Dealing with Climate Change: Pt 1

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- **Earth sustains life**
- **Weather changes fast**
- **Climate changes slowly**
- **Greenhouse gases keep Earth warm**
- **Burning fossil fuels – coal, oil and gas – is having a big effect on climate by increasing greenhouse gases: CO_2 and H_2O**

January 2, 2012: NASA

Climate Change

- **One of the many great challenges for the 21st century - present path is unsustainable**
- **We are already decades late in taking action**

J. S. Sawyer (1972): Man-made CO_2 and the "greenhouse" effect

Charney Report (1979): Carbon dioxide and Climate

UN Framework Convention on Climate Change (1992) in Rio, Brasil

- To stop "Dangerous Climate Change"

- **It is a global issue & a local issue**
  a societal issue & a personal issue

- **Clash between Earth science**
  and economic & social values

Outline

- **Science of climate change: Part 1**
  - **Global scale: actual and future**
  - **What is happening to Vermont**

- **The transition we face: Part 2**
  - **Managing the earth system**
  - **Why is it difficult?**
  - **How to deal with it**

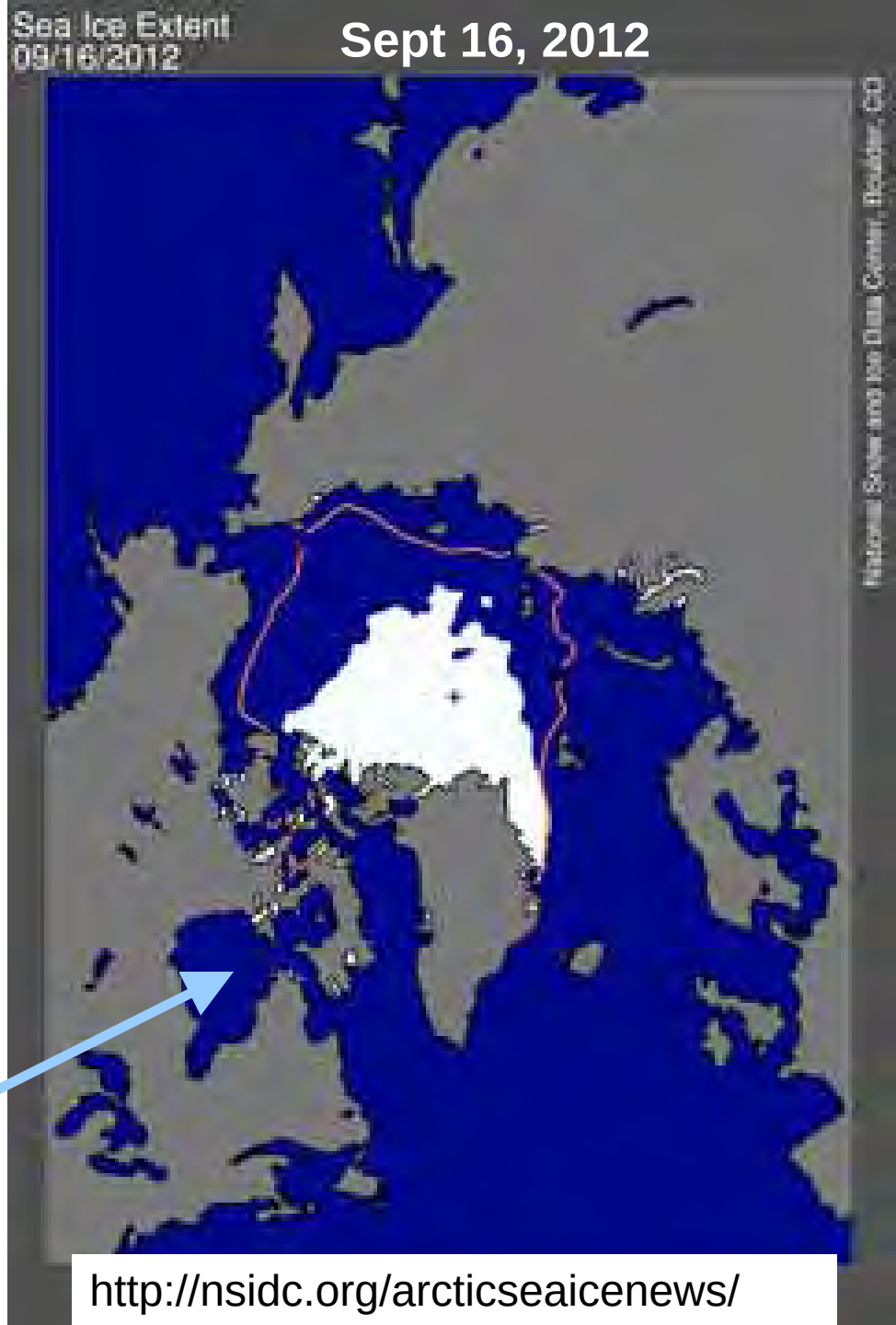
Discussion

- **Half the Arctic Sea Ice Melted in 2012**
  - ***less 2013***

- ***Positive feedbacks:***
- ***Less ice, less reflection of sunlight***
- ***More evaporation, larger vapor greenhouse effect***
- ***Ice thin: most 1-yr-old***

End of Nov. 2011 Hudson Bay was still nearly ice-free:

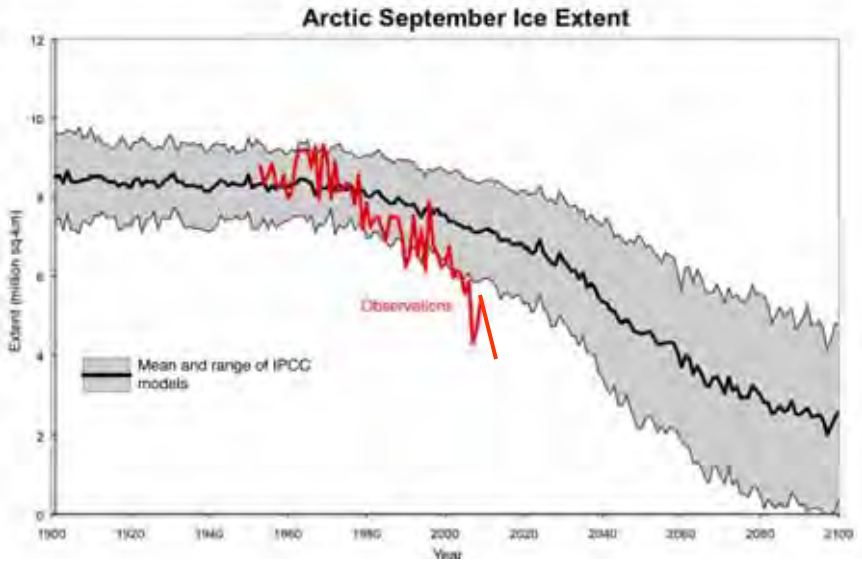
Open water in Oct. Nov. gives warmer Fall in Northeast

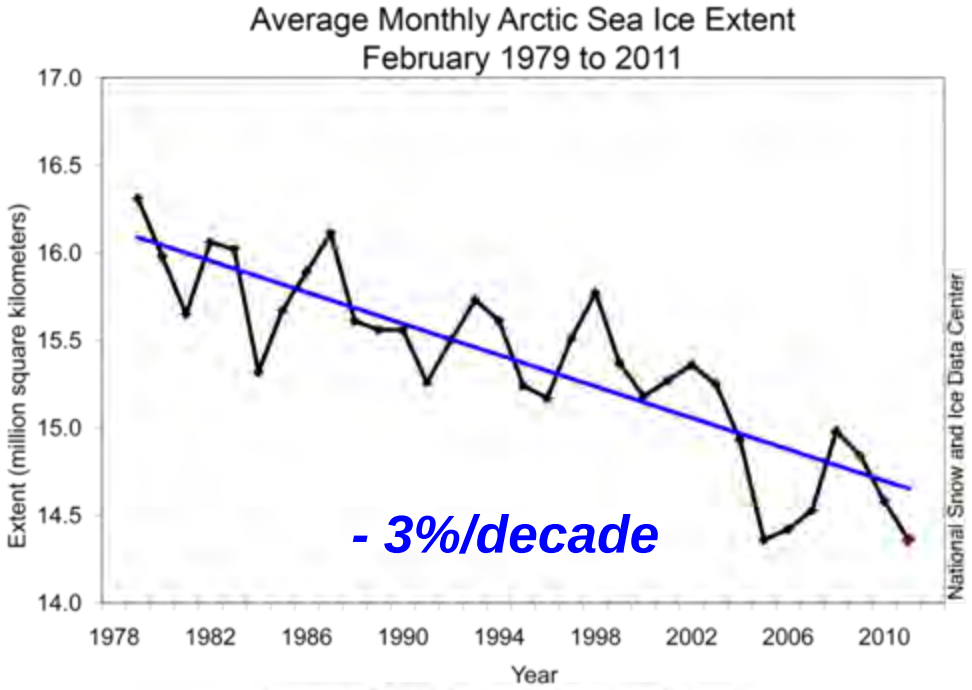


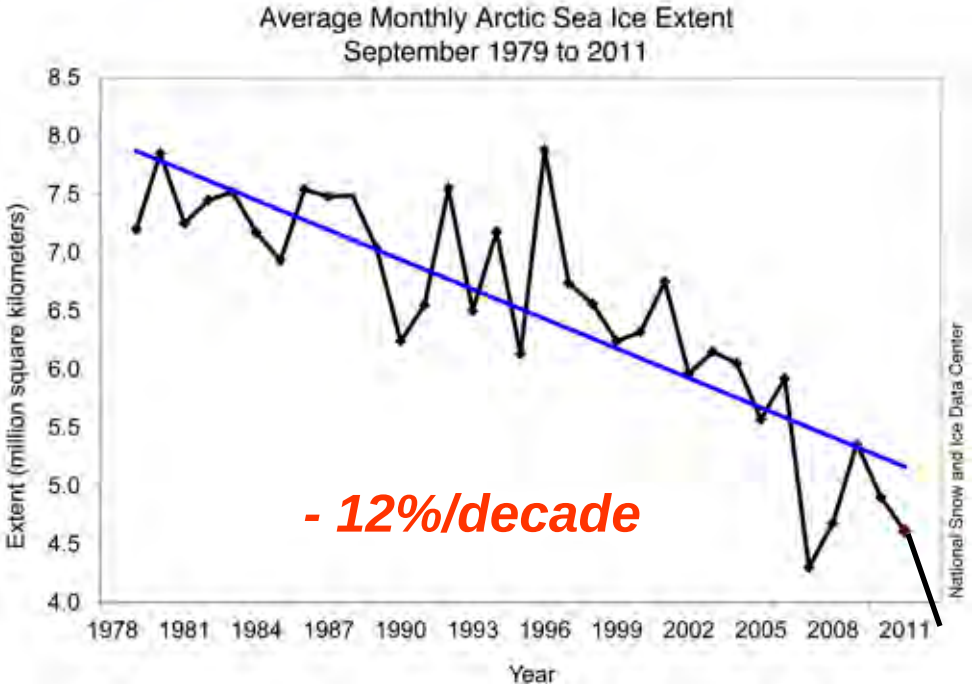
http://nsidc.org/arcticseaicenews/

Sea Ice Trends

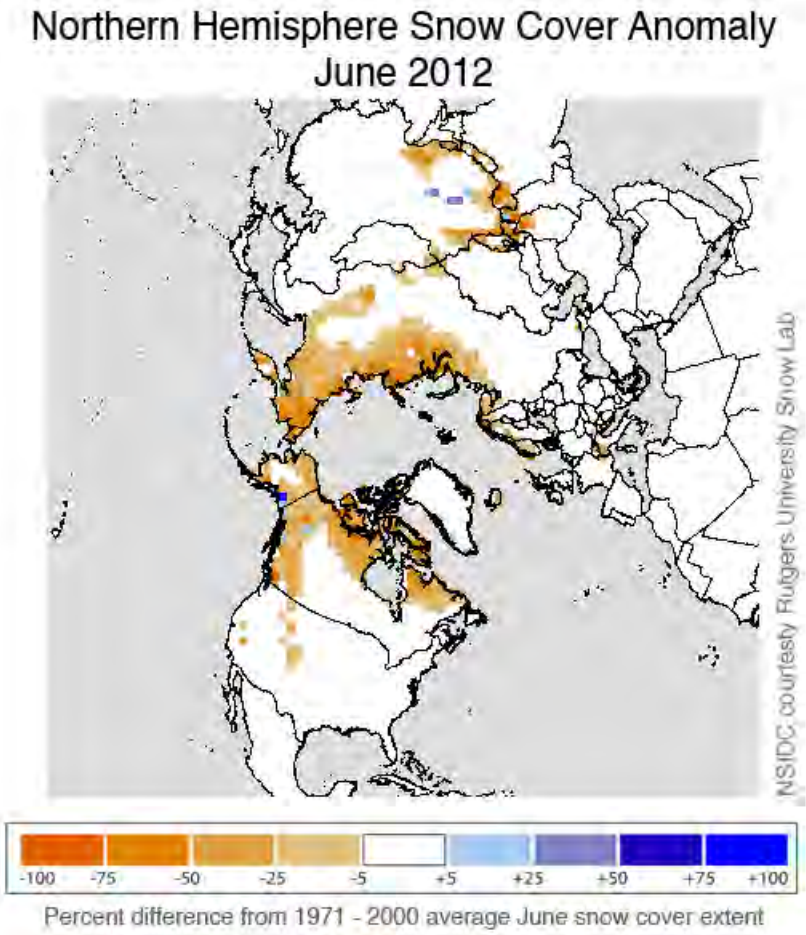
- Sea ice is thinning rapidly
- Observed September decline appears to be faster than IPCC-AR4 climate model projections
- *[AR5 projections should be faster]*

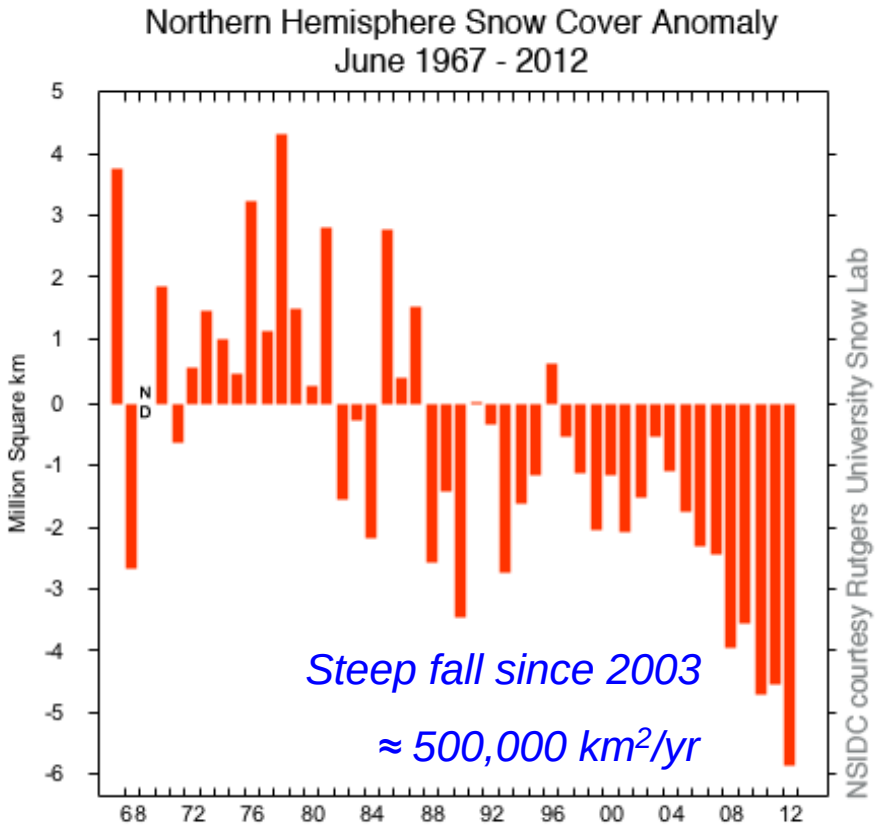






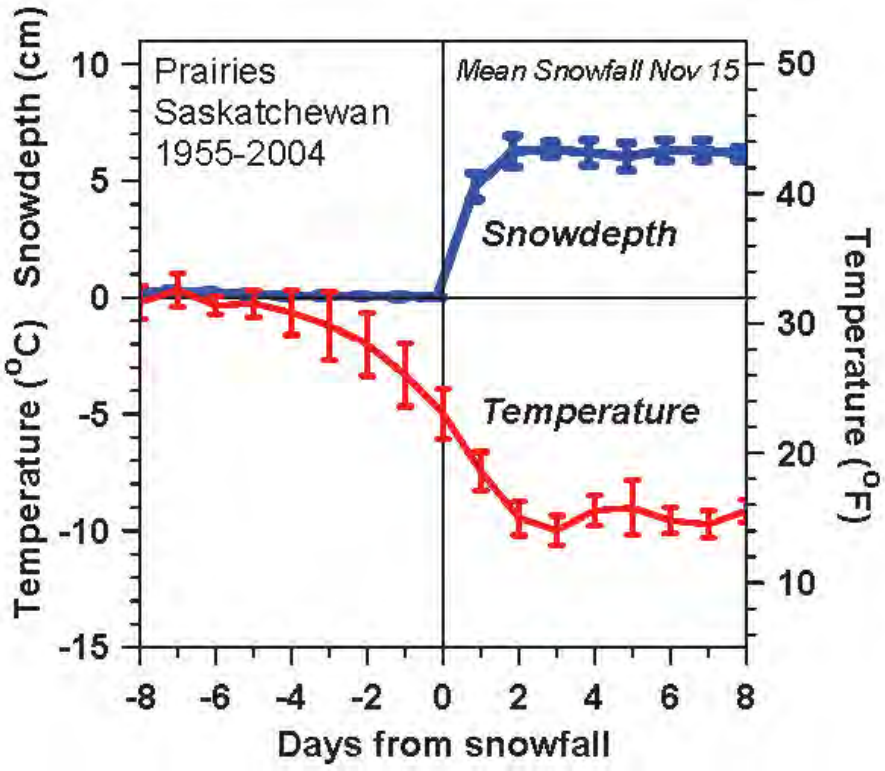
June 2012 snow cover minimum

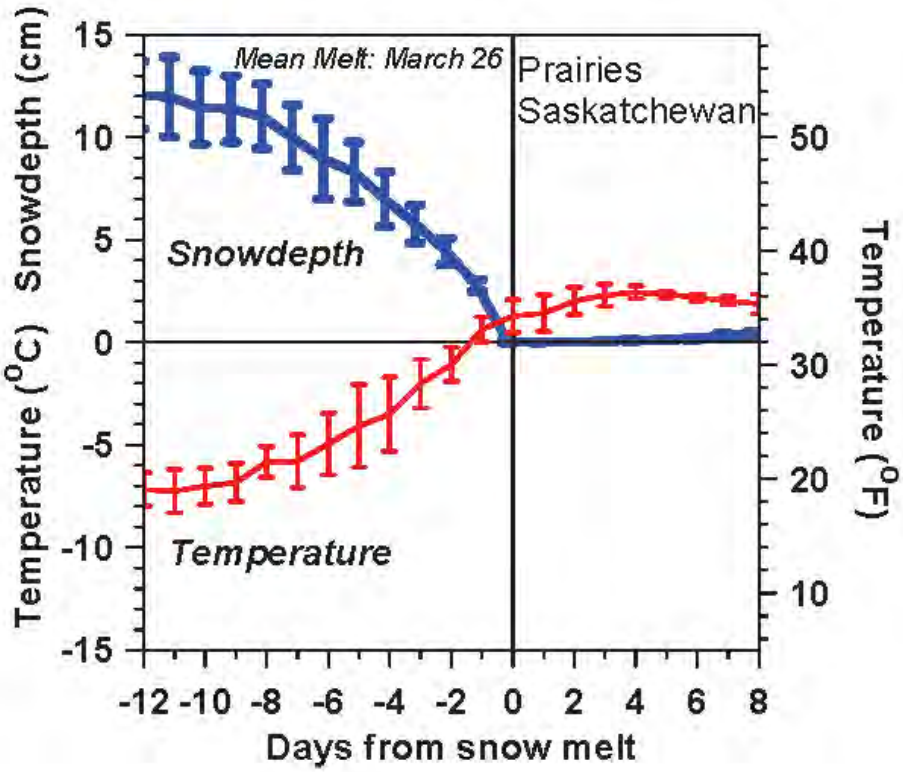




- **Arctic warming rapidly**
  - **Melting fast**
  - ***Much faster than IPCC models***
- **Northeast winters**
  - ***Same positive feedbacks***

Snowfall and Snowmelt



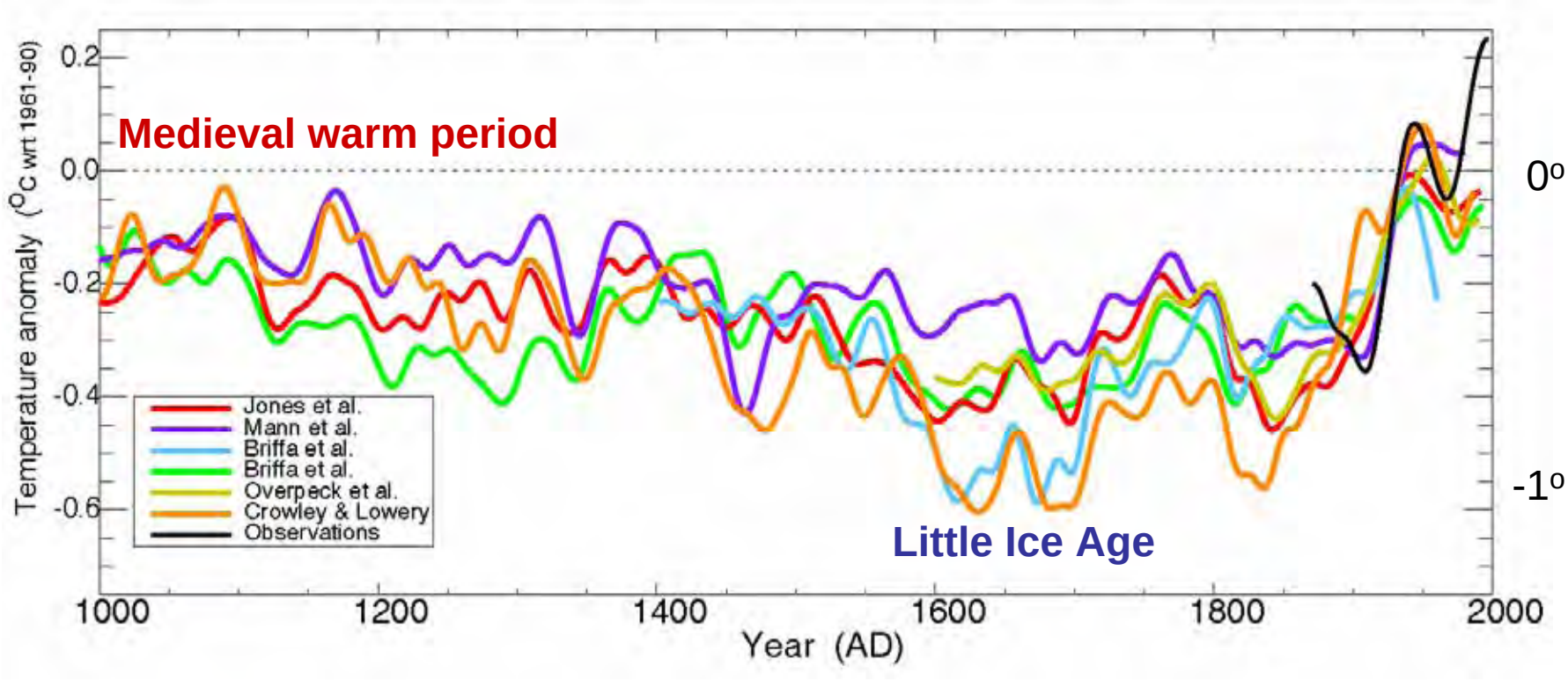


- **Temperature falls 16F (9C) with first snowfall**
- **Similar change with snowmelt**
- ***Snow reflects sunlight; reduces evaporation and water vapor greenhouse – changes 'local climate'***

Betts et al. 2014

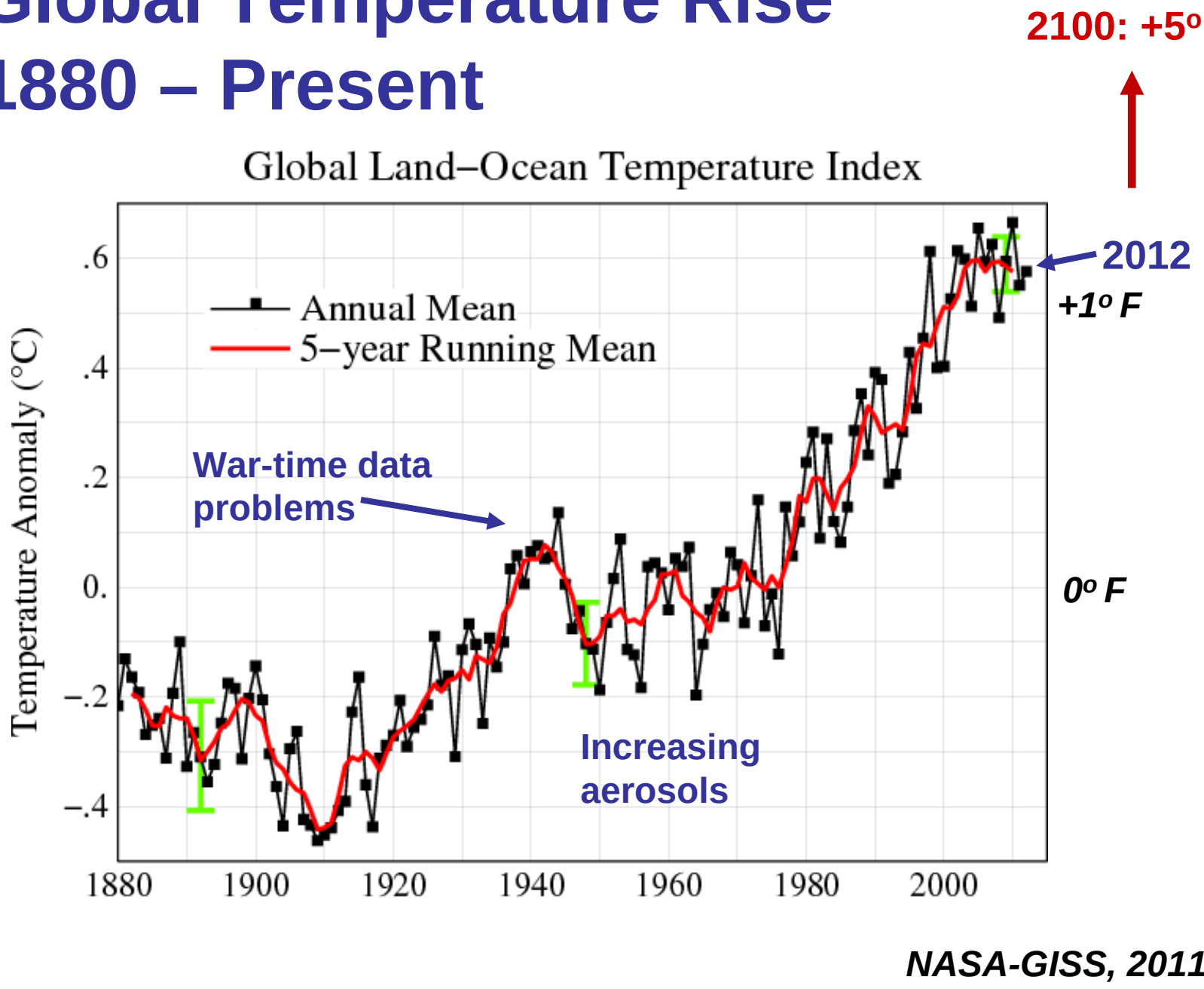
2100: +5°F

Millennial Temperature Record



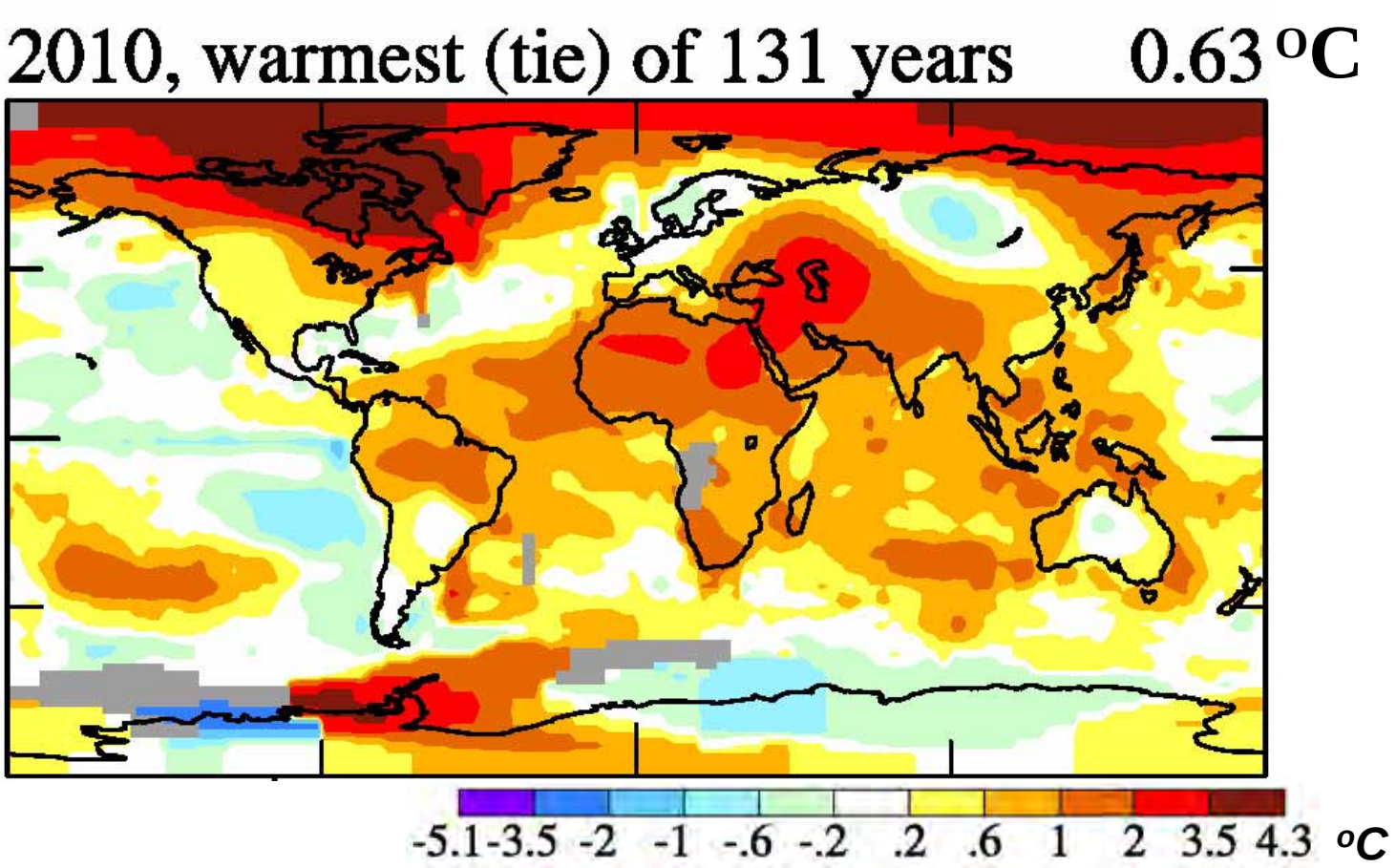
- **"Proxy" records from before the time of thermometers provide uncertain data, but they're all we have**

Global Temperature Rise 1880 – Present



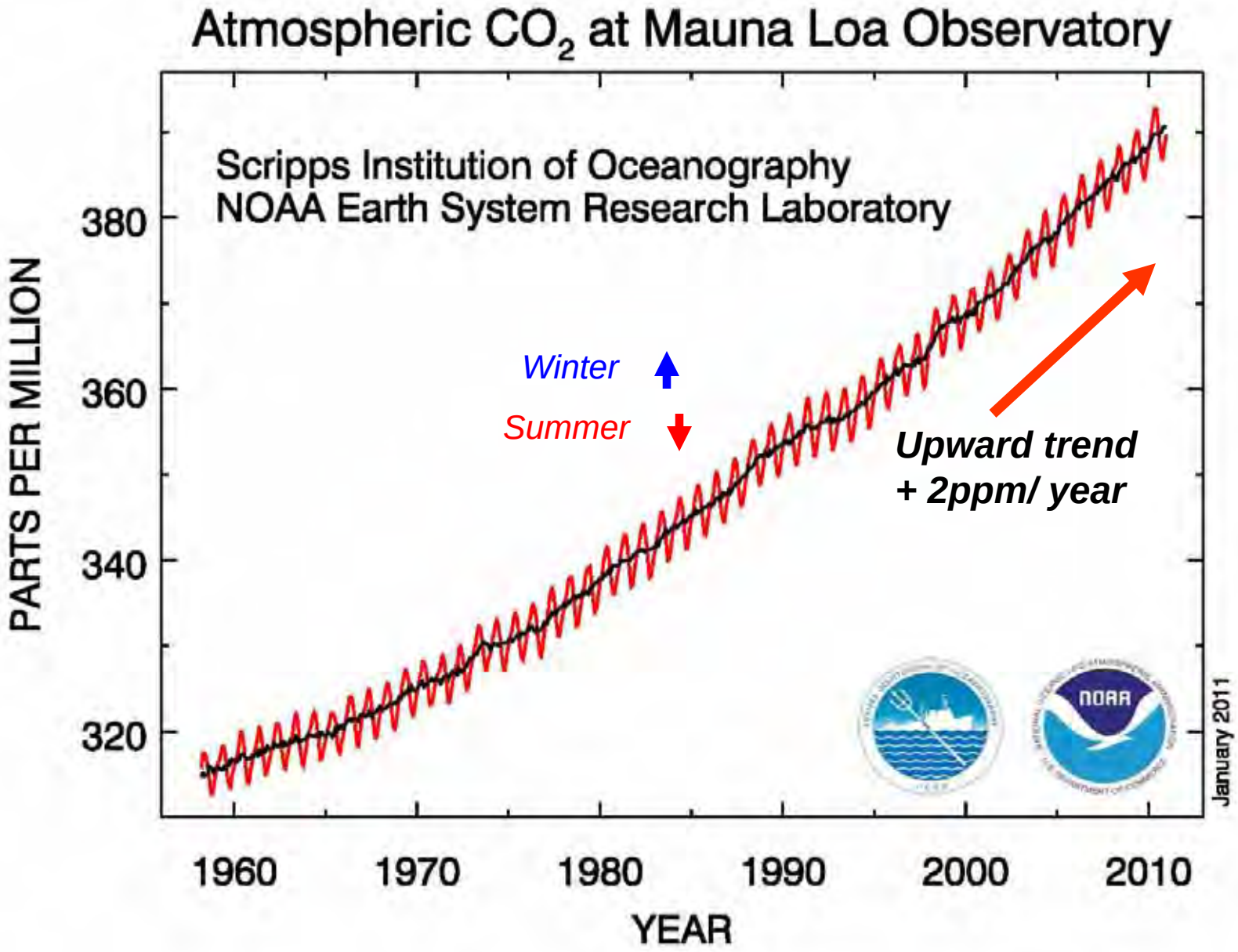
NASA-GISS, 2011

Global Picture 2010



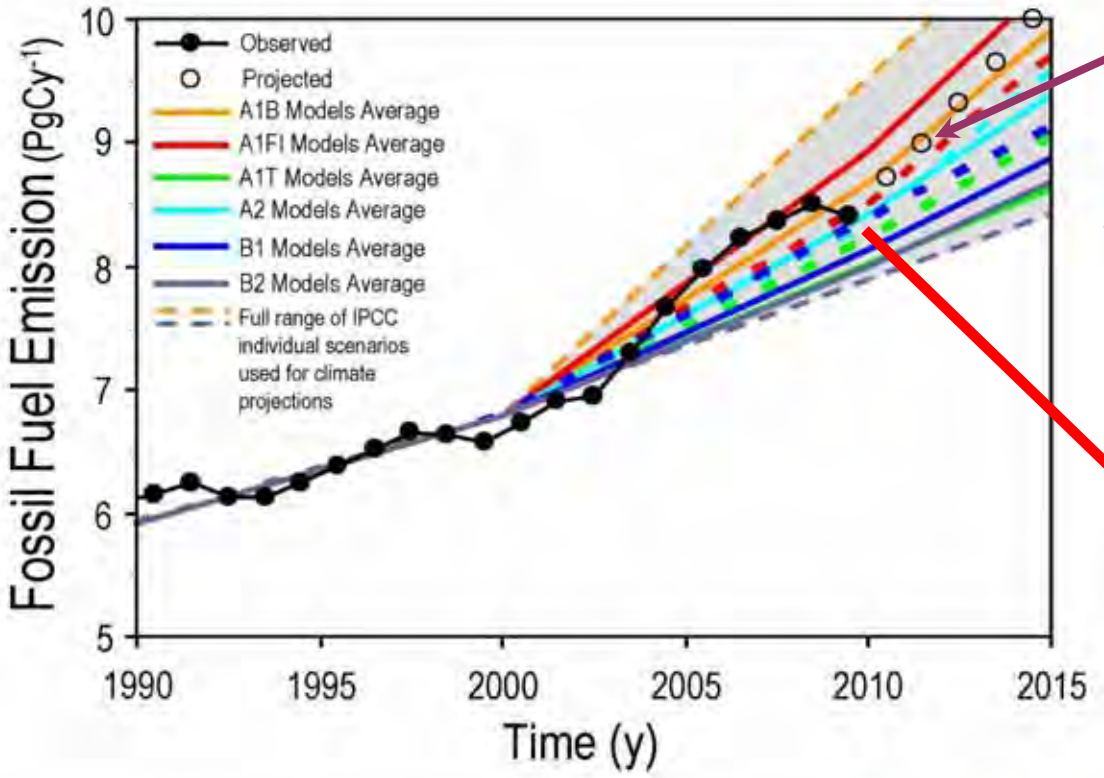
- **Record summer temps**
  - **Russia (100°F) Moscow fires**
  - **Pakistan (128°F) Extreme monsoon floods**

Carbon Dioxide Is Increasing



2009 Was "Good" for the Earth

Fossil Fuel Emissions: Actual vs. IPCC Scenarios



Back on growth: 2010, 2011

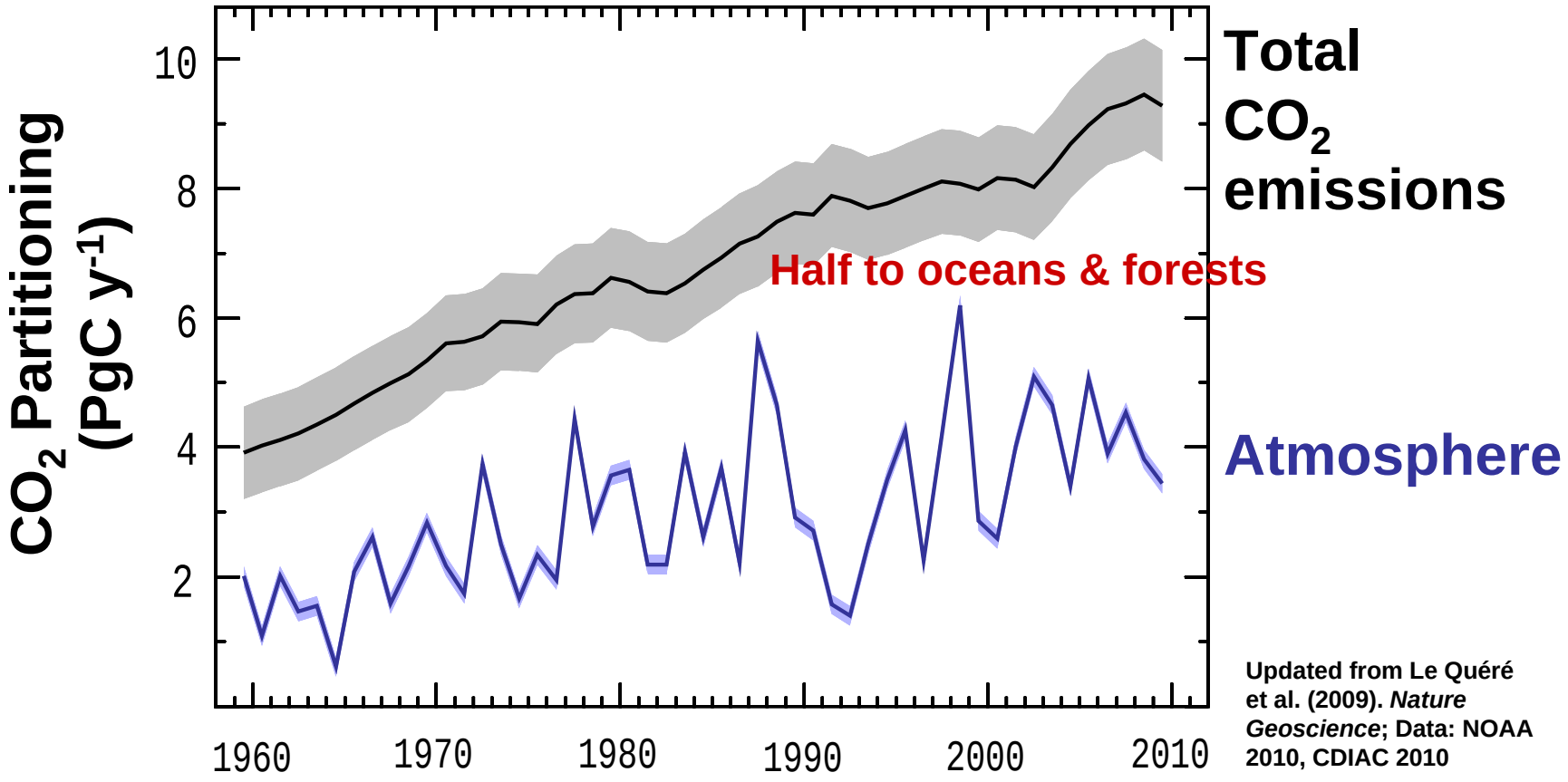
Emission Scenarios

- 4%/year

Updated from Raupach et al. 2007, PNAS; Data: Gregg Marland, Thomas Boden-CDIAC 2010; International Monetary Fund 2010

Key Diagnostic of the Carbon Cycle

Evolution of the fraction of total emissions that remain in the atmosphere

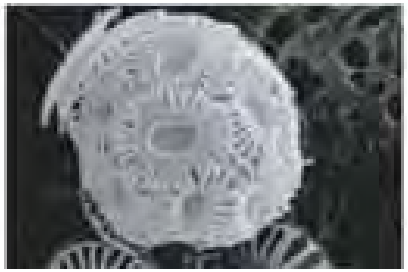


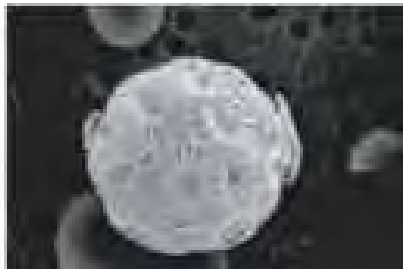
It takes at least a century to remove CO_2 from the atmosphere, and many centuries to remove it from oceans

Rising Ocean Acidity Threatens Organisms

- **From the Tropics to the Arctic, the seas are sucking up emissions of CO_2 — from burned fossil fuels**
- **When CO_2 dissolves in water, carbonic acid is produced; the oceans are becoming more acidic**

(Ruttiman, *Nature,* 31 Aug. 2006)





Why Is More Carbon Dioxide in the Air a Problem?

- **The air is transparent to sunlight, which warms the Earth**
- **But some gases in the air trap the Earth's heat , reradiate down, and keep the Earth warm (30^{o}C)**
- **These are "Greenhouse gases"- water vapor, carbon dioxide, ozone, methane (H_2O, CO_2, O_3, CH_4, CFCs..)**
- **CO_2 is rising fast: by itself only a small effect**

But as CO_2 Increases, Strong Water Cycle Feedbacks

- **Earth warms, and evaporation and water vapor in the air increases and this triples the warming**
- **As Earth warms, snow and ice decrease, so less sunlight is reflected, so winters and the Arctic are warming faster**
- **Doubling CO_2 will warm Earth about 5°F**
  - **Much more in the North, over land, in winter**
  - **Climate change we are seeing in Vermont will continue**

Global Warming Is Unequivocal

IPCC: February 2, 2007 (AR5: 2013-14)

Since 1970, a rise in:

- Global surface temperature
- Lower atmosphere temperatures
- Global sea-surface temperatures
- Global sea level
- Ocean heat content
- Water vapor
- Rainfall intensity
- Extratropical precipitation
- Hurricane intensity
- Drought
- Extreme high temperatures
- Heat waves

Decrease in:

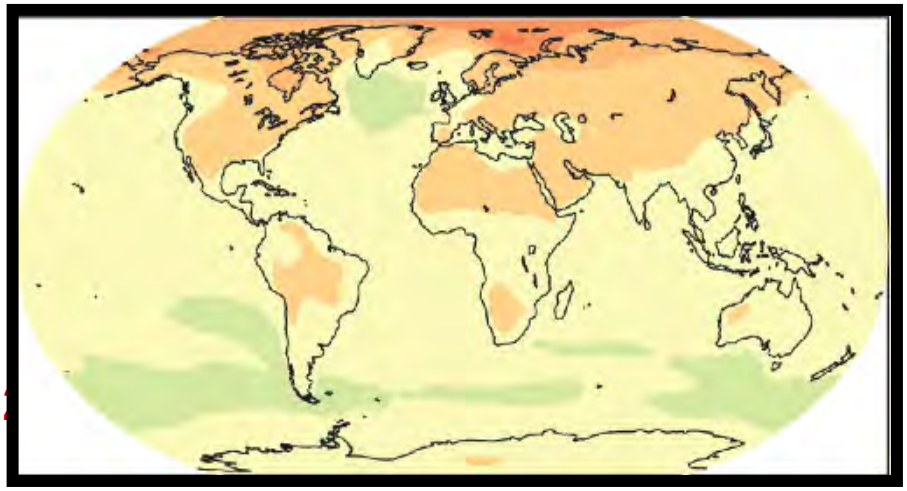
- NH snow extent
- Arctic sea ice
- Glaciers
- Ocean pH (increasing acidity)

(www.ipcc.ch)

Predicted Change in Temperature

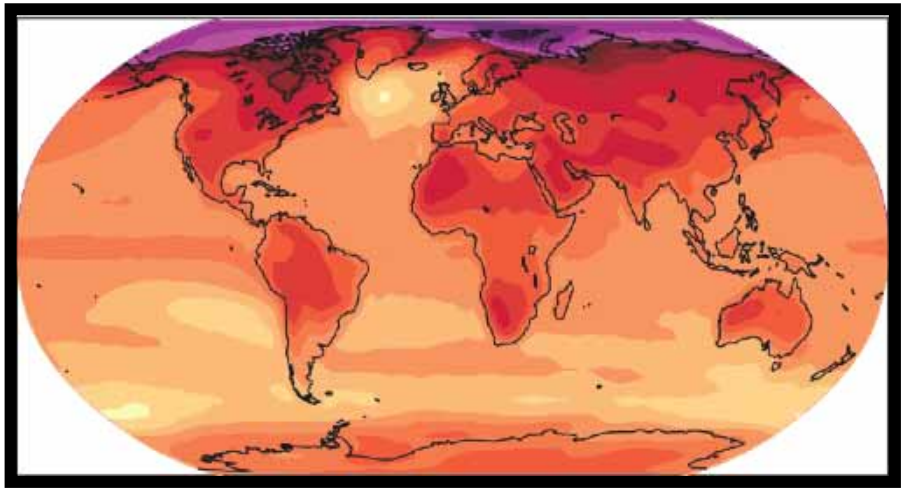
2020-2029 and 2090-2099, relative to 1980-1999 (ºC)

“Committed”

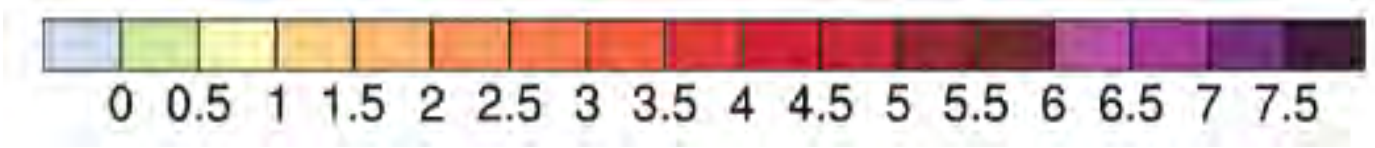


(We did nothing for the last 20 years)

Still up to us!



(We could halve this if we act now)



[ºC]

Sea-level Rise Will Eventually Flood Coastal Cities

- **Late 20th-century sea-level rise: 1 foot / century**
- **21st century: Likely to triple to 3 - 4 feet / century**
  - **And continue for centuries (accelerating for business as usual)**

- ***http://www.nature.com/news/us-northeast-coast-is-hotspot-for-rising-sea-levels-1.10880***

Many Challenges Face Us

- **Extreme weather: Floods, fires, & drought**

  - 32 weather disasters >$1B in 2011

- **Melting Arctic and permafrost—methane release is positive feedback**
- **Ecosystem collapse, including perhaps forest and ocean ecosystems**
- **Collapse of unsustainable human population**

Changes in Vermont

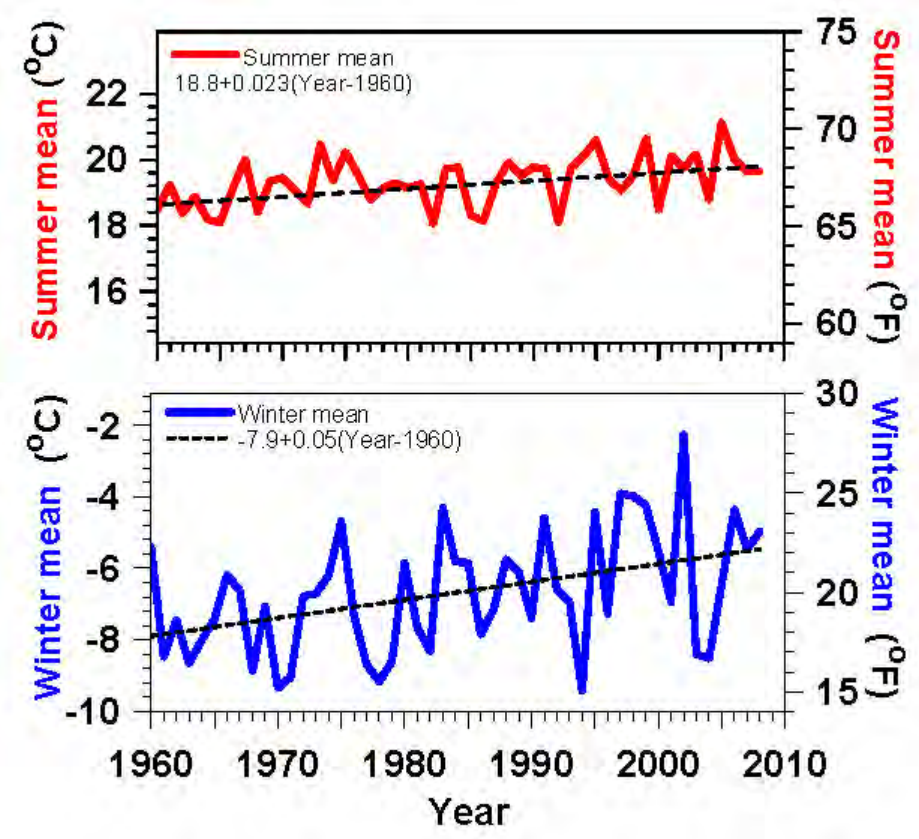
- **PAST 40/50 years** ***(global CO_2 forcing detectible)***
- **Warming twice as fast in winter than summer**
- **Winter minimums increasing even faster**
- **Lakes frozen less by 7 days / decade**
- **Growing season longer by 3-4 days / decade**
- **Spring coming earlier by 2-3 days / decade**

(Betts, 2011)

- **Extreme weather increasing**
- ***Evaporation increases with T***
- ***More 'quasi-stationary weather patterns'***

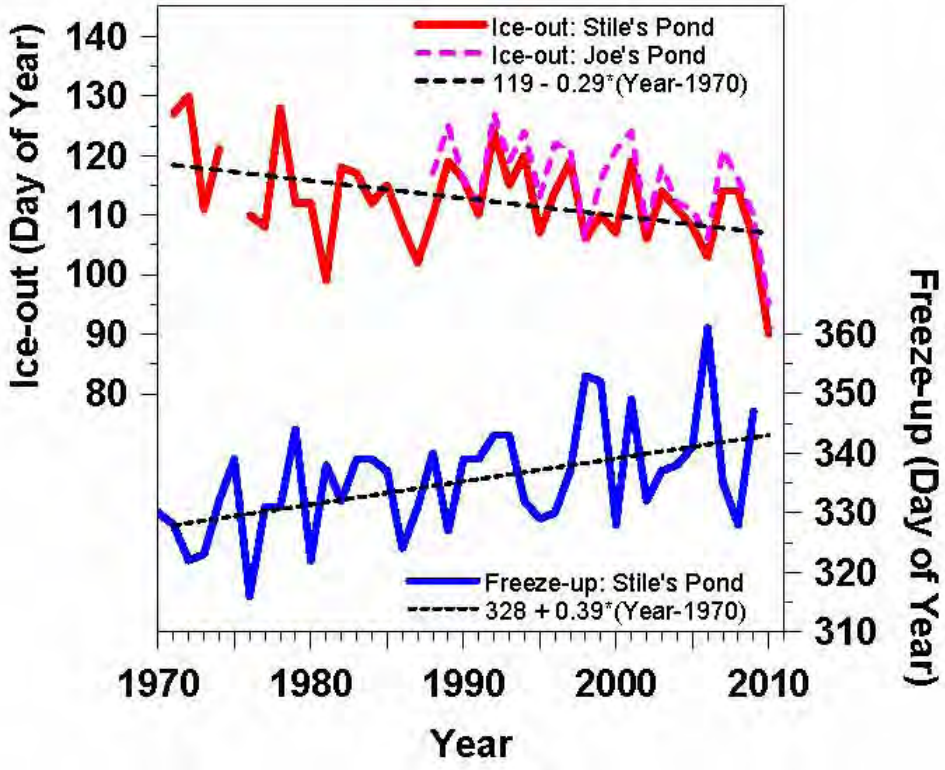
Vermont Temperature Trends
1961-2008

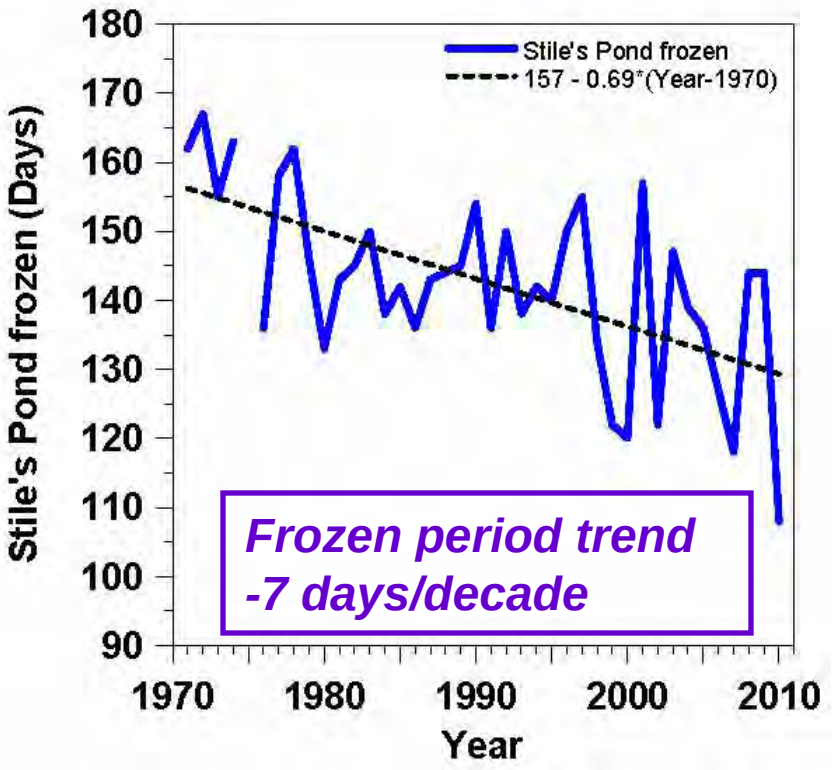
- **Summer +0.4°F / decade**
- **Winter +0.9°F / decade**
- **Larger variability, larger trend**
- ***Less snow (and increased water vapor) drive larger winter warming***



Lake Freeze-up & Ice-out Changing

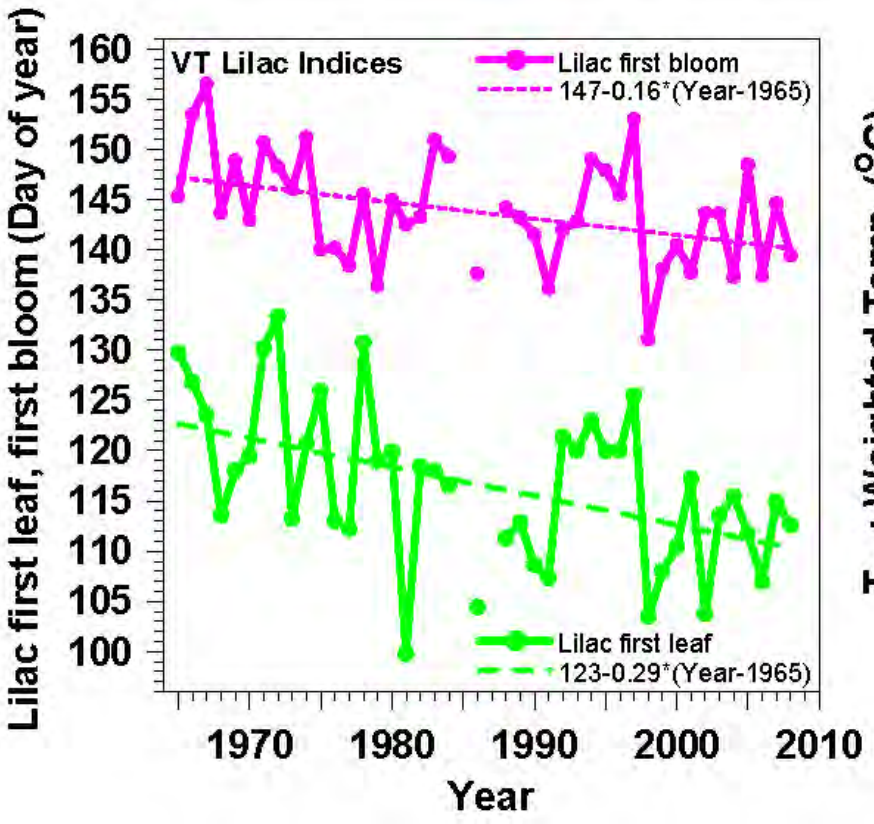
Frozen Period Shrinking Fast

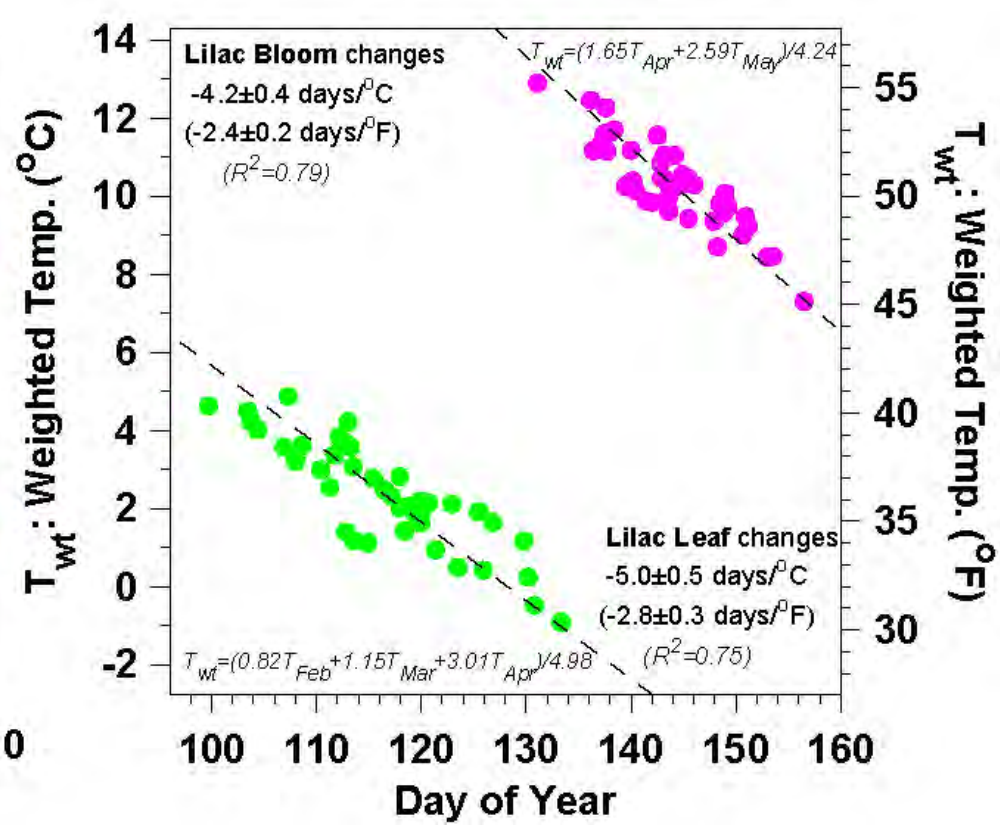




- Ice-out earlier by 3 days / decade
- Freeze-up later by 4 days / decade

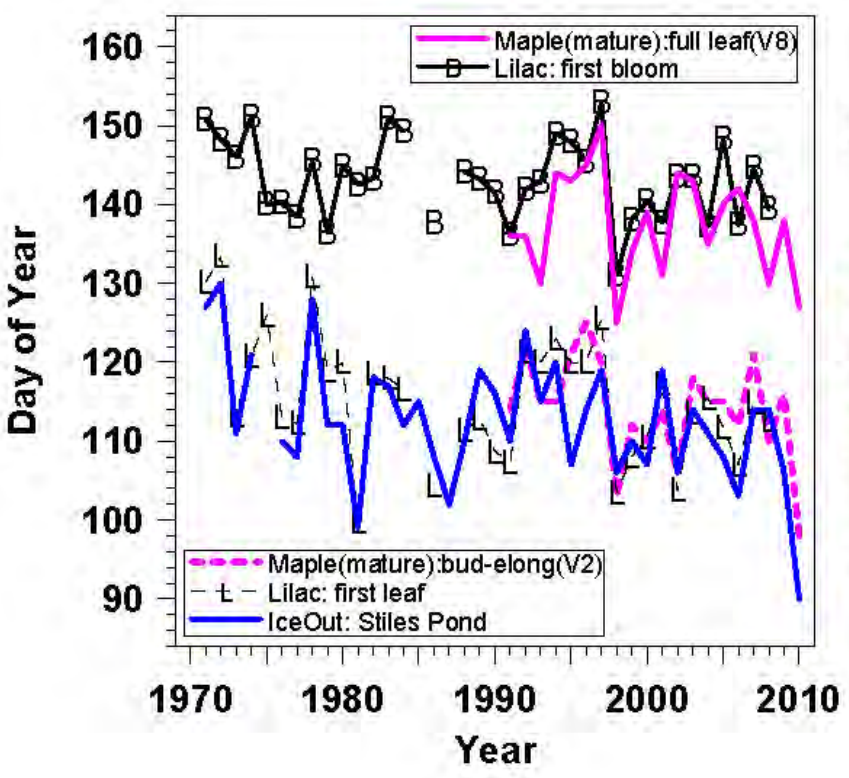
Lilac Leaf and Bloom in Spring

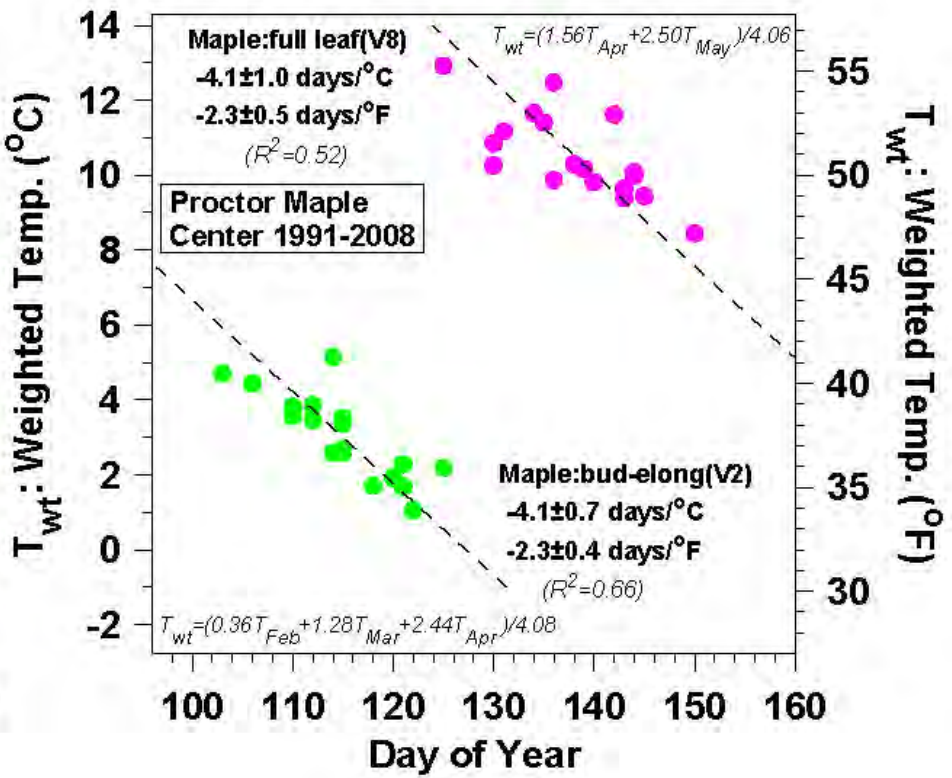




- **Leaf-out earlier by 3 days/decade (tracks ice-out)**
- **Bloom earlier by 1.5 days/decade**
- **Leaf & bloom change 2.5 days/°F (4.5 days/°C)**

Maples and Lilacs in spring





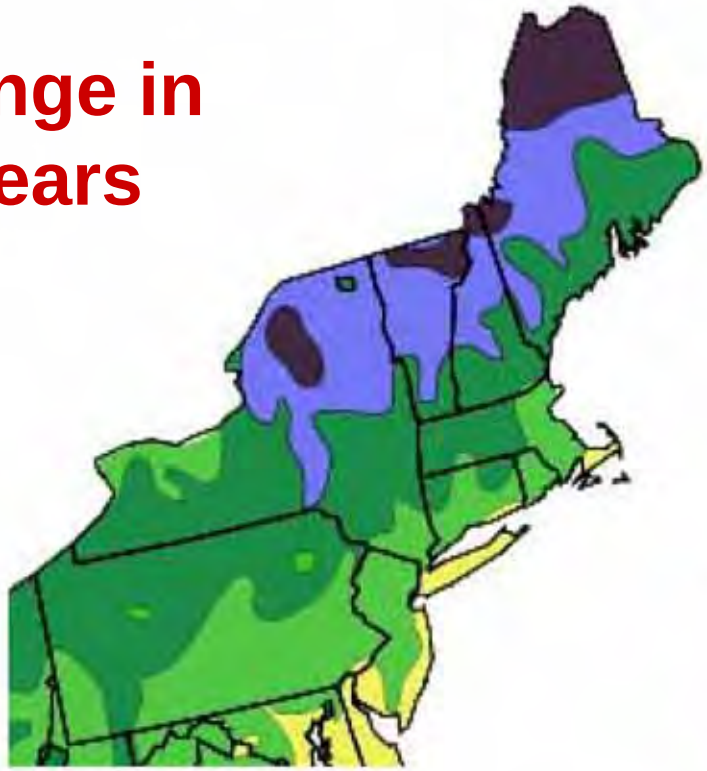
- **Maple bud elongation mirrors lilac leaf**
- **Maple leaf-out mirrors lilac bloom**

Vermont Winter 2006

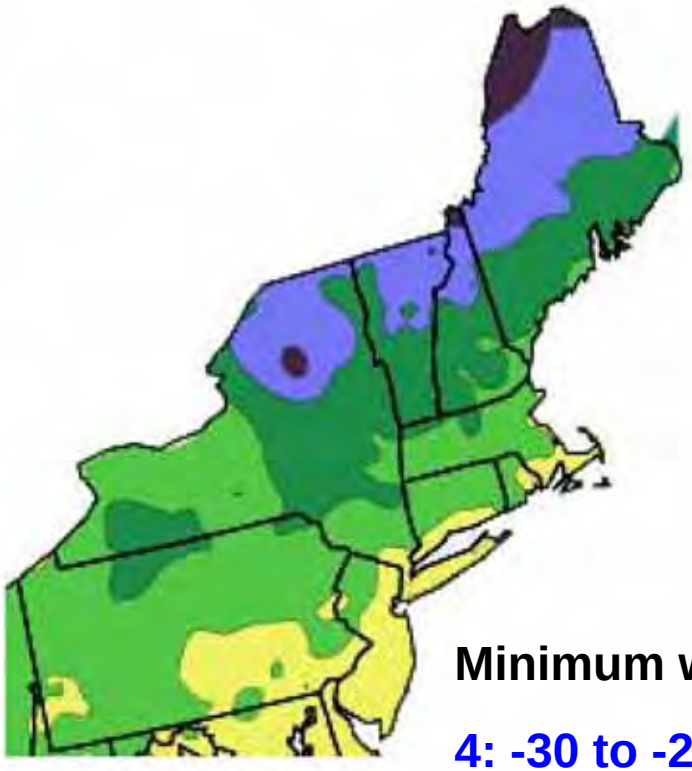
- **Snow reflects sunlight, except where trees shadow**
- **Cold; little evaporation, clear sky; earth cools to space**
- ***2011-12 warm winter, snow melts → positive feedback***
- ***2013-14 more snow and colder***

Winter Hardiness Zones - Northeast

Change in 16 years



1990



2006

Zone

2 3 4 5 6 7 8 9 10

Minimum winter T

4: -30 to -20°F

5: -20 to -10°F

6: -10 to 0°F

USDA Hardiness Zones

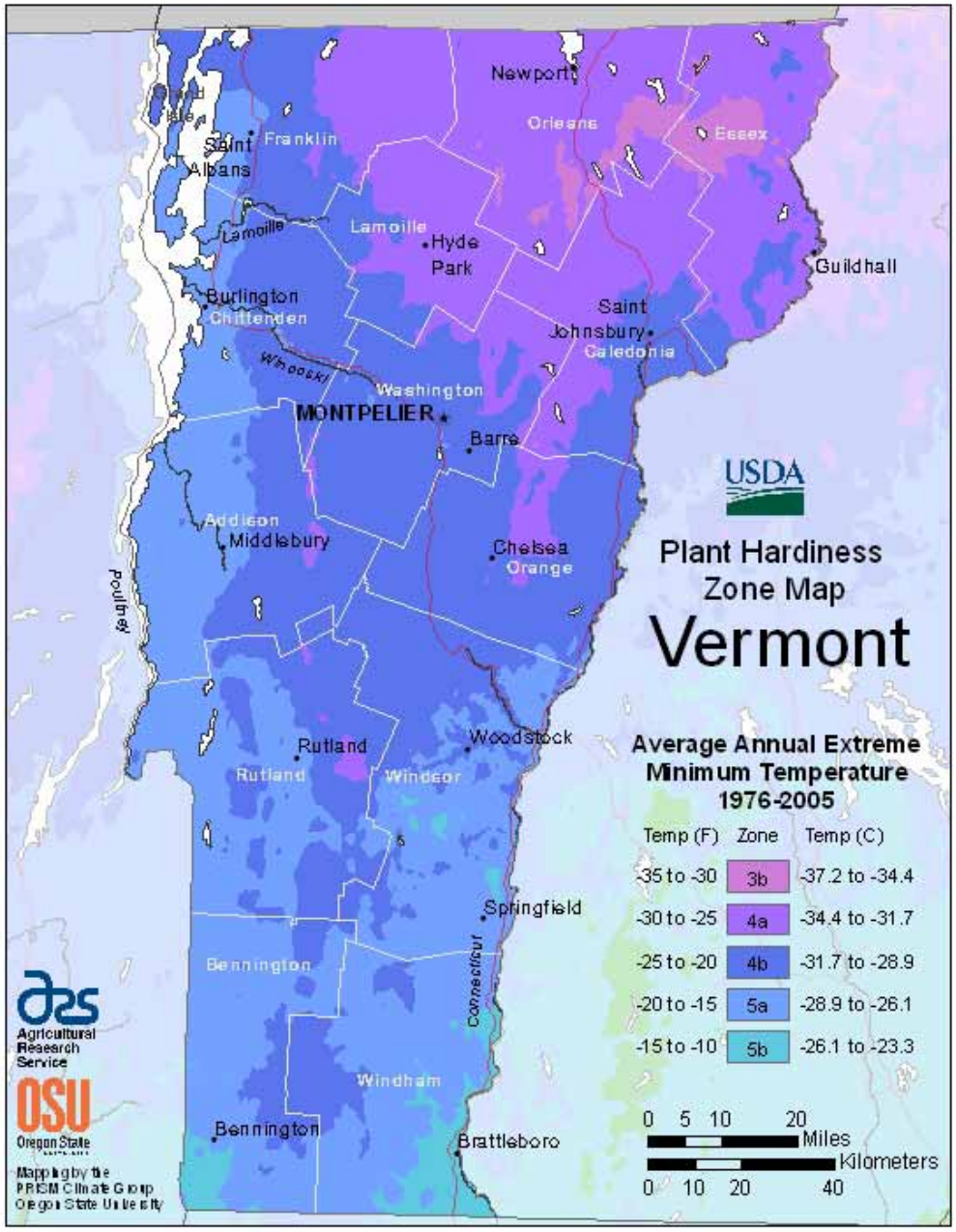
Detailed Map *(most recent)*

- **VT Hardiness Zone Map 1976-2005**
  - **mean 1990**
  - **South now zone 6**

- **Half-zone in 16 yrs = 3.1°F/ decade**
  - ***triple the rise-rate of winter mean T***
  - ***3 zones/century***

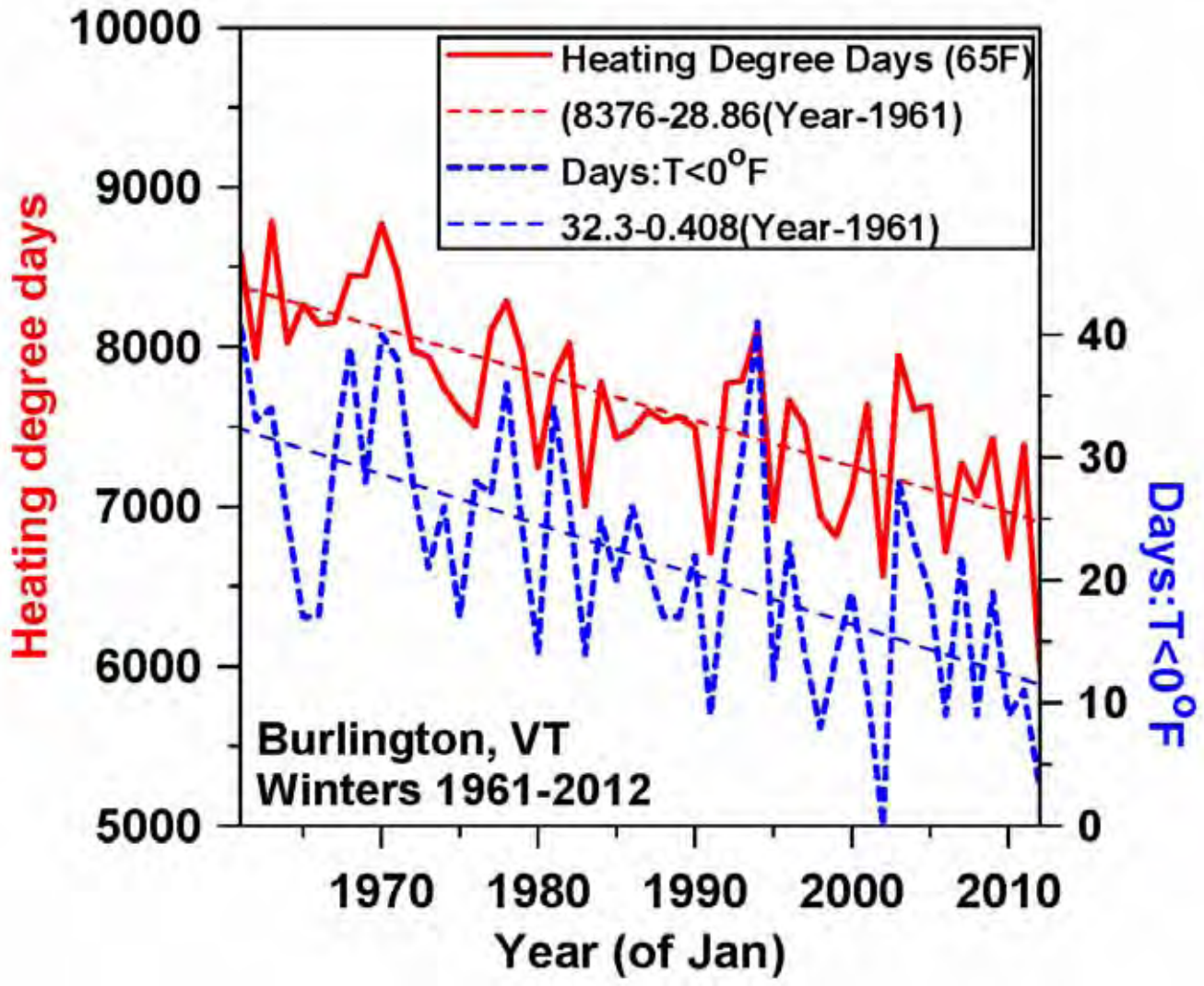
- ***http://planthardiness.ars.usda.gov/PHZMWeb/***

(Krakauer, Adv. Meteor. 2012)



Heating Degree Days and Days below 0°F (Burlington)

- **Heating degree days *falling 290/decade***
- **T_{min}<0°F *falling 4 days /decade***



Bennington & Brattleboro are becoming zone 6 *(T_{min} > -10F)*

- **Hardy peaches: 2012**
- **More pests survive winter**

- **What is this?**
  - **Oct 1, 2012**

Bennington & Brattleboro are becoming zone 6

- **Hardy peaches: 2012**
- **More pests survive winter**

- **What is this?**
  - **Oct 1 2012**

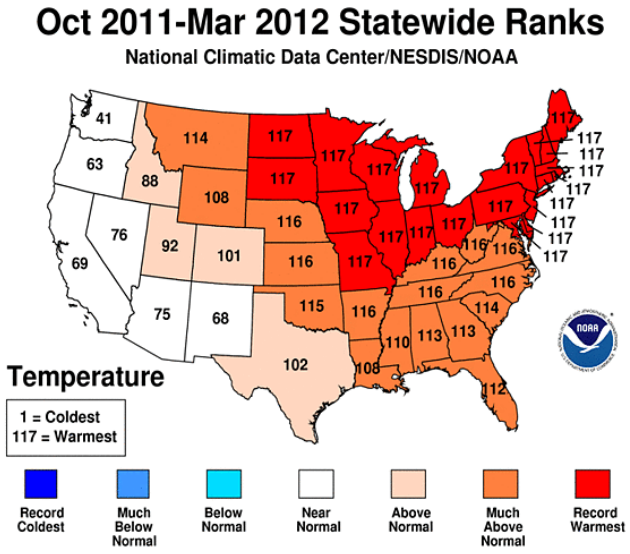
- **Avocado**
  - **Didn't survive frost**
  - **2100 survive in CT**
  - **Our forests?**

January 2, 2012

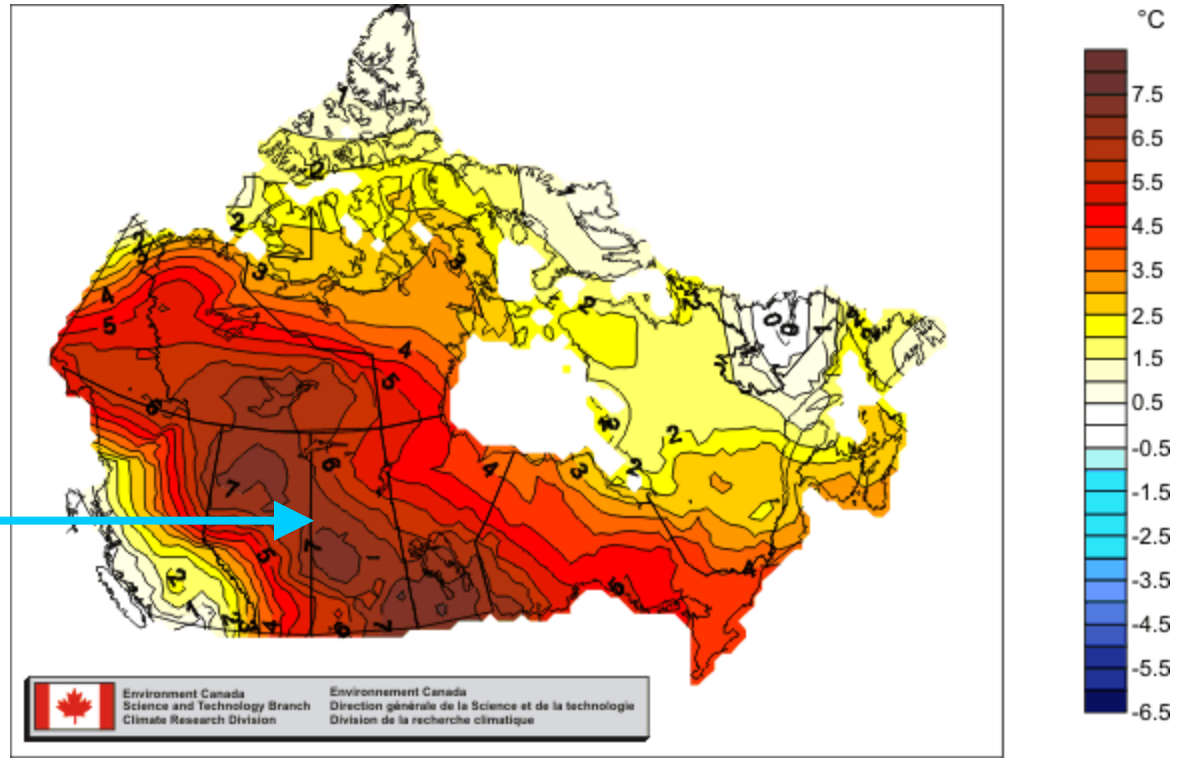
March 11, 2012

October 2011– March 2012

- **Warmest 6 months on record**
- **My garden frozen only 67 days**
- **No permanent snow cover west of Green Mntns**
- **Contrast snowy winter 2010-11**



Across the border: Canada



+12ºF

- **Winter 2011-12: Far above "normal"**
  - **Canada's winters also warming 0.9ºF/decade**
- ***Climate doesn't see the border!***

Early Spring: Daffodils, Forsythia

79ºF on March 22, 2012

Pittsford Vermont

3/22/12

Pittsford Vermont

3/24/12

December 21, 2012

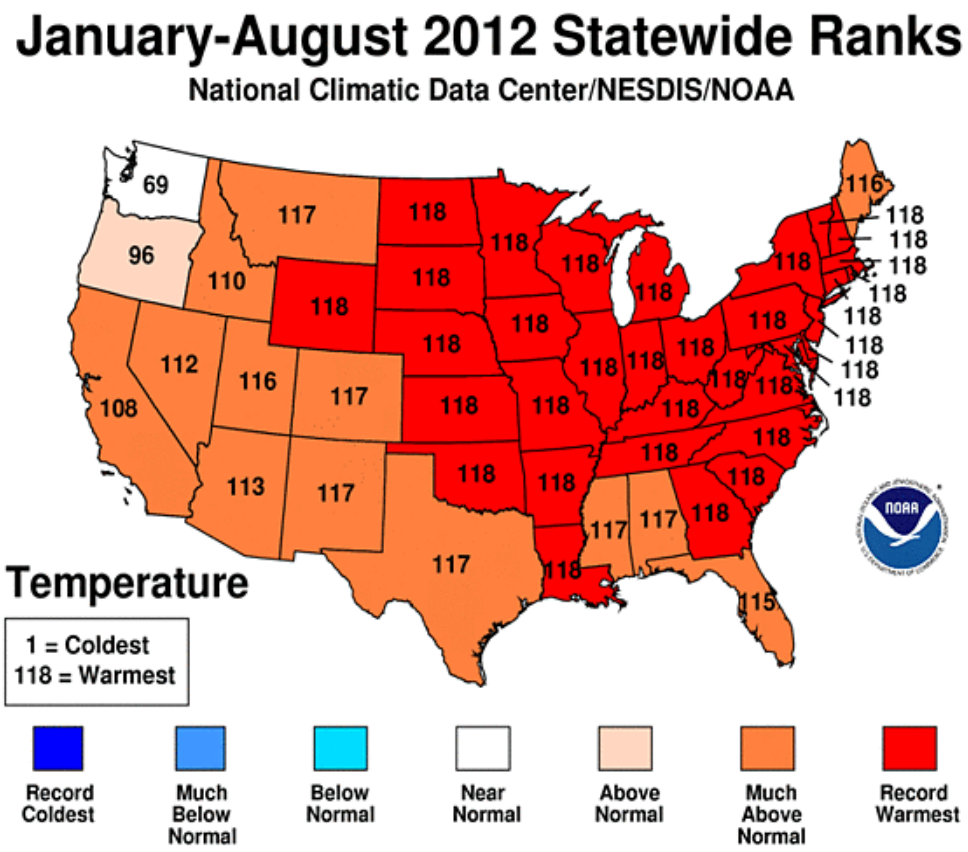
January 15, 2013

Past Winter

- Dec 25: Ground froze hard
- Dec 27-28: Foot of snow
  - Air temperatures plunged but ground thawed under snow
- Jan 12-14: 45-50F: Snow melted
- Jan 15: Time to dig again..
- Followed by freeze-up.. Melt
- Final Melt - March 11

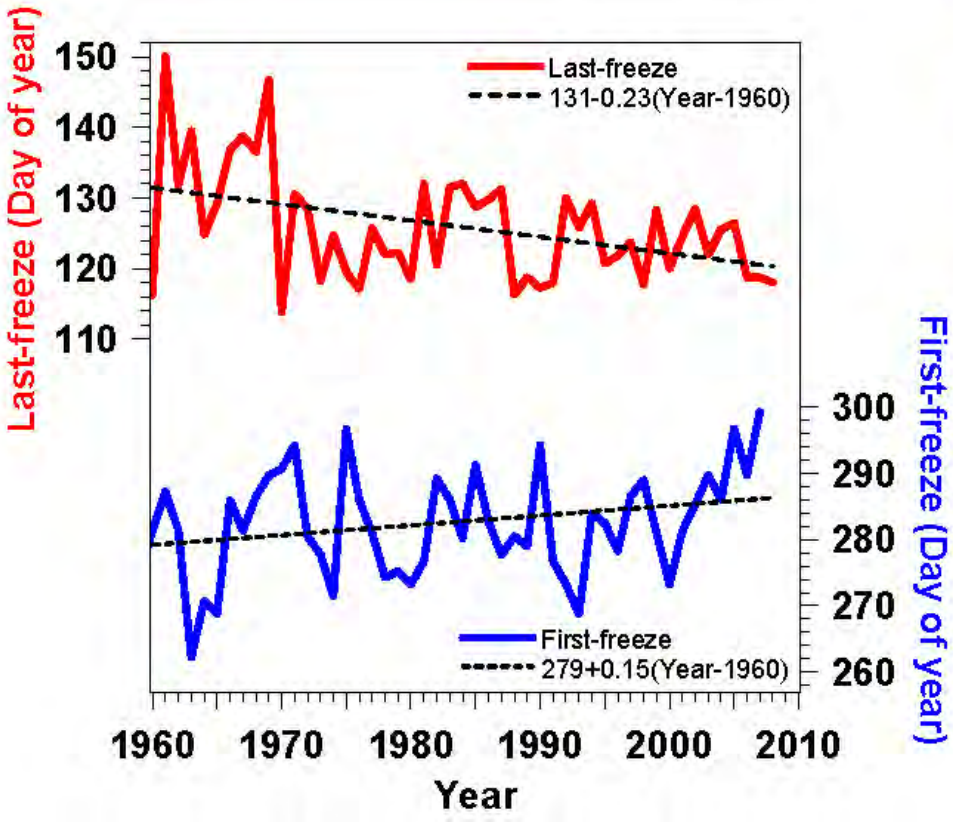
2012 Exceptionally Warm

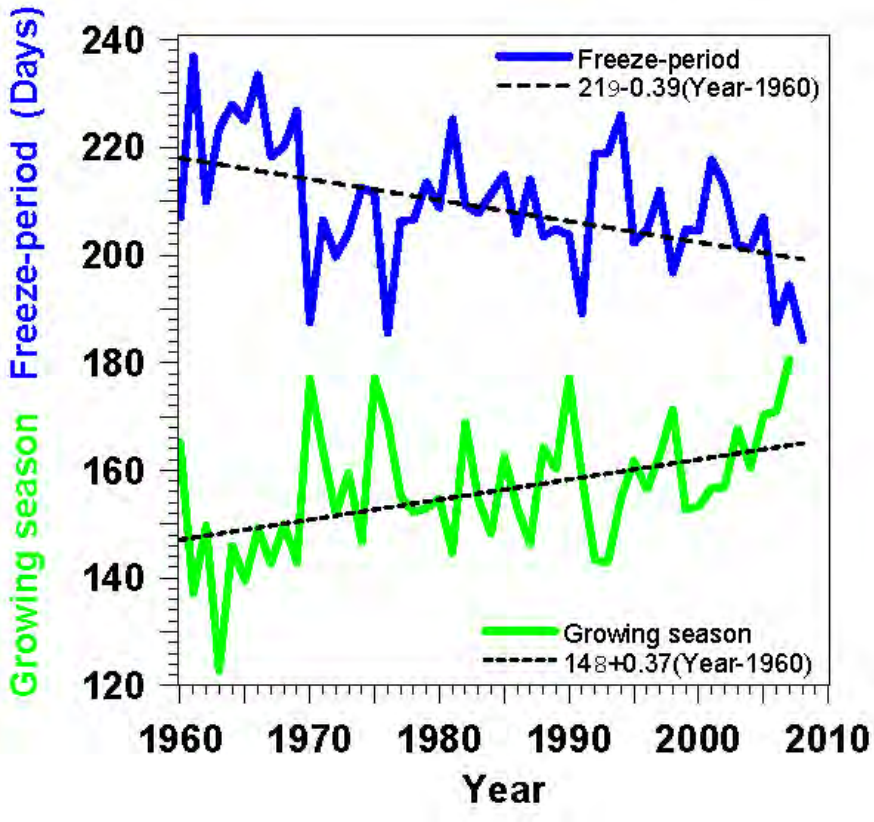
- Burlington Area Extremes
- Highest Average Temperature degrees F
- Days: 9/1/2011 - 8/31/2012
- Length of period: 365 days
- Years: 1850-2012
- Rank Value Ending Date
- **1 50.4 8/31/2012**
- 2 48.4 8/31/2002, 8/31/1949
- 4 48.2 8/31/2010
- 5 48.0 8/31/1999
- 6 47.9 8/31/2006
- 7 47.8 8/31/1991, 8/31/1995
- 9 47.6 8/31/1899, 8/31/1903



http://www.ncdc.noaa.gov/temp-and-precip/maps.php

First and Last Frosts Changing



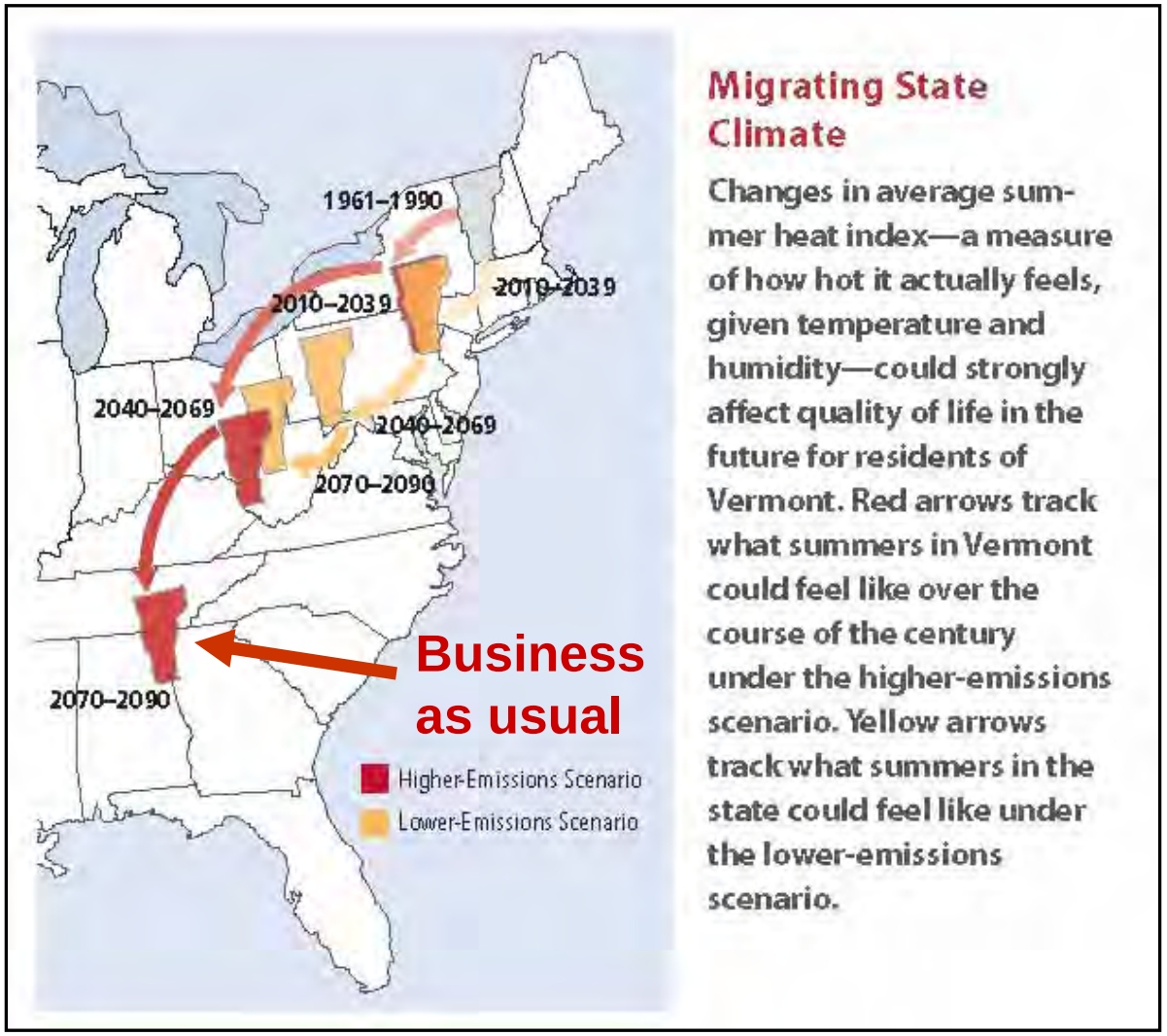


- **Growing season for frost-sensitive plants increasing 3.7 days / decade**
- **A help for growing “local food”**

Vermont's Future with High and Low GHG Emissions

What about skiing?

What about tropics?



NECIA, 2007

Increasing CO_2 is long-lived driver

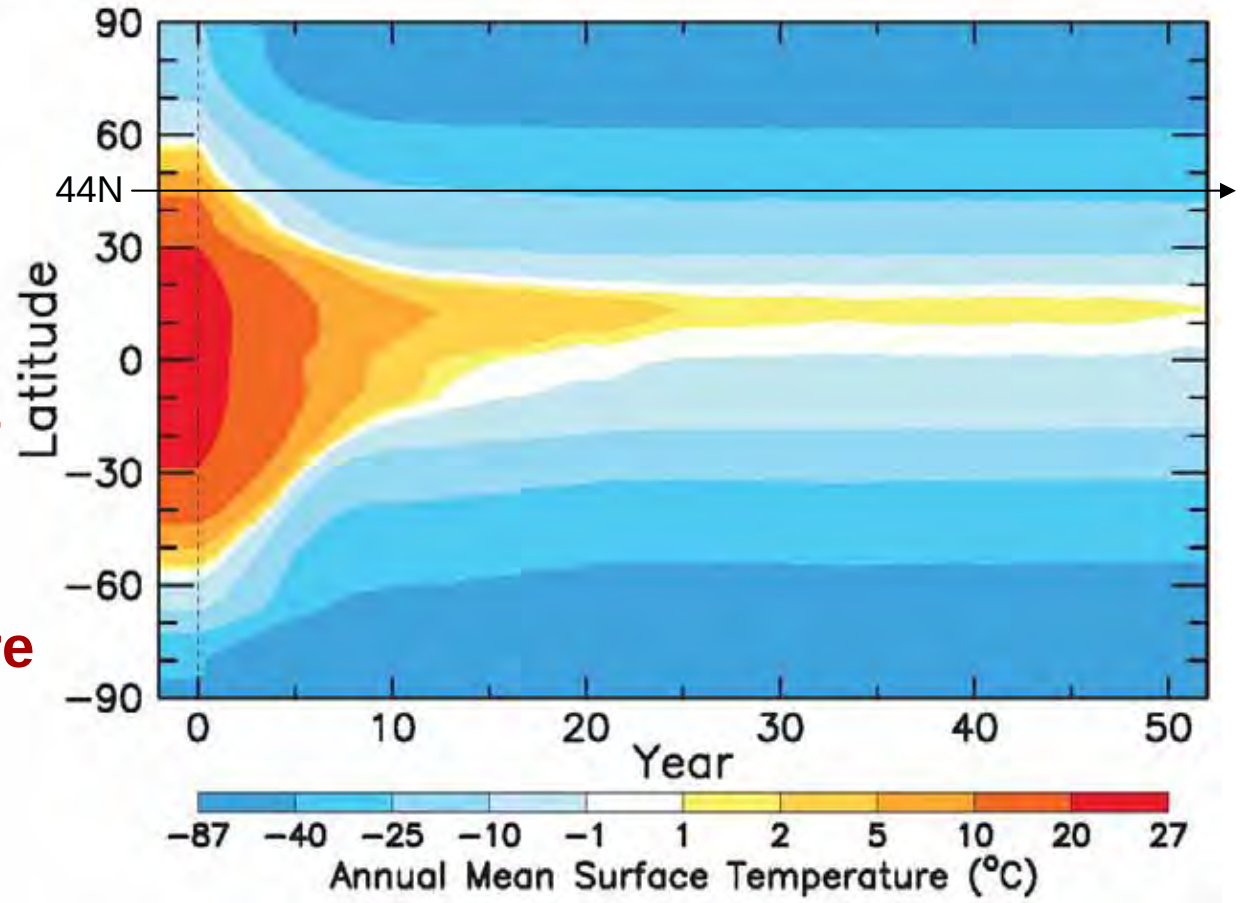
Water: *Strong Positive Feed-backs*

- **GHGs up → Oceans, land warmer → Evaporation up**
- **Water Vapor up**
  - **WV infrared greenhouse up**
    - **Approx triples climate warming of planet**
    - **Locally reduces night-time cooling**
      - **Winter T_{min} increase: less severe winters**
      - **Longer growing season between frosts**
  - **Latent heat release in storms up**
    - **Increases precipitation rates**
      - **Increases precipitation extremes**
    - **Increases wind-speeds and storm damage**
    - **Increases snowfall from coastal storms in winter**
- **Snow and ice down, less sunlight reflected**
    - **Warmer Arctic in summer**
    - **Warmer northern winters**
  - **Less ice-cover: more evaporation**
  - **More lake-effect snowstorms**

CO_2 is the Primary Control Knob in the Climate System

Fig. 3. Zonally averaged annual mean surface temperature change after the zeroing out of noncondensing GHGs.

(Lacis et al., Science, 2010)



Remove CO_2 and other 'non-condensing' GHG from climate model &

Global Temperature plunges

- **Falls 5°C in 1 year; 35°C in 50 years**
- **Water vapor falls 90%; cloud-cover goes to 75%; sea-ice to 50%**

Extreme Weather (precip.)

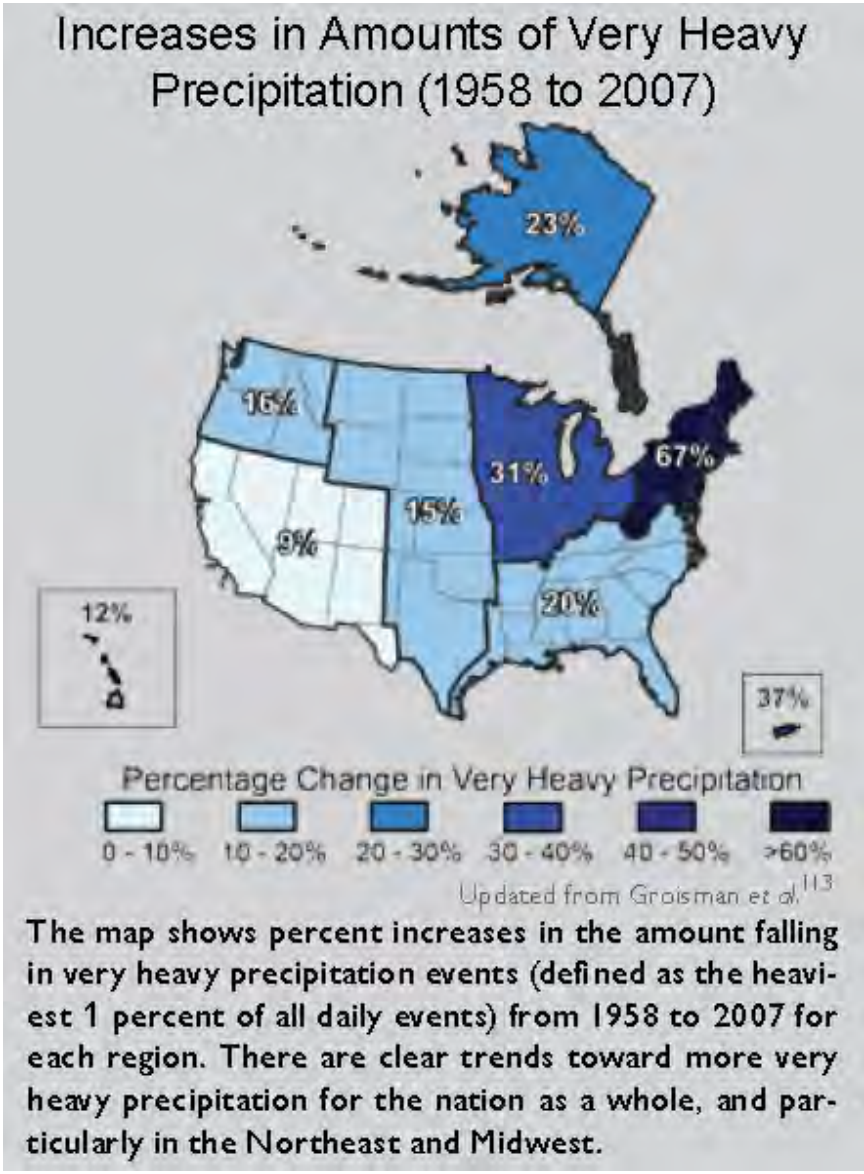
- **Precip. is condensation of atmospheric water vapor - larger latent heat release drives storms**
- ***Saturation vapor pressure at cloud-base increases steeply with temperature (4%/ºF)***

- **Quasi-stationary large-scale flow means longer rain events in low-pressure convergent regions, and longer droughts in high-pressure divergent regions**
- ***As climate changes, quasi-stationary large-scale modes appear to be more frequent***
  - ***Cause may be Arctic warming: needs more study***

Very Heavy Precipitation Is Increasing

(USGCRP, 2009)

- **Precipitation Extremes**
- **Most of the observed increase in precipitation during the last 50 years has come from the increasing frequency and intensity of heavy downpours.**
- **67% increase in Northeast**
- ***Nine out of ten recent summers have been 'wet'***



The map shows percent increases in the amount falling in very heavy precipitation events (defined as the heaviest 1 percent of all daily events) from 1958 to 2007 for each region. There are clear trends toward more very heavy precipitation for the nation as a whole, and particularly in the Northeast and Midwest.

Summer "stormflow" increasing

Most >50%

Lent (2010) USGS, Me

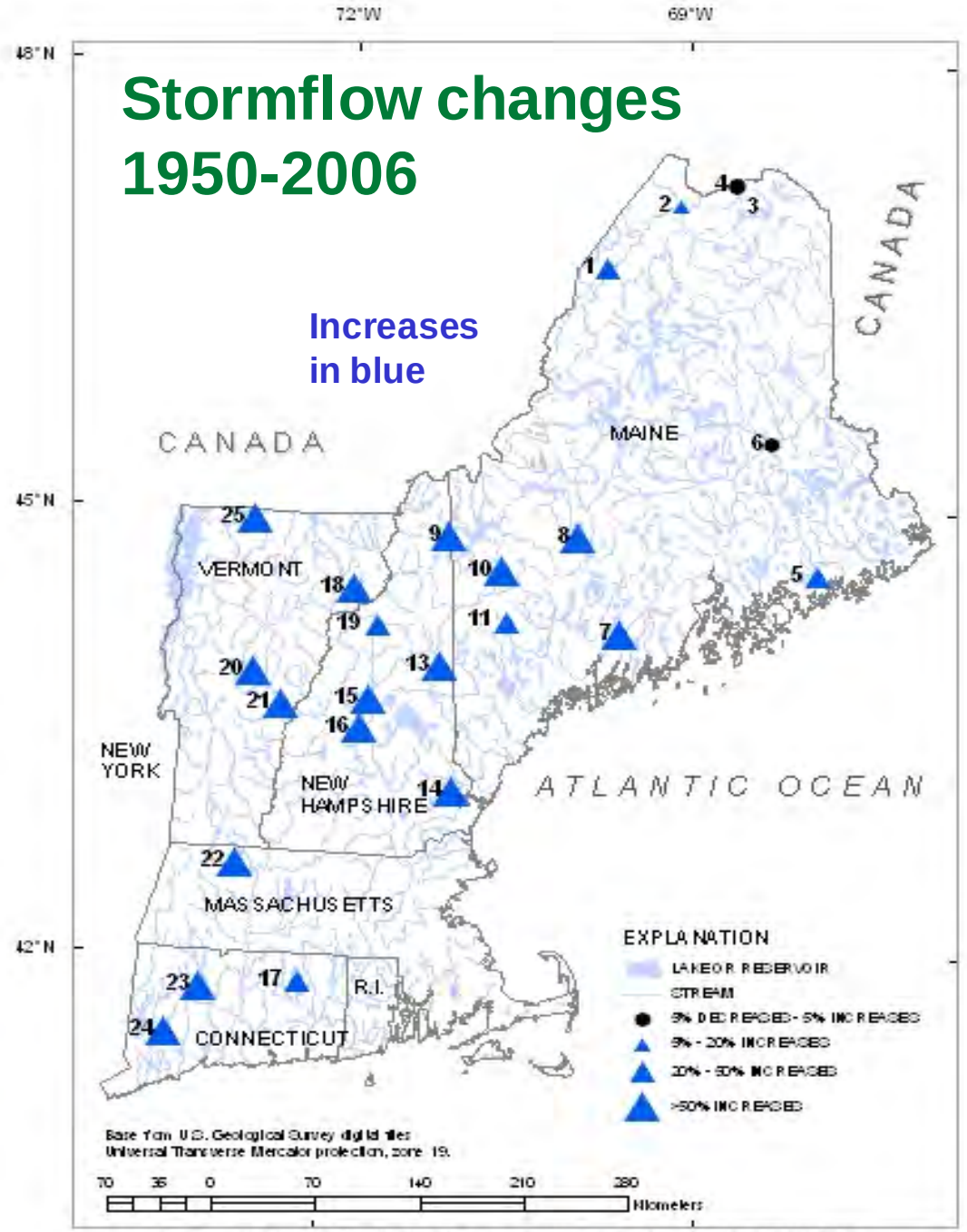
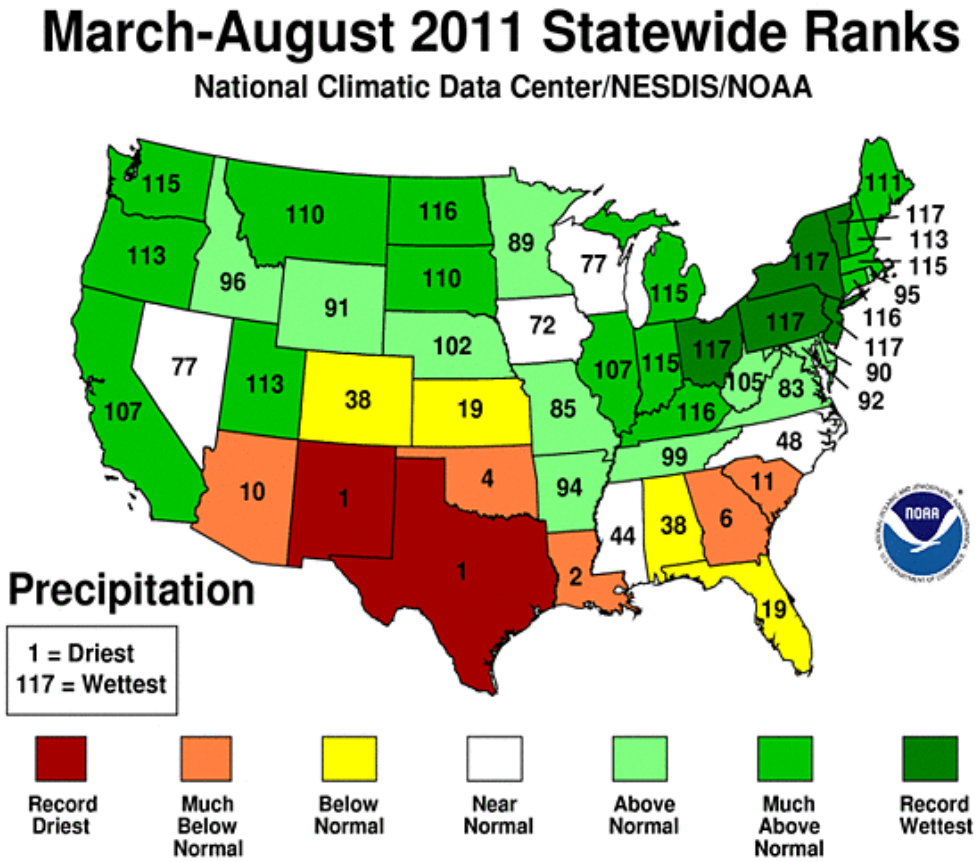


Figure 4. Geographic distribution of summer stormflow trends, 1950-2006.

2011 Floods: VT and NY

- **Record spring flood: Lake Champlain**
- **Record flood with tropical storm Irene**

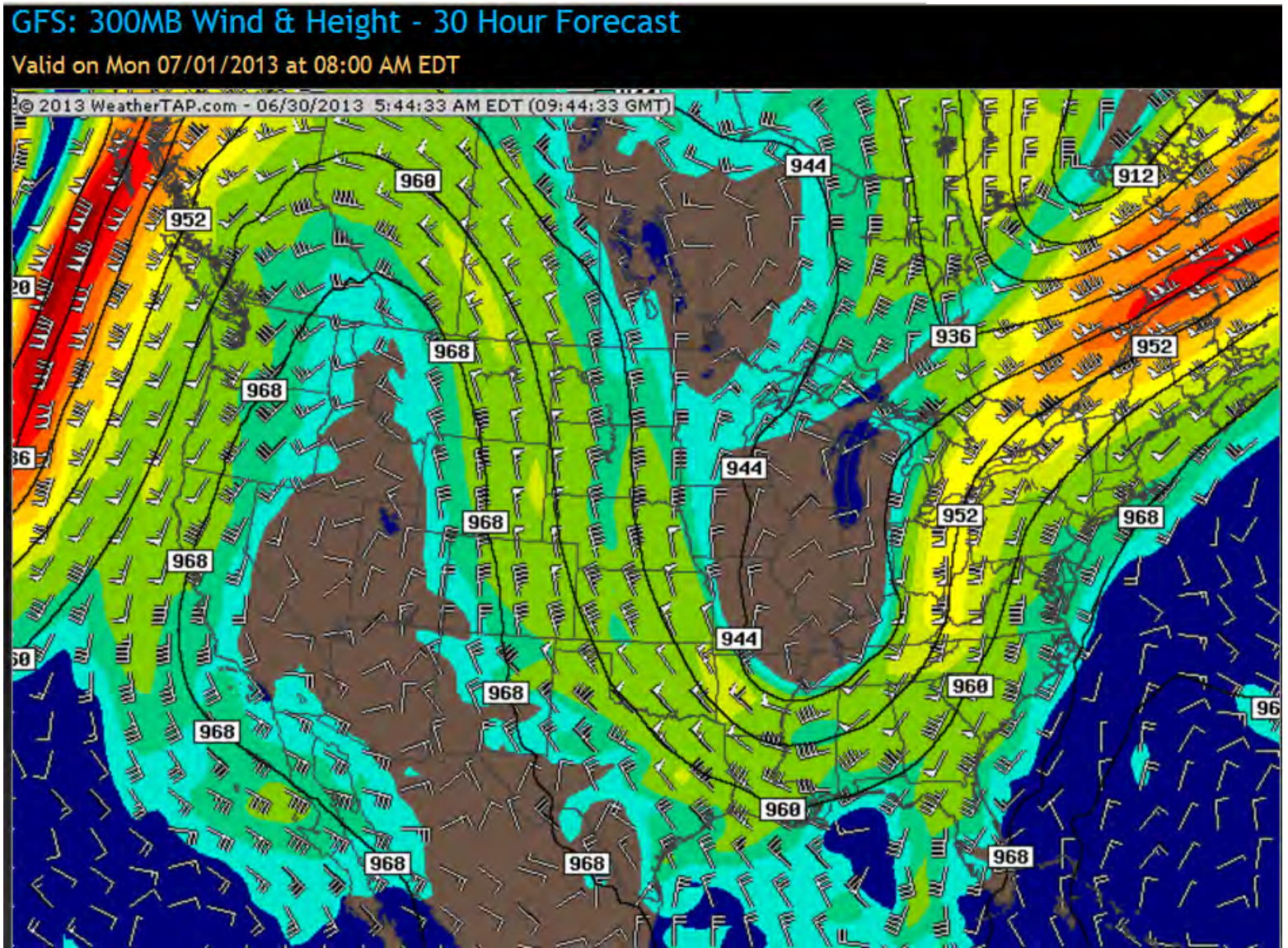


March-August, 2011

- **Record wet : OH to VT**
- **Record drought: TX & NM**
- **'Quasi-stationary' pattern**

Jet Stream Patterns Slowing Down and Amplifying, Giving More Extreme Weather

(Francis and Vavrus, 2012)



Blocking Pattern - Unique track

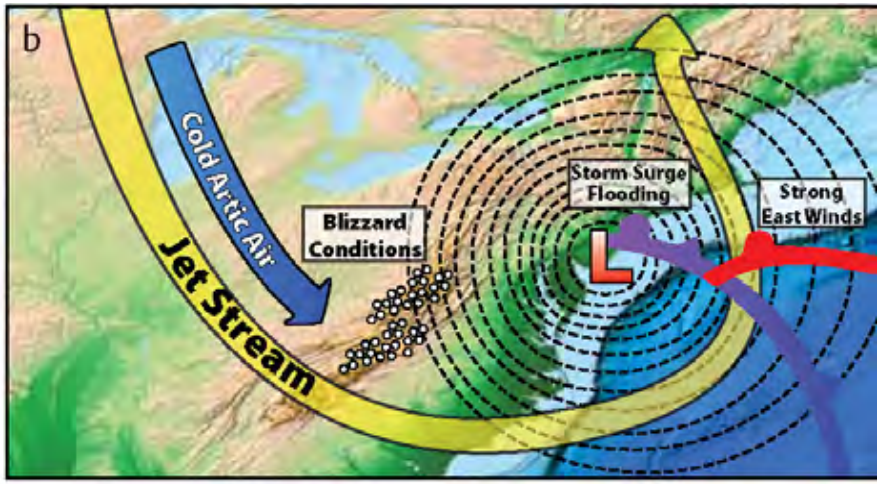


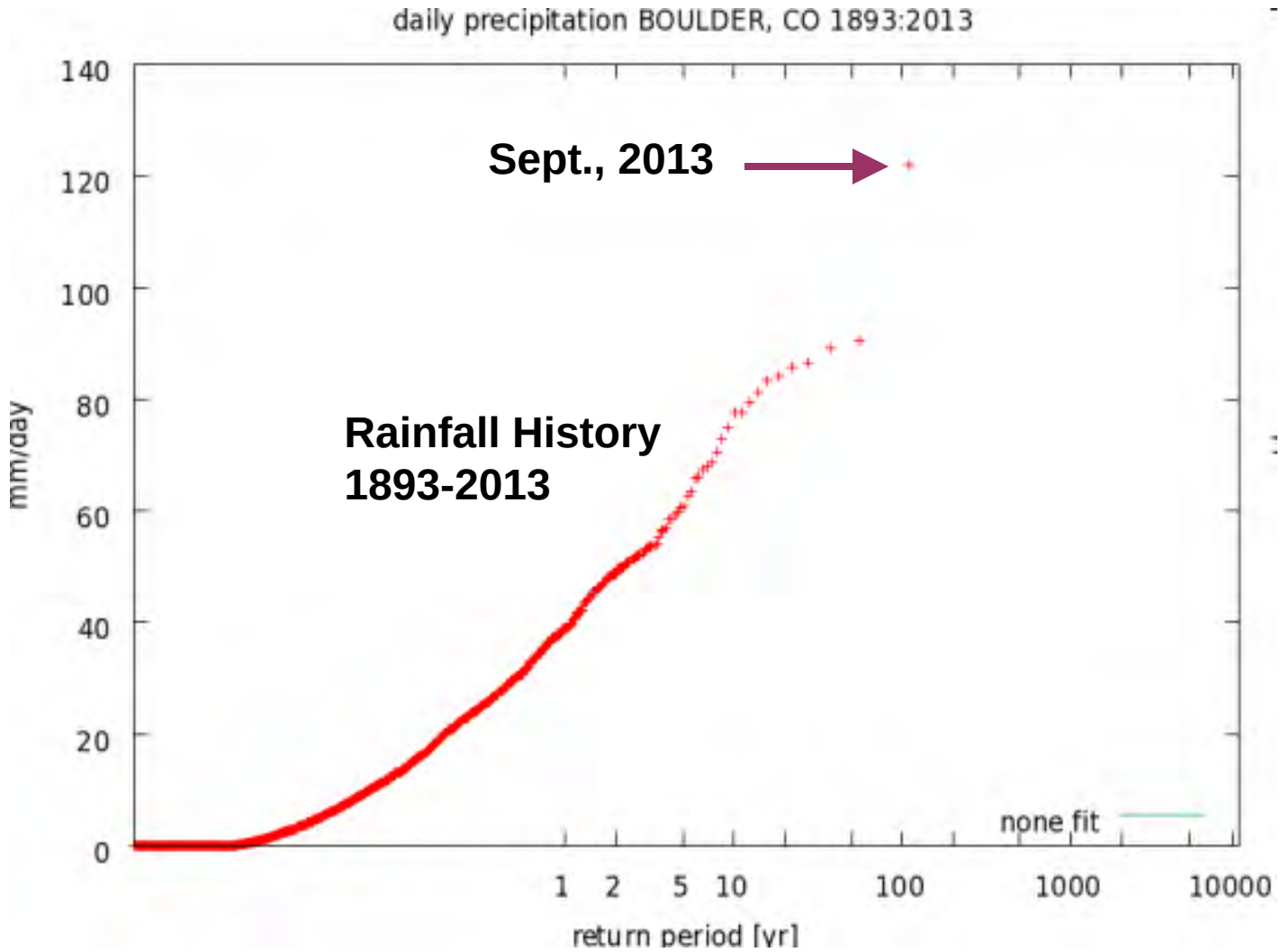
Figure 1. (a) Atmospheric conditions during Hurricane Sandy's transit along the eastern seaboard of the United States, including the invasion of cold Arctic air into the middle latitudes of North America and the high-pressure blocking pattern in the northwest Atlantic. (b) After the convergence of tropical and extra-tropical storm systems, the hybrid Superstorm Sandy made landfall in New Jersey and New York, bringing strong winds, storm surge, and flooding to areas near the coast and blizzard conditions to Appalachia.

- **High amplitude jet-stream + blocking pattern + strong cyclone + hurricane winds + full moon high tide = record storm surge + disaster**

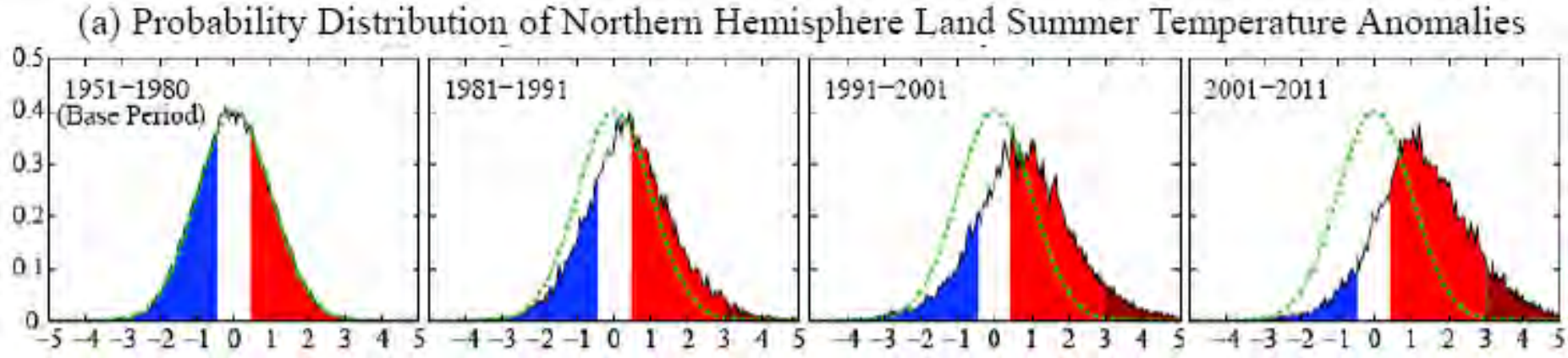
[Greene et al., Oceanography, 2013]

Colorado Flooding a “1,000-Year” Event

O 15-hr



Temperature Extremes are a Sign of Global Warming



(Hansen, 2012)

- **Frequency of occurrence (vertical axis) of local June-July-August temperature anomalies for Northern Hemisphere land in units of local standard deviation (horizontal axis). The normal (gaussian) distribution bell curve is shown in green.**

- **Large increase in anomalies > +3σ is global warming**

(± 3σ includes 99.7% of data in 1951-1980 base period)

Western Forest Fires: 2000s

- 1,000 acre fires: twice as many as 1970s
- 10,000 acre fires: seven times as many as 1970s
- 100,000 acre wildfires do not appear in records before the late 1980s.
- Burn season 2.5 months longer than 1970s
- Early snowmelt; warmer, drier spring & summer and forest management practice
- Each 1^{o}C warming quadruples area burned

What Lies Ahead?

- **Accelerating change, increasing extremes**
- **Increasing adaptation and rebuilding costs**
- **Environmental damage that will transform or destroy ecosystems- locally and globally**
- **Freely dumping waste streams from society into atmosphere, streams, lakes and oceans is unsustainable – long term costs now exceed $1000 trillion**
- ***Will need fossil carbon tax (a "waste" tax) to incentivize mitigation and pay for the long-term adaptation and health costs***

Discussion

- **http://alanbetts.com**

  - this talk http://alanbetts.com/talks

  - articles at http://alanbetts.com/writings

  - papers at http://alanbetts.com/research

- ***Vermont Climate Change Indicators***
- ***Seasonal Climate Transitions in New England***

Media Resources

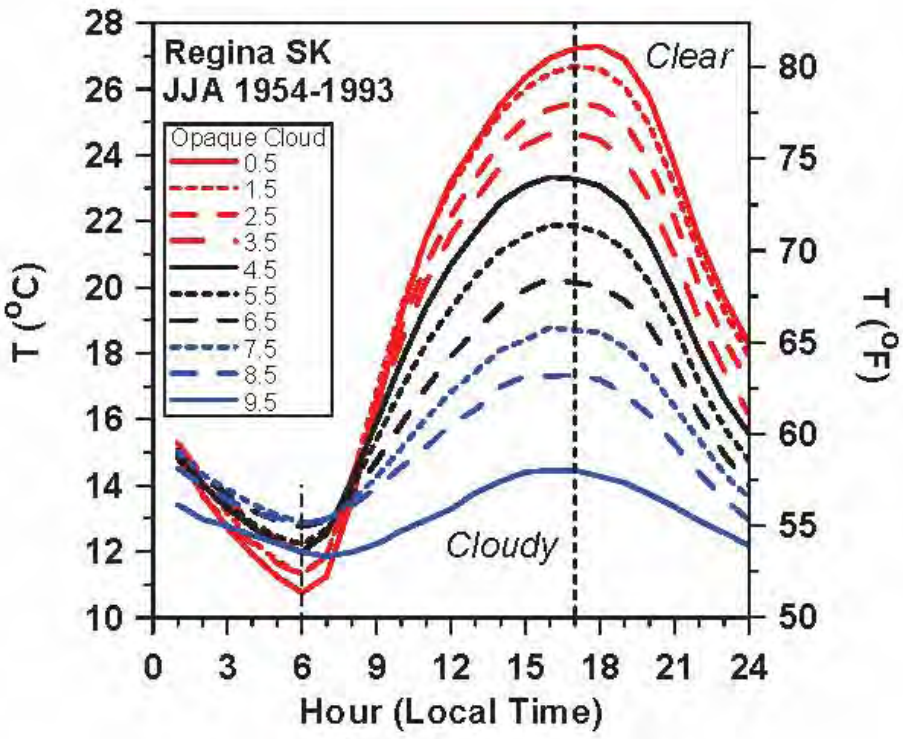
- **Sunday Environment page in Rutland Herald/Montpelier Times Argus:**
  2008-2013 – 60 articles
  http://alanbetts.com/writings
- ***Environmental Journalism Revisited***

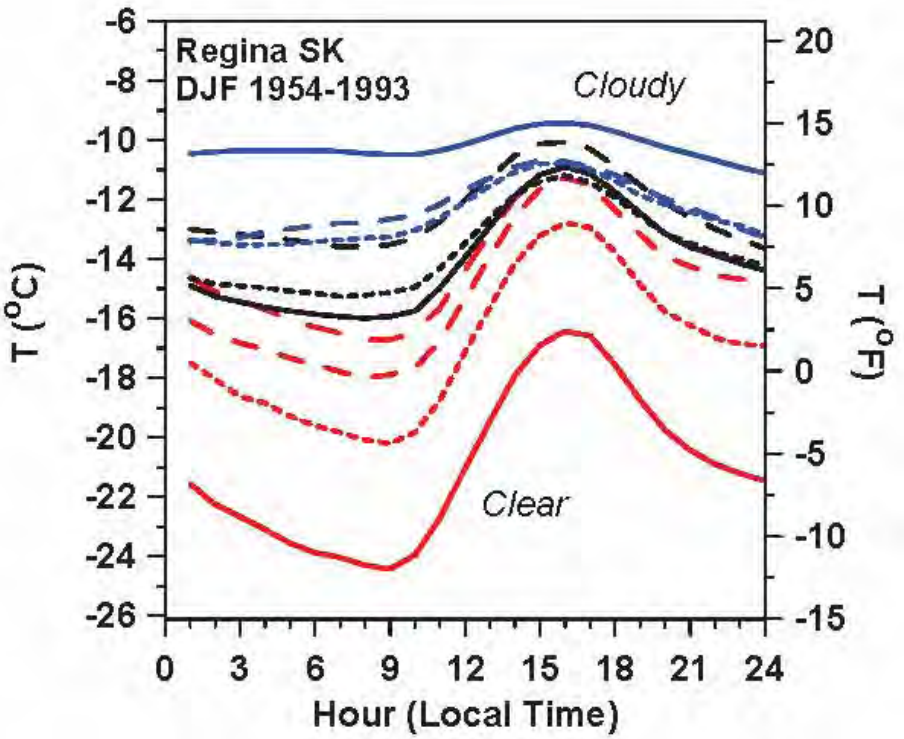
- **Media Commentaries: VPR/PEG-TV**
  http://alanbetts.com/talks

2011 Classic Flood Situations

- **Spring flood: heavy rain and warm weather, melting large snowpack from 2010 winter**
  - **70F (4/11) and 80F(5/27) + 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 6-8 ins rain on wet soils**
  - **Extreme flooding**
  - **(Floyd on 9/17/1999 had similar rain - but with dry soils there was less flooding)**

Clouds: Summer & Winter Climate





- **Summer:** **Clouds reflect sunlight (soil absorbs sun)**
  - **no cloud, hot days; only slightly cooler at night**
- **Winter:** **Clouds are greenhouse (snow reflects sun)**
  - **clear & dry sky, cold days and very cold nights**

Betts et al. 2013

Spring Climate Transition

- **Before leaf-out**

Little evaporation → **Dry atmosphere, low humidity**
→ **Low water vapor greenhouse**
→ **Large cooling at night**
→ **Large diurnal temp. range**
giving warm days, cool nights and frost

- **After leaf-out**

Large evaporation → **Wet atmosphere, low cloudbase**
→ **Small cooling at night**
→ **Reduced maximum temperature**
→ **Reduced chance of frost**

- ***Spring is coming earlier***

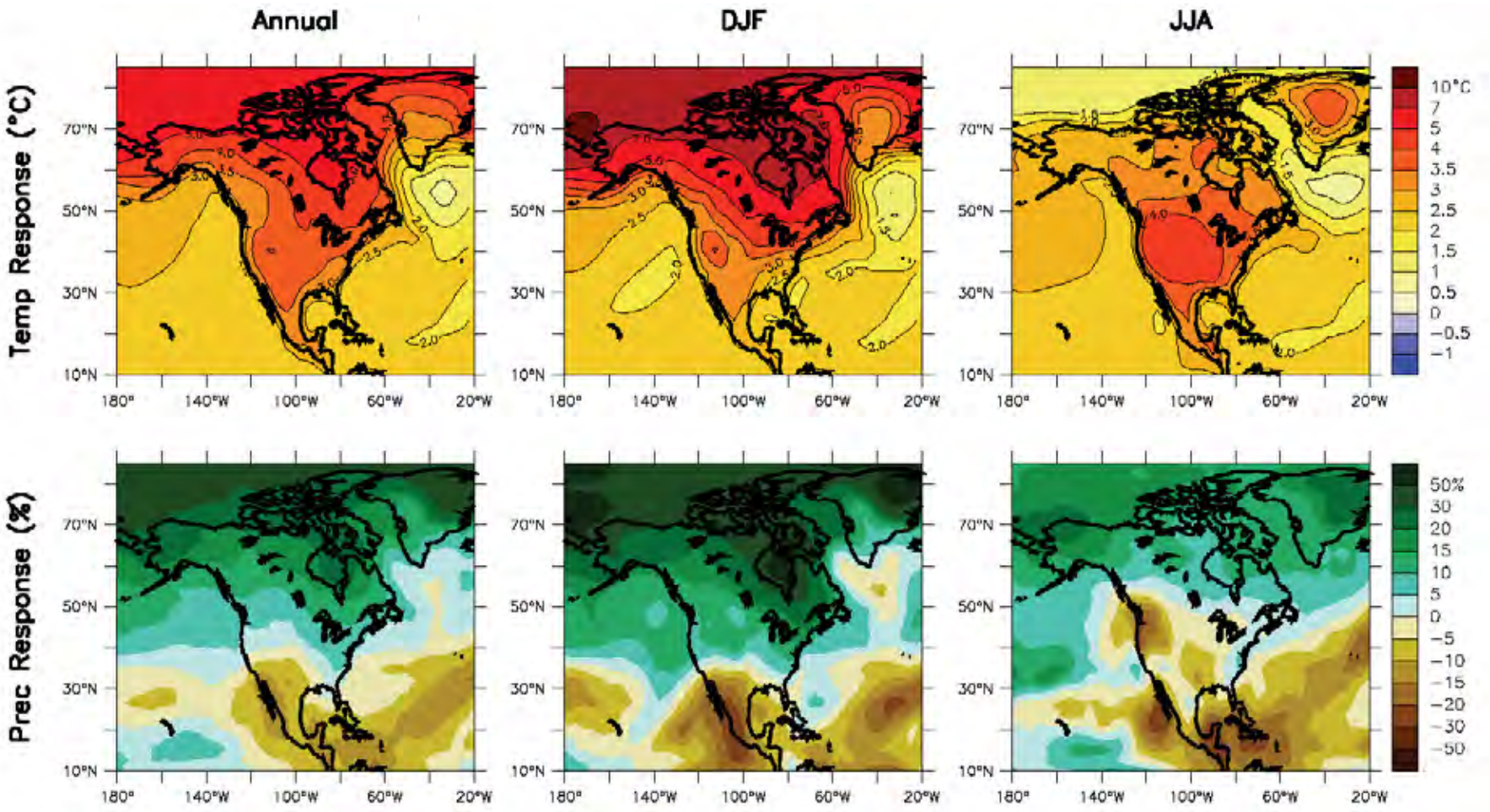
Fall Climate Transition

- **Vegetation postpones first killing frost**
- **Deciduous trees still evaporating: moist air with clouds**
- **Water vapor & cloud greenhouse reduces cooling at night and prevents frost**
- **Till one night, dry air advection from north gives first hard frost.**
- **Vegetation shuts down, leaves turn, skies become clearer and frosts become frequent**
- ***The opposite of what happens in Spring with leaf-out!***

Clear dry blue sky after frost. Forest evaporation has ended; water vapor greenhouse is reduced, so Earth cools fast to space at night

Later frost: Growing season getting longer

North American Changes: T, Precip.



- Temperature and precipitation changes over North America from an average of 21 AOGCM projections for A1B (high emission) scenarios.
- Top row: Annual mean, winter (DJF) and summer (JJA) temperature change between 1980 to 1999 and 2080 to 2099. **[NE winter: +4.5C, +8F]**
- Bottom row: for fractional change in precipitation. **[NE winter: +25%]**

What do we know from past?

- **Reconstruct past climate**

- Ice core history: T, CO_2, CH_4 through many ice-ages - nearly a million years
- Ocean sediments
- Tree rings – a few thousand years

Ice-core history!

Last four ice-age cycles