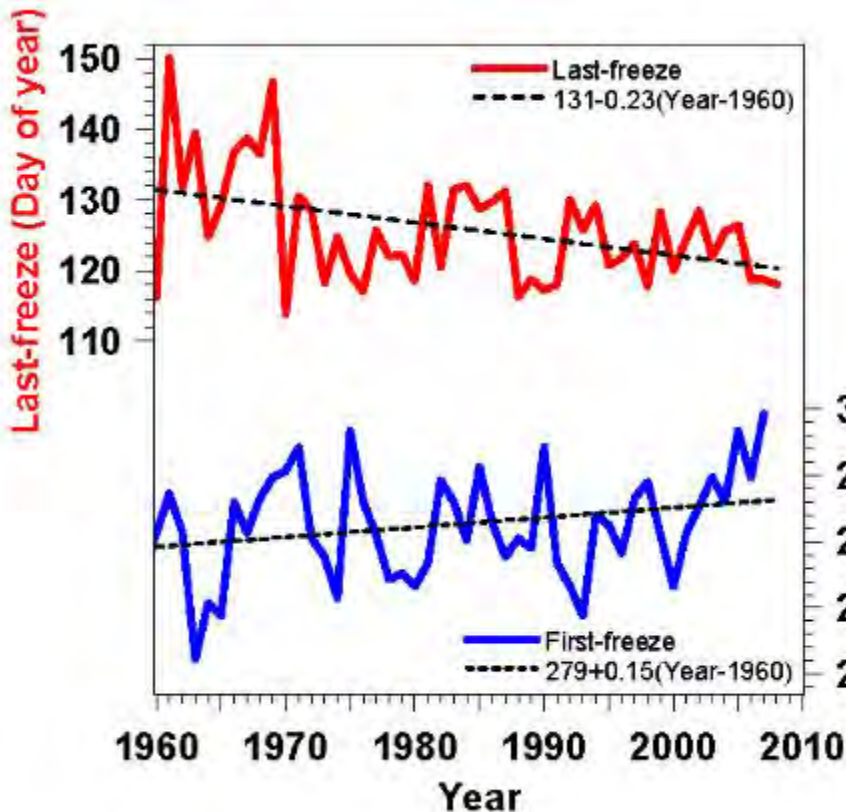
*Stiles Pond:
"Eye on the
Sky"*

Lilac First Leaf Earlier



- First leaf and ice-out changing: -3 days/decade
- Large variability linked to temperature: -5 days/ $^{\circ}\text{C}$
- (No-snow – Snow) winter = $6 * 5 \approx -30$ days earlier leaf-out

First and Last Frosts Changing

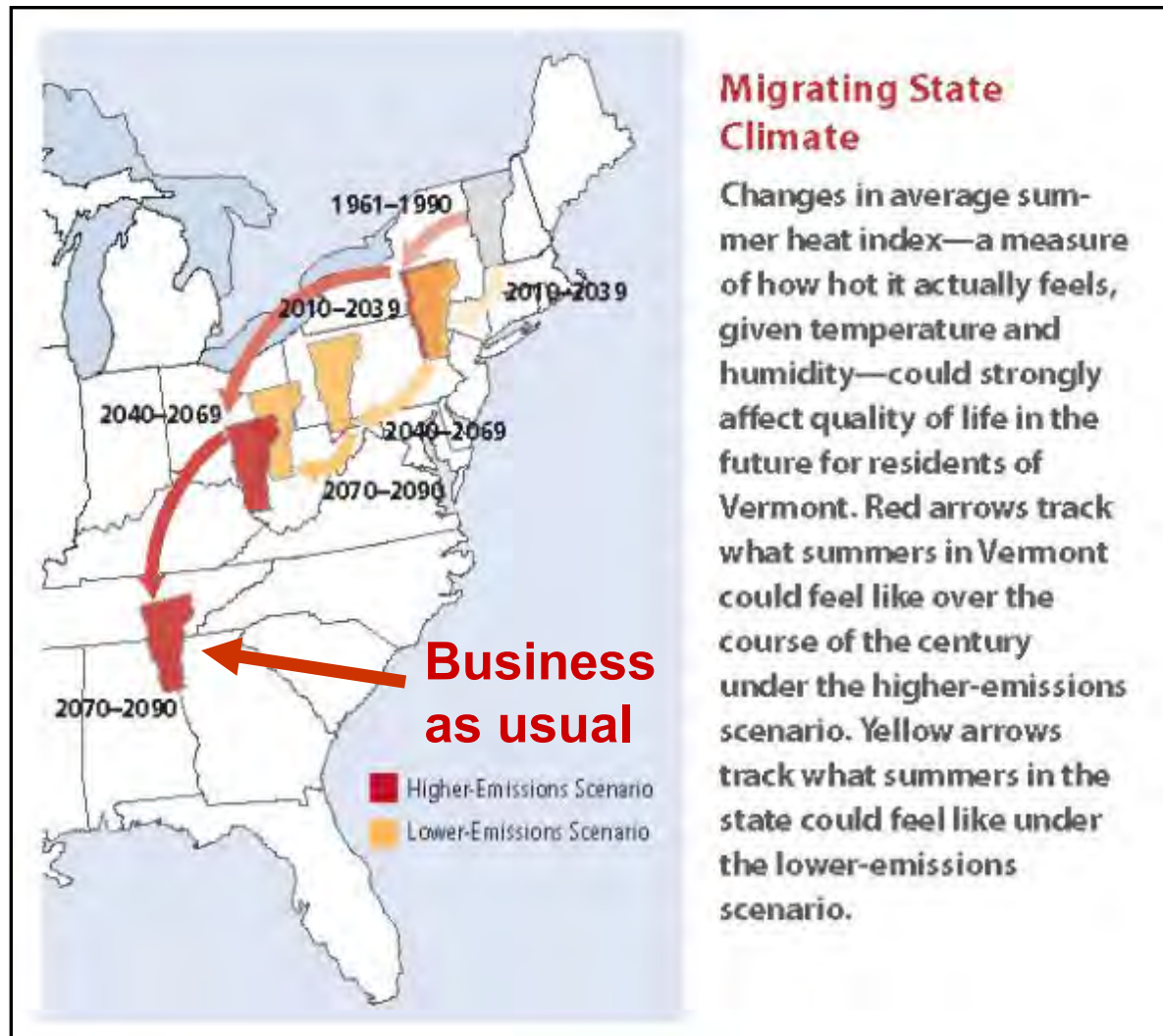


- Growing season for frost-sensitive plants increasing **3.7 days / decade**
- A help for growing “local food”

Vermont's Future with High and Low GHG Emissions

What
about VT
forests?

Sub-tropical
drought areas
moving into
southern US



**NECIA,
2007**

Arctic warming 2x Tropics

NH patterns more 'stationary'

- North-south T gradient weakening
- Weaker westerly flow; Jet-stream wavy
- Ocean circulation changing
 - Greenland melting; fresh water
- ***Understanding still incomplete***

3-month mean

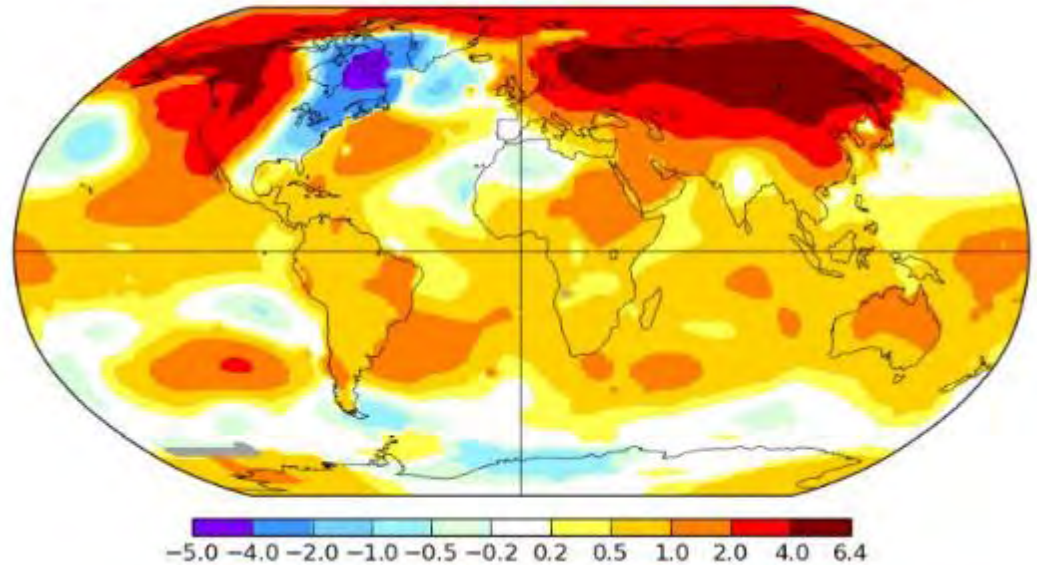
Jan-Feb-Mar 2015

Warm Atlantic, record temp in west; cold NE, strong coastal storms - Boston record snow

Jan-Mar 2015

L-OTI(°C) Anomaly vs 1951-1980

0.86



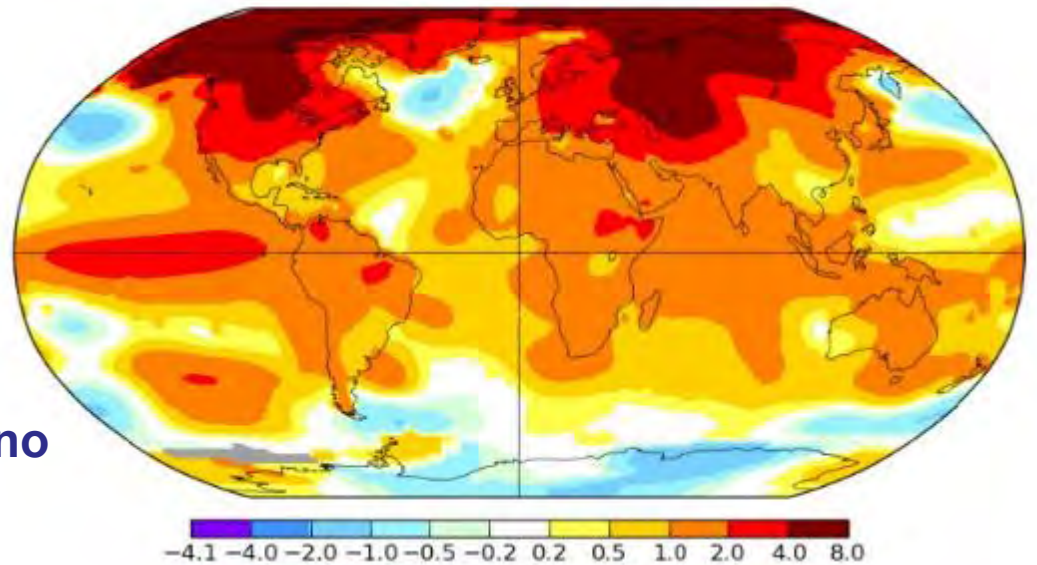
Jan-Feb-Mar 2016

Warm Atlantic, warm NE, little snow, warm Arctic; Pacific El Nino

Jan-Mar 2016

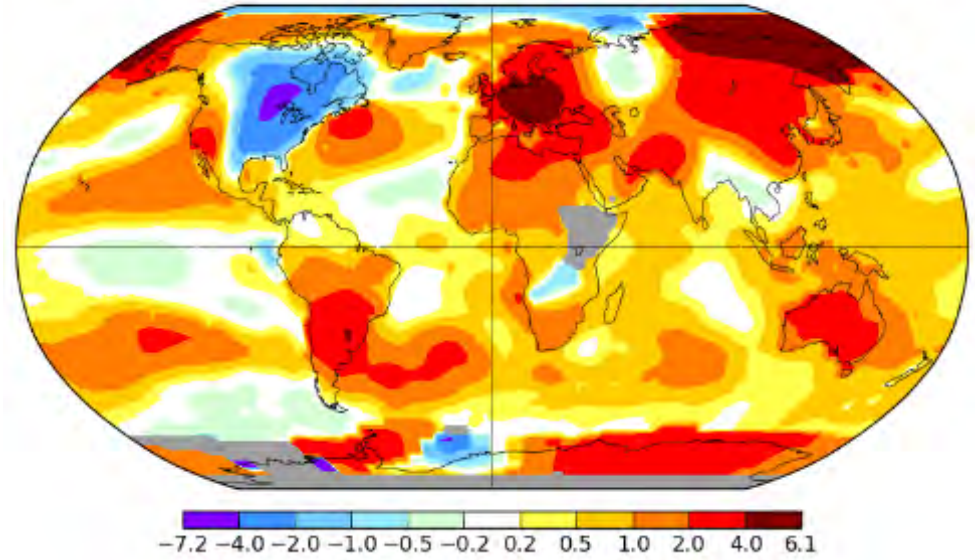
L-OTI(°C) Anomaly vs 1951-1980

1.24



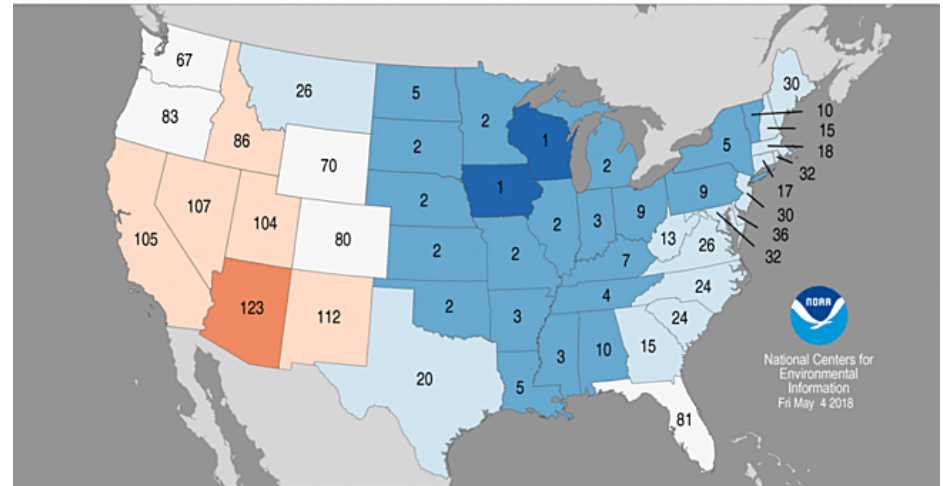
April-2018

Warm Atlantic,
(Record) cold N. America
Warm Europe



Statewide Average Temperature Ranks
April 2018
Period: 1895-2018

Record coldest: Wisconsin, Iowa
2nd coldest: Minnesota, S.Dakota,
Nebraska, Kansas, Oklahoma,
Missouri, Michigan



National Centers for Environmental Information
Fri May 4 2018

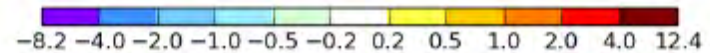
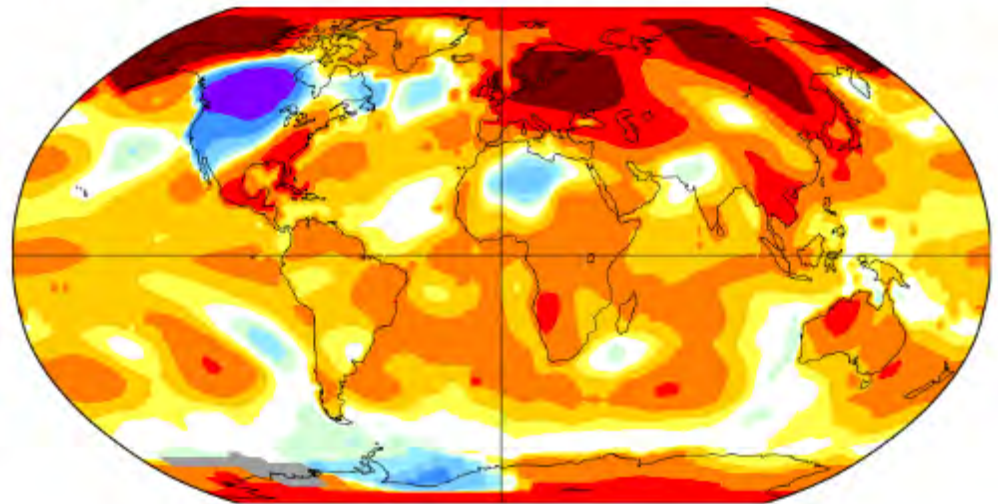
Feb-2019

**Extreme cold, central US, Canada
Extreme warmth UK (Moor fires),
Europe, Asia, NW Alaska**

February 2019

L-OTI(°C) Anomaly vs 1951-1980

0.94



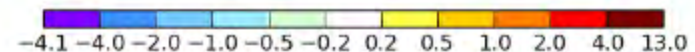
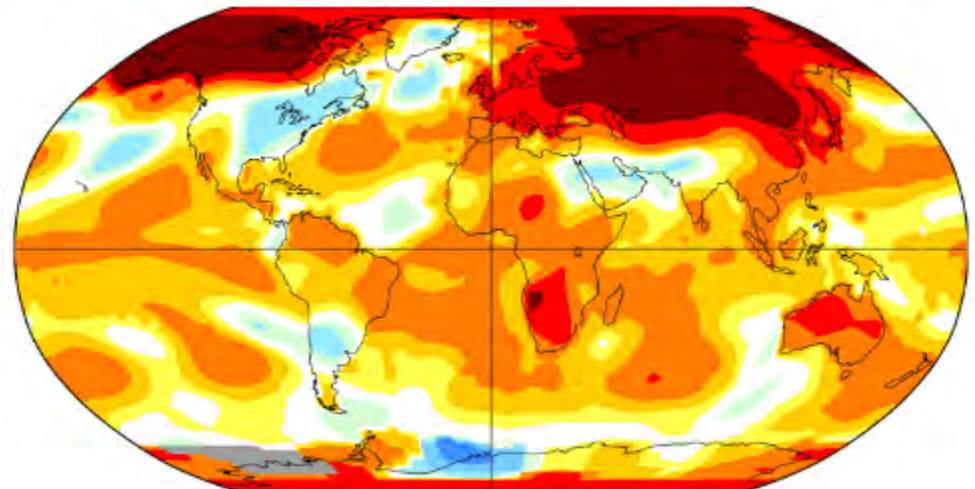
March-2019

**Cold eastern US, Canada
Extreme warmth UK, Europe, Asia
Alaska**

March 2019

L-OTI(°C) Anomaly vs 1951-1980

1.18



Feb-2019

*Second warmest
in South-east*

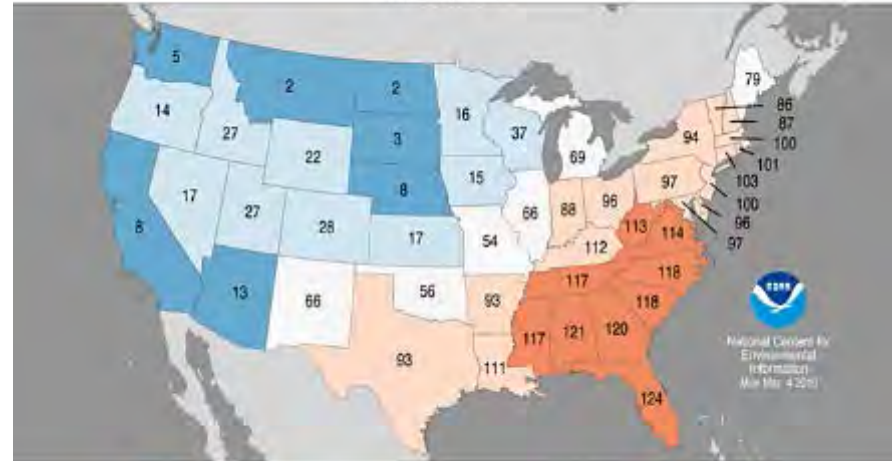
*Second coldest
in north-central*

*Very wet across
much of US*

Statewide Average Temperature Ranks

February 2019

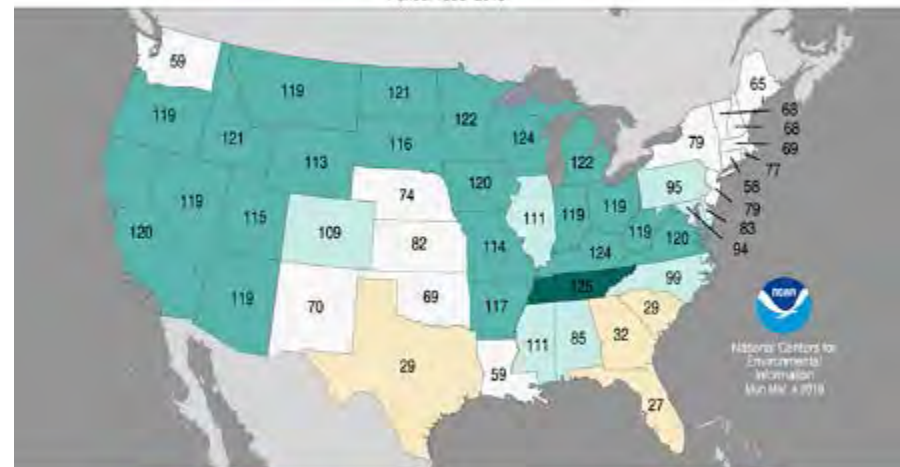
Period: 1895-2019



Statewide Precipitation Ranks

February 2019

Period: 1895-2019



May-2019

Record temps
in Florida &
South-east

Still cold
in north-central

Statewide Average Temperature Ranks

May 2019

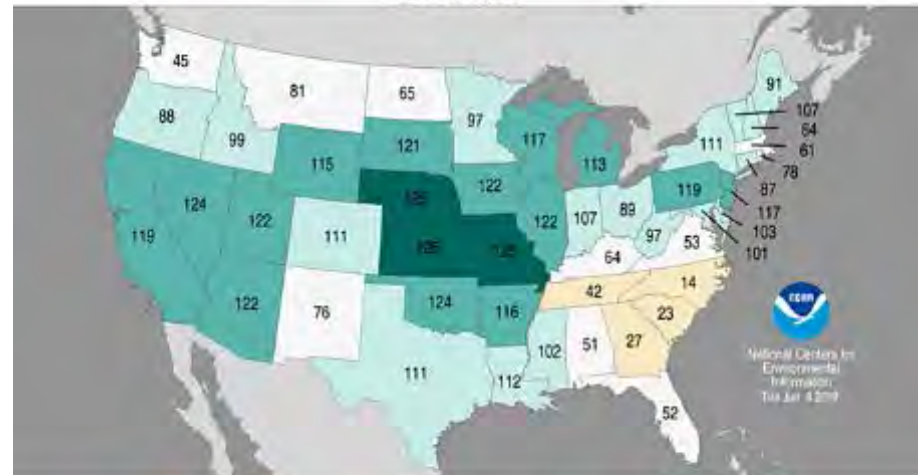
Period: 1895-2019



Statewide Precipitation Ranks

May 2019

Period: 1895-2019



Record wet across
Central US

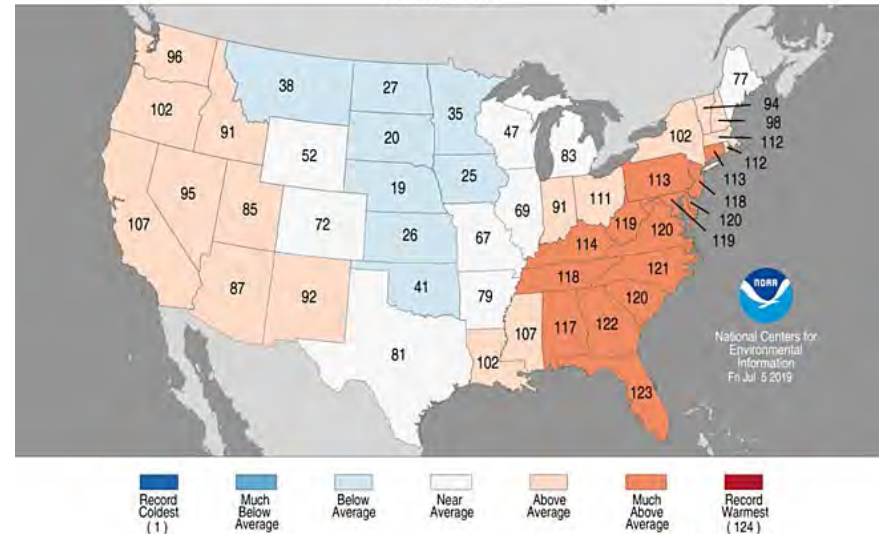
Jul-2018 to Jun-2019

*Warm in South-east
Cold in north-central*

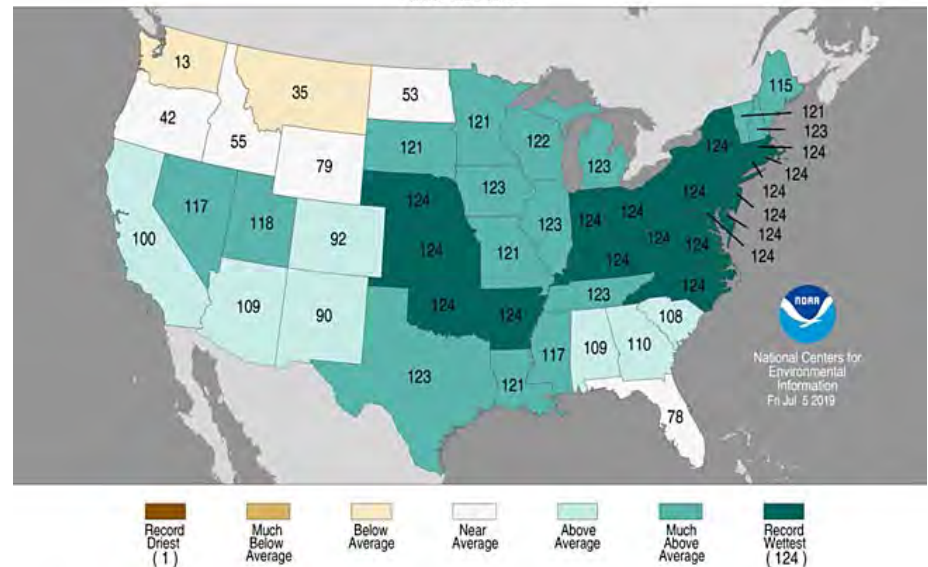
*Very wet across eastern
& central US*

*2019 Mississippi flooding
longest on record*

Statewide Average Temperature Ranks
July 2018–June 2019
Period: 1895–2019



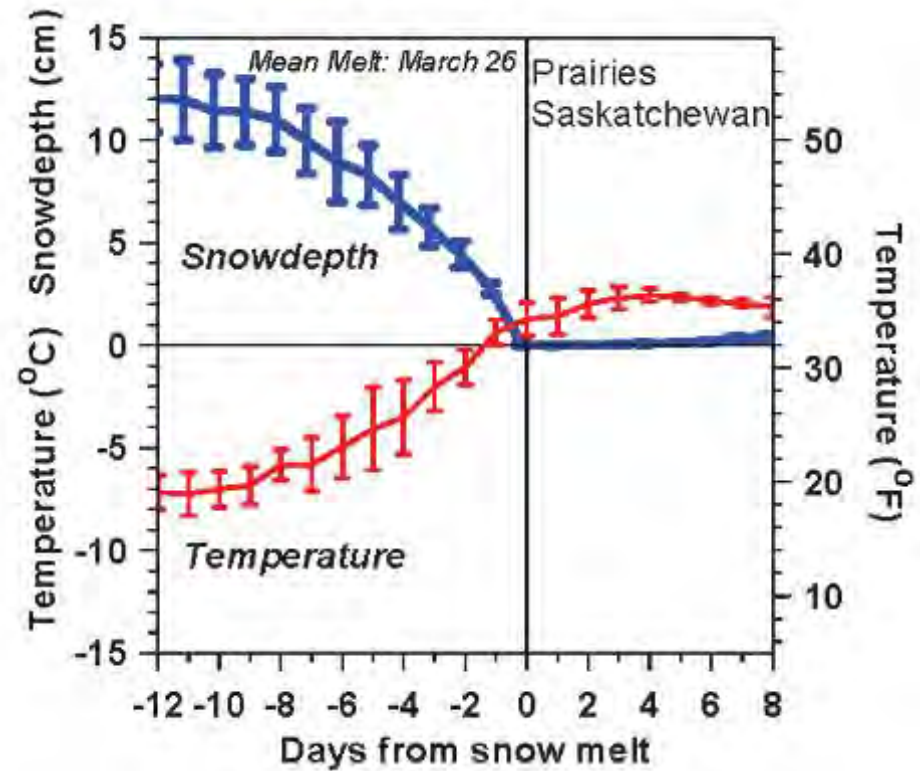
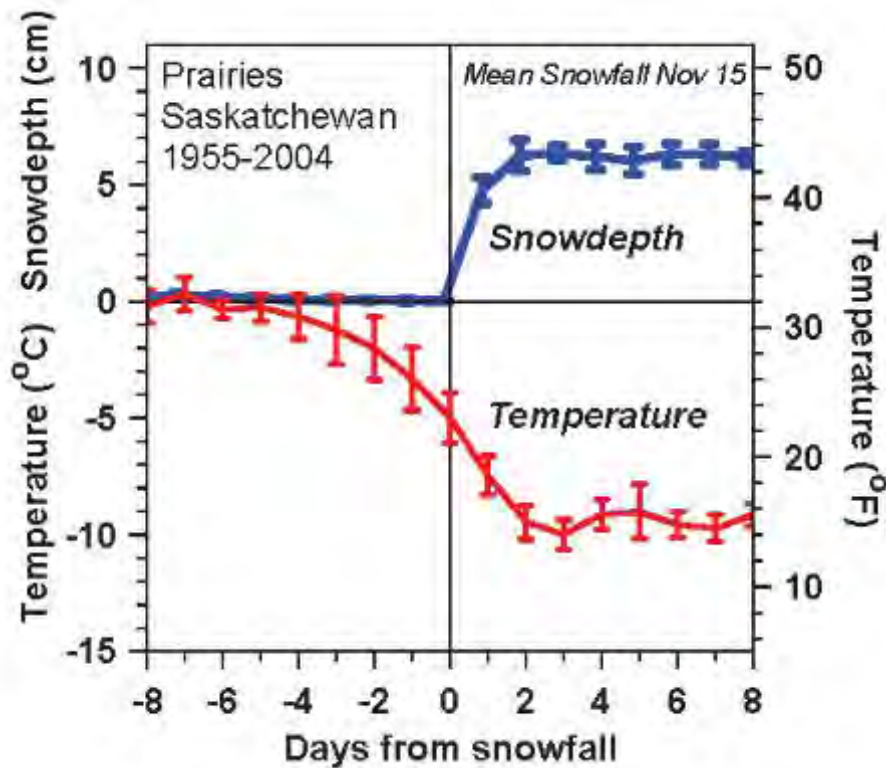
Statewide Precipitation Ranks
July 2018–June 2019
Period: 1895–2019



CA Tornadic Supercell, 2" hail: 24 May 2019

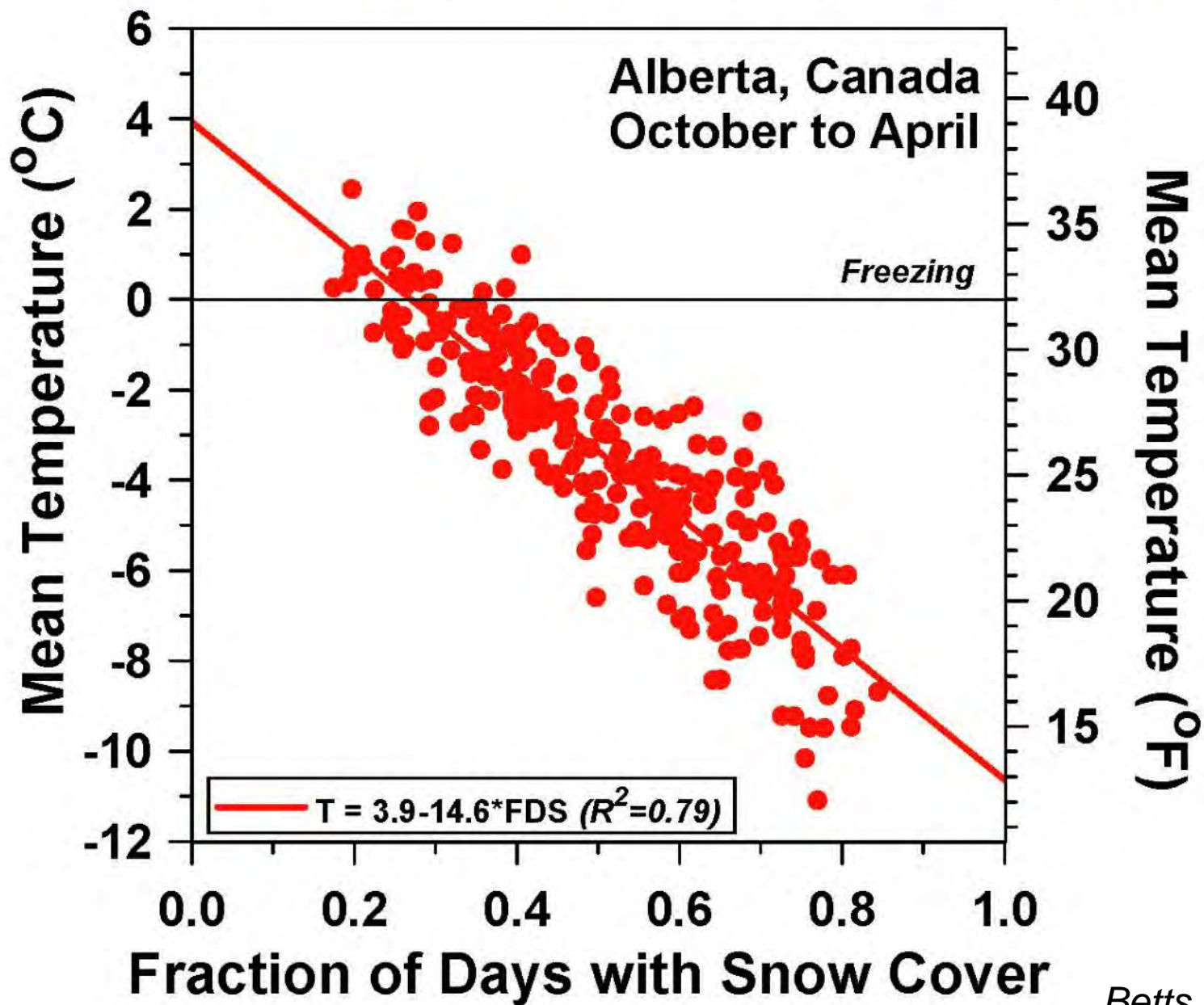


Snow Cover Critical

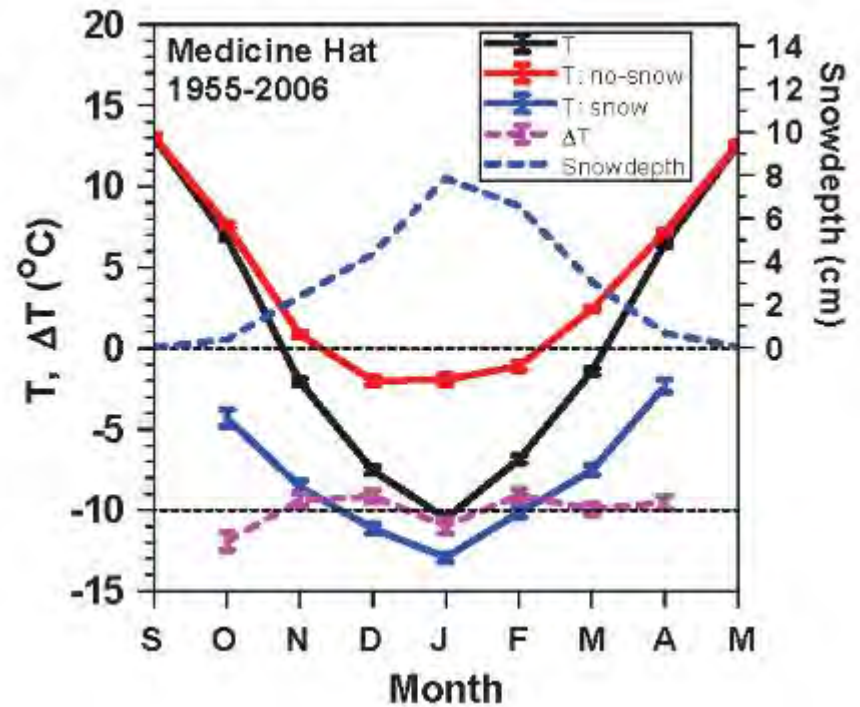
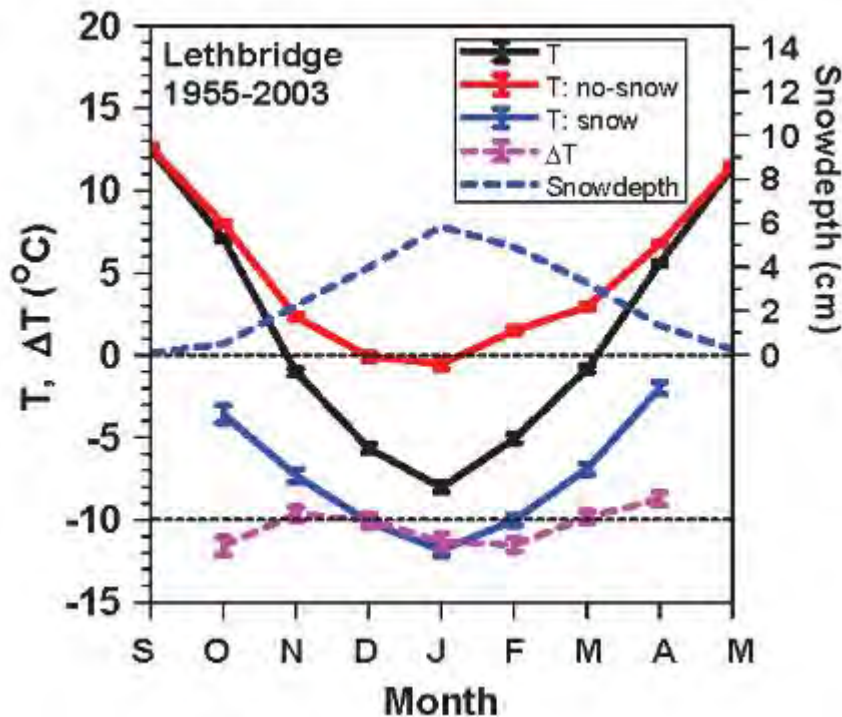


- Temperature changes 10°C with snow cover
- Snow cover is a 'climate switch'
- *Fast transitions in 'local climate'*
 - *Snow reflects sunlight, insulates ground*
 - *Reduces evaporation and water vapor greenhouse*

More snow cover - Colder temperatures



Impact of Snow on Climate



Separate mean climatology into days
with no-snow and snowdepth >0

$$\Delta T = T:\text{no-snow} - T:\text{snow} = -10.2(\pm 1.1)^{\circ}\text{C}$$

Impact of Snow

- **Distinct warm and cold season states**
- **Snow cover is the “climate switch”**

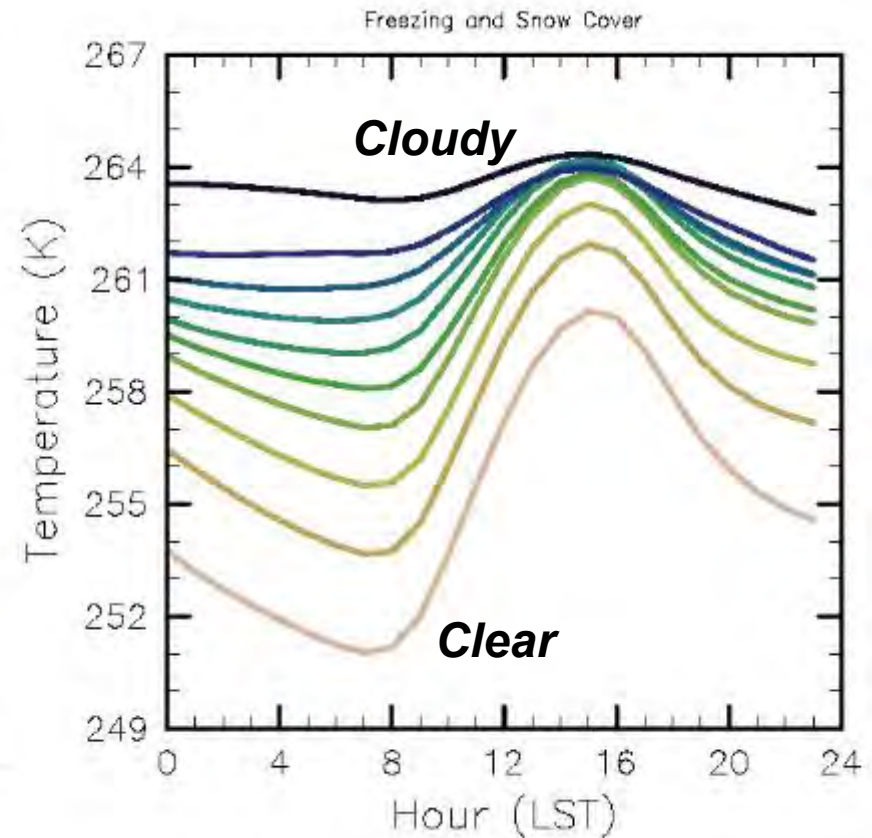
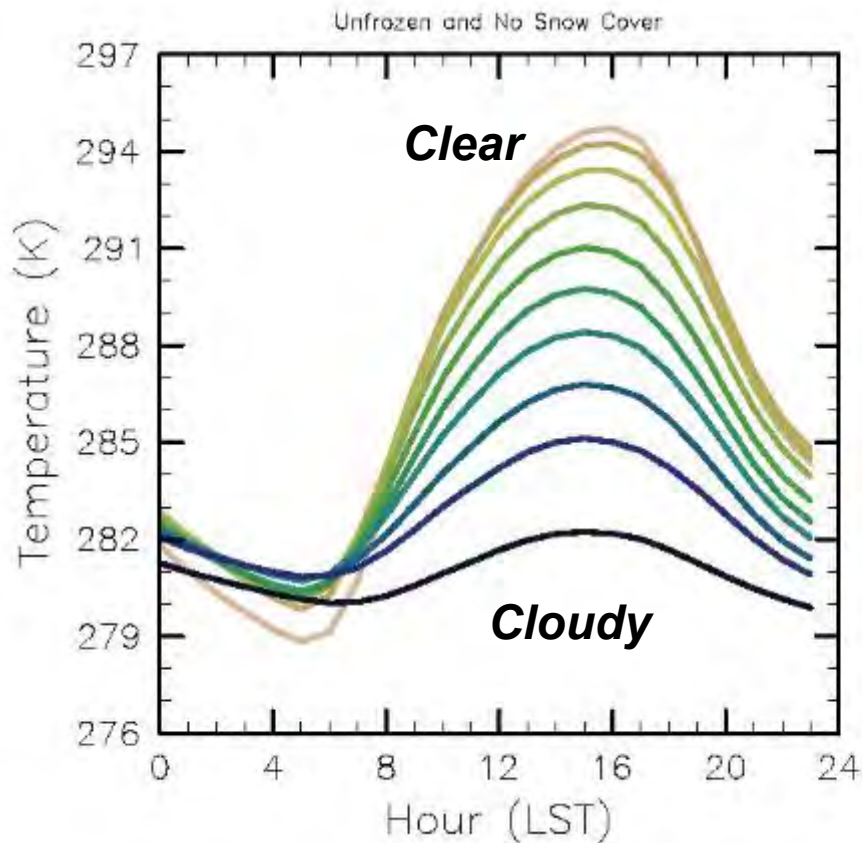
With snow

- Prairies: Temperature falls 10°C (18°F)
 - snow reflects 70%
- Vermont: Temperature falls 6°C (10°F)
 - snow reflects 35% (because more forest)

Warm & Cold Climates: $T > < 0^{\circ}\text{C}$

$T_m > 0^{\circ}\text{C}$: no snow: 150,000 days

$T_m < 0^{\circ}\text{C}$: snow: 75,000 days



- **Warm $> 0^{\circ}\text{C}$: Clouds reflect sunlight**
- **Cold $< 0^{\circ}\text{C}$: Clouds are greenhouse & snow reflects sun**

Precipitation Increase with Temperature

- **Coupling of water vapor to temperature**
 - *increase 7%/degC; 4%/degF*
- **Cloud-base temp. and height to humidity**
 - *$(T-T_d)/8$ gives cloud-base in km*
- **Cloud liquid water and precip. rate**
 - *Increase with T (7%/degC); decrease with cloud-base height (-2g/kg/km)*

Review of forecast models

- Hurricane track forecast skill good for Sandy, Harvey, Florence

– *Rapid intensification not as good*

- Dorian

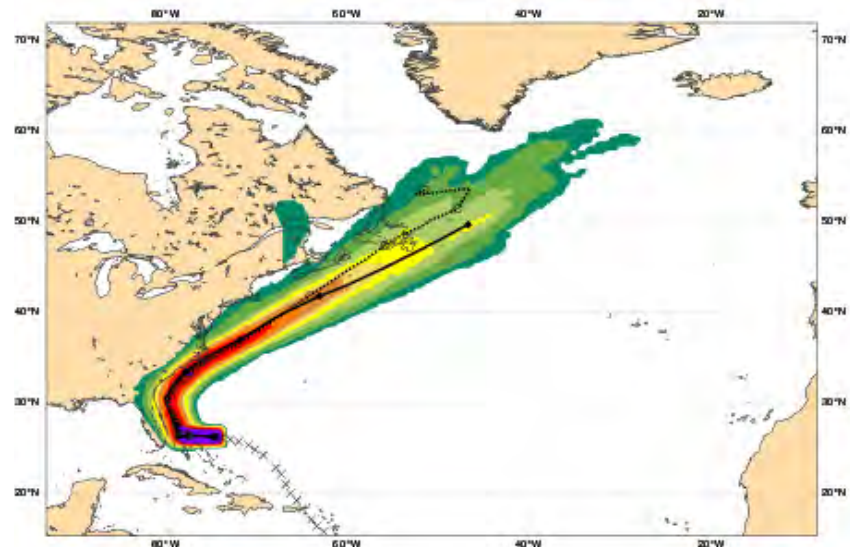
Base time: Sun 01 Sep 2019 00 UTC

Date 20190901 00 UTC @ECMWF

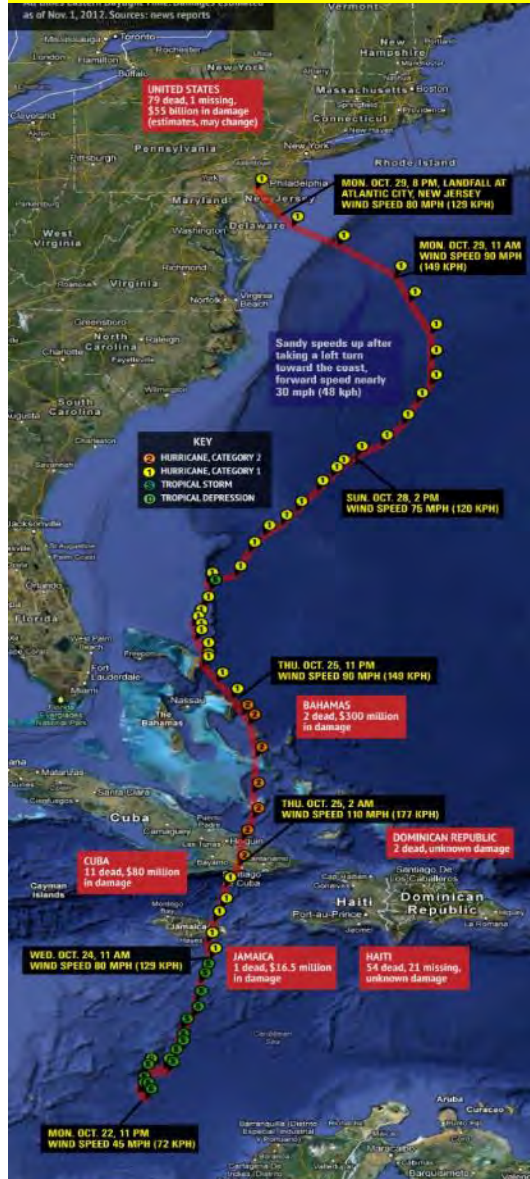
Probability that **DORIAN** will pass within 120 km radius during the next 240 hours

tracks: **solid**=HRES; **dot**=Ens Mean [reported minimum central pressure (hPa) 941]

5-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80 80-90 > 90%

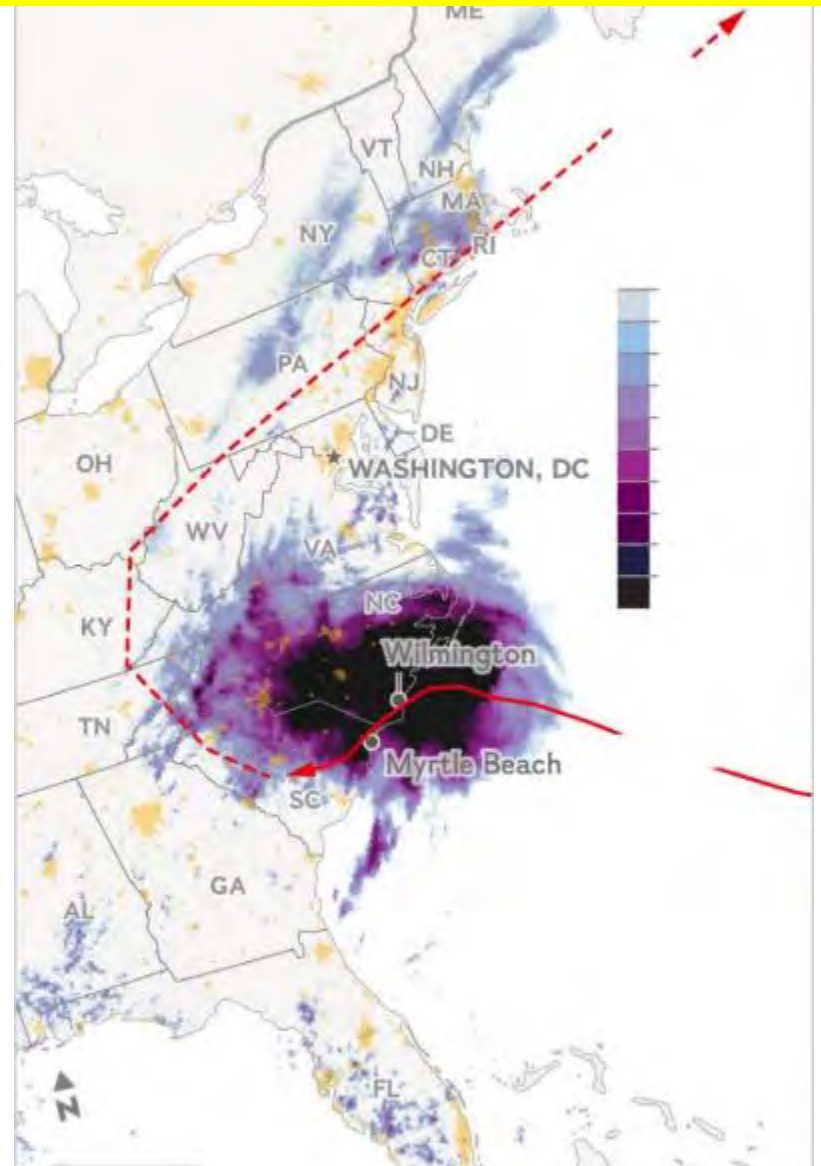


Sandy: Oct 22-30, 2012



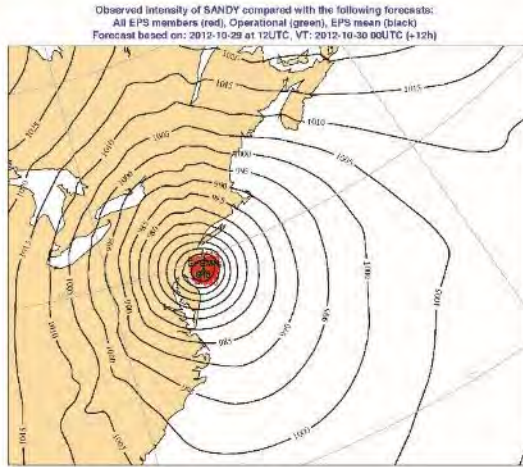
Cuba
Oct 25

Florence: Sept 14-17, 2018

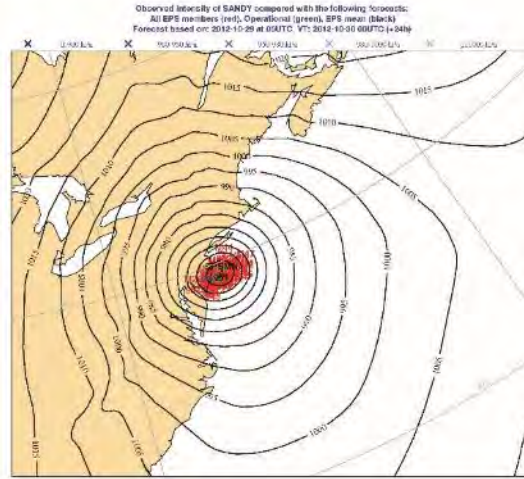


Sandy: 2012-10-30 (ECMWF)

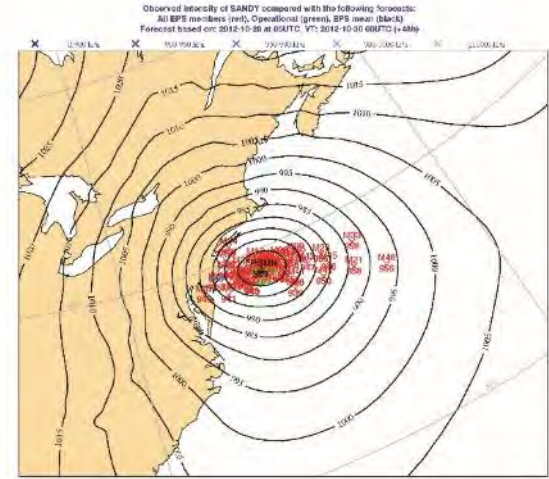
12h



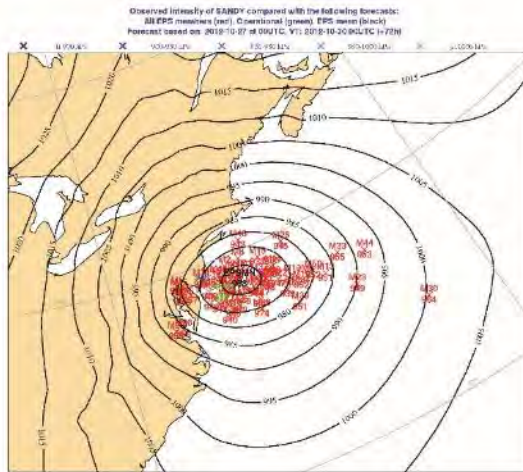
24h



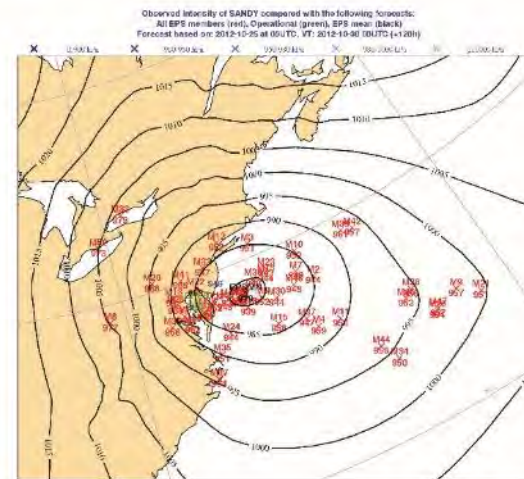
48h



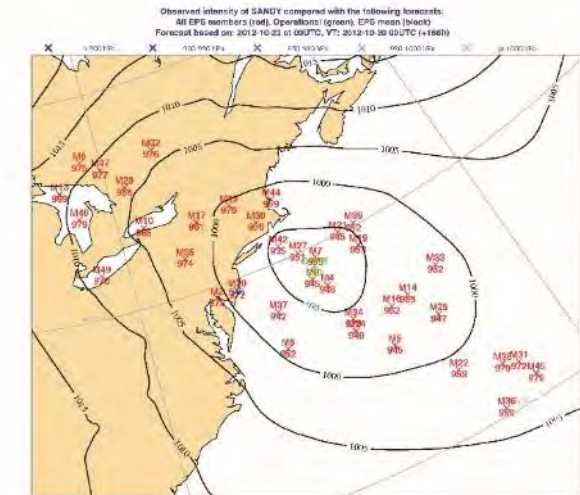
3d



5d



7d

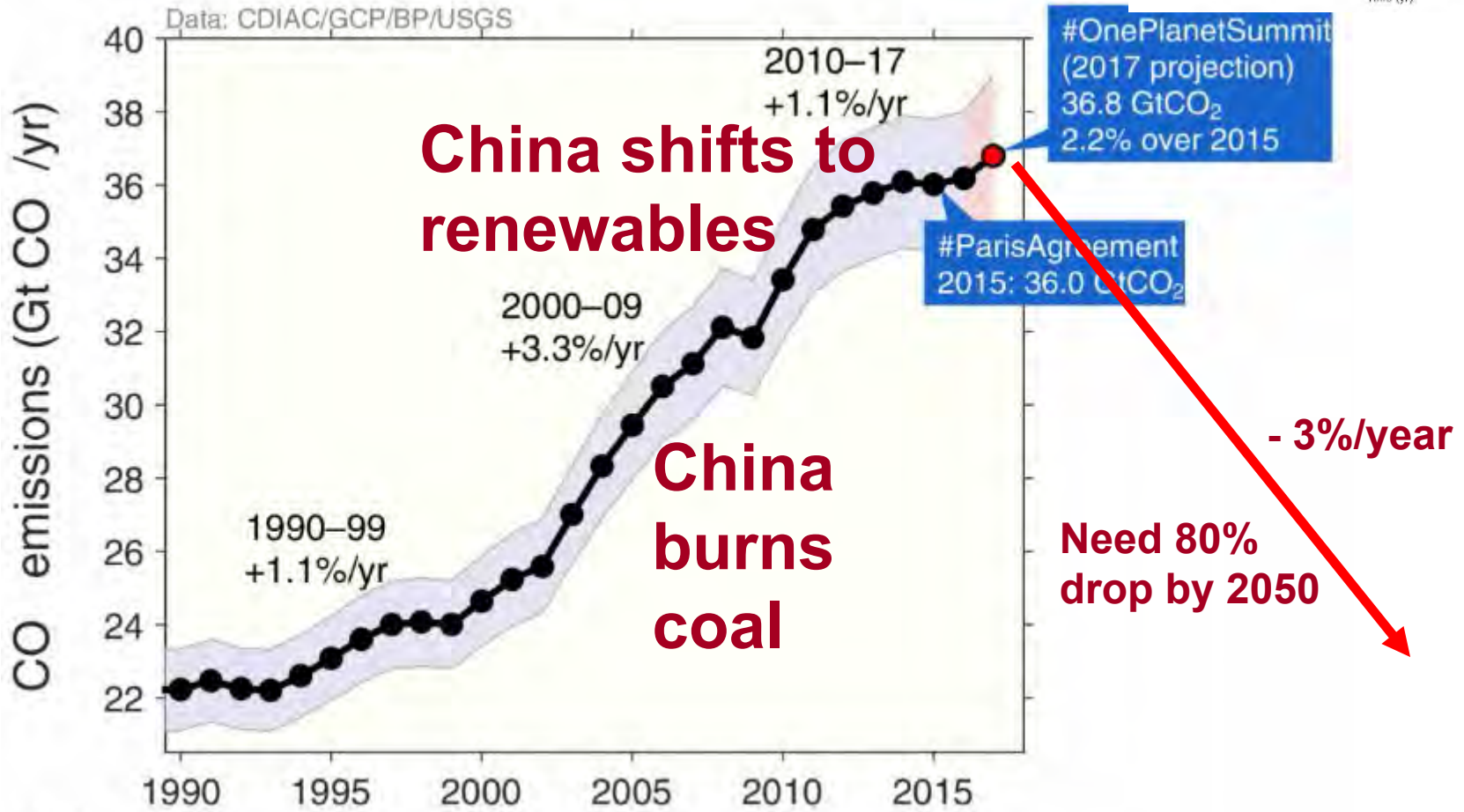
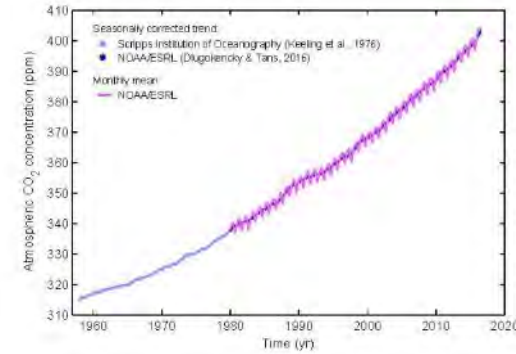


Promised to Stop “Dangerous Climate Change”?

- signed by 197 countries *(UNFCCC 1992)*

- **Can we? Quickly stabilize atmospheric CO₂**
- **This means an 80% drop in CO₂ emissions!**
- **This is possible but very difficult**
 - **Fossil fuels have driven our industrial growth and population growth for 200 years**
 - **“Lifestyle” has become dependent on fossil fuels**
 - **Powerful vested interests: trillions \$ at stake**

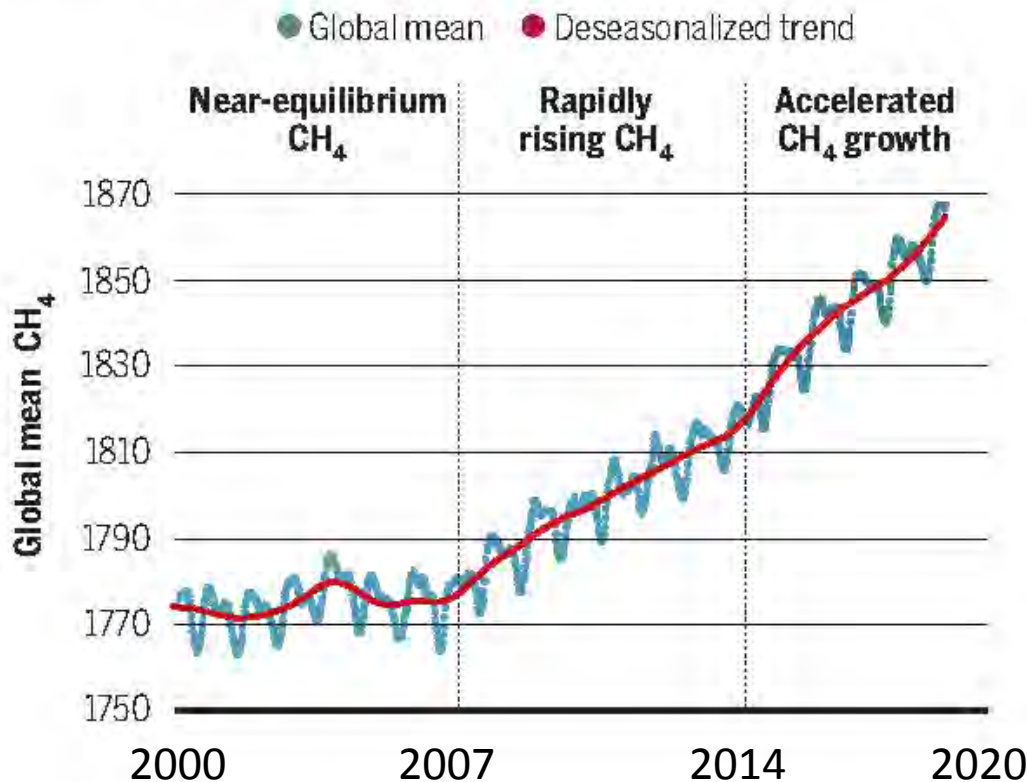
Growth of CO₂ Emissions slowed – now increasing



CH₄ Emissions were flat but now increasing

Methane trends

Data from U.S. National Oceanic and Atmospheric Administration observing stations show that global mean atmospheric CH₄ started to rise in 2007, with a sharper increase beginning in 2014 (2).



Causes uncertain:

- 1) Emissions from livestock and tropical wetlands
- 2) Emissions from fossil fuel production and biomass burning
- 3) Atmospheric sink reductions

What can we “safely” burn?

- Only 750 Gt more for an even chance of keeping warming below 2°C
Requires leaving 2/3 of remaining fossil fuels in ground
- Only 21 years left at 36 Gt/year
- *Rapid phase-down extends period*

How do we do it?

Systems Engineering

- **Change the rule-book from maximizing profit**
 - *Ask: Is this cost-effective for our children?*
- **Minimize human waste products** dumped into the Earth's atmosphere and ocean
 - *Shift from fossil fuel ASAP*
- **Maximize the efficiency** with which our society uses energy and fresh water
- **Maximize the use of renewable energy**

Adaptive Risk Management

- *Start planning* *Srikrishnam et al. EOS 2019*
- **Build/repair for sequential upgrades based on increasing risks**
- **Follow the critical regional statistics for wind, ice, flood flows: *annual update***
- **Monitor the global and regional drivers**
 - **Arctic ice melt**
 - **NH circulation changes**
 - **Seasonal, Monthly, Weekly temperature**

Available Climate Services

- 2011: Formation of 'Climate Service' by NOAA forbidden by Congress (Republican 'denialists' said it would produce unacceptable climate science)
- 2015: National Centers for Environmental Information (NCEI) formed with Regional Climate Centers: manages data; does what it can
- **2018: NCA4: Fourth National Climate Assessment is Interagency: US Global Change Research Program**
 - ***Global Change Research Act of 1990***
 - **Read North-east section: good research review**
[EPA efforts to stop ECA4 failed]
- ***Contrast UK Climate Projections 2018: high resolution 12km projections for next 20 yrs, based on range of global projections with data & climate impact narratives***

Review: Weather/climate

- ***GHG increase means Earth warming***
 - *93% of heat stored in oceans*
 - *Stronger storms*
- **Arctic warming twice as fast as equator**
 - As N-S temperature gradient falls, jet stream more wavy, more stationary patterns
- **Slower moving storms means more rainfall and more flooding**
- **Winter extremes increasing as polar vortex weakening, spilling cold air**
- **Past statistics poor guide to future catastrophes**
 - *“This event is unprecedented & all impacts are unknown and beyond anything experienced (Harvey)”*

Review: Challenges

- **Capitalism based on fossil fuel & exploiting planet is incompatible with a stable climate**
 - Trillions at stake; enough to bribe politicians
 - A trillion in mitigation saves \$50 trillion this century
 - Yet resistance to escalating carbon tax
 - Suppression of climate change science
 - *Global Rebellion has started*
- **Long-term costs now off-scale (\$100's trillions)**
 - No budget to pay them
 - Insufficient funds to rebuild from weather disasters
 - Will need C-tax to keep emergency services running
- *You will be in the front line*
 - *Are you going to sit and watch it happen or help drive change now?*

Discussion

**Talk available at
<http://alanbetts.com>**

Powerful interests threatened

- **Fossil fuels reserves are worth \$20-30T**
 - Big money: “of course we will burn them”
 - Regulating or taxing emissions of CO₂ is an ‘unfair cost to the free market’
 - Too bad if the Earth’s ecosystems are destroyed: ‘others’ can pay the price (our kids)
- ***US controlled global oil supply/price for 80 years***
 - Fueled ‘fossil’ capitalism and exploitation of the Earth
 - *Hidden by deceit: now driving ‘ecocide’*

“Oil, Power and War” *Matthieu Auzanneau*

March 15, 2019

- School strikes, 123 countries, 1.6 million students, demanding climate action



Next is Sept. 20-27, 2019

Capetown

Greta Thunberg (born Jan 2, 2003)



Swedish parliament last year



Crossing Atlantic in August

On 20 August 2018, Greta Thunberg decided to not attend school until the 2018 Sweden general election on 9 September, after heat waves and wildfires in Sweden. She sat outside the Swedish parliament every day during school hours with the sign *Skolstrejk för klimatet* (*school strike for the climate*), asking the government to comply with its Paris agreement to reduce carbon emissions.

After the general elections, she continued to strike only on Fridays, prompting global 'Friday' protests by students who realized they and their children were to be sacrificed



"we can't change the world by playing by the rules, because the rules have to be changed."

[Fridaysforfuture.org](https://www.fridaysforfuture.org)

Global Strike: Sept. 20-27

Extinction Rebellion

- Destruction of Earth now a Civil Rights issue
 - Can only be checked by civil disobedience
 - To defend the rights of our children
 - To defend the rights of the Earth
- Shut down London 4/15 to 4/17 till UK and Scottish governments declared “Climate Emergency”
- Other countries following <https://rebellion.earth>
 - Large reductions this decade
 - By 2050, illegal to burn fossil carbon
 - “Carbon abolition” movement

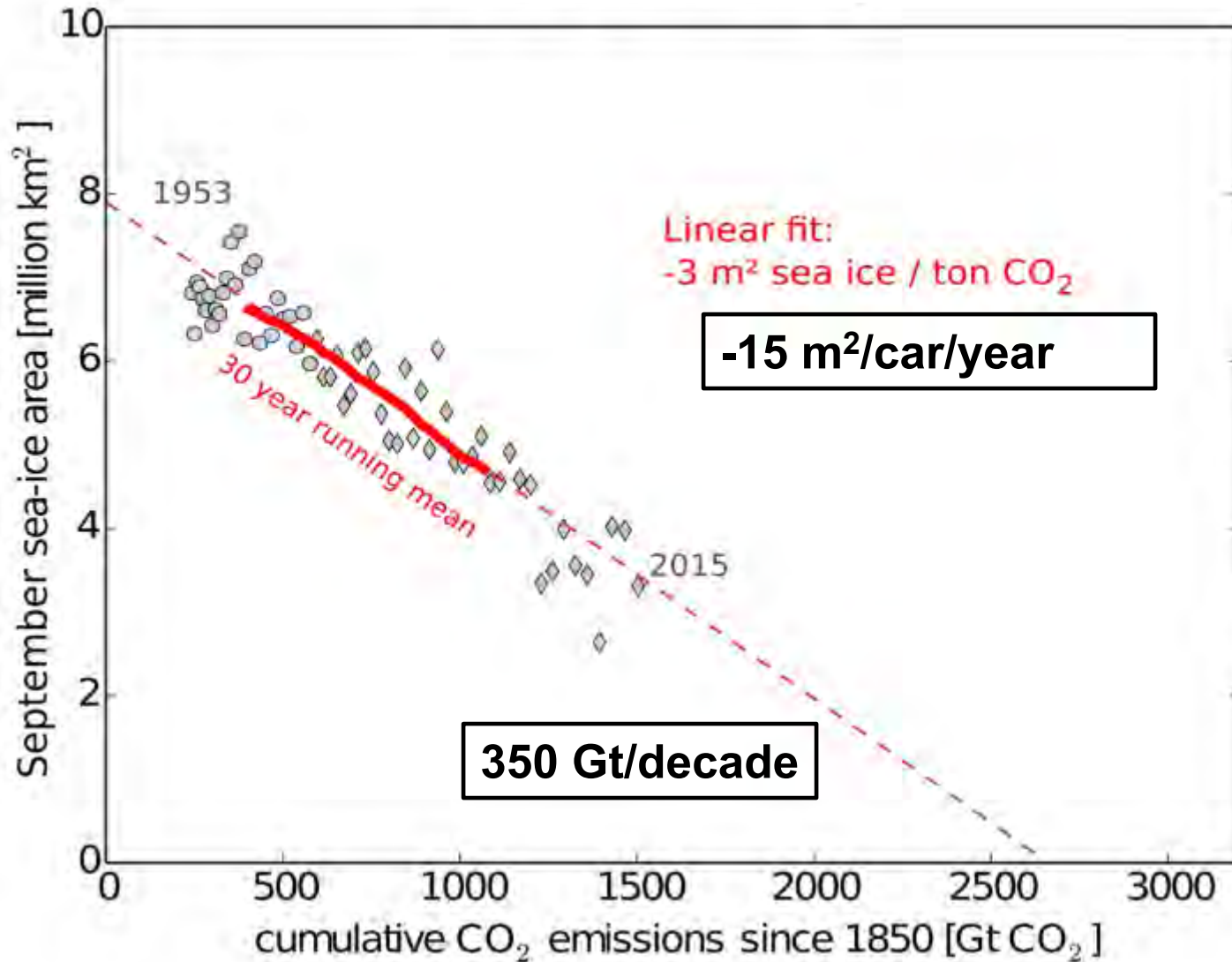
Vermont Groups planning actions: October 2019

- **Half the Arctic Sea Ice Melted in 2012**
- **Open water in Oct. Nov. gives warmer Fall in Northeast**

- *Positive feedbacks:*
- *Less ice, less reflection of sunlight*
- *More evaporation, larger vapor greenhouse effect*
- *Same feedbacks as in our winters*



September Arctic Sea Ice Loss



Efficient transport

- Gasoline to hybrid: 50% gain to 50mpg
- Hybrid to plug-in hybrid: now 135mpg
- Electricity from community solar array



>3000lbs and 135 mpg
Payload: 750 lbs at 60 mph



180lbs: solar panel on roof
Payload: 350lbs at 20 mph

73lb Cargo bike;
300 lbs at 20 mph

