



Climate Change: the Real Story



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Outline

- **Science of climate change**
 - **Global and local**
 - **What is happening to Vermont?**
 - **Why is extreme weather increasing?**
- **The transition we face**
 - **Can we stabilize the climate?**
 - **Why is it difficult?**

Discussion

Earth sustains life

- Burning fossil fuels is increasing greenhouse gases and melting polar ice
- Climate is warming and extreme weather is increasing
- Water plays crucial role everywhere

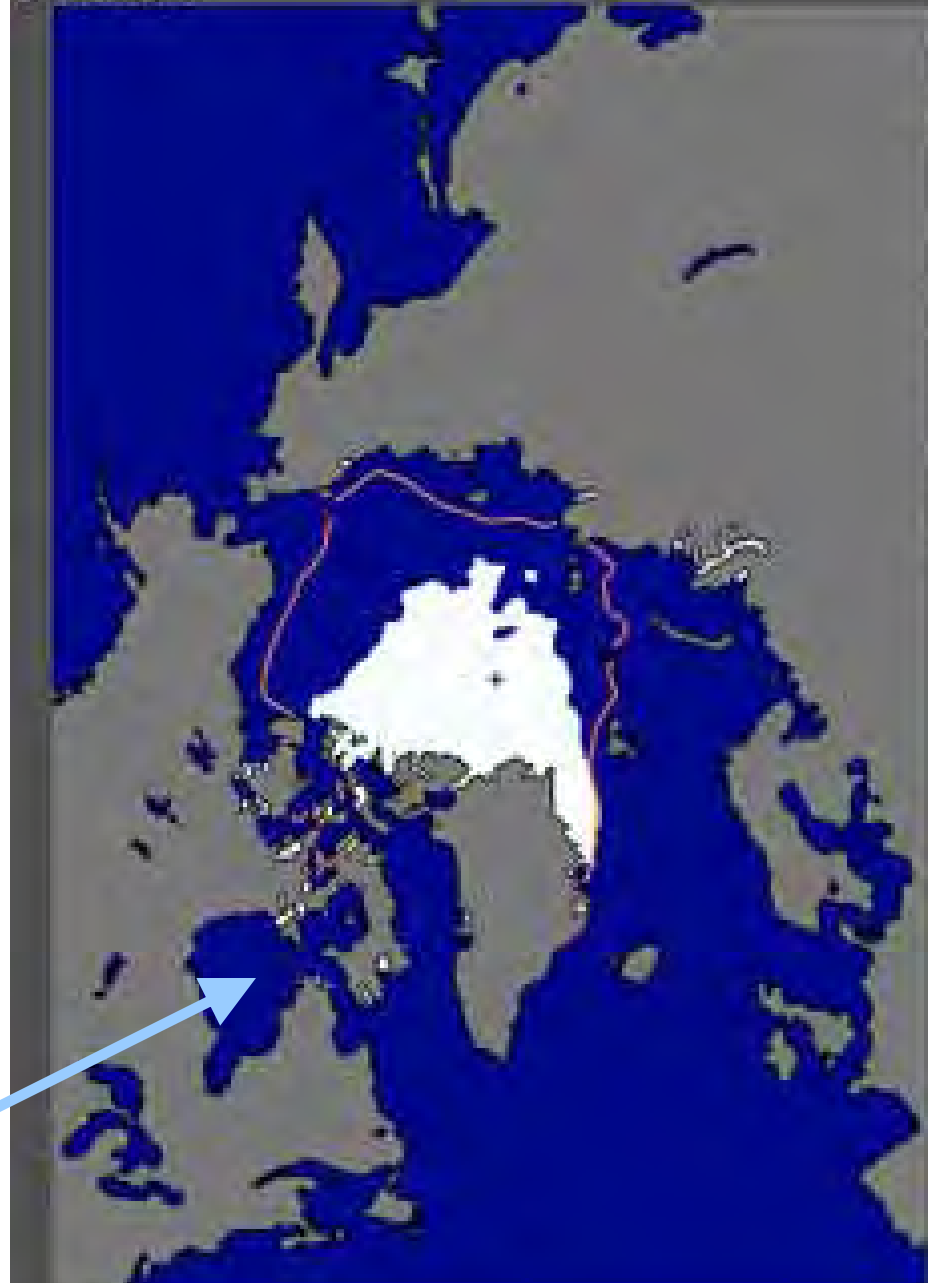
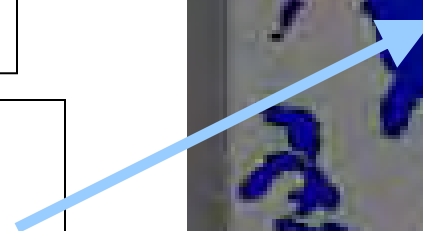


January 2, 2012: NASA

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

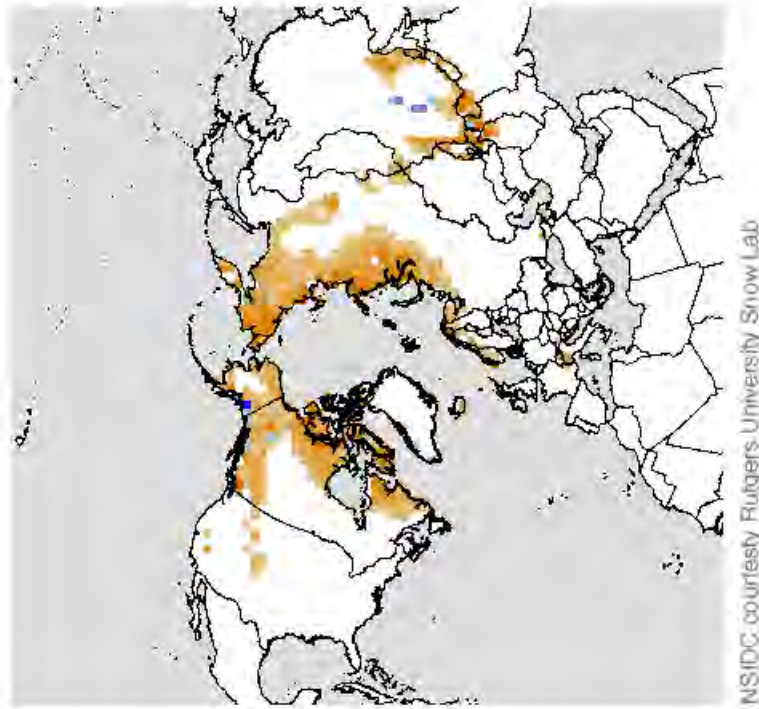
- *Amplifying feedbacks:*
- *Less ice, less reflection of sunlight*
- *More evaporation, larger vapor greenhouse effect*
- *Ice thin: most 1-yr-old*

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



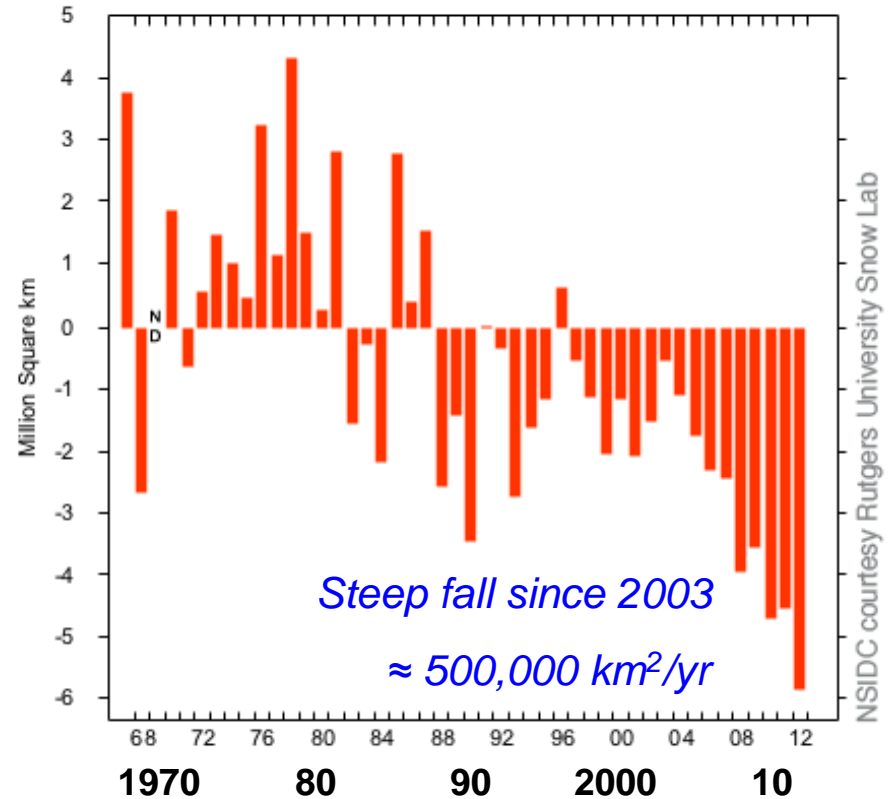
June 2012 snow cover minimum

Northern Hemisphere Snow Cover Anomaly
June 2012



Percent difference from 1971 - 2000 average June snow cover extent

Northern Hemisphere Snow Cover Anomaly
June 1967 - 2012



- Arctic warming rapidly
 - Melting fast
 - Faster than IPCC models
- New England winters also
 - Same amplifying feedbacks

What Is Happening to Vermont?

- Warming twice as fast in winter than summer
- Winter minimums increasing even faster
- Lakes frozen less **by 7 days / decade**

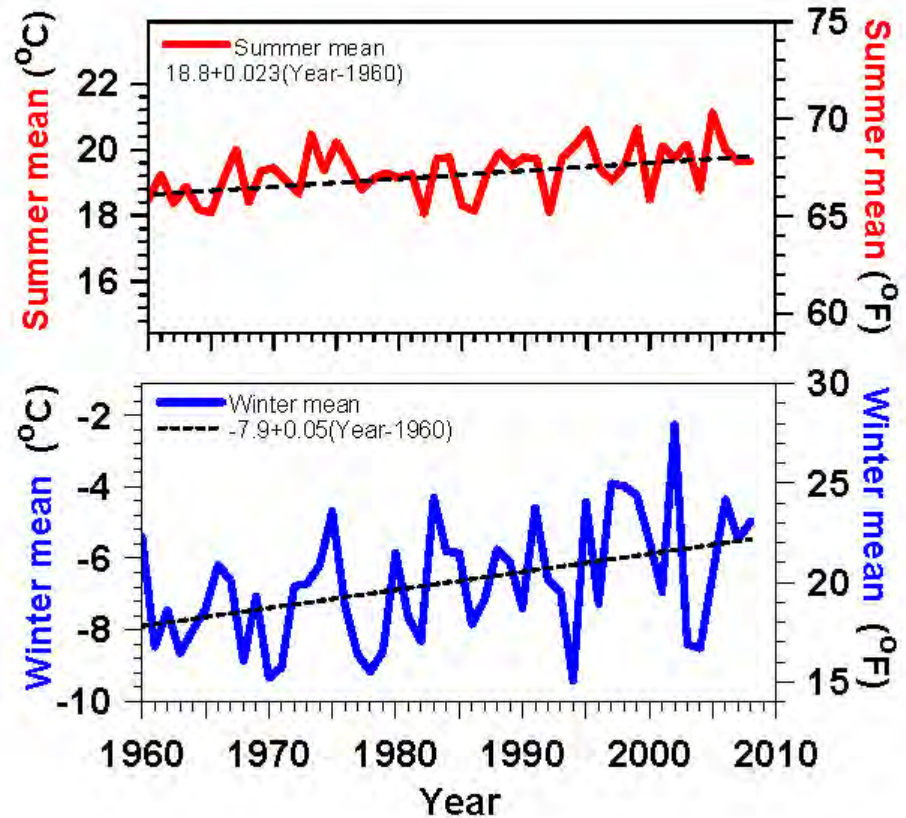
- Growing season longer **by 3-4 days / decade**
- Spring coming earlier **by 2-3 days / decade**

(Betts, 2011)

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

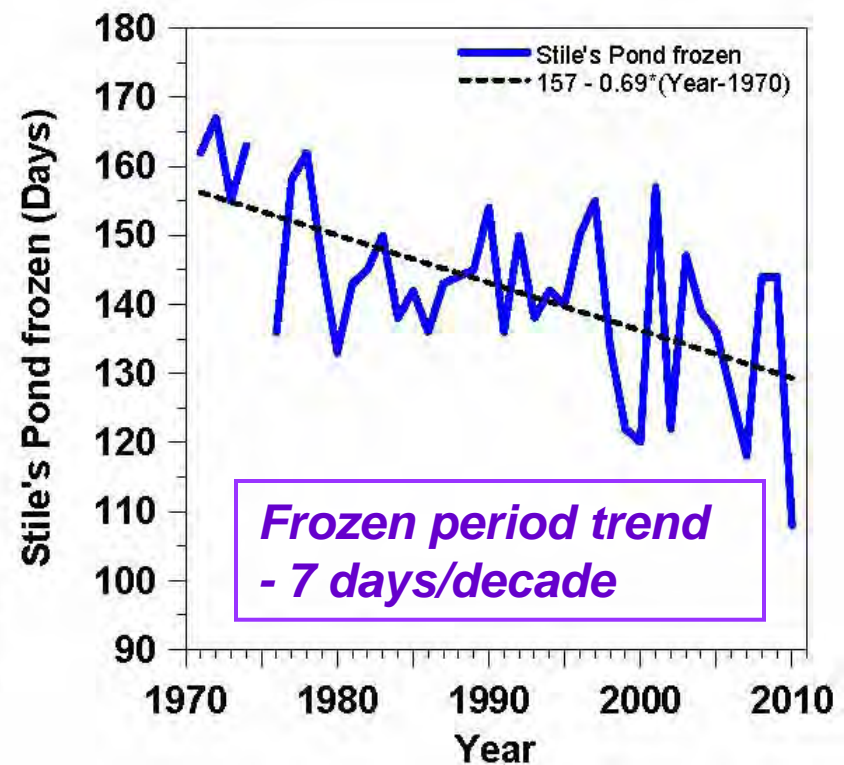
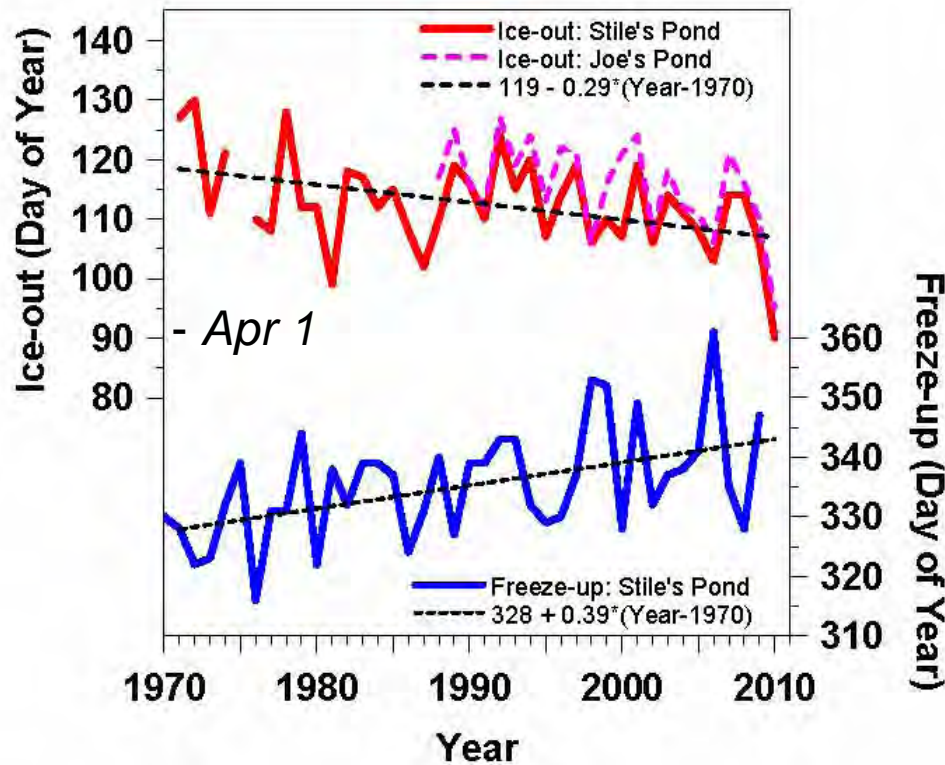
Vermont Temperature Trends 1961-2008

- **Summer $+0.4^{\circ}\text{F}$ / decade**
- **Winter $+0.9^{\circ}\text{F}$ / 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

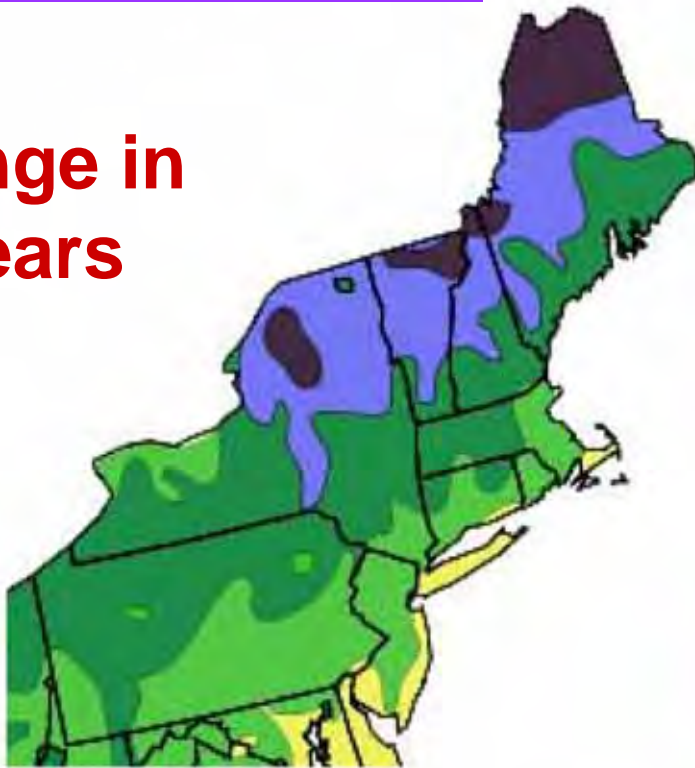


- Ice-out earlier **by 3 days / decade**
- Freeze-up later **by 4 days / decade**
- *Soil ice probably similar*

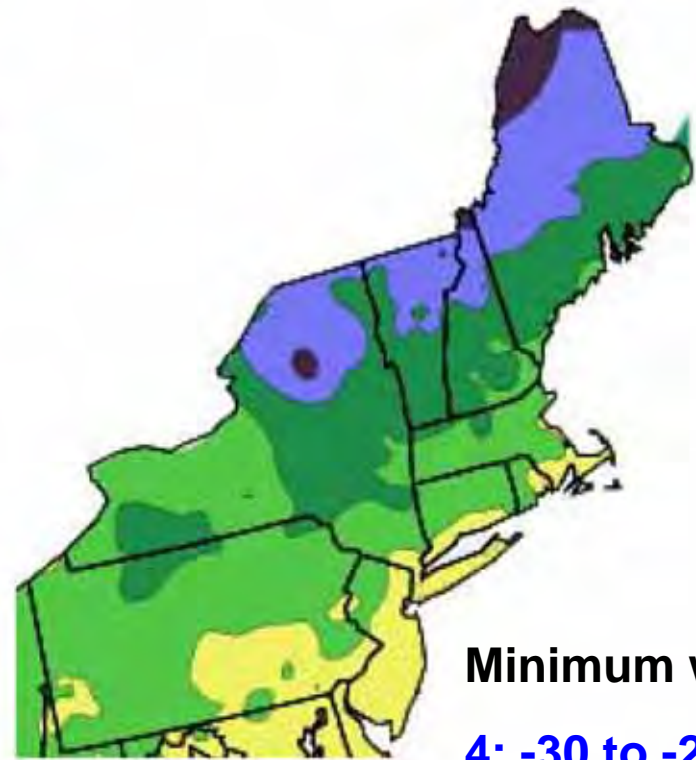
Winter Hardiness Zones

– winter cold extremes

Change in
16 years



1990



2006

Minimum winter T

4: -30 to -20°F

5: -20 to -10°F

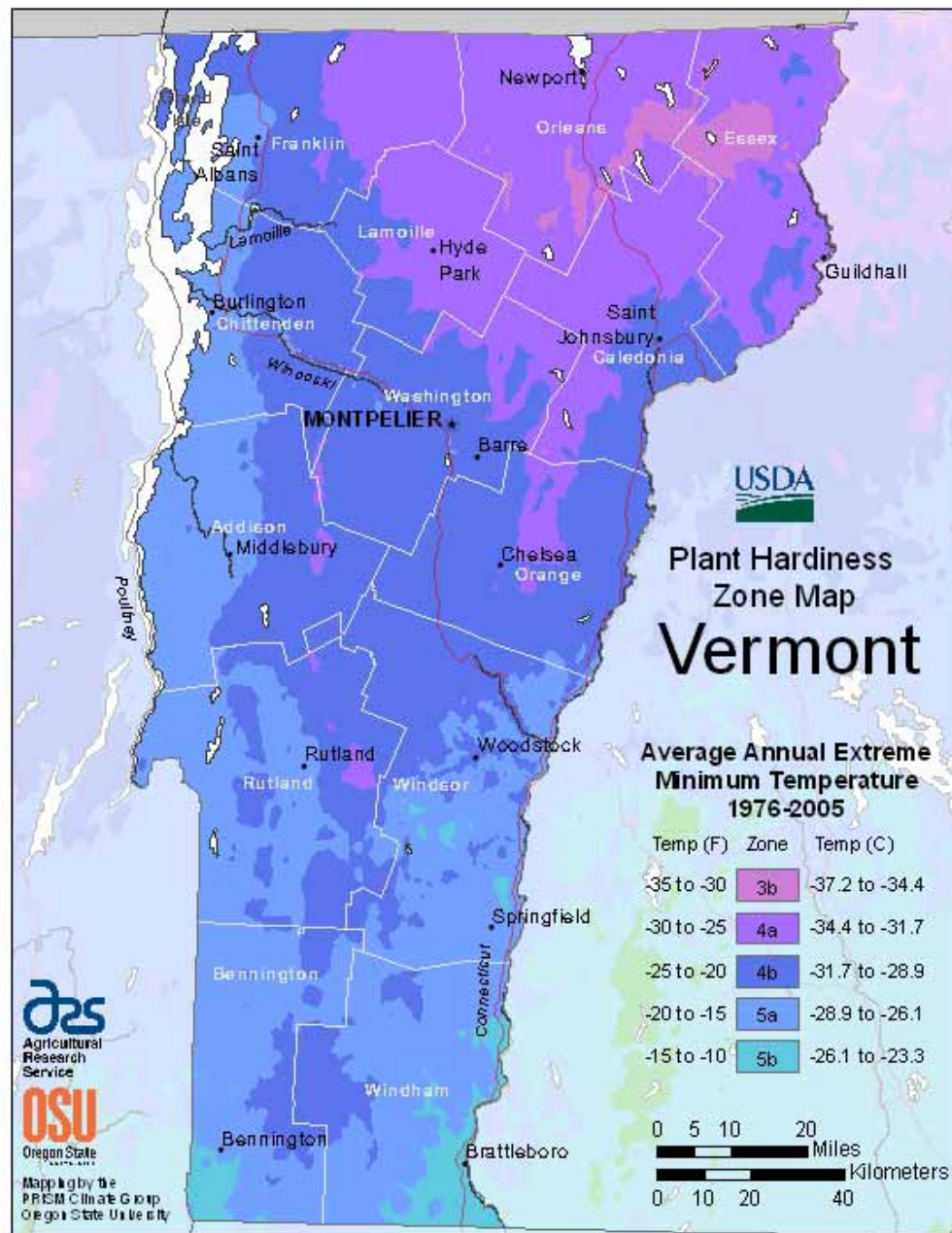
6: -10 to 0°F



USDA Hardiness Zones

Detailed Map (most recent)

- **USDA : VT
Hardiness Zone
Map 1976-2005**
 - mean 1990
 - South into zone 6
- **Half-zone in 16 yrs
~ 3°F/ 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

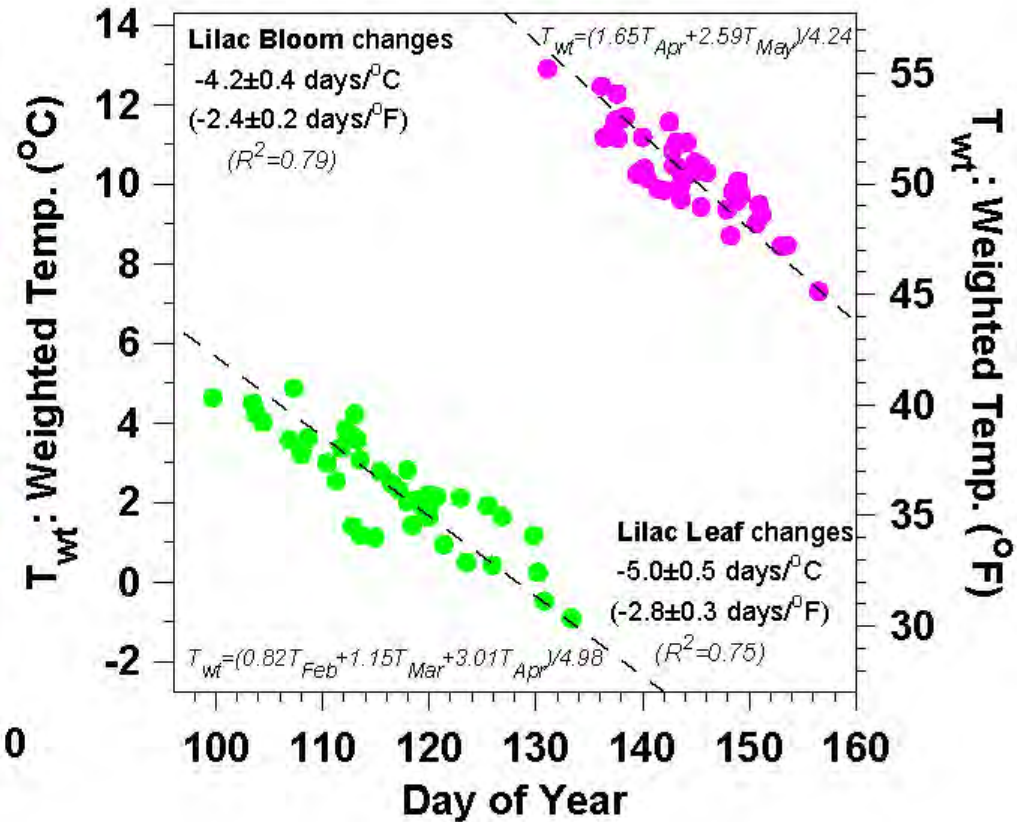
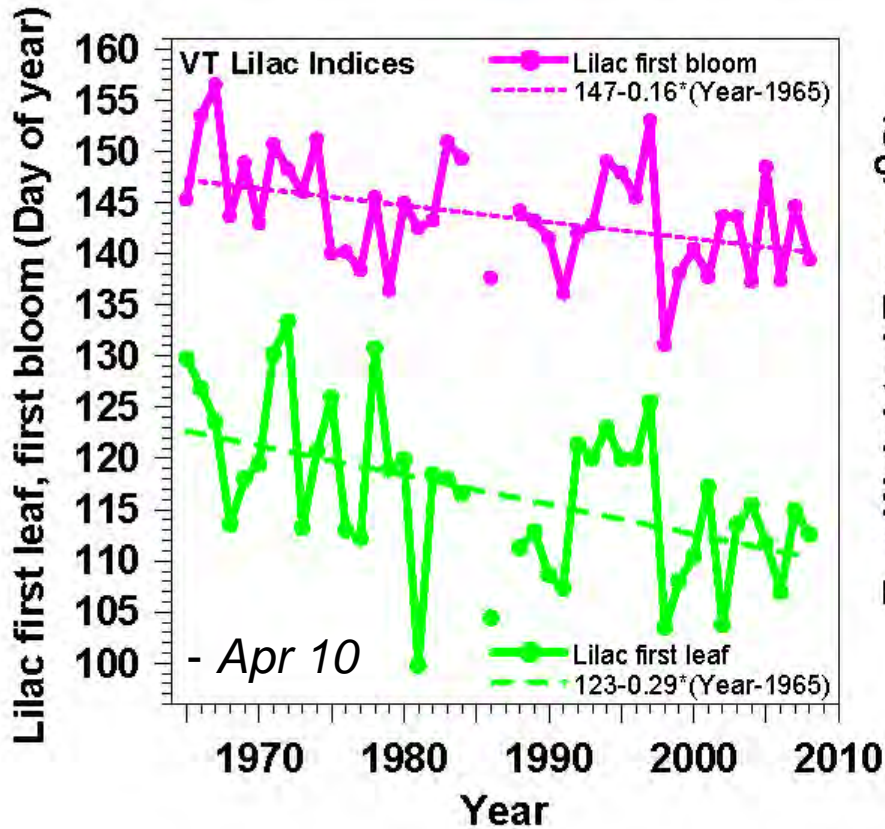
• What is this?

- **Avocado**

- Didn't survive frost
- Late century: in CT
- Our grand-children

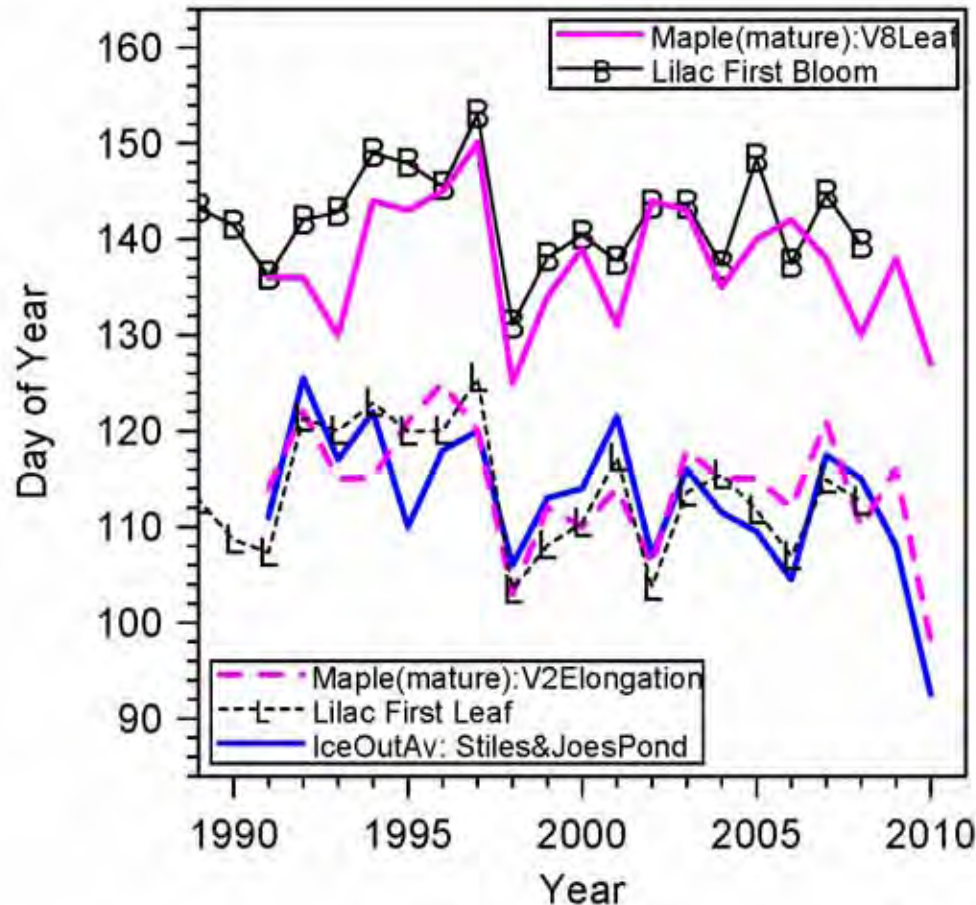


Lilac Leaf and Bloom



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

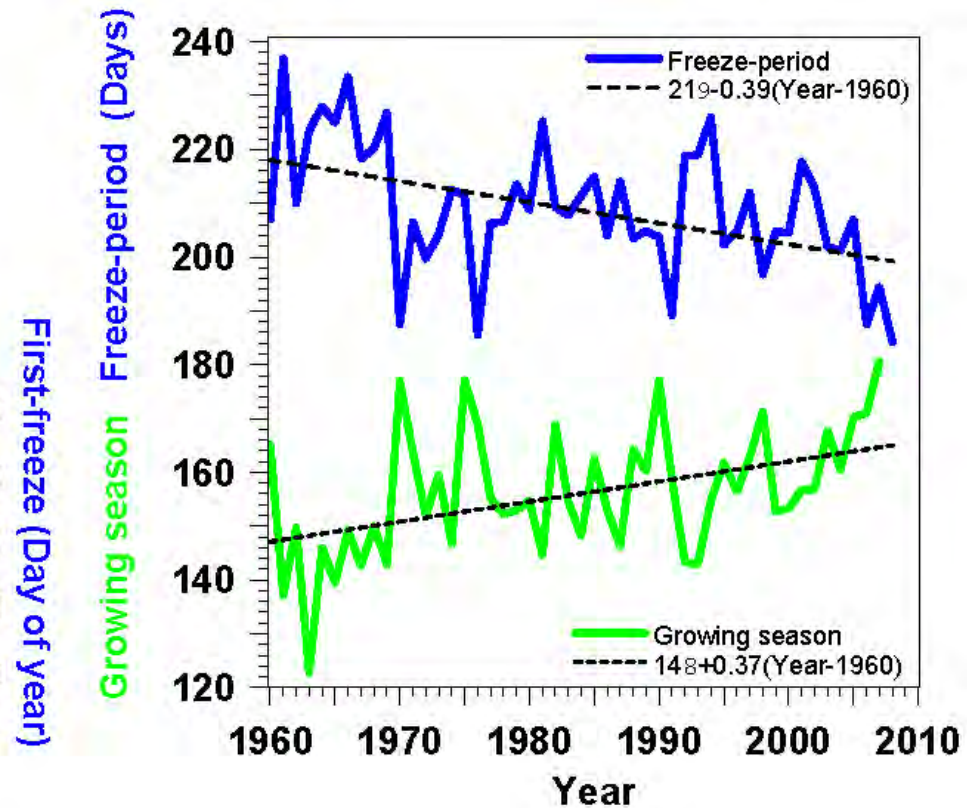
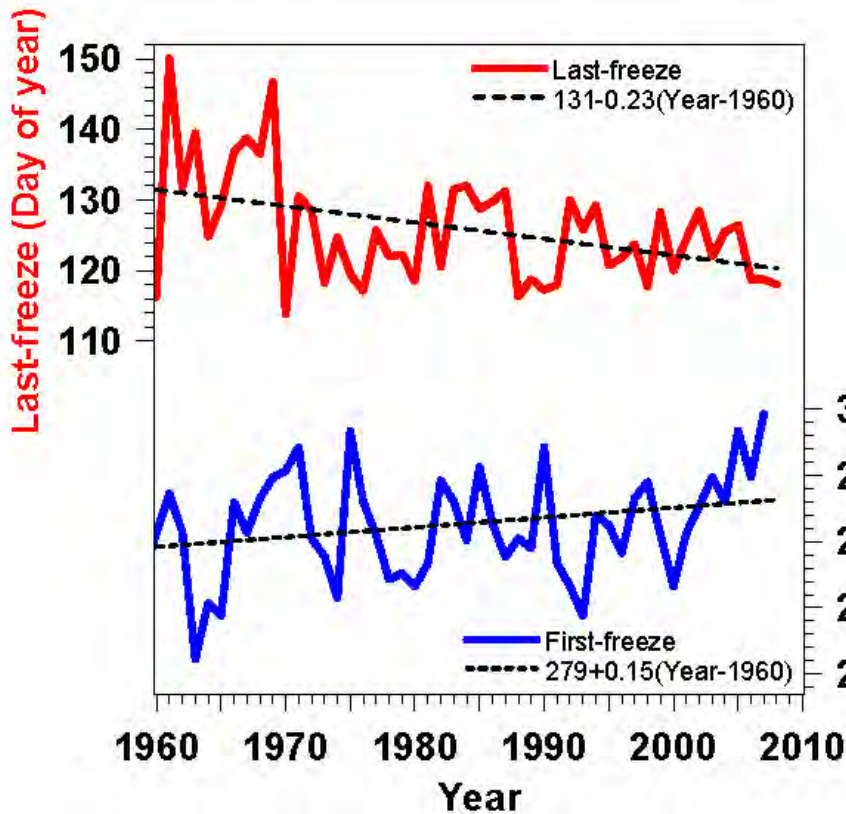
Sugar Maples in Spring



- 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

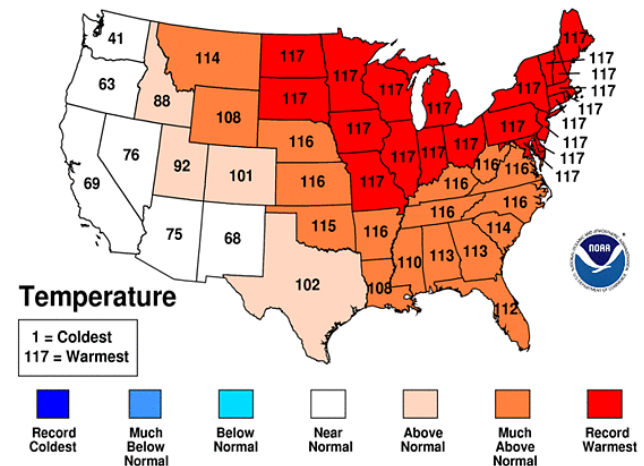


October 2011– March 2012

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

Oct 2011-Mar 2012 Statewide Ranks

National Climatic Data Center/NESDIS/NOAA



Daffodils in Bloom

March 22 – 79°F

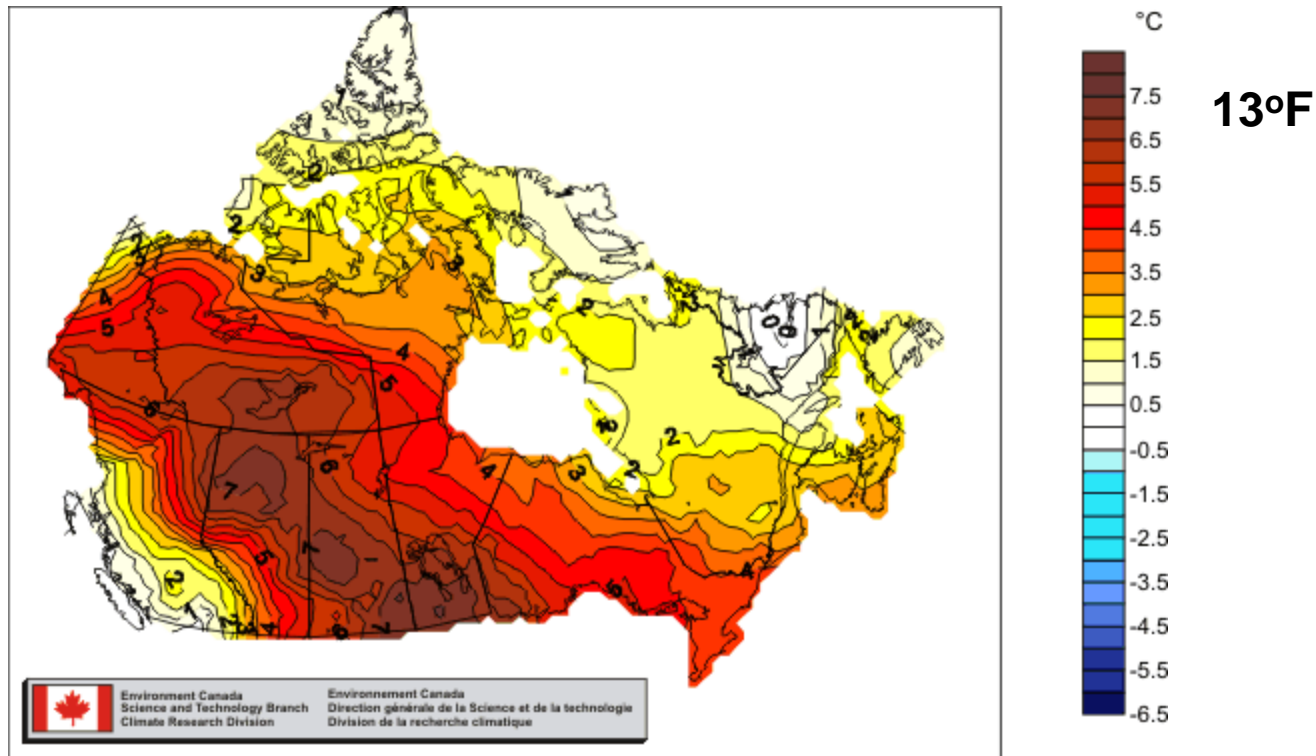


Pittsford

Vermont

3/22/12

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!**

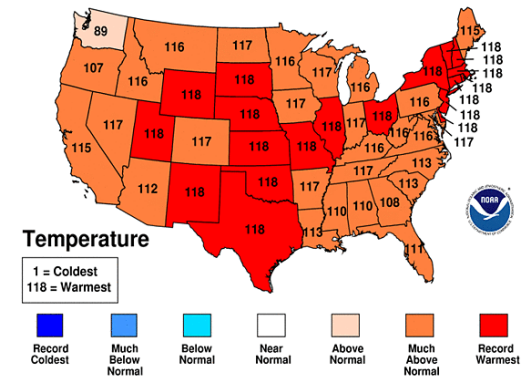
2012 Exceptionally Warm

- 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)

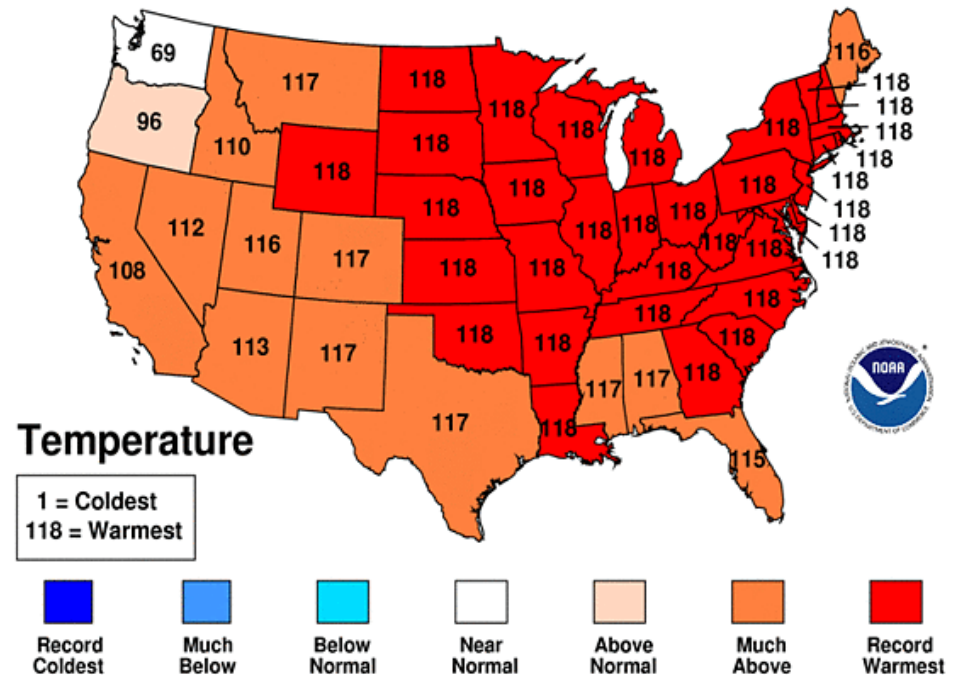
January-December 2012 Statewide Ranks

National Climatic Data Center/NESDIS/NOAA



January-August 2012 Statewide Ranks

National Climatic Data Center/NESDIS/NOAA



December 21, 2012

January 15, 2013



**Past
Winter**

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

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)***

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!*



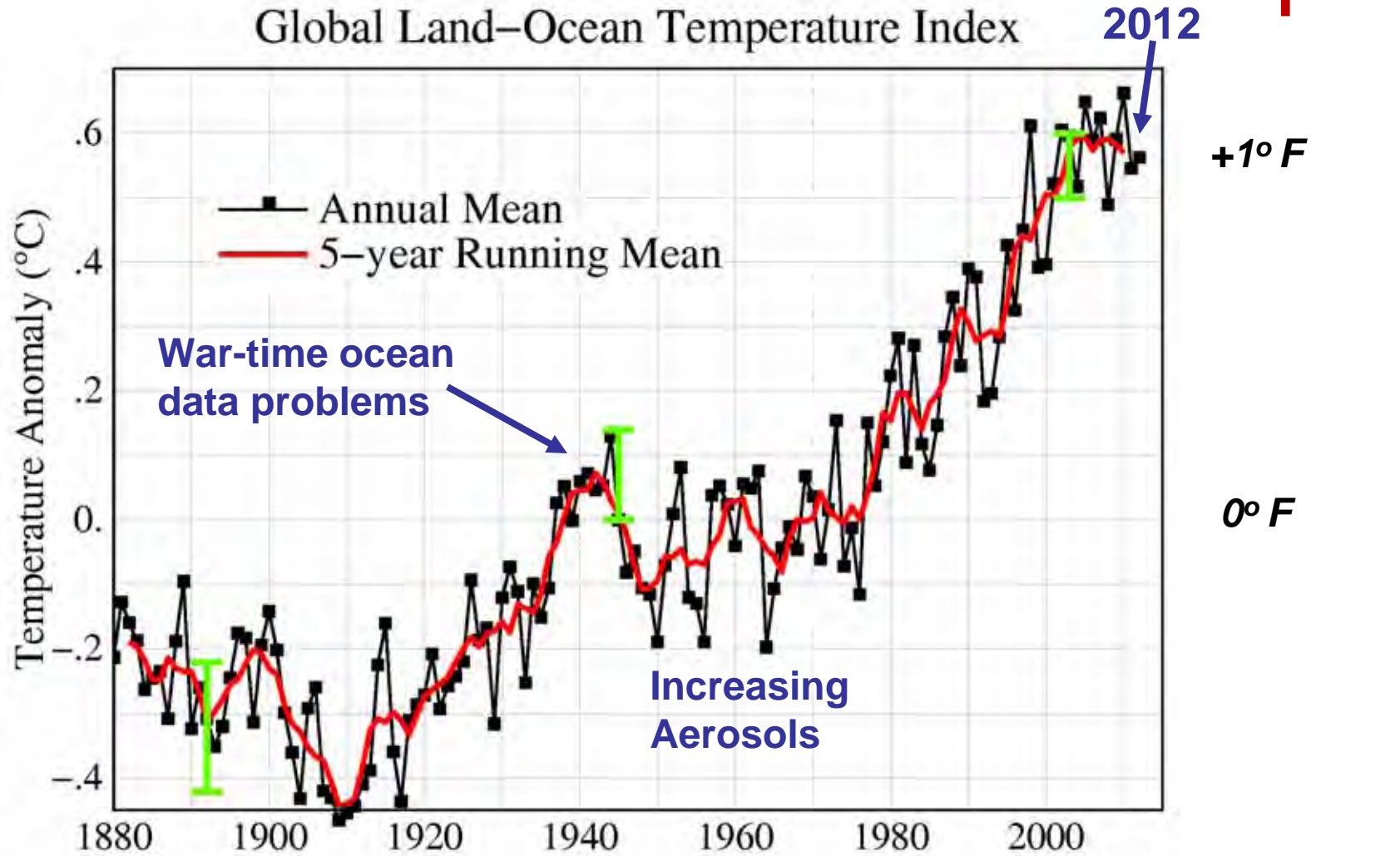
Clear dry blue sky after frost. Forest evaporation has ended; water vapor greenhouse is reduced, so Earth cools fast to space at night

Later frost: Growing season getting longer

Global Climate Change

- One of the many great challenges for the 21st century - present path is unsustainable
- Known it would be a problem for 4 decades
 - J. S. Sawyer (1972): Man-made CO₂ and the “greenhouse” effect*
- Earth science conflicts with historic values (and vested interests in fossil fuel economy)
- It is a global issue and local issue

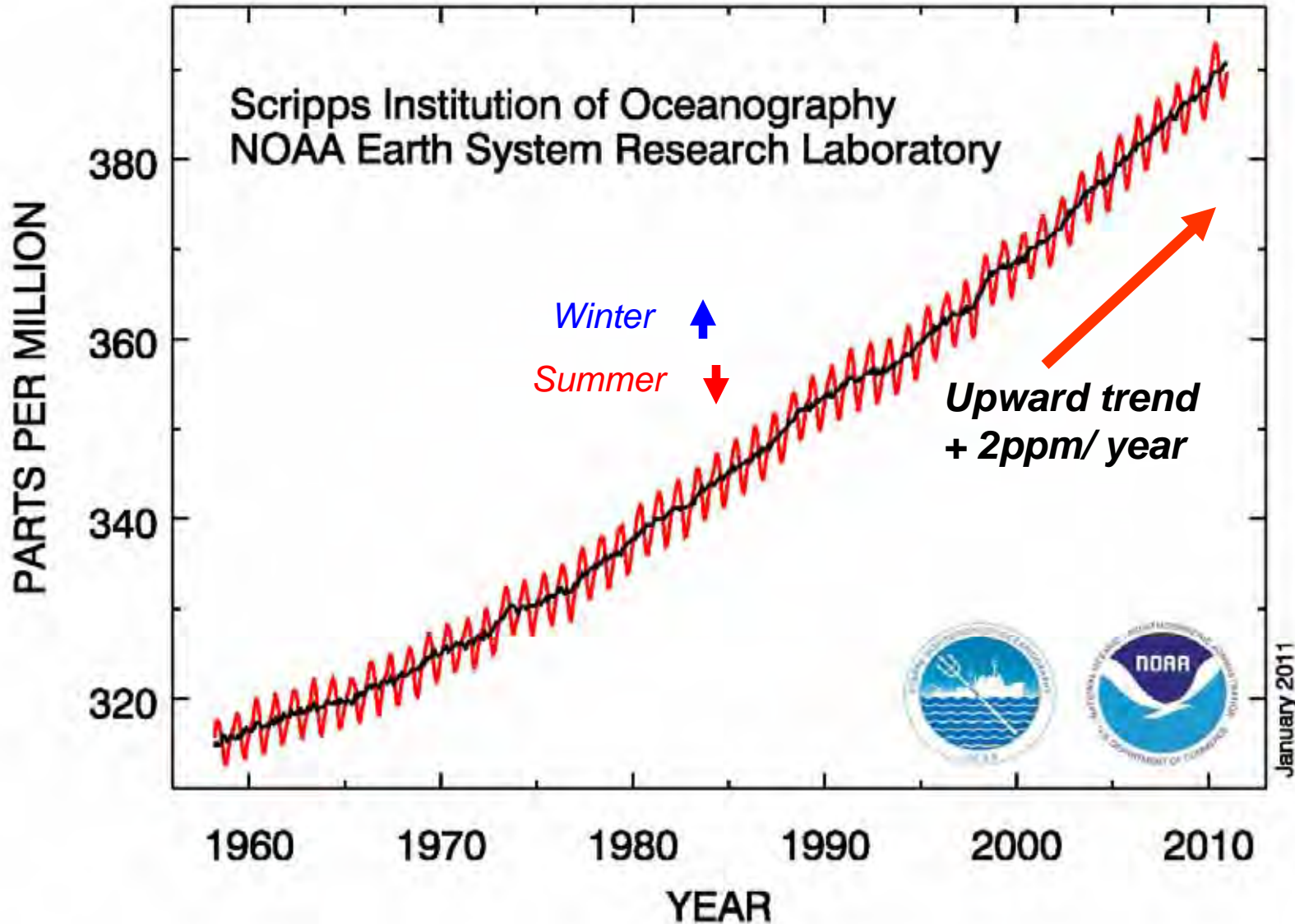
Global Temperature Rise 1880 – Present



NASA-GISS, 2013

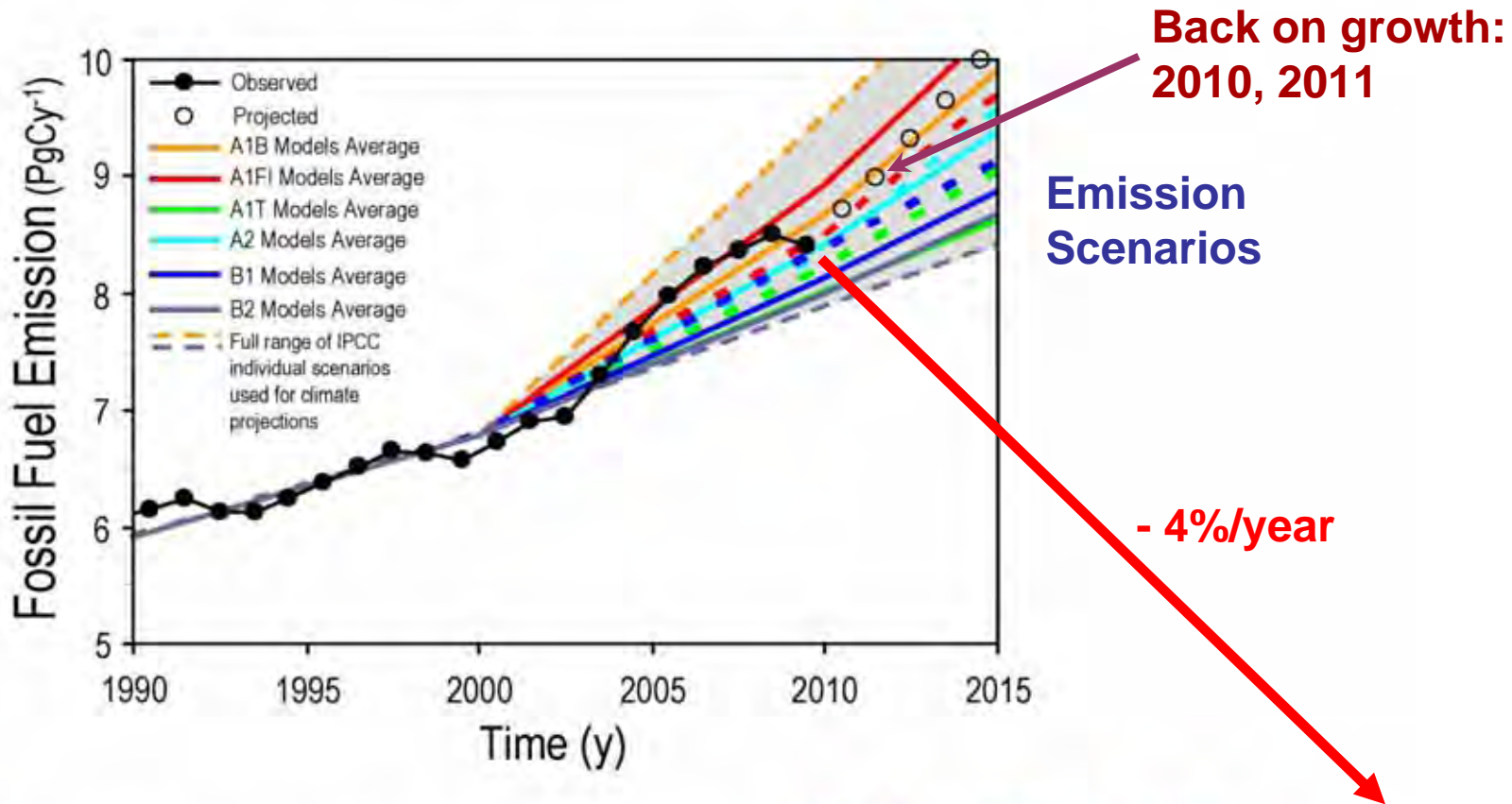
Carbon Dioxide Is Increasing

Atmospheric CO₂ at Mauna Loa Observatory

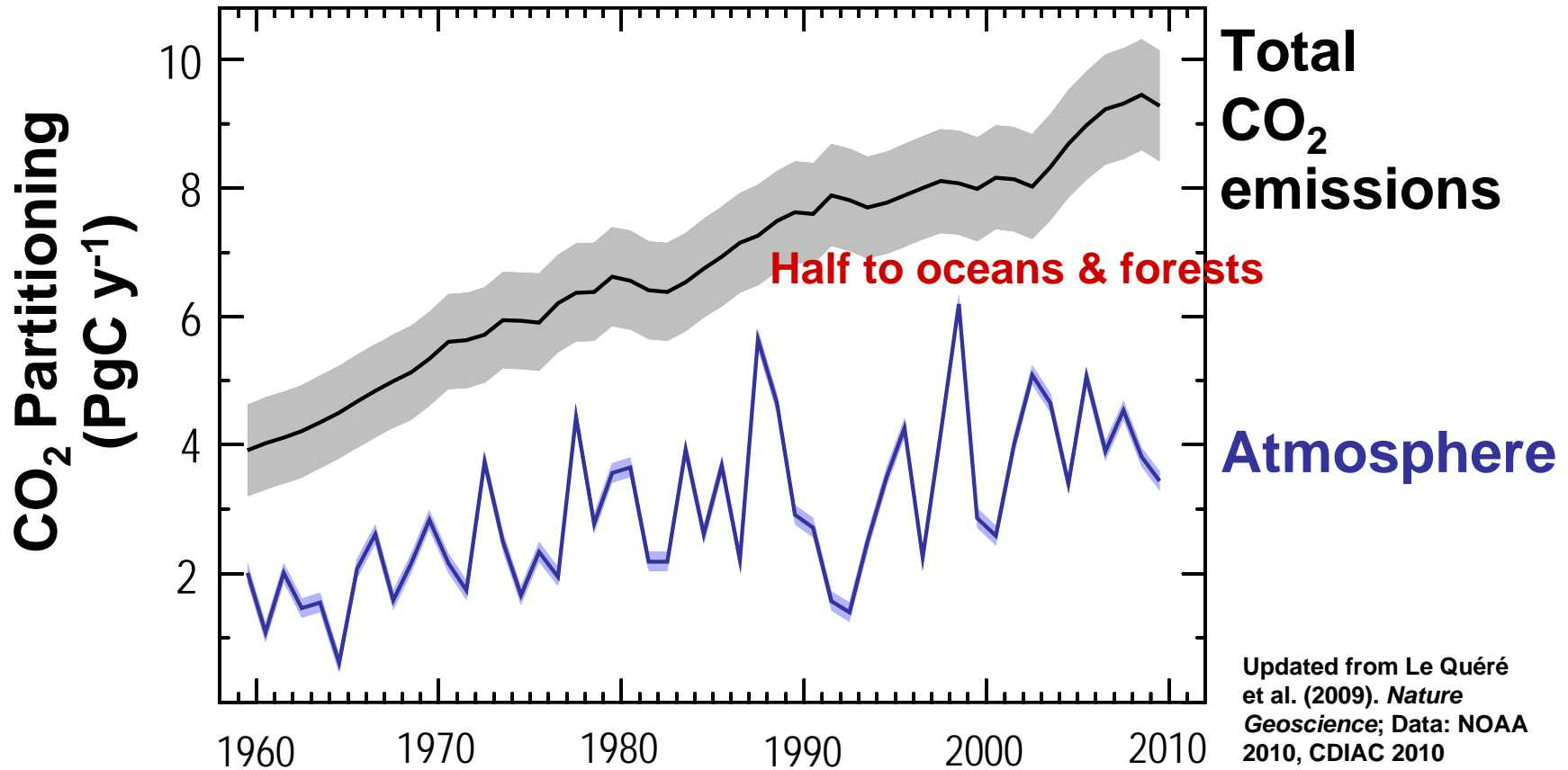


2009 Was “Good” for the Earth

Fossil Fuel Emissions: Actual vs. IPCC Scenarios



Only Half of Total CO₂ Emissions Remain in the Atmosphere



It takes at least a century to remove CO₂ from the atmosphere, and many centuries to remove it from oceans

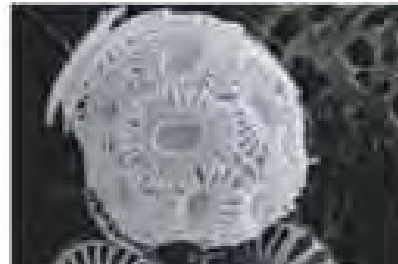
Rising Ocean Acidity Threatens Organisms



- 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:** H₂O, CO₂, CH₄, O₃, CFCs trap the infrared from the surface, giving climate suitable for life by warming planet 60°F
- Rise of CO₂ 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 CO₂ rise
- As Earth warms, snow & ice decrease and reduced SW reflection amplifies warming in Arctic in summer and mid-latitudes in winter
- Doubling CO₂ 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

Decrease in:

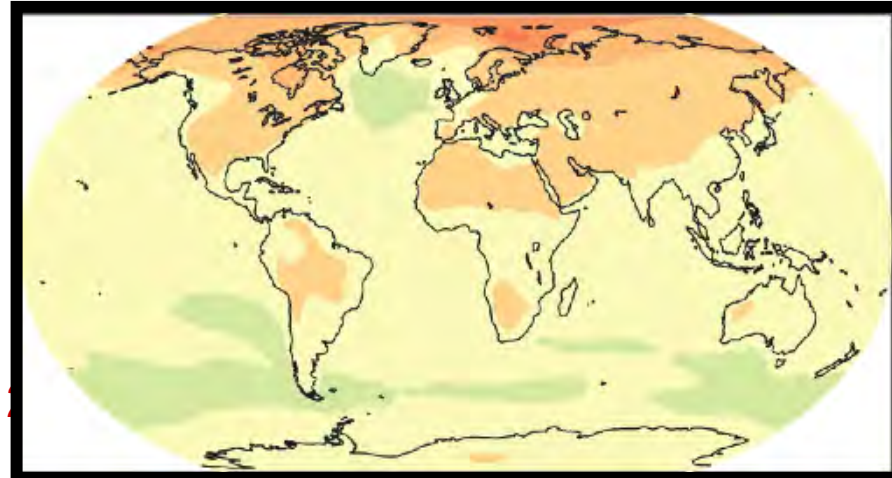
- NH snow extent
- Arctic sea ice
- Glaciers
- Ocean pH (increasing acidity)



Predicted Change in Temperature

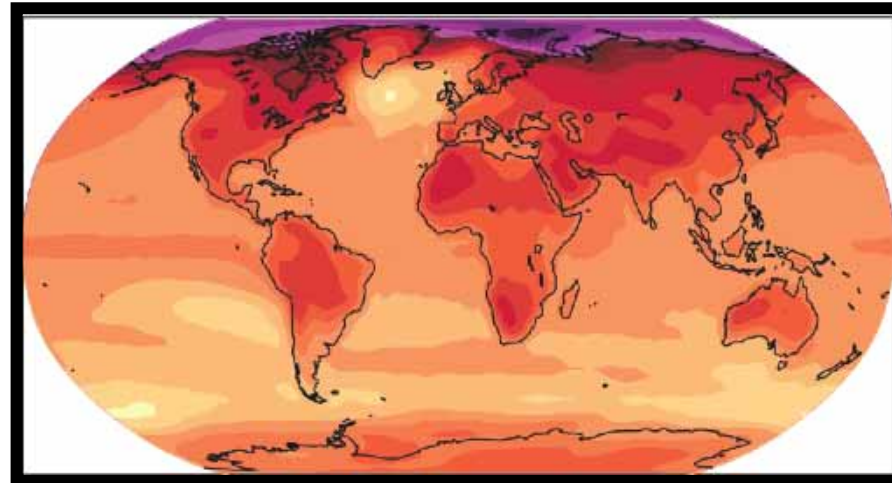
2020-2029 and 2090-2099, relative to 1980-1999 (°C)

“Committed”



(We did nothing for the last 20 years)

Still up to us!



(We could halve this if we act now)

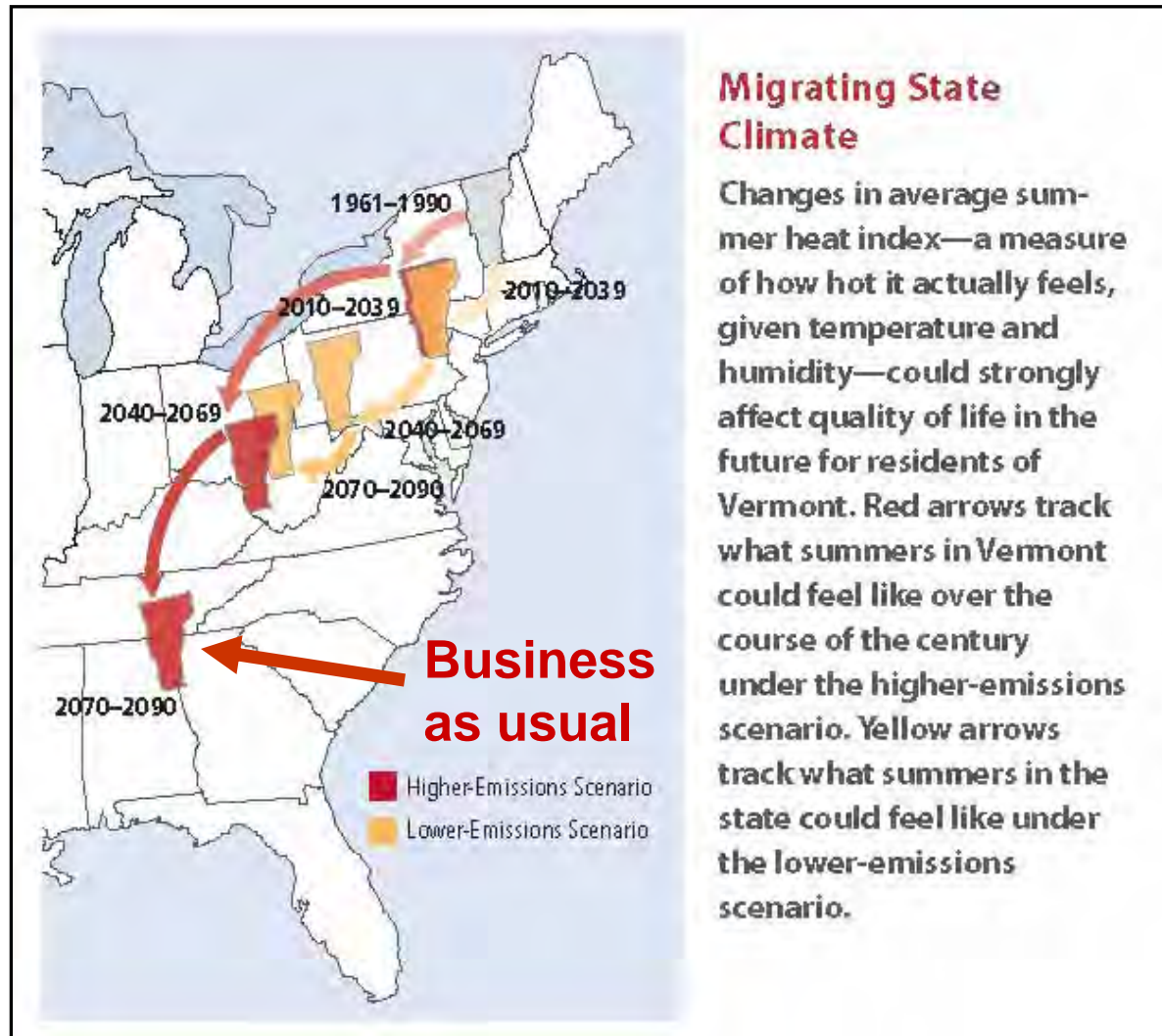


[°C]

Vermont's Future with High and Low GHG Emissions

What
about VT
forests?

Sub-tropical
drought areas
moving into
southern US

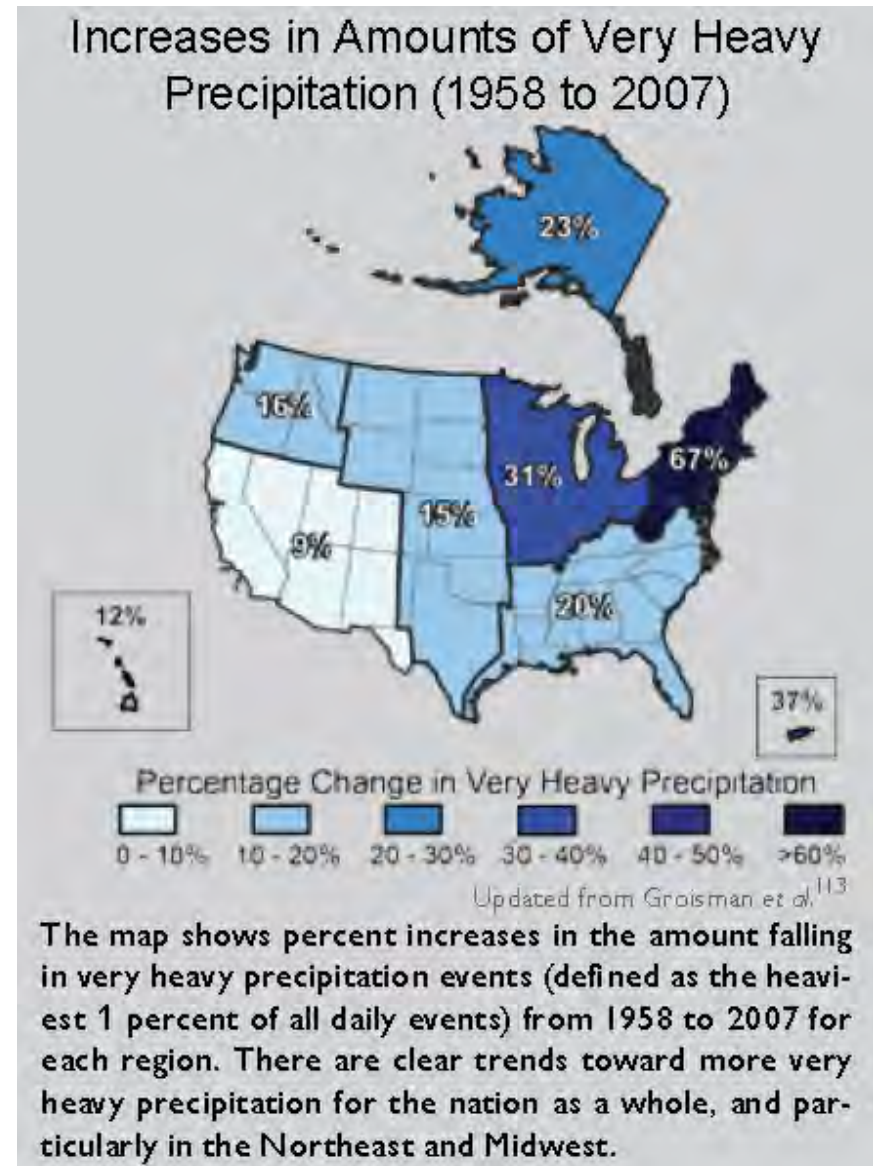


*NECIA,
2007*

Very Heavy Precipitation Is Increasing

(USGCRP, 2009)

- **Precipitation Extremes**
- Most of the observed precipitation increase during the **last 50 years** has come from the increasing frequency and intensity of heavy downpours.
- **67% increase in Northeast**



**Summer
“stormflow”
increasing**

**Most rivers
>50%**

***Lent (2010)
USGS, Me***

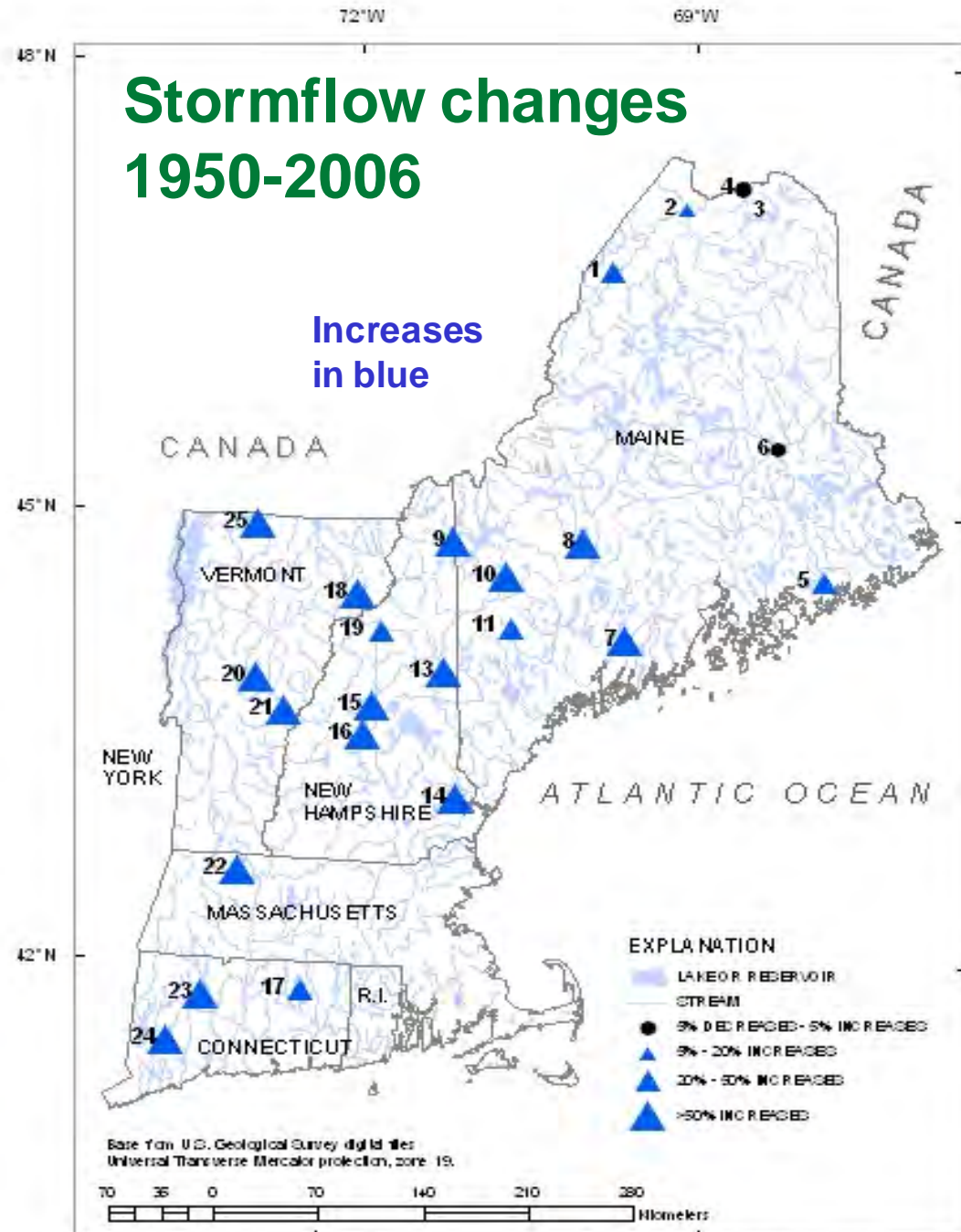


Figure 4. Geographic distribution of summer stormflow trends, 1950-2006.

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 (7%/°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 VT Flood Situations

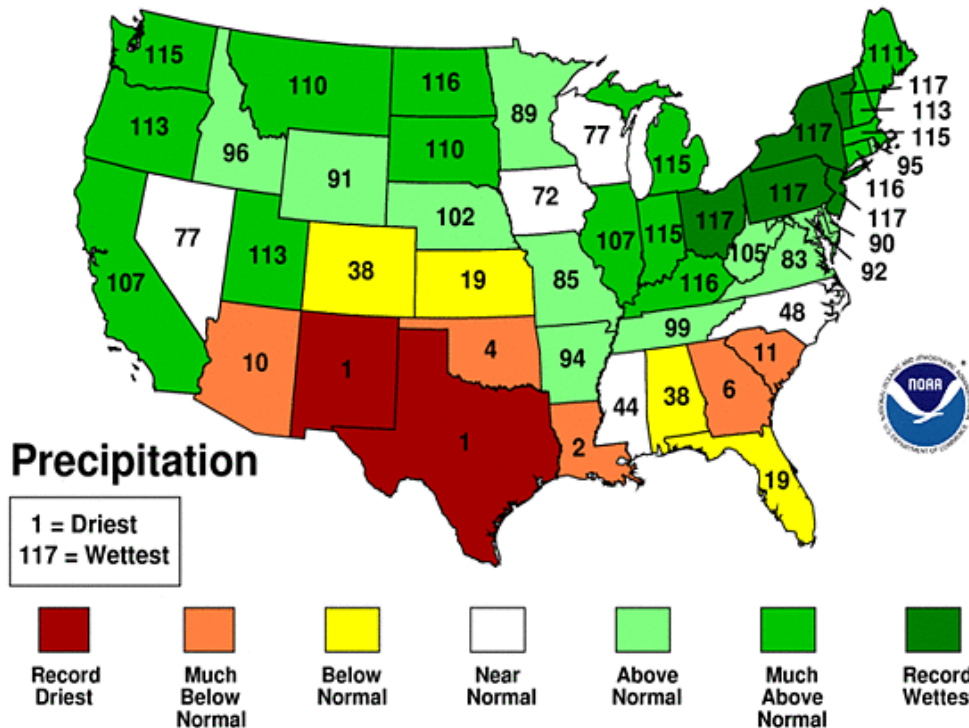
- **Spring flood:** heavy rain and warm weather, melting large snowpack from 2010-11 winter
 - 70F (4/11) and 80F(5/27) + heavy rain
 - record April, May rainfall: 3X at BTV
 - Severe Winooski flood
 - Lake Champlain record flood stage of 103ft
- **Irene flood: tropical storm** moved up east of Green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

2011 Floods: VT and NY

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

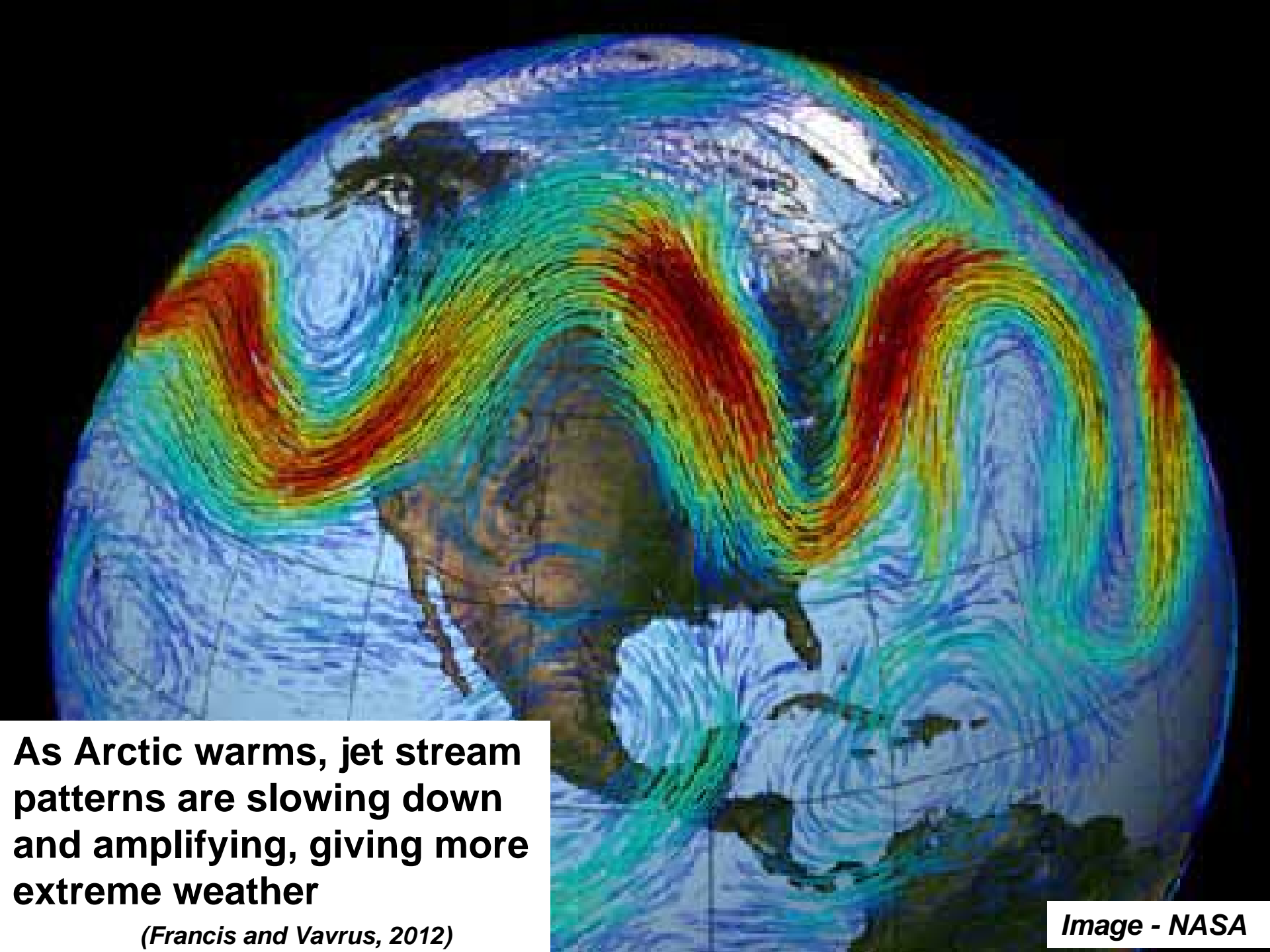
March-August 2011 Statewide Ranks

National Climatic Data Center/NESDIS/NOAA



March-August, 2011

- Record wet : OH to VT
- Record drought: TX & NM
- ‘Quasi-stationary’ pattern



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

(Francis and Vavrus, 2012)

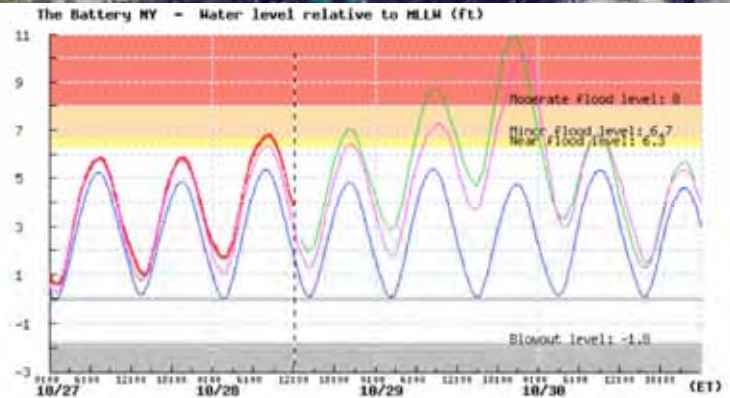
Image - NASA

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 in mean sea-level**
 - **Gulfstream warm + 5°F**
 - **Blocking high: NE Canada**
 - **13 ft storm surge**



Increasing CO₂ is long-lived driver

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
 - Increases snowfall from coastal storms in winter
- **Snow and ice down, less sunlight reflected**
 - Warmer Arctic in summer
 - Warmer northern winters
 - Less ice-cover: more evaporation
 - More lake-effect snowstorms

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**
 - stress on food supplies

Can We Stop “Dangerous Climate Change”?

- **Yes: Quickly stabilize atmospheric CO₂**
- **This means an 80% drop in CO₂ 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 CO₂ to 1,000 ppm—and in time melt icecaps**
 - **Can we “sequester” CO₂ (put it back in the earth)?**

Why Is It Difficult for Us?

- **Fossil fuels reserves are worth \$20-30T**
 - Regulating emissions of CO₂ 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
 - 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 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 to incentivize mitigation and pay for the long-term costs**

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**
- **We must manage our society better!**

Broad Guidelines or Rules to Minimize Impacts

- **Minimize the lifetime of human waste products** 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 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**

The Future Is Not Our Past

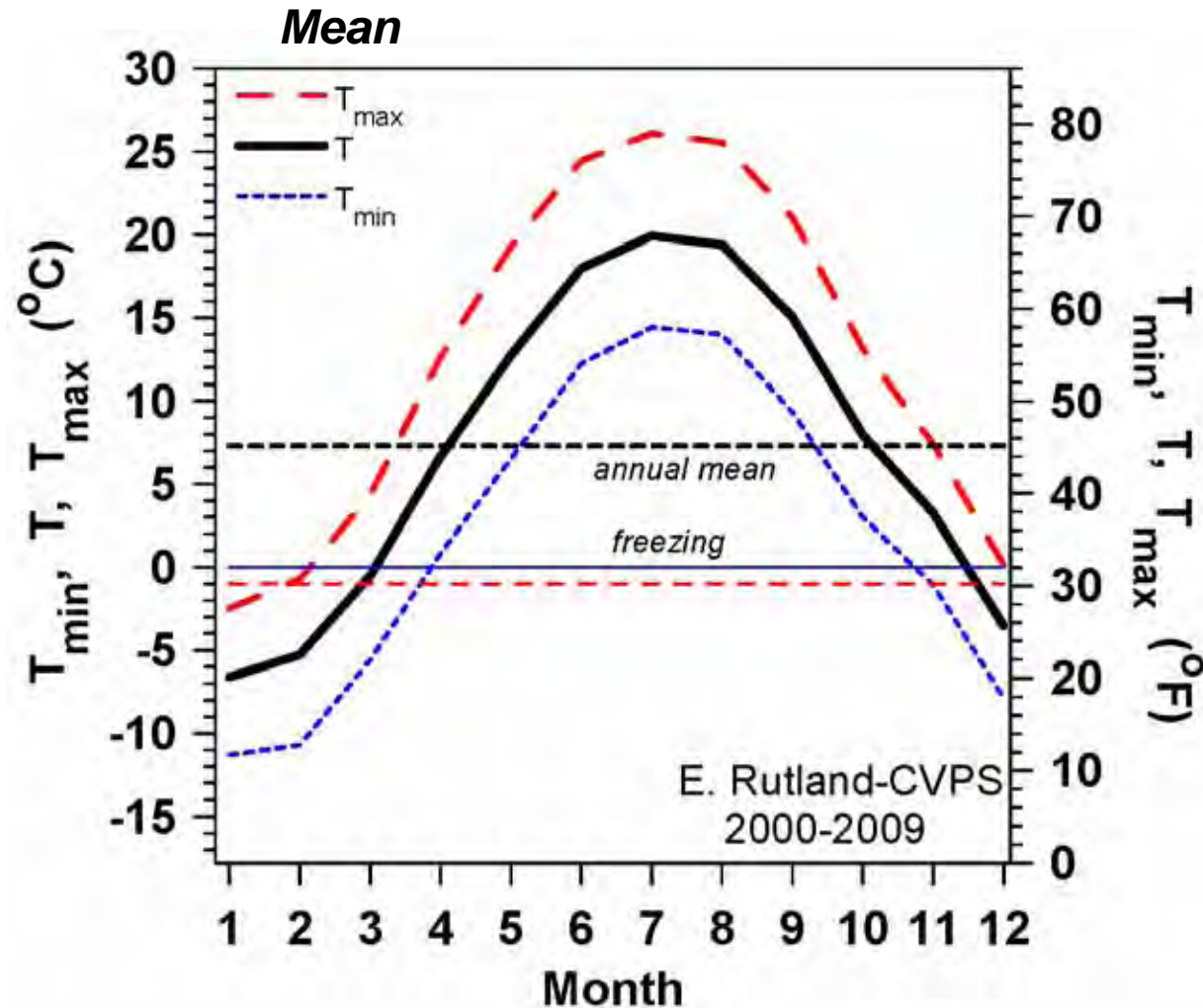
- **Collectively, we create the future, so we need to plan for a transition to a sustainable society**
- **Efficient society**
- **Renewable technologies to replace fossil fuels**
- **Needs real, deep community discussion**

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*

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



What Do We Need To Do?

- **The transition to a sustainable society will take decades and a community effort**
- **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

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°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
 - Increase soil organic matter

But If Growth Can't Save Us, Surely Technology Can?

- We have lost sight of the **critical distinction** between the human-made world and the natural world
- **We understand the human-made world, the world of computers & technology—because we made it—it is predictable and controllable, except when we are careless (& earthquakes)**
[E. F. Schumacher (1977). *A Guide for the Perplexed*]
- **The same is not true of the natural world – which is far more complex and alive. Our understanding is limited; prediction & control are not possible**

But If Growth Can't Save Us, Surely Technology Can?

- Now our world of technology is having a global impact on the natural world and **it must be carefully managed** — because we are dependent on the natural world
 - **But this is incompatible with our ideology**

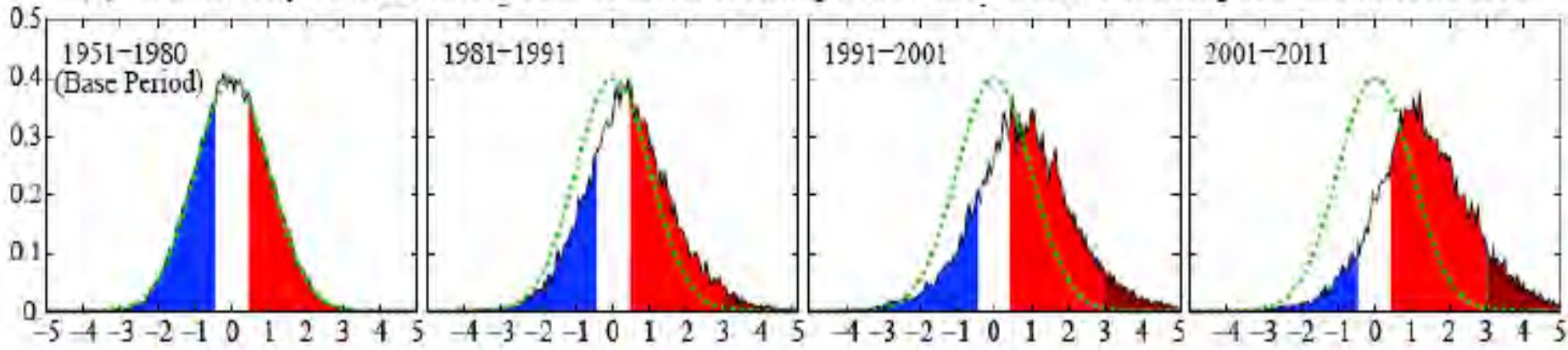
Technology can be Useful



**30 mph Danish electric tricycle:
with 150 mile range**

Increasing Temperature Extremes is “Global Warming”

(a) Probability Distribution of Northern Hemisphere Land Summer Temperature Anomalies



(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 $> +3\sigma$ is global warming**
 - Increased from baseline 0.15% to 10% in 45 years

Sea-level Rise Will Eventually Flood Coastal Cities

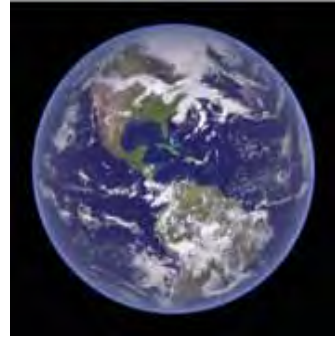
- **Late 20th-century sea-level rise: 1 foot / century**
- **21st century: Likely to triple to 3 - 4 feet / century**
 - **And continue for centuries (accelerating for business as usual)**
- *<http://www.nature.com/news/us-northeast-coast-is-hotspot-for-rising-sea-levels-1.10880>*

‘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]**

Our Choices Are Bounded



- *Whether we use technical, social or religious language*
- **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 or theological doctrine**
- **The response of the Earth system to our human-centered arrogance will be so large this century that we will rethink our doctrine**
- **We would be wise to rethink sooner rather than later**