Climate Change and Vermont

Dr. Alan K. Betts

Atmospheric Research, Pittsford, VT 05763

akbetts@aol.com
http://alanbetts.com

Vermont Climate Assessment

UVM, Burlington, Vermont

RACC
Research on Adaptation to Climate Change

Sept. 25, 2013

- 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 & local issue**
  a societal issue & personal issue

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

Outline

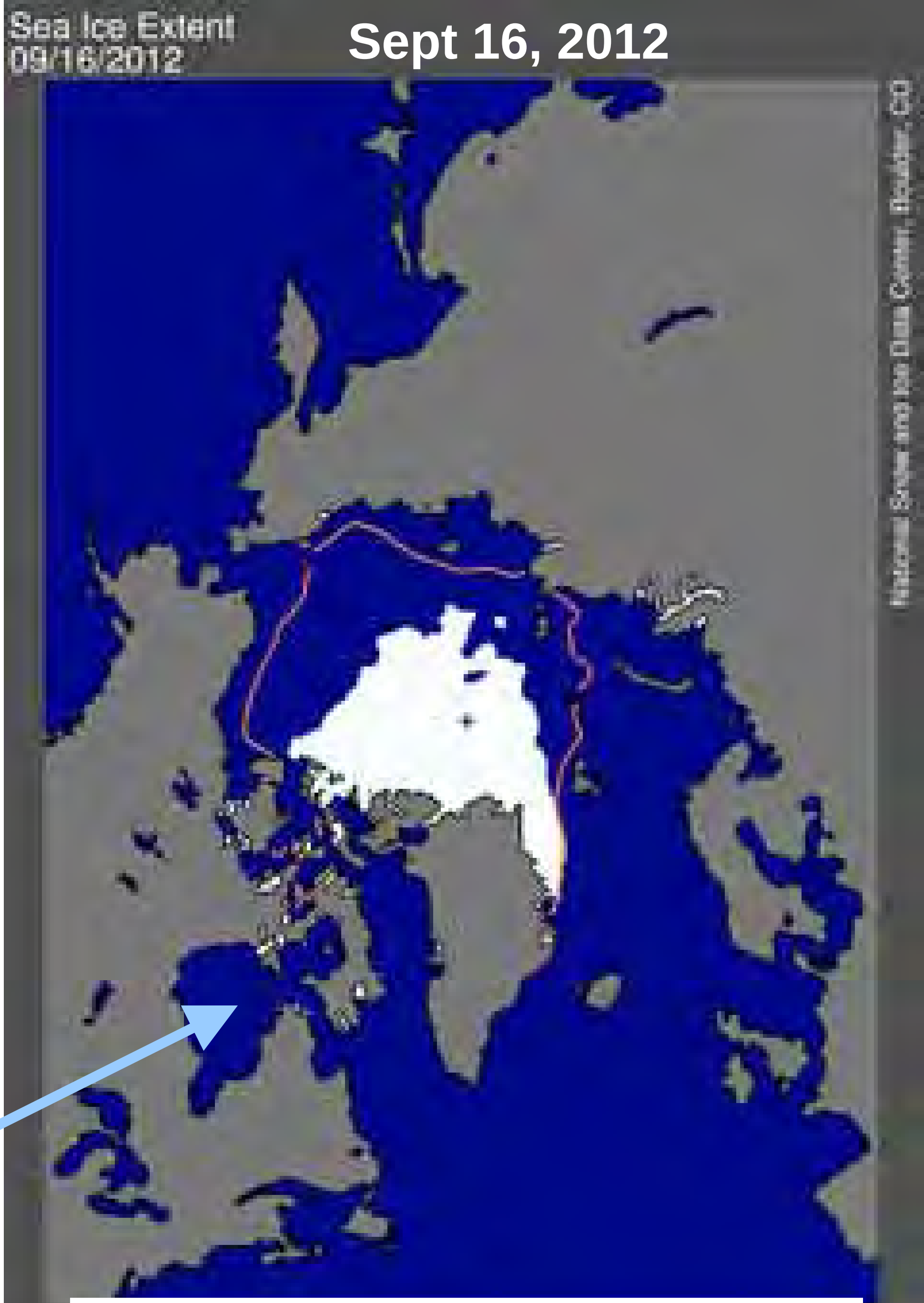
- Science of climate change
  - Global scale: actual and future
  - What is happening to Vermont
- The transition we face
  - Managing the earth system
  - What are the challenges?
- Discussion
  - – General
  - – Discuss chapters of VCA

- **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:

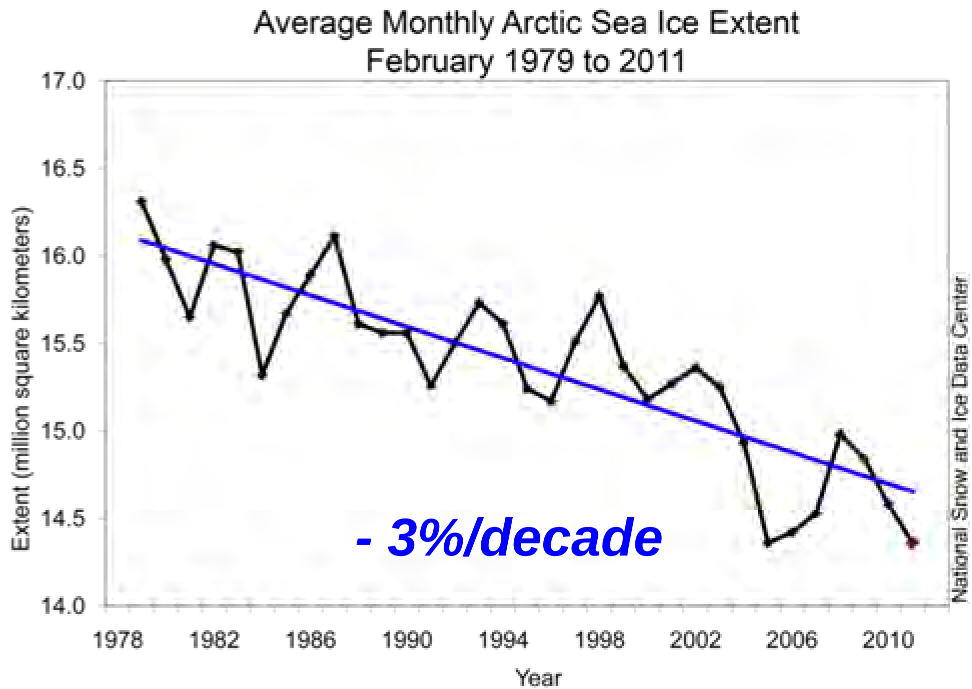
Open water in Oct. Nov. gives warmer Fall in Northeast

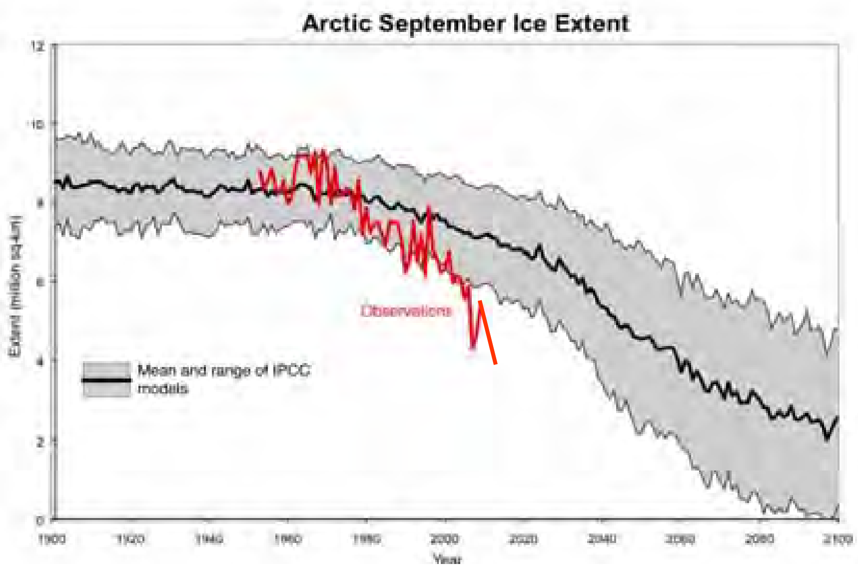


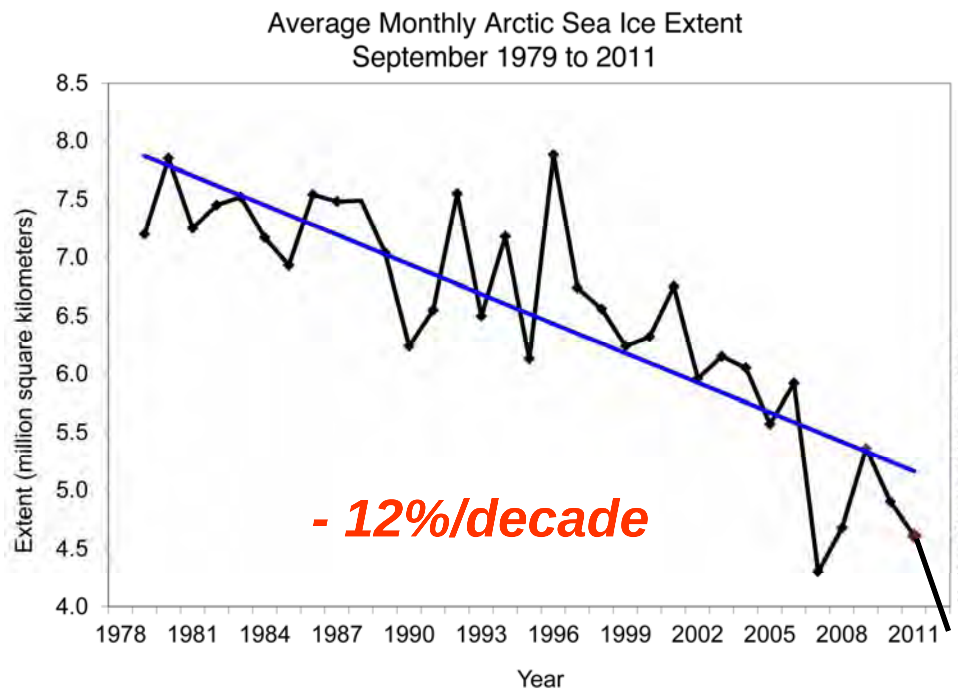
http://nsidc.org/arcticseaicenews/

Sea Ice Trends

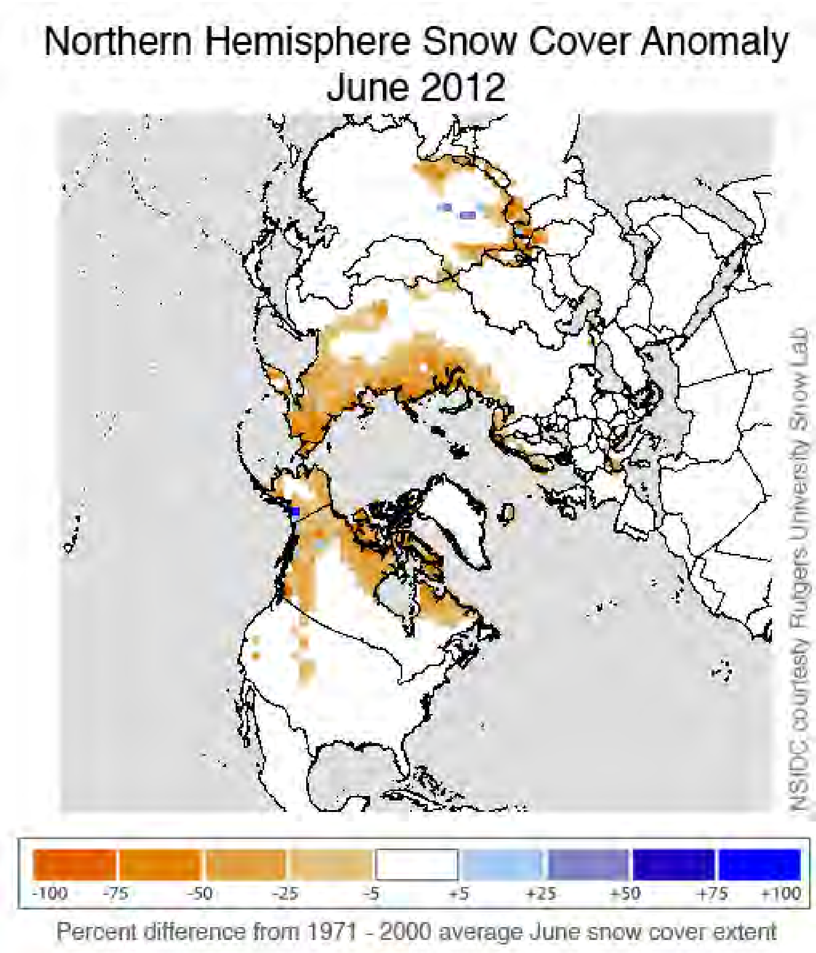
- **Sea ice is thinning rapidly**
- **Observed September decline appears to be faster than IPCC-AR4 climate model projections**
- ***[AR5 projections should be faster]***

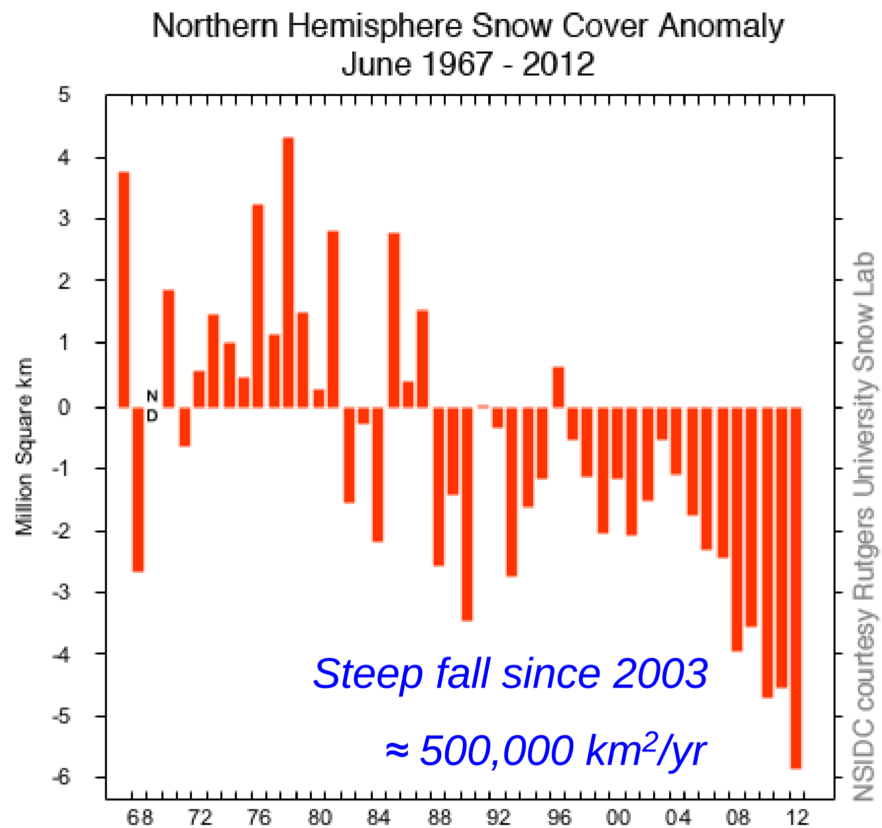






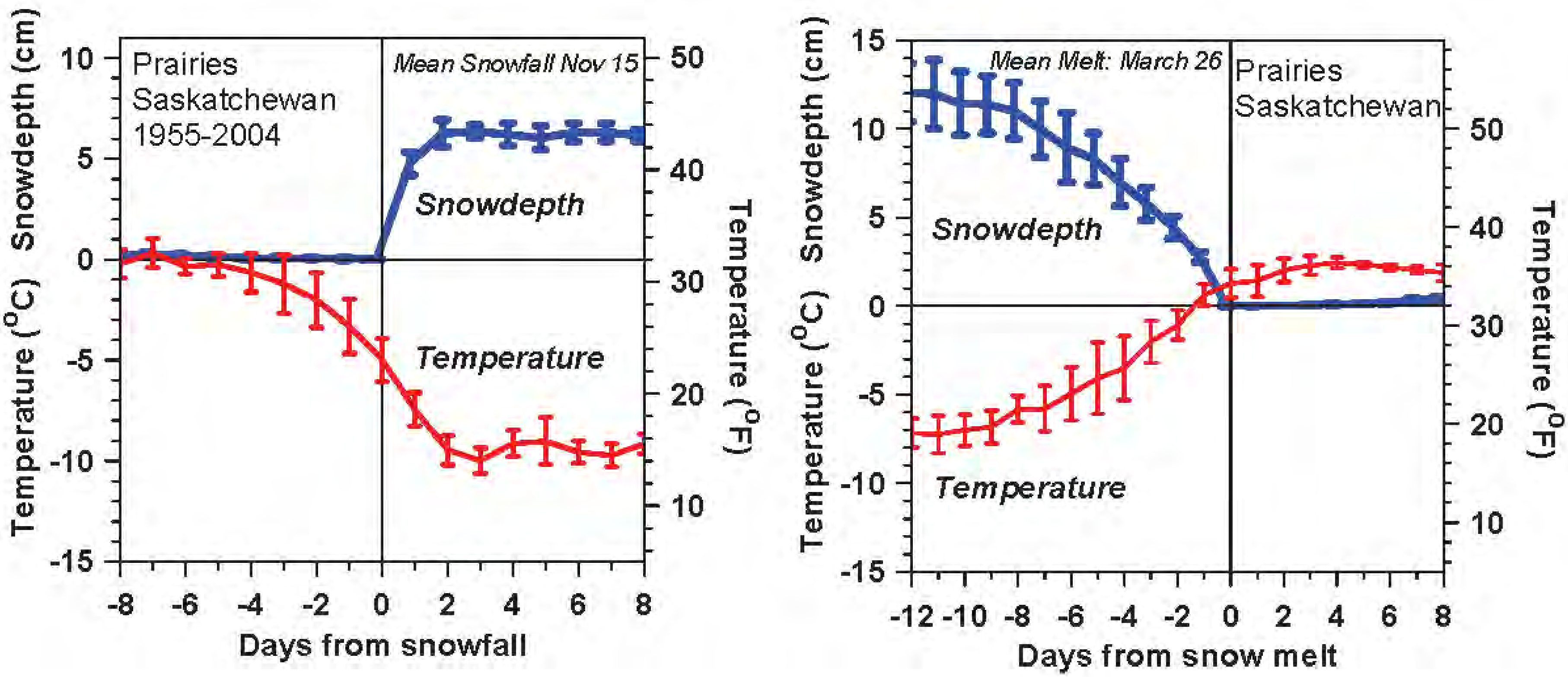
June 2012 snow cover minimum





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

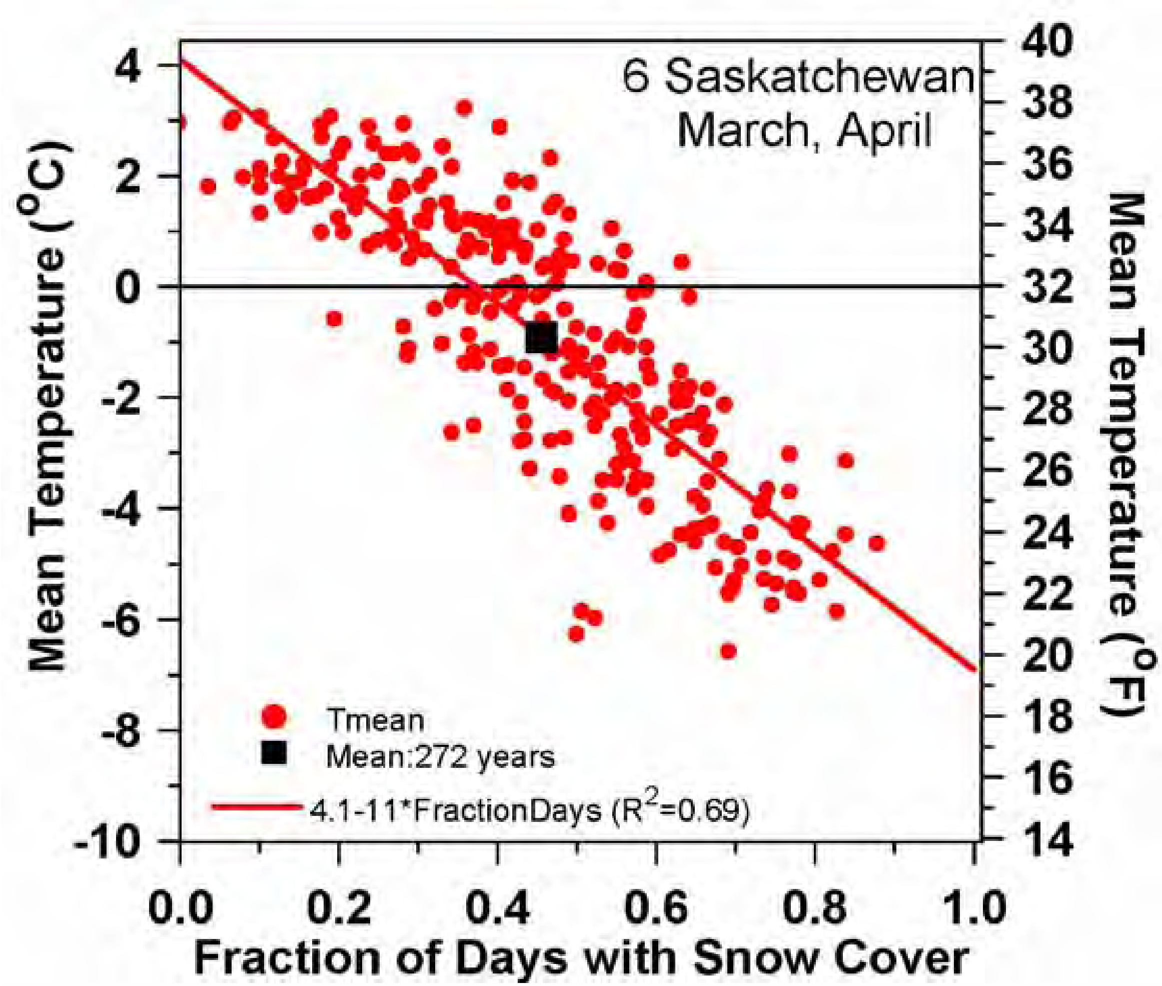
Snowfall and Snowmelt



- **Temperature falls 18F (10C) with first snowfall**
- **Similar change with snowmelt**
- ***Snow reflects sunlight; reduces evaporation and water vapor greenhouse – changes 'local climate'***

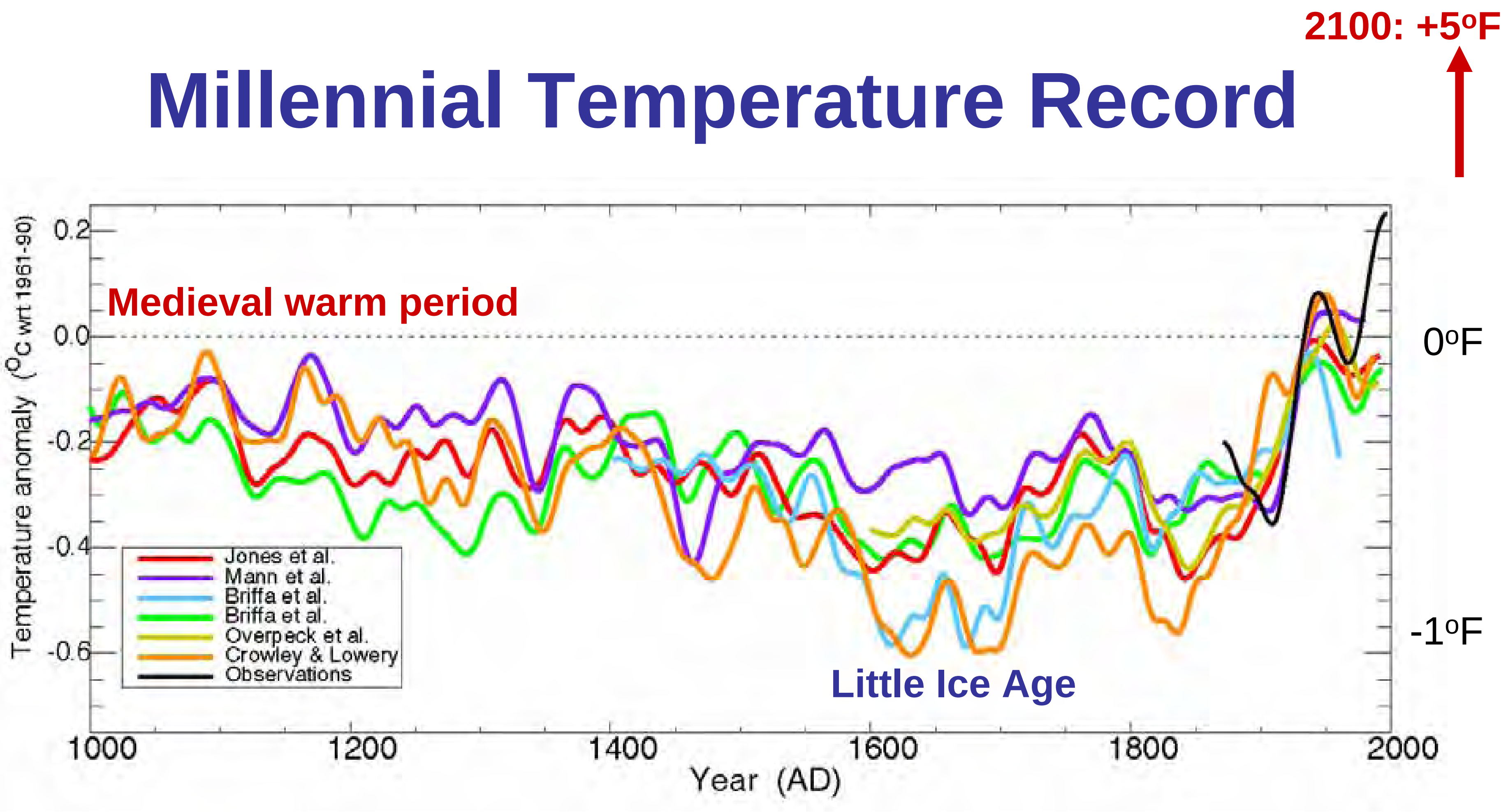
Betts et al. 2013

Impact of snow on climate



- **100% snow-cover cools mean climate about 11°C (20°F) from snow-free condition**

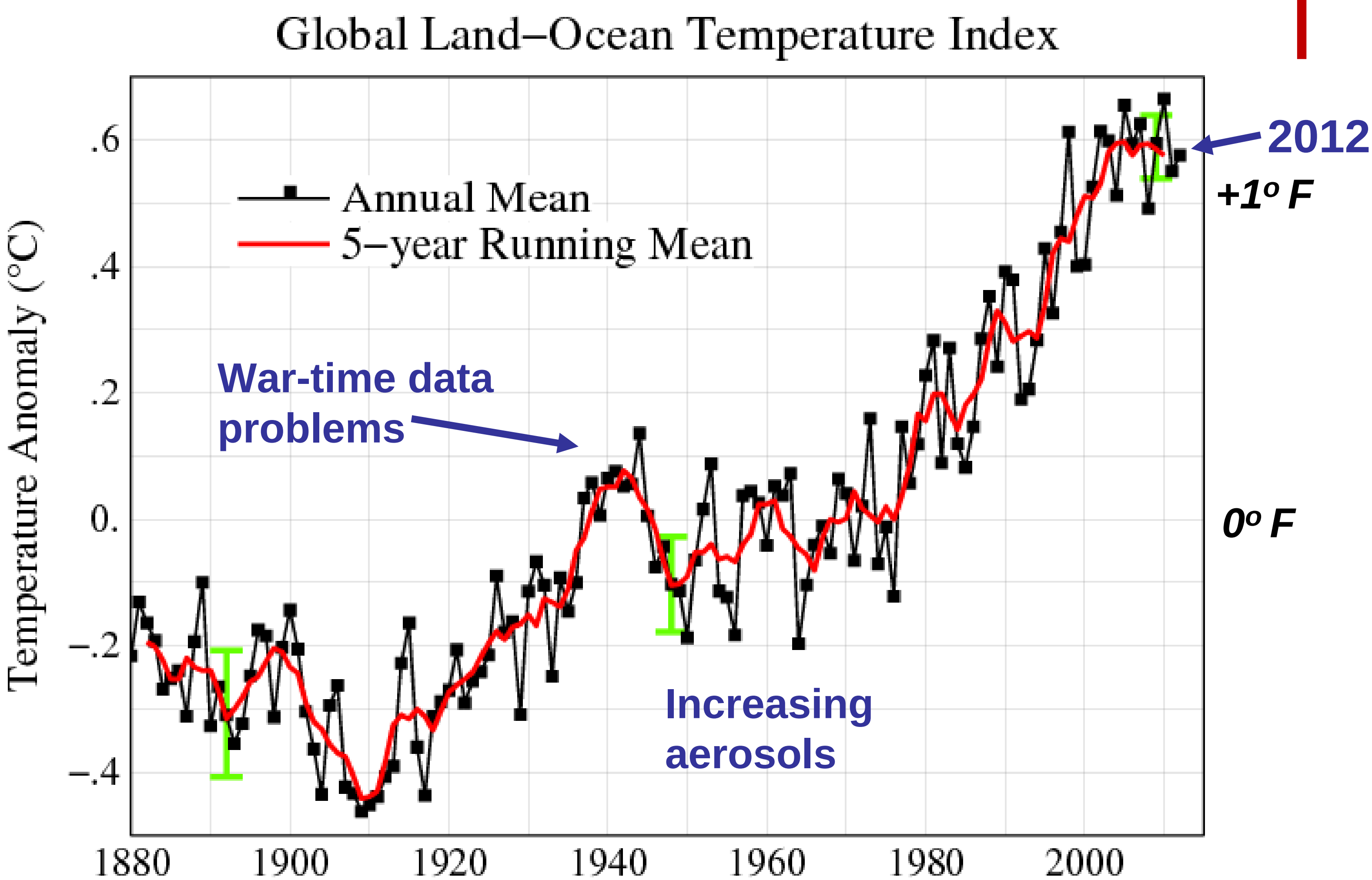
Millennial Temperature Record



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

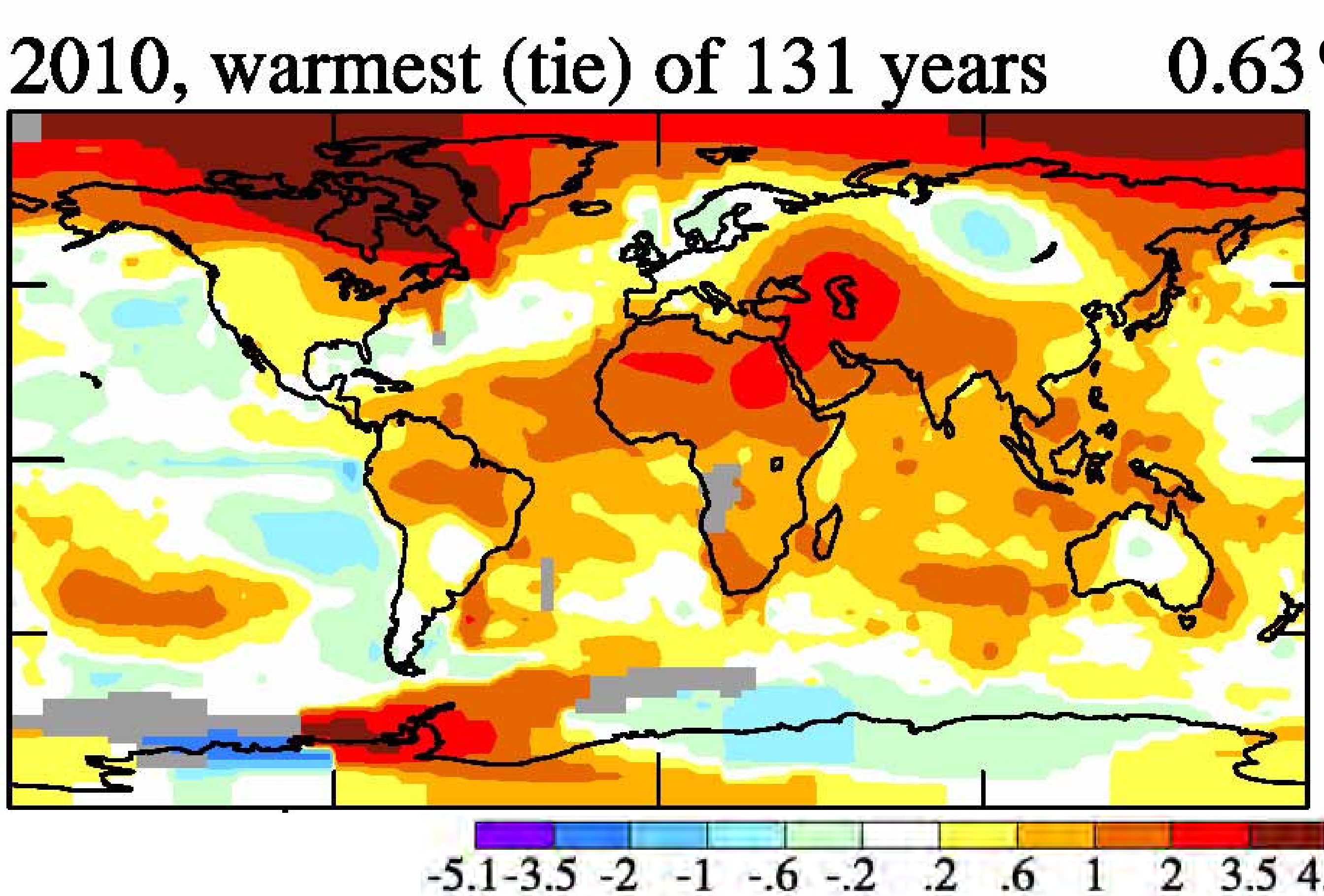
Global Temperature Rise 1880 – Present

2100: +5ºF



NASA-GISS, 2011

Global Picture 2010

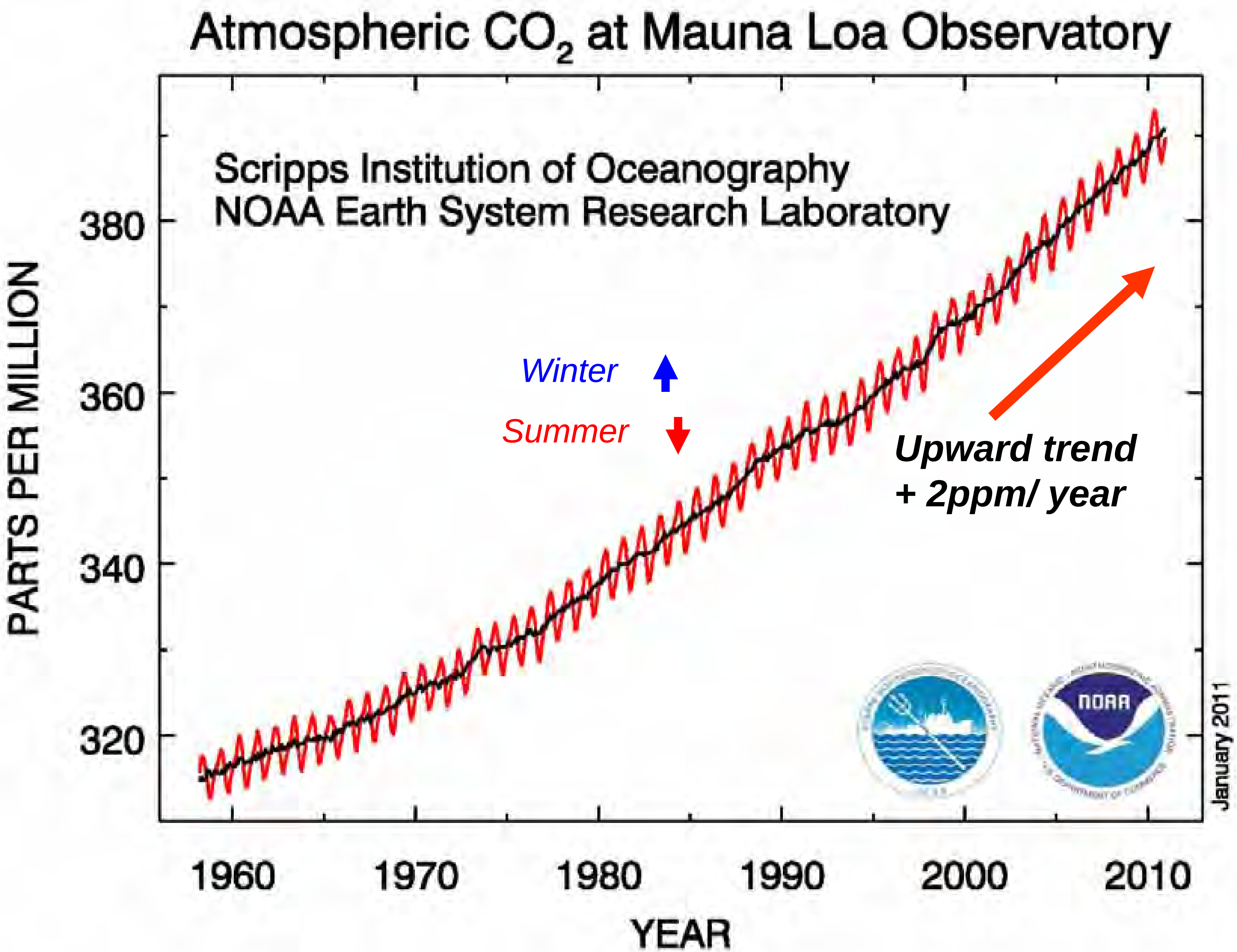


(1.2°F)

ºC

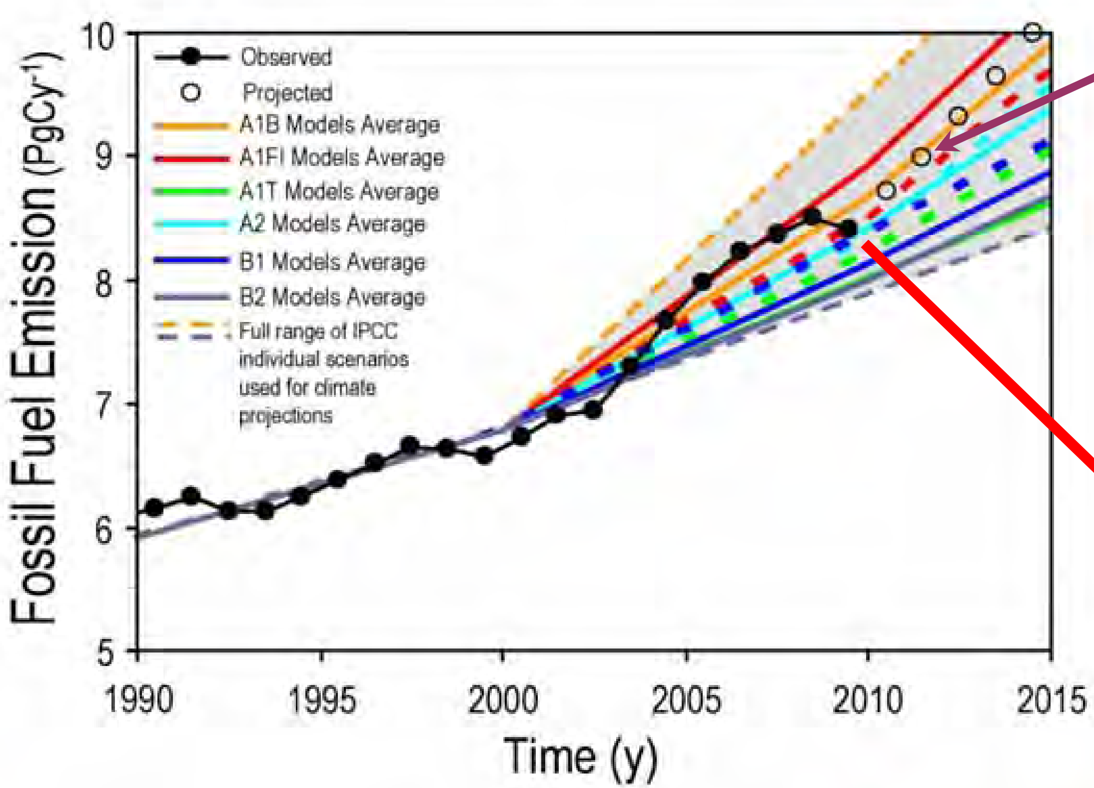
- **Record summer temps**
  - **Russia (100°F) Moscow fires**
  - **Pakistan (128°F) Extreme monsoon floods**

Carbon Dioxide Is Increasing



2009 Was “Good” for the Earth

Fossil Fuel Emissions: Actual vs. IPCC Scenarios



Back on growth: 2010, 2011

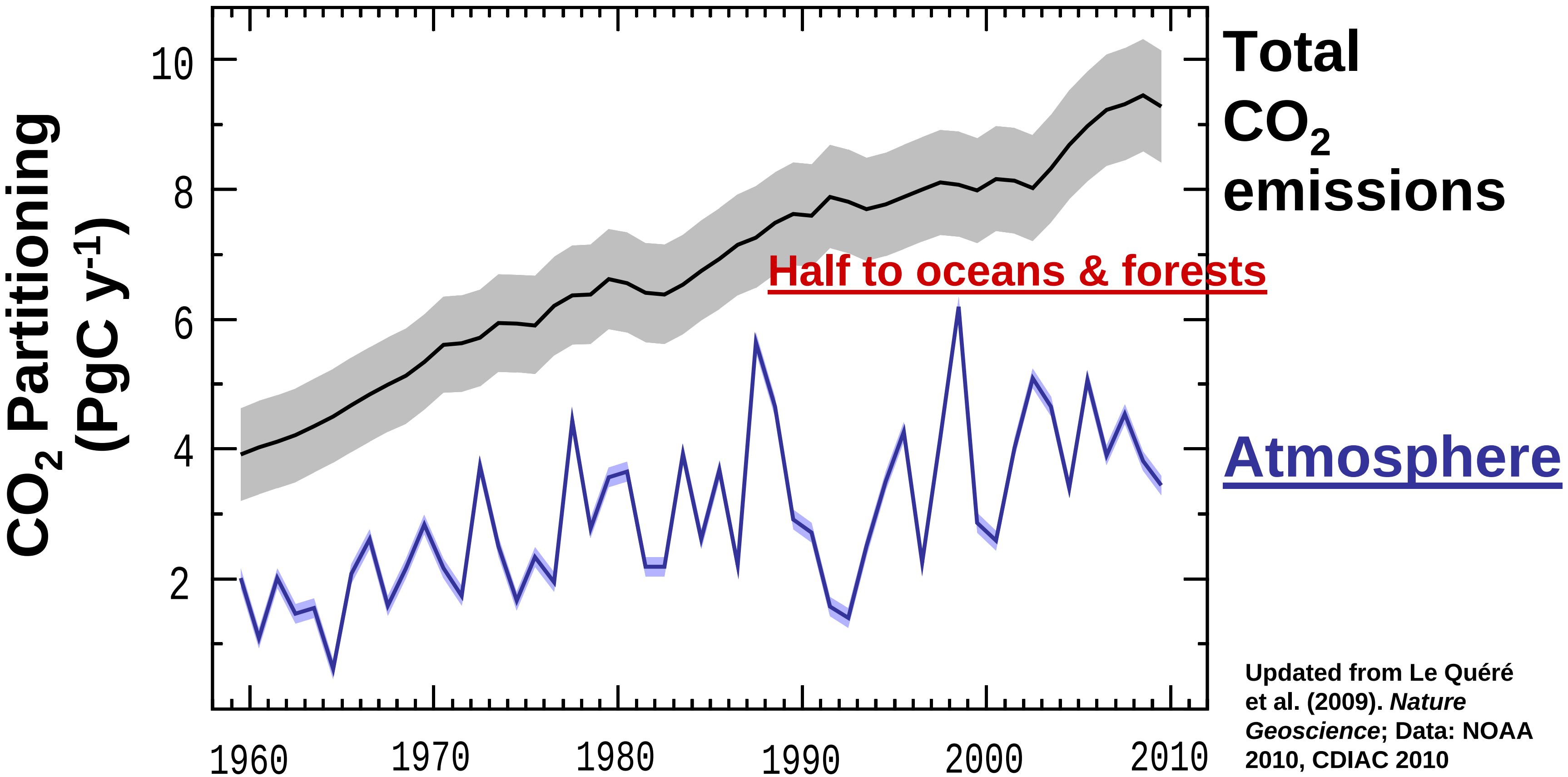
Emission Scenarios

- 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



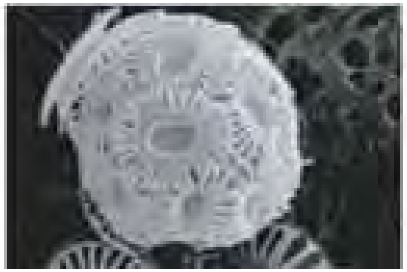
Updated from Le Quéré et al. (2009). *Nature Geoscience*; Data: NOAA 2010, CDIAC 2010

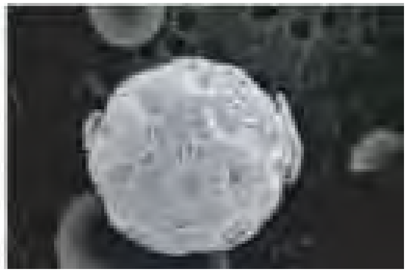
It takes at least a century to remove CO_2 from the atmosphere, and many centuries to remove it from oceans

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 (<u>30^{o}C</u>)**
- **These are "Greenhouse gases"- water vapor, carbon dioxide, ozone, methane, nitrous oxide (H_2O, CO_2, O_3, CH_4, N_2O, CFCs..)**
- **CO_2 is rising fast: <u>by itself only a small effect</u>**

But as CO_2 Increases, Strong Water Cycle Feedbacks

- **Earth warms, and evaporation and water vapor in the air increases and <u>this triples the warming</u>**
- **As Earth warms, snow and ice decrease, so less sunlight is reflected, so winters and the Arctic are <u>warming faster</u>**
- **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: Sept. 26, 2013)

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)

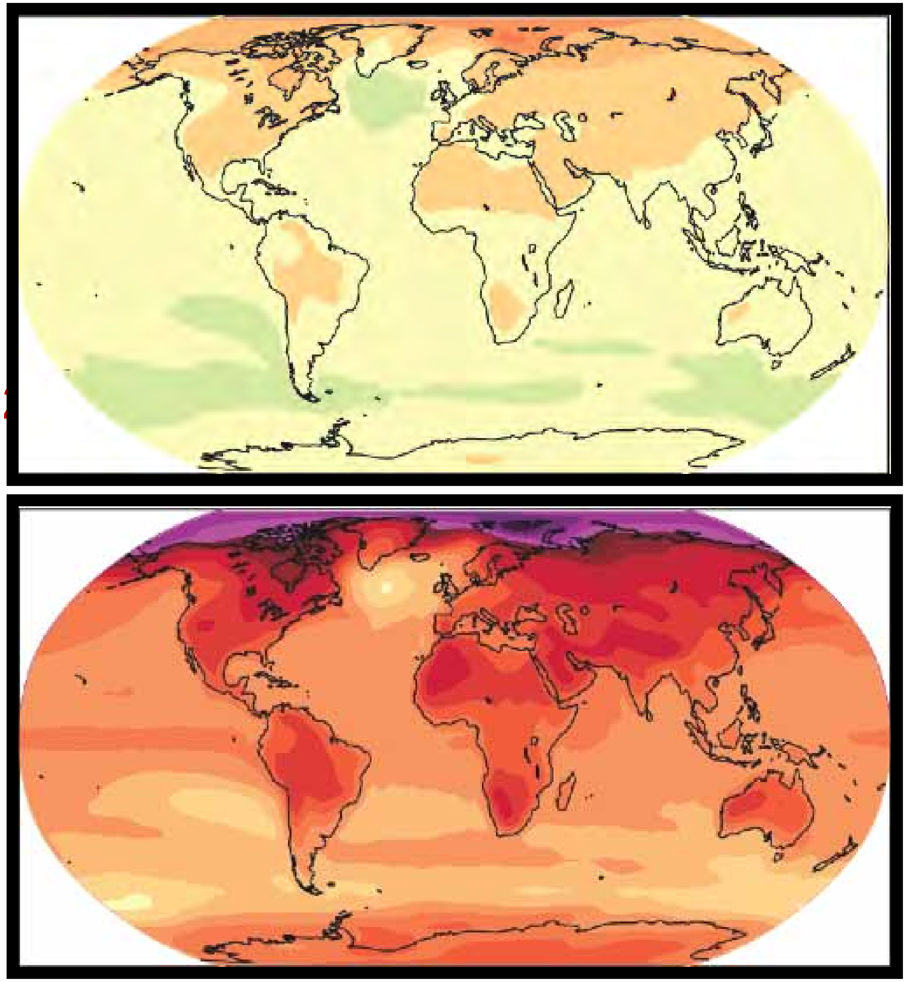
(www.ipcc.ch)

Predicted Change in Temperature

2020-2029 and 2090-2099, relative to 1980-1999 (^{o}C)

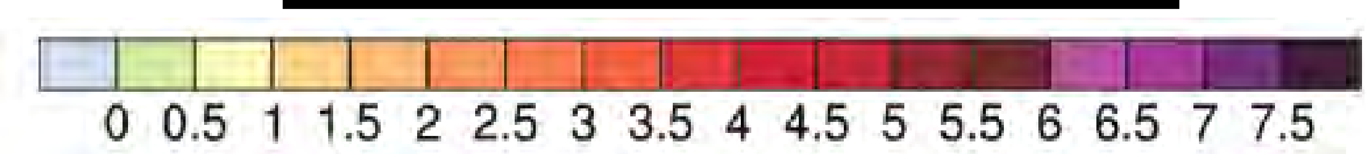
“Committed”

(We did nothing for the last 20 years)



Still up to us!

(We could halve this if we act now)



[^{o}C]

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

What Is Happening to Vermont?

- **Local climate change indicators past 40/50 years**

- **Warming twice as fast in winter than summer**
- **Winter severity decreasing even faster**
- **Lakes frozen less by 7 days / decade**
- **Growing season longer by 3.7 days / decade**
- **Spring coming earlier by 2-3 days / decade**

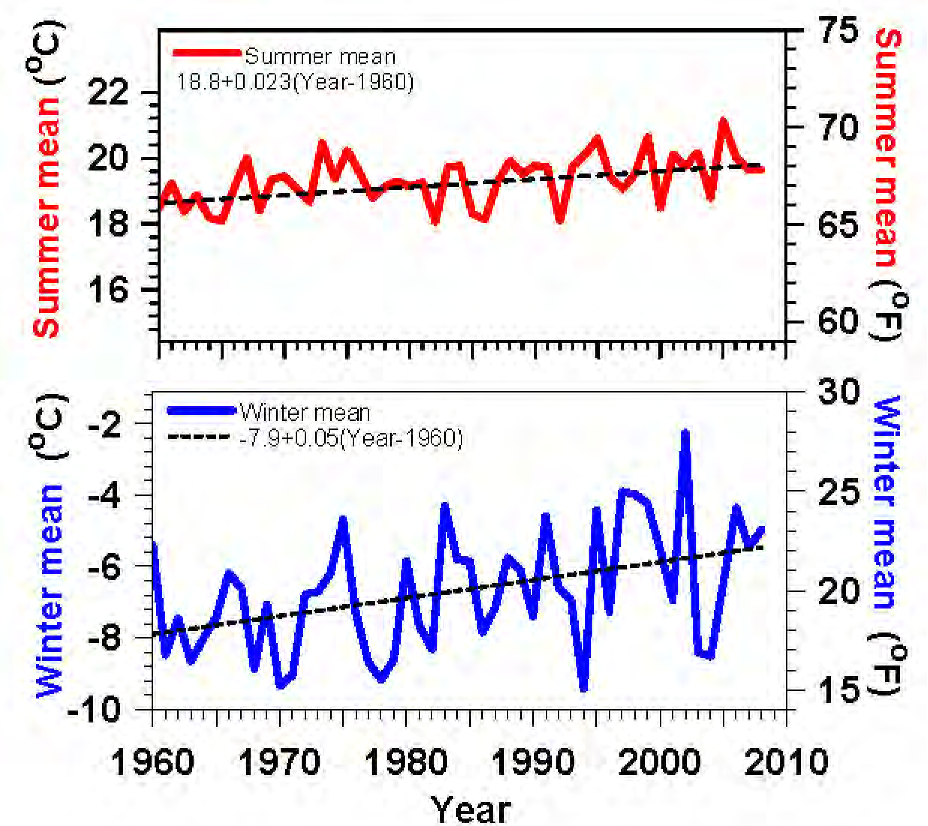
- **Extremes increasing**
- ***Evaporation increases with T***
- ***More ‘quasi-stationary weather patterns’***

Vermont Temperature Trends
1961-2008

- **Summer +0.4°F / decade**

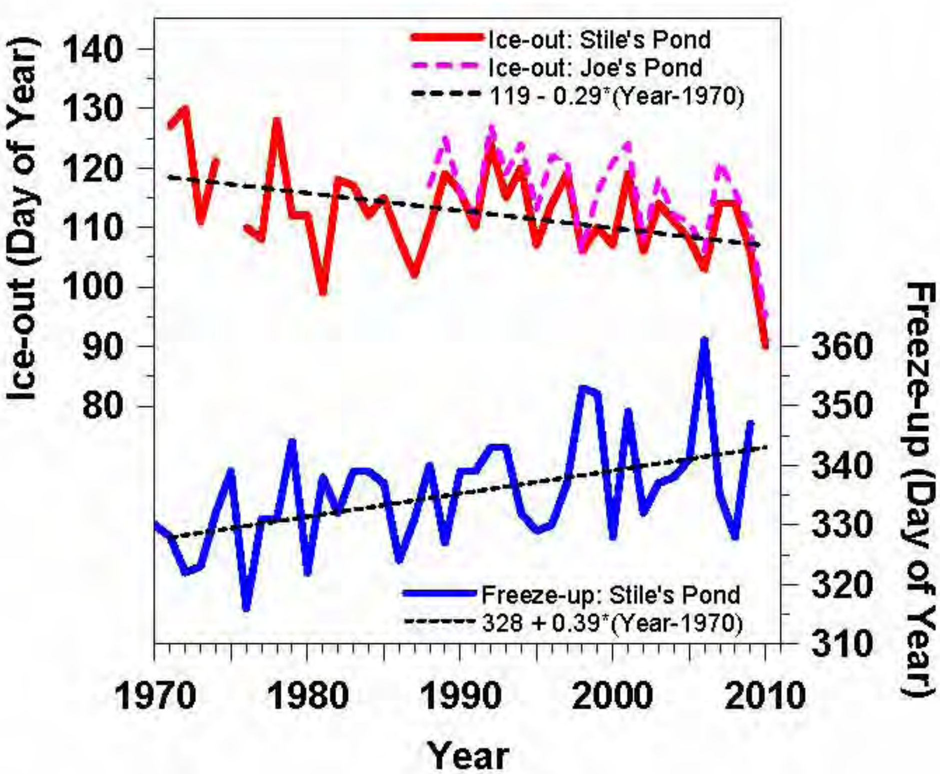
- **Winter +0.9°F / decade**
- **Larger variability, larger trend**

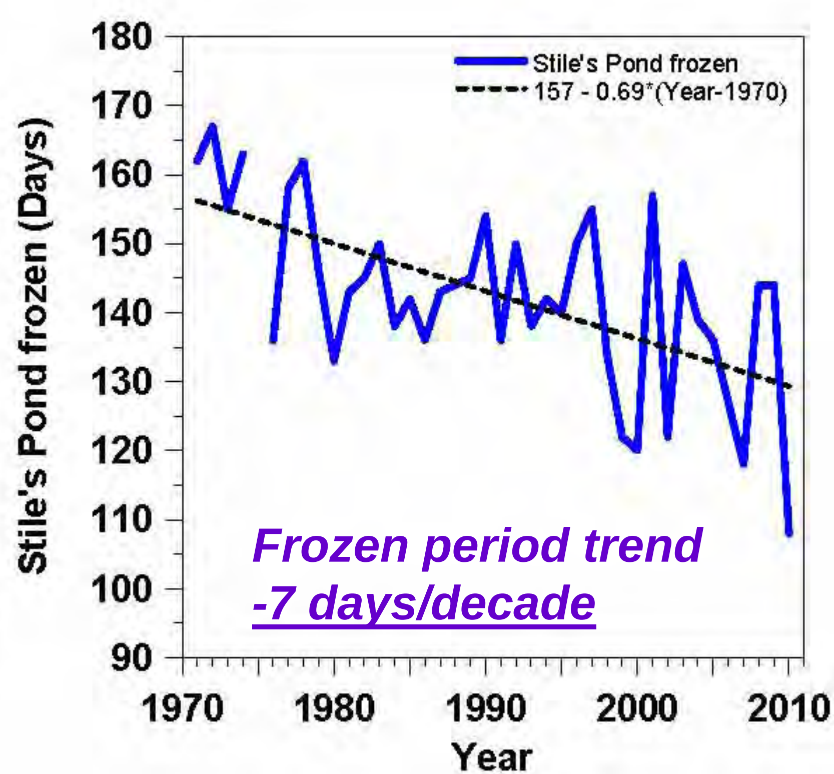
- ***Less snow (and increased water vapor) drive larger winter warming***



Lake Freeze-up & Ice-out Changing

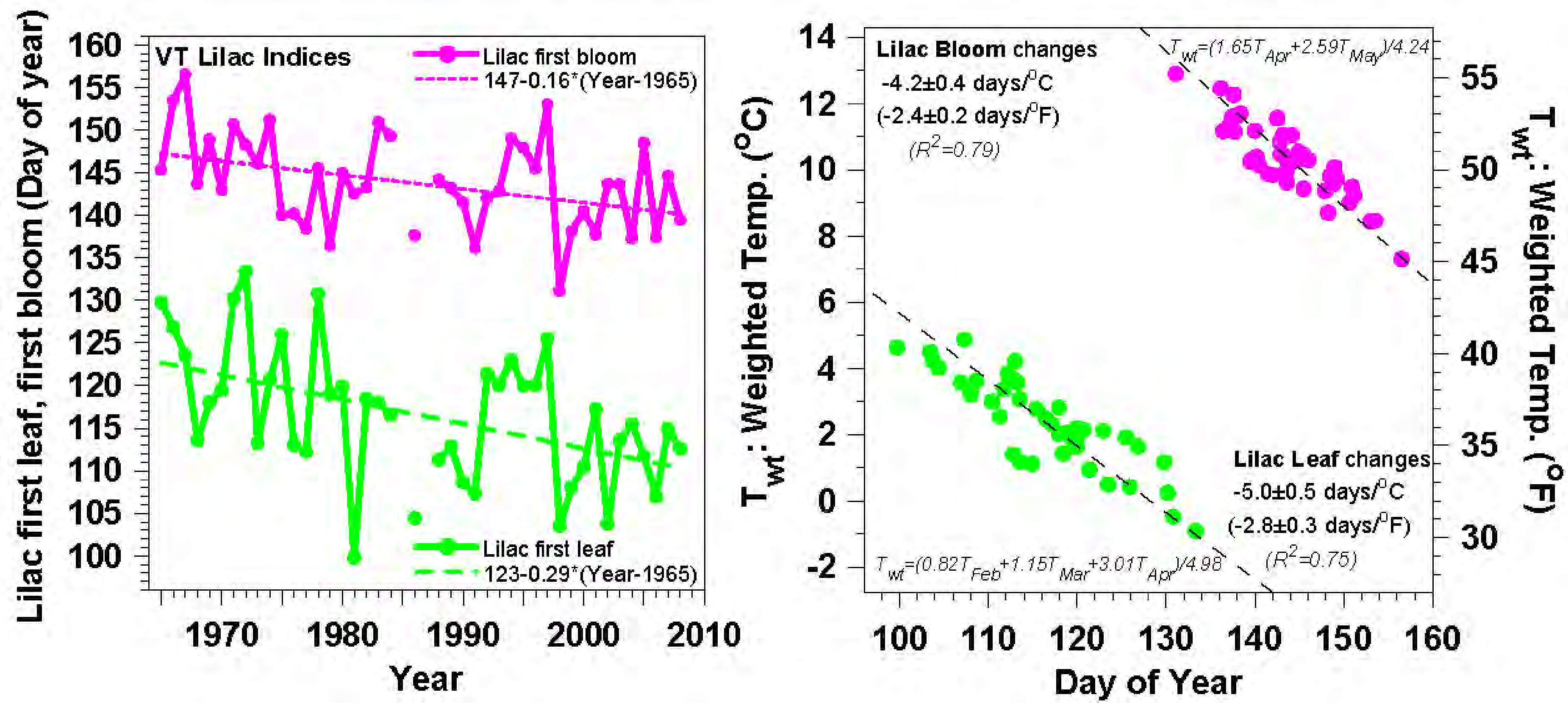
Frozen Period Shrinking Fast





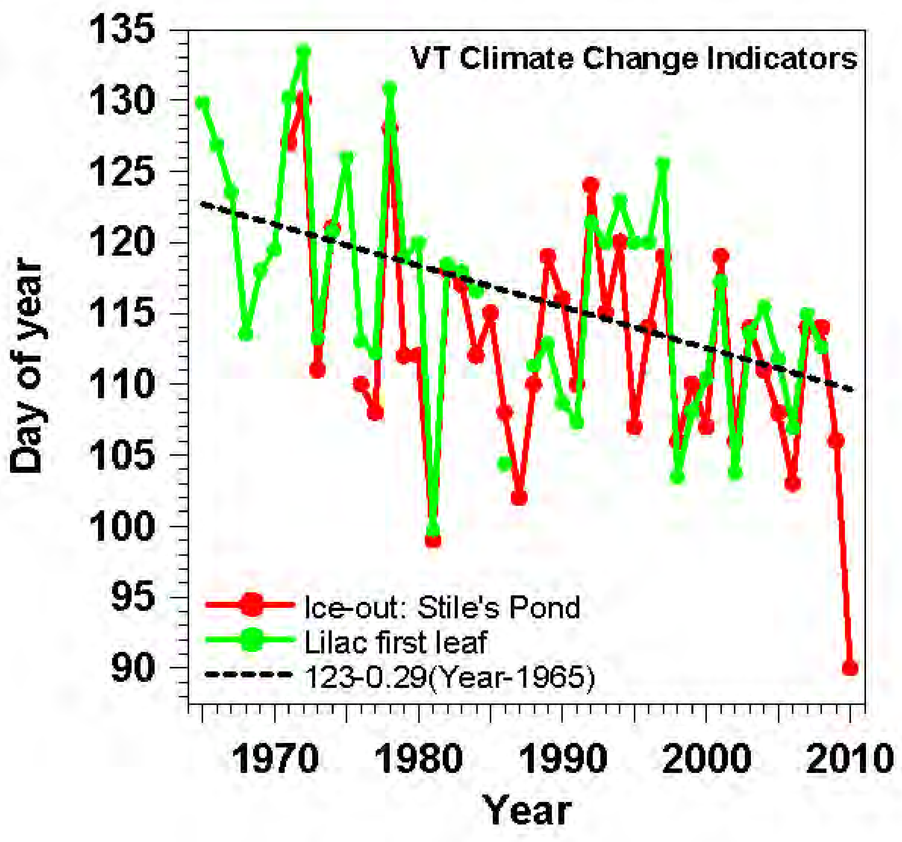
- Ice-out earlier by 3 days / decade
- Freeze-up later by 4 days / decade

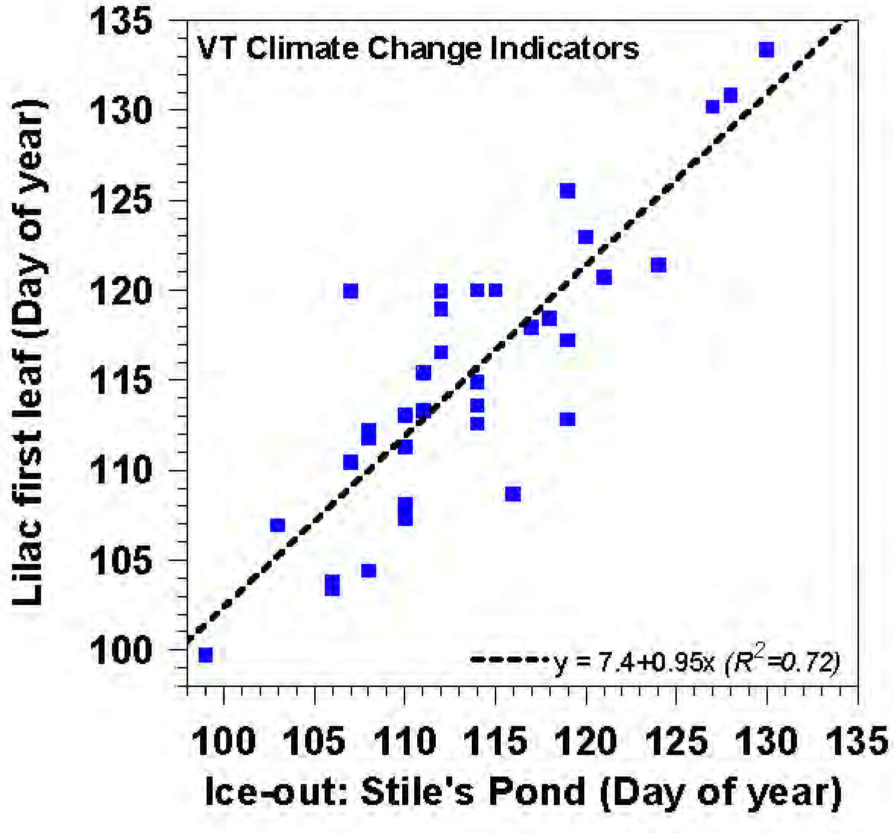
Lilac Leaf and Bloom in Spring



- **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)**

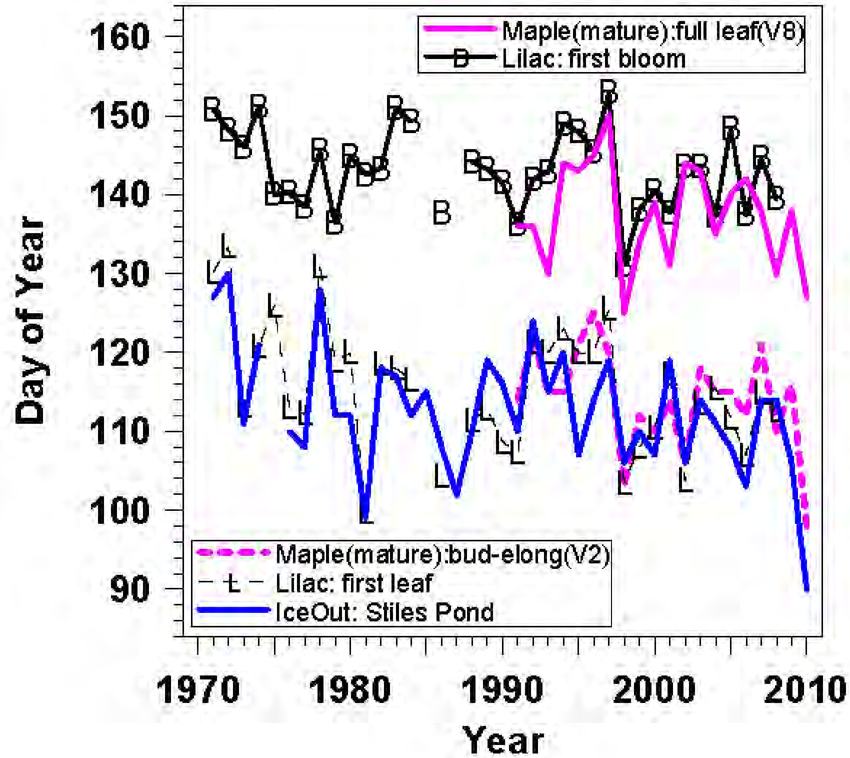
Lilac Leaf-out and Ice-out Coupled

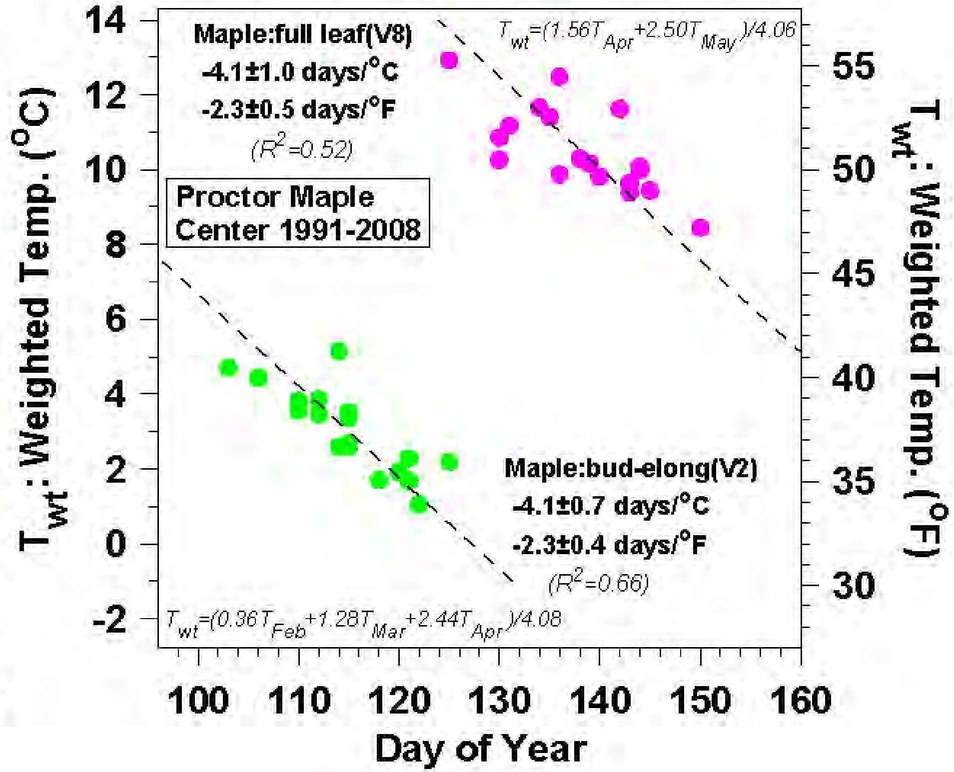




- **Lilac leaf and lake ice-out both depend on Feb. Mar. and April temperatures**
- **Trends indicate earlier spring**

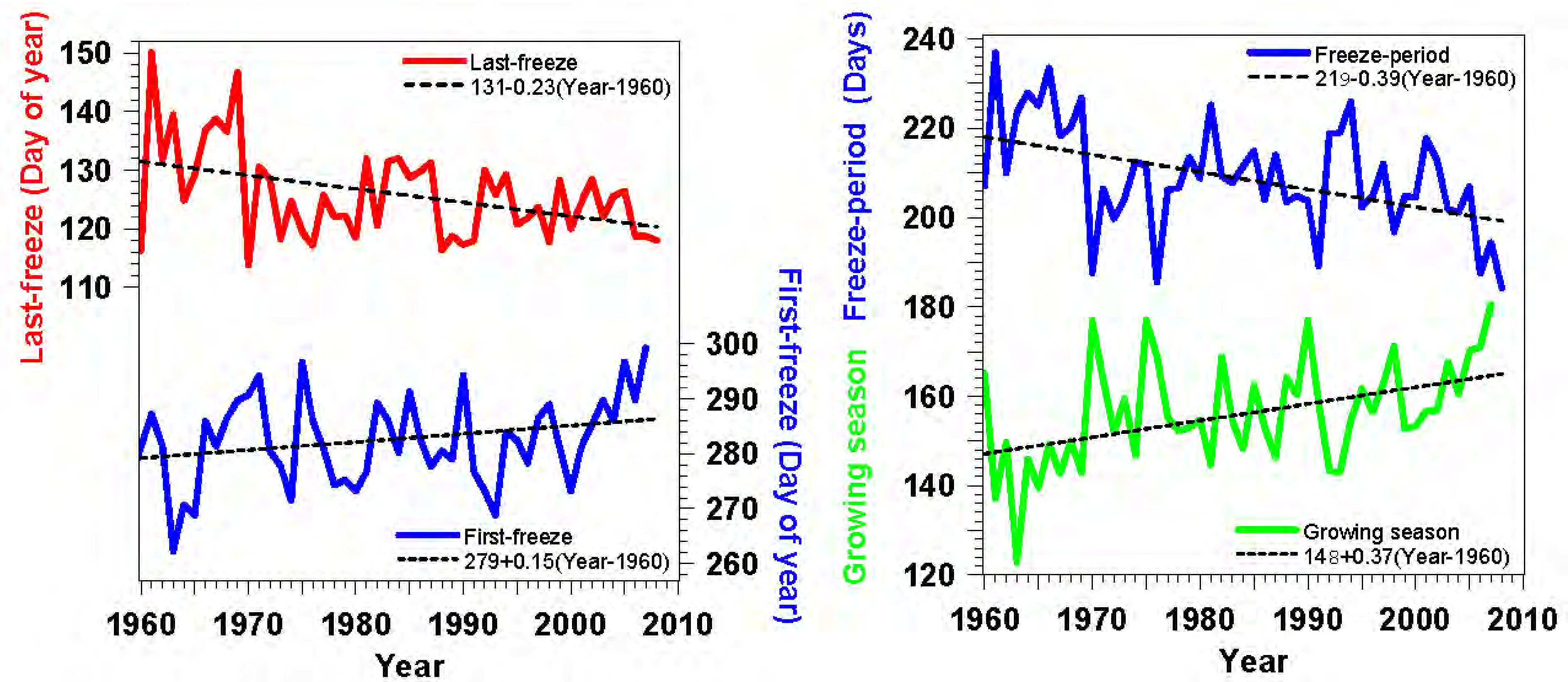
Maples and Lilacs in spring





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

First and Last Frosts Changing



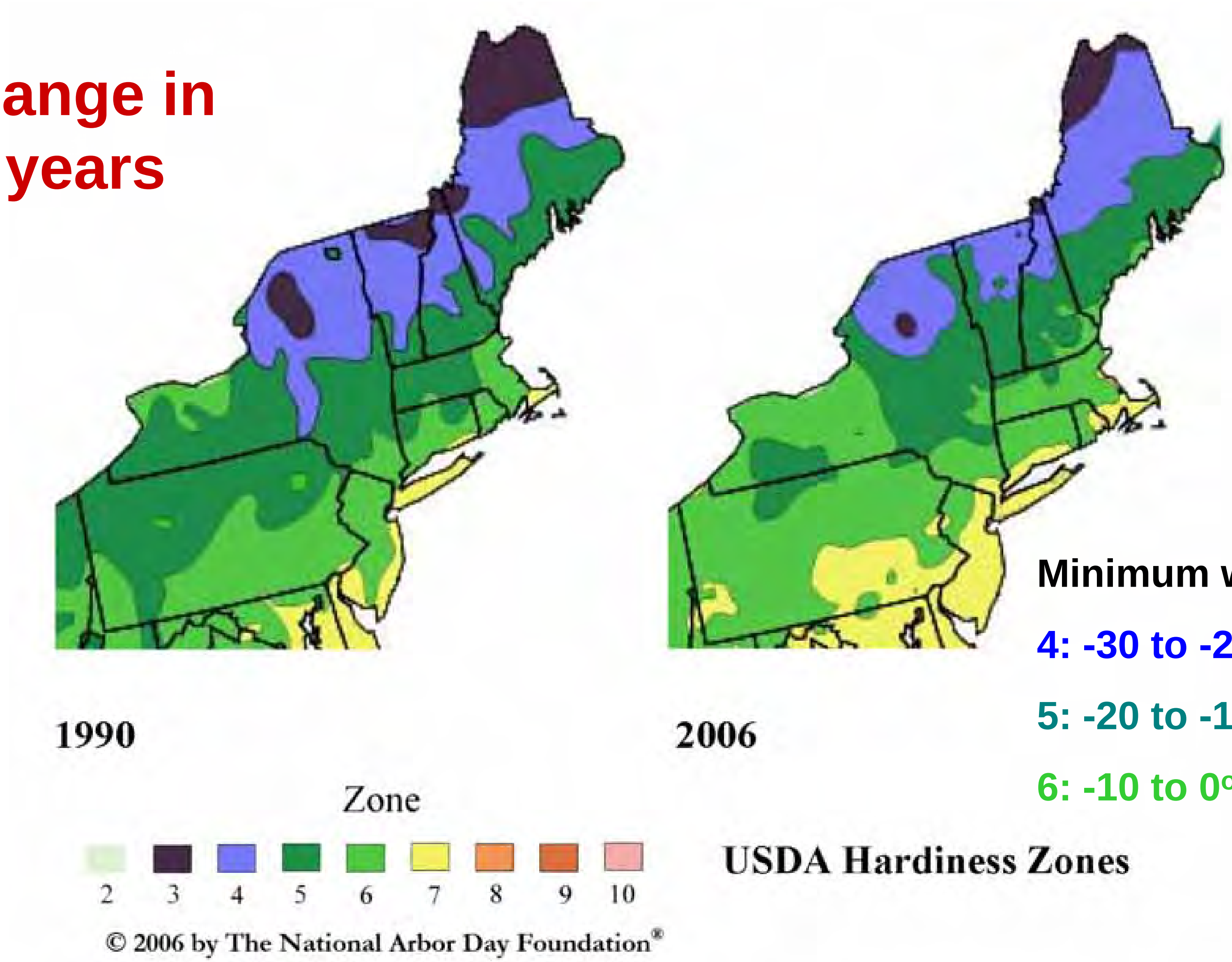
- **Growing season for frost-sensitive plants increasing 3.7 days / decade**
- **A help for growing "<u>local food</u>"**

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***

Winter Hardiness Zones - Northeast

Change in 16 years



Minimum winter T

4: -30 to -20°F

5: -20 to -10°F

6: -10 to 0°F

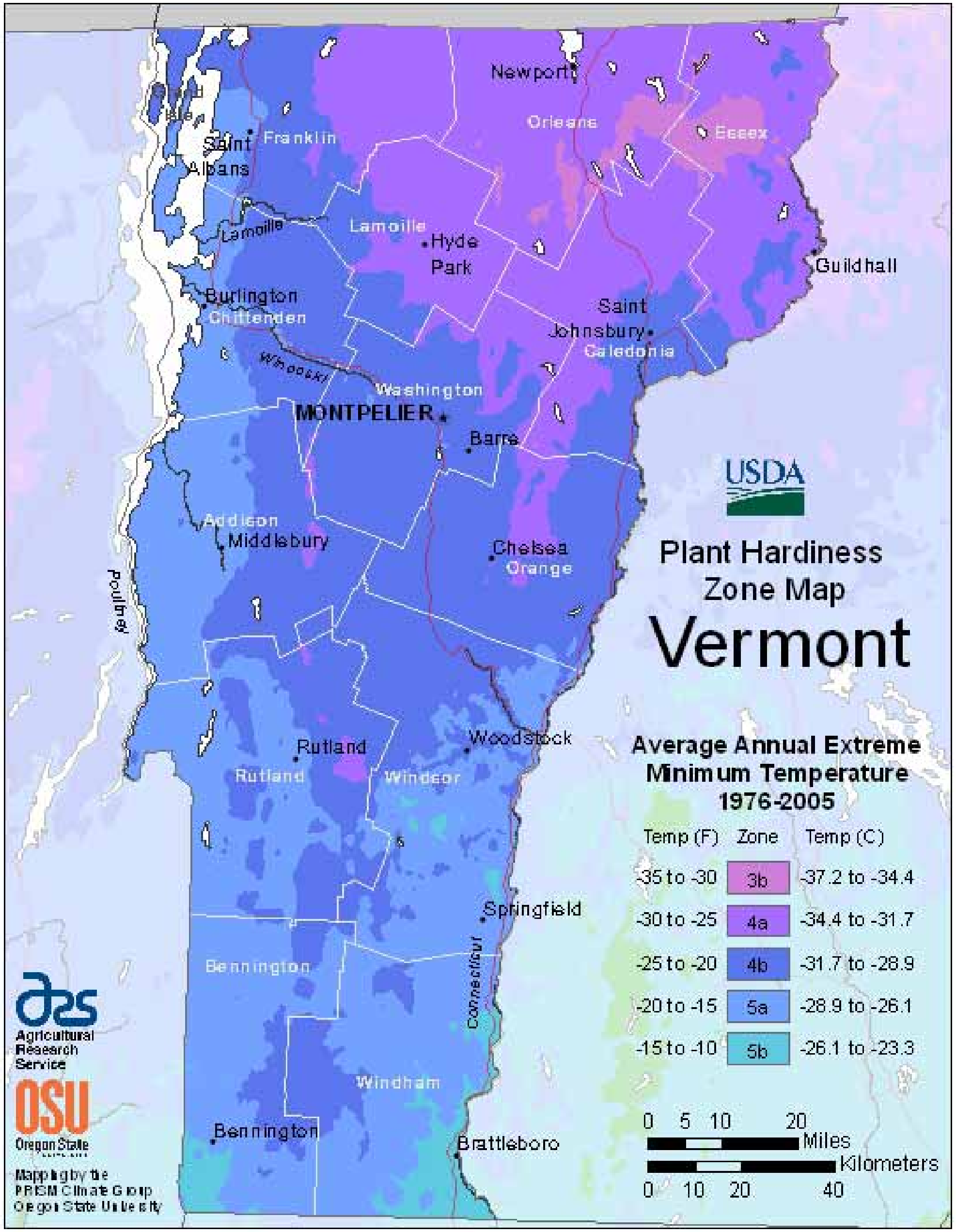
Detailed Map
(most recent)

- **VT Hardiness Zone Map 1976-2005**
  - **<u>mean 1990</u>**
  - **South now zone 6**

- **Half-zone in 16 yrs = 3.1ºF/ decade**
  - ***<u>triple the rise-rate of winter mean T</u>***
  - ***3 zones/century***

- ***<u>http://planthardiness.ars.usda.gov/PHZMWeb/</u>***

(Krakauer, Adv. Meteor. 2012)



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

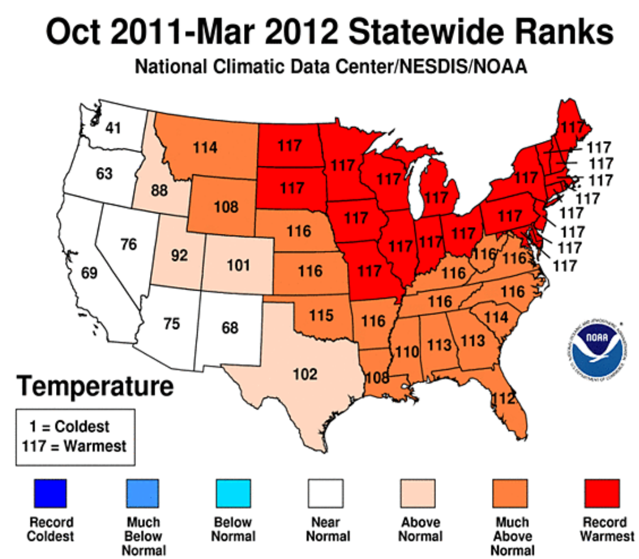
- Avocado
  - Didn't survive frost
  - 2100 survive in CT
  - Our forests?

January 2, 2012

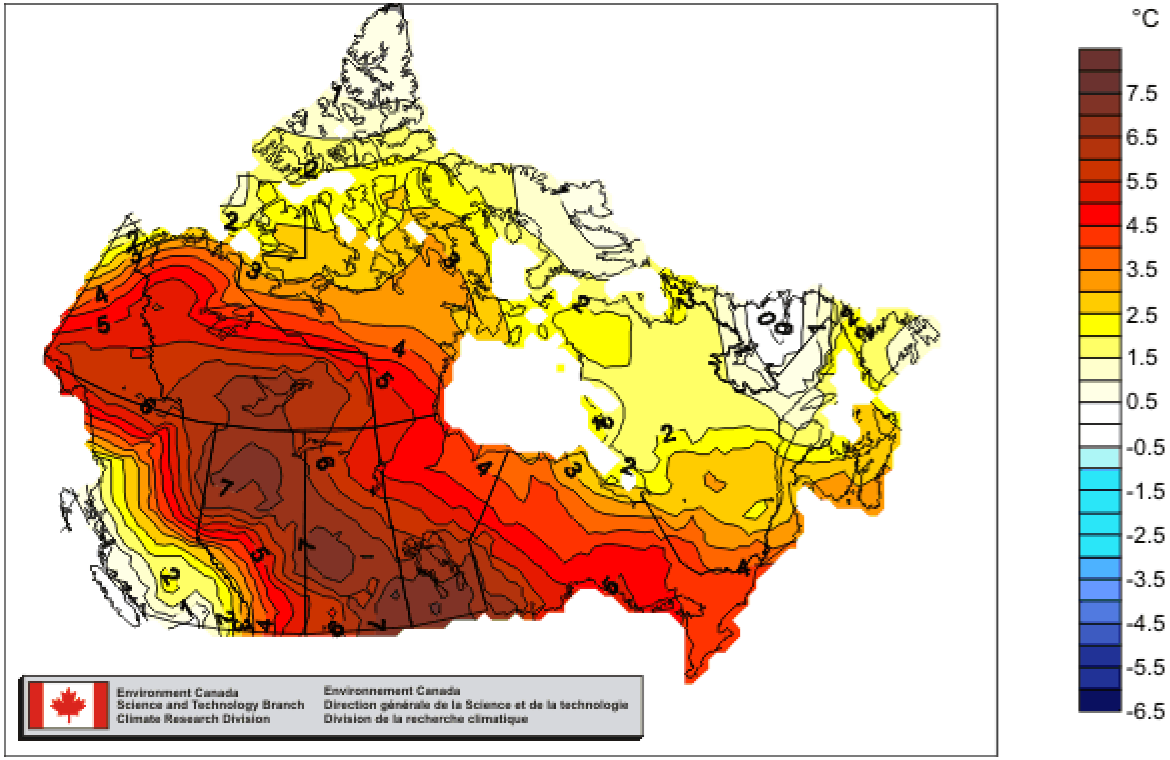
March 11, 2012

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



- **Winter 2011-12: 3.6ºC (6.5ºF) 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

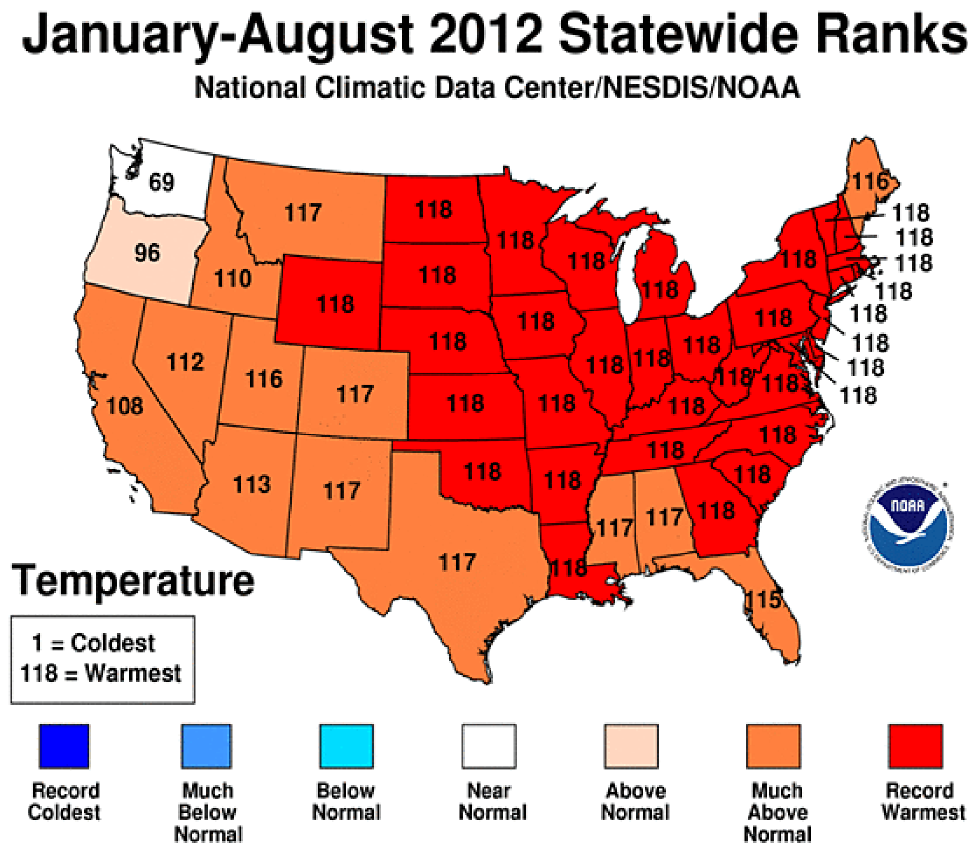
3/22/12

Pittsford Vermont

3/24/12

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

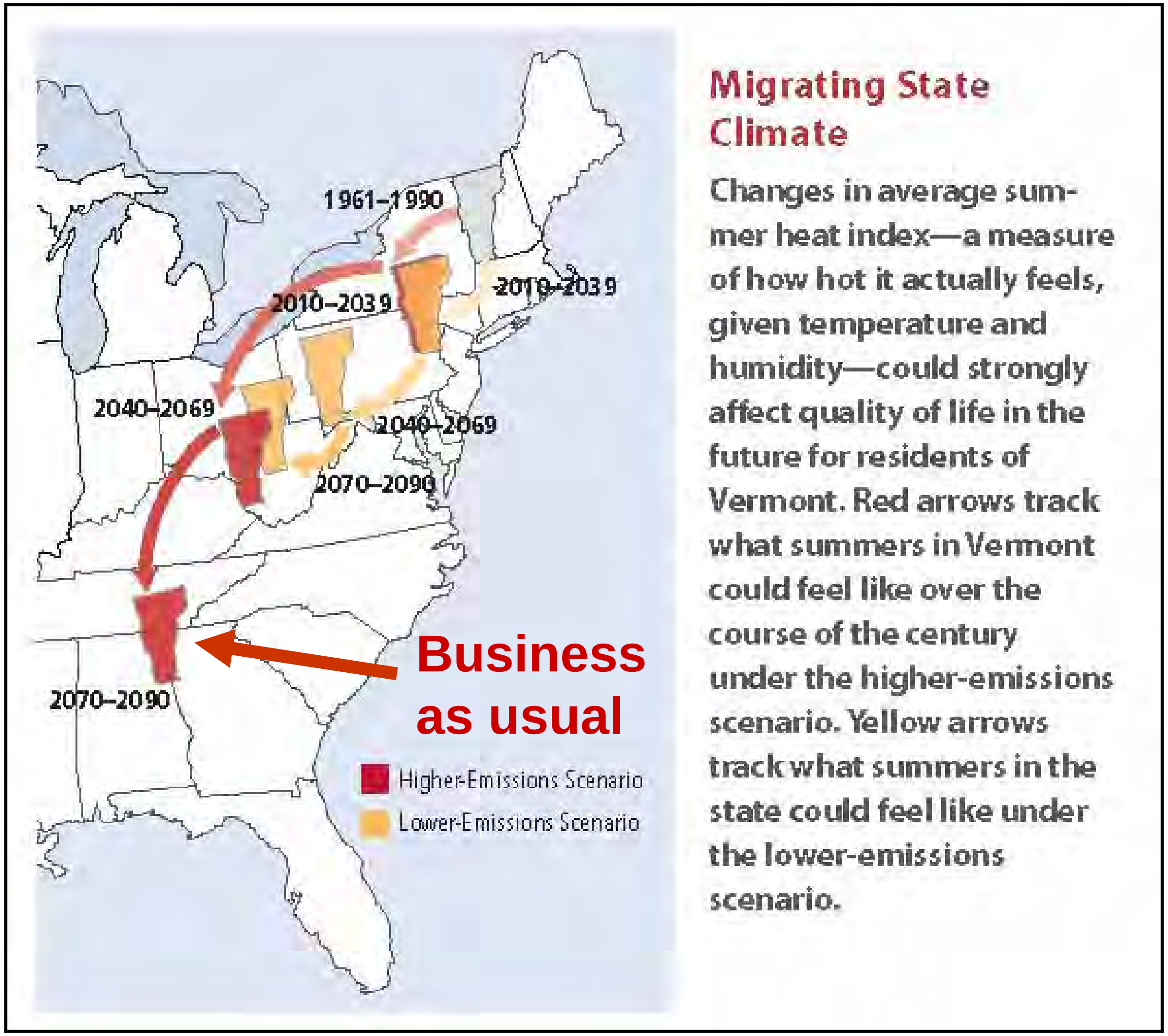


http://www.ncdc.noaa.gov/temp-and-precip/maps.php

Vermont's Future with High and Low GHG Emissions

What about skiing?

What about tropics?



NECIA, 2007

Extreme Weather (precip.)

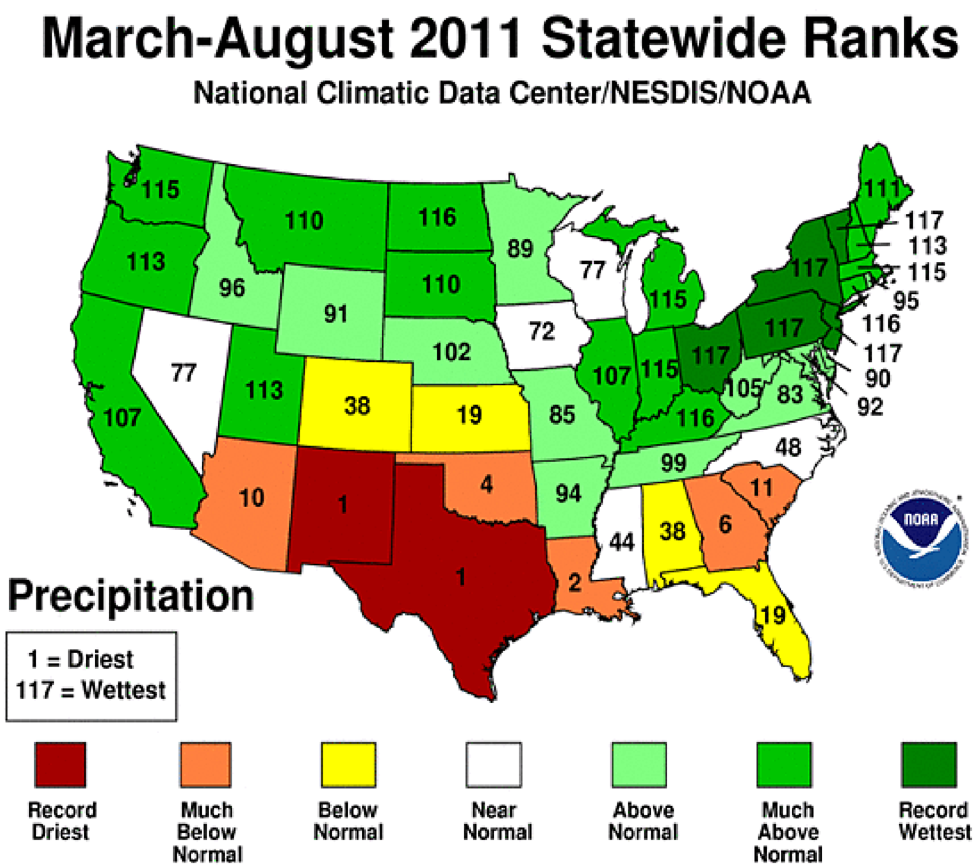
- **Precip. is condensation of atmospheric water vapor - larger latent heat release drives storms**
- ***Saturation vapor pressure at cloud-base increases steeply with temperature (4%/^{o}F)***
- **<u>Quasi-stationary </u>large-scale flow means longer rain events in low-pressure convergent regions, and longer droughts in high-pressure divergent regions**
- ***As climate changes, <u>quasi-stationary</u> large-scale modes appear to be more frequent***
  - *Cause may be Arctic warming: needs more study*

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

2011 Floods: VT and NY

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

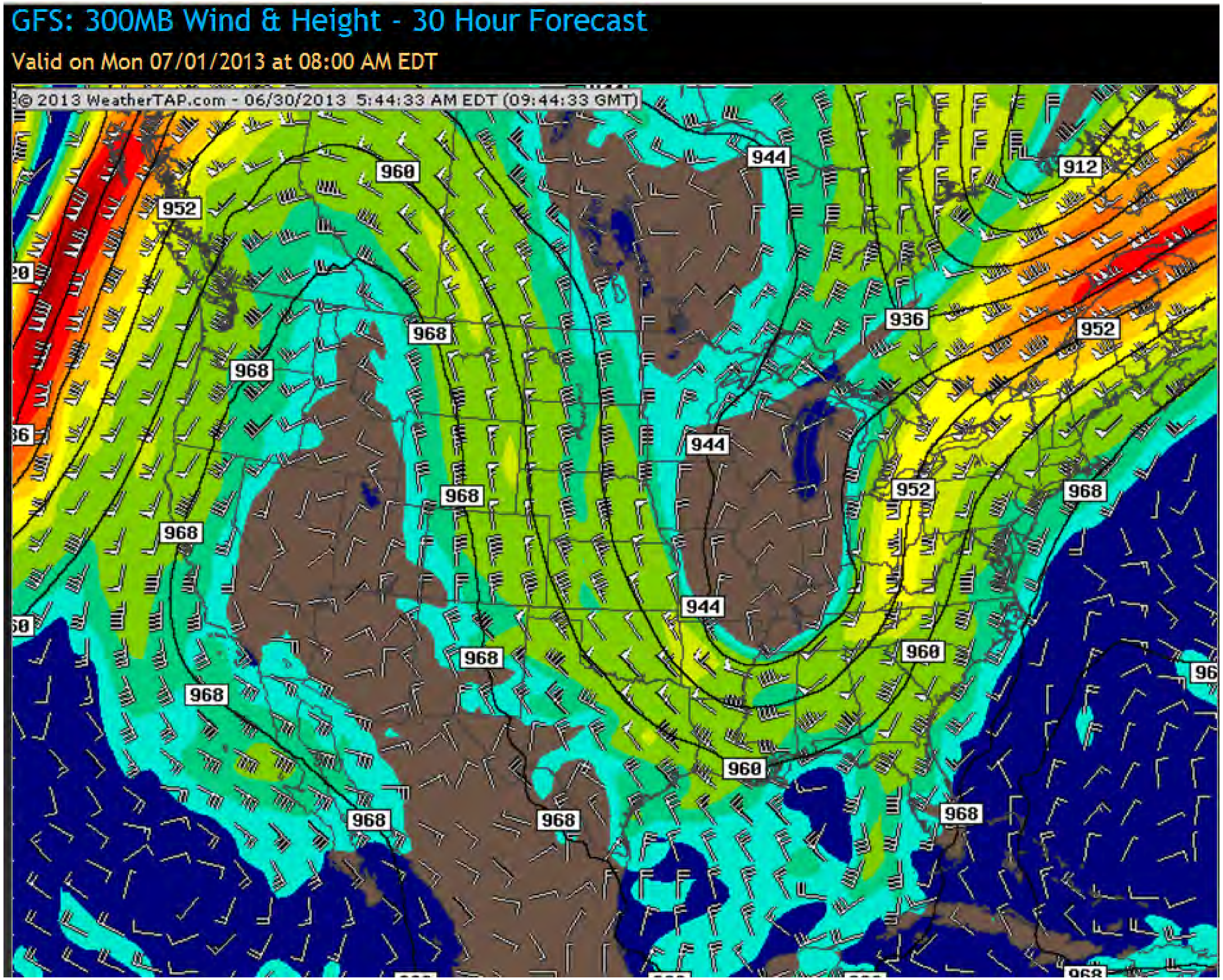


March-August, 2011

- 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

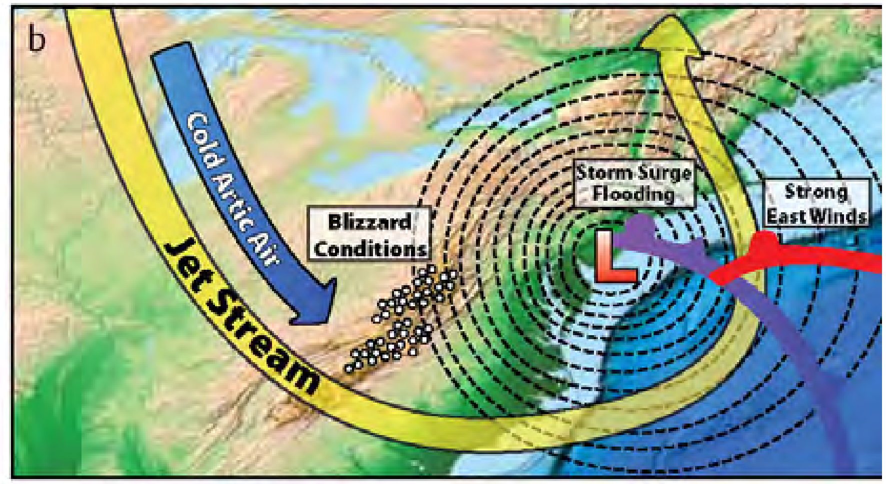


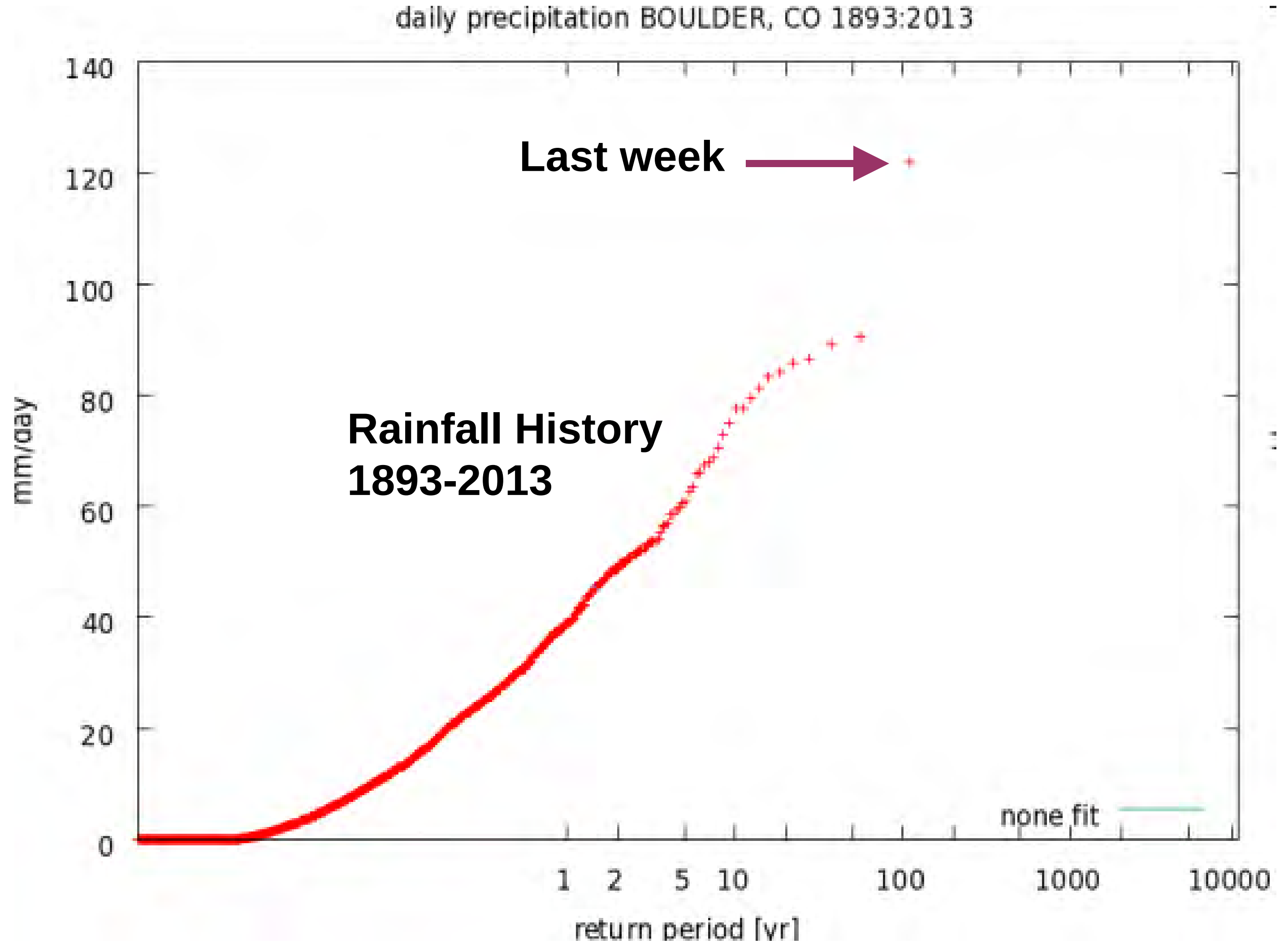
Figure 1. (a) Atmospheric conditions during Hurricane Sandy's transit along the eastern seaboard of the United States, including the invasion of cold Arctic air into the middle latitudes of North America and the high-pressure blocking pattern in the northwest Atlantic. (b) After the convergence of tropical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



Outline

- Science of climate change
  - Global scale: actual and future
  - What is happening to Vermont
- The transition we face
  - Managing the earth system
  - What are the issues and challenges?
- Discussion
  - General
  - Discuss chapters of VCA

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 costs***

Can We Stop "Dangerous Climate Change"?

(UNFCCC 1992)

- **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**

Managing Our Relation to the Earth System

- **Our technology and our <u>waste-streams</u> are having large local and global impacts on the natural world and must be carefully managed — *because we are dependent on the natural ecosystems***

- **We need new ‘rules’ because**
  - **Our numbers and industrial output are so large**
  - **Maximizing consumption and profit have led to present predicament**

Guidelines to Minimize Impacts

- *Planning a trajectory for sustainability*
- **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**

Surely Technology Can Save Us?

- Critical for transition but real issue is

- Our world of technology is having a global impact on the natural world, which is alive, complex and beyond our ‘control’
- So technology must be carefully managed — particularly our waste-streams — because we are dependent on the natural world
  - But this is challenging with our ideology

Technology can be Useful

Trucks or Lightweight vehicles?

30 mph Danish electric tricycle:

with 150 mile range

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**

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)?

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

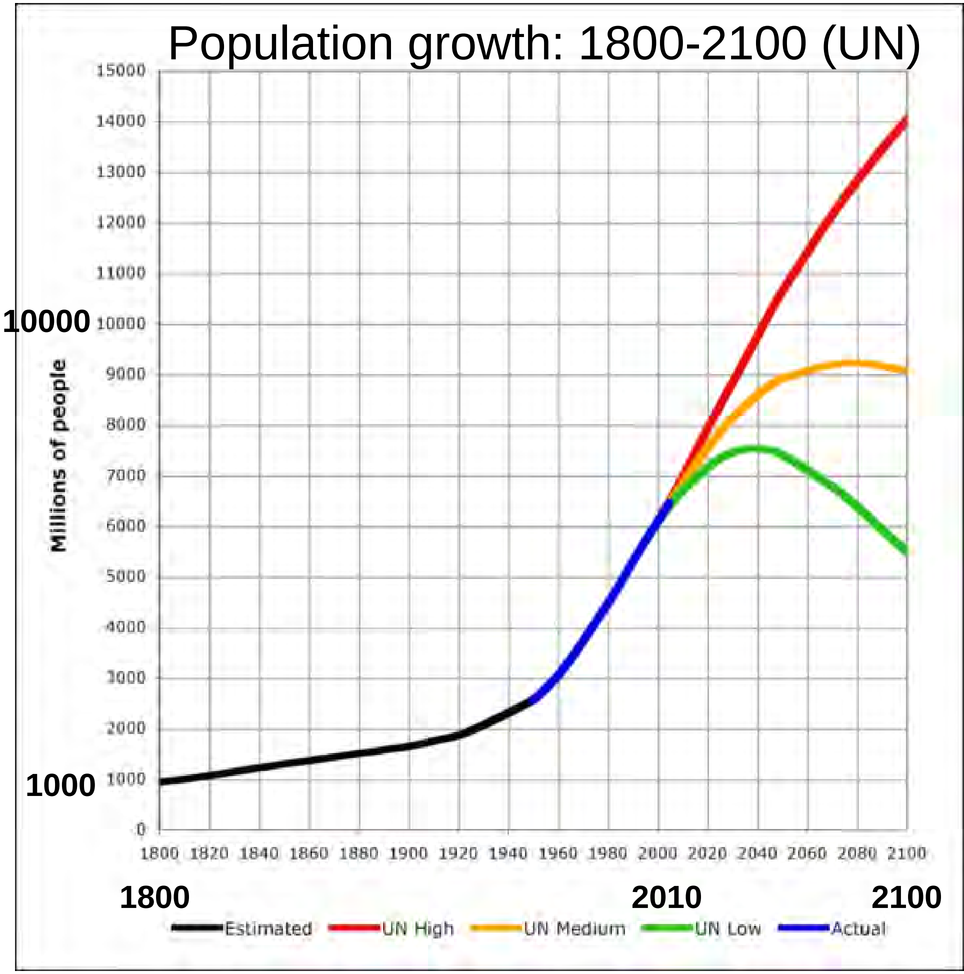
Why Is It Difficult for Us?

- Fossil fuels reserves are worth $20-30T
- Is regulating/costing emissions of CO_2 an “unfair cost” to the “free market”?

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

We Passed the Carrying Capacity of the Earth in the 1980s (?)

- **Population is still rising**
- **Consumption still rising**
- **Fossil fuel use still rising**
- ***We still 'believe' in Growth***
- ***Global poverty & suffering are growing: the future looks bleak for billions***
- ***In a finite world, growth leads to overshoot & collapse***



Our Choices Are Bounded

- Humanity is an integral part of the earth system and dependent on its stability
- We do not have the freedom to do what we wish, whatever our economic, political or theological doctrine
- The response of the Earth system to human-centered arrogance will be sufficiently large this century that we will rethink our doctrine
- We would be wise to rethink sooner rather than later

Big Picture Issues!

- Regulation can be good – Reagan, G.H. Bush and Riley (EPA) pushed through the Montreal Protocol and the Clean Air Act Amendments over business opposition and saved the Earth from an ozone catastrophe
- Technology must be managed to minimize human impacts on the Earth
- Impacts have to be <u>fully</u> costed
- People need a vote, so they need to be informed and can support change

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
  - That deal with society’s fears

The Future Is Not Our Past

- Collectively, we create the future, so we need to plan for a transition to a sustainable society
- Face the future with an attitude of

“Bold Humility”

(Frances Moore Lappé: RAFFL, Rutland, 2007)

- Efficient society with renewable technologies
- Balance community solutions and government interventions
- Ask
  - Is this an efficient and sustainable way of doing this?
  - Do I have a deep understanding and connection to Earth?

Community-Transition

- The transition to a sustainable society will take decades and a community effort
  - www.transitionnetwork.org

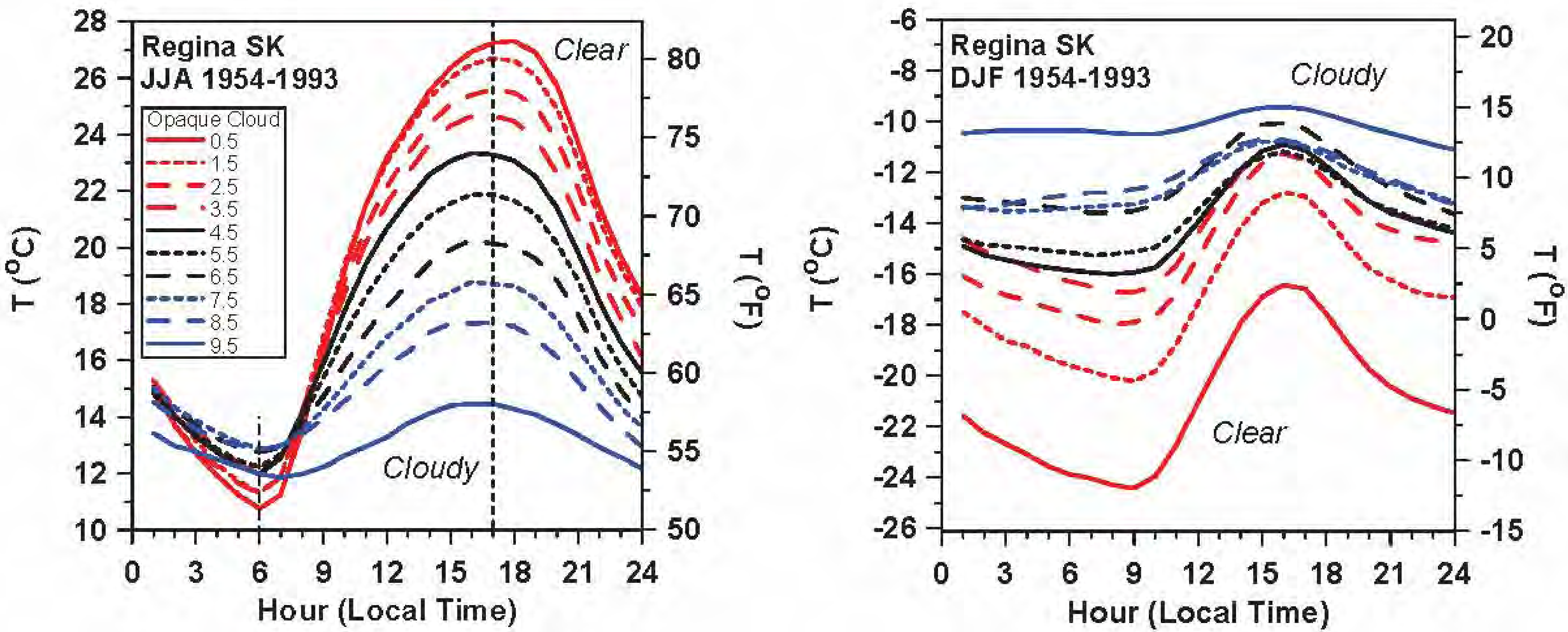
- Food: local agriculture & gardens
- Energy: Double energy efficiency ….

  - home heating – district heating + cogen
  - renewable electricity mix
  - efficient transportation system
  - careful forest management
- Finance: relocalization in real world

Discussion

- <u>http://alanbetts.com</u>
- Vermont Climate Assessment
  - Make it accurate, informative and <u>interesting</u>
  - Future not predictable, but we play creative role
  - Keys are waste management, resilience, economics, government, community
  - Write papers, get reviews and revise

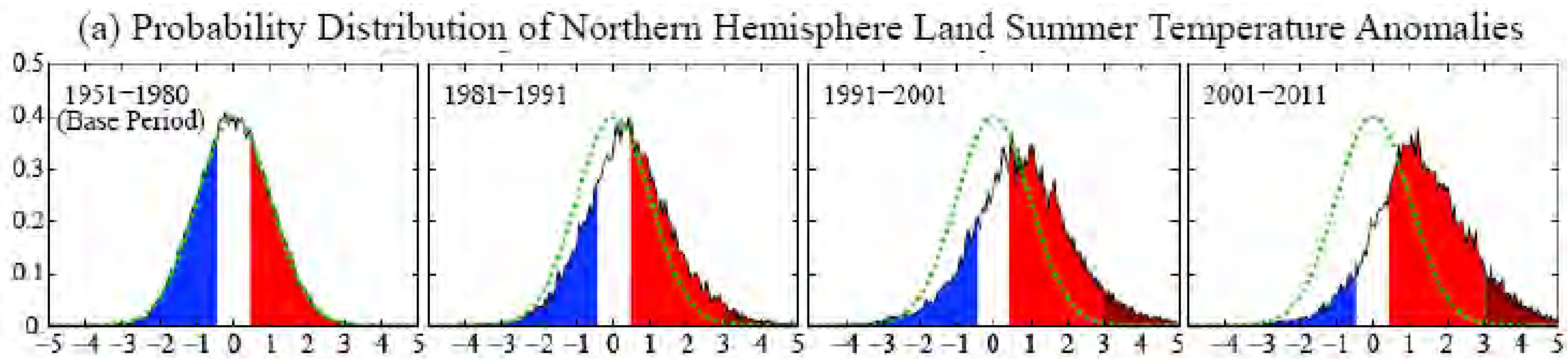
Clouds: Summer & Winter Climate



- **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

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.**

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

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

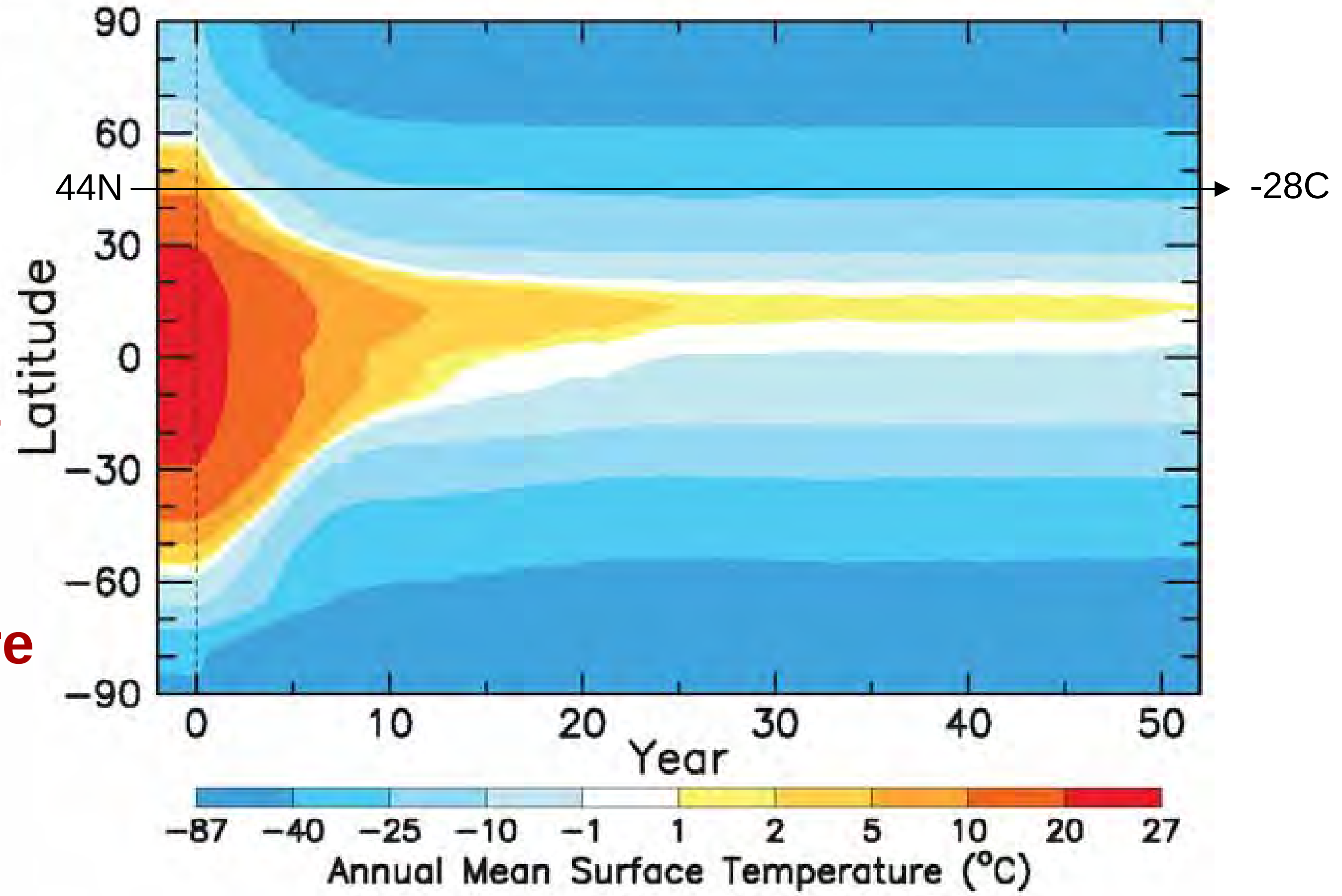
Western Forest Fires: 2000s

- 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

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%**

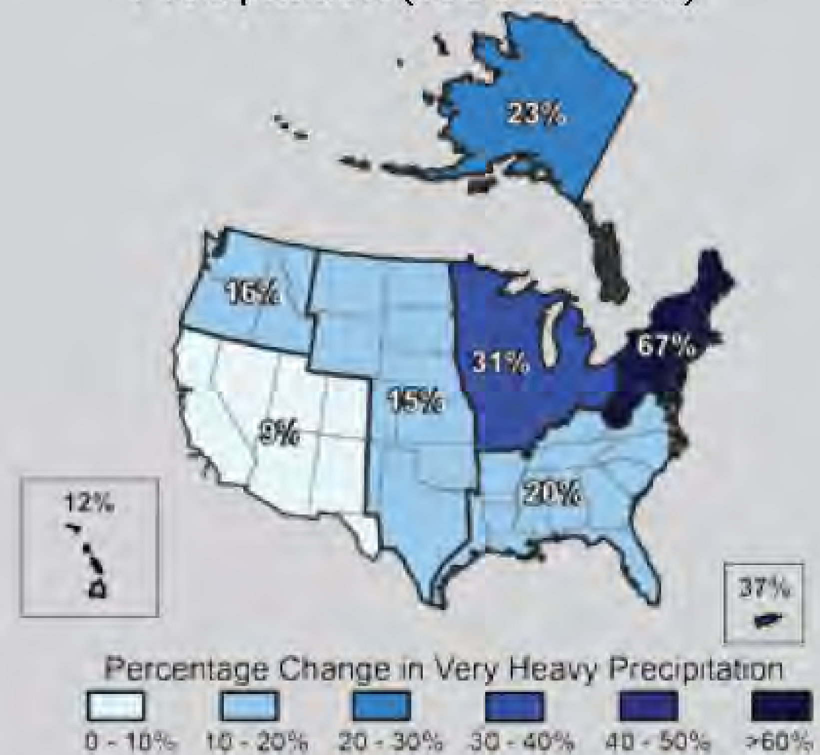
Climate and Resilience

- Trend to milder winters; longer growing season; earlier spring – variability large
- Trend to more precipitation in cool season; more wet snow and mixed in winter
- Warmer summers; heavier rain in summer; periods of drought – increase infiltration and water storage – *forests stabilize climate*
- Agriculture issues
  - Build soil carbon and organic matter for water storage and fertility
  - Recycle nutrients and phosphorus

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**

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



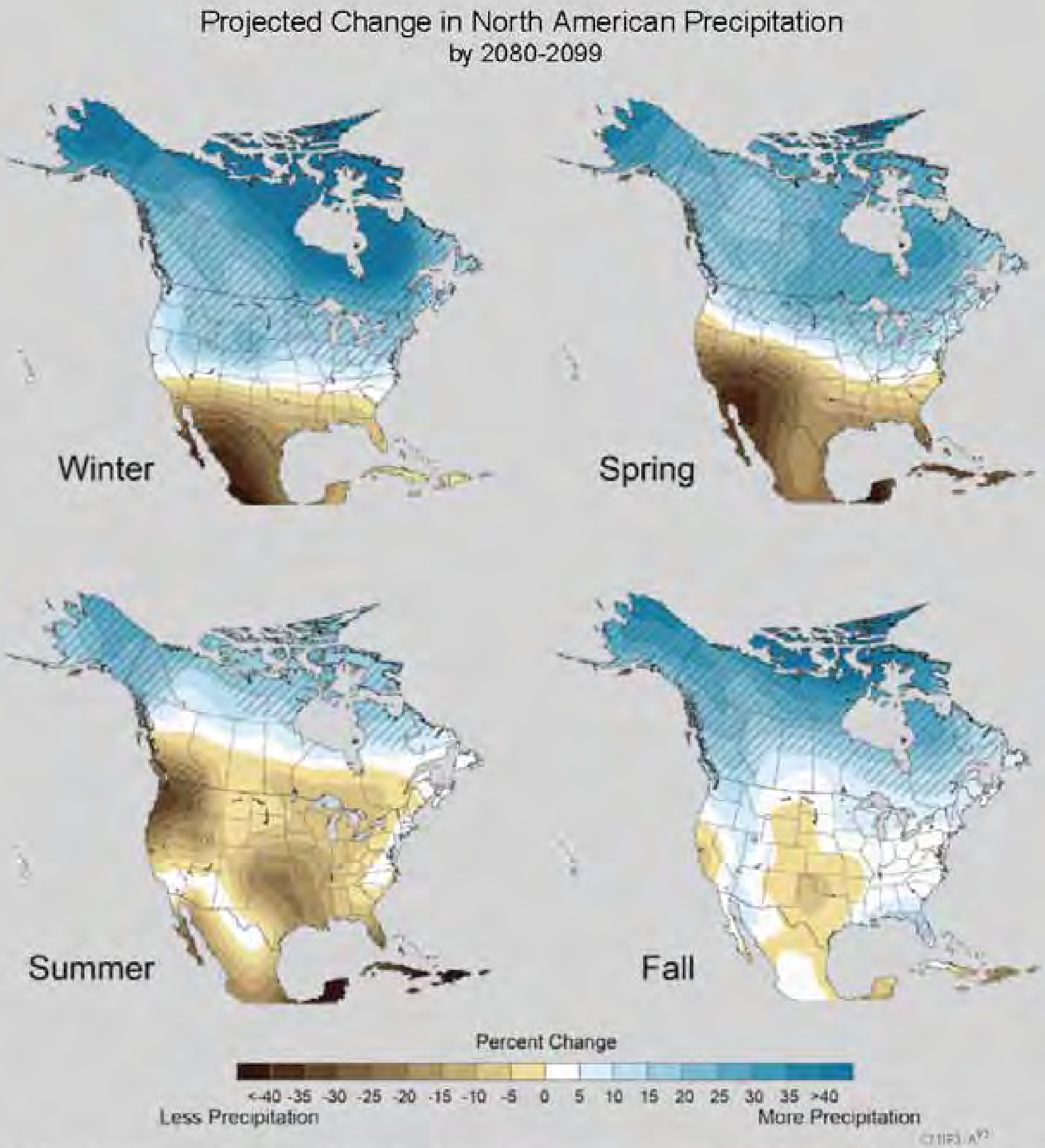
Updated from Groisman et al.[113]

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.

Projected Precip. Increase by 2090

- ***For Vermont***
- **15% in winter,**
- **10% in spring**
- **5% in fall**

- **No change, summer**
- **Heavier rain and more drought**



The maps show projected future changes in precipitation relative to the recent past as simulated by 15 climate models. The simulations are for late this century, under a higher emissions scenario.[1] For example, in the spring, climate models agree that northern areas are likely to get wetter, and southern areas drier. There is less confidence in exactly where the transition between wetter and drier areas will occur. Confidence in the projected changes is highest in the hatched areas.

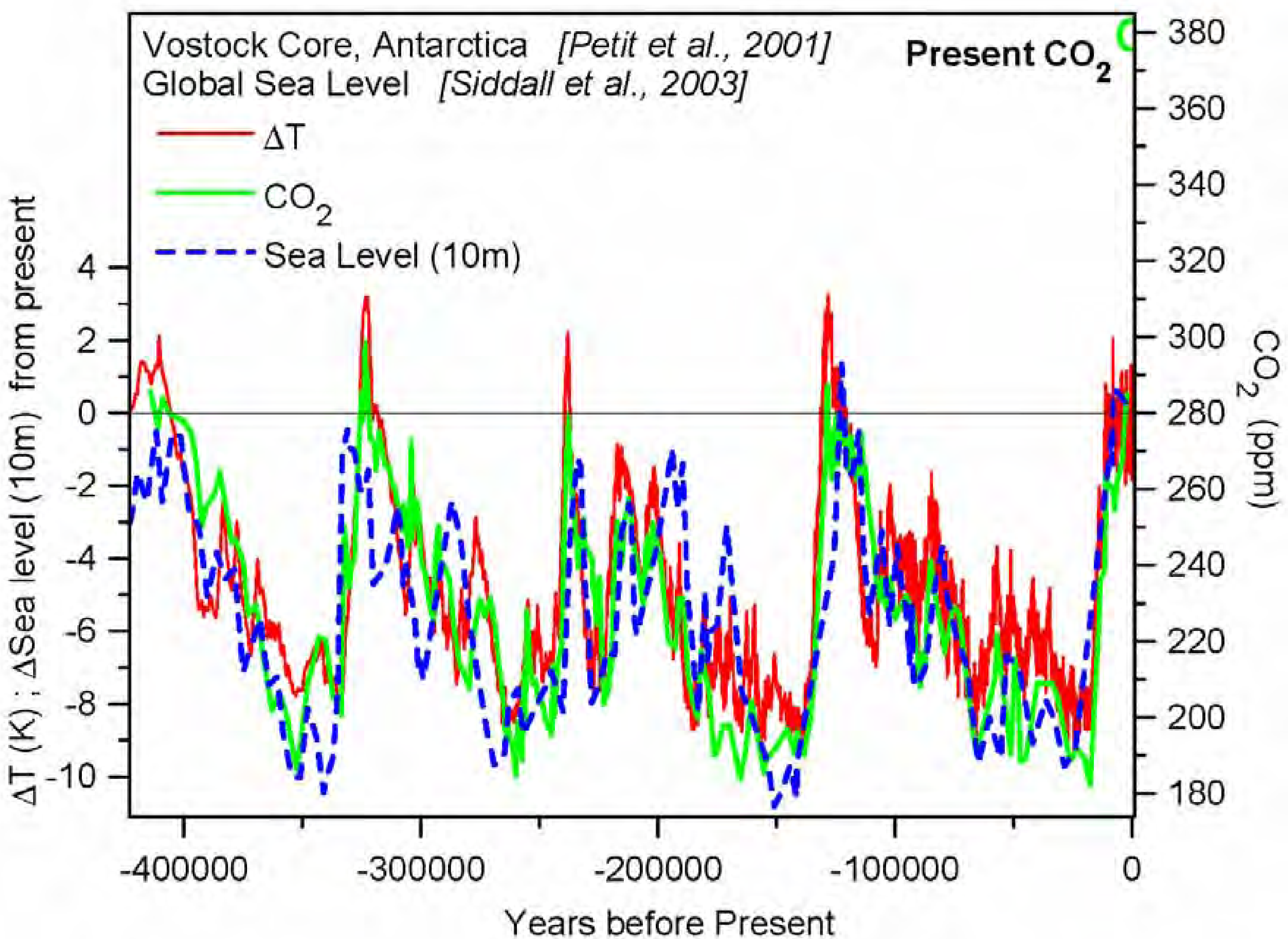
What do we know from past?

- **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



‘Anti-global warming’ tactics [*delay, confuse and deny*]

- **Fabricate ‘data’ or cherry-pick the science for unsolved issues and ignore the big picture. ‘This disproves global warming’ *or* ‘Science isn’t resolved; we need more science.’**
- **Models can’t predict the future with certainty, so the models are ‘unreliable’, ‘can’t be trusted’. Given this uncertainty, *we cannot be held responsible for the future*.**
- **If climate change were real, it would require collective government regulation of the ‘free market’, which we are opposed to; so *climate change must be a ‘hoax/conspiracy’***
- **It is too costly to make structural changes to our society, and it would affect profit margins.**
- **[We will wait till China and India take action]**
- **[The poor in Africa need energy]**

- **Strengths of science:**

  - integrity, honesty and communication

  - *particularly valuable in a society lost in ignorance and deceit*

- **Limits of science:**

  - tangible, measurable and communicable

  - *hard to deal with the complexity and interconnectedness of the living natural world*

Perspective for the 21st century

- **Much of western philosophy and theology formed when humanity had a limited understanding of its place in the natural world; but the structures of belief didn’t matter too much**

  ***because our impact was small*.**

- **All this started to change with the industrial revolution powered by fossil fuels. Now humanity has a *global impact on the natural world*, and understanding our place in it is paramount.**

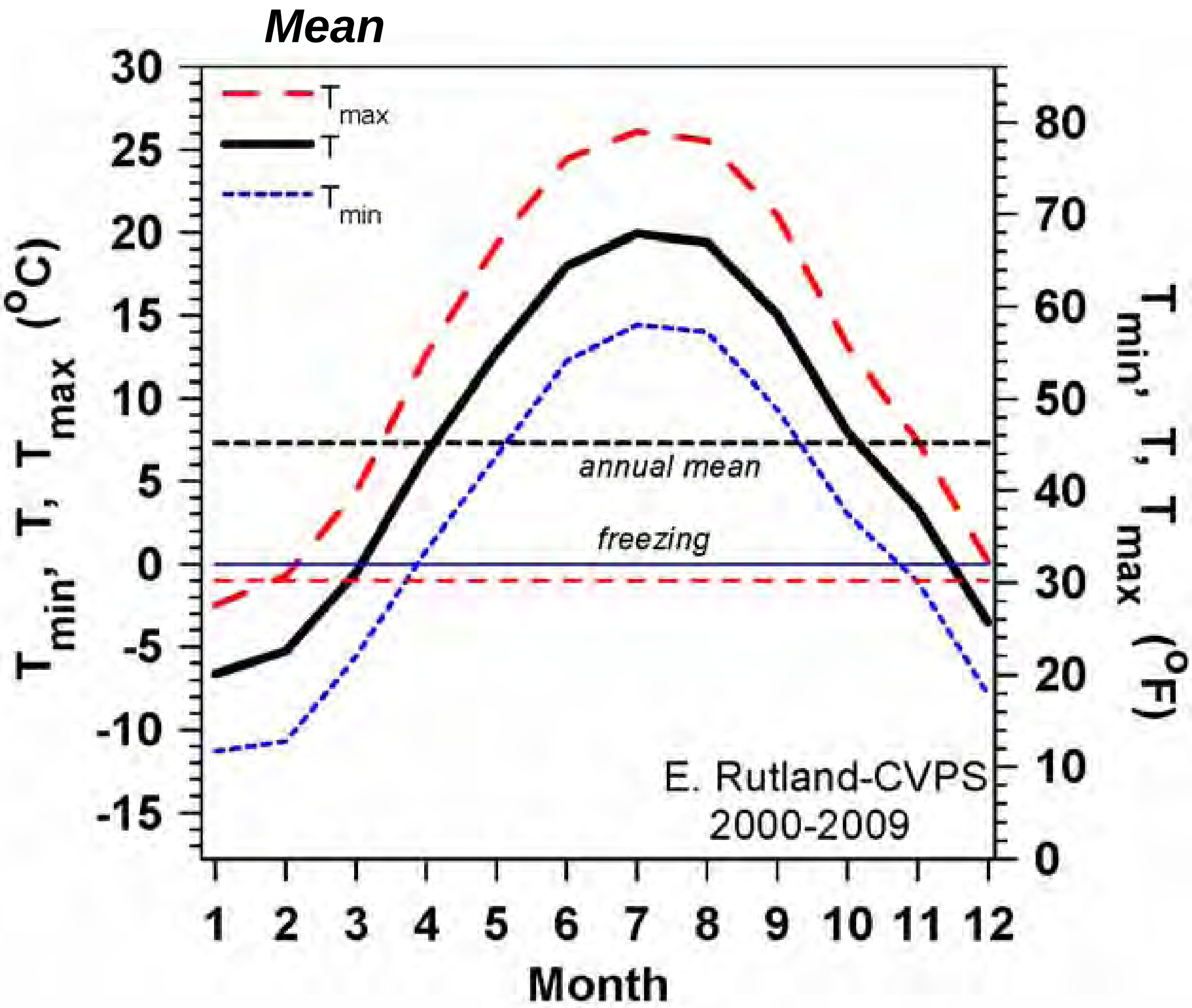
- ***Science and technology created this situation*, and must help us find a way out, by helping us understand the earth as a global system, now out-of-balance.**

But science has become ‘valueless’

- **Centuries-old split of science from ethics/religion**
- **Science preserved its factual integrity, but makes no value choices**
- **Theology & political society feel free to choose doctrine over understanding ‘reality’**
- ***No-one accepts responsibility for the Earth***
- ***So collapse of our ‘human system’ is possible***

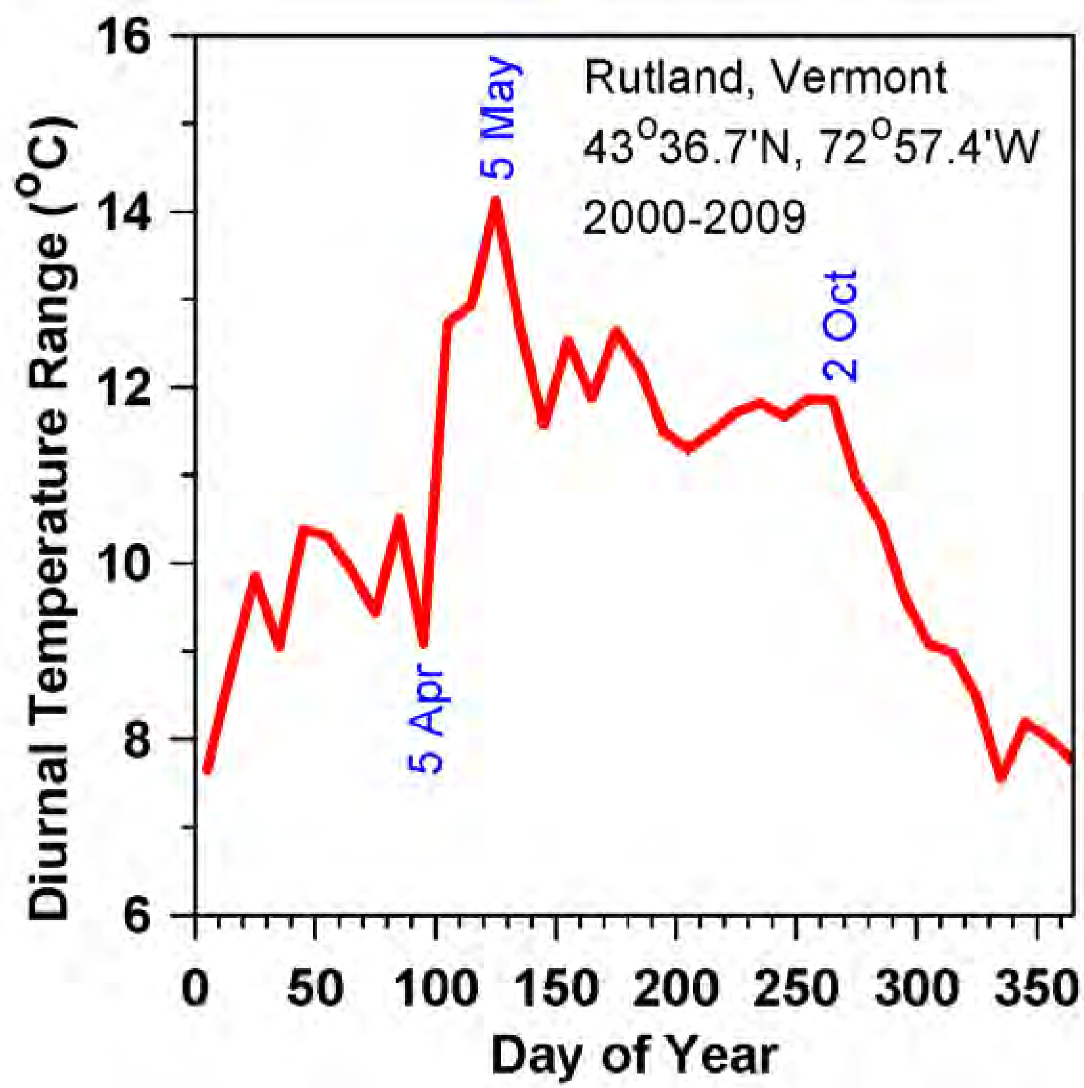
Climate of Vermont

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



Diurnal Temperature Range

- T_{max}-T_{min}
- **Mean daily range of T varies with season**
- Related to RH and LW_{net}



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

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

- **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!***

Later frost: Growing season getting longer