Vermont's Changing Climate

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Climate Change in Vermont Workshop

VT Dept. of Forests, Parks and Recreation

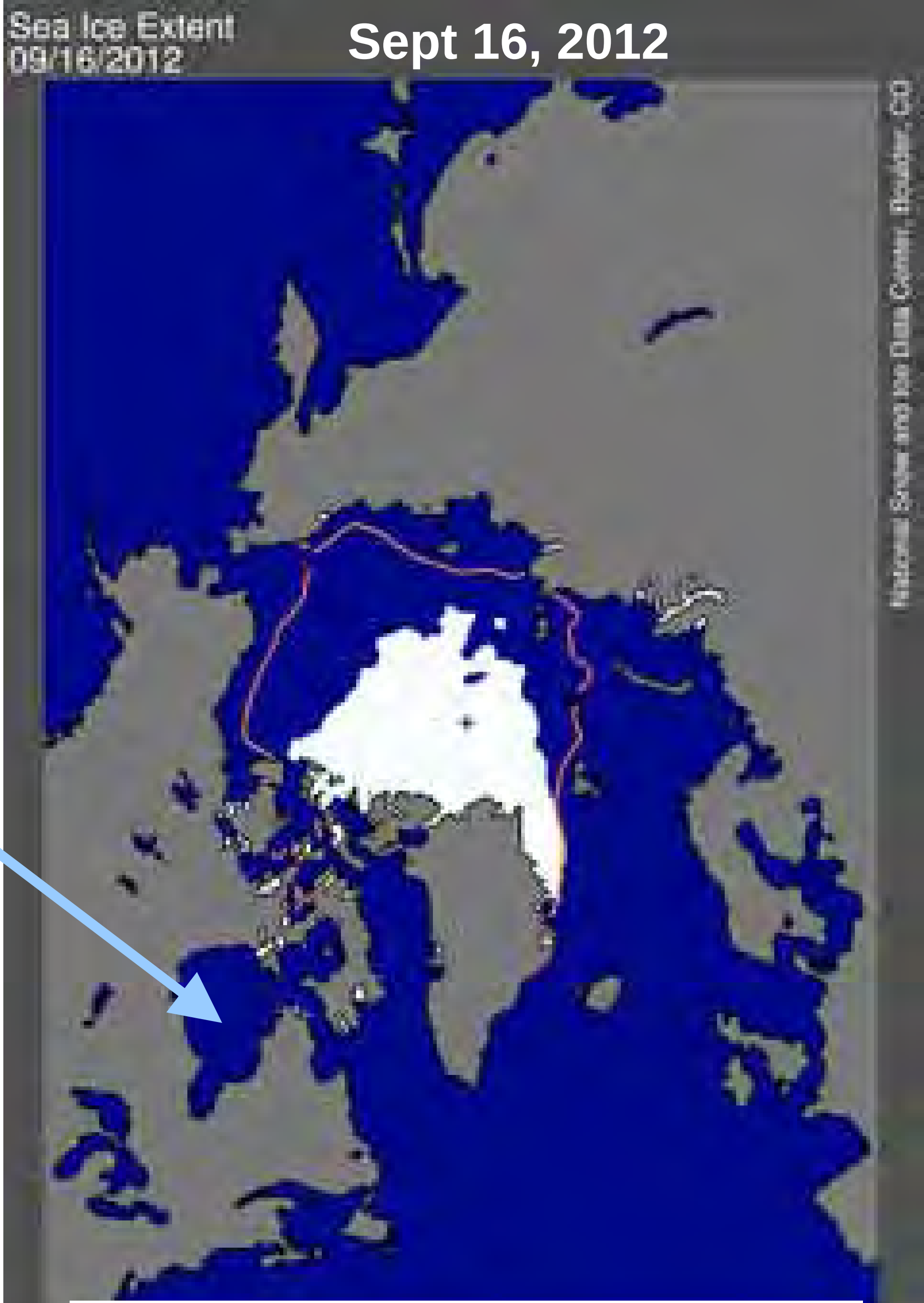
VTC, Randolph, VT

December 3-4, 2013

RACC
Research on Adaptation
to Climate Change

- ***Rise of CO$_2$ + Water Cycle amplifiers is driving climate change***
- **Half the Arctic Sea-ice Melted in 2012**
- **Open water in Oct. Nov. gives warmer Fall in Northeast**

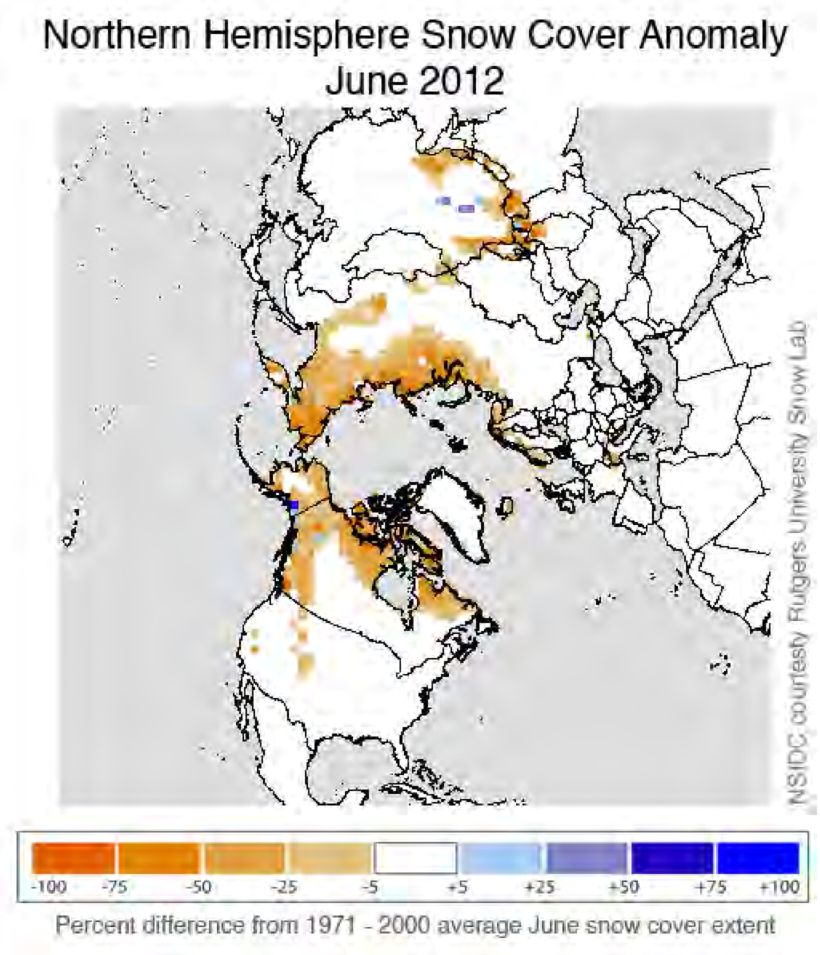
- ***Amplifying feedbacks:***
- ***Less ice, less reflection of sunlight***
- ***More evaporation, larger vapor greenhouse effect***
- ***Ice thin: most 1-yr-old***

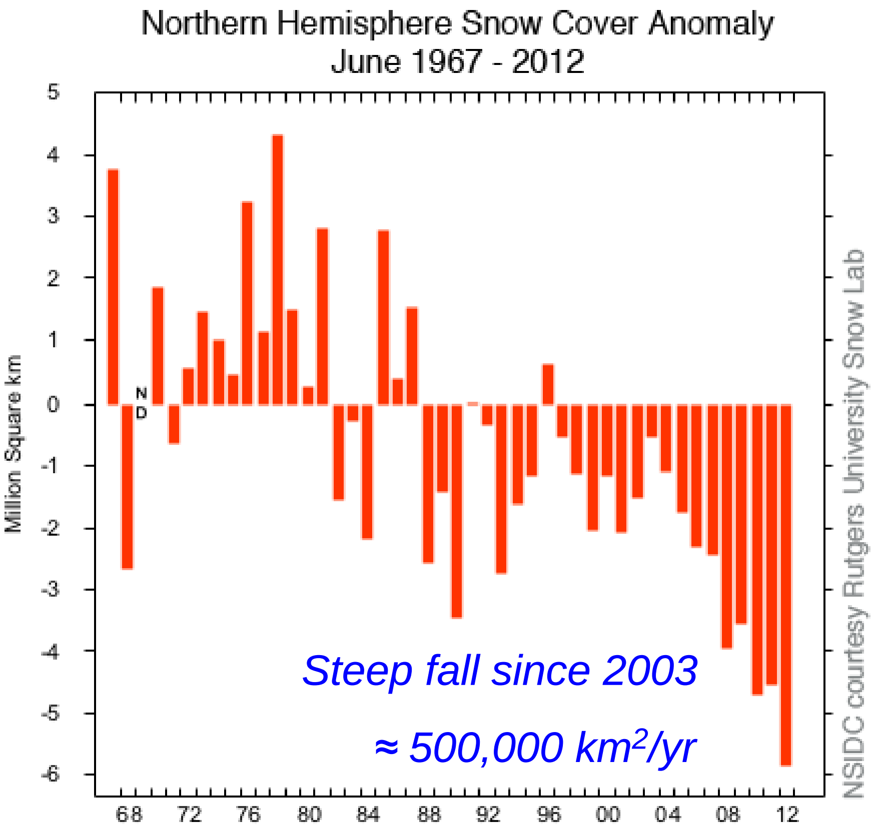


Sept 16, 2012

http://nsidc.org/arcticseaicenews/

June 2012 snow cover minimum





Steep fall since 2003

≈ 500,000 km^2/yr

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

What Is Happening to Vermont?

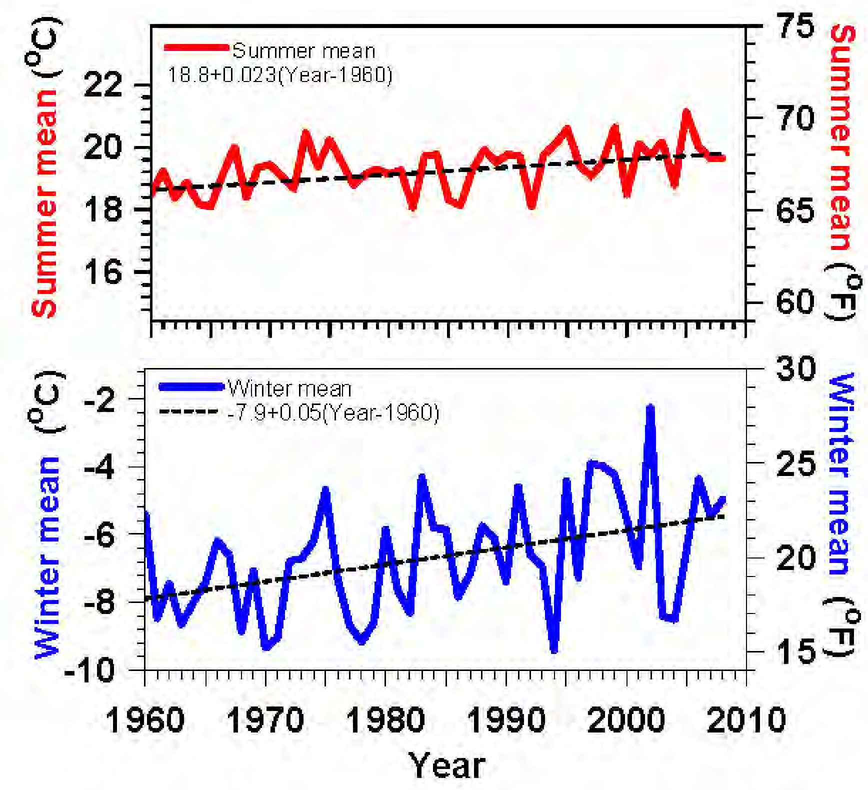
- PAST 40/50 years *(global CO_2 forcing detectible)*

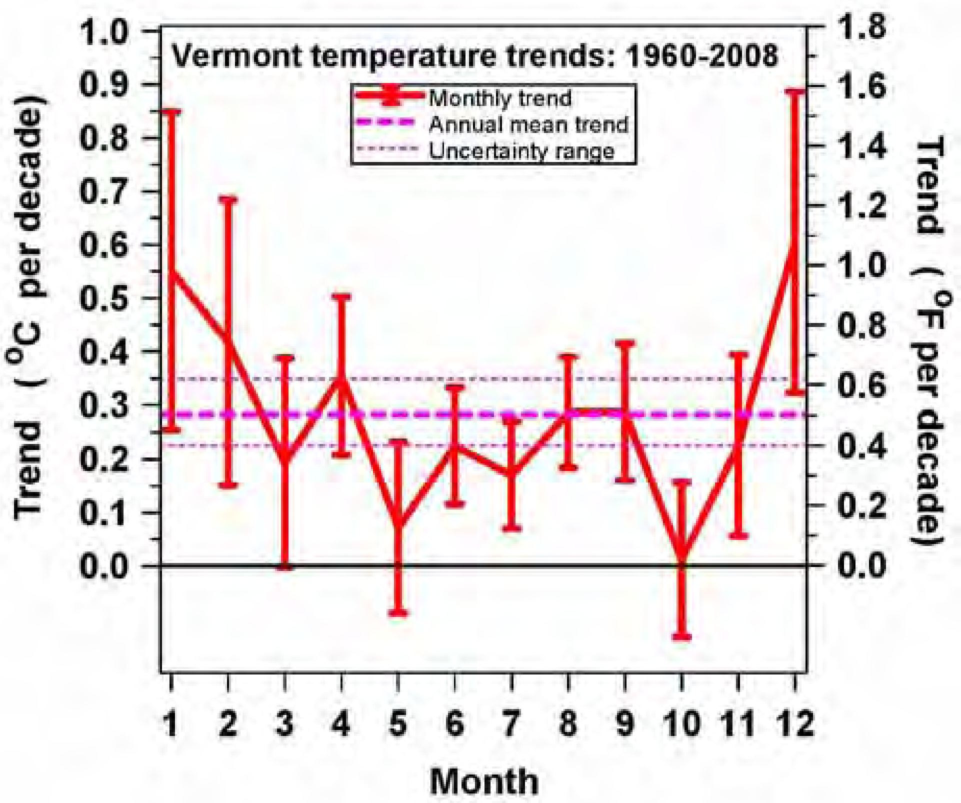
- Warming twice as fast in winter than summer
- Winter severity decreasing
- Lakes frozen less by 7 days / decade
- Growing season longer by 3-4 days / decade
- Spring coming earlier by 2-3 days / decade

(Betts, 2011)

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

VT Temperature Trends

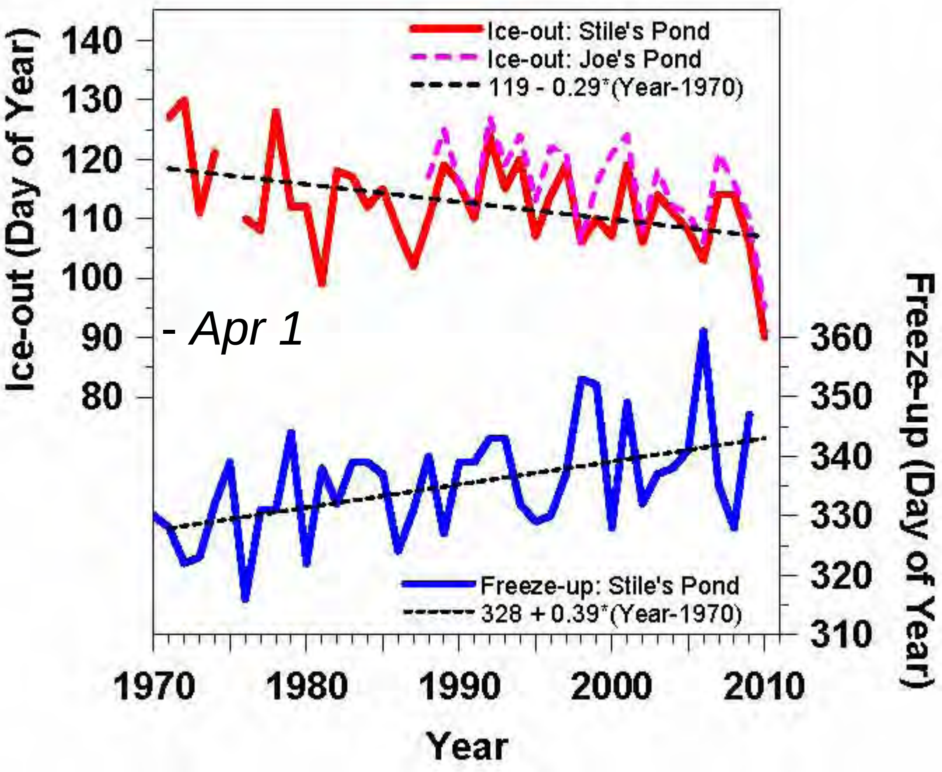


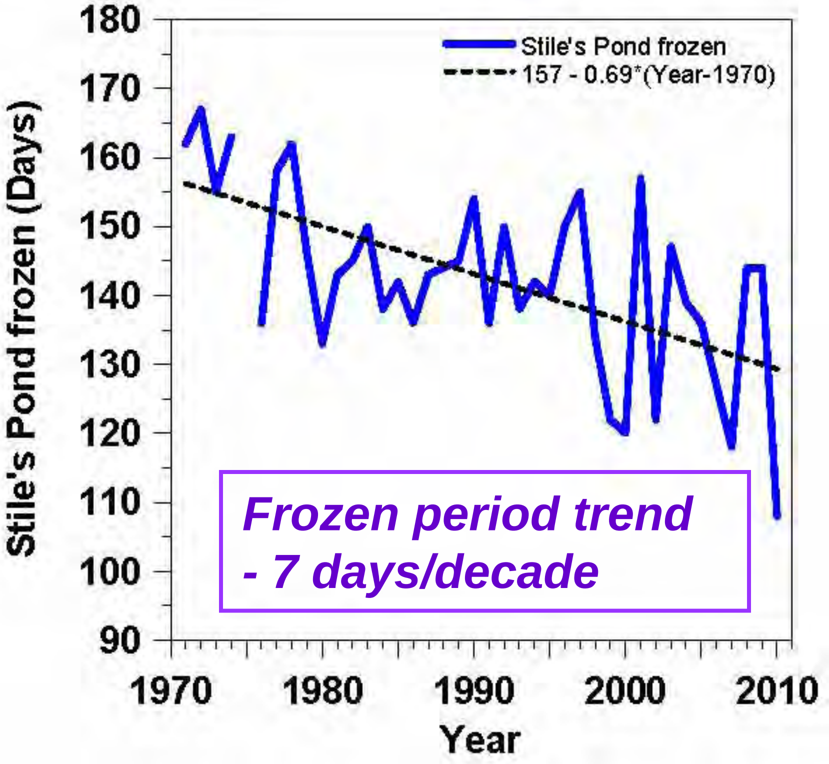


- Summer 0.4±0.12°F (0.23±0.07°C) per decade
- Winter 0.91±028°F (0.5±0.16°C) per decade
  - Larger trend, larger variability (warmer if less snow)

Lake Freeze-up & Ice-out Changing

Frozen Period Shrinking Fast

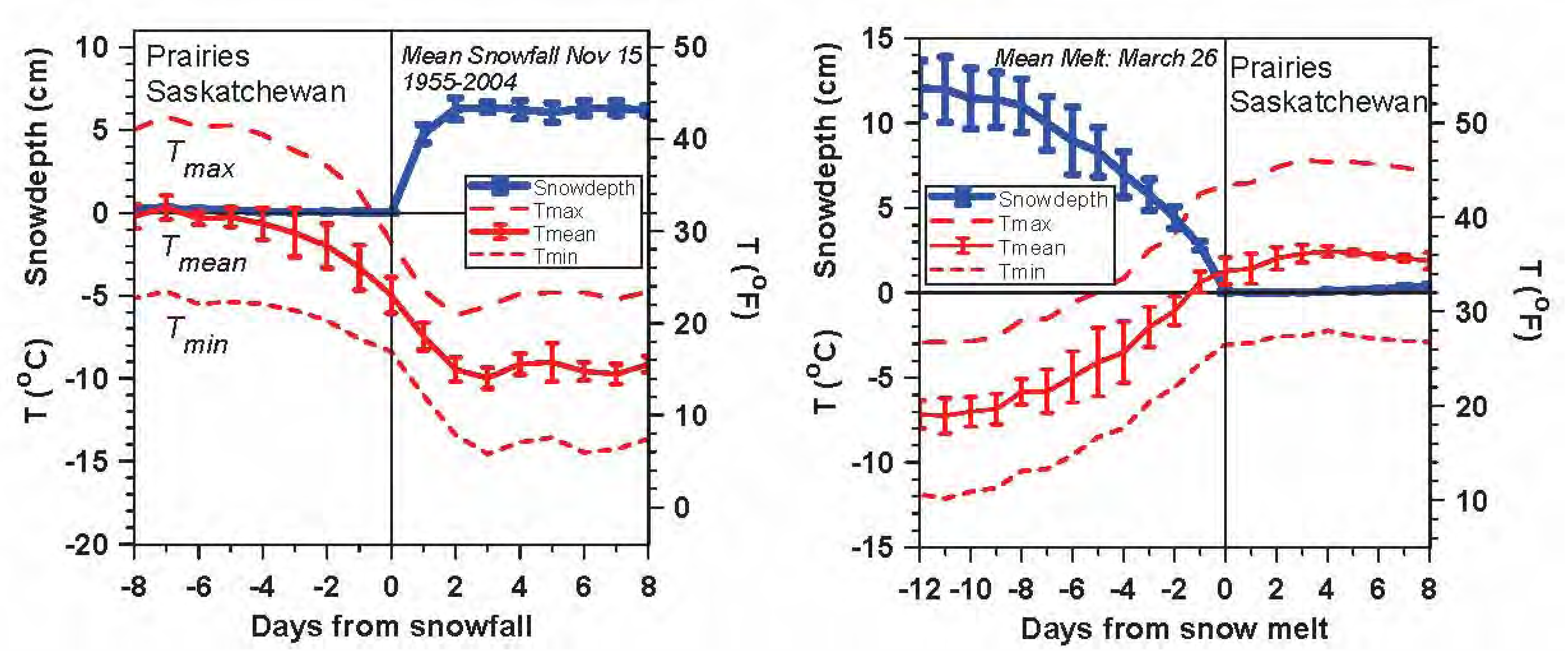




- **Ice-out earlier by 2.9 (±1.0) days / decade**
- **Freeze-up later by 3.9 (±1.1) days / decade**
- ***River and soil ice probably similar***

Snowfall and Snowmelt

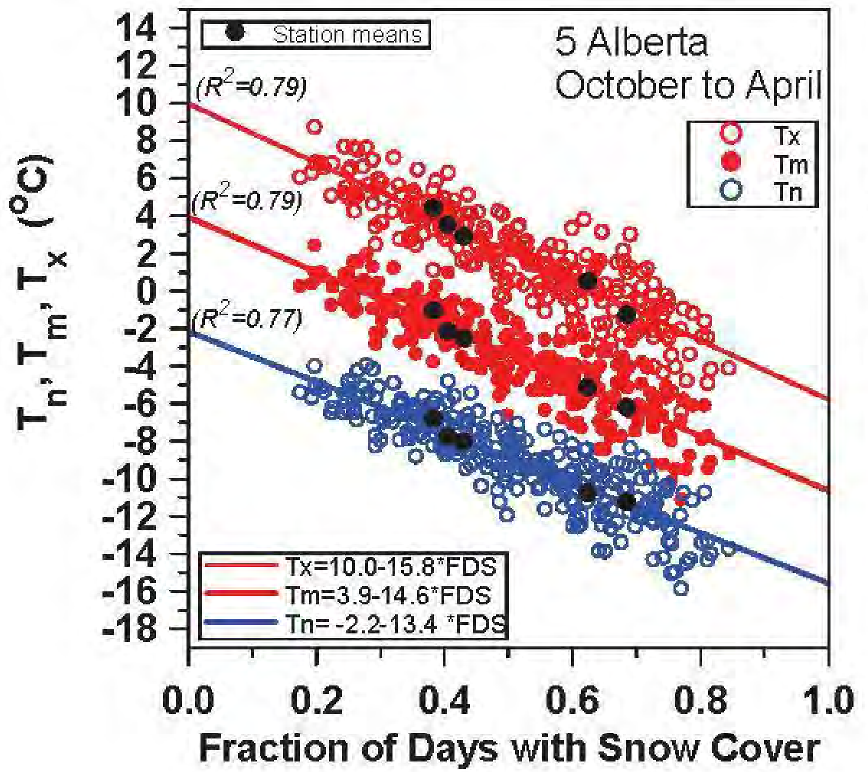
Winter and Spring transitions

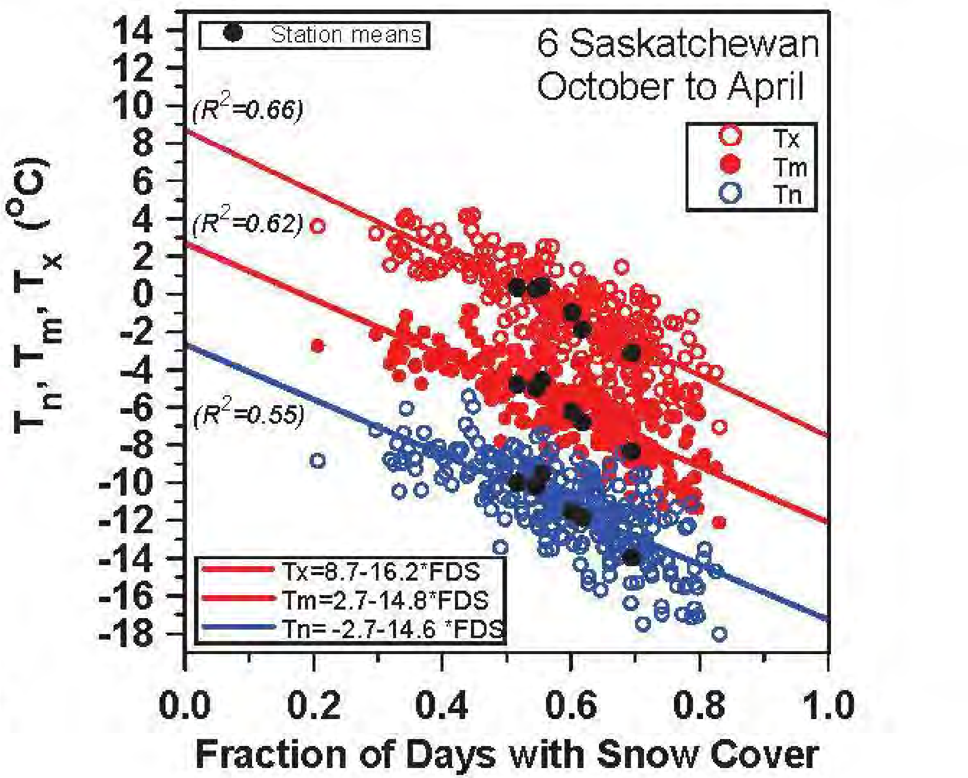


- **Temperature falls/rises 10K with first snowfall, snowmelt**
- ***Snow reflects sunlight; reduces evaporation and water vapor greenhouse***
  - ***Local climate switch between warm and cold seasons***
  - ***Same feedbacks that are speeding Arctic ice melt in summer***

Betts et al. 2014

Snow Cover: Cold Season Climate



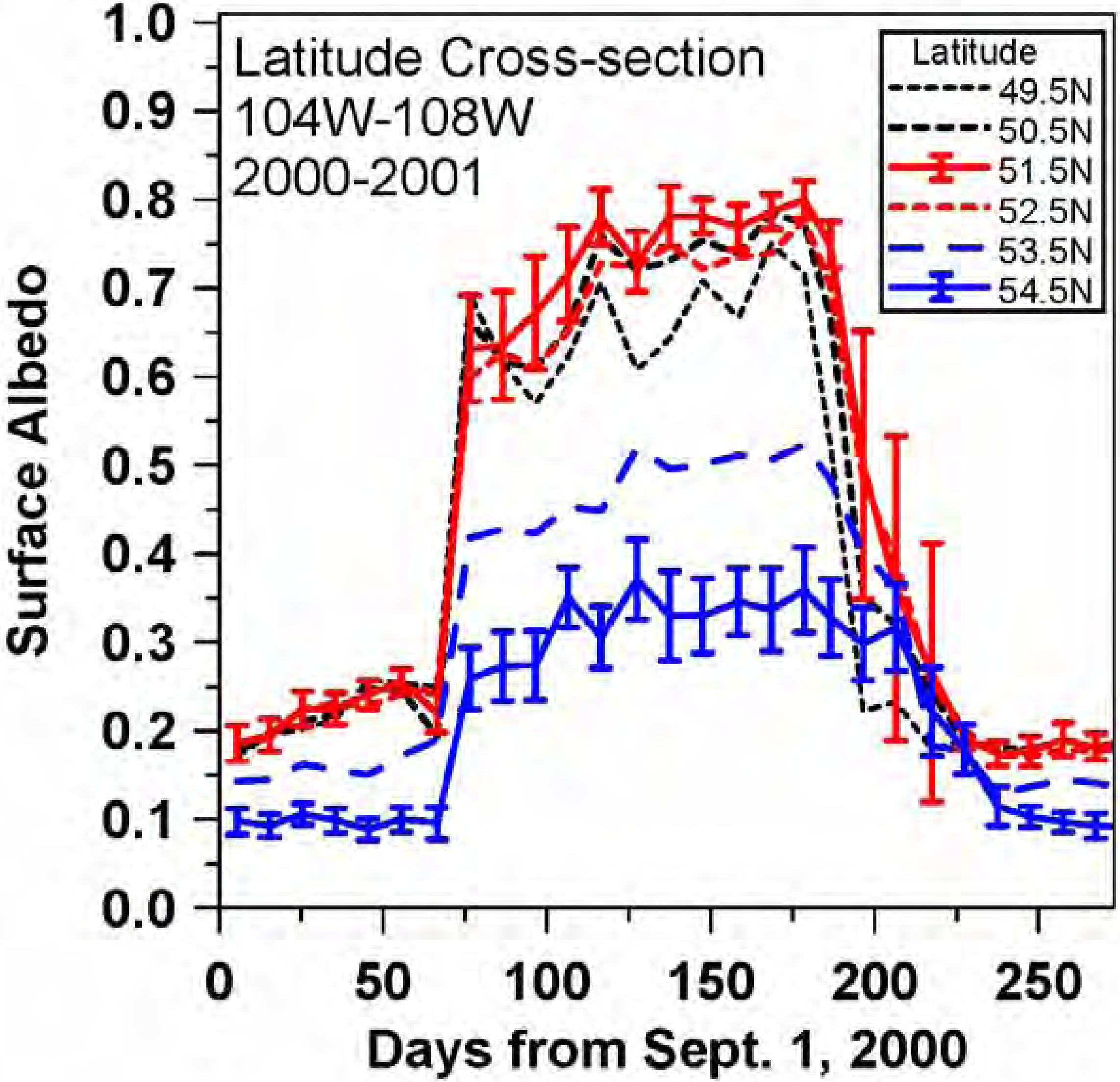


- **Alberta: 79% of variance explained**
- **Slopes**
  - **Max: T_x -16.0°C**
  - **Mean: T_m -14.7°C (26.5°F)**
  - **Min: T_n -14.0°C**

Albedo through Winter

- **Prairies albedo**
  α_s: **0.2 to 0.7**
- **Boreal forest**
  α_s: **0.1 to 0.35**

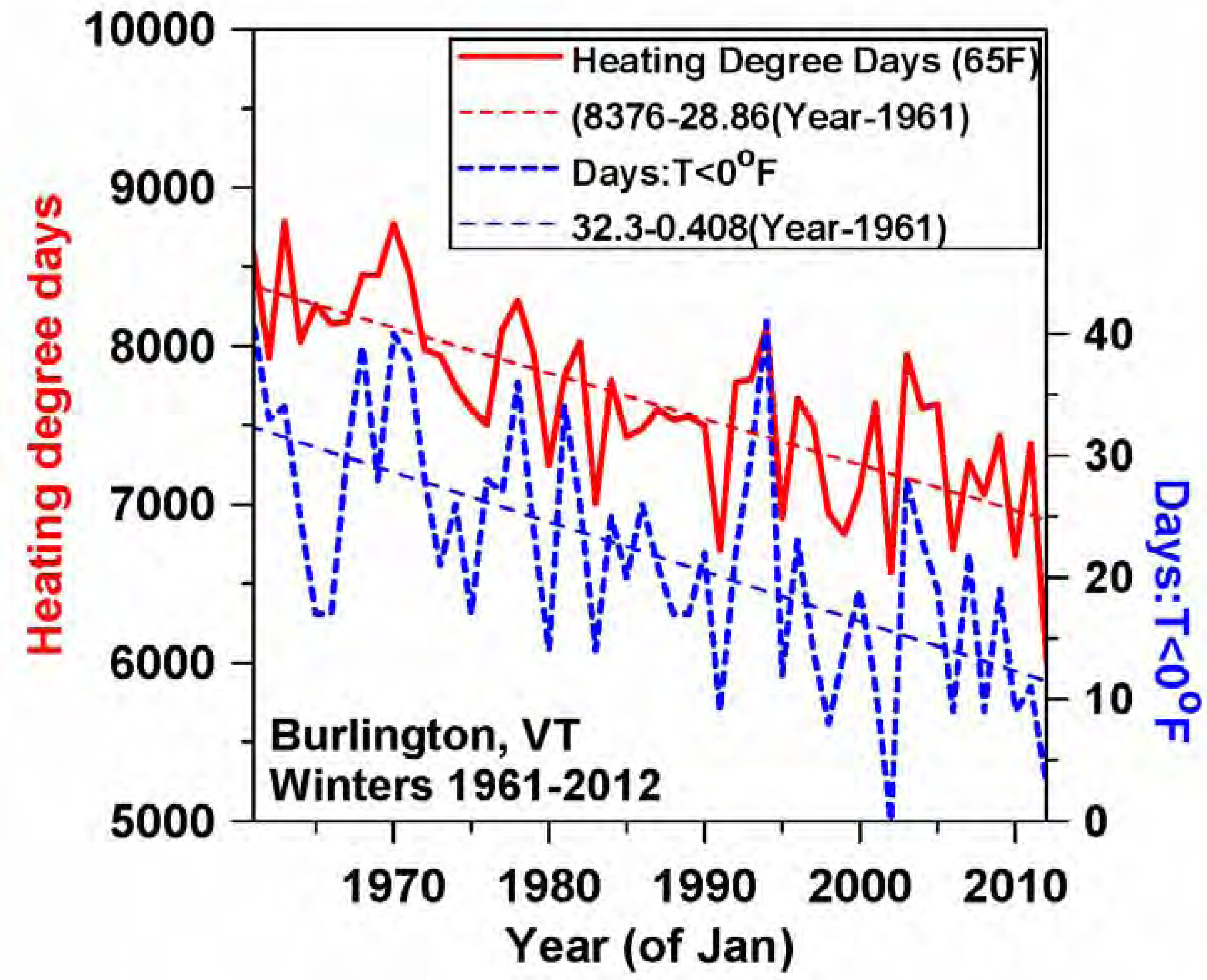
- ***MODIS: 10day, 250m, avg. to 50x50km to latitude bands***



Heating Degree Days and Days below 0°F *(-17.8°C)* (Burlington)

- **HDD trend 289 (±37) per decade**

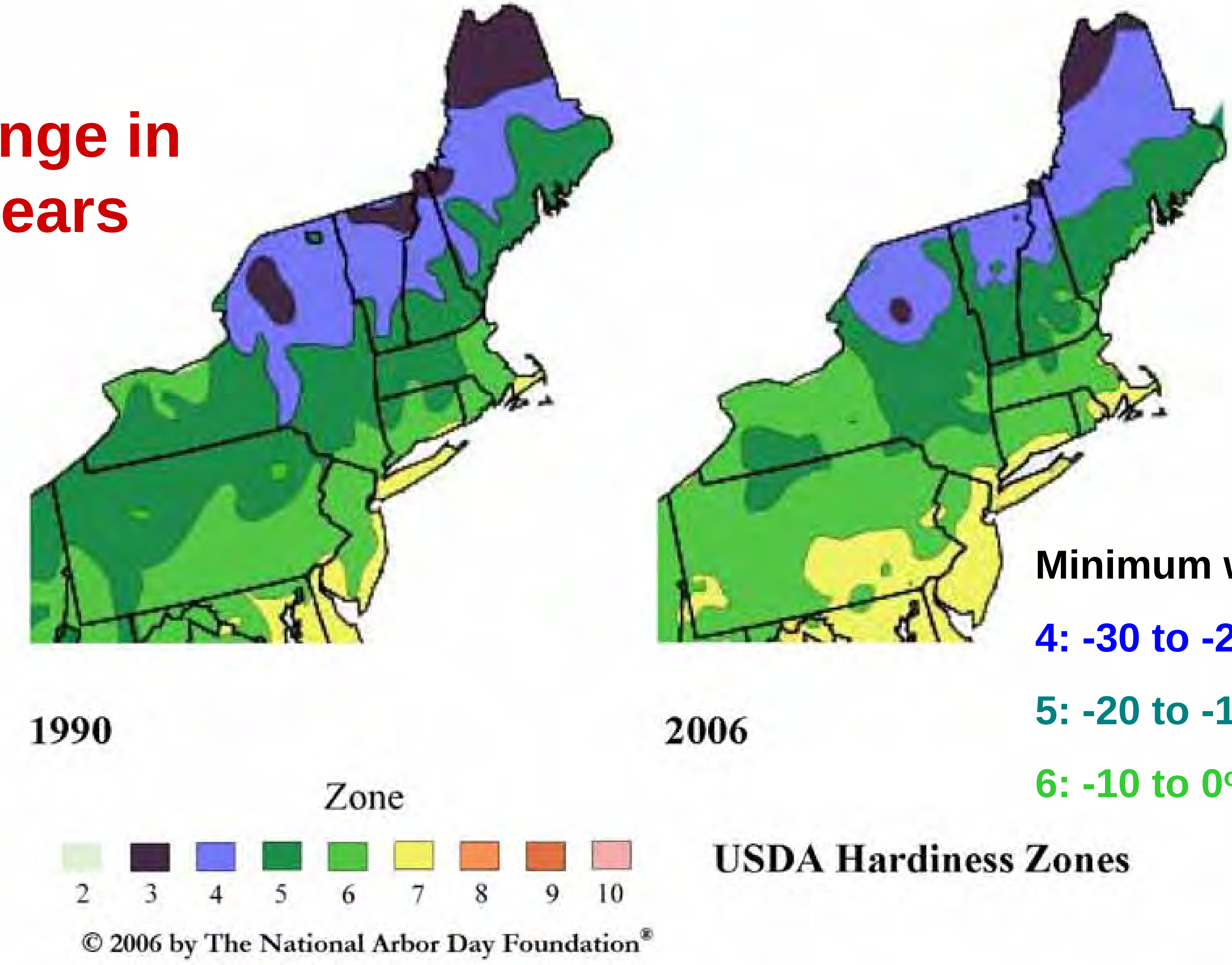
- **T_{min}<0°F 4.1 (±0.7) days per decade**



Winter Hardiness Zones

– *winter cold extremes*

Change in 16 years



© 2006 by The National Arbor Day Foundation®

Minimum winter T

4: -30 to -20^{o}F

5: -20 to -10^{o}F

6: -10 to 0^{o}F

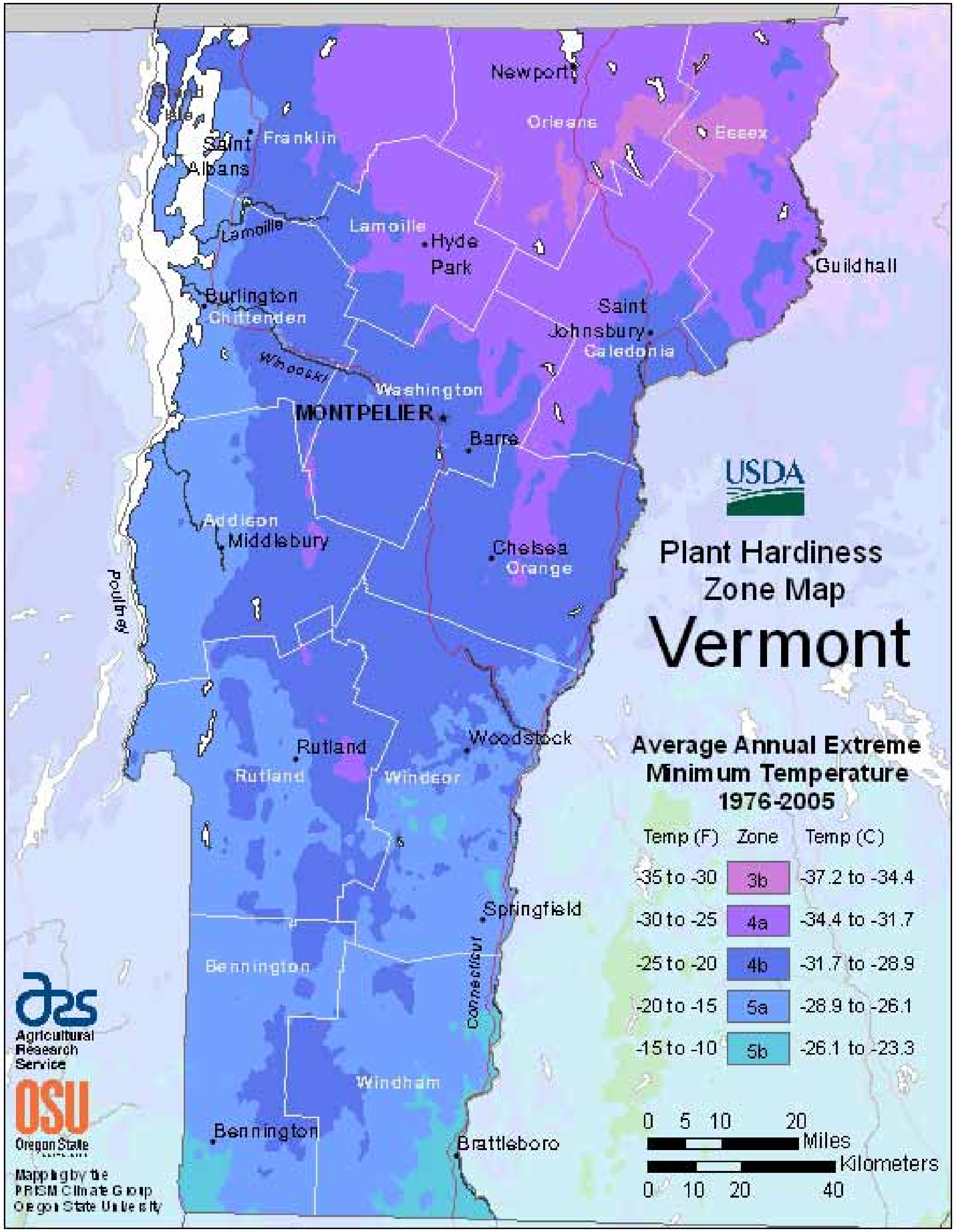
Detailed Map
(most recent)

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

- Half-zone in 16 yrs
  = 3.1ºF/ decade
  - *triple the rise-rate of winter mean T*

  - *3 zones/century*

- *http://planthardiness.ars.usda.gov/PHZMWeb/*
- *Krakauer, Adv. Meteor. 2012*



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**
  - **2100 survive in CT ≈ zone 9-10 ?**

Spring Climate Transitions

- **Before leaf-out**

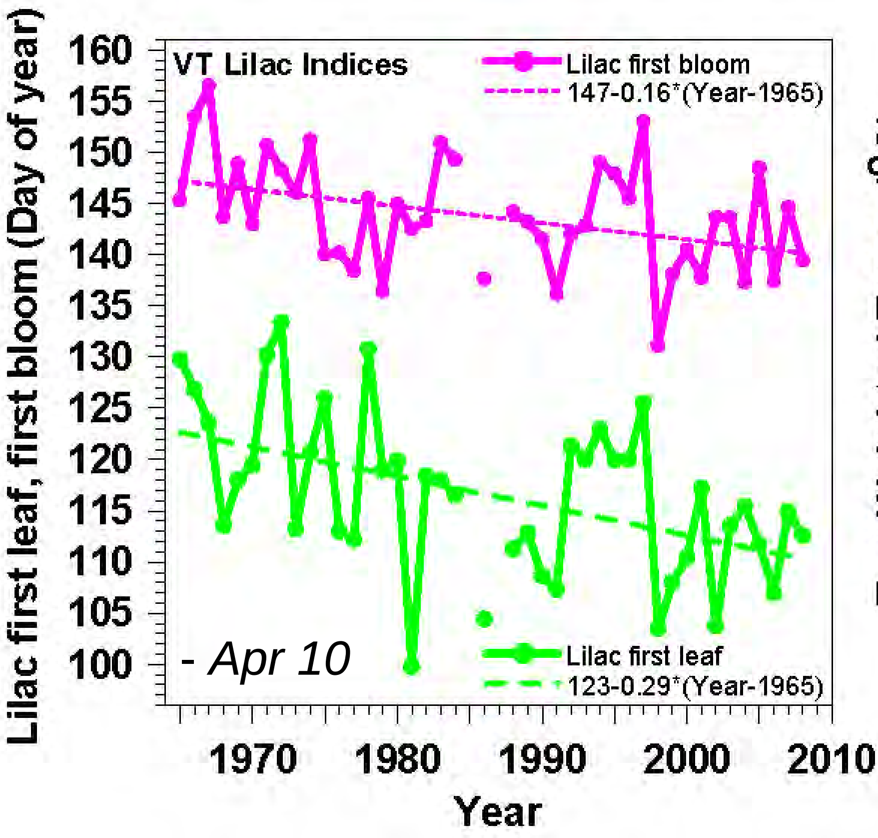
Little evaporation → Dry atmosphere, low humidity
→ Low water vapor greenhouse
→ Large cooling at night
→ Large diurnal temp. range
giving warm days, cool nights and frost

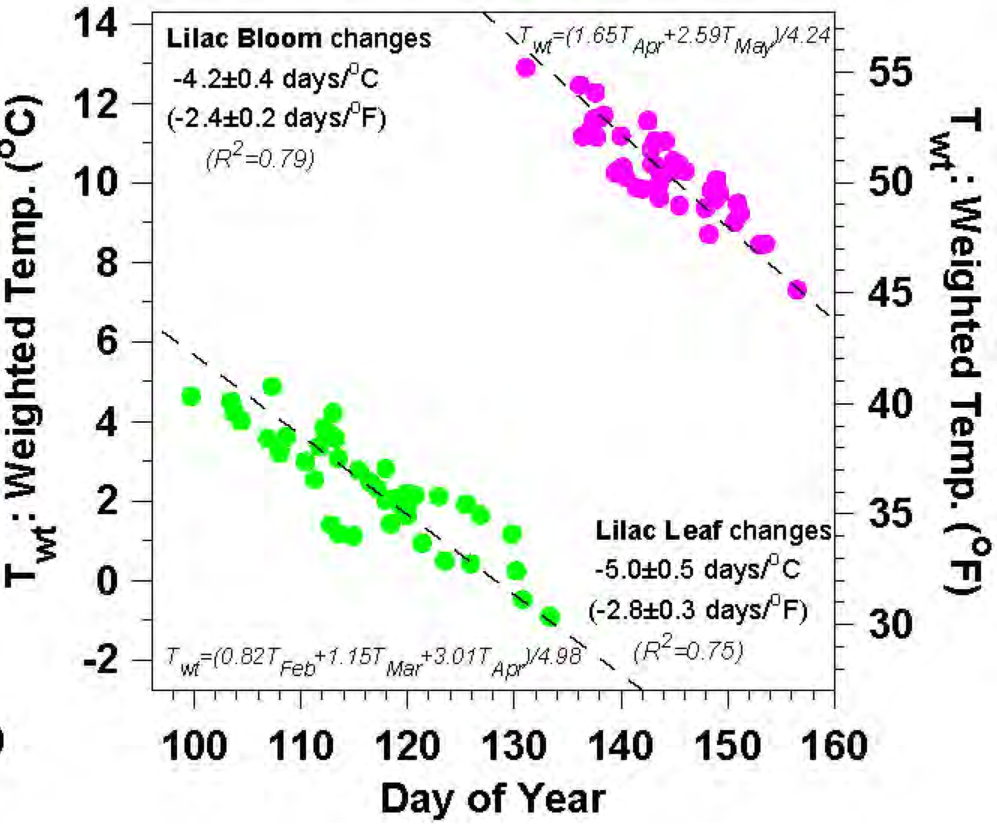
- **After leaf-out**

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

- ***Spring is coming earlier: 2012 was extreme***

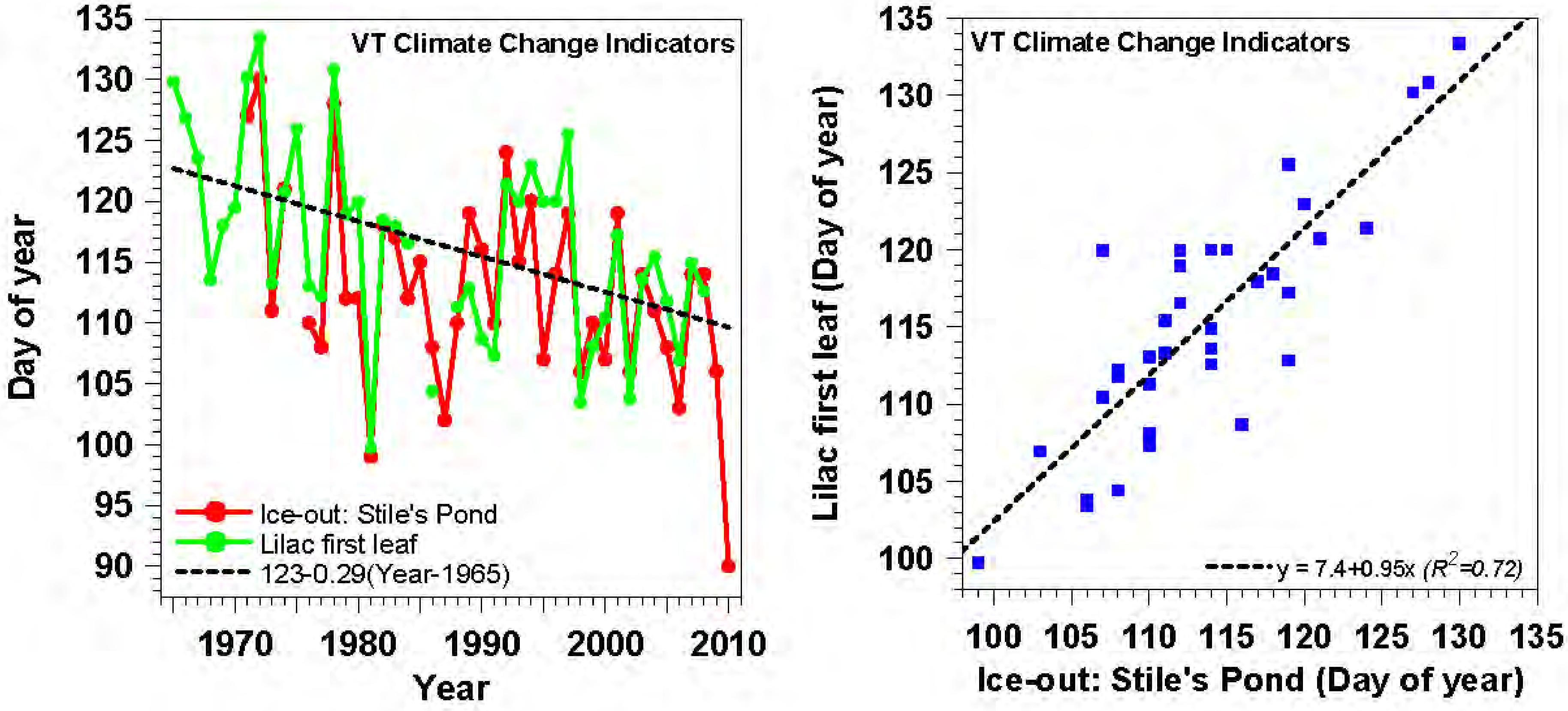
Lilac Leaf and Bloom





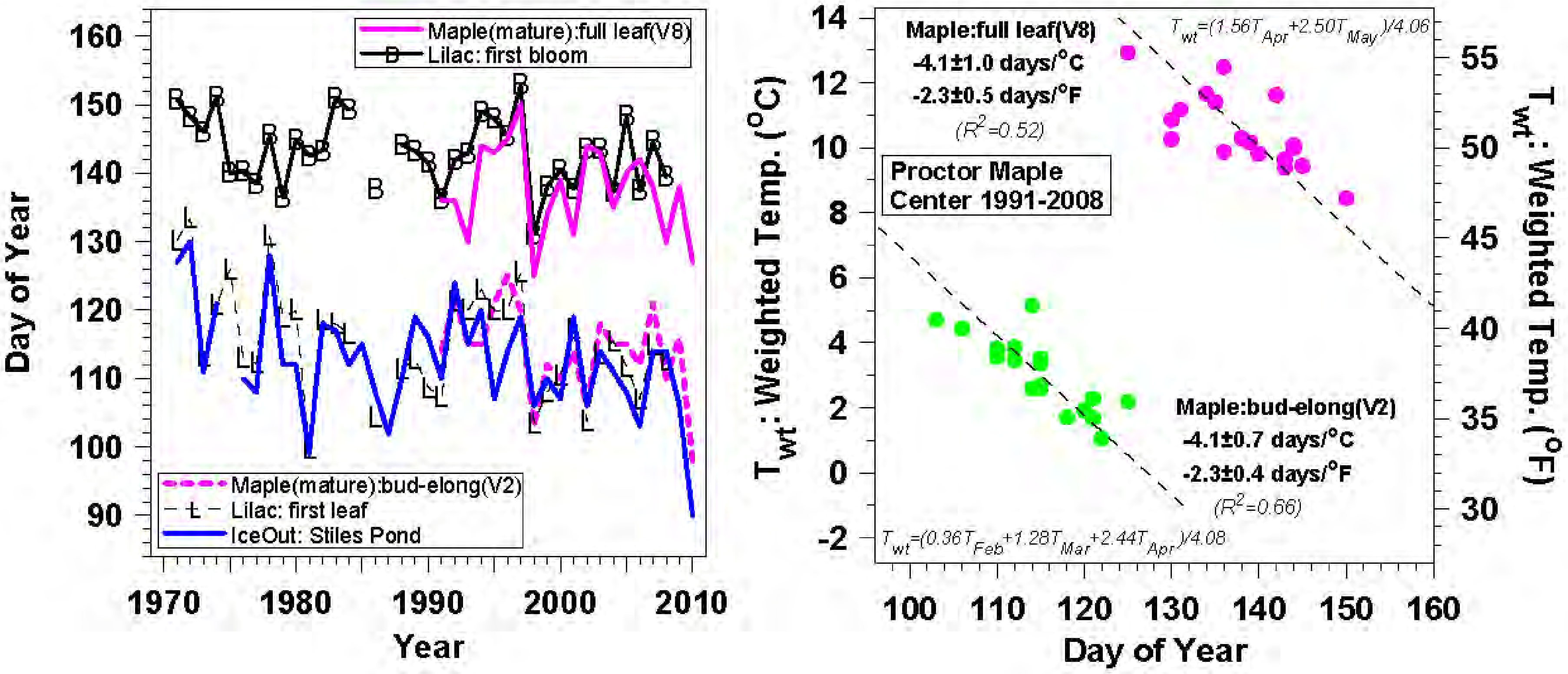
- **Leaf-out -2.9 days/decade; Bloom -1.6 days/decade**
- ***Large year-to-year variation related to temperature: 2.5 days/ °F or 4.5 days/ °C***

Lilac Leaf-out and Ice-out Coupled



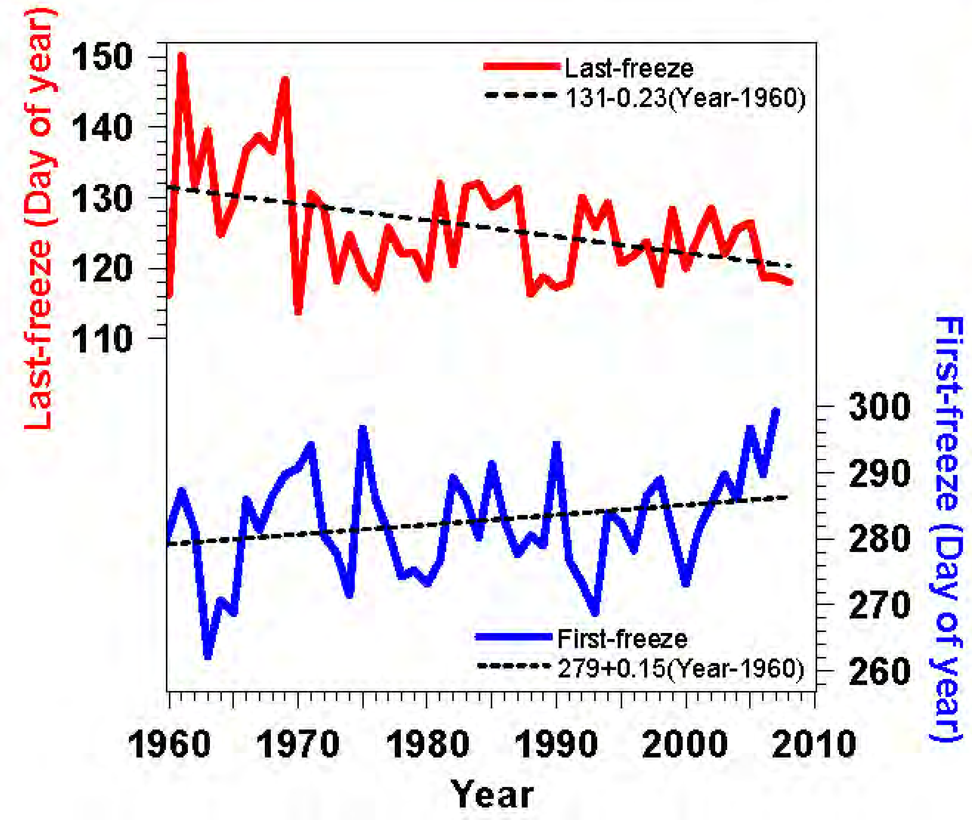
- **Lilac leaf and lake ice-out both depend on Feb. Mar. and April temperatures**
- **Trends indicate earlier spring**

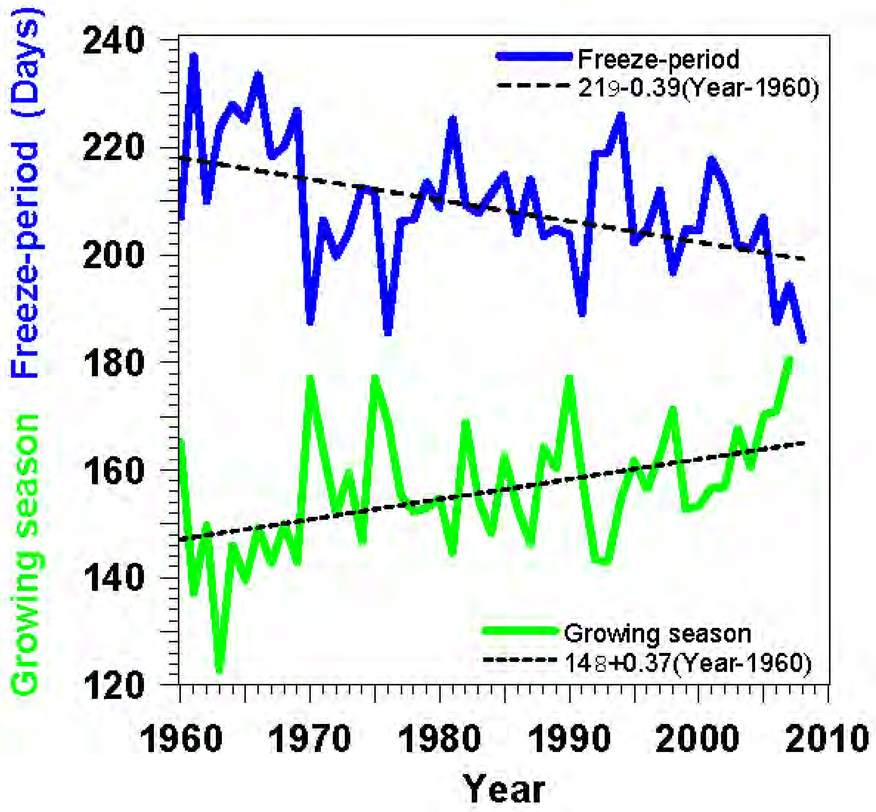
Maples and Lilacs in spring



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

First and Last Frosts Changing

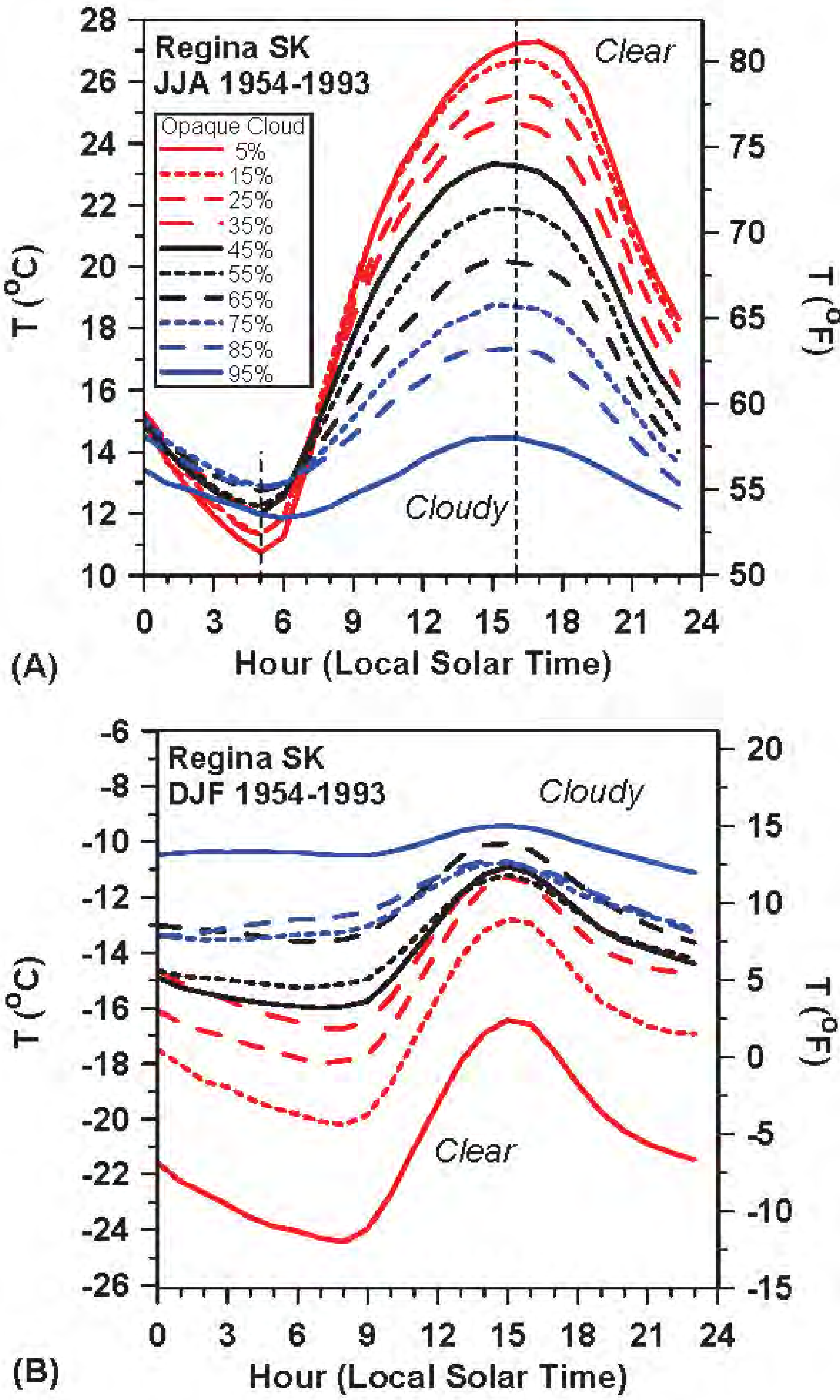




- **Growing season for frost-sensitive plants increasing 3.7 days / decade**
- ***Important for agriculture; local food supply***

Cloud Impacts

- **Summer:** Clouds reflect sunlight
  - no cloud, hot days; only slightly cooler at night
- **Winter:** Clouds are greenhouse
  - snow reflects low sun
  - clear & dry sky, cold days, very cold nights
- **Fast transition with snow in 5 days**



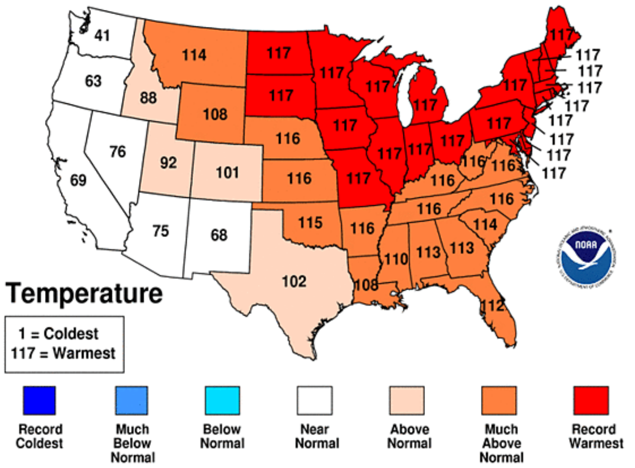
Betts et al. 2013

January 2, 2012

March 11, 2012

October 2011– March 2012

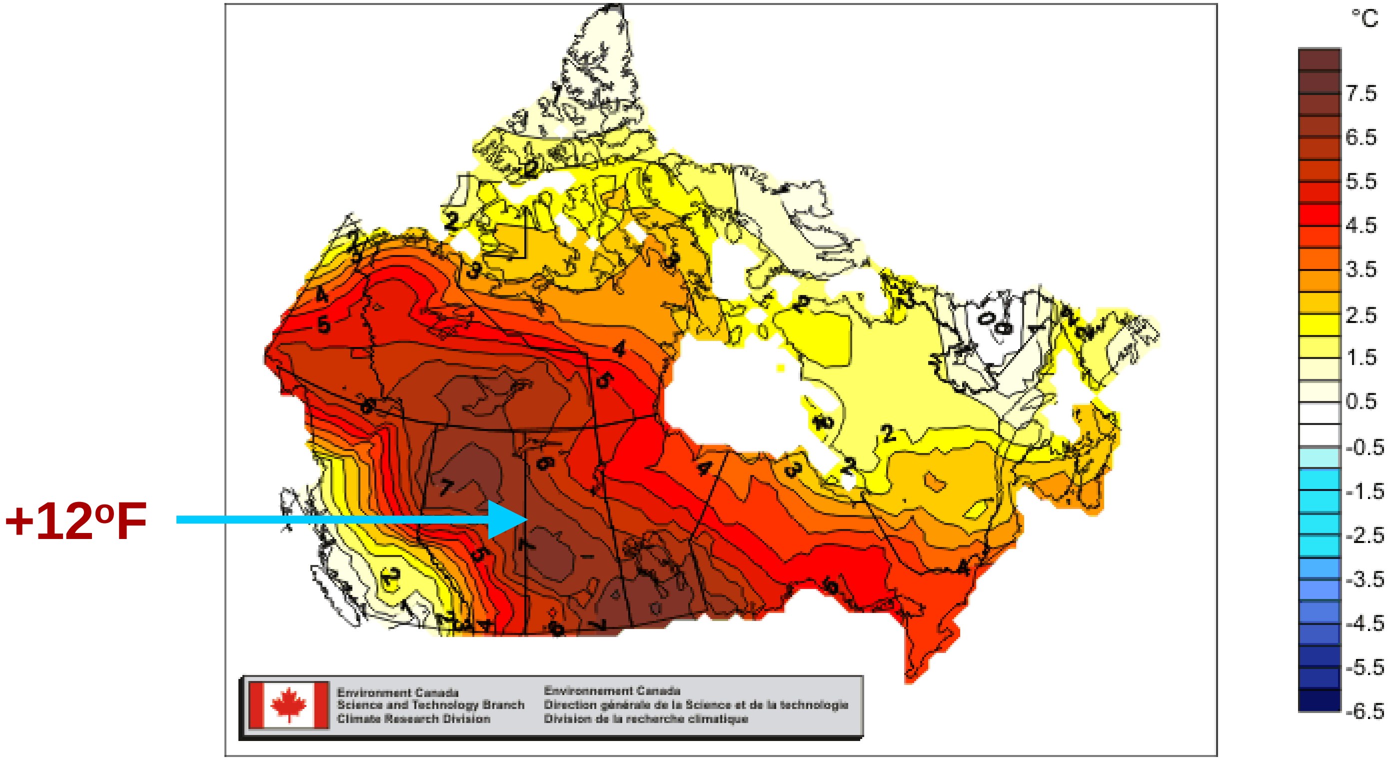
- **Warmest 6 months on record**
- **My garden frozen only 67 days**
- **No permanent snow cover west of Green Mountains**
- **Contrast snowy winter 2010-11**



Oct 2011-Mar 2012 Statewide Ranks

National Climatic Data Center/NESDIS/NOAA

Across the border: Canada


+12ºF

Environment Canada
Science and Technology Branch
Climate Research Division

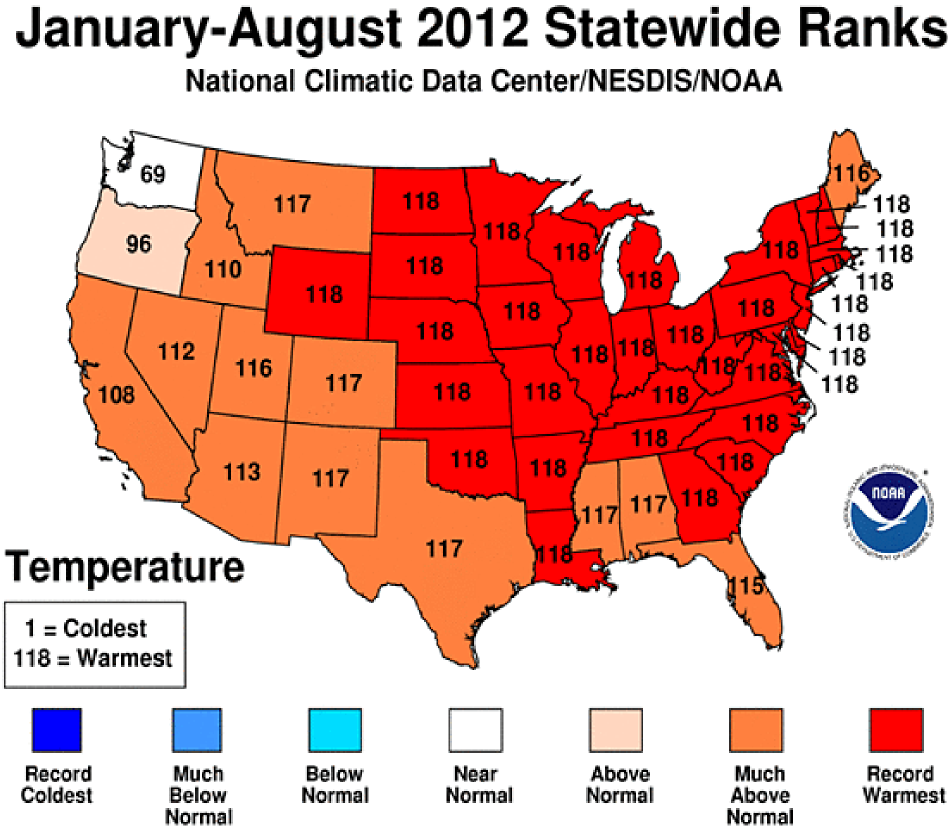
Environnement Canada
Direction générale de la Science et de la technologie
Division de la recherche climatique

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

Last Year Exceptionally Warm

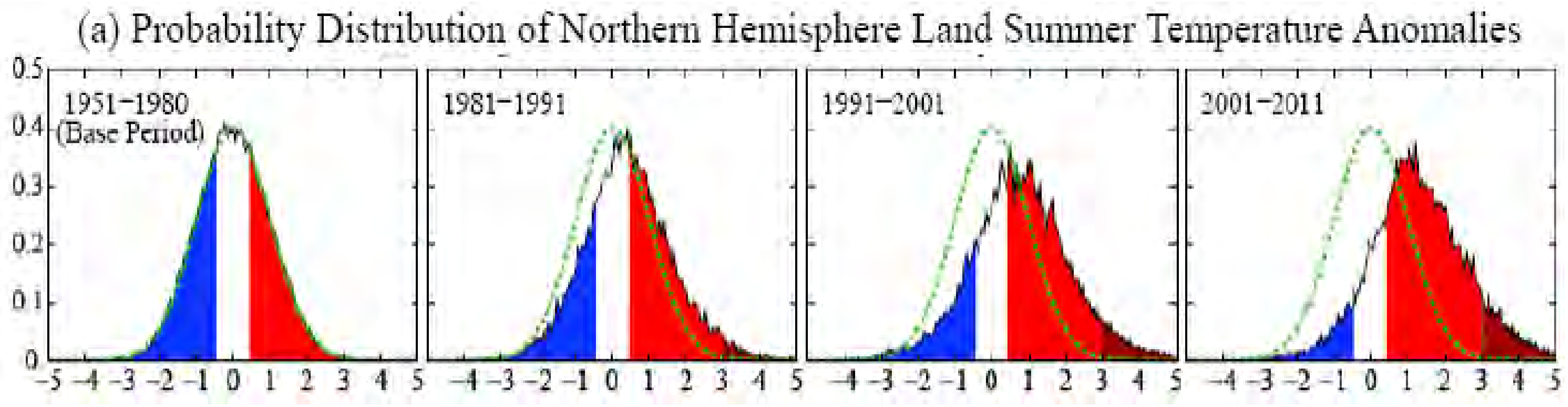
- Burlington Area Extremes
- Highest Average Temperature degrees F
- Days: 9/1/2011 - 8/31/2012
- Length of period: 365 days
- Years: 1850-2012
- Rank Value Ending Date
- **1 50.4 8/31/2012**
- 2 48.4 8/31/2002, 8/31/1949
- 4 48.2 8/31/2010
- 5 48.0 8/31/1999
- 6 47.9 8/31/2006
- 7 47.8 8/31/1991, 8/31/1995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

(Scott Whittier: NWS-BTV)



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

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**
  - ***Baseline 0.15% has increased to 10% in 45 years***

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..**
- **Followed by freeze-up.. melt**

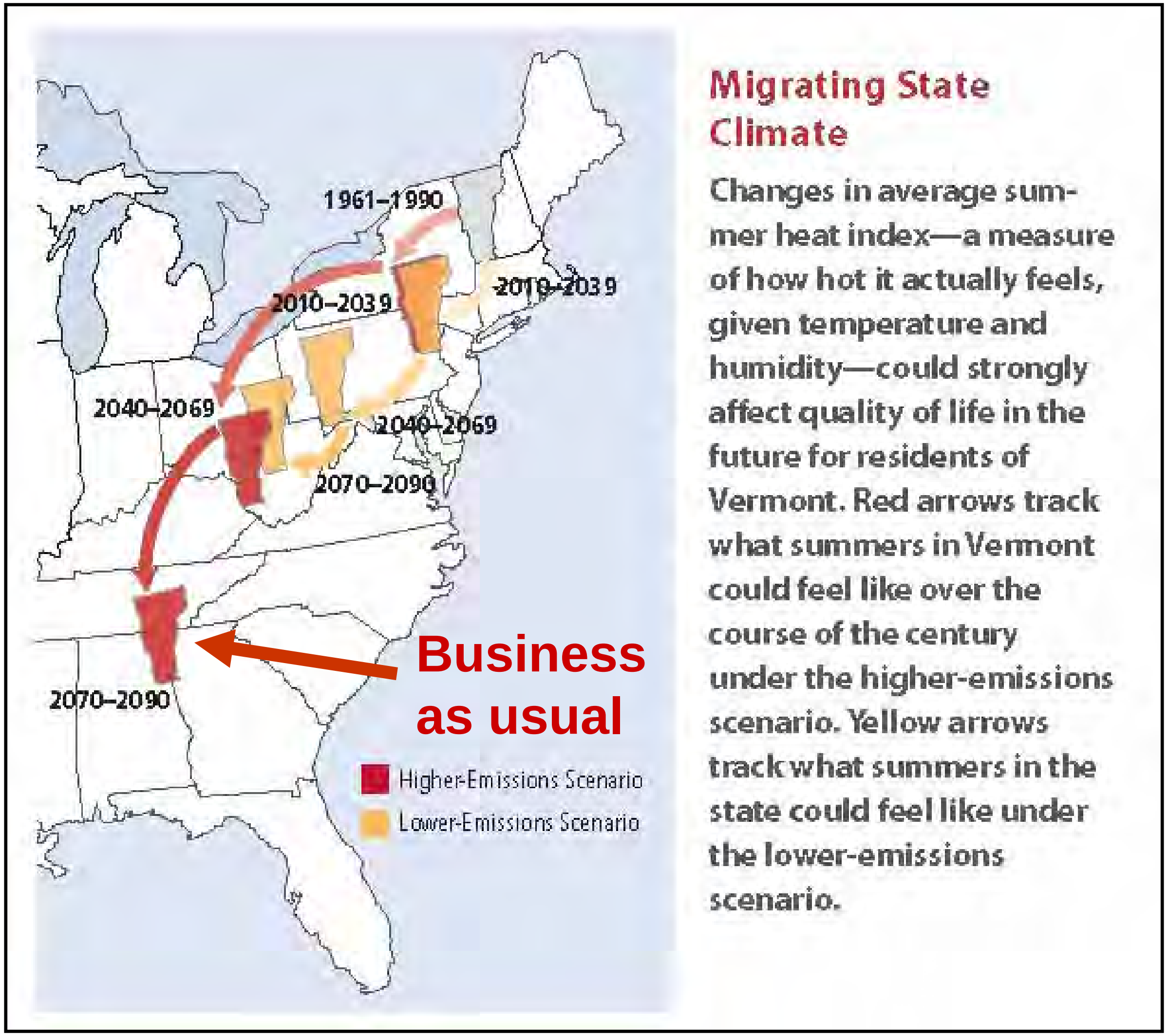
Vermont Winter 2006

- **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)***

Vermont's Future with High and Low GHG Emissions

What about VT forests?

Sub-tropical drought areas moving into southern US



Business as usual

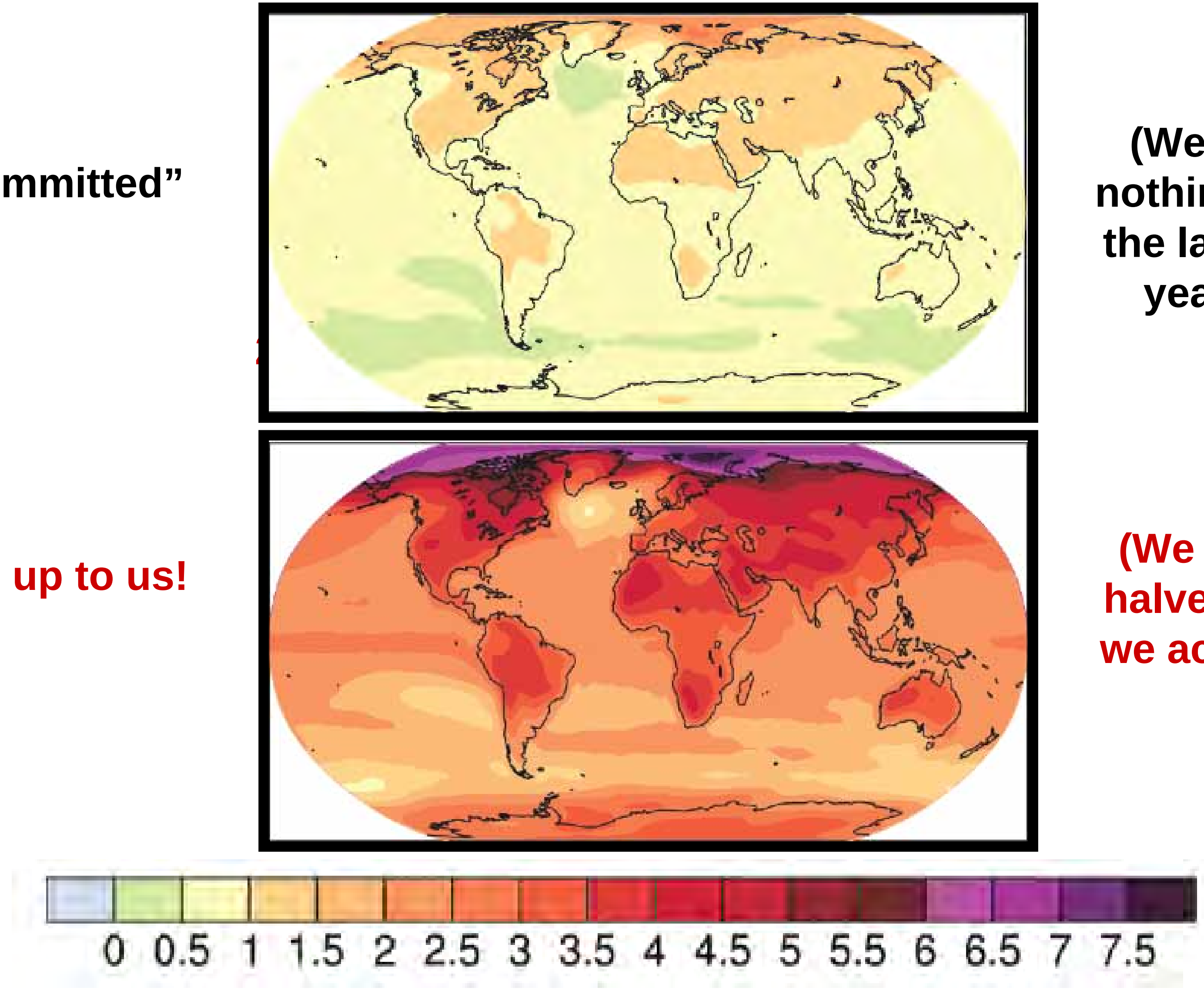
Migrating State Climate

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

Predicted Change in Temperature

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



[^{o}C]

“Committed”

(We did nothing for the last 20 years)

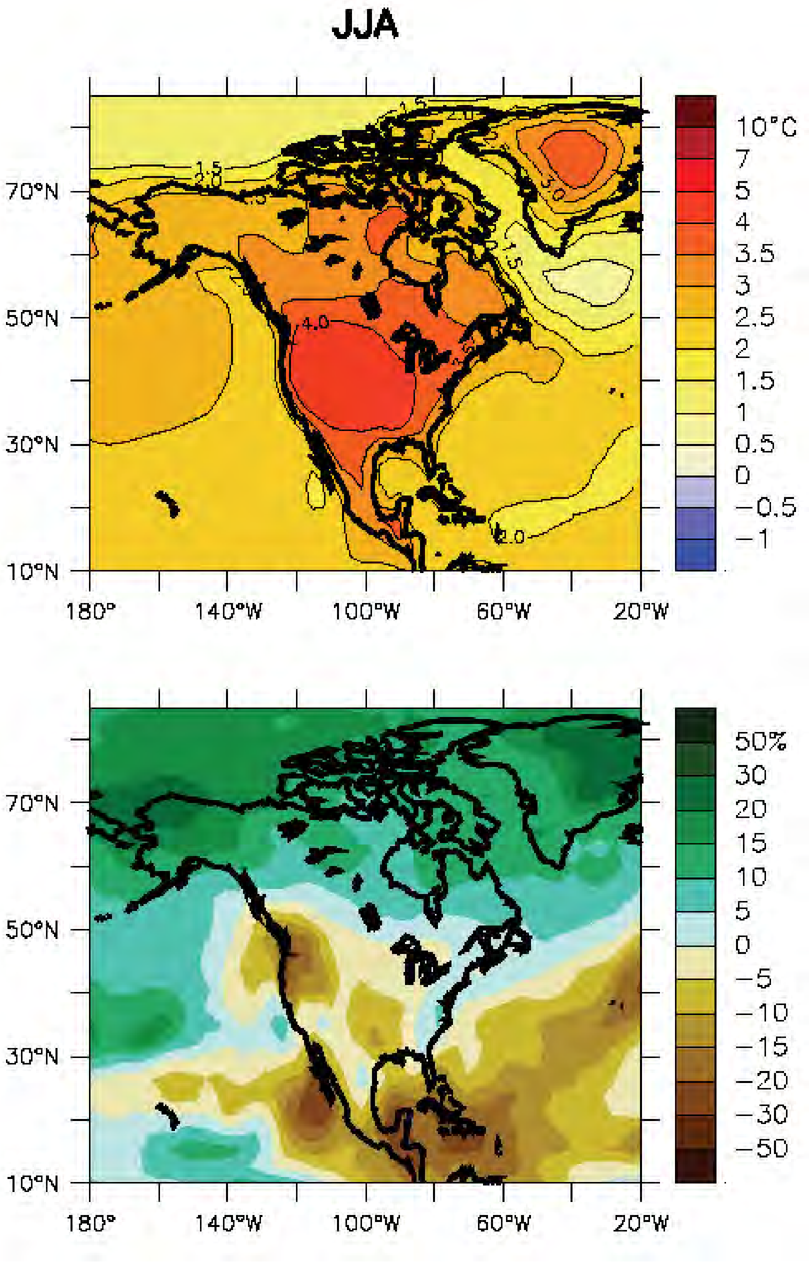
Still up to us!

(We could halve this if we act now)

Warmer Summers

Change of temp. & precip. by 2090, high emission scenario, *IPCC AR4*

- Higher temperature maxima and minima
- Heavier, more intense rain (think tropical)
- Periods of drought
- Warmer rivers
- Ecosystem stress



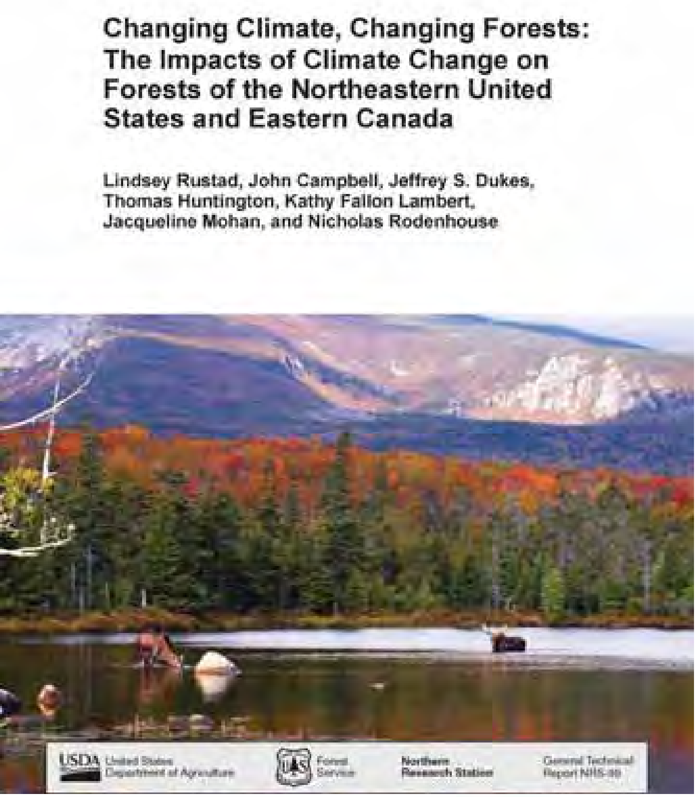
Winter Trends *(USGCRP 2009)*

- Trends since 1970
  - Winter temps rising 1^{o}F/decade
  - Less winter precipitation falling as snow and more as rain
  - Reduced snowpack
  - Earlier breakup of winter ice on lakes and rivers
  - Earlier spring snowmelt resulting in earlier peak river flows

- Projections to late century
  - Winters in the Northeast are projected to be much shorter with fewer cold days and more precipitation
  - The length of the winter snow season would be cut in half across northern New York, Vermont, New Hampshire, and Maine, and reduced to a week or two in southern parts of the region

- Reality
  - Northern winters may be shrinking faster than model projections
  - Winter extremes increasing

http://www.nrs.fs.fed.us/pubs/41165



Changing Climate, Changing Forests: The Impacts of Climate Change on Forests of the Northeastern United States and Eastern Canada

Lindsey Rustad, John Campbell, Jeffrey S. Dukes, Thomas Huntington, Kathy Fallon Lambert, Jacqueline Mohan, and Nicholas Rodenhouse

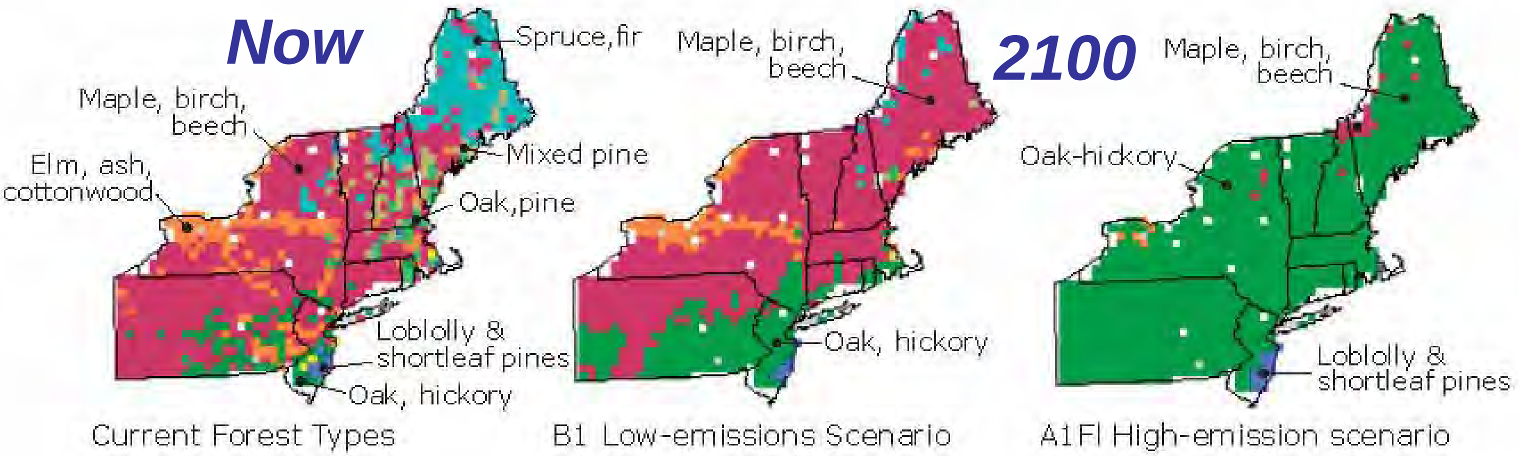
USDA United States Department of Agriculture

Forest Service

Northern Research Station

General Technical Report NRS-99

“Nothing is certain about climate change except that it poses a tremendous challenge to forests,” according to [Michael T. Rains](), Director of the Forest Service’s [Northern Research Station](). “Forest Service science is developing tools such at this report that will inform decision-making and contribute to making the nation’s forests more resilient to changing conditions.”



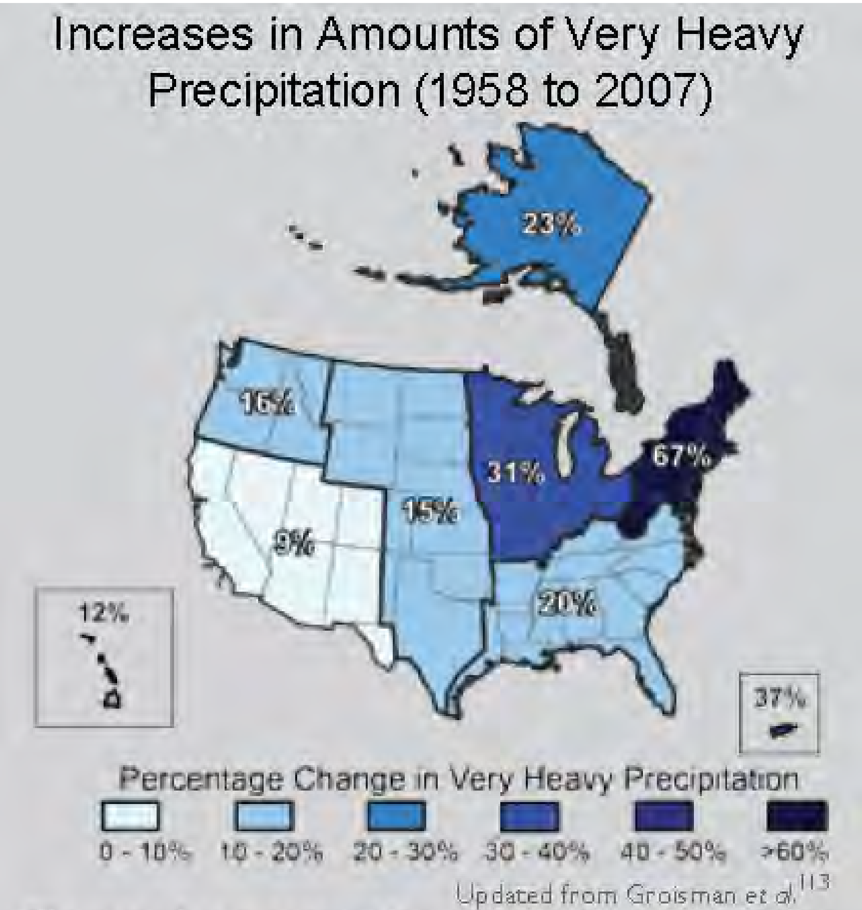
Climate “Suitable” Species!

Very Heavy Precipitation Is Increasing

(USGCRP, 2009)

- <u>Precipitation Extremes</u>
- **Most of the observed increase in precipitation during the <u>last 50 years</u> 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**

Increases in Amounts of Very Heavy Precipitation (1958 to 2007)

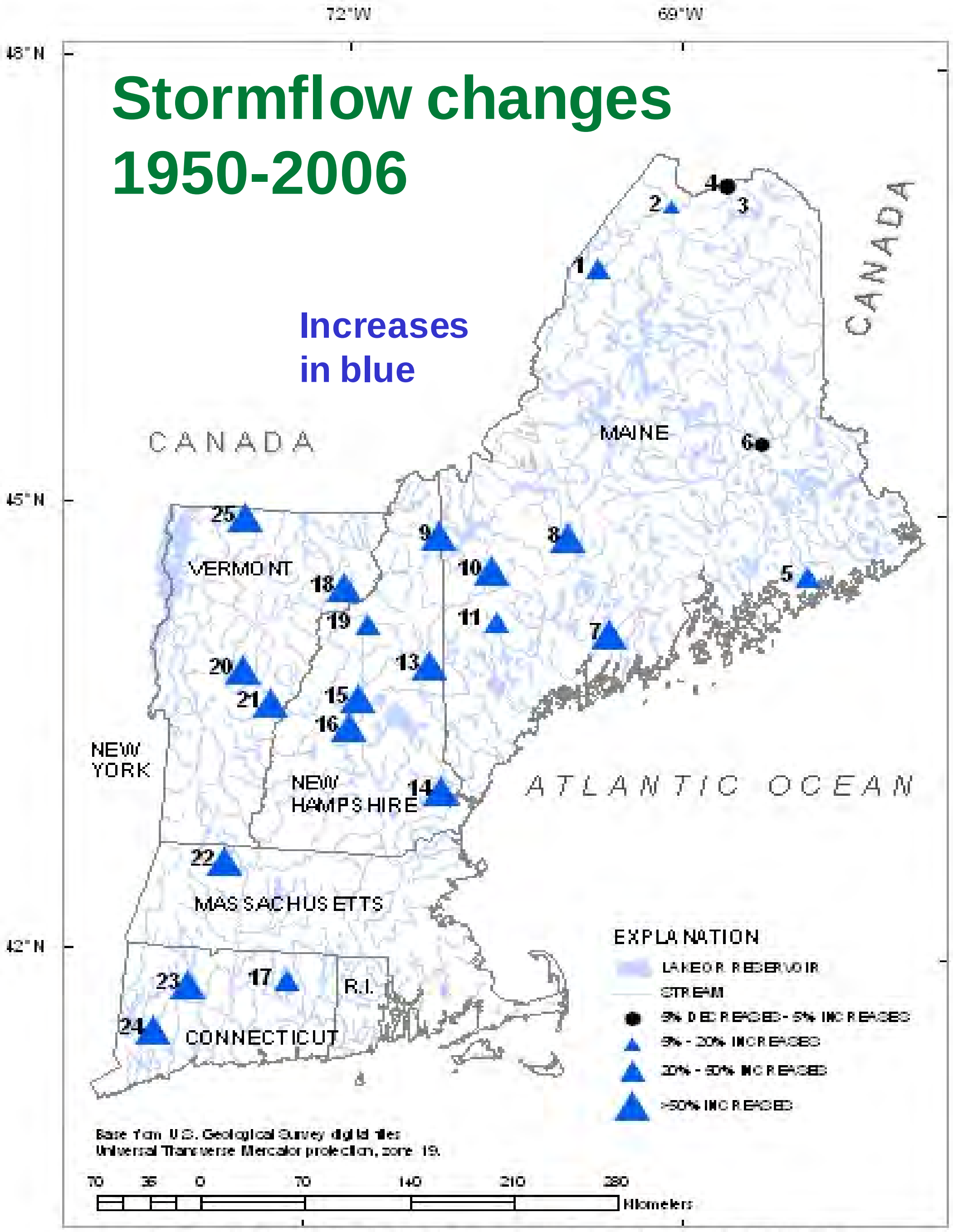


Updated from Groisman et al.[113]

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



Stormflow changes 1950-2006

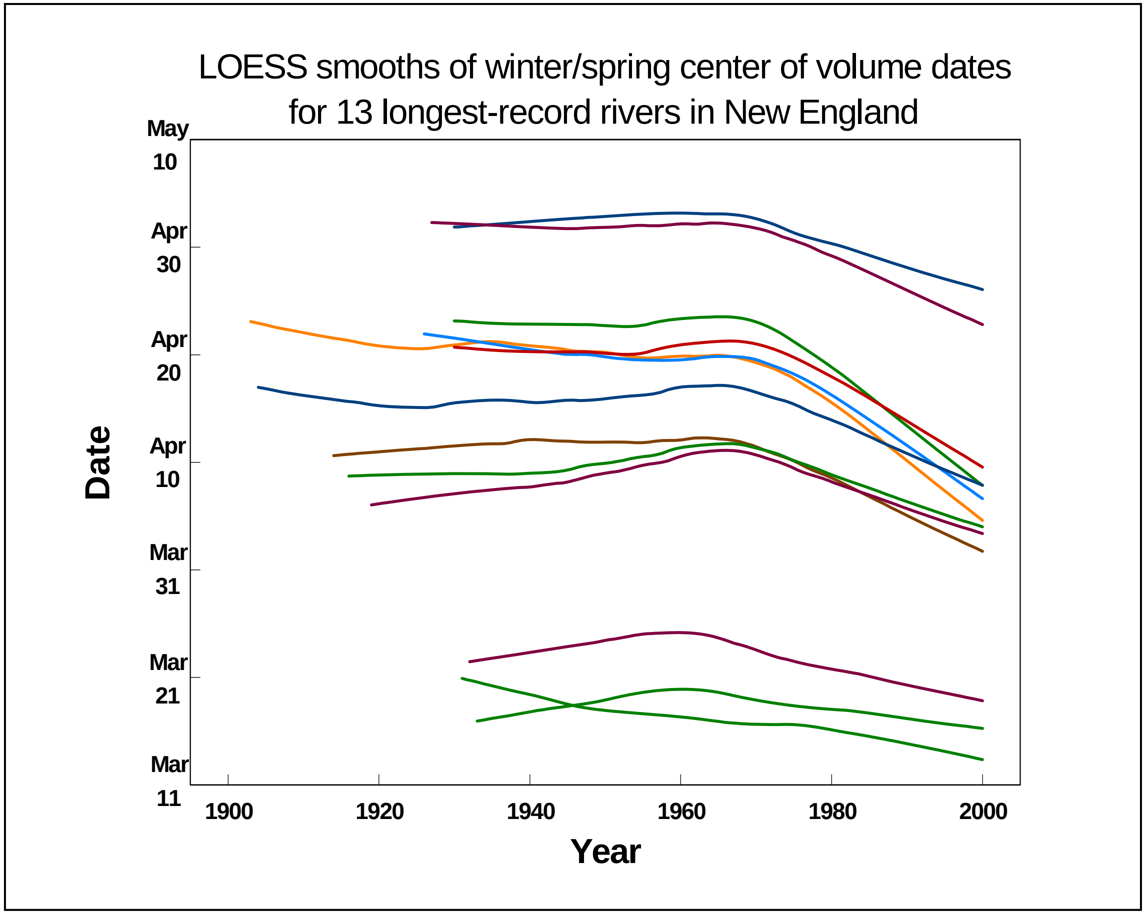
Increases in blue

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

Hydrology Sensitive to Climate

Lent (2010), USGS, Me

- **Spring runoff dominates the annual hydrograph**
- ***Significantly earlier in northern New England in recent years***
  - ***≈3 days/decade***
- ***Timing related to air temperatures in Spring***



(Hodgkins and others, 2003)

Many Wet Summers in Vermont – until 2012

- **2004, 2006, 2008, 2009, (2010), 2011, 2013 wet**
- **Direct fast evaporation off wet canopies**
- ***Positive evaporation-precipitation feedback, coupled to synoptic system frequency***

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***

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 (6-7%/^{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: needs more study***

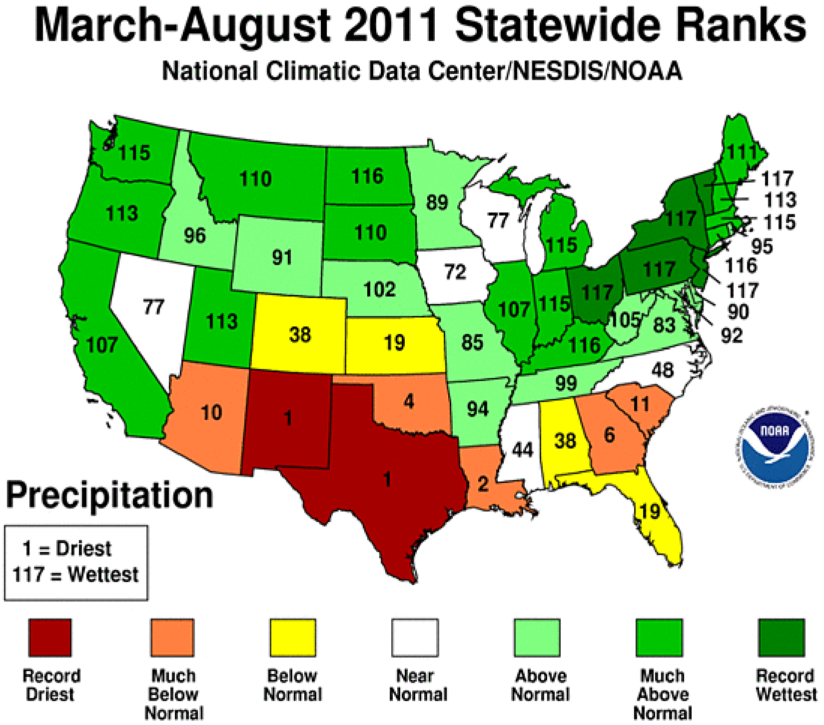
2011 Classic Flood Situations

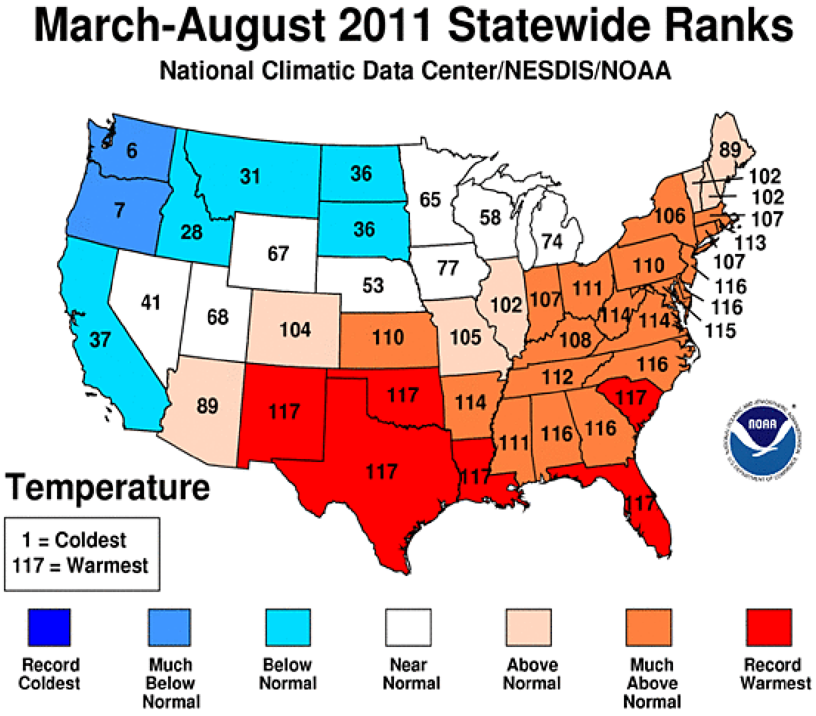
- **Spring flood**: heavy rain and warm weather, melting large snowpack from 2010 winter
  - 70F (4/11) and 80F(5/27) + heavy rain
  - record April, May rainfall: 3X at BTV
  - Severe floods on Winooski and Adirondack rivers
  - Lake Champlain record flood stage of 103ft

- **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)

2011 Floods: VT and NY

- **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***

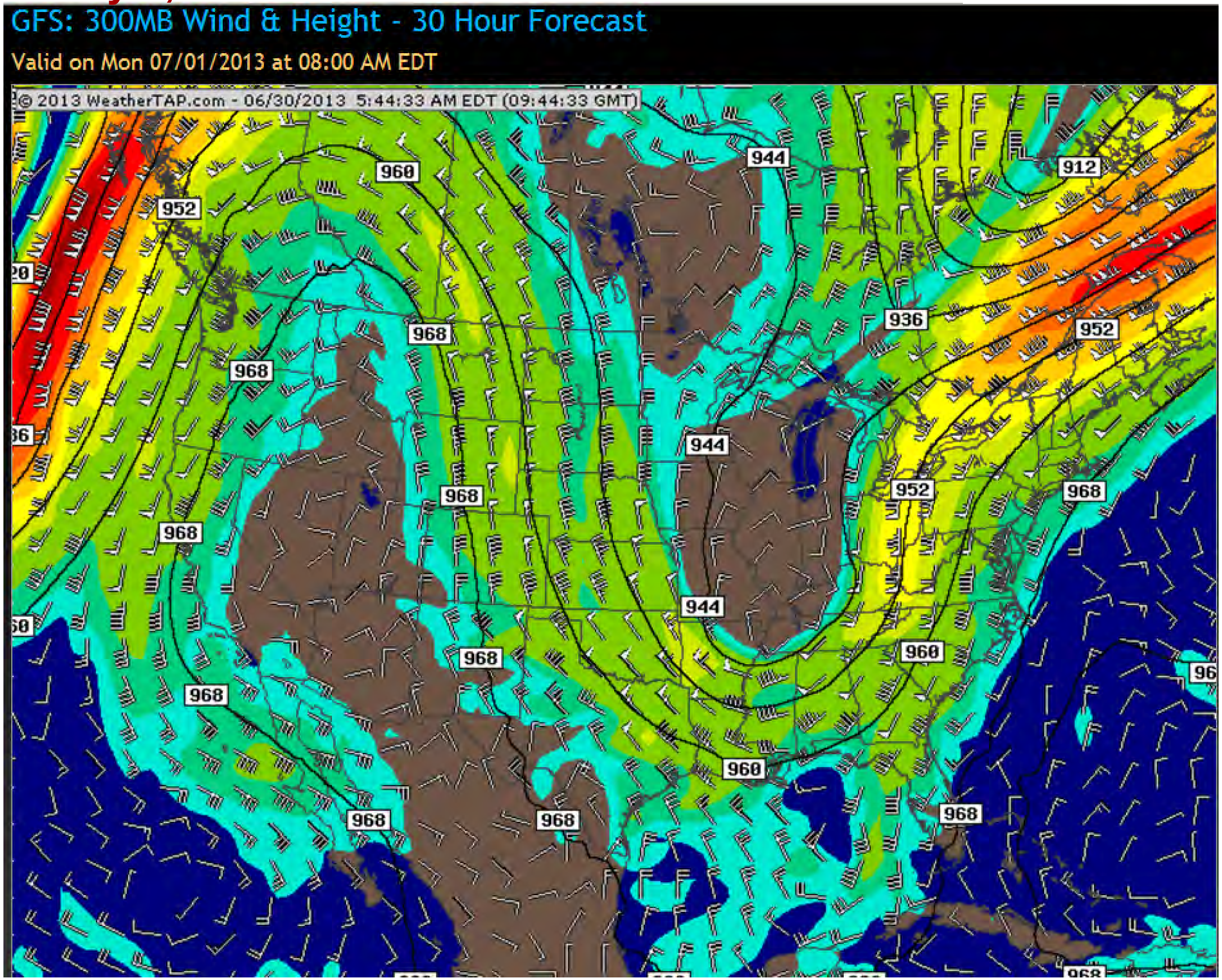




Jet Stream Patterns Slowing Down and Amplifying, Giving More Extreme Weather

July 1, 2013

(Francis and Vavrus, 2012)



GFS: 300MB Wind & Height - 30 Hour Forecast

Valid on Mon 07/01/2013 at 08:00 AM EDT

Blocking Pattern - Unique track

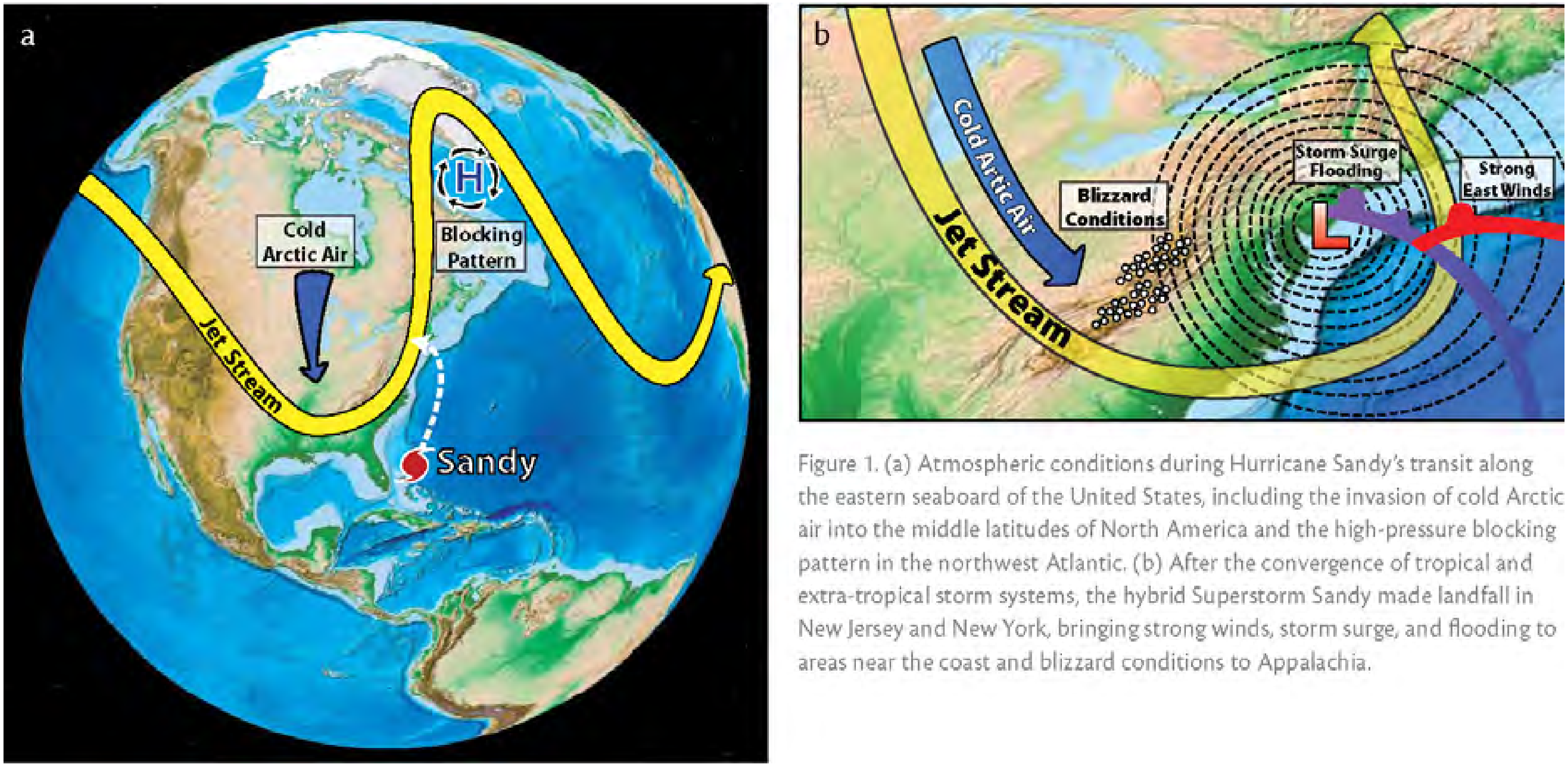


Figure 1. (a) Atmospheric conditions during Hurricane Sandy's transit along the eastern seaboard of the United States, including the invasion of cold Arctic air into the middle latitudes of North America and the high-pressure blocking pattern in the northwest Atlantic. (b) After the convergence of tropical 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]

Forest/Agriculture 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 related to variable snow
  - T_{min} extremes increasing +3^{o}F/decade (moister air)

- 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

Discussion

- **Background papers:** **http://alanbetts.com/**
  - ***Vermont Climate Change Indicators***
  - ***Seasonal Climate Transitions in New England***
  - ***Climate with clouds and snow***
  - ***Many talks and newspaper articles***

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

Current Reality

- Northern winters may be shrinking faster than model projections
  - Model ice-coupled feedbacks too weak?
  - Winter extremes increasing: eg 2010, 2011

- Our limited seasonal forecast skill is related to Pacific and Atlantic ocean temperatures
  - Now Arctic warming is major factor
  - Changing NH circulation: blocking patterns
  - Limited understanding: *less than decade of data*

Models Strengths and Weaknesses

- **Weather:** Sandy landfall forecast at 7-days lead-time
- Climate: Mean state changes
- Temperature mean trends and statistics
  - Depend on model sensitivity to clouds/ice-melt
  - Cloud field changes uncertain, Arctic ice-melt too slow
  - Bias of model Temps. ***from freezing*** critical

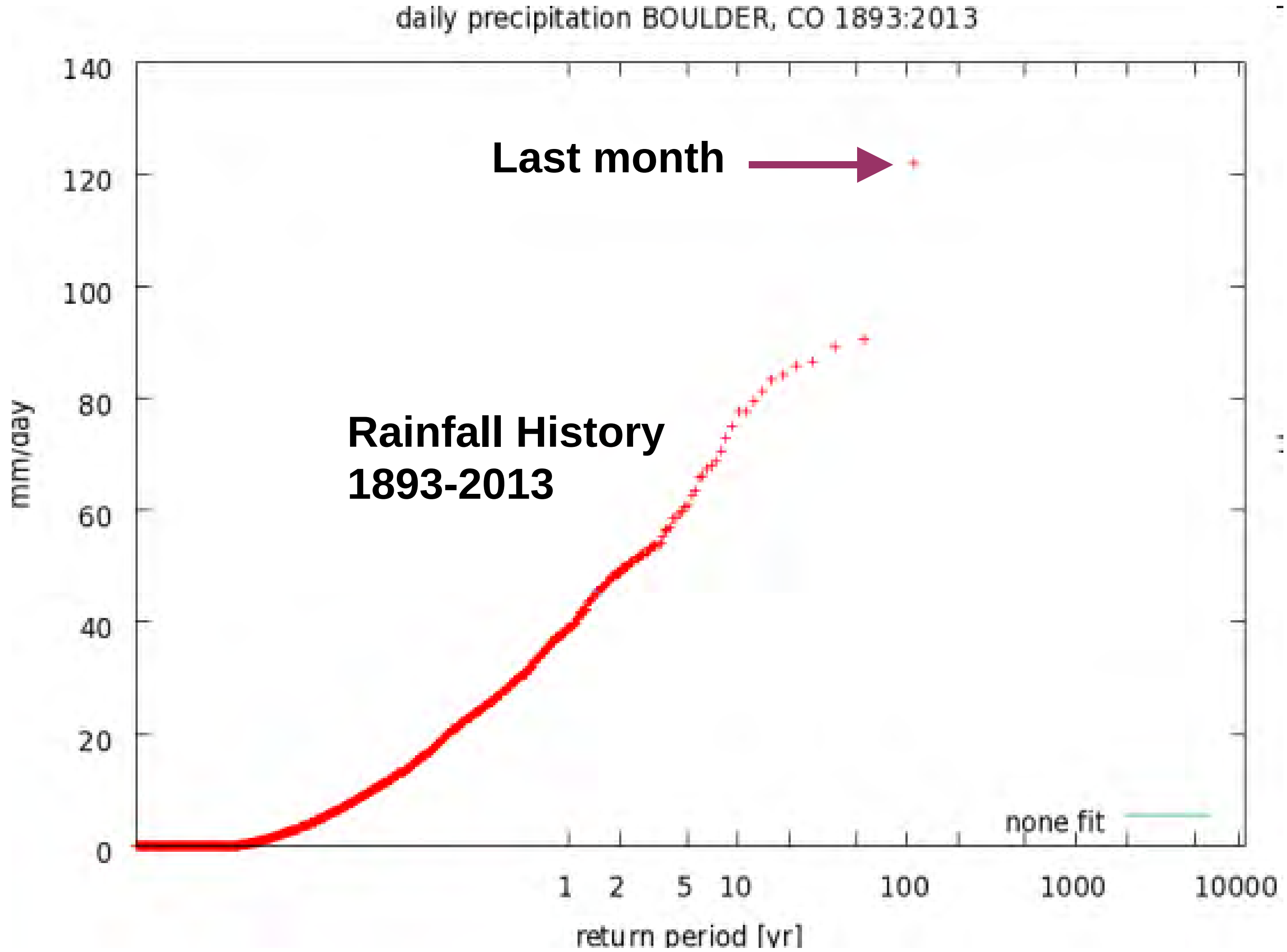
- Large-scale mean precipitation trends
  - Circulation mode changes less certain
  - Precipitation extremes less certain
- Diurnal cycle trends poorly forecast
- Arctic melt-rate under-forecast
  - Appears to be changing circulation modes
- Biogeochemical feedbacks uncertain
  - Methane release, CO_2 fertilization

A Path Towards ‘Sustainability’

- ***Necessary to:***
- **Minimize the lifetime of human waste products in the Earth system and eliminate waste with critical biosphere interactions**
- **Maximize recycling and re-manufacturing to minimize waste-streams and the use of non-renewable raw materials**
- **Maximize the efficiency with which our society uses energy (and fresh water)**
- **Maximize the use of renewable resources**

Colorado Flooding
a “1,000-Year” Event

O 15-hr



Last month

Rainfall History
1893-2013

Increasing Extreme Weather

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

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

- **.. and global weather patterns are changing**

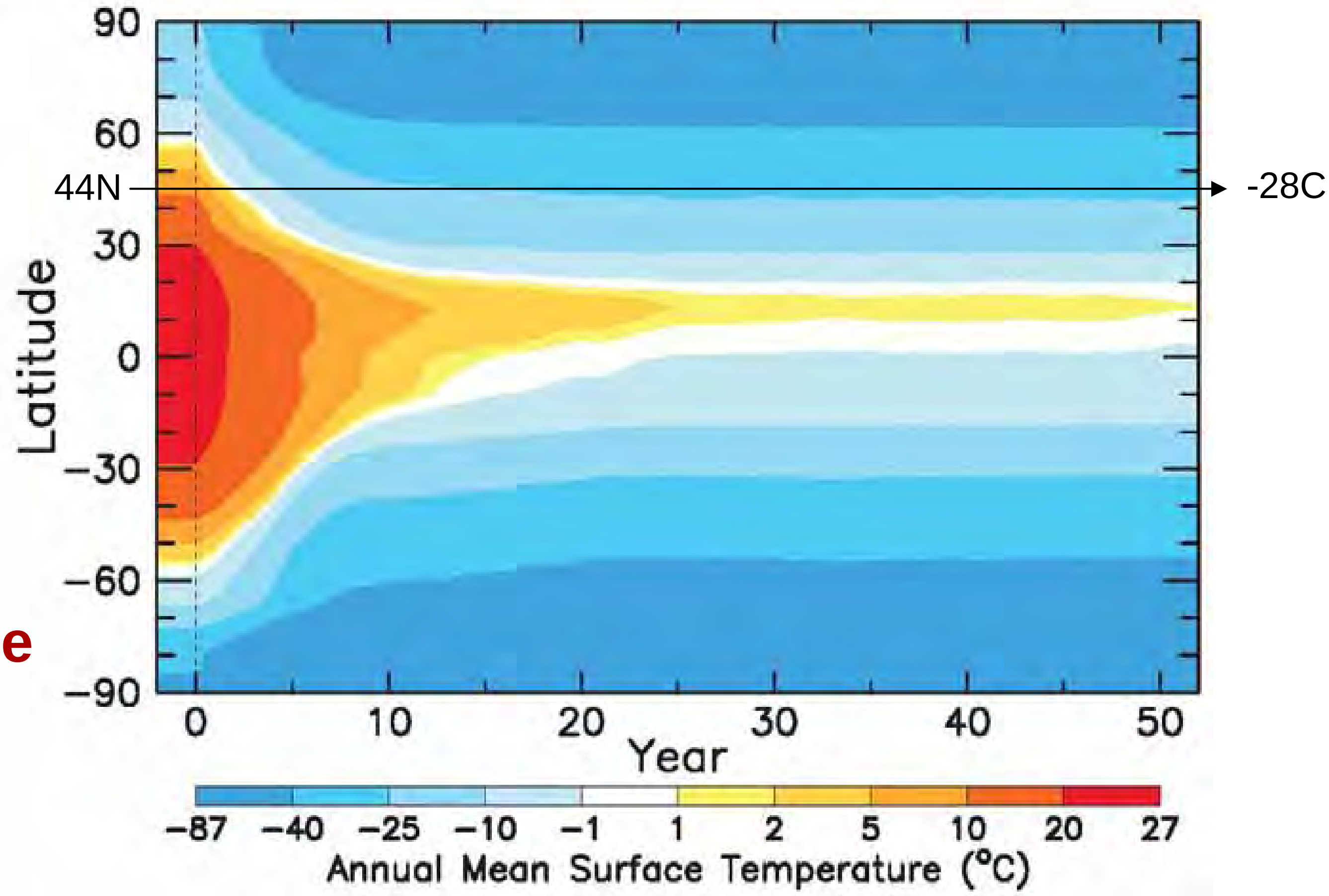
CO_2 is the Primary Control Knob in the Climate System

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^{o}C in 1 year; 35^{o}C in 50 years**
- **Water vapor falls 90%; cloud-cover goes to 75%; sea-ice to 50%**