Climate Change in Mountainous Regions

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Learning Objectives

- After this class you should:
  - Have a basic understanding of recent global and regional climate trends and their drivers
  - Recognize the significance of climate change for mountainous regions
  - Be able to distinguish between climate variability and change and how they affect and complicate the interpretation of long-term trends and weather events
  - Have a basic understanding of how future climate change will affect snow over the western US and Utah

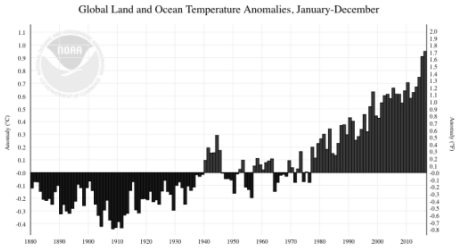
Discussion

What aspects of our understanding of climate change do we know with medium or high confidence?

In what areas do we still have large uncertainties?

Recent Global Climate Trends

Recent Temperature Trends

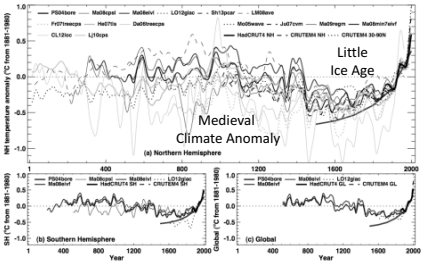


"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, [and] sea level has risen."
– IPCC (2013)

NOAA/NCEI

A Longer View

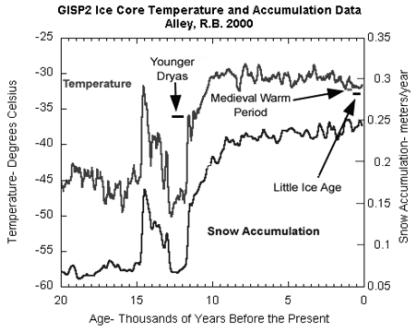
Anomalies relative to 1881–1980 mean



"The mean NH temperature of the last 30 or 50 years very likely exceeded any previous 30- or 50-year mean during the past 800 years…Confidence is lower in this finding prior to 1200, because the evidence is less reliable and there are fewer independent lines of evidence."
– IPCC (2013)

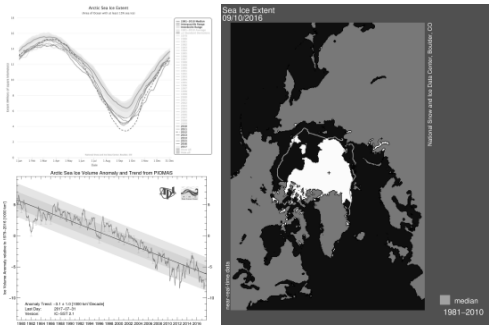
Masson–Delmotte et al. (2013, IPCC AR5)

An Even Longer View



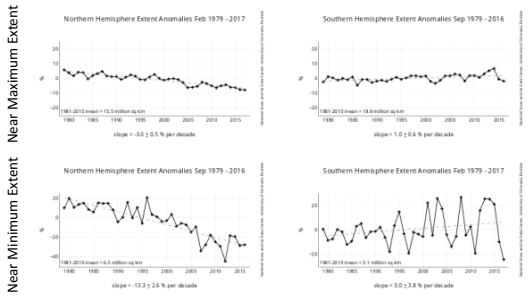
Source: NRC (2002), Alley (2000), https://www.ncdc.noaa.gov/paleo/pubs/alley2000/alley2000.html

Arctic Sea Ice



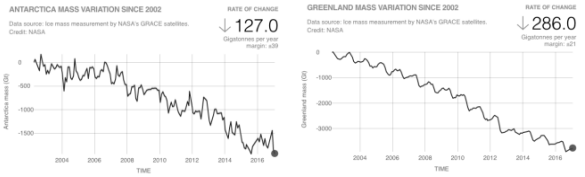
Source: http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/
http://nsidc.org/arcticseaicenews/2015/09/2015_arctic-minimum/

Arctic vs. Antarctica



Source: https://nsidc.org/data/seaice_index/

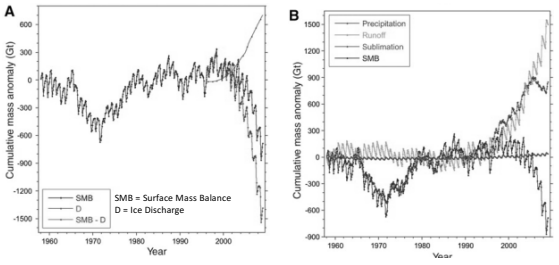
Land Ice (Antarctica/Greenland)



365 Gigatones = 1 mm sea level rise

Source: Grace satellite, http://climate.nasa.gov/vital-signs/land-ice/

Greenland Mass Balance



"The total 2000–2008 mass…is equally split between surface processes (runoff and precipitation) and ice dynamics. Without the moderating effects of increased snowfall and refreezing, post-1996 Greenland ice sheet mass losses would have been 100% higher."

Source: van den Broeke (2009, Science)

Glaciers

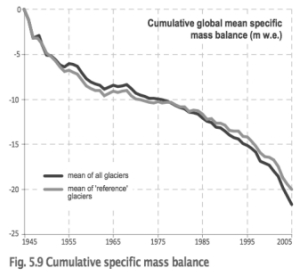
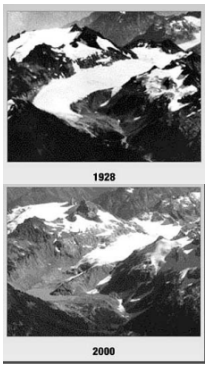


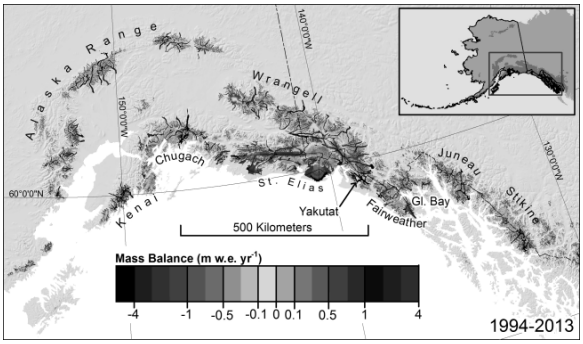
Fig. 5.9 Cumulative specific mass balance



South Cascade Glacier, WA

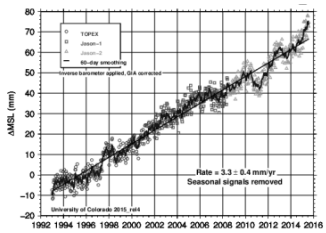
Source: http://www.grid.unep.ch/glaciers/pdfs/glaciers.pdf, USGS

Glaciers



Source: https://news.agu.org/press-release/alaska-glaciers-make-large-contributions-to-global-sea-level-rise/

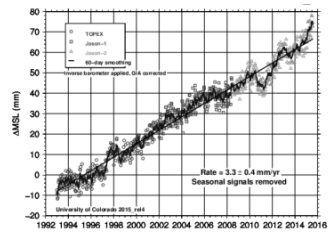
Sea Level Rise



Rise since 1870 = 195 mm (7.5 inches)
Rate of rise is increasing
Current rate = 3.3 mm/yr = 1.3 in/decade

Source: http://sealevel.colorado.edu/

Sea Level Rise



Contributors (1993–2010)*
Ocean Thermal Expansion = 1.1 mm/yr
Glacial Mass Loss = .76 mm/yr
Greenland Ice Sheet = .33 mm/yr
Antarctic Ice Sheet = .27 mm/yr
Land Water Storage = .38 mm/yr

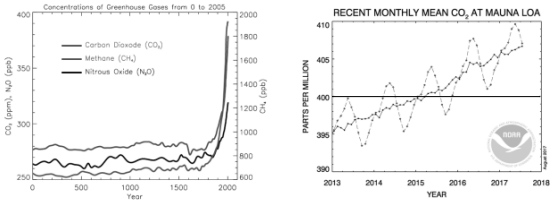
*Middle of estimate range noted

Source: http://sealevel.colorado.edu/

Attribution of Recent Climate Change

Source: 2005 Cox Radio Interactive & Cox Radio, Inc.

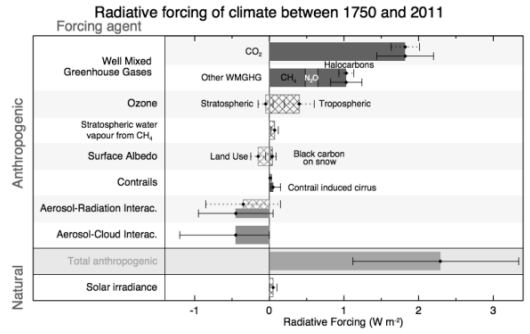
Greenhouse Gas Concentrations



- CO2 more than 35% higher than pre-industrial
  - Half of increase since mid 1970s
  - Very likely exceeds highest natural concentrations over at least the last several hundred thousand years
- Increases in other greenhouse gases too

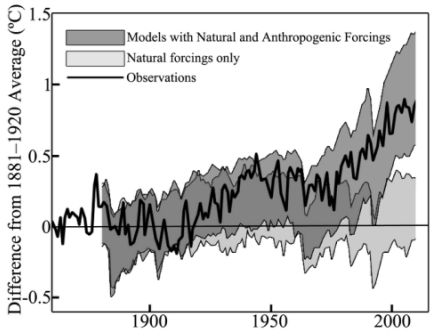
Source: Forster et al. (2007), https://www.esrl.noaa.gov/gmd/ccgg/trends/

Known Climate Forcings



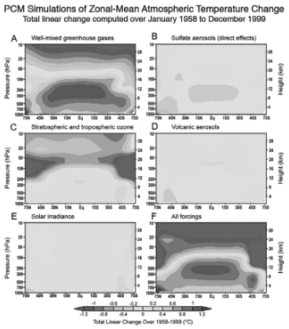
Source: Myhre et al. (2013)

Climate Model Sensitivity



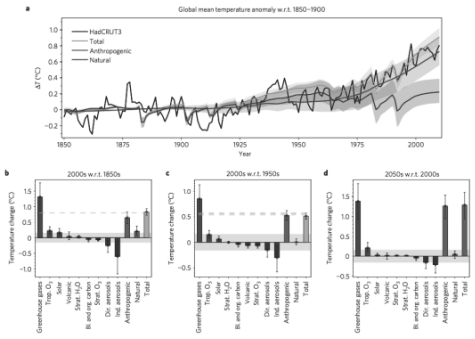
Source: Steenburgh (2014), adapted from Knutson et al. (2013)

Climate Fingerprinting



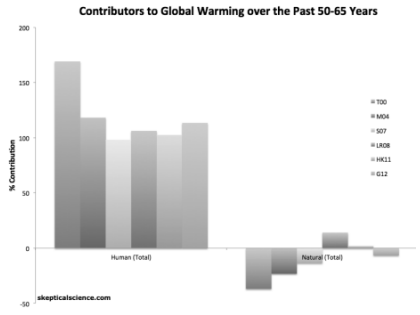
Source: http://www.globalchange.gov/sites/globalchange/files/sap1-1-draft3-all.pdf

Recent Estimates



Source: Huber and Knutti (2012)

Recent Estimates



Source: http://www.skepticalscience.com/a-comprehensive-review-of-the-causes-of-global-warming.html

Key Remaining Uncertainties

- Aerosol-radiation and aerosol-cloud-radiation interactions
- Future climate forcings
  - Trajectory of anthropogenic forcings like GHG concentrations, aerosols, dust, etc.
- Sensitivity of climate to those forcings (still a wide range of possible outcomes)
- Regional climate and impacts
- Shifts in weather and climate extremes
  - Water is often the agent that delivers climate change impacts

Climate Change in Mountainous Regions

Discussion

What makes mountains important for the study of climate change and its impacts?

What are some of the possible consequences of climate change in mountainous regions?

Significance of Mountains

"*Mountains are important sources of water, energy, minerals, forest and agricultural products and areas of recreation. They are storehouses of biological diversity, home to endangered species and an essential part of the global ecosystem.*"
– UN (1992)

Source: Beniston (2003)

Significance of Mountains

- Mountains cover about 25% of continental surfaces
  - Mountains, Hills, and Plateaus cover 46%
- 26% of world's population lives in mountains or their foothills
- 40% of world's population lives in watersheds originating in mountainous regions
- Mountain-based resources indirectly provide sustenance for over half the world's population

Source: Meybeck et al. (2001), Beniston (2003)

Significance of Mountains

- Mountains are unique areas for detecting climate change and assessing climate-related impacts
  - Vegetation, snow, ice, and hydrology vary rapidly with elevation and over short distances
  - Mountains have high biodiversity with large ecosystem gradients (ecotones)
  - Mountains are often climate and ecosystem islands compared to the surrounding plains

Source: Beniston (2003)

Specific Areas of Concern

- Water, snow, and ice
  - Amount, timing, and seasonality of precipitation and snowfall
  - Depth and duration of the seasonal snowpack
  - Changes in "permanent" snow and ice
  - Amount, timing and seasonality of runoff
  - Extreme events and hazards such as floods, landslides, avalanches, etc.
- Vegetation, forests, and biodiversity
  - Vulnerability to climate-change thresholds
  - Impacts to natural and human-managed ecosystems and agriculture
- Health
  - Shifts in vector-borne diseases (e.g., Malaria)
- Tourism
  - Skiing, hiking, etc.

Source: Beniston (2003)

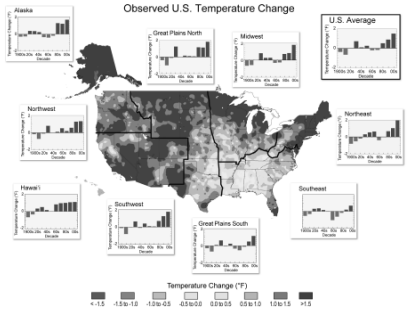
The Western US

Discussion

How do you think climate change will affect the aforementioned areas of concern in the western US?

How will changes vary regionally and with aspect and elevation?

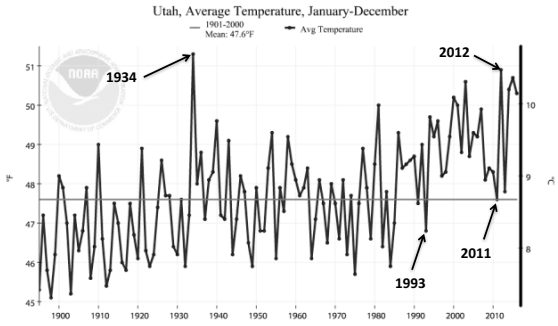
US Temperature Trends



Note: Based largely on low-elevation stations & doesn't capture the small-scale variability

Source: http://nca2014.globalchange.gov/highlights/report-findings/our-changing-climate

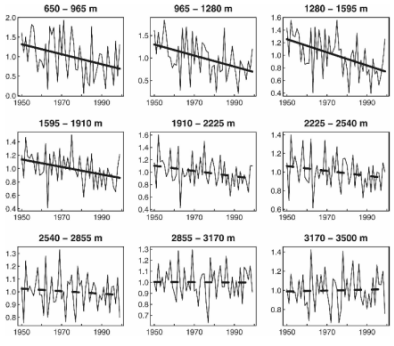
Utah



NOAA/NCEI

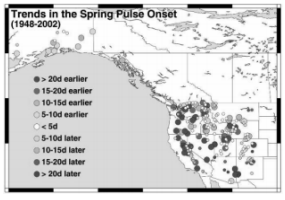
Western Snowpack Trends

SWE/P
Fraction of winter precipitation retained in the snowpack on April 1st

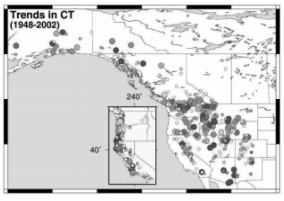


Source: Pierce et al. (2008)

Western Streamflow Trends



Timing of spring-pulse onset



Date of center of mass of annual flow
(Inset: Non-snowmelt-dominated guages)

"The immediate forcings for the spatially coherent parts of the year-to-year fluctuations and longer-term trends of streamflow timing have been higher winter and spring temperatures. Although these temperature changes are partly controlled by the [Pacific decadal oscillation (PDO)], a separate and significant part of the variance is associated with a springtime warming trend that spans the PDO phases."
– Stewart et al. (2005)

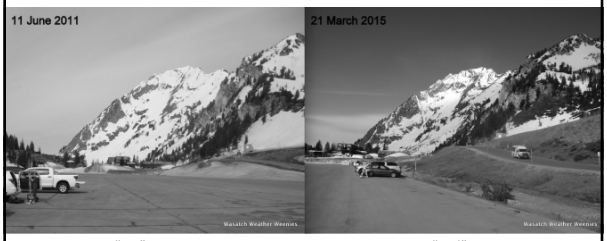
Source: Stewart et al. (2005)

Weather/Climate Variability vs. Change

"Weather is mood, climate is personality"
– Marshall Shepherd

Source: http://news.uga.edu

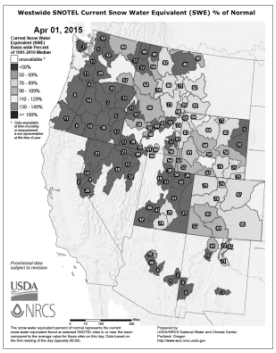
A Tale of Two Seasons



"Big" Year

"Bad" Year

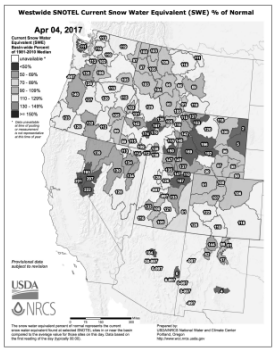
WY2015: West



"This Is the New Normal"
- CA Gov. Jerry Brown

Source: NRCS

WY2017: West



"This drought emergency is over, but the next drought could be around the corner. Conservation must remain a way of life."
- CA Gov. Jerry Brown

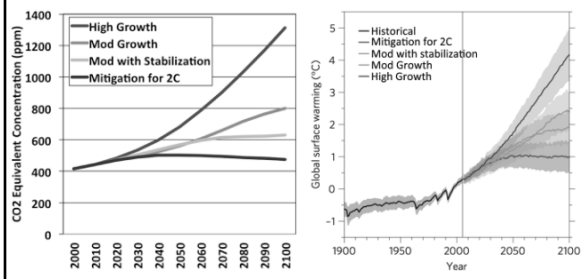
Source: NRCS

Discussion

What is the new normal?

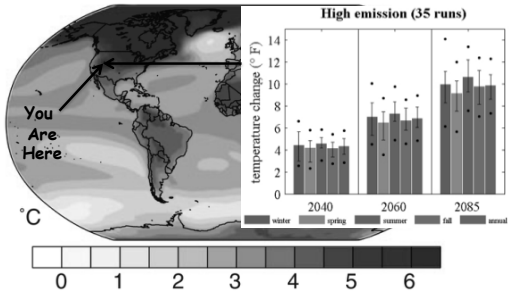
The Future

Future Projections



Source: IAMC RCP Database, Steenburgh (2014, adapted from Knutti and Sedlacek 2012)

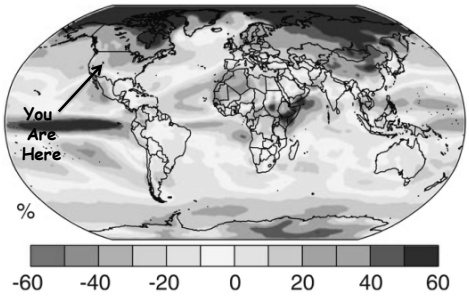
Wintertime Temperature Change



1986–2005 to 2080-2099
High-Growth Scenario

Source: Steenburgh (2014, adapted from Diffenbaugh and Giorgi 2012), Court Strong

Wintertime Precipitation Change



1986–2005 to 2080-2099
High-Growth Scenario

Source: Steenburgh (2014, adapted from Diffenbaugh and Giorgi 2012), Court Strong

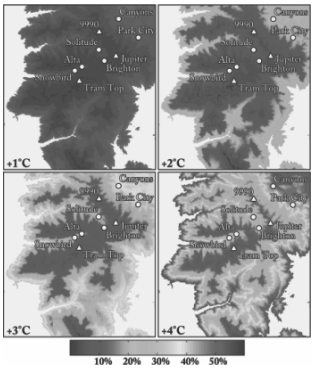
Discussion

What do you think this means for the future of snow and skiing in the west?

Snowfall Vulnerability

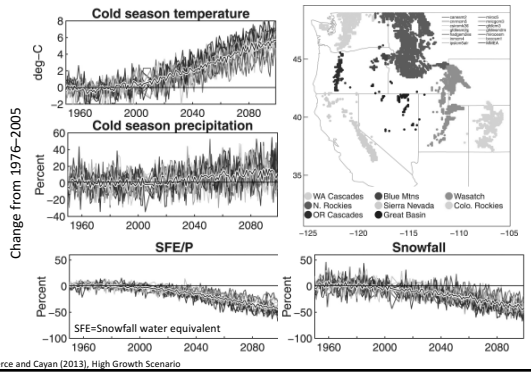
Vulnerability greatest @ lower elevations

Upper elevations less vulnerable (but not immune)



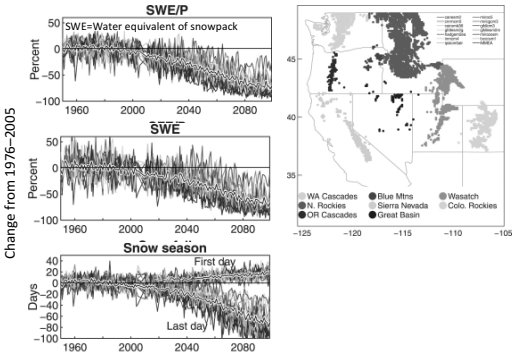
Source: Steenburgh (2014, adapted from Jones 2010)

Downscaled Projections



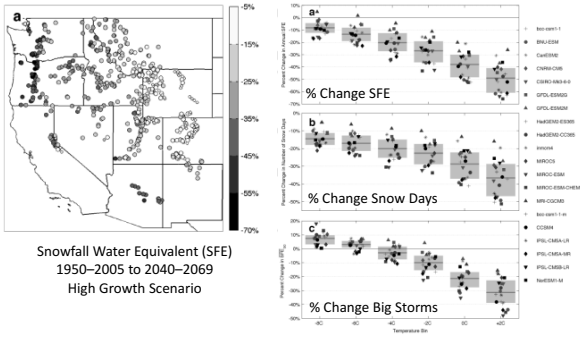
Pierce and Cayan (2013), High Growth Scenario

Downscaled Projections



Pierce and Cayan (2013), High Growth Scenario

Snowfall Projections



Lute et al. (2015)

Summary

- Warming of the climate system is unequivocal
- Multiple lines of evidence support the conclusion that most (perhaps all) of the recent warming is human caused
- Future warming depends on future emissions and other human influences and the sensitivity of the climate system
- Impacts on mountainous regions vary regionally and with elevations and extend to people in non-mountaonous regions
- The competitive advantages of high elevation resorts will likely increase in time due to the uneven loss of snow and snowpack with altitude

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