Vermont's Changing Climate

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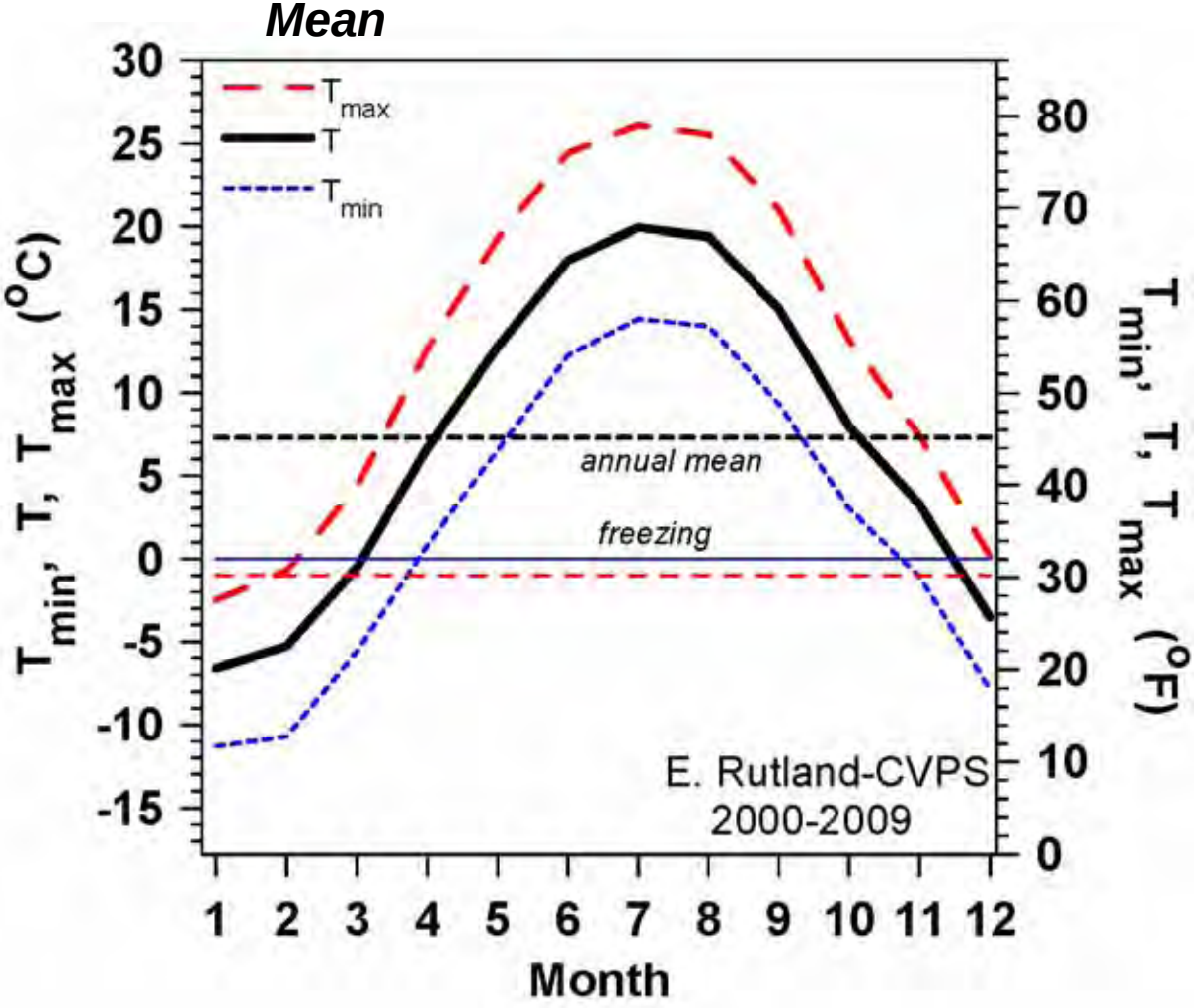
Salisbury Conservation Commission

Salisbury, VT

January 17, 2013

Climate of Vermont

- **Climate is a mean (10-30y)**
- **T_{max}, T, T_{min}**
- **Large seasonal range in VT**
- ***Freezing T of water critical to climate***

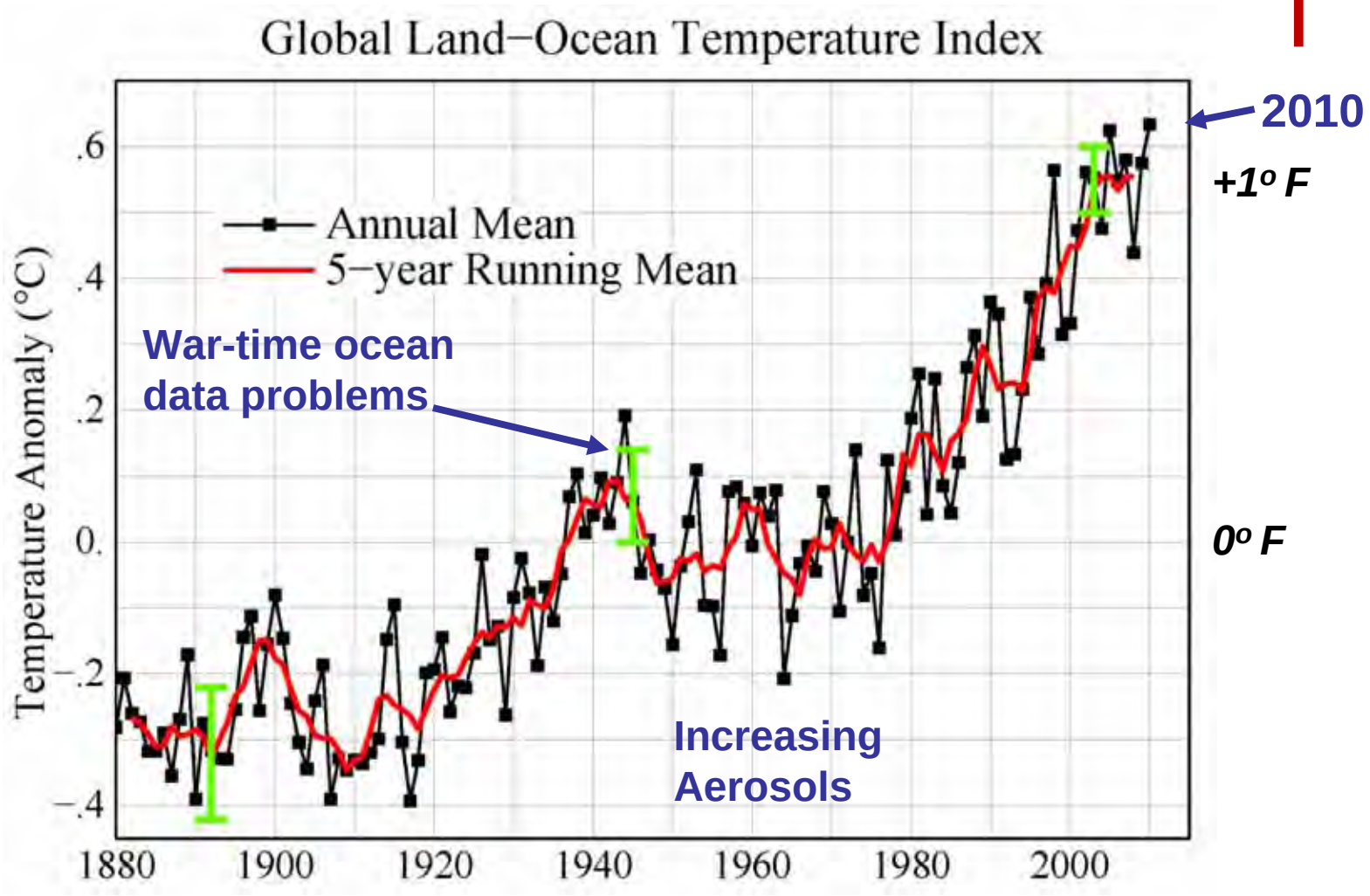


Earth sustains life

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

January 2, 2012: NASA

Global Temperature Rise 1880 – Present

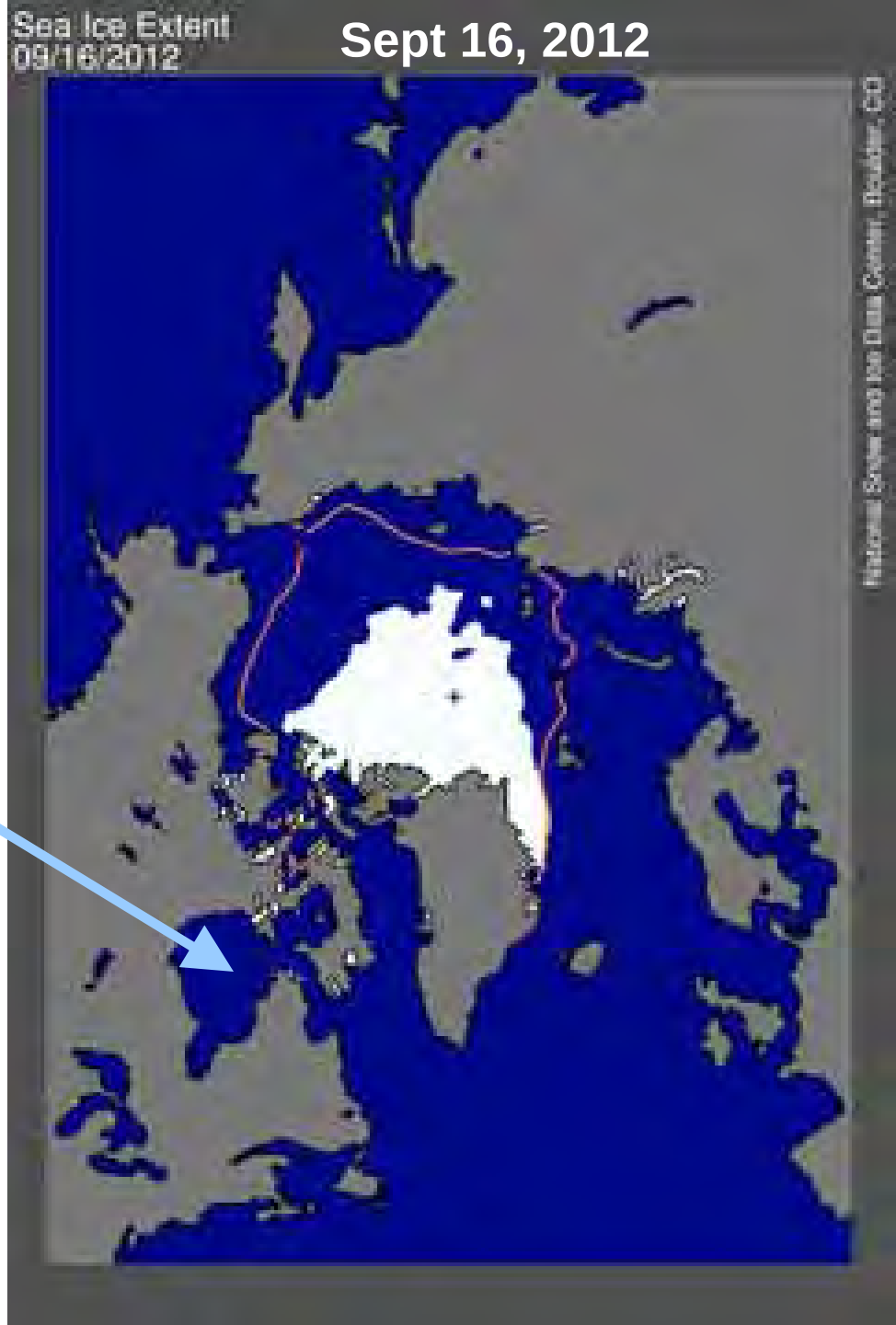


NASA-GISS, 2011

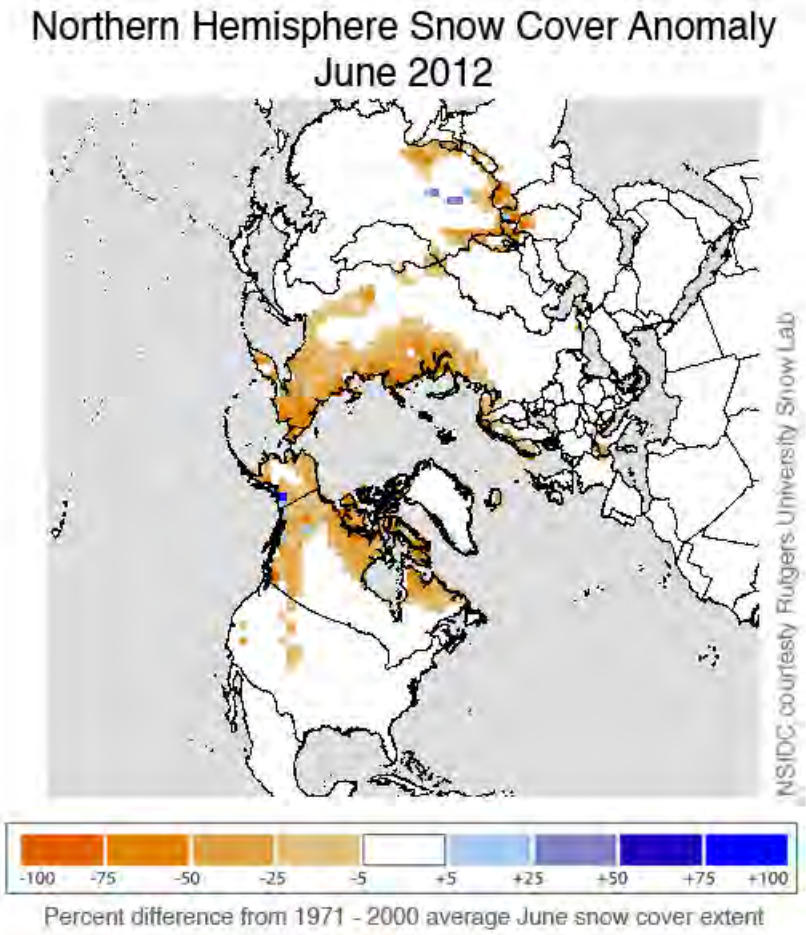
- **Half the Arctic Sea Ice Melted in 2012**
- **Open water in Oct. Nov. gives warmer Fall in Northeast**

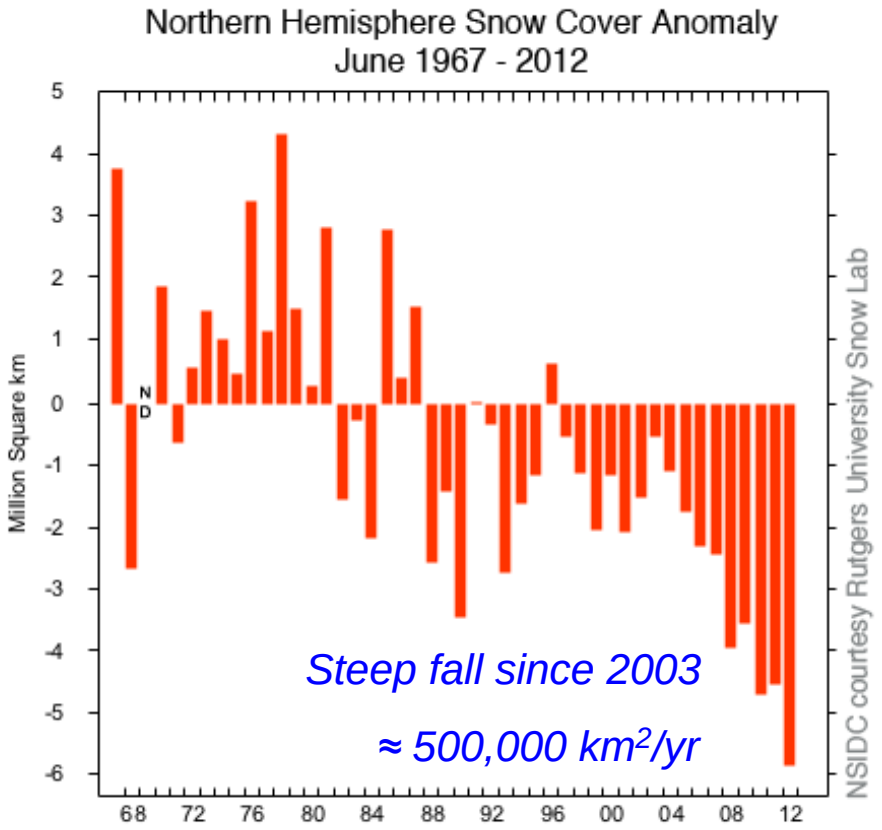
At the end of Nov. 2011 Hudson Bay was still nearly ice-free

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



June 2012 snow cover minimum





- **Arctic warming rapidly**
  - **Melting fast**
- **New England winters also**
  - **Same amplifying feedbacks**

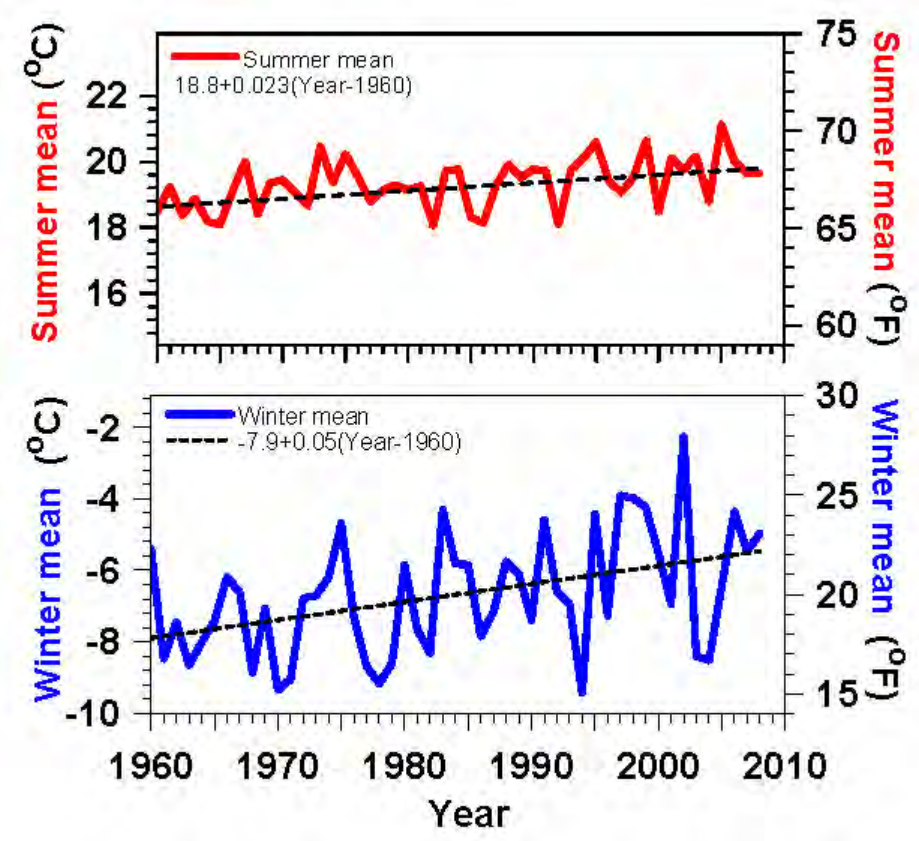
What Is Happening to Vermont?

- **PAST 40/50 years (Impact of rising CO_2 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**

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

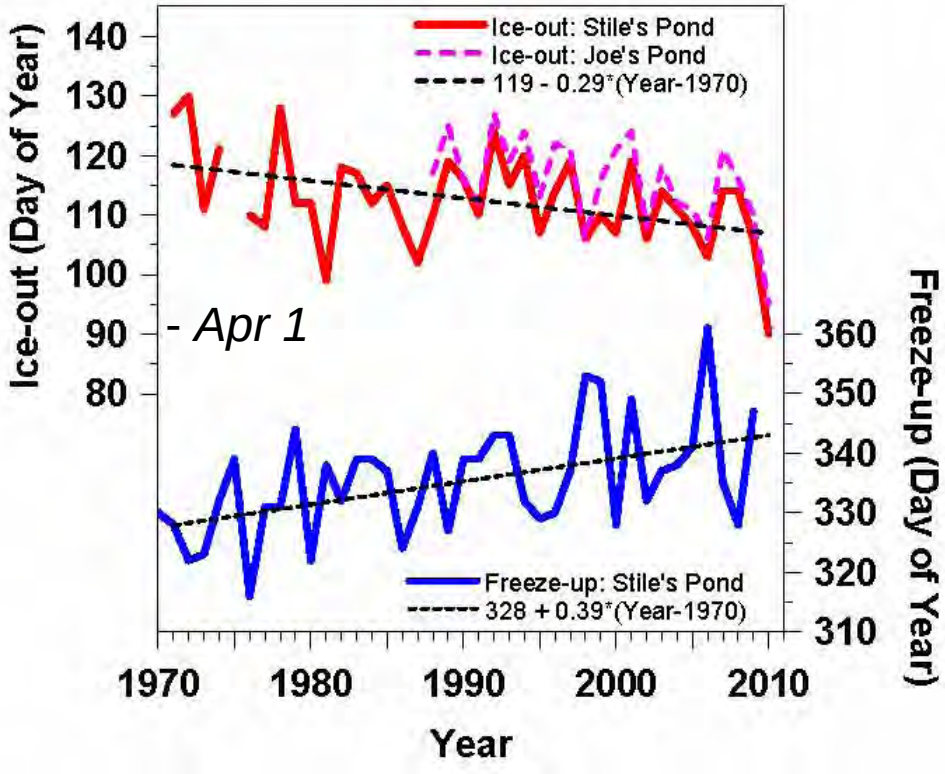
Vermont Temperature Trends 1961-2008

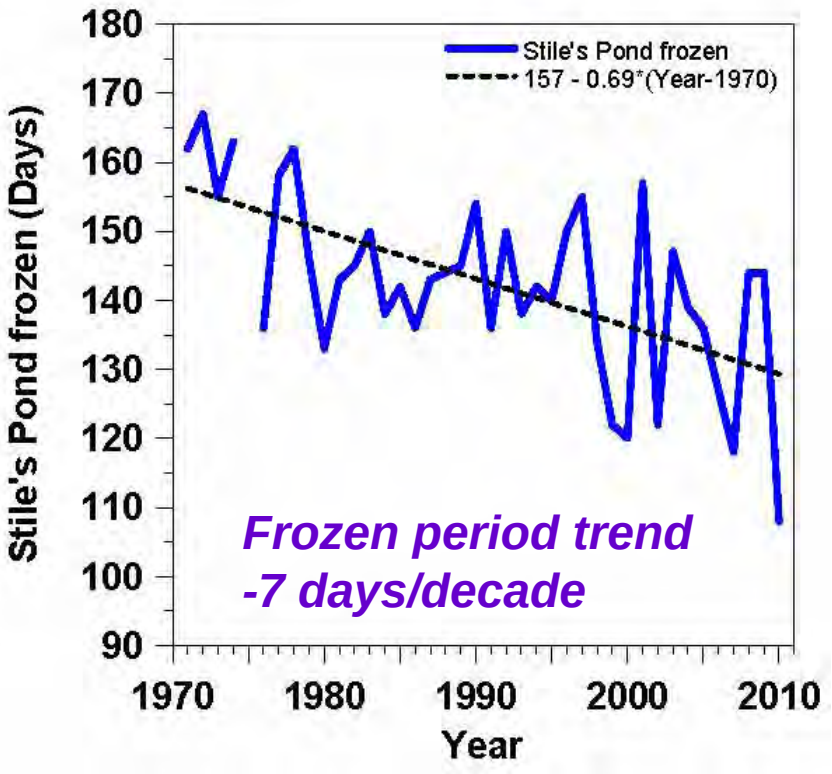
- **Summer +0.4°F / decade**
- **Winter +0.9°F / decade**
- **Larger variability, larger trend**
- ***Less snow (and increased water vapor) drive larger winter warming***



Lake Freeze-up & Ice-out Changing

Frozen Period Shrinking Fast



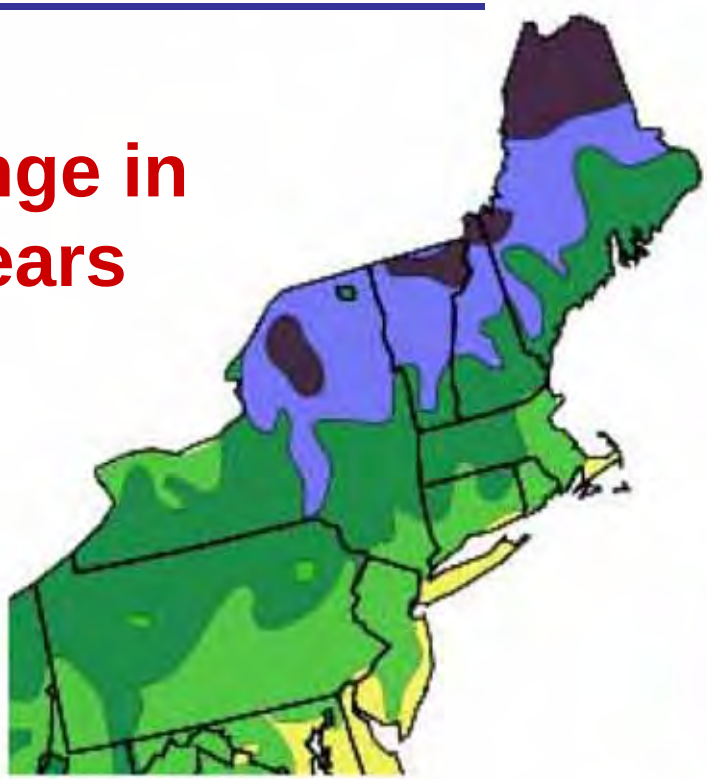


- **Freeze-up later by 4 days / decade**
- **Ice-out earlier by 3 days / decade**
- ***Spring runoff peak 3 days / decade earlier***

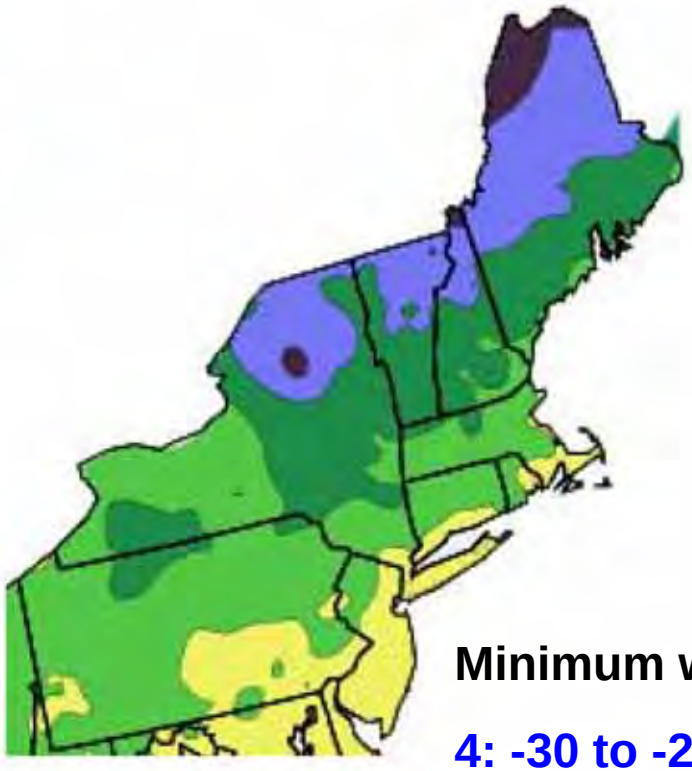
Winter Hardiness Zones

– winter cold extremes

Change in 16 years



1990



2006

Zone

2 3 4 5 6 7 8 9 10

USDA Hardiness Zones

Minimum winter T

4: -30 to -20°F

5: -20 to -10°F

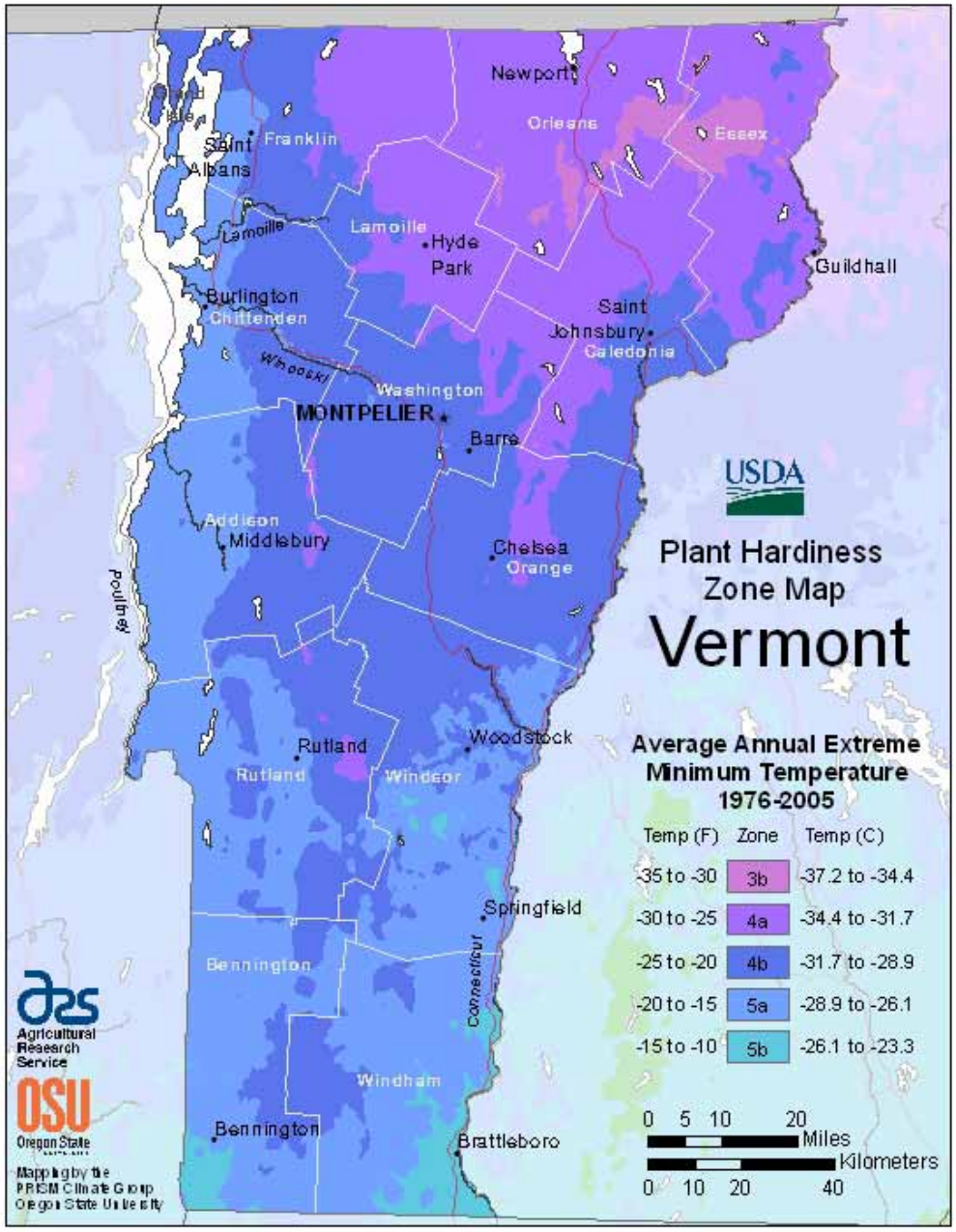
6: -10 to 0°F

Detailed Map *(most recent)*

- **USDA : VT Hardiness Zone Map 1976-2005**
  - **mean 1990**
  - **South into zone 6**

- **Half-zone in 16 yrs ~ 3ºF/ decade**
  - **triple the rise-rate of winter mean T**

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



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

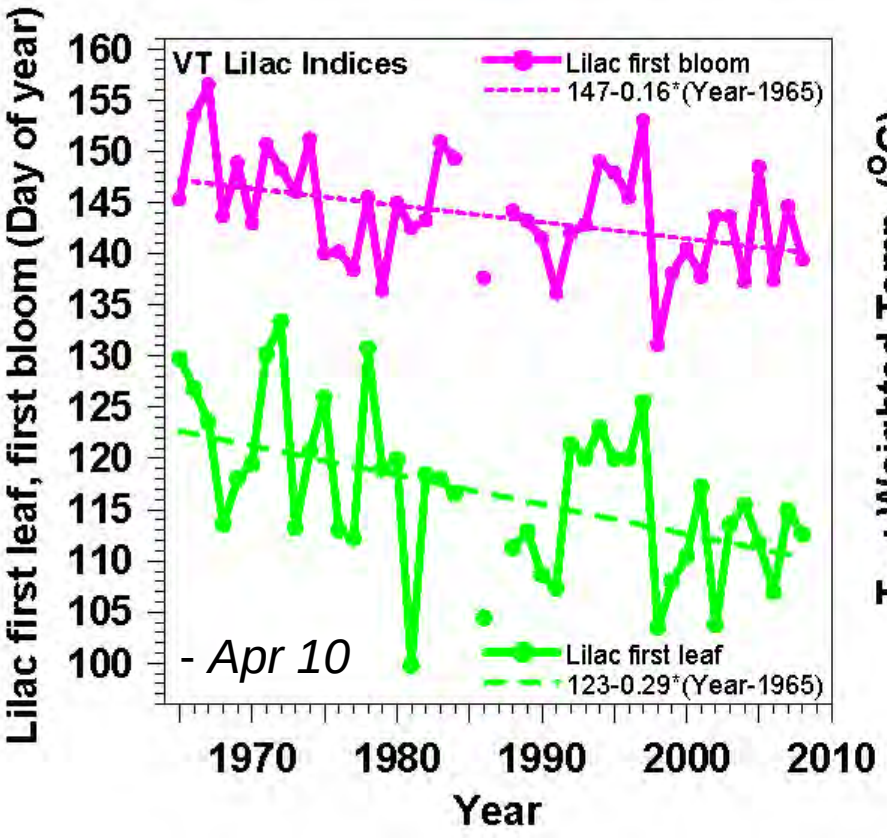
- **Hardy peaches: 2012**
- **More pests survive winter**
- **What is this?**

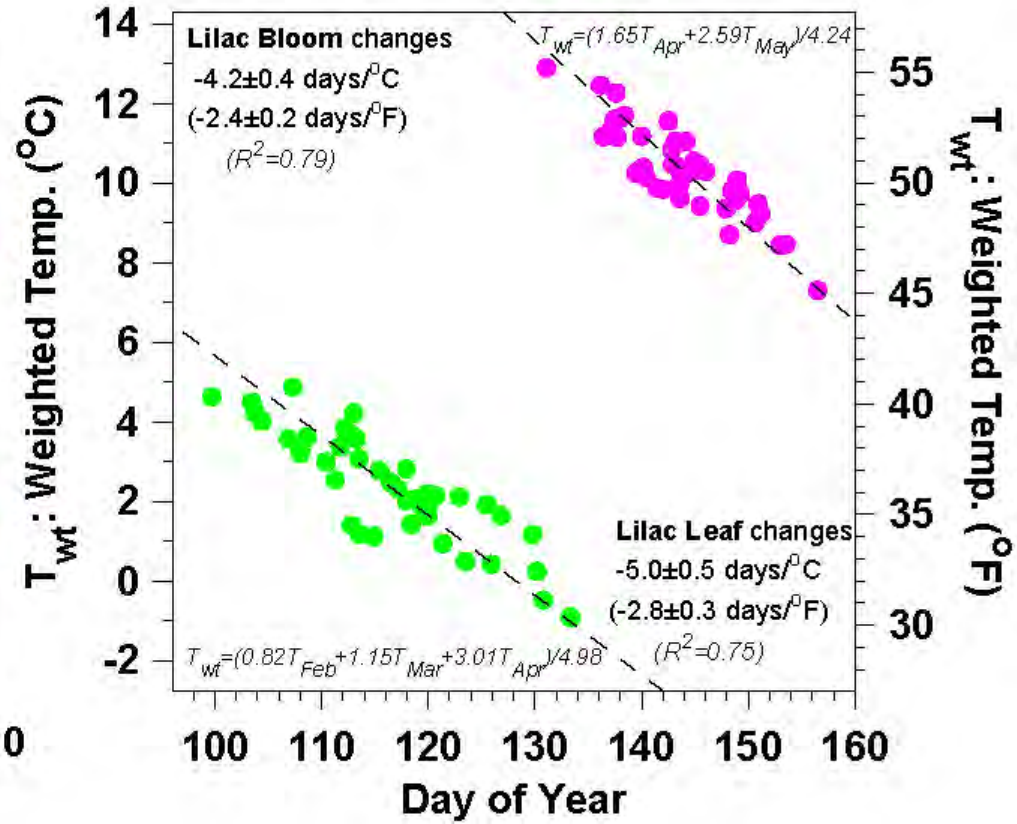
Bennington & Brattleboro are becoming zone 6

- **Hardy peaches: 2012**
- **More pests survive winter**
- **What is this?**

- **Avocado**
  - **Didn’t survive frost**
  - **Late century: in CT**
  - **Our grand-children**

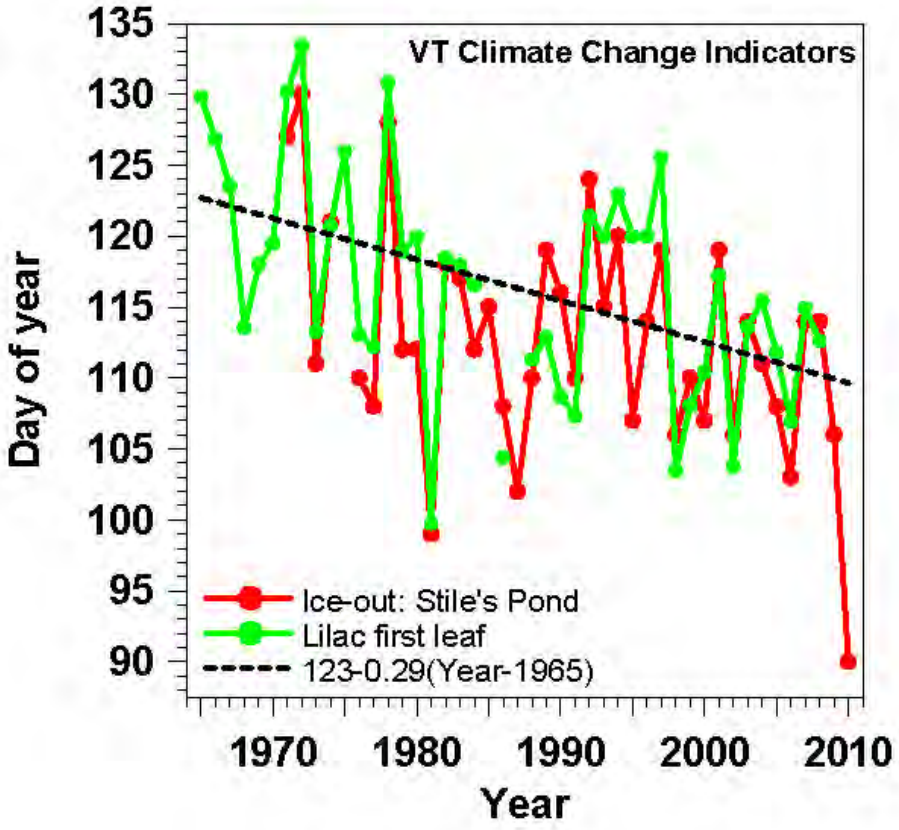
Lilac Leaf and Bloom

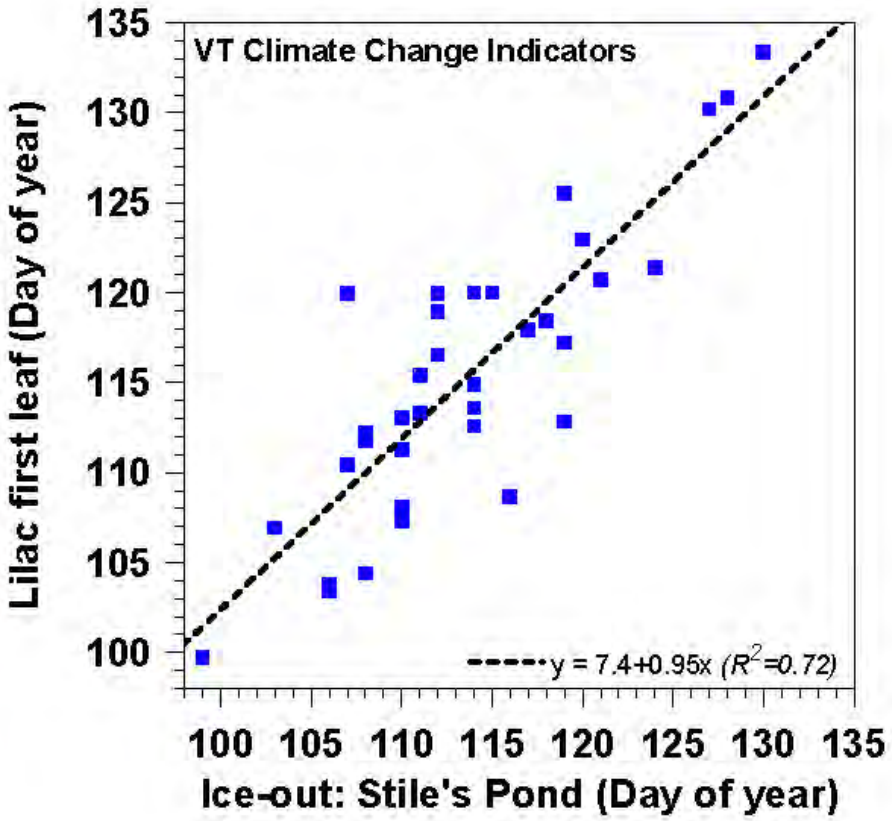




- **Leaf-out -2.9 days/decade; Bloom -1.6 days/decade**
- **Large year-to-year variation related to temperature: 2 to 3 days/ ºF**

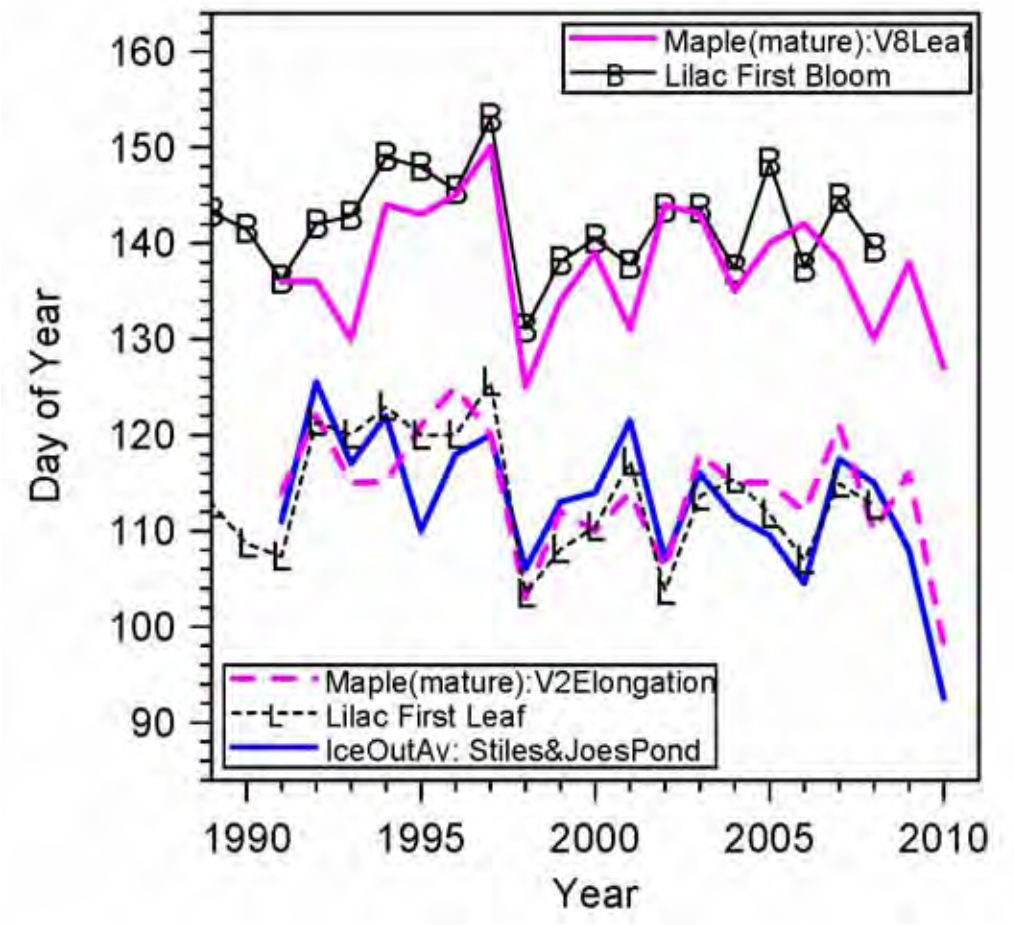
Lilac Leaf-out and Ice-out Coupled





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

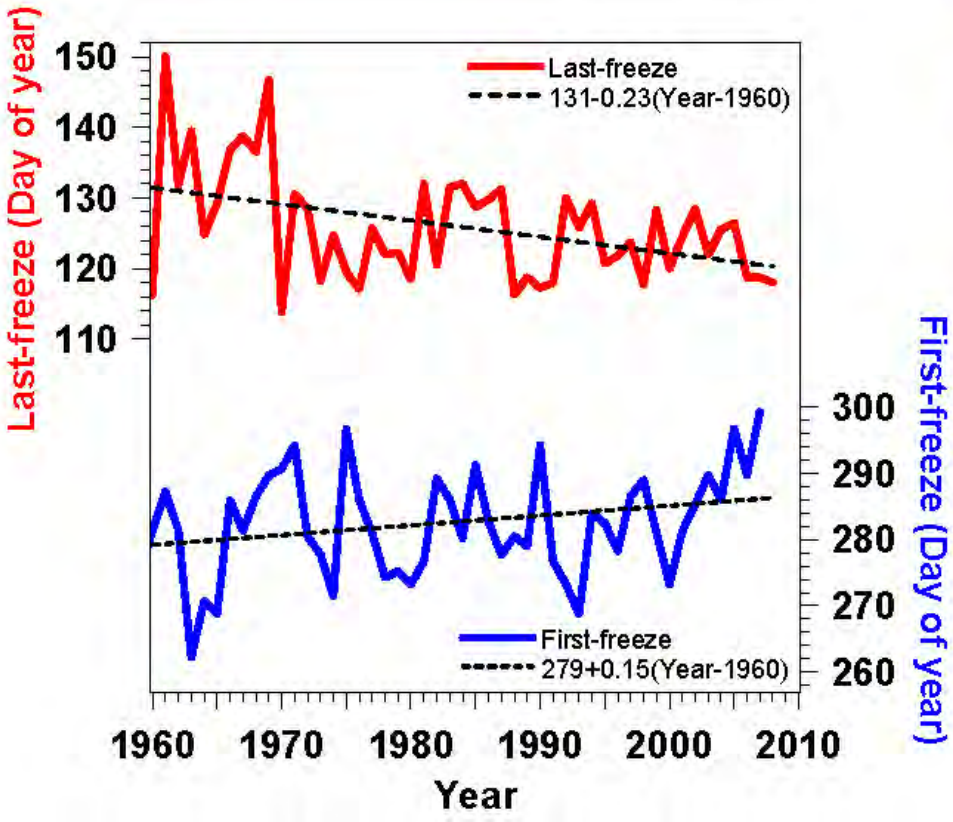
Sugar Maples in Spring

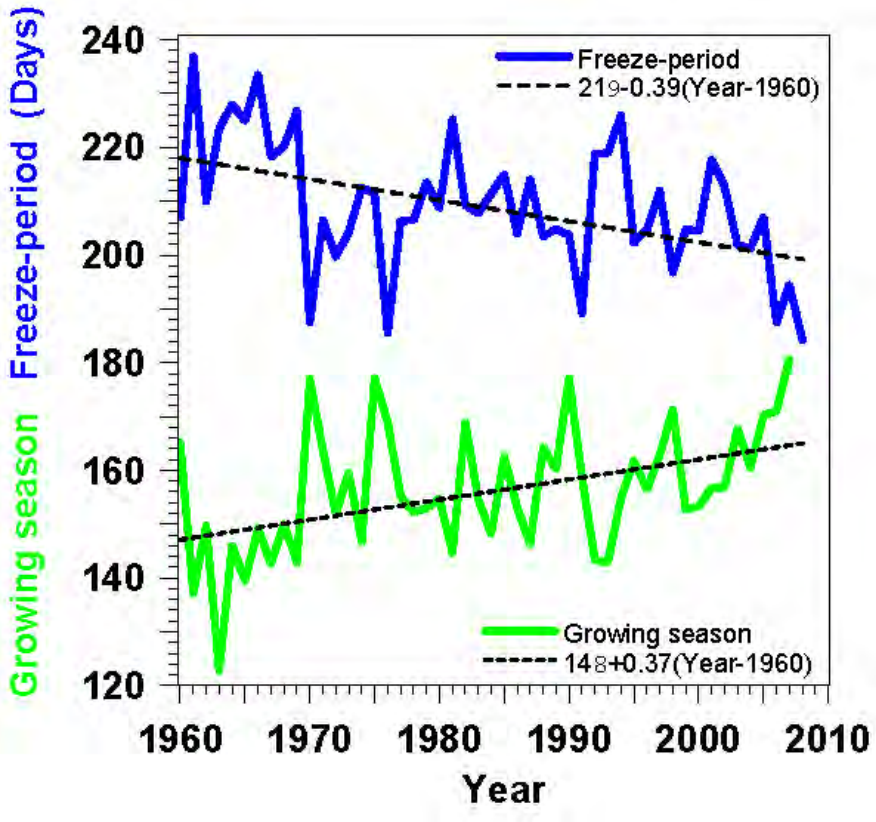


- **Ice-out, lilac leaf, maple bud elongation correlated**
- **Lilac bloom and maple leaf-out correlated**

Data: Sandy Wilmot, ANR

First and Last Frosts Changing





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

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

January 7, 2007

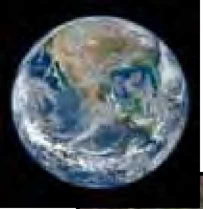
December 2006:

- **Warmest on record**

January 10, 2008

Warm Fall:

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

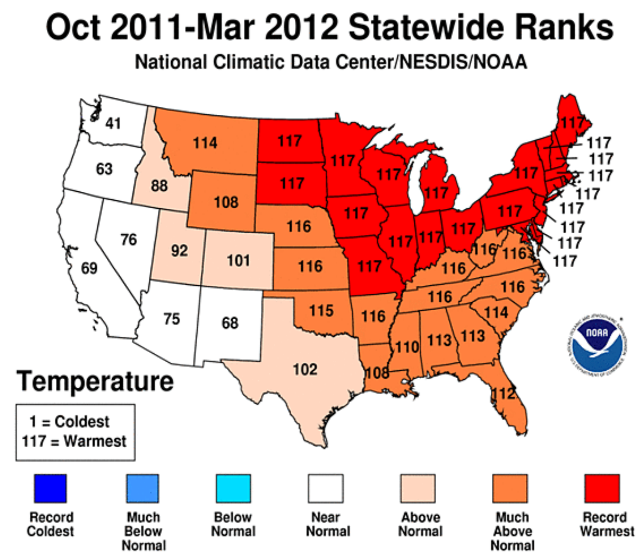


January 2, 2012

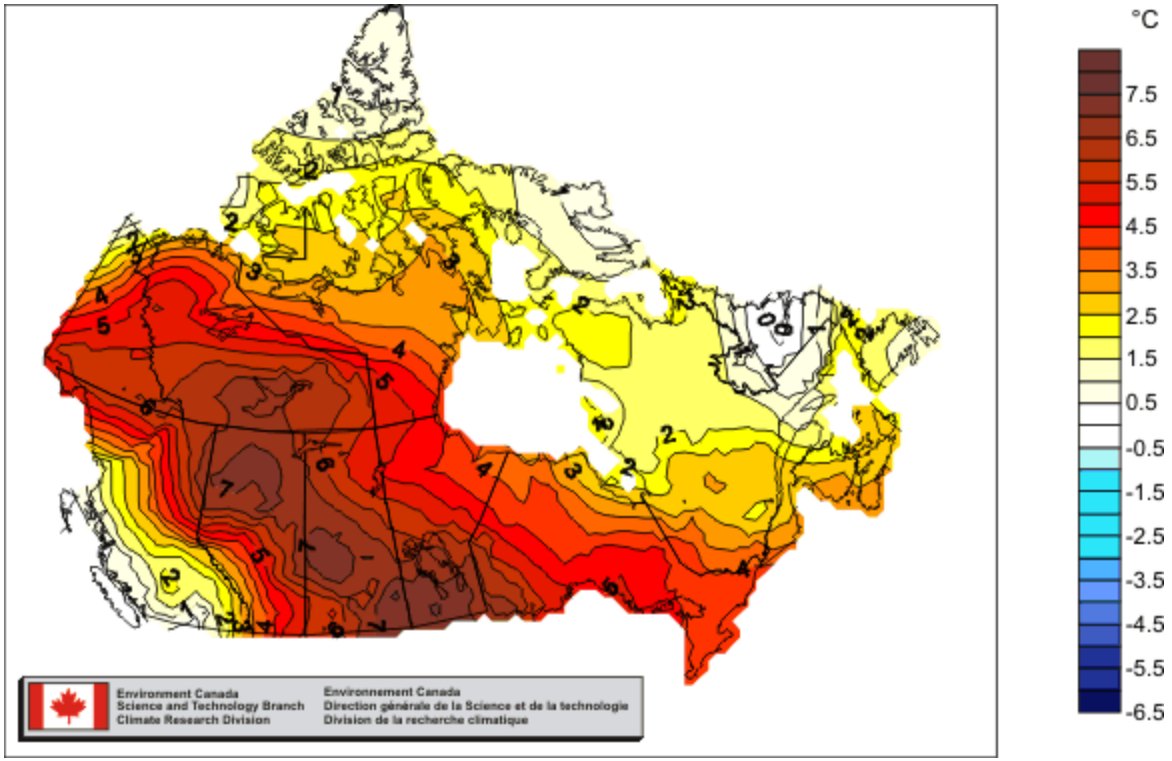
March 11, 2012

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**



Across the border: Canada



- **Winter 2011-12: 3.6°C (6.5°F) above normal**
  - **Canada's winters also warming 0.9°F/decade**
- **Climate doesn't see the border!**

Early Spring: Daffodils, Forsythia

79ºF on March 22, 2012

Pittsford Vermont

3/22/12

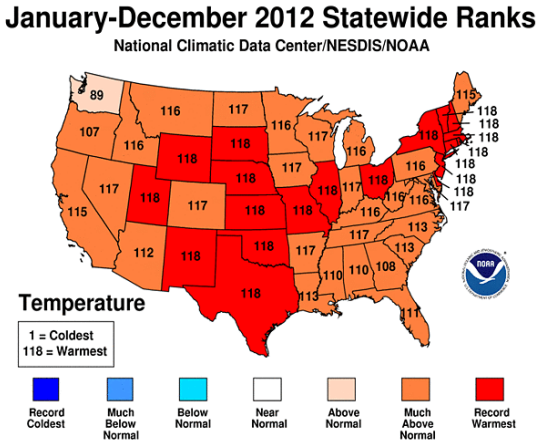
Pittsford Vermont

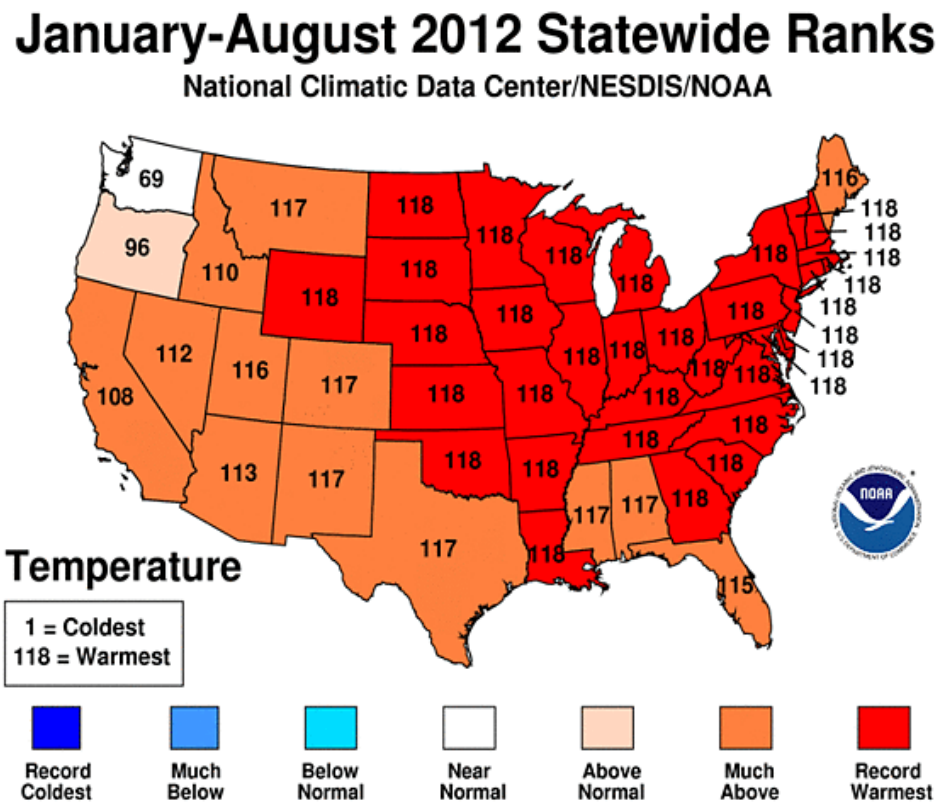
3/24/12

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

(Scott Whittier: NWS-BTV)





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

Vermont Winter 2006

- **Sun is low; snow reflects sunlight, except where there are trees - shadows**
- **Sunlight reflected, stays cold; little evaporation, clear sky; earth cools to space**
- ***Feedbacks Amplify: Less snow, warmer winters (2012)***

December 21, 2012

January 15, 2013

Past Month

- 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..**

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: 2012 was extreme***

Summer dry-down

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

- ***Can lock-in drought in central US: as 2012***

Many Wet Summers in Vermont – till 2012

- **2004, 2006, 2008, 2009, (2010), 2011 all wet**
- **Direct fast evaporation off wet canopies**
  - ***Evaporation-precipitation feedback increases rain***

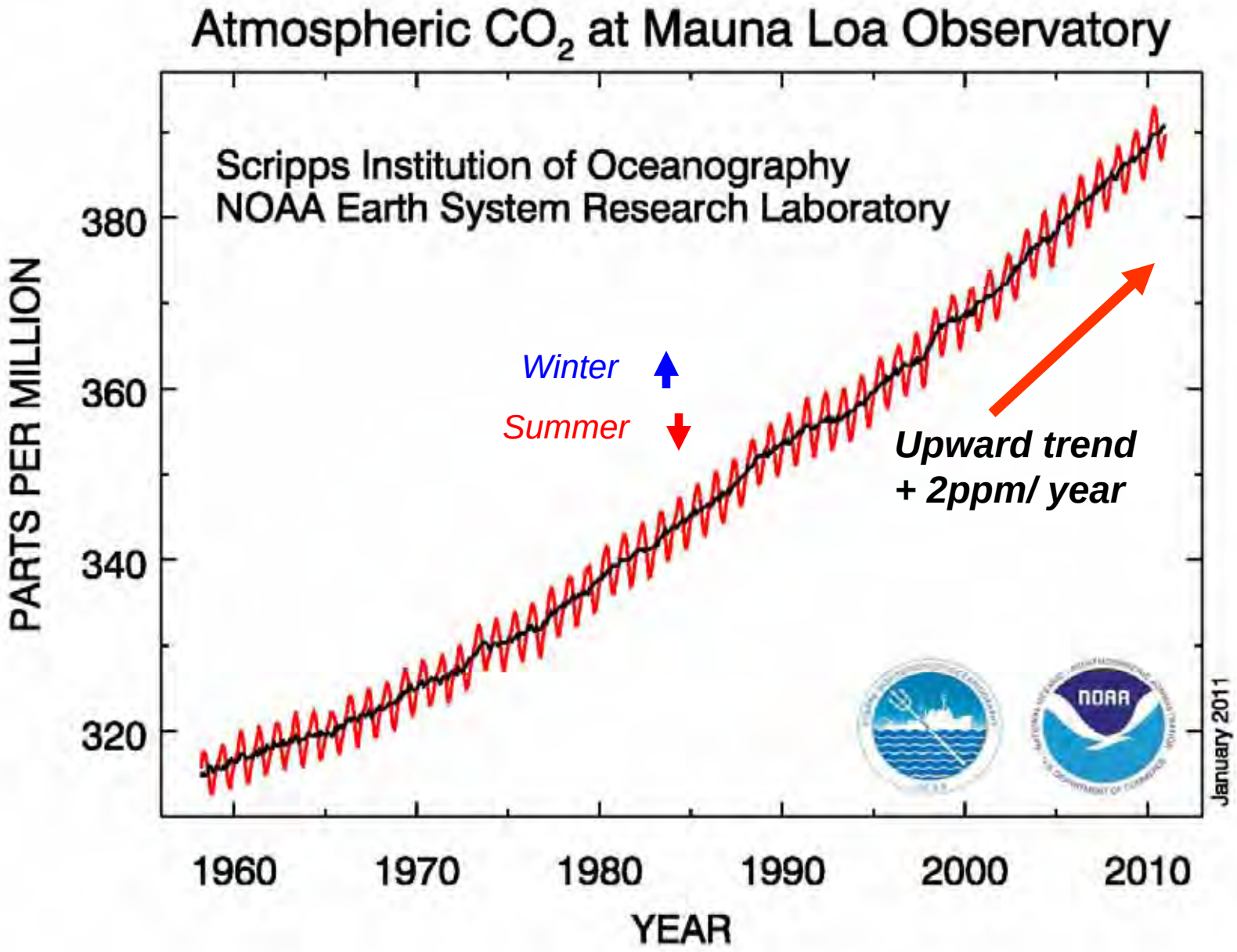
Fall Climate Transition

- **Vegetation delays first killing frost**
- **While deciduous trees still evaporating: moister 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 dies, 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

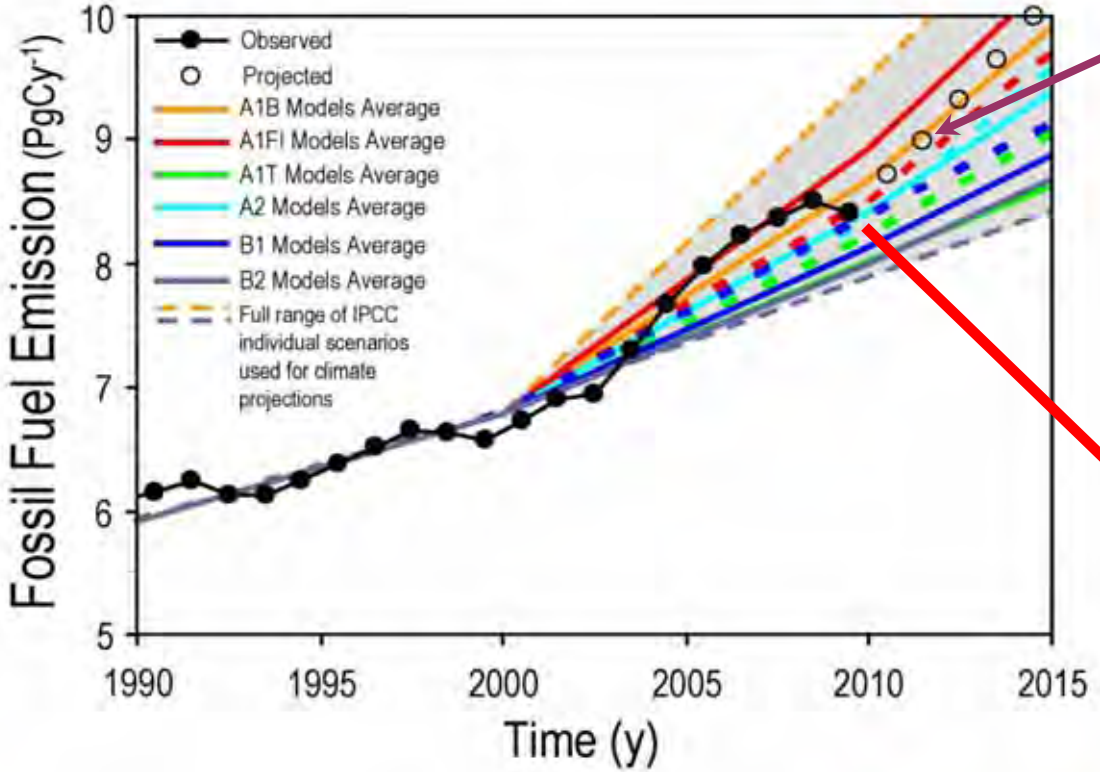
Later frost: Growing season getting longer

Carbon Dioxide Is Increasing



2009 Was "Good" for the Earth

Fossil Fuel Emissions: Actual vs. IPCC Scenarios



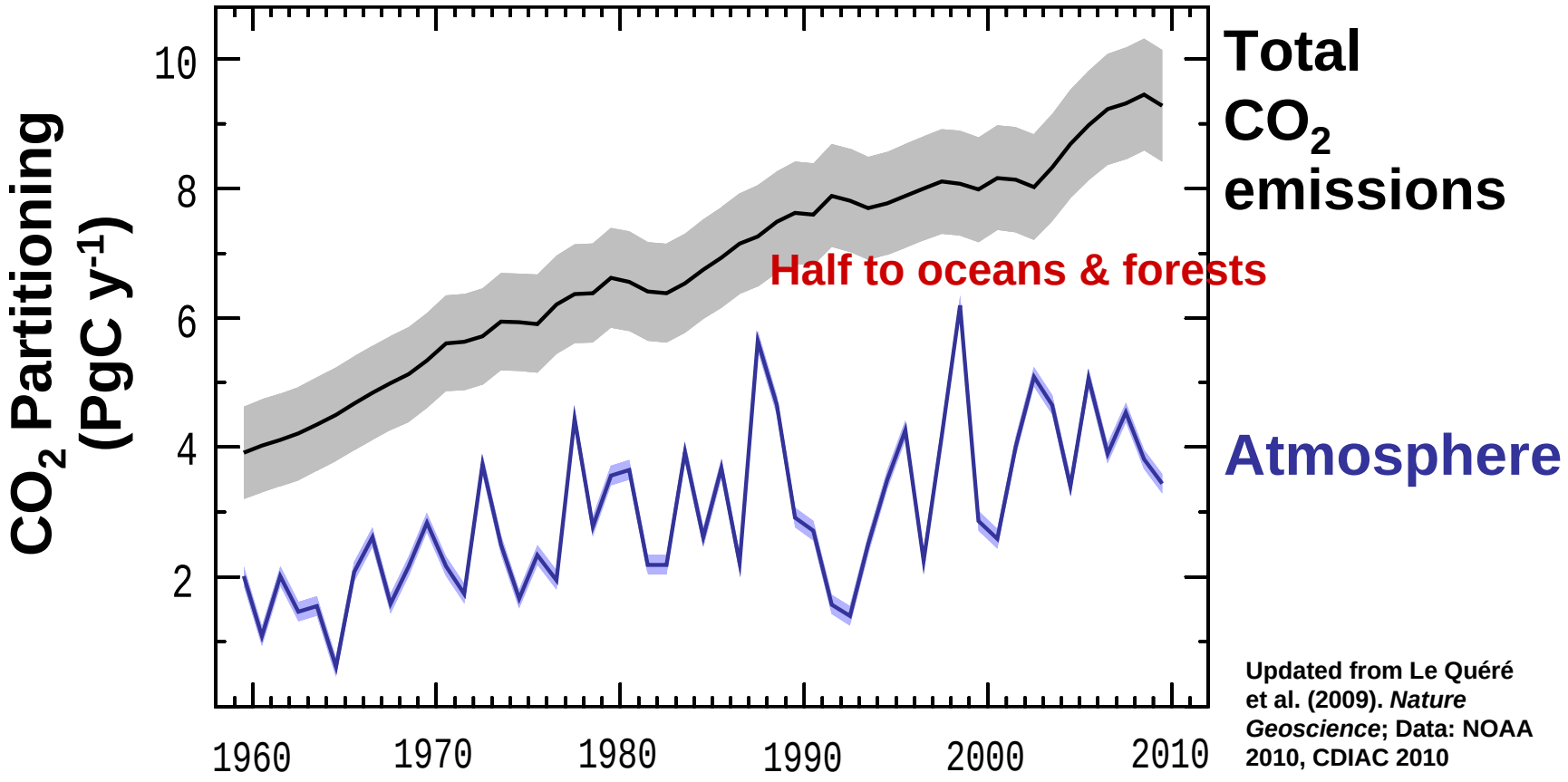
Back on growth: 2010, 2011

Emission Scenarios

- 4%/year

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

Only Half of Total CO_2 Emissions Remain in the Atmosphere

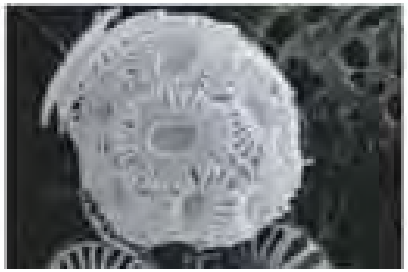


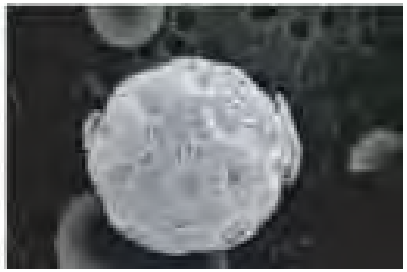
It takes at least a century to remove CO_2 from the atmosphere, and many centuries to remove it from oceans

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 trap the infrared from the surface, giving climate suitable for life by warming planet 60^oF**
- **Rise of CO_2 alone has only 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 5°F (3°C)**
  - **Much more in the cold regions and over land, which responds faster than oceans**

Global Warming Is Unequivocal
IPCC: February 2, 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

(www.ipcc.ch)

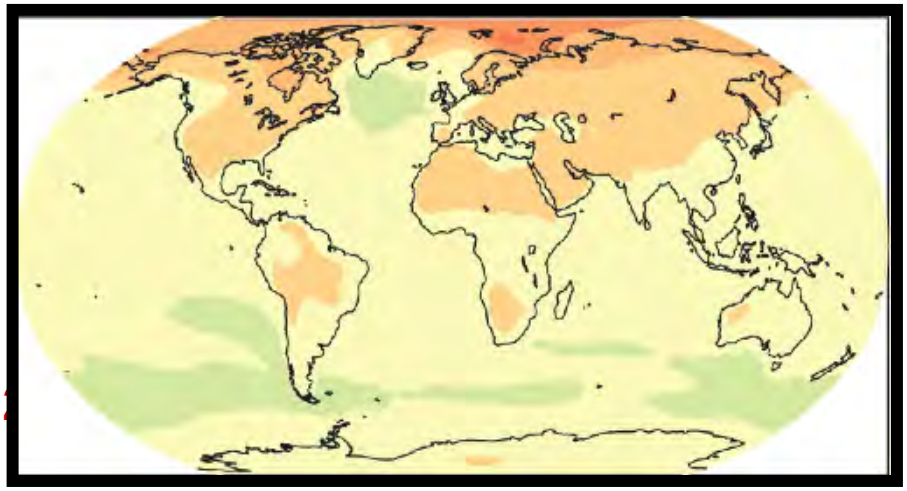
Decrease in:

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

Predicted Change in Temperature

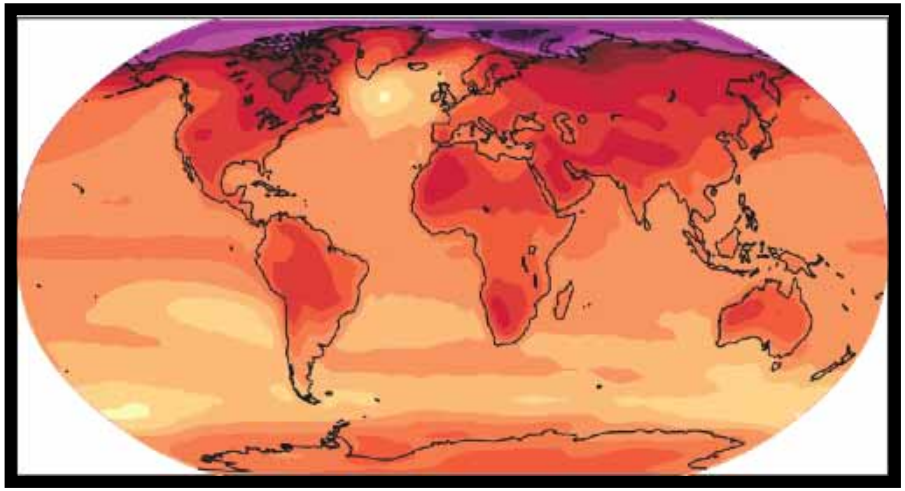
2020-2029 and 2090-2099, relative to 1980-1999 (ºC)

“Committed”

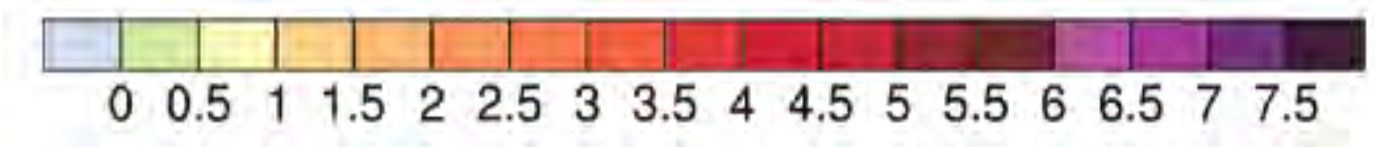


(We did nothing for the last 20 years)

Still up to us!



(We could halve this if we act now)

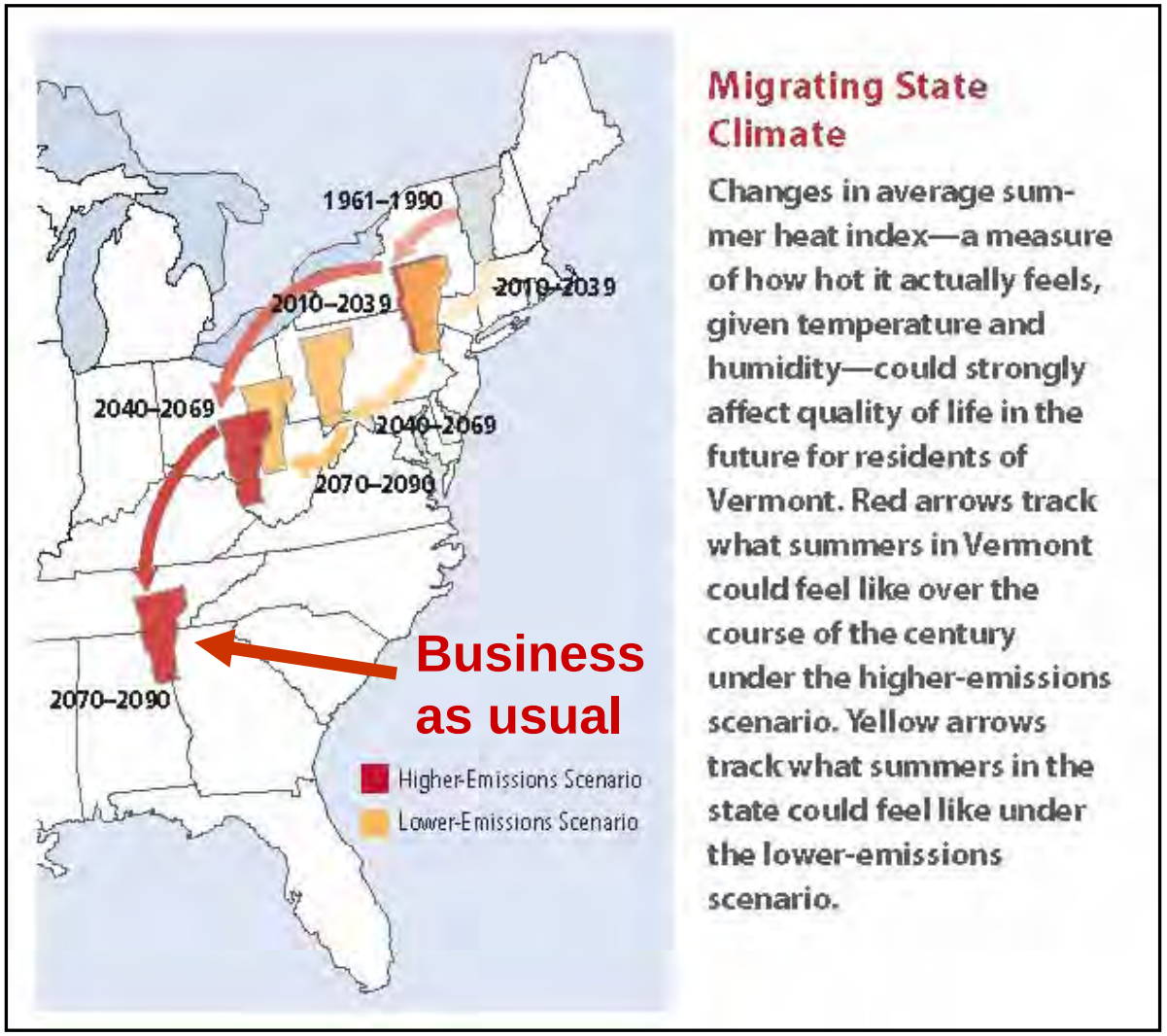


[ºC]

Vermont's Future with High and Low GHG Emissions

What about skiing?

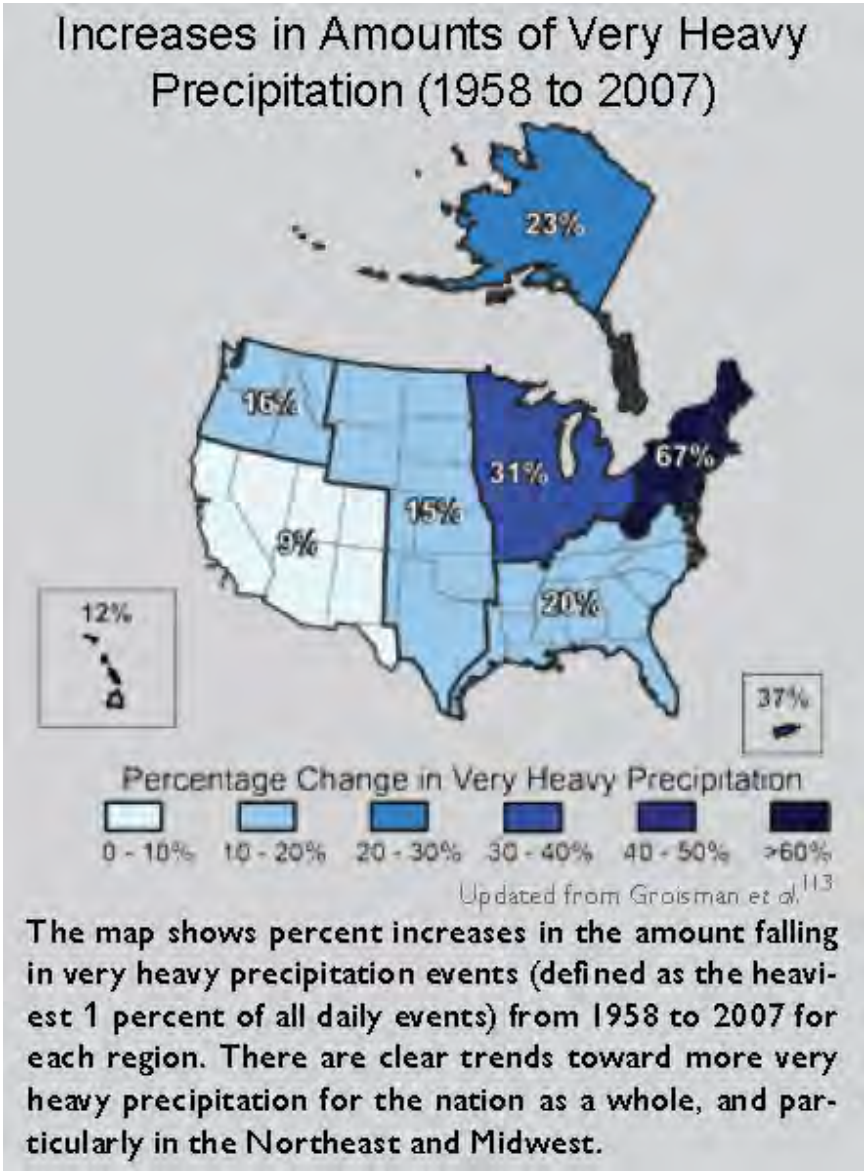
What about tropics?



NECIA, 2007

Very Heavy Precipitation Is Increasing

- **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**
- **NE stormflow increasing**
  (Lent, USGS, 2010)



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 increases 20-50%

Lent (2010) USGS, Me

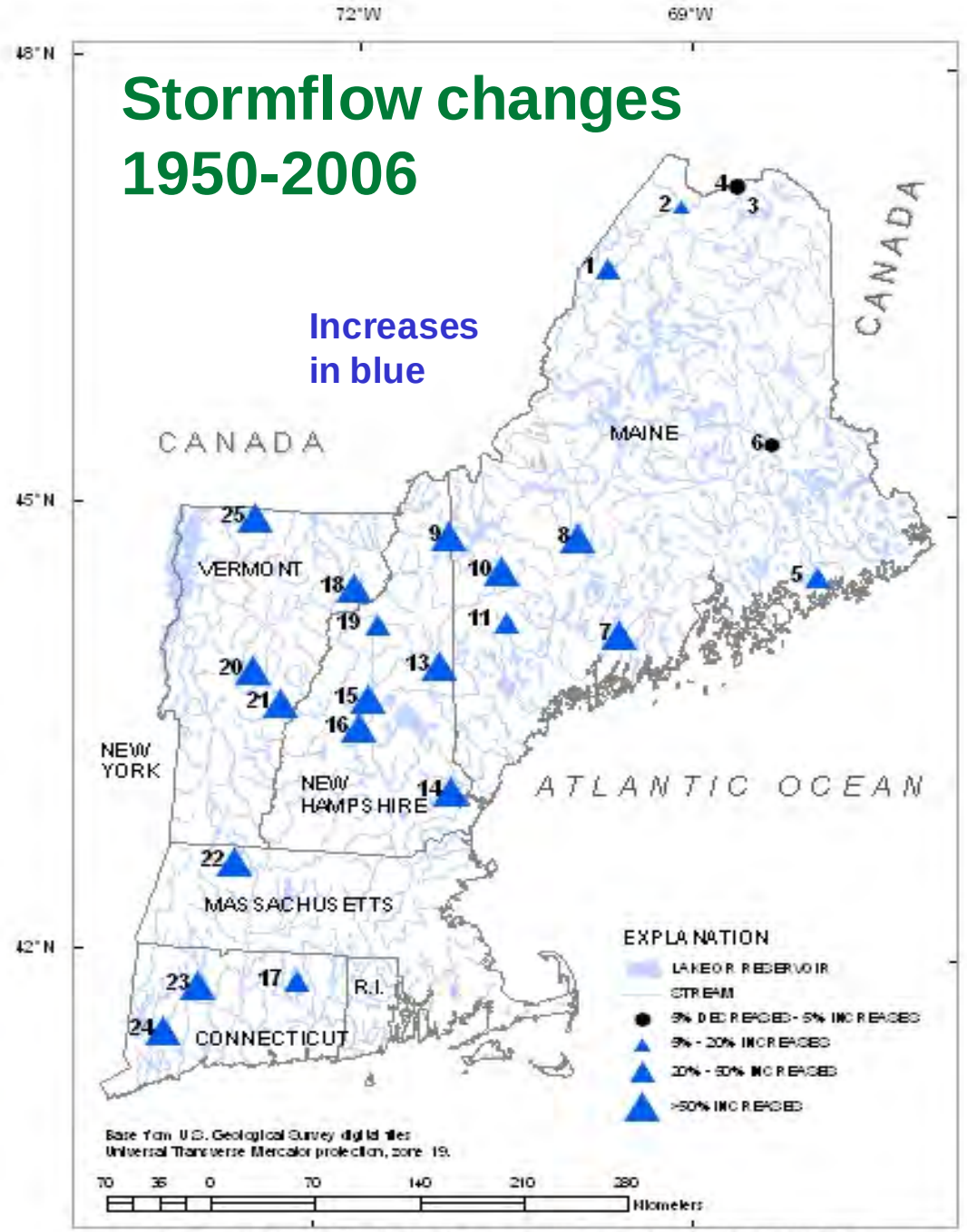


Figure 4. Geographic distribution of summer stormflow trends, 1950-2006.

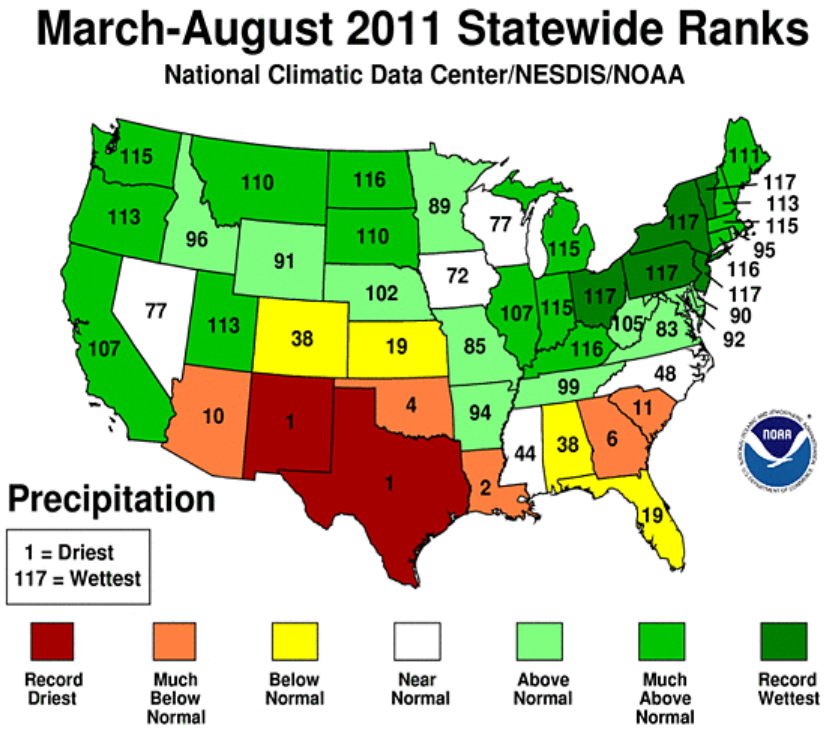
Extreme Weather (precip.)

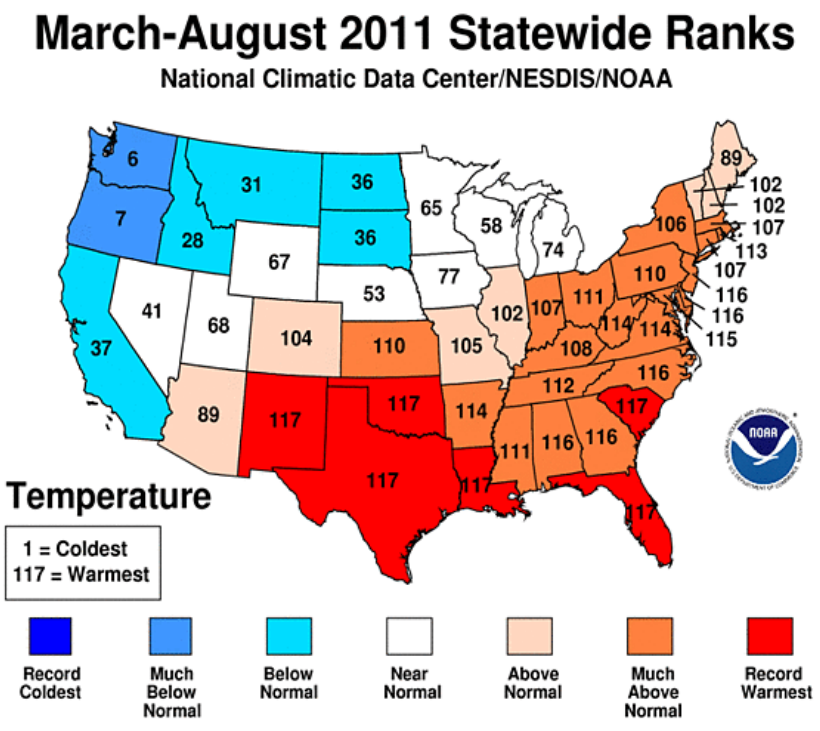
- **Precip. is condensation of atmospheric water vapor - large latent heat release drives storms**
- ***Saturation vapor pressure at cloud-base increases steeply with temperature (6%/^{o}C)***

- **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***

2011 Vermont Floods

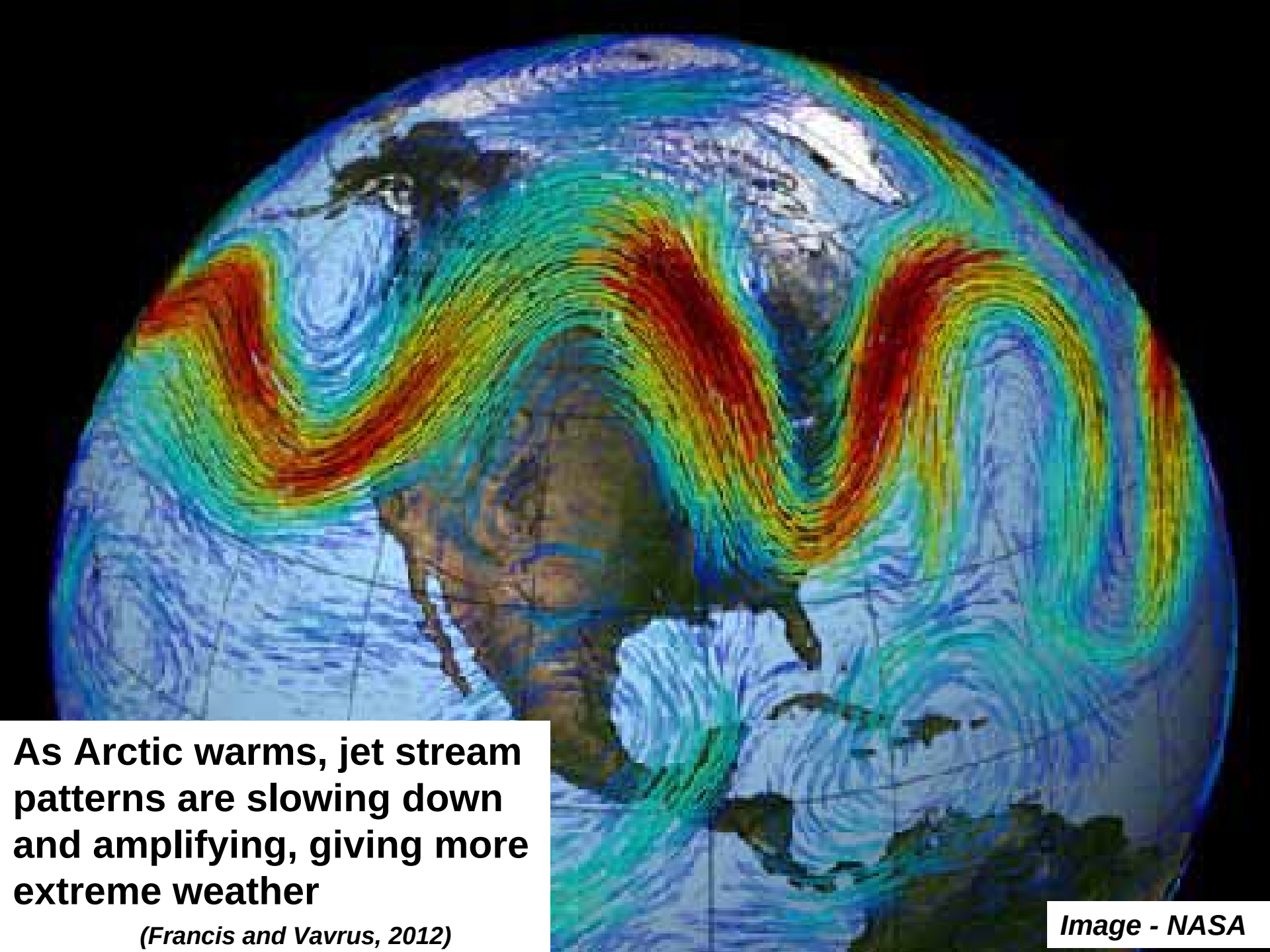
- **Record spring flood on Lake Champlain**
- **Record floods following TS Irene**
- **Record wet March-August, 2011: OH to VT**
  (but record drought in TX & NM)
- ***Quasi-stationary pattern for 6 mos***





2011 Classic VT 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 Winooski flood**
  - **Lake Champlain record flood stage of 103ft**
- **Irene flood: tropical storm moved up east of Green Mountains**
  - **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)**



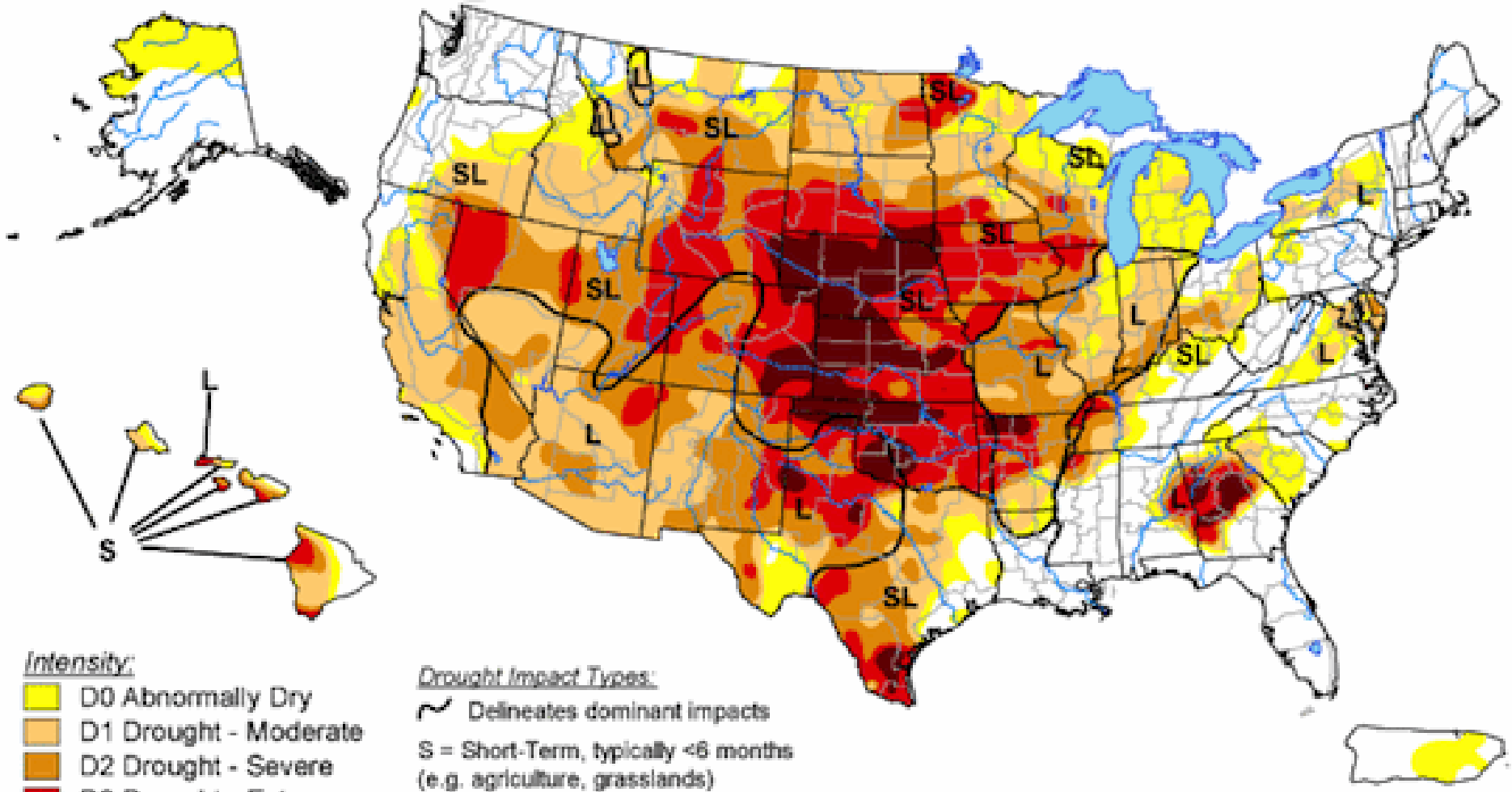
As Arctic warms, jet stream patterns are slowing down and amplifying, giving more extreme weather

(Francis and Vavrus, 2012)

Image - NASA

U.S. Drought Monitor

September 25, 2012
Valid 7 a.m. EDT



Intensity:

- D0 Abnormally Dry
- D1 Drought - Moderate
- D2 Drought - Severe
- D3 Drought - Extreme
- D4 Drought - Exceptional

Drought Impact Types:

~ Delineates dominant impacts

S = Short-Term, typically <6 months (e.g. agriculture, grasslands)

L = Long-Term, typically >6 months (e.g. hydrology, ecology)

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

http://droughtmonitor.unl.edu/

Released Thursday, September 27, 2012

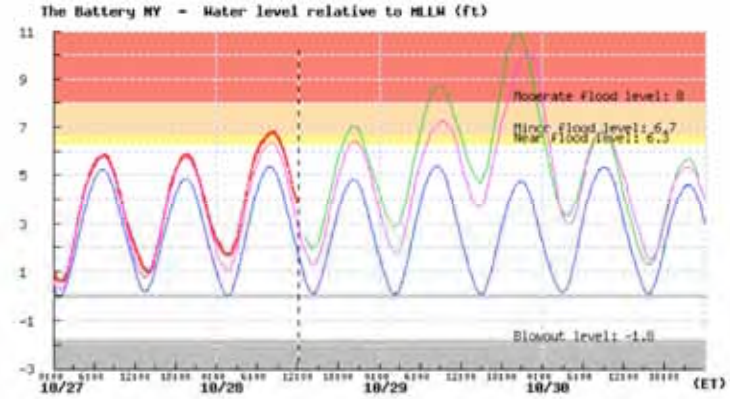
Author: Anthony Artusa, NOAA/NWS/NCEP/CPC

Three Successive Years of East-Coast Tropical Storm Disasters

- **September 21, 2010: Hurricane Igor with winds and record rainfall devastates eastern Newfoundland, isolating 150 communities as swollen rivers washed away the only roads into town and all connecting bridges. The worst storm ever in a province known for its storms.**
- **August 28, 2011: Tropical Storm Irene devastates Vermont, as heavy rain washes out roads and bridges, cutting off 20 towns**
- **October 29, 2012: Hurricane Sandy devastates New Jersey and New York City with winds and record storm surge flooding the subway tunnels, airports and shorelines**

Disasters Happen in Strong Storms

- **Hurricane Sandy hits NYC and floods subway tunnels: Oct 29 2012**
- **Extreme weather event + climate change = disaster**
  - **≈ 1ft rise of mean sea-level**
  - **Gulfstream warm + 5ºF**
  - **Blocking high: NE Canada**
  - **≈ 2ft extra storm surge**
  - **Extra 3ft = disaster**



Increasing Extreme Weather

- ***The answer to the oft-asked question of whether an (extreme) event is caused by climate change is that <u>it is the wrong question.</u>***

- ***<u>All weather events are affected by climate change</u> because the environment in which they occur is warmer and moister than it used to be.*** ***(Trenberth: Climatic Change 2012)***

Water: *Amplifying 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**
- **Snow and ice down**
  - **Less sunlight reflected**
    - **Warmer Arctic in summer**
    - **Warmer northern winters**
  - **Less ice-cover: more evaporation**

Many Challenges Face Us

- **Sea-level rise: 3 - 5 feet / century likely**
- **Extreme weather: Floods, fires, & drought**

  - 32 weather disasters >$1B in 2011
- **Melting Arctic and permafrost—methane release is amplifying feedback**
- **Ecosystem collapse, including perhaps forest and ocean ecosystems**
- **Collapse of unsustainable human population**

Can We Stop "Dangerous Climate Change"?

- **Yes: Quickly stabilize atmospheric CO_2**
- **This means an 80% drop in CO_2 emissions!**
- **This is very difficult**
  - **Fossil fuels have driven our industrial growth and population growth for 200 years**
  - **Our "lifestyle" has become dependent on fossil fuels**

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, shale-gas & shale-oil 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)?**

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"**
  - **Yet we are still subsidizing fossil fuels**
- **Politics lost in fantasy**
  - **Ignoring Earth system and climate issues**
  - **Ignoring future costs**
    - **So. Manhattan within 1-ft of flooding with Irene**
    - **Did they put waterproof doors on tunnels? No**

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**

What Do We Need?

- So we need honest, truthful, smart pathways forward
  - That will not frighten people into paralysis
  - That will spread hope, not anger or despair
  - That sidestep ideological barriers with new language
  - That develop adaptive governance
    - The US Constitution gives no rights to the Earth
  - That respect Earth system processes & limits

Discussion

- **This talk http://alanbetts.com/talks**
- **Rutland Herald articles at**

  http://alanbetts.com/writings
- **Interesting papers at**

  http://alanbetts.com/research

  – ***Vermont Climate Change Indicators***

  – ***Seasonal Climate Transitions in New England***

Agricultural planning

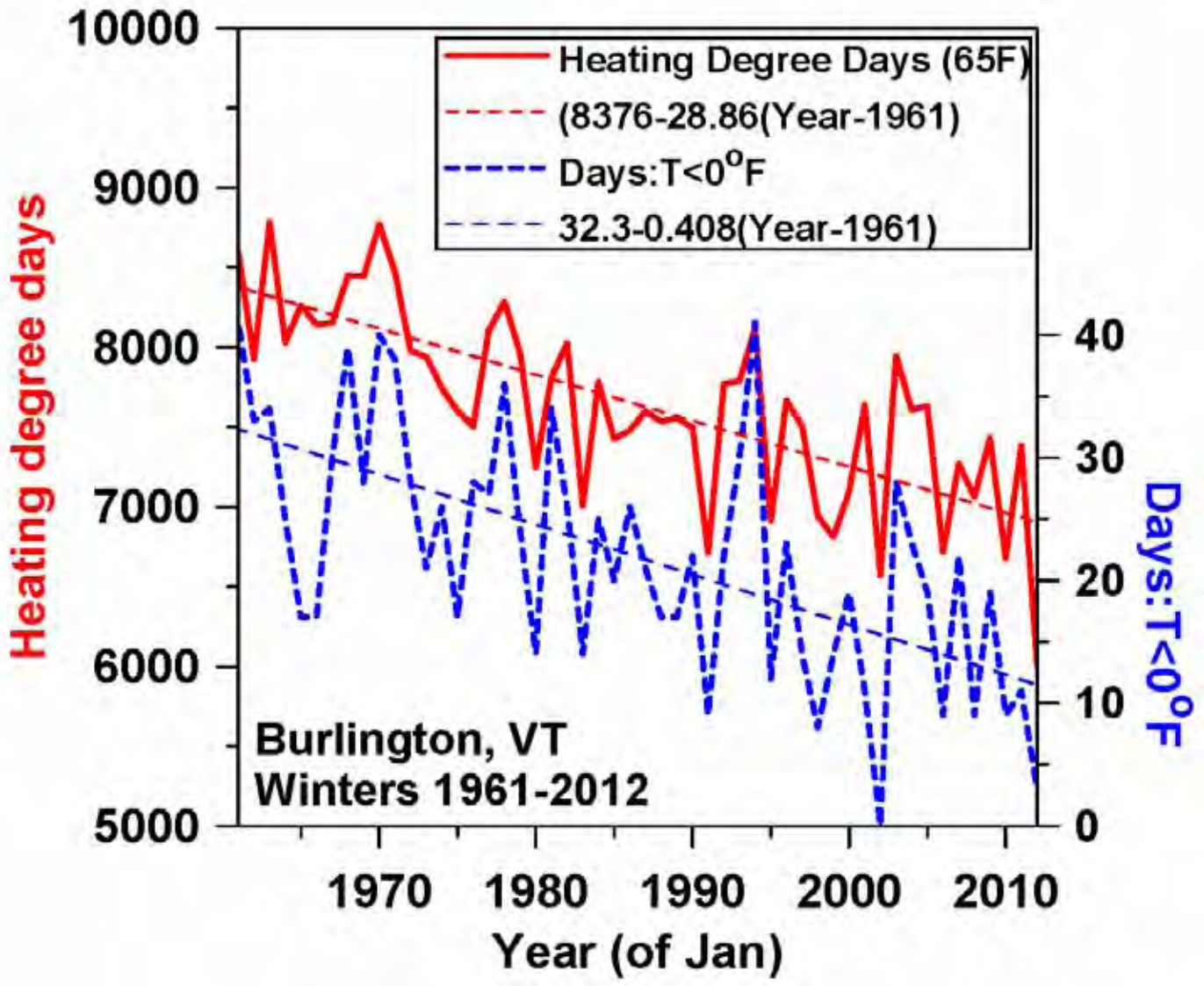
- **Frozen ground and lakes: -7d/decade**
- **Earlier melt, earlier spring leaf-out: - 3d/decade**
- **Frost-free growing season: +4d/decade**
  - **Greenhouse, row cover seasonal extenders**
- **Winter extremes increasing with variable snow**
  - **T_{min} extremes increasing +2-3^{o}F/decade**

- **More winter precipitation**
  - **Wetter snow; more mixed phase; more frequent melt**
- **Variable summer precipitation**
  - **Heavier rain-rates, longer storms, longer droughts**
  - **Maximize soil water infiltration; water storage**
  - **Manage to reduce soil erosion**
  - **Design infrastructure to handle larger runoff**

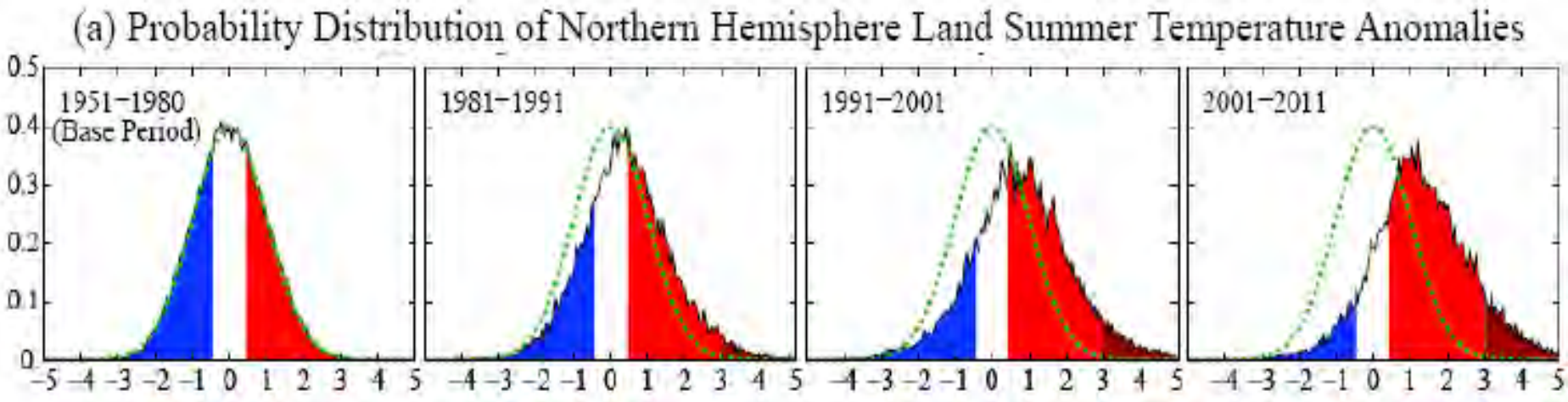
Heating Degree Days and Days below 0°F (Burlington)

- **HDD trend 289 (±37) /decade**
- **T_{min}<0°F 4.1 (±0.7) days /decade**

- **Good for home heating**
- **Bad for killing pests**



Increasing Temperature Extremes is "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**
  - **Increased from baseline 0.15% to 10% in 45 years**