Historic Trends & Future Climatic Projections for VT

Dr. Alan K. Betts
Atmospheric Research, Pittsford, VT 05763

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

VULNERABILITY ASSESSMENT WORKSHOP
Montpelier, VT
July 9, 2012
Climate of Vermont

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

- $T_{\text{max}} - T_{\text{min}}$

- Mean daily range of $T$ varies with season

- Related to RH and $LW_{\text{net}}$
• 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: \( \text{CO}_2 \) and \( \text{H}_2\text{O} \)

January 2, 2012: NASA
What Is Happening to Vermont?

• PAST 40/50 years (anthropogenic forcing detectible)

• Warming twice as fast in winter than summer

• Winter severity decreasing

• Lakes frozen less by 6.9 (±1.5) days / decade

• Growing season longer by 3.7 (±1.1) days / decade

• Spring coming earlier by 2-3 days / decade

• Extremes increasing

• Evaporation increases with $T$

• More ‘stationary weather patterns’
Vermont Temperature Trends
1961-2008

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

Note: trends since 1961: early 1950’s warmer. Trends for last 4-5 decades consistent with model projections for the next few decades
Slope Depends on Start-Date

Attribution for temperature change
(AR4, Chapter 9, p.703)

- **Blue**: natural forcings
- **Red**: natural & anthropogenic forcings
- **Separate around 1960-1970** (Solid line is data: Bands represent 90% of models)
Global Temperature Rise
1880 – Present

NASA-GISS, 2011
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
- Rivers and soils similar?
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
Latest detailed map

- USDA: VT Hardiness Zone Map 1976-2005 [mean 1990]

- A trend of half a zone in 16-20 years is +2.5-3.1°F/decade [triple rise of winter mean]

- http://planthardiness.ars.usda.gov/PHZMWeb/
Heating Degree Days and Days below 0°F (Burlington)

- HDD trend 289 (±37) /decade
- \( T_{\text{min}} < 0°F \) 4.1 (±0.7) days /decade
Lilac Leaf and Bloom

- Leaf-out -2.9 days/decade; Bloom -1.6 days/decade
- Large year-to-year variation related to temperature: 4 to 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
First and Last Frosts Changing

- Growing season for frost-sensitive plants increasing $3.7 \pm 1.1$ days / decade
- A help for growing “local food”
Shrinking Winter: Pittsford, VT (Freeze-up used to be mid-November)

December 2006:
• Warmest on record

January 7, 2007

January 10, 2008
Warm Fall:
• Record Arctic sea-ice melt
• Snow cover in December, ground unfrozen
October 2011– March 2012

- Warmest 6 months on record
- My garden frozen only 67 days
- No permanent snow cover west of Green Mtns
- Contrast snowy winter 2010-11
Early Spring: Daffodils, Forsythia
79°F on March 22, 2012

Pittsford Vermont
3/22/12

Pittsford Vermont
3/24/12
Temperature and Precipitation Maps


- Visual grasp of spring 2012 climate extreme
- Continental-scale patterns: Records keep falling
- Note fires in dry Colorado
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
- *Positive feedback: Less snow, warmer winters (2012)*
Arctic Sea Ice Loss Has Accelerated

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

- Record ice loss in 2007
  - most ice now thin and only 1-2 years old
- Open water in Oct. Nov. favors warmer Fall

(www.nsidc.org)

At the end of Nov. Hudson Bay was still nearly ice-free.
Sea Ice Trends

• Sea ice is thinning rapidly

• Observed September decline appears to be faster than IPCC-AR4 climate model projections

• AR5 projections should be faster!
June snow cover minimum

- New minimum by $10^6$ km$^2$ (1971-2000 ref)
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
Summer dry-down

- Wet in spring
- Soil moisture falls: summer dry-down
- Low humidity & little rain
- Can lock-in drought in central US
Recently Many Wet Summers in Vermont

- **Direct fast evaporation off wet canopies**
- *Positive evaporation-precipitation feedback, coupled to synoptic system frequency*
Cooling Degree Days and Days $T_{\text{max}} > 90^\circ\text{F}$

- CDD trend 37 (±11) /decade
- $T_{\text{max}} > 90^\circ\text{F}$ no trend - 2004-2011 were wet
- 2002 last summer with ‘average’ rain
Fall Climate Transition

- Vegetation postpones first killing frost
- Deciduous trees still evaporating: moist air with clouds
- Water vapor & cloud greenhouse reduces cooling at night and prevents frost
- Till one night, dry air advection from north gives first hard frost.
- Vegetation shuts down, leaves turn, skies become clearer and frosts become frequent

- The opposite of what happens in Spring with leaf-out!

Later frost: Growing season getting longer
Carbon Dioxide Is Increasing

Atmospheric CO$_2$ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

Winter
Summer
Upward trend + 2ppm/year
2009 Was “Good” for the Earth

Fossil Fuel Emissions: Actual vs. IPCC Scenarios

- 4%/year

Back on growth: 2010, 2011
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 absorb and reradiate IR from the surface, giving climate suitable for life by warming planet 30°C

• CO₂ rise alone has a small warming effect

BUT…
Water Phase Changes 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 and ice decrease and reduced SW reflection **amplifies warming** in Arctic in summer and mid-latitudes in winter.
- Doubling CO$_2$ will warm globe about 3°C (5°F)
  - Much more in the North and over land, which responds faster than oceans
  - (also transpiration coupling of vapor and CO$_2$ fluxes)
Climate Change Projections

• IPCC 2007 (Fourth Assessment - AR4)
• AR5 in progress with improved models – expect no large change
• Higher resolution: Improved aerosols, sea-ice & carbon cycle (probably slightly increased climate sensitivity and wider range between models)
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)
Climate Model Predictions

Temperature A1B: 2080-2099

DJF Precipitation A1B: 2080-2099

JJA Precipitation A1B: 2080-2099

Temperature A1B: 2080-2099

DJF

JJA

°C

(mm day⁻¹)

°C

(mm day⁻¹)
• Mean of 16 CMIP3 models
More confidence where shaded

Northern areas wetter
Observed Changes: Total Precip and Heavy Precip. (upper 1%)

While U.S. annual average precipitation has increased about 5 percent over the past 50 years, there have been important regional differences as shown above.

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.
Since 1970, the annual average temperature in the Northeast has increased by 2°F, with winter temperatures rising twice this much.

Warming has resulted in many other climate-related changes including:

- More frequent days with temperatures above 90°F
- A longer growing season
- Increased heavy precipitation
- 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
- Rising sea surface temperatures and sea level

Over the next several decades, temperatures in the Northeast are projected to rise an additional 2.5 to 4°F in winter and 1.5 to 3.5°F in summer.

By mid-century and beyond, however, today's emissions choices would generate starkly different climate futures; the lower the emissions, the smaller the climatic changes and resulting impacts.

By late this century, under a higher emissions scenario:

- 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.
- Cities that today experience few days above 100°F each summer would average 20 such days per summer, while certain cities, such as Hartford and Philadelphia, would average nearly 30 days over 100°F.
- Short-term (one- to three-month) droughts are projected to occur as frequently as once each summer in the Catskill and Adirondack Mountains, and across the New England states.
- Hot summer conditions would arrive three weeks earlier and last three weeks longer into the fall.
- Sea level in this region is projected to rise more than the global average.
Vermont’s Future with High and Low GHG Emissions

What about skiing?

What about tropics?

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
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)

Many Challenges Face Us

• Extreme weather: Floods, fires, & drought
  - 32 weather disasters >$1B in 2011

• Melting Arctic and permafrost—methane release is positive feedback

• Ecosystem collapse, including perhaps forest and ocean ecosystems

• Collapse of unsustainable human population
Extreme Weather (precip.)

- *Precip. is condensation of atmospheric water vapor (large latent heat release)*
- *Saturation vapor pressure at cloud-base increases steeply with temperature (6%/°C)*
- *More latent heat organizes storms, increasing convergence of vapor*
- *Quasi-stationary large-scale flow means longer rain events in low-pressure convergent regions, and longer droughts in high-pressure divergent regions*
- *As climate changes, quasi-stationary large-scale modes appear to be more frequent*
- *Wet surface: more evaporation and runoff*
2011 Vermont Floods

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

- Two classic VT flood situations

  - Spring flood: heavy rain and warm weather, melting large snowpack
    - 70F (4/11) and 80F(5/27) + heavy rain
    - record April, May rainfall: 3X at BTV

- Irene flood: tropical storm moved up east of Green Mountains dumping 6ins rain on wet soils (Floyd on 9/17/1999 had similar rain - but with dry soils there was less flooding)
Discussion

• This talk http://alanbetts.com/research

• VTCCAdaptClimateChangeVTBetts10-29.pdf http://www.anr.state.vt.us/anr/climatechange/Adaptation.html

• Vermont Climate Change Indicators

• Seasonal Climate Transitions in New England
- **Highlights:** ice-out and first leaf: probable 14-36 days earlier
- **Sea-level misprint:** was cm for expansion (?); now USGS 3-4ft with ice-melt

---

**Changes on NH Climate expected by 2100.**
Assumptions to be used when assessing habitat and species vulnerability.

<table>
<thead>
<tr>
<th>Stressor</th>
<th>Indicator</th>
<th>Changes expected by 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct temperature effects</td>
<td>Temperature increase in winter</td>
<td>Low: Increases 5-8°F. High: Increases 9-13°F.</td>
</tr>
<tr>
<td></td>
<td>Temperature increase in summer</td>
<td>Low: Increases 3-7°F. High: Increases 6-14°F.</td>
</tr>
<tr>
<td></td>
<td># of days above 90°F (10 now)</td>
<td>Low: 30 days. High: 70 days.</td>
</tr>
<tr>
<td></td>
<td># of days above 100°F</td>
<td>Low: 6 days. High: 20 days.</td>
</tr>
<tr>
<td></td>
<td>Days with snow</td>
<td>Low: Decreases 33%. High: Decreases 50%.</td>
</tr>
<tr>
<td></td>
<td>River ice-out</td>
<td>Earlier by 11-13 days</td>
</tr>
<tr>
<td>Changes in precipitation</td>
<td>Winter precipitation</td>
<td>Increases 20-30% with a higher percentage as rain.</td>
</tr>
<tr>
<td></td>
<td>Frequency of heavy rains</td>
<td>Increased</td>
</tr>
<tr>
<td></td>
<td>Summer drought</td>
<td>Increased frequency of 1-3 month droughts, becoming annual under high emissions scenario.</td>
</tr>
<tr>
<td>Hydrology</td>
<td>Change in stream flow</td>
<td>More headwater streams become intermittent during summer months. Reduced summer flow in most rivers.</td>
</tr>
<tr>
<td>Fire</td>
<td>Change in fire frequency</td>
<td>Higher temperatures and more drought events lead to increased fire frequency</td>
</tr>
<tr>
<td>Wind</td>
<td>Change in wind intensity</td>
<td>More frequent and more intense storms lead to higher frequency of damaging wind events.</td>
</tr>
<tr>
<td>Sea level rise</td>
<td>Sea level rise by expansion</td>
<td>Low: 31&quot;. High: 75&quot;.</td>
</tr>
<tr>
<td>Ocean acidification/salinity change</td>
<td>Changes in pH/salinity of seawater</td>
<td>Decrease in pH. Salinity varies depending on freshwater runoff and latitude.</td>
</tr>
<tr>
<td>Human response to climate change</td>
<td>Infrastructure changes</td>
<td>Seawalls, dams, culverts, wind power, transmission lines and other changes in developed and undeveloped landscapes change habitat permeability and alter habitat type and quality.</td>
</tr>
<tr>
<td>Altered species interactions</td>
<td>Growing season length</td>
<td>Up to 43 days longer</td>
</tr>
<tr>
<td></td>
<td><strong>First leaf</strong></td>
<td>Earlier by 6.7-15 days</td>
</tr>
<tr>
<td></td>
<td>Lilac bloom</td>
<td>Earlier by 6.3-16 days</td>
</tr>
</tbody>
</table>