Climate Change in the Northeast

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Earth sustains life

- **Burning fossil fuels is increasing greenhouse gases and melting polar ice**
- **Climate is warming and extreme weather is increasing**

January 2, 2012: NASA NPP VIIRS composite

Climate Change

- **One of 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

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

- **Clash of Earth science with social values**

Outline

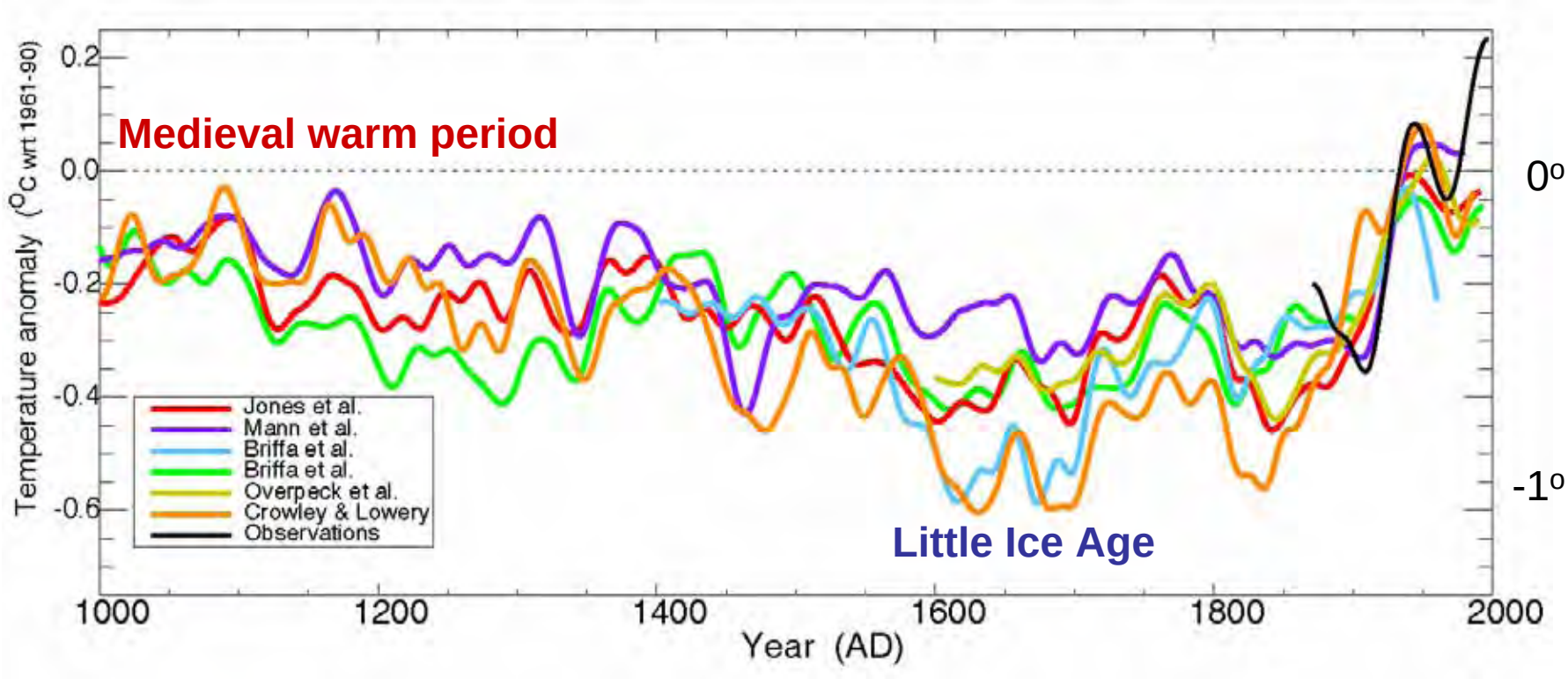
- **Science of climate change**
  - **Global scale: actual and future**
  - **What is happening to New England**

    - Localization of climate research

Discussion

2100: +5°F

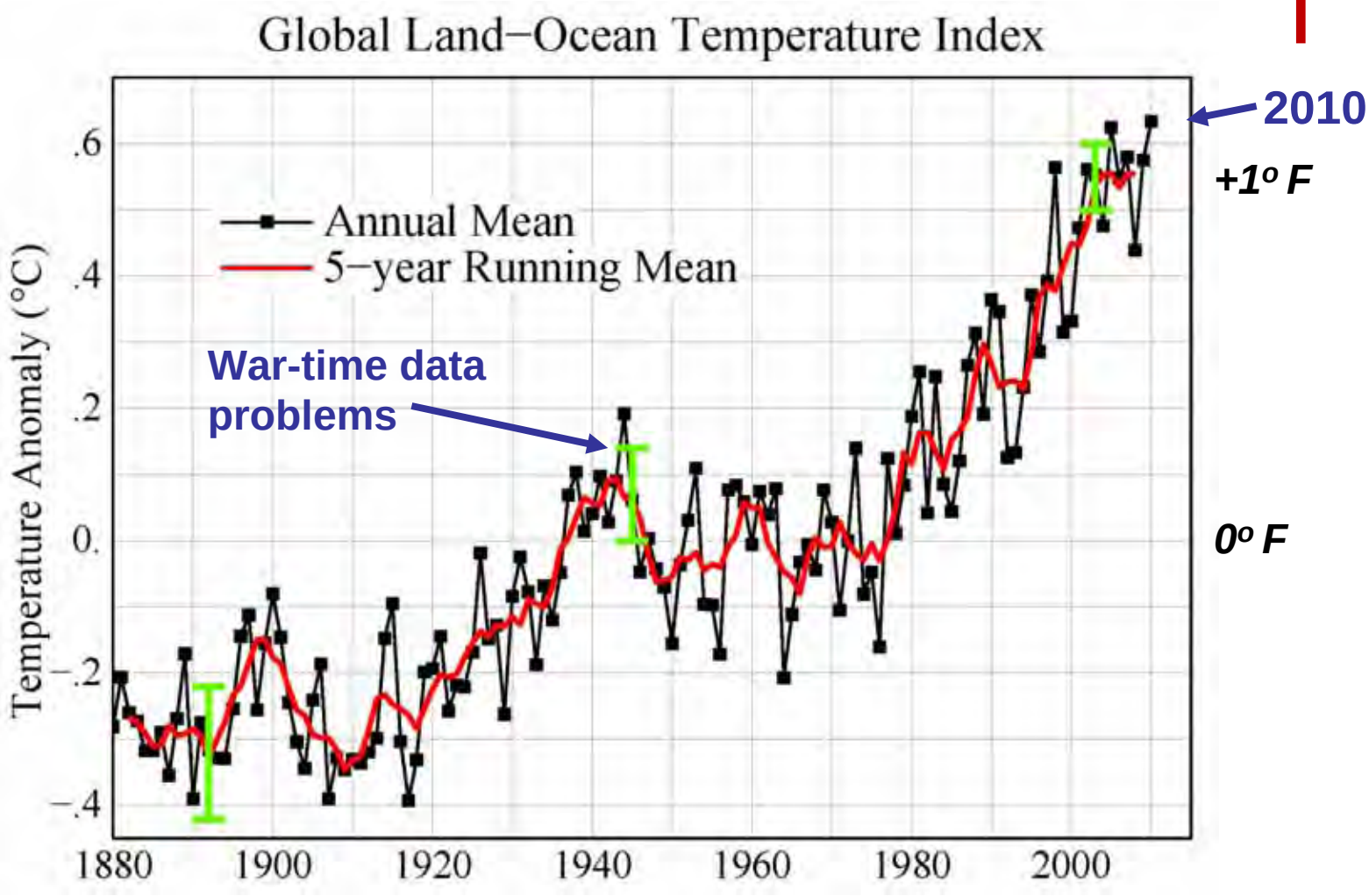
Millennial Temperature Record



- **"Proxy" records from before the time of thermometers provide uncertain data, but they're all we have**
- **Black line is 150-yr instrument record**

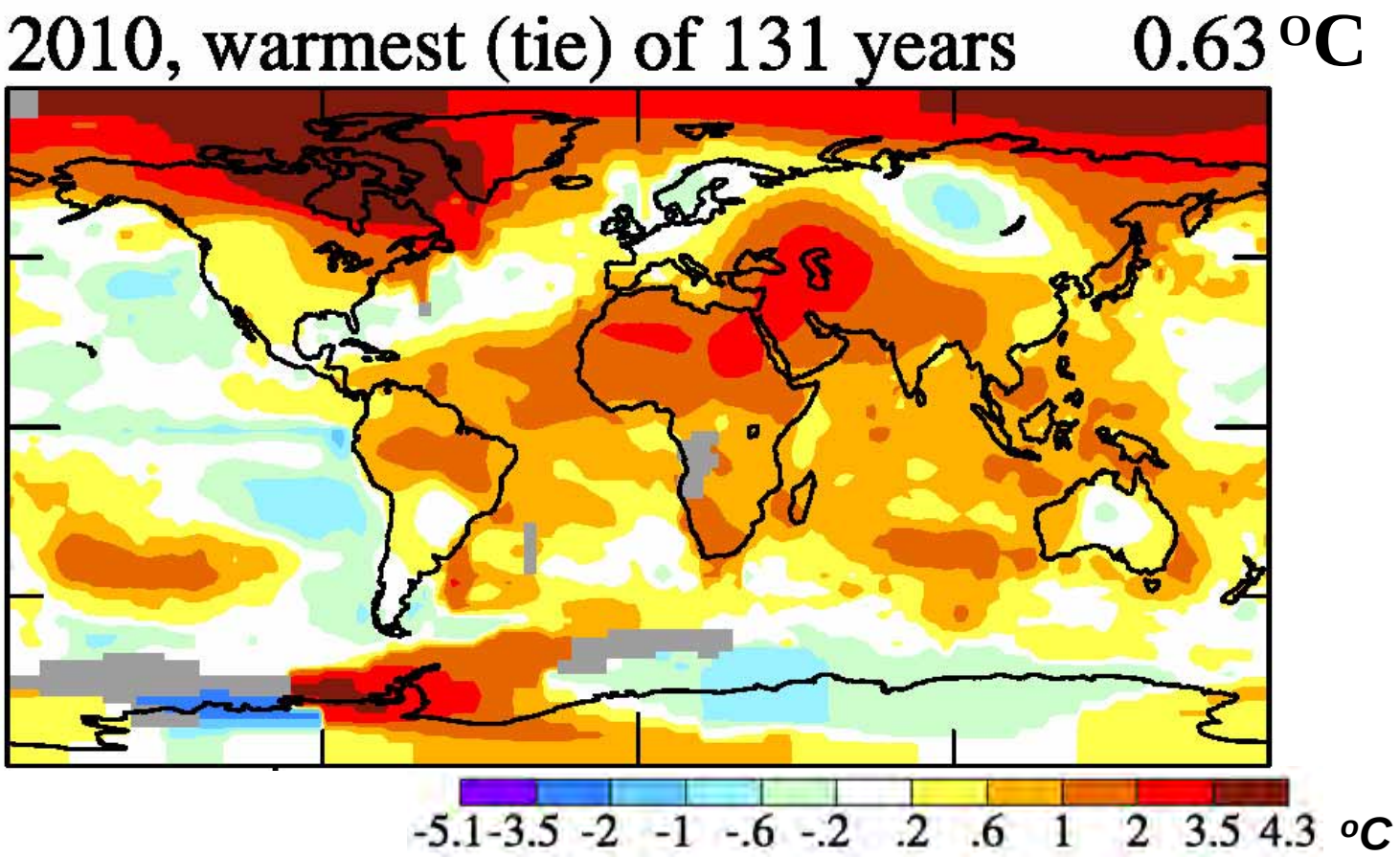
Global Temperature Rise 1880 – Present

2100: +5ºF



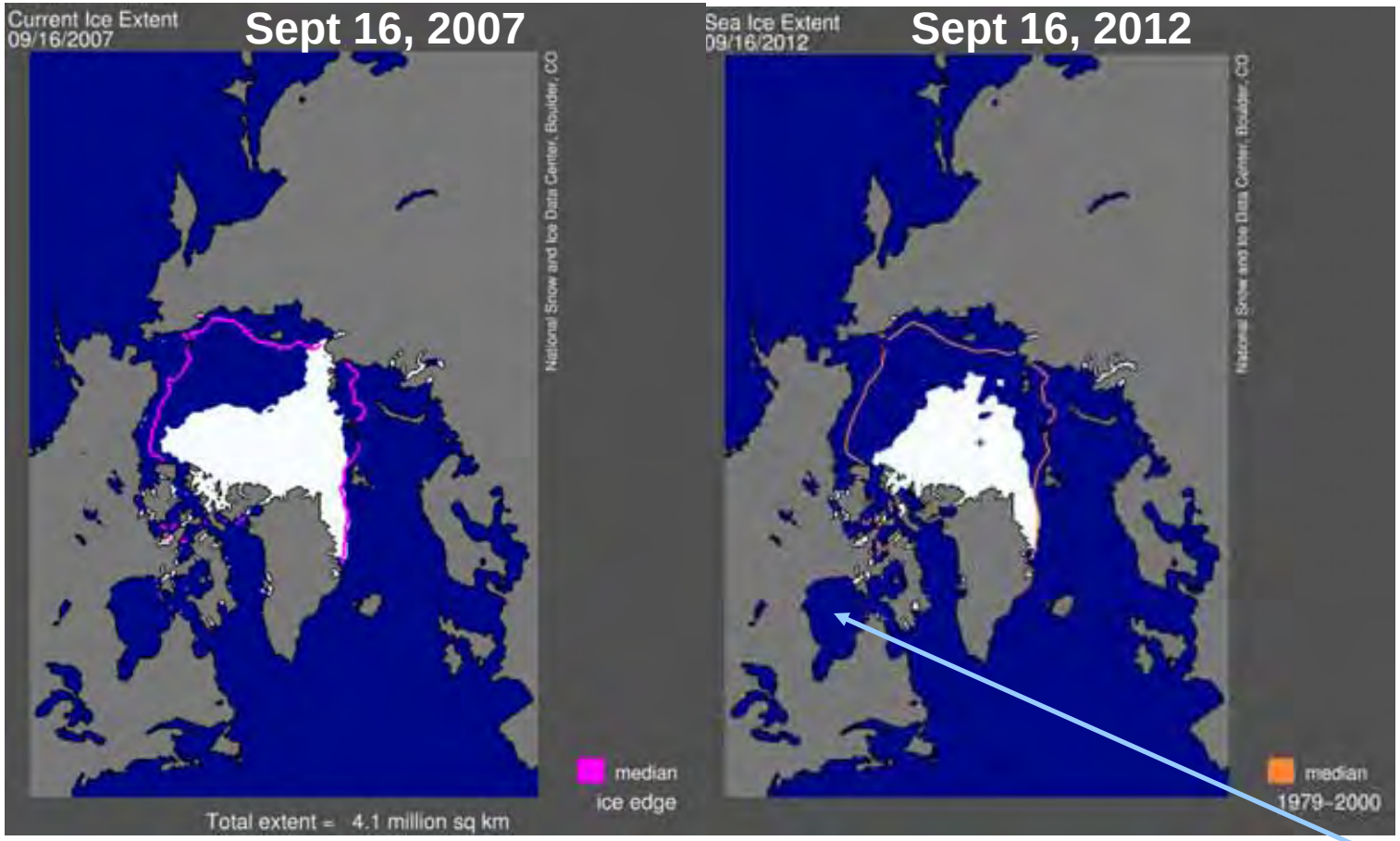
NASA-GISS, 2011

Global Picture 2010



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

Arctic Sea Ice Loss Has Accelerated



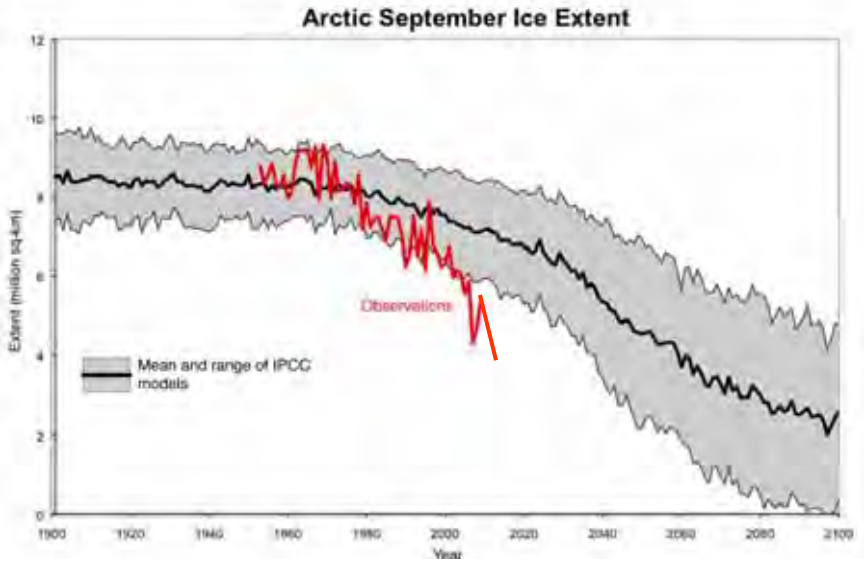
- **Positive feedbacks speed melting**
- **Less ice, less sunlight reflected**
- **More evaporation, larger water vapor greenhouse effect**

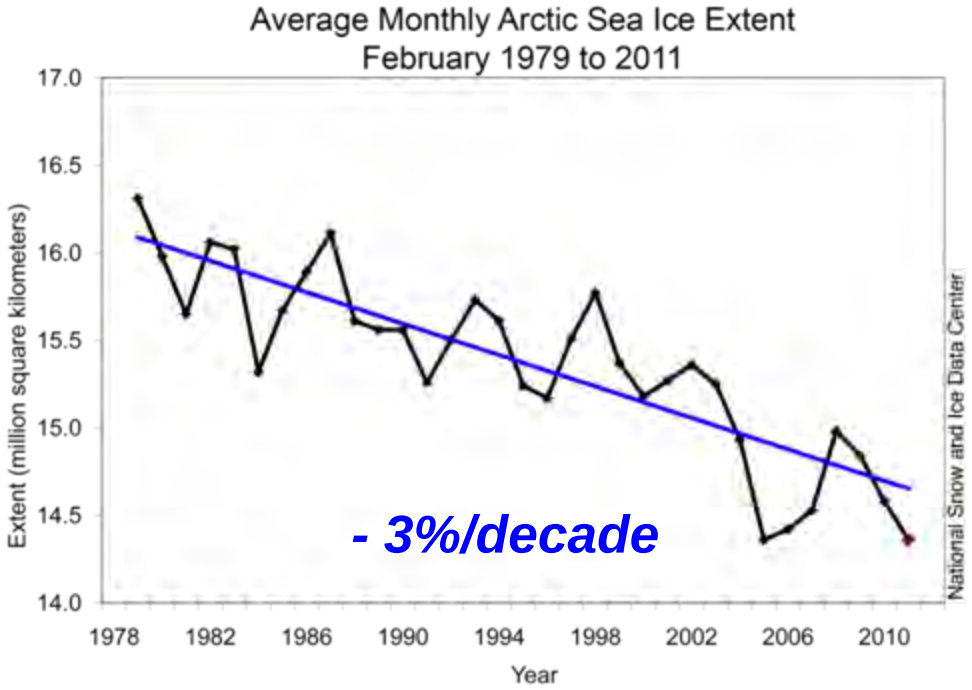
- **New Record Ice-loss: 2012** ***(www.nsidc.org)***
  - **most ice now thin (3-4ft) and only 1-year-old**
- **Open water in Oct. Nov. favors warmer Fall**

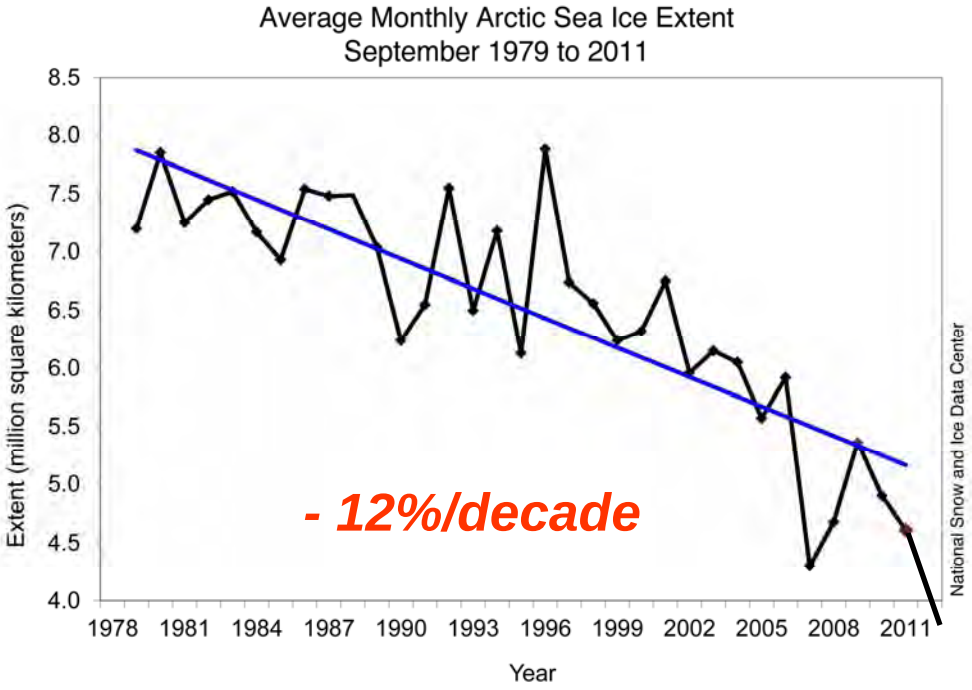
At the end of Nov. 2011 Hudson Bay was still nearly ice-free.

Sea Ice Trends

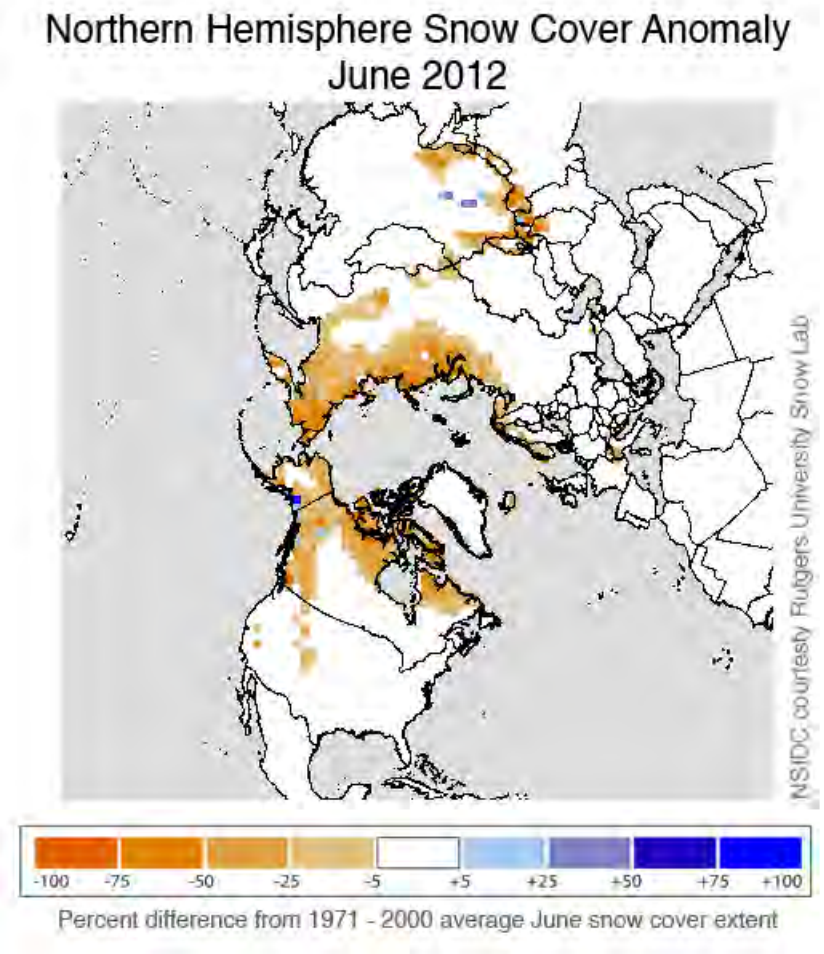
- Sea ice is thinning rapidly
- Observed September decline appears to be faster than IPCC-AR4 climate model projections
- *AR5 projections should be faster!*

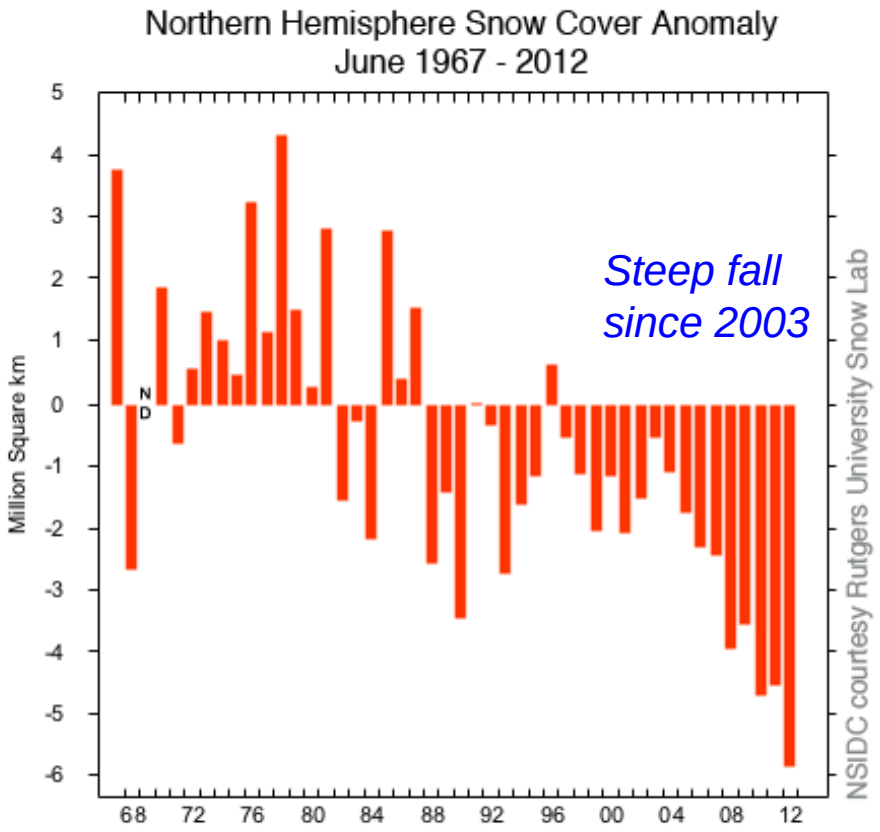






June 2012 snow cover minimum

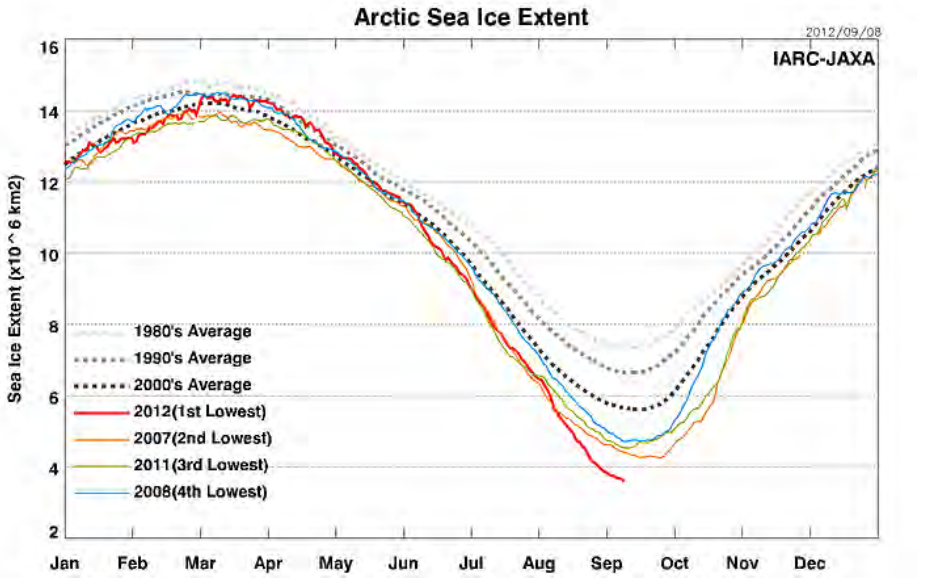




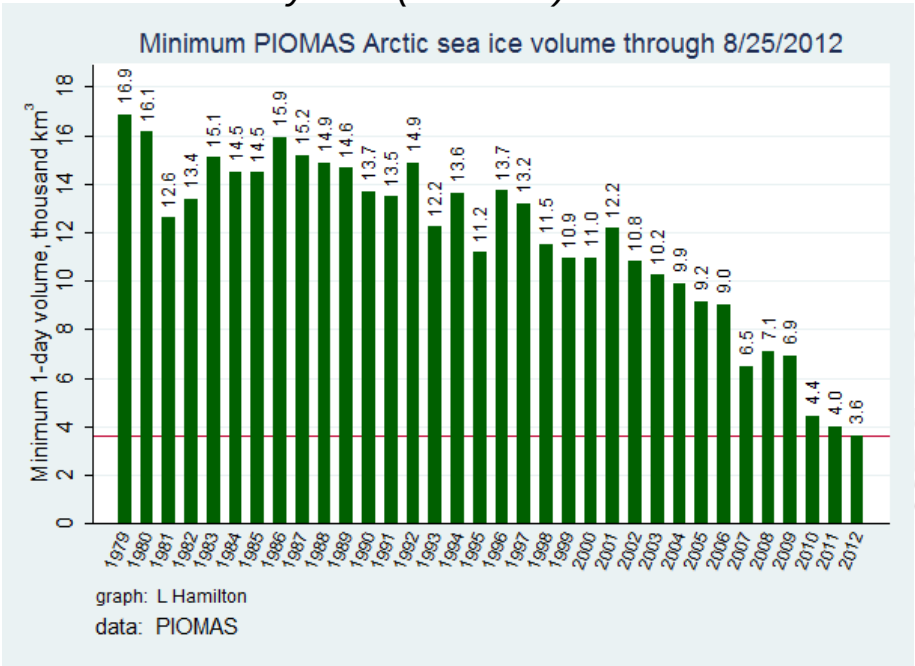
- **New minimum by 10^6 km^2 (1971-2000 ref)**

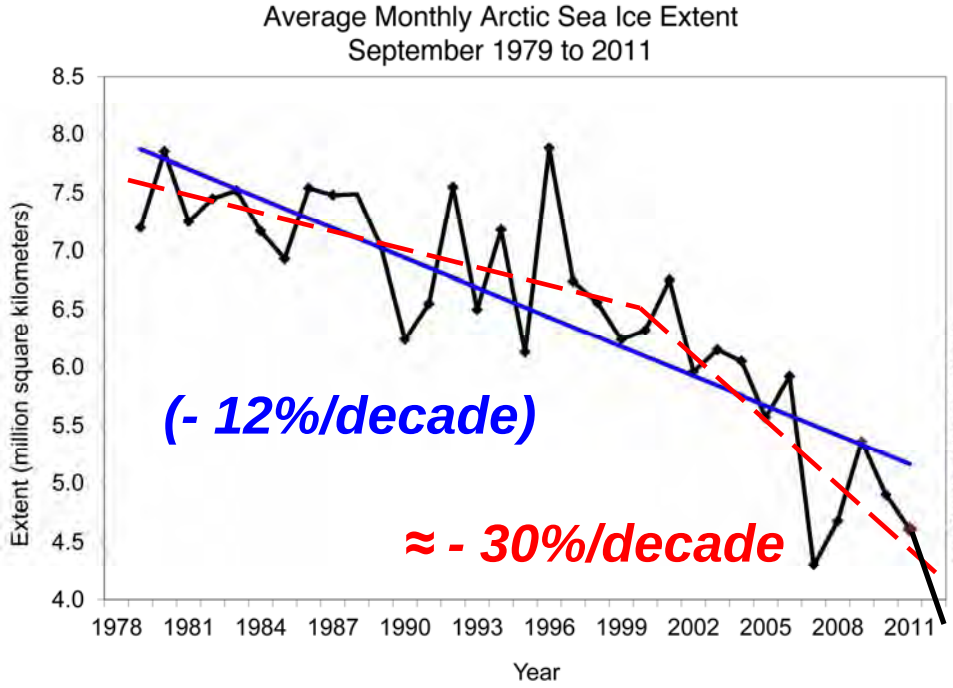
Sea Ice Trends

- **Sea ice is thinning rapidly**
- **Observed September decline appears to be steeper in last decade**

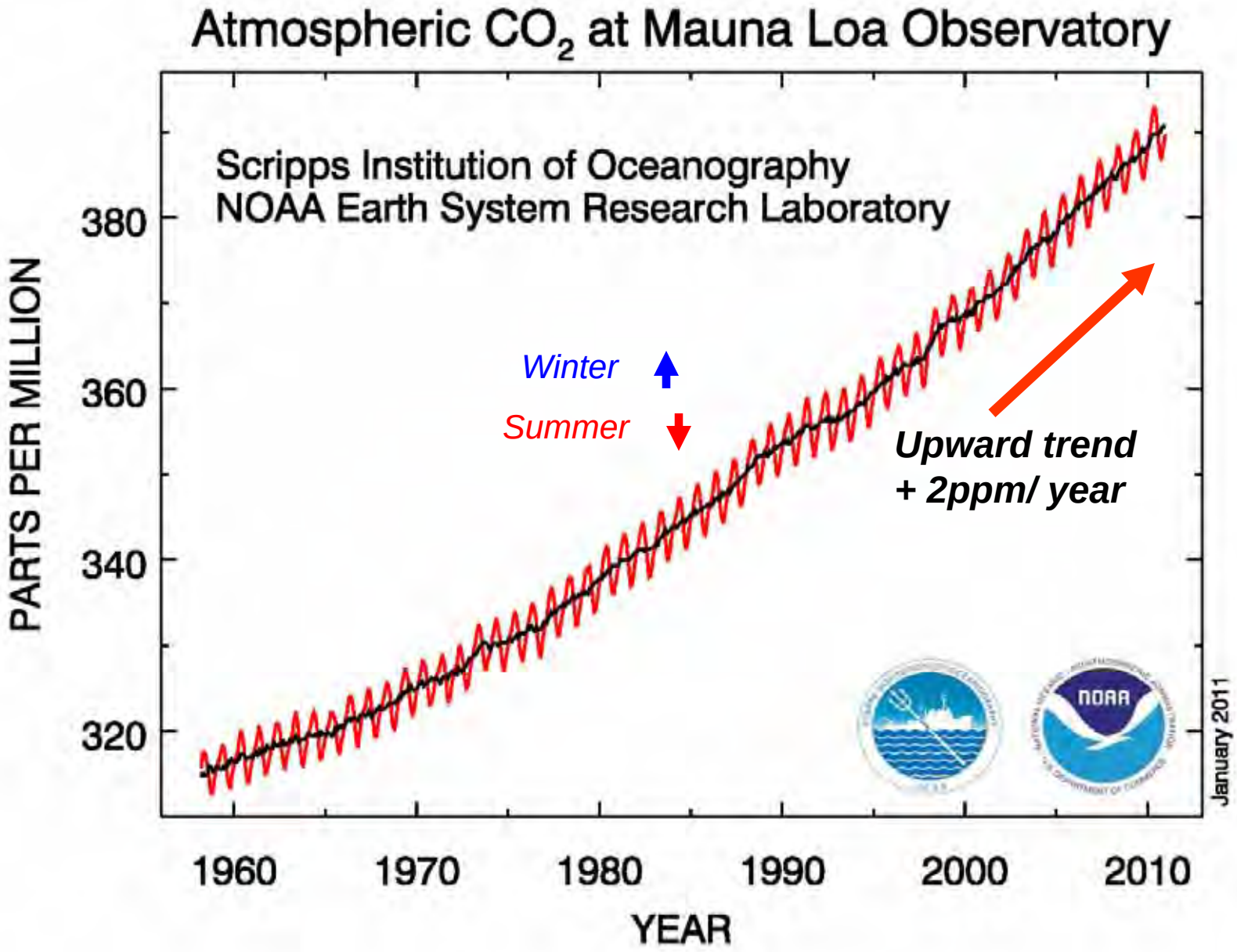


Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS)



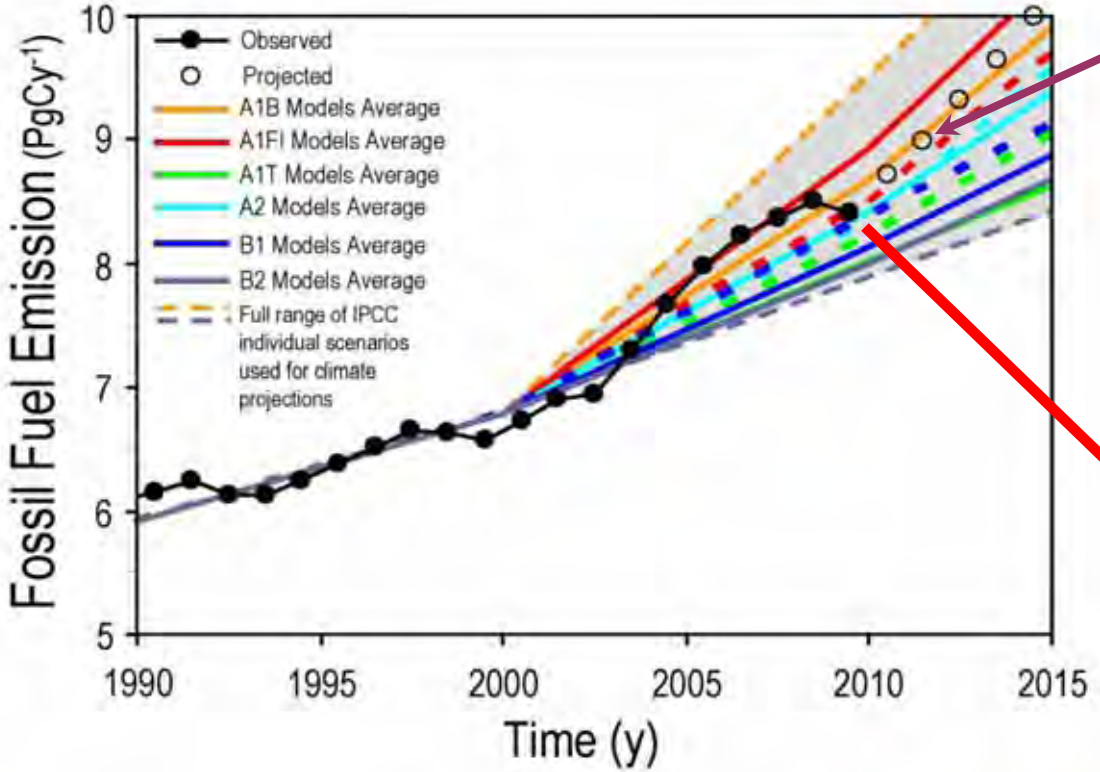


Carbon Dioxide Is Increasing



2009 Was "Good" for the Earth

Fossil Fuel Emissions: Actual vs. IPCC Scenarios



Back on growth: 2010, 2011

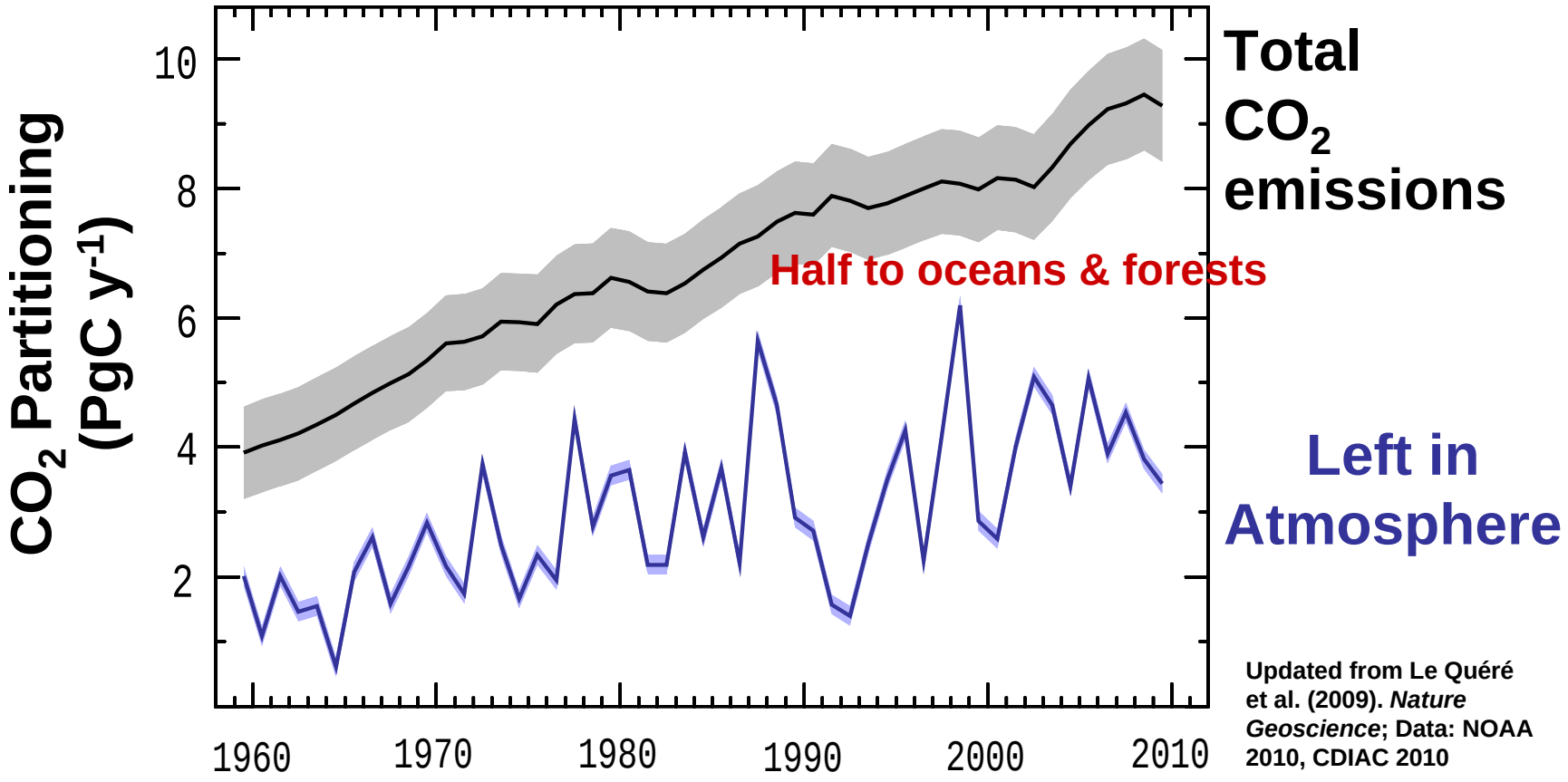
Emission Scenarios

- 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

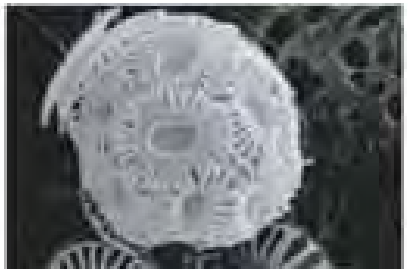


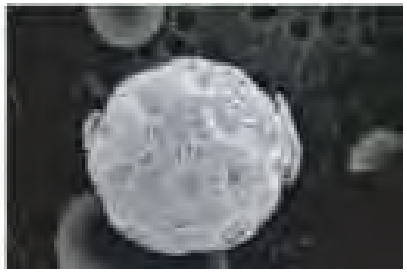
It takes at least a century to remove CO_2 from the atmosphere, and many centuries to remove it from oceans

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)





Rise of Greenhouse Gases (GHG) Shift Energy Balance of Planet

- **The atmosphere is transparent to light from the sun, but not to infrared radiation from the earth**
- **GHG: H_2O, CO_2, CH_4, O_3, CFCs absorb and reradiate IR from the surface, giving climate suitable for life by warming planet 30^oC**
- **CO_2 rise alone has a small warming effect**

  BUT…

Water, Snow & Ice Give Positive Radiative Feedbacks

- **As Earth warms, evaporation and water vapor increase and this is 3X amplifier on CO_2 rise**
- **As Earth warms, snow & ice decrease and reduced SW reflection amplifies warming in Arctic in summer and mid-latitudes in winter**
- **Doubling CO_2 will warm globe about 3°C (5°F)**
  - **Much more in the North and over land, which responds faster than oceans**

Global Warming Is Unequivocal

IPCC: Fourth Assessment, Feb., 2007

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:

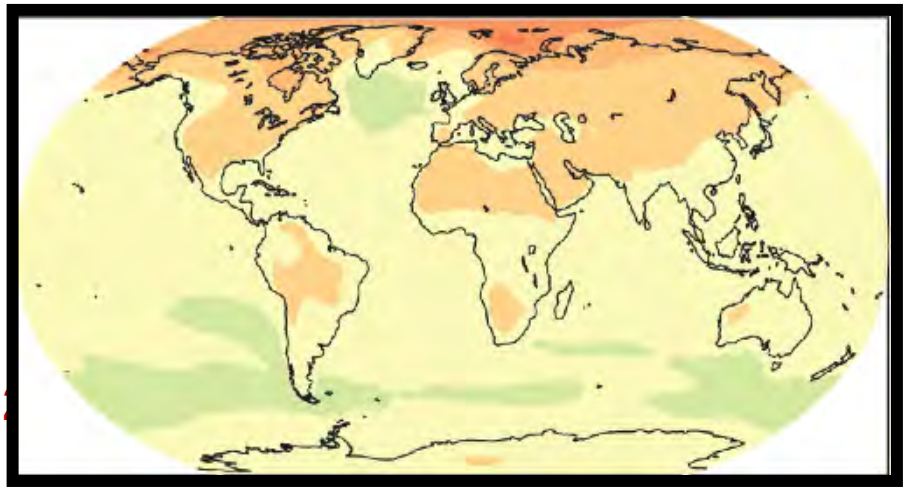
- NH snow extent
- Arctic sea ice
- Glaciers
- Ocean pH (increasing acidity)

(www.ipcc.ch)

Predicted Change in Temperature

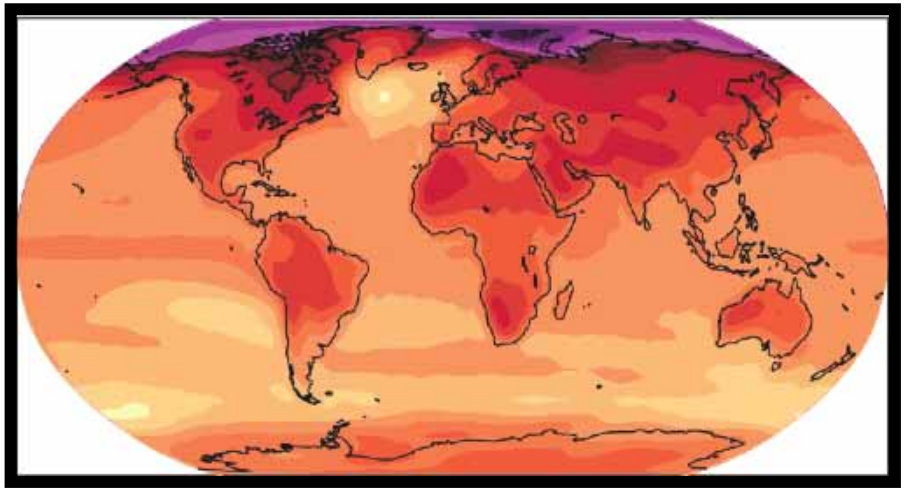
2020-2029 and 2090-2099, relative to 1980-1999 (ºC)

“Committed”

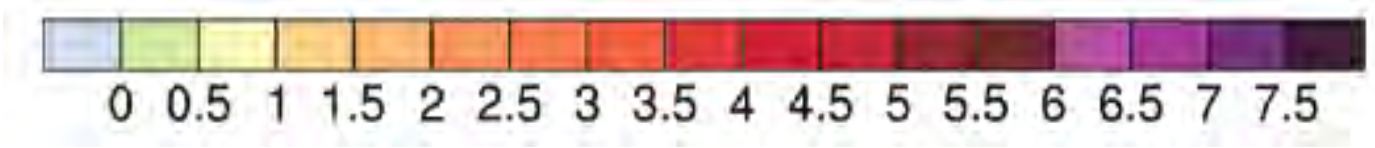


(We did nothing for the last 20 years)

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***

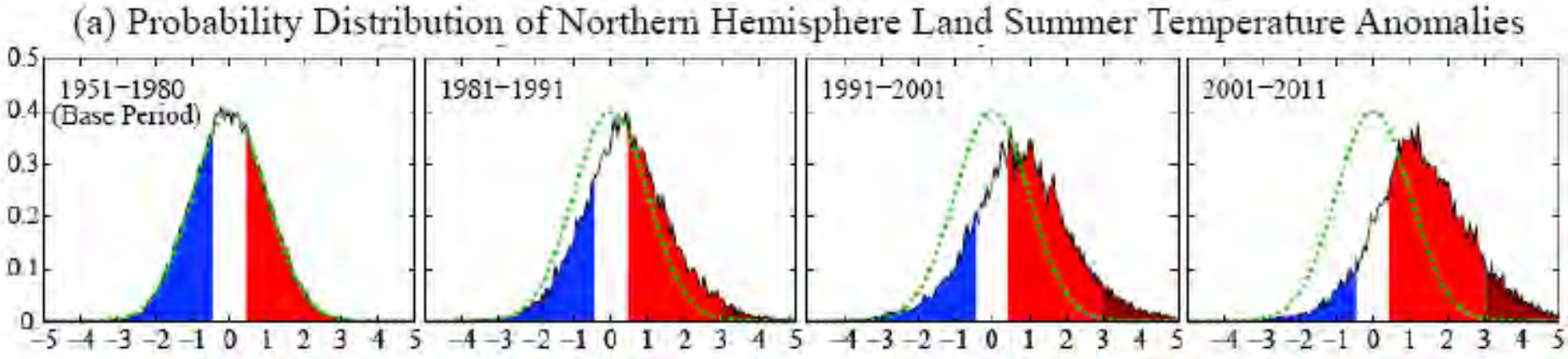
Many Challenges Face Us

- **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**

Extreme summer T anomalies have increased from 0.2% of land area to about 10% in 40 years



(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**

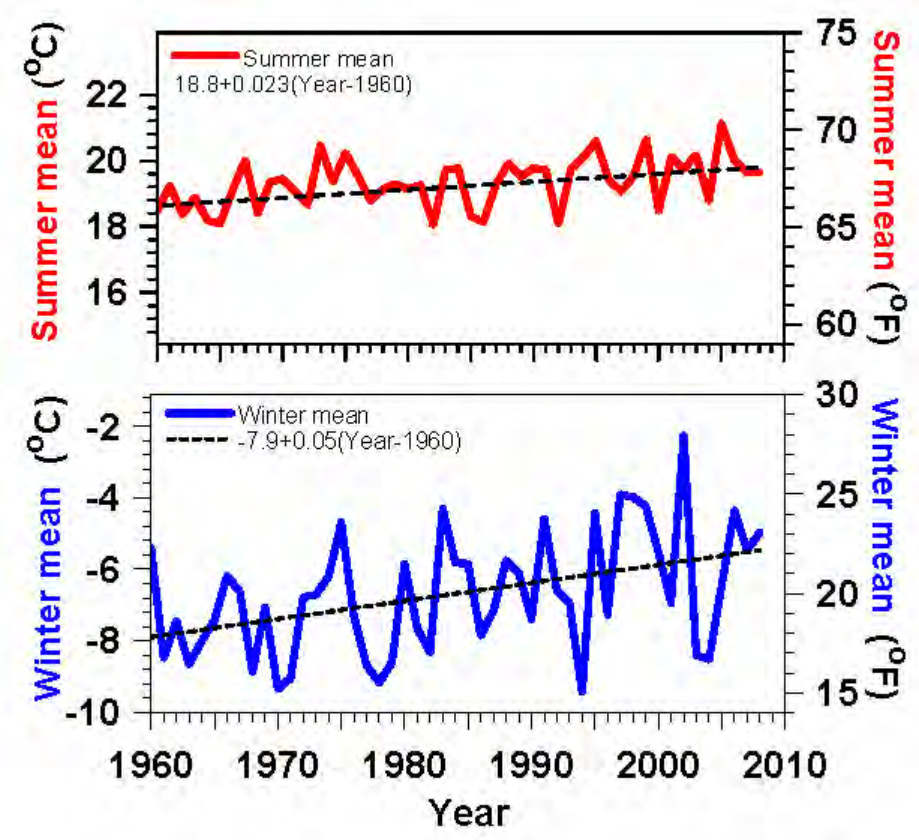
(± 3σ includes 99.7% of data in 1951-1980 base period)

Local Example as Illustration: What Is Happening to Vermont

- **PAST 40/50 years** **(anthropogenic forcing detectible)**
- **Warming twice as fast in winter than summer**
- **Winter severity decreasing**
- **Lakes frozen less by 6.9 (±1.5) days / decade**
- **Growing season longer by 3.7 (±1.1) days / decade**
- **Spring coming earlier by 2-3 days / decade**
- **Extremes increasing**
- ***Evaporation increases with T***
- ***More 'quasi-stationary weather patterns'***

Vermont Temperature Trends
1961-2008

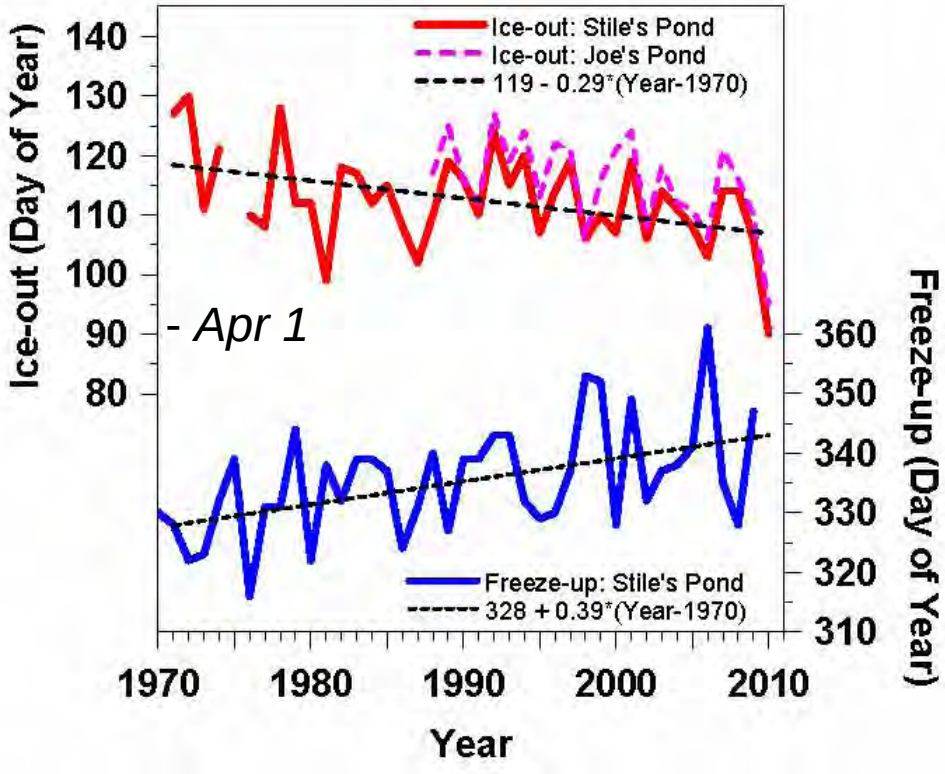
- **Summer +0.4°F / decade**
- **Winter +0.9°F / decade**
- **Larger variability, larger trend**
- ***Less snow (and increased water vapor) drive larger winter warming***

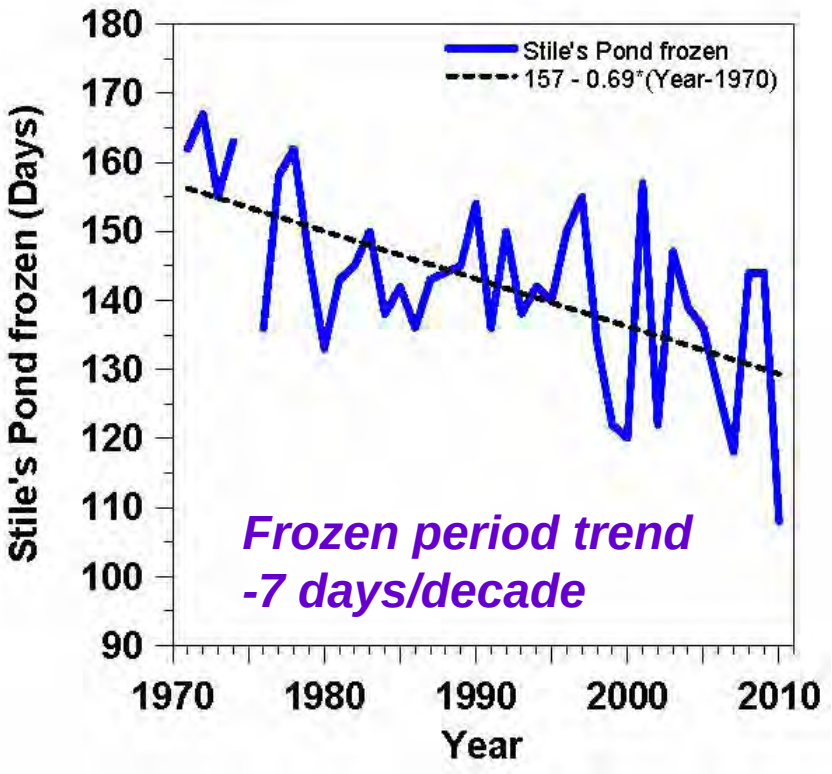


Note: trends since 1961: early 1950's warmer. Trends for last 4-5 decades consistent with model projections for the next few decades

Lake Freeze-up & Ice-out Changing

Frozen Period Shrinking Fast



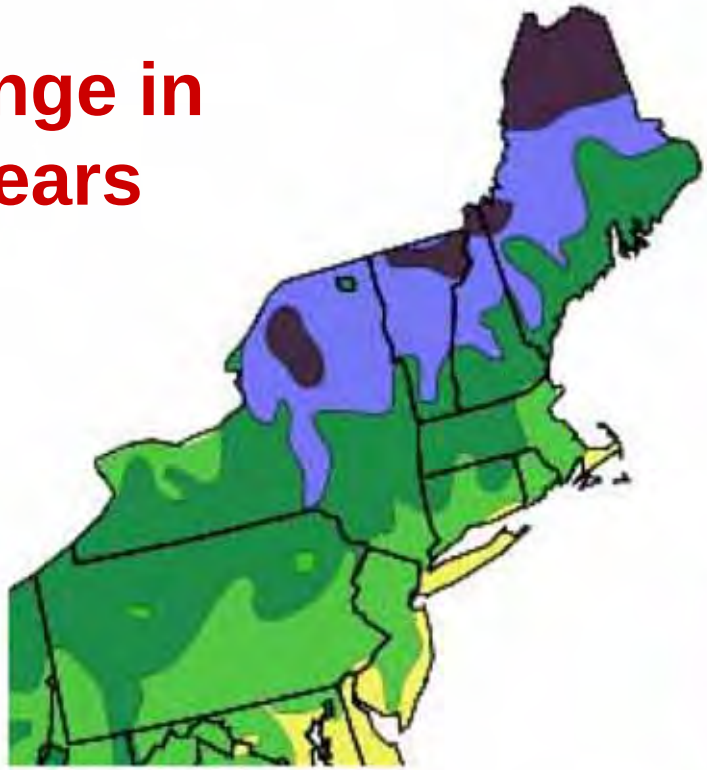


- **Ice-out earlier by 2.9 (±1.0) days / decade**
- **Freeze-up later by 3.9 (±1.1) days / decade**
  - ***Are soils similar?***

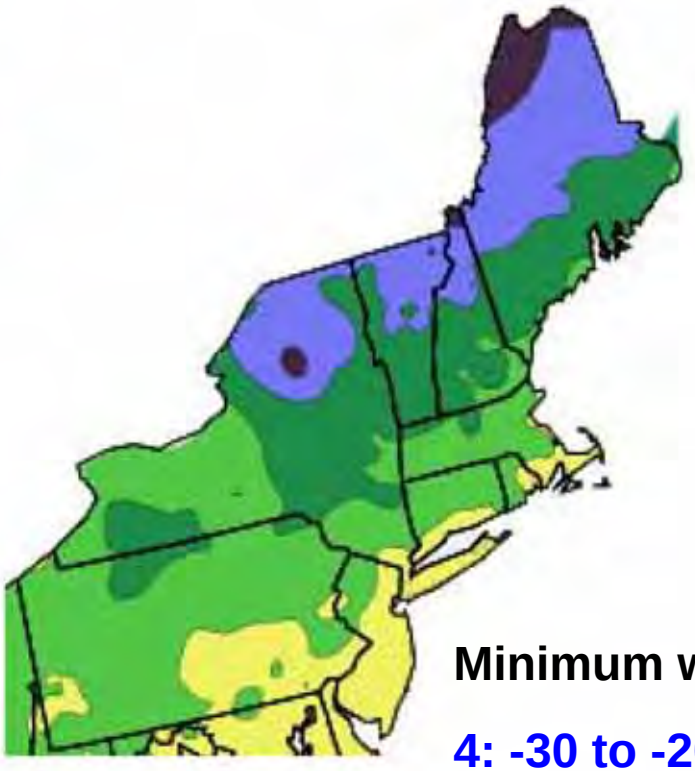
Betts, 2011a

Winter Hardiness Zones - Northeast

Change in 16 years



1990



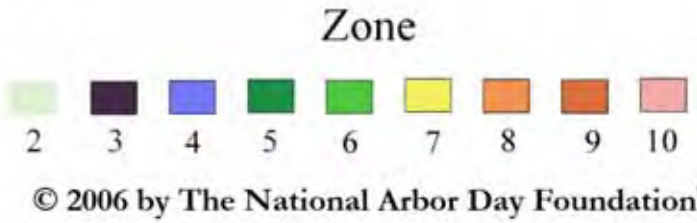
2006

Minimum winter T

4: -30 to -20°F

5: -20 to -10°F

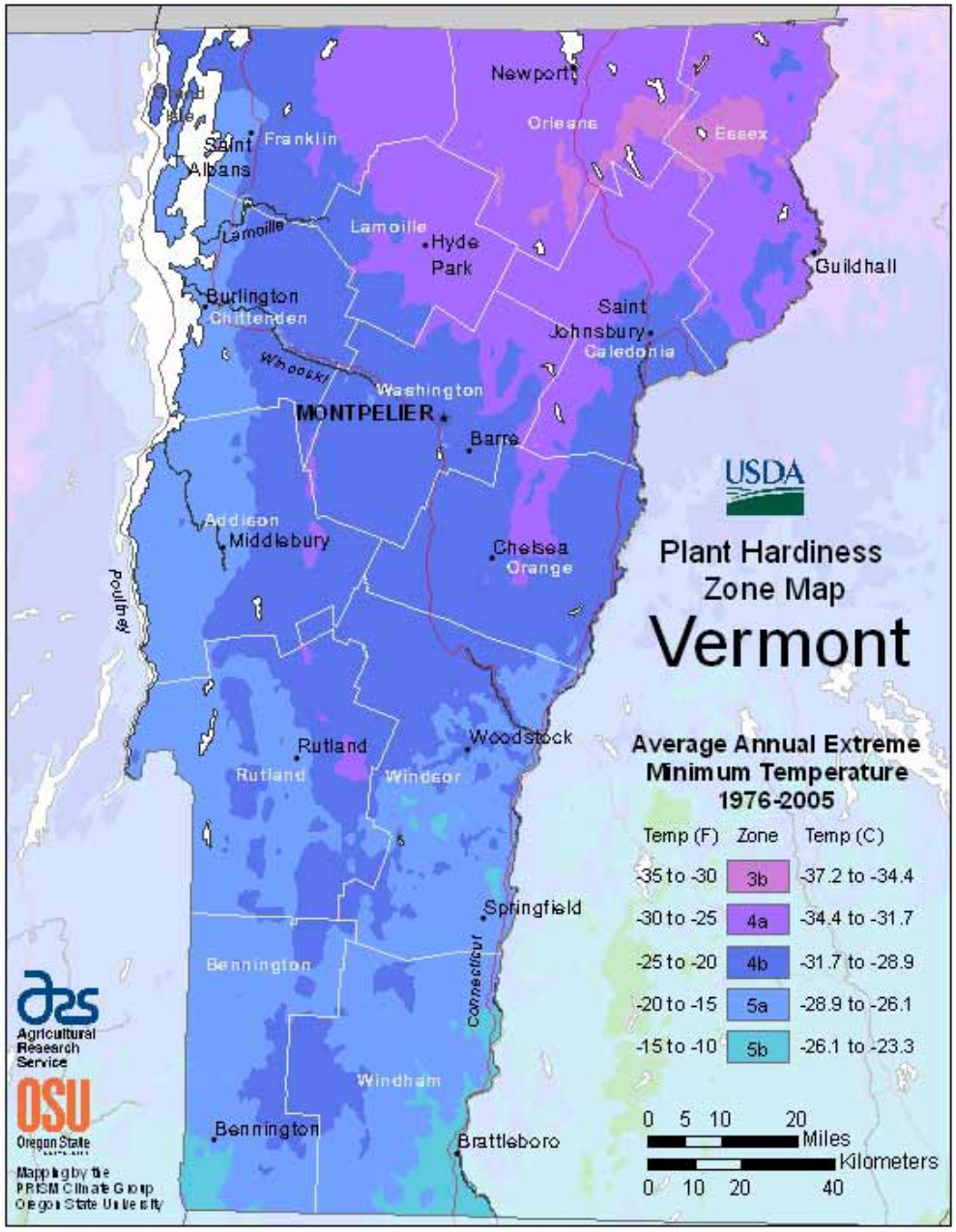
6: -10 to 0°F



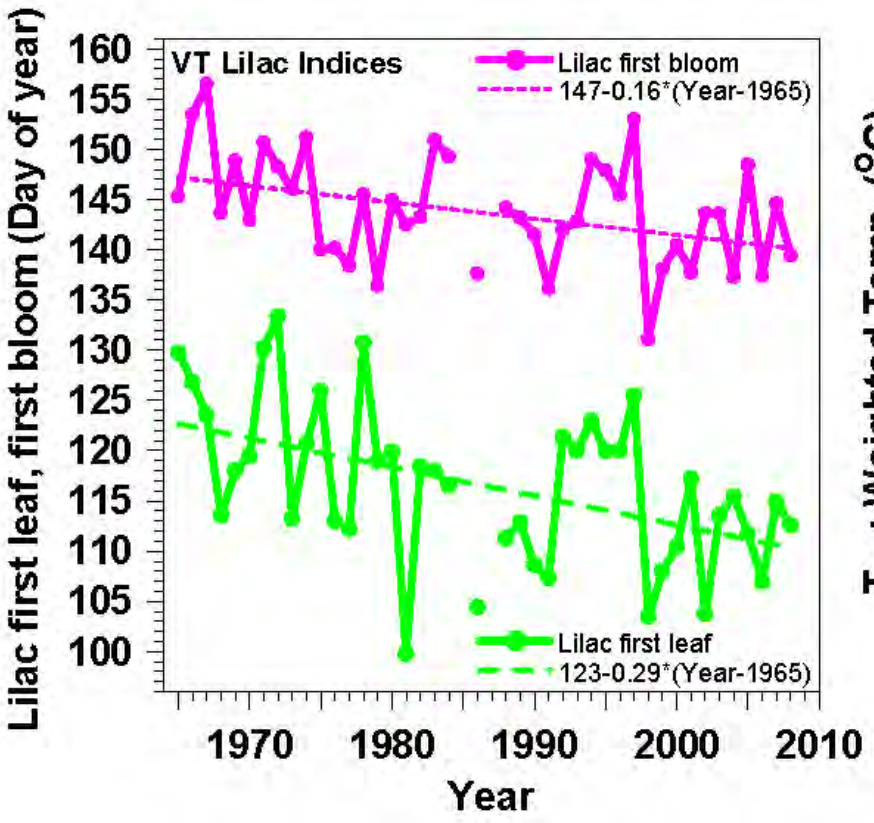
USDA Hardiness Zones

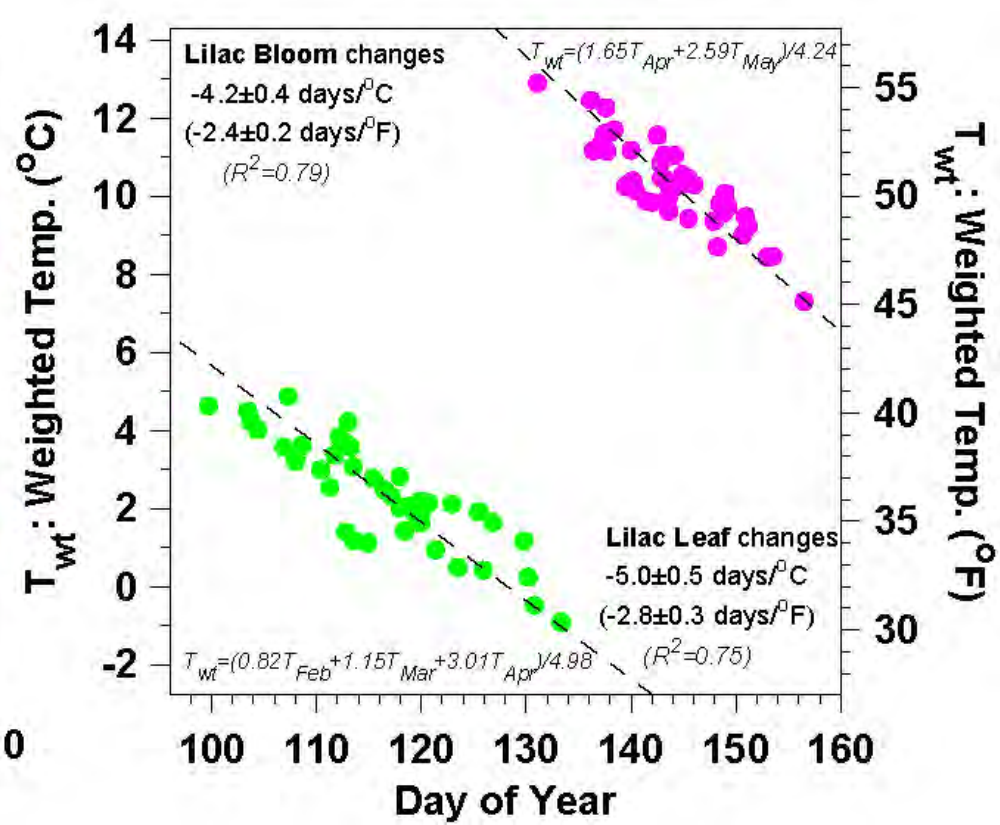
Latest detailed map

- **USDA : VT Hardiness Zone Map 1976-2005 [mean 1990]**
- **A trend of half a zone in 16-20 years is +2.5-3.1ºF/decade [triple the rise of winter mean]**
- **http://planthardiness.ars.usda.gov/PHZMWeb/**



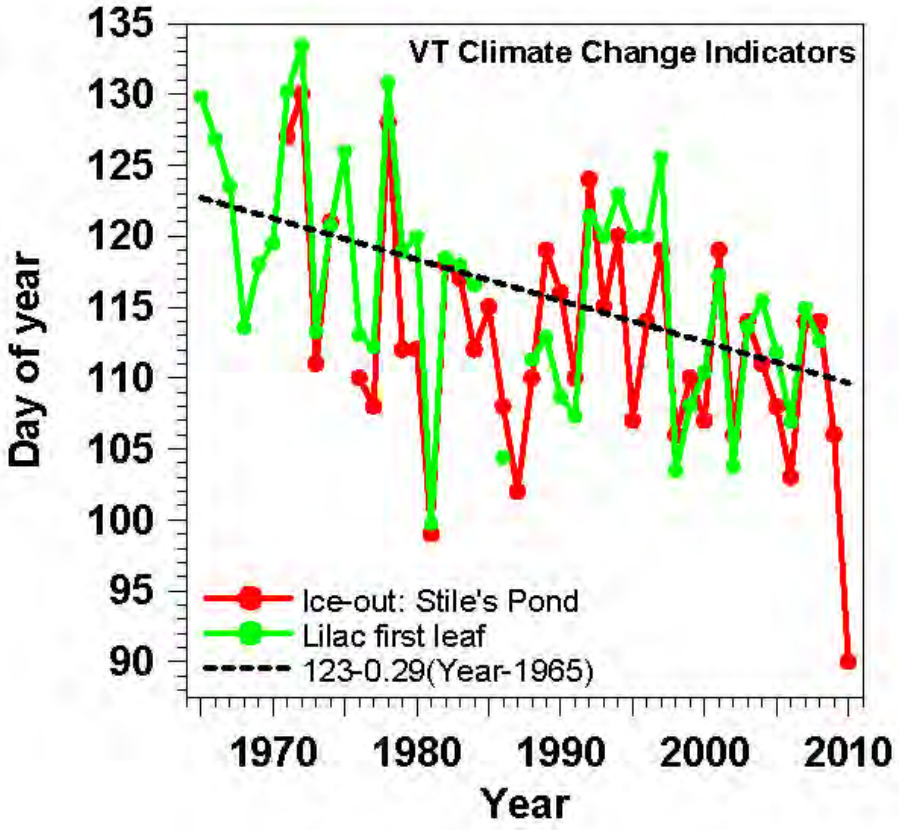
Lilac Leaf and Bloom in Spring

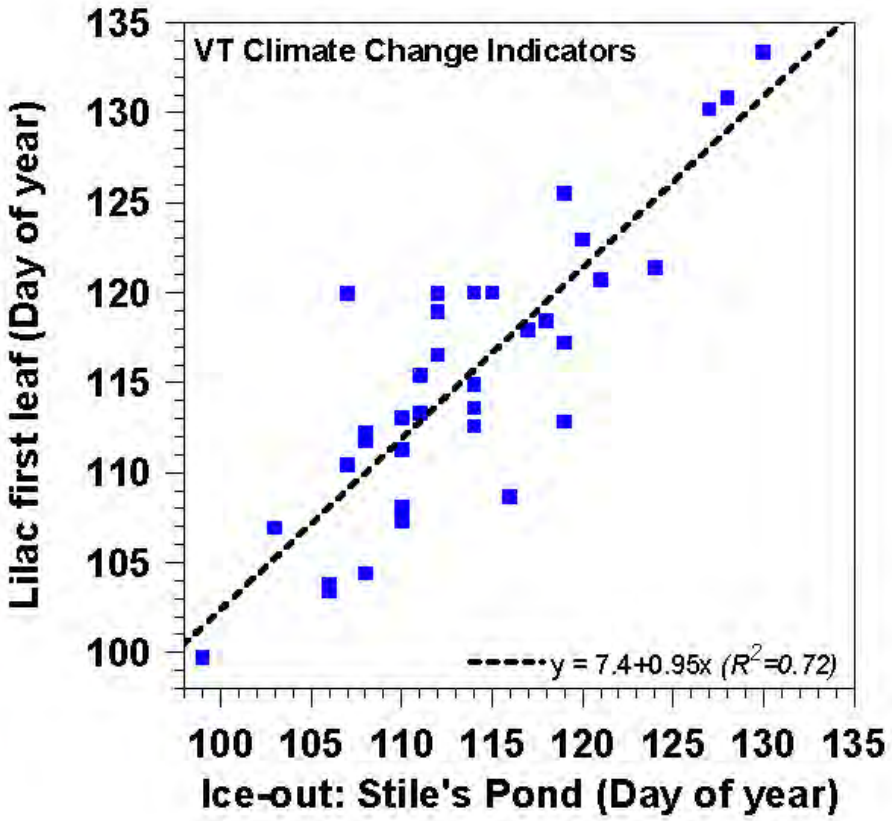




- **Leaf-out earlier by 2.9 days/decade (tracks ice-out)**
- **Bloom earlier by 1.6 days/decade**
- **Leaf & bloom change 4.5 days/°C**

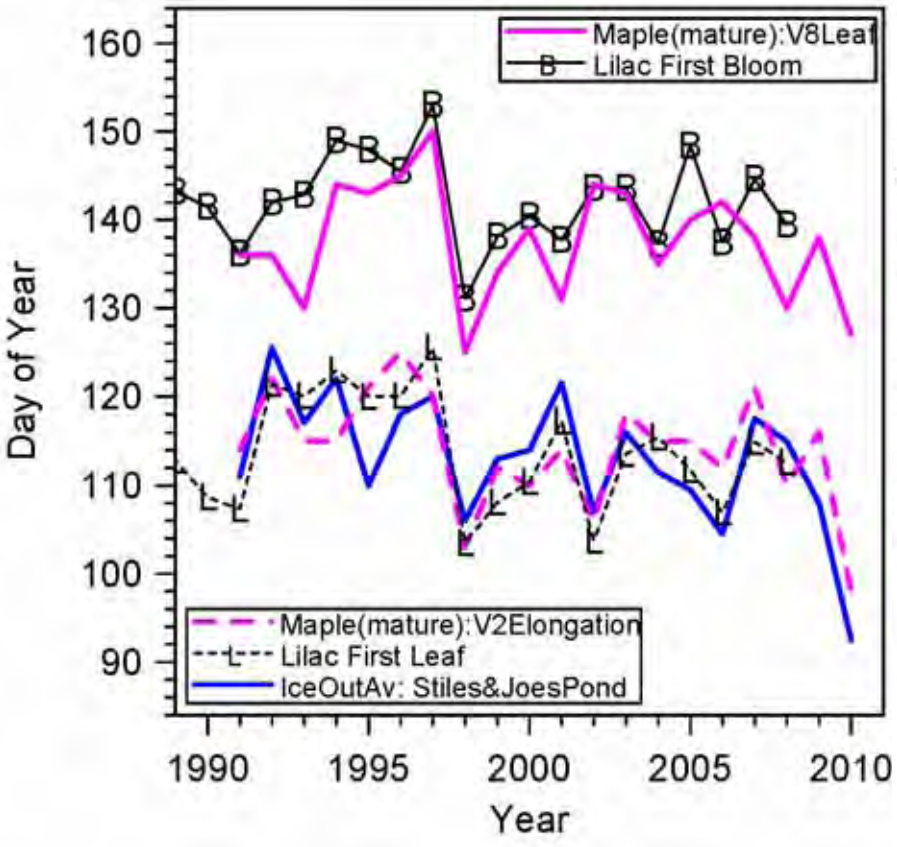
Lilac Leaf-out and Ice-out Coupled

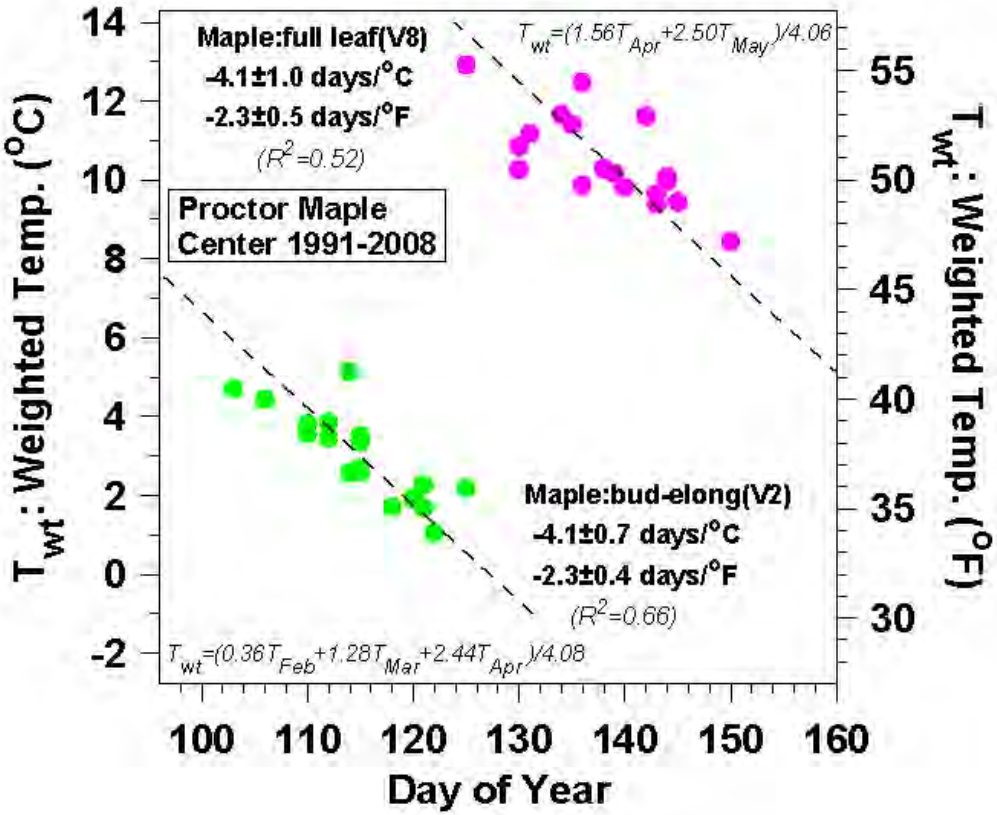




- **Lilac leaf and lake ice-out both depend on Feb. Mar. and April temperatures**
- **Trends indicate earlier spring**

Sugar Maples in Spring





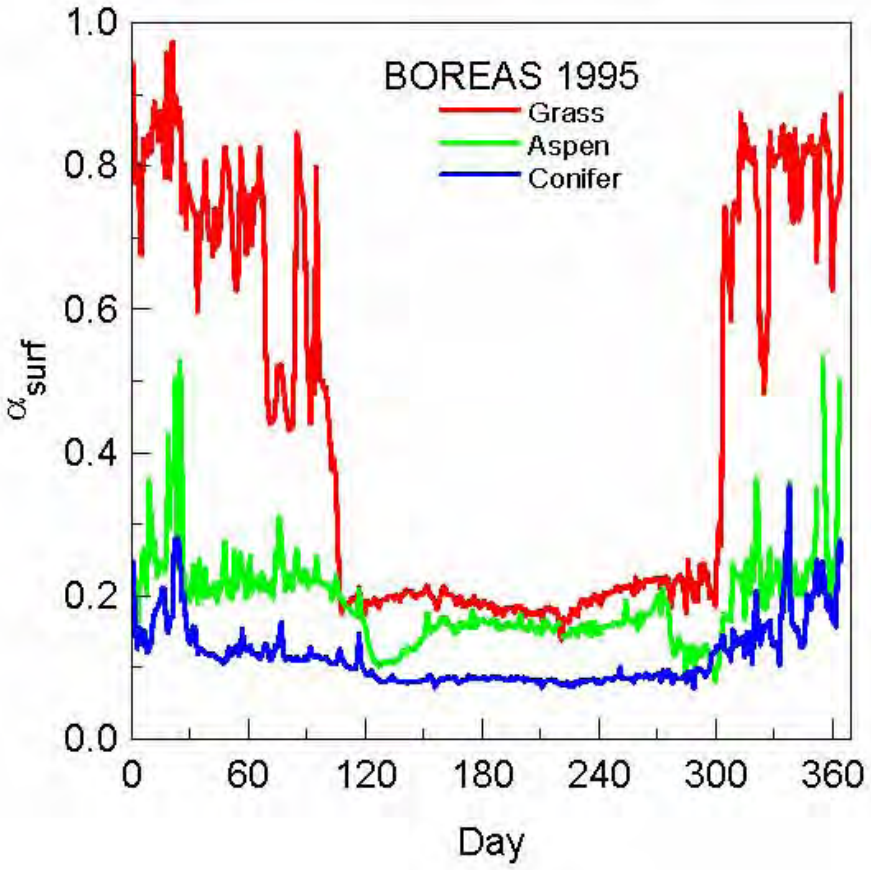
- **Ice-out, lilac leaf, maple bud elongation correlated**
- **Lilac bloom and maple leaf-out correlated**
- **Interannual slope: 4 days/°C**

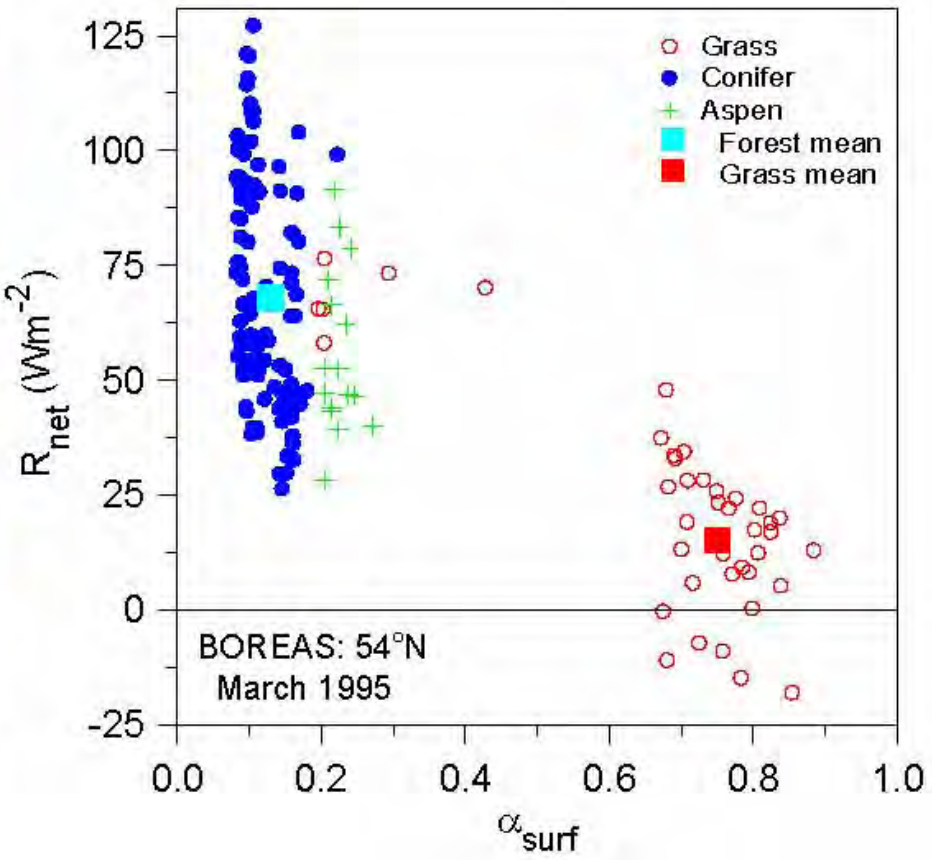
Data: Sandy Wilmot, VT ANR

Vermont Winter 2006

- **Snow reflects sunlight, except where trees shadow**
- **Cold; little evaporation, clear sky; earth cools to space**
- ***2012 warm winter, snow melts → positive feedback***

Surface albedo





- **Impact of landscape differences (forest/grass) on R_{net} are large in spring**

Winter transition

- **Winter Temps. plunge with first heavy snow because of reflection of sunlight**
  - **Local snow/ice-albedo feedback**
- **Evaporation falls with frozen temps & cloud decreases. Clear sky outgoing LW_{net} increases and locks in colder temperatures**
  - **Regional water vapor greenhouse feedback**
- **Snow cover insulates surface, so ground flux drops.**

Rough Energetics

- **Winter SW_{down}(clear) ≈ 130 Wm^{-2}**
- **10cm fresh snow changes albedo from 0.15 to 0.75 & drops SW_{net} from 110 to 30 Wm^{-2}**
- **Residual 30 Wm^{-2} sublimes 1cm snow/day**
- **Snow loss increases as snow ages**
  - **– snow lasts ≈ 5 days,**
  - **– reducing solar heating to ≈ zero**
- **2012 winter – no permanent snow cover west of Green Mountains in VT - warm**

Shrinking Winter: Pittsford, VT
(Freeze-up used to be mid-November)

January 7, 2007

December 2006:

- **Warmest on record**

January 10, 2008

Warm Fall:

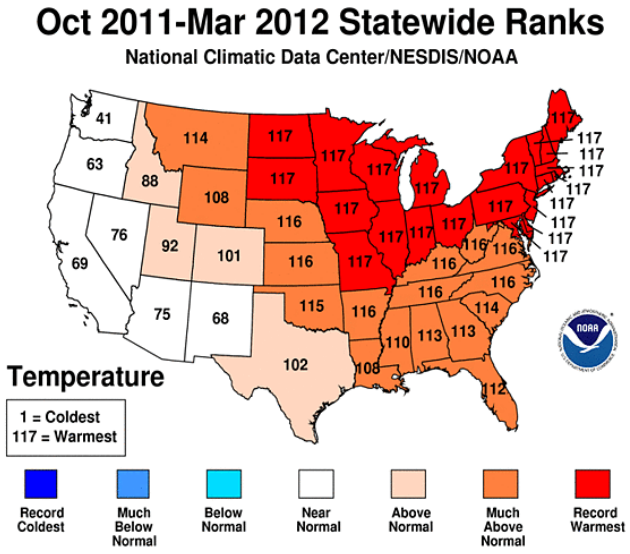
- **Record Arctic sea-ice melt**
- **Snow cover in December, ground unfrozen**

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 Mountains**
- **Contrast snowy winter 2010-11**



Early Spring: Daffodils, Forsythia

79ºF on March 22, 2012

Pittsford Vermont

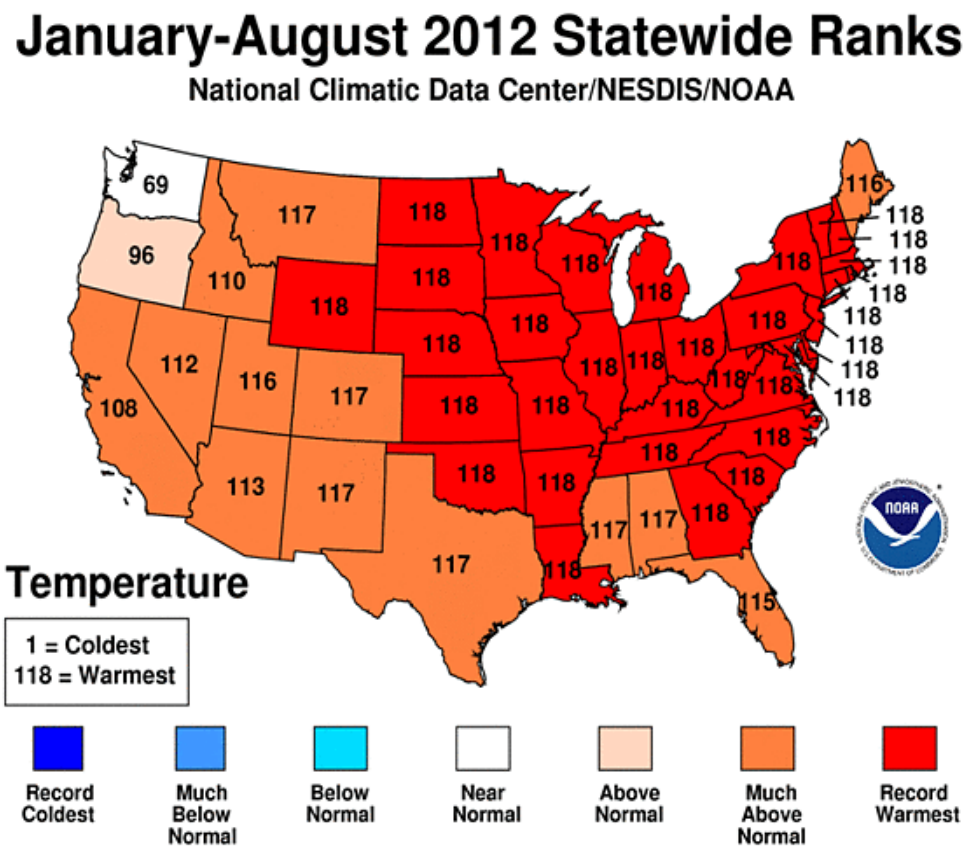
3/22/12

Pittsford Vermont

3/24/12

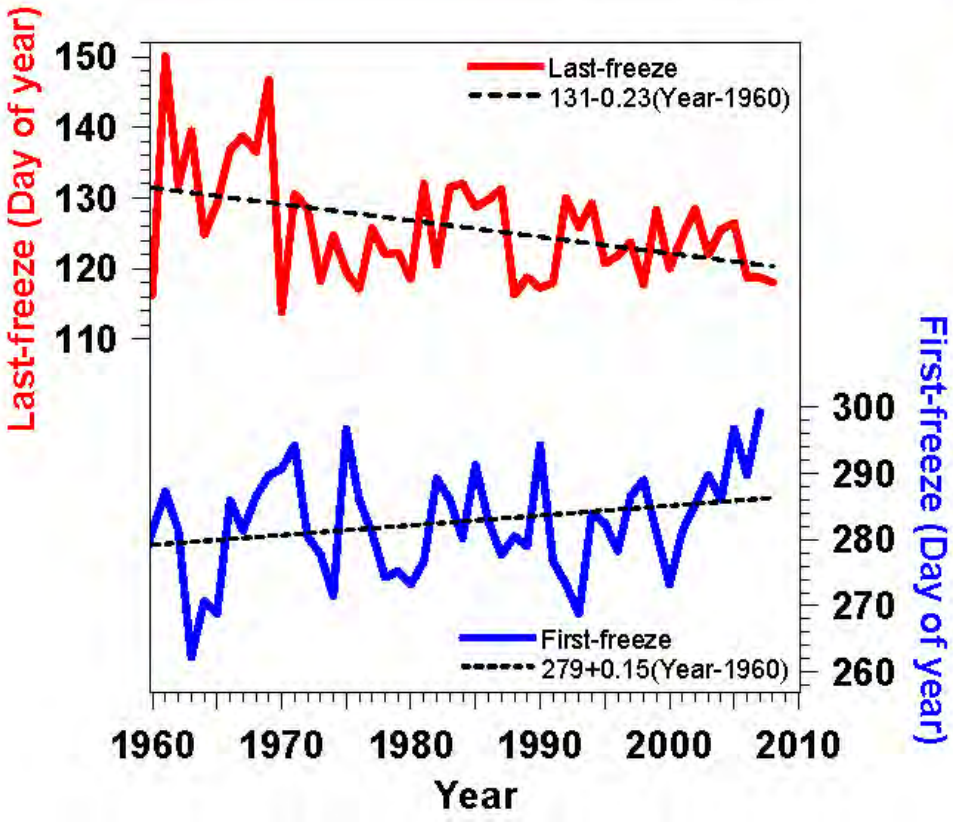
This Year Exceptionally Warm

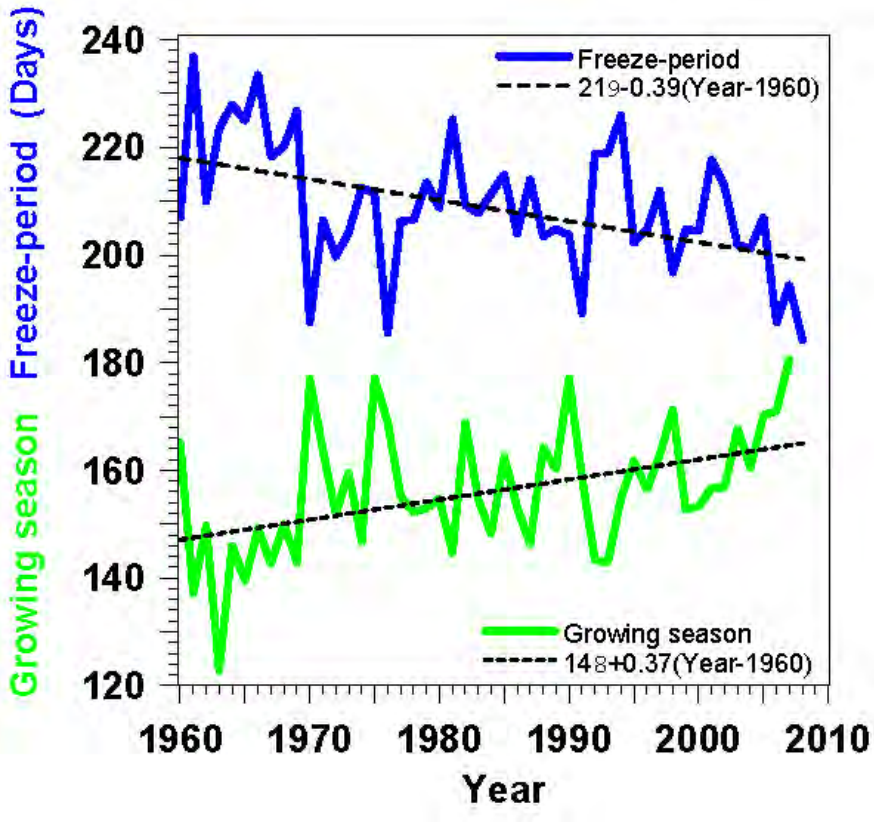
- Burlington Area Extremes
- Highest Average Temperature degrees F
- Days: 9/1/2011 - 8/31/2012
- Length of period: 365 days
- Years: 1850-2012
- Rank Value Ending Date
- **1 50.4 8/31/2012**
- 2 48.4 8/31/2002, 8/31/1949
- 4 48.2 8/31/2010
- 5 48.0 8/31/1999
- 6 47.9 8/31/2006
- 7 47.8 8/31/1991, 8/31/1995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

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

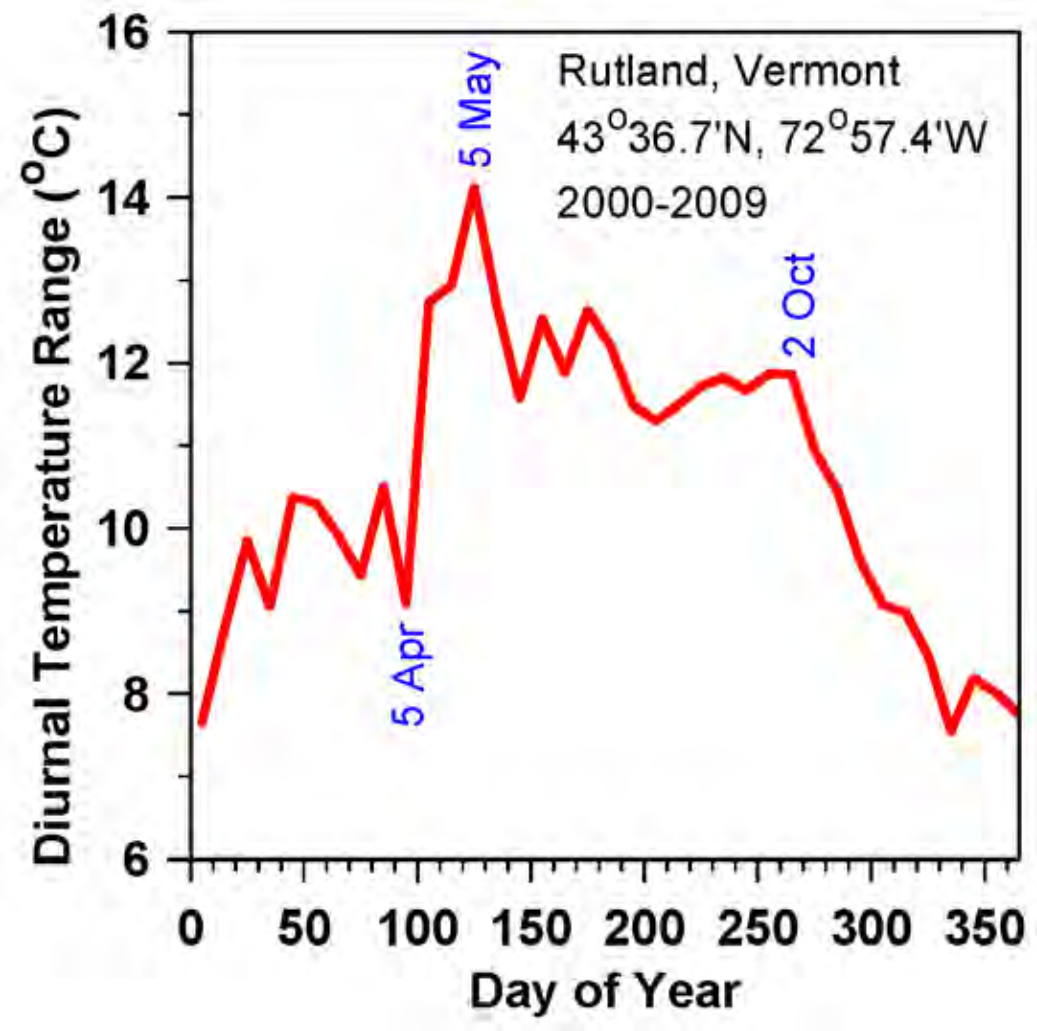
- **After leaf-out**

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

- ***Spring is coming earlier***

Diurnal Temperature Range (DTR)

- **DTR to seasonal transitions**
- **↑ 5 April to 5 May**
- **↓ Forest leaf-out (transpiration)**
- **Flat till leaf fall early Oct.**



Betts, 2011b

Summer dry-down

- **Wet in spring**
- **Soil moisture falls: summer dry-down**
- **Low humidity & little rain**

- ***May help lock-in drought in central US as 2012***

Recently Many Wet Summers in Vermont

- **2004, 2006, 2008, 2009, (2010), 2011 all wet**
- **Direct fast evaporation off wet canopies**
- ***Positive evaporation-precipitation feedback, coupled to synoptic system frequency***

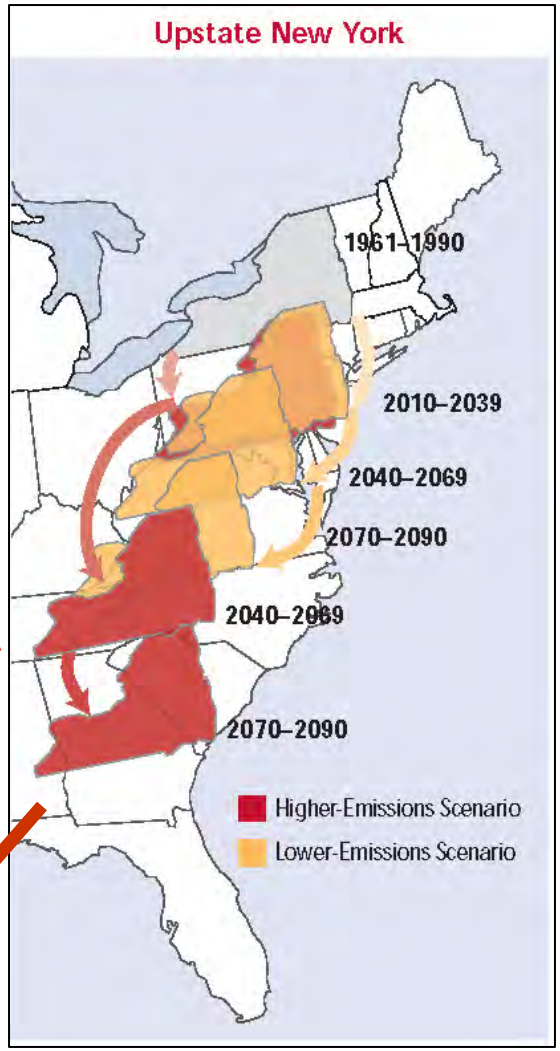
Fall Climate Transition

- **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

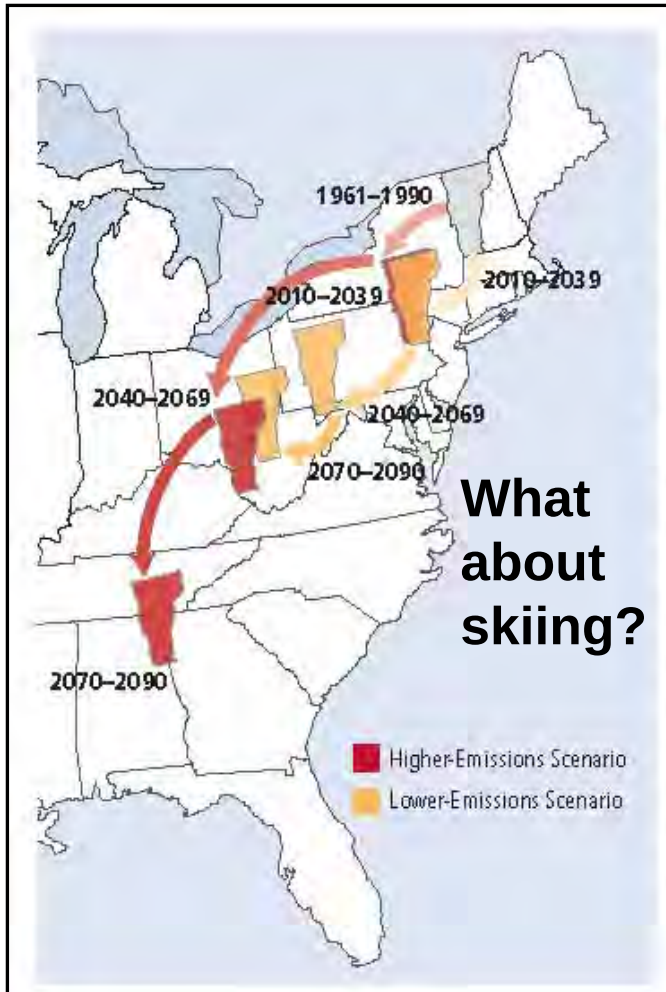
Later frost: Growing season getting longer

NY and Vermont's Future with High and Low GHG Emissions



Business as usual

What about tropics?



What about skiing?

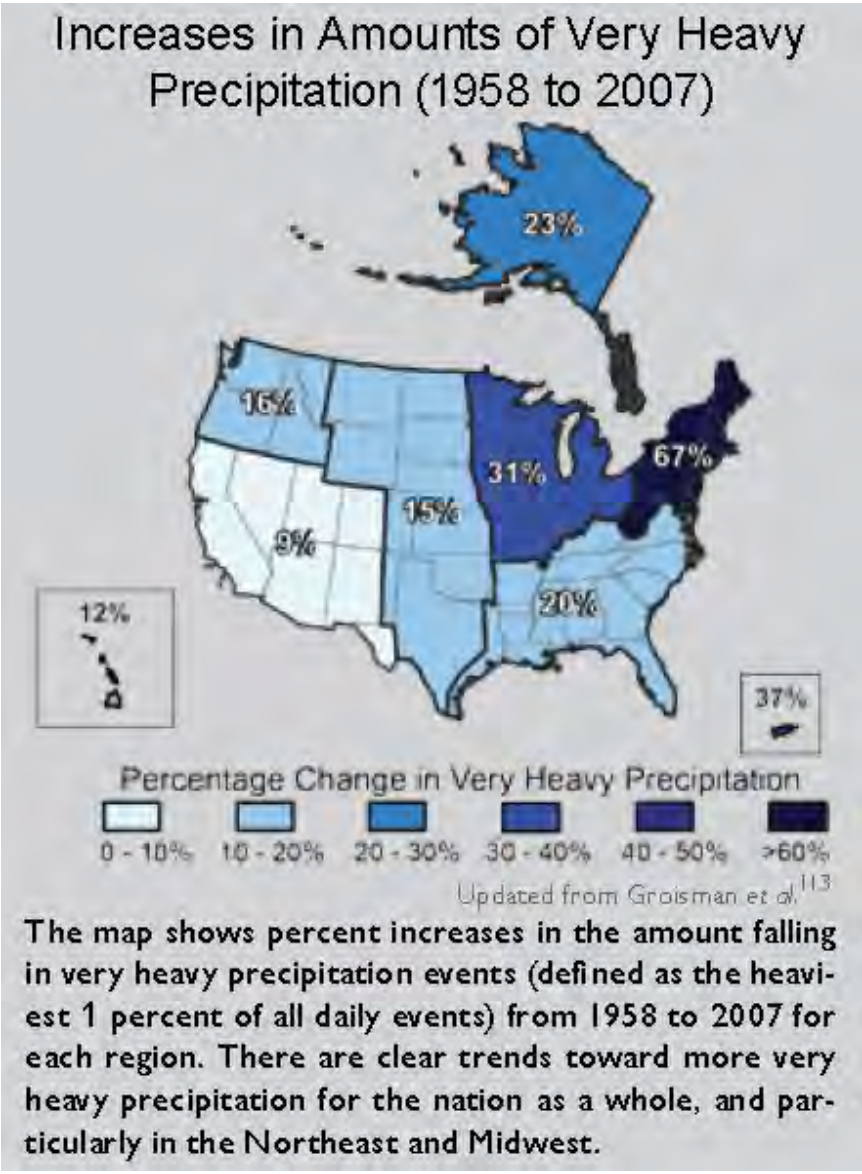
Migrating State Climate

Changes in average summer heat index—a measure of how hot it actually feels, given temperature and humidity—could strongly affect quality of life in the future for residents of Vermont. Red arrows track what summers in Vermont could feel like over the course of the century under the higher-emissions scenario. Yellow arrows track what summers in the state could feel like under the lower-emissions scenario.

NECIA, 2007

Very Heavy Precipitation Is Increasing

- **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**
- **Little change or a decrease in the frequency of light and moderate precipitation**
- **Vermont streamflow is increasing**



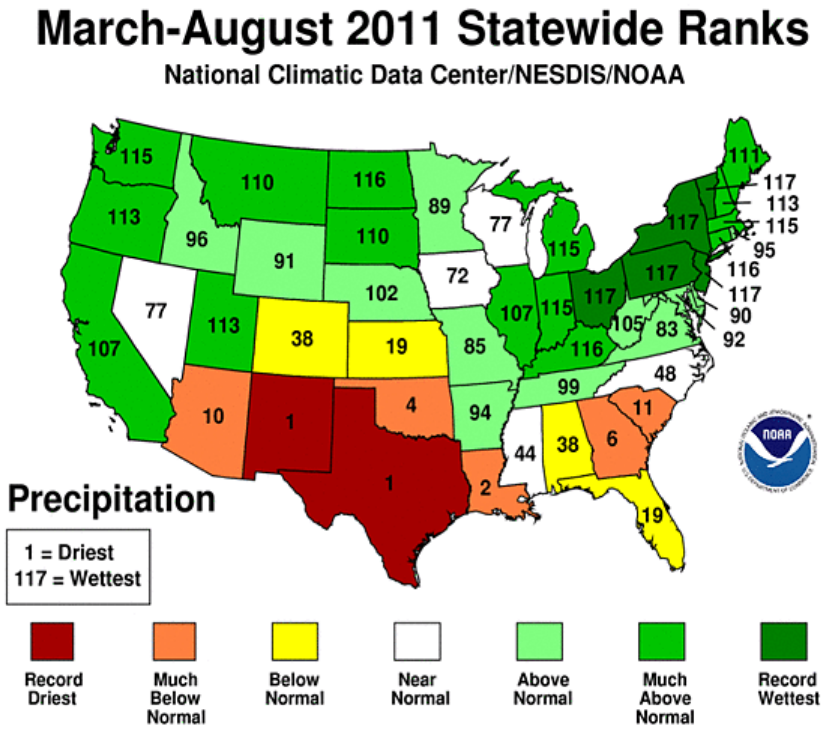
The map shows percent increases in the amount falling in very heavy precipitation events (defined as the heaviest 1 percent of all daily events) from 1958 to 2007 for each region. There are clear trends toward more very heavy precipitation for the nation as a whole, and particularly in the Northeast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

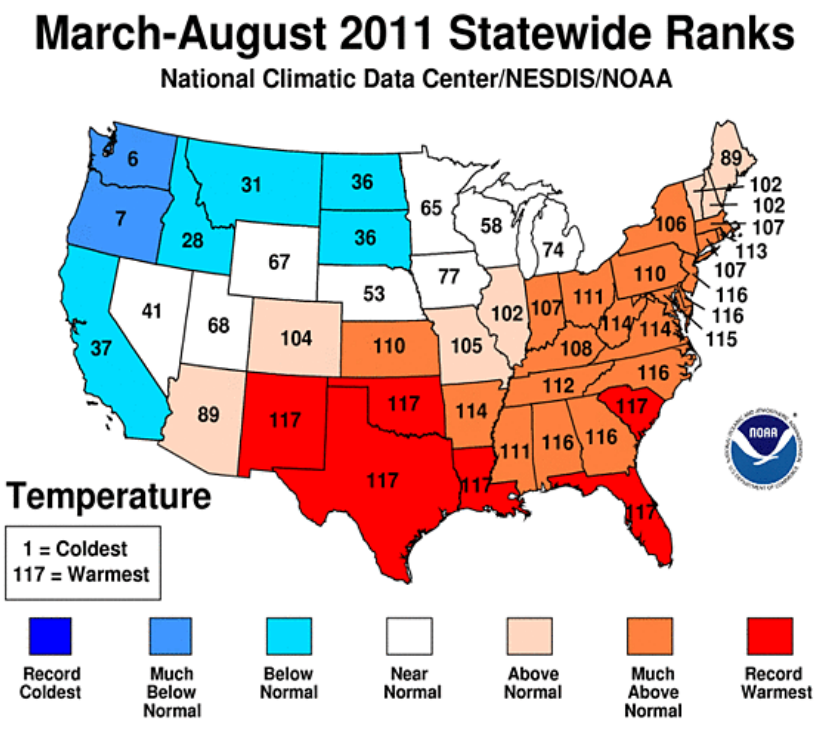
Extreme Weather (precip.)

- ***Precip. is condensation of atmospheric water vapor (large latent heat release)***
- ***Saturation vapor pressure at cloud-base increases steeply with temperature (6%/^{o}C)***
- ***More latent heat organizes storms, increasing convergence of vapor***
- ***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***
- ***Wet surface: more evaporation and runoff***

2011 Vermont Floods

- **Record spring flood on Lake Champlain**
- **Record floods following TS Irene**
- **Record wet March-August, 2011: OH to VT (but record drought in TX & NM)**
- **‘Stationary modes’**





Adaptation to non-stationary climate?

- **Built infrastructure: bridges, culverts, streams, flood-plains…. More capacity, more space for natural flows, frequent stats updates**
- **Agriculture: crops suited to extended growing seasons & warmer climate, water management of floods & extended drought.**
- **Preserving natural resources: forests, lakes, fish, wildlife: very challenging – minimize human stresses**

How Do We Manage the Earth?
(When there is so much we don't know)

- **Need a long time horizon:**
  - **Generational to century *(Forest timescale)***
- **We need some new rules / guidelines !**
  - **Our numbers are so great**
  - **Our industrial impact is too large**
  - **Maximizing profit as a guiding rule has failed us**
- **Re-localize to regain control / responsibility and minimize transport**

Broad Guidelines/ Rules to Minimize Impacts

- **Minimize the lifetime of human waste in the Earth system and eliminate waste with critical biosphere interactions**

- **Minimize the use of non-renewable raw materials, and**
- **Maximize recycling and re-manufacturing**

- **Maximize the efficiency with which our society uses energy and fresh water, and**
- **Maximize the use of renewable resources**

What Will This Mean For You?

- **Society (and engineers) need to rethink relationship to the natural environment and its ecosystems in less than one generation**
- **Our ‘lifestyle’ is disconnected from what the earth can sustain and the large inertia of the earth system is masking the extent of the crisis we face**
- **Individual can rethink priorities but societal changes are needed: from towns to global**

- **Ask**
  - **Is this an efficient and sustainable way of doing this?**
  - **Do I have a deep understanding and connection to Earth?**

Discussion

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

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

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

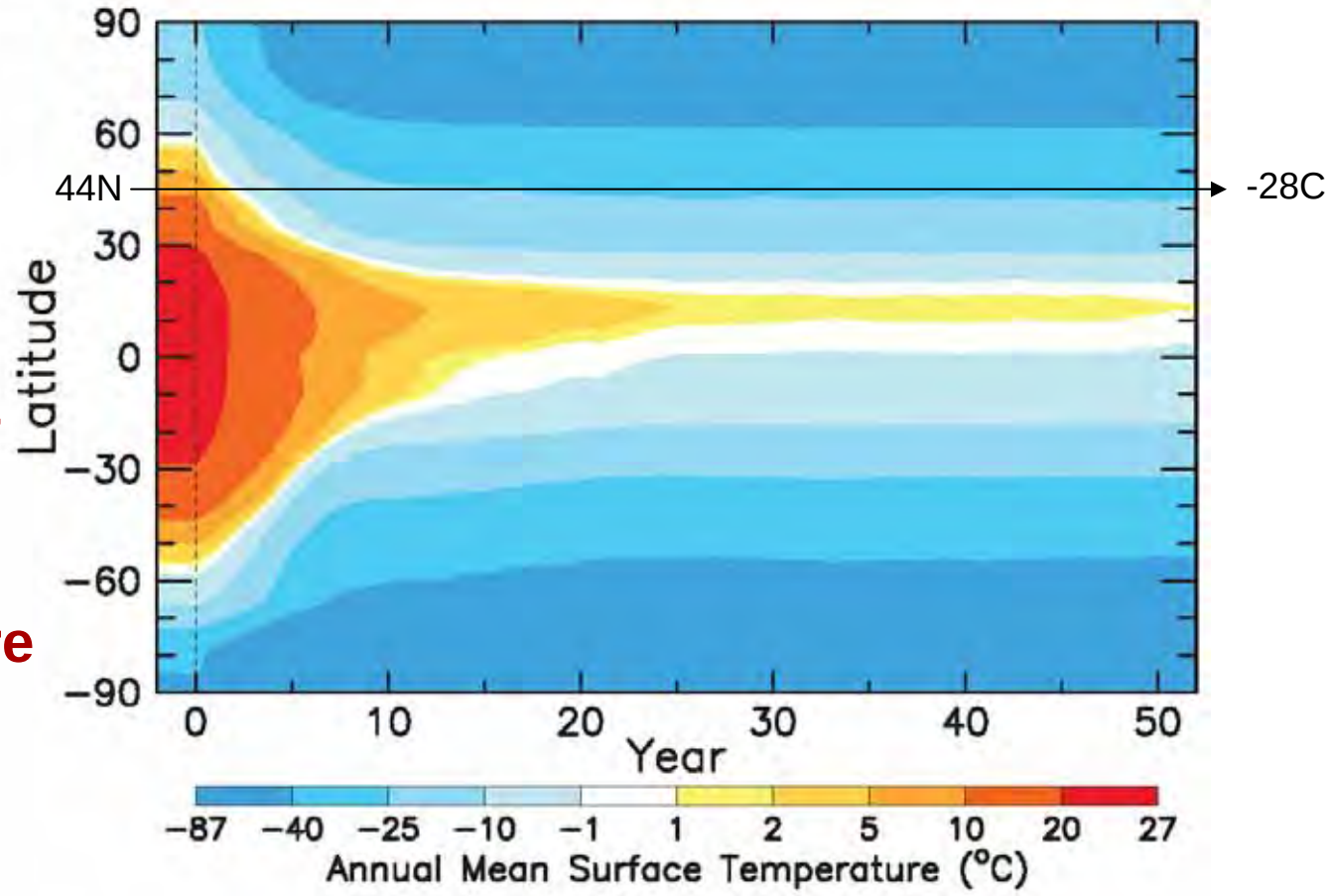
  - papers at http://alanbetts.com/research

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

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%**

Efficiency Comes First

- **We need to double or triple our energy efficiency because…**
  - **We cannot replace current fossil fuel use with biofuels & renewable energy**
  - **Oil and gas reserves are limited, but coal & oil shale reserves are sufficient to push CO_2 to 1,000 ppm—and in time melt icecaps**
    - **Can we "sequester" CO_2 (put it back in the earth)?**

Examples of Long-Lived ‘Waste’

- **CFCs – refrigerants – very stable – lifetime centuries - broken down by sunlight in stratosphere – catalyze ozone destruction, which protects earth from UV**
- **CO_2 from fossil fuels – lifetime centuries – a greenhouse gas that traps earth’s heat radiation – pushing earth to warmer climate**
- **Nuclear waste – plutonium-239: half-life 24000 years – nuclear weapons**

Why Is It Difficult for Us?

- **The "American dream" is crumbling**
  - **"Economic growth" based on fossil fuels, debt, and consumerism is unsustainable — and a disaster for the planet!**
- **Individual "rights" and the needs of humanity must be balanced against the needs of the earth's ecosystem**
- **We don't know how to guide and manage technology —so the result is tremendous successes and catastrophic failures**

Why Is It Difficult for Us?

- **Fossil fuels reserves are worth $20-30T**
- **Regulating emissions of CO_2 is an "unfair cost" to the "free market"**

- **Real Earth system issues being ignored**
- **Our politics are facing collapse – becoming fantasy disconnected from the real world**

Last four ice-age cycles