Introduction to Mountain Weather and Climate

Atmos 6250: Mountain Meteorology
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Reading

Meyers, M., and W. J. Steenburgh, 2013: Mountain weather prediction: Phenomenological challenges and forecast methodology. Mountain Weather Research and Forecasting: Recent Progress and Current Challenges. T. Chow, S. de Wekker, and B. Snyder, Eds., Springer, 1–34.

Beniston, M., 2003: Climate change in mountain regions: A review of possible impacts. *Climatic Change*, **59**, 5–31.

Questions

How much of the Earth's land surface is covered by mountains?

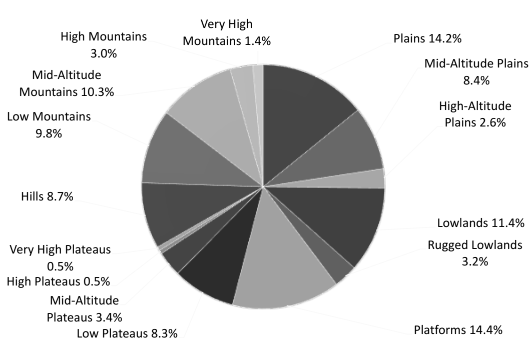
What fraction of the Earth's population lives in mountainous areas?

Global Relief Topology*

*Does not include glaciated areas of Greenland and Antarctica

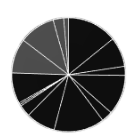
Source: Meybeck et al. (2001), *Mountain Research and Development*

Global Relief Topology

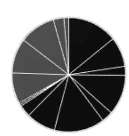


Source: Meybeck et al. (2001), *Mountain Research and Development*

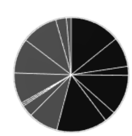
Global Relief Topology



Mountains Only
24.5%



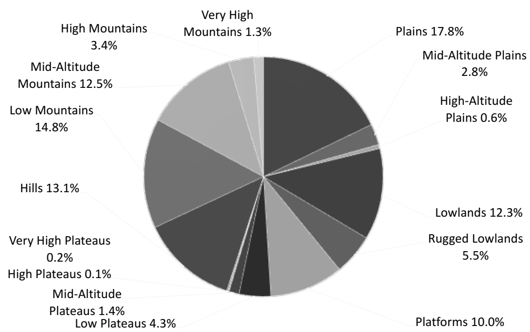
Mountains & Hills
33.2%



Mountains, Hills, & Plateaus
45.9%

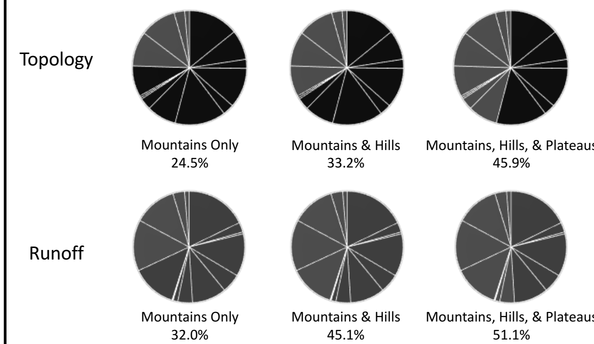
Source: Meybeck et al. (2001), *Mountain Research and Development*

Global Runoff (Internal & External)



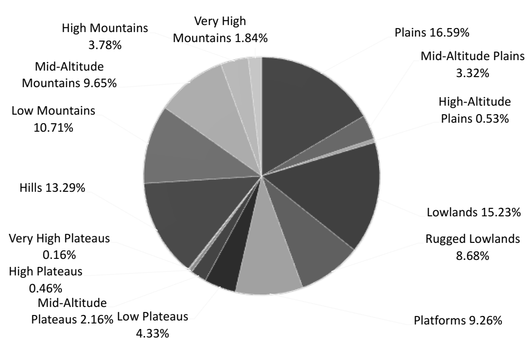
Source: Meybeck et al. (2001), *Mountain Research and Development*

Topology vs Runoff



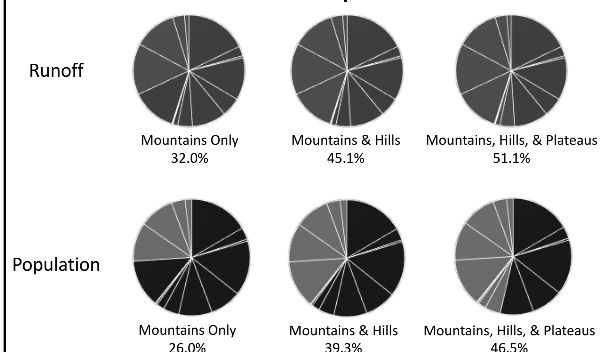
Source: Meybeck et al. (2001), *Mountain Research and Development*

Global Population



Source: Meybeck et al. (2001), *Mountain Research and Development*

Runoff vs. Population



Source: Meybeck et al. (2001), *Mountain Research and Development*

Key Points

- Mountains, hills, plateaus cover nearly half (45.9%) the global land surface and contain nearly half (46.5%) of the world's population
- Mountains and hills generate a greater fraction of runoff relative to their area than other landforms, serving as global "water towers"
- You don't need to live in mountains or hills to be affected by their weather, climate, and hydrologic impacts

Mountain Weather Hazards and Economics

©SL Trib/Galbraith

Forecast Challenges in Mountainous Regions

- Extreme topography, hydrologic, meteorological, climatological, and socio-economic contrasts
- Sparse or unrepresentative observations
- Weather forecasts must be spatially detailed
- Many models poorly resolve or account for local topographic, atmospheric, land-surface, ecologic, and hydrologic processes

Questions

What weather-related hazards are strongly influenced by orography?

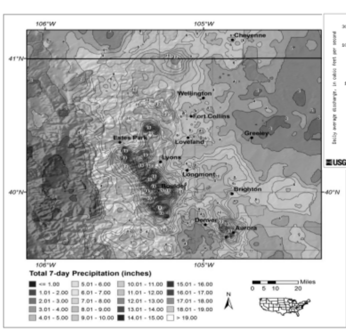
Weather-Related Hazards Strongly Influenced by Orography

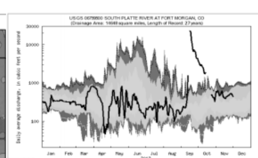
- Floods and flash floods
- Debris flows
- Wildland and urban-interface fires
- Air quality
- Snowstorms
- Icestorms
- Avalanches
- High winds (e.g., downslope, gap)
- Severe convective storms (hail, flash floods, etc.)
- Transportation and road maintenance

Floods

- Produced by prolonged precipitation events
- Often associated with orographic precipitation enhancement
- Modulation of intensity and spatial distribution of precipitation by topography can determine the catchment basins affected
- Additional factors can include snowmelt, ecology, etc.

Example: Front Range Sep 2013





8 Fatalities
19,000 homes/buildings damaged
1,500 homes/buildings destroyed
$3 Billion in losses

Source: NOAA (2014, http://www.nws.noaa.gov/om/assessments/pdfs/14colorado_floods.pdf)

Big Thompson Canyon Before

Source: http://www.denverpost.com/2013coloradofloods/ci_24115527/before-after-photos-colorado-flood-2013

Big Thompson Canyon After

Source: http://www.denverpost.com/2013coloradofloods/ci_24115527/before-after-photos-colorado-flood-2013

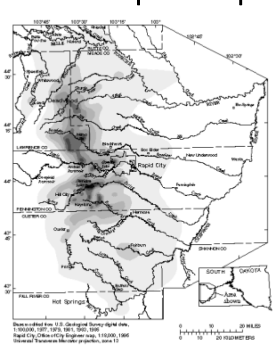
Impacts Away from Mountains

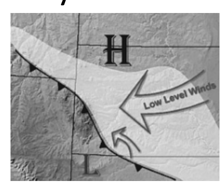
Source: http://www.denverpost.com/2013coloradofloods/ci_24115527/before-after-photos-colorado-flood-2013, Map: Google

Flash Floods

- Rapid flooding often produced by heavy rain associated with convective storms (although there are other mechanisms)
- Mountains can play a role by influencing the formation and movement (or lack thereof) of deep convection and mesoscale convective systems

Example: Rapid City Flood 1972





238 killed
3,000 injured
1335 homes destroyed
Dam failures contributed to losses

Source: http://www.weather.gov/unr/1972-06-09

Flash Flood Example: Black Hills 1972

Impacts also felt away from mountains (Rapid City)

Source: http://pubs.usgs.gov/fs/fs-037-02, Photos by Perry Rahn

Weather-Related Debris Flows

- Heavy mountain precipitation or snowmelt leads to a water-laden mass of soil and rock flowing (sometimes violently) down a mountainside
- Initiated typically on slopes > 25 degrees
  - Can move into lower angle areas
- Major concern on fire-denuded slopes

Thistle, UT Slide of April 1983

4 million m^3 of debris

Produced lake that flooded Thistle, UT-6, UT-89, and railroad

Lake drained by tunneling

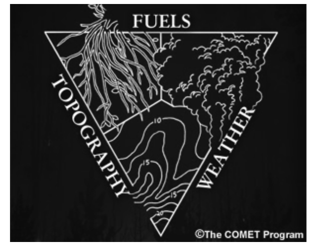
$400+ Million in damage

Most expensive landslide in US history

Easy to see today!

Source: http://geochange.er.usgs.gov/sw/changes/natural/elnino/

Wildland Fire



Weather and topography form two sides of the fire environment triangle and play an important role in generating extreme fire behavior

Source: COMET

Bigger and More Frequent Fires

Large wildfire activity increased suddenly and markedly in the mid-1980s, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons. The greatest increases occurred in mid-elevation, Northern Rockies forests, where land-use histories have relatively little effect on fire risks and are strongly associated with increased spring and summer temperatures and an earlier spring snowmelt.
- Westerling et al. (2006), Science

Trends 1984–2011 by Ecoregion

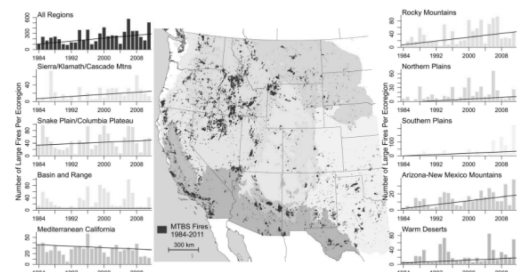


Figure 1. Western U.S. trends for number of large fires in each ecoregion per year. The center map illustrates ecoregions based on Levels II and III of the Omernik ecoregion system. The Wyoming Basin and Colorado Plateau ecoregions had too few large fires for trend analysis at the ecoregion level, and are shown in gray. MTBS-mapped fires are shown in red. The surrounding bar plots display the number of large fires in each ecoregion over the 1984–2011 study period. The black line on each plot indicates the Theil-Sen estimated slope for each ecoregion, with slope values and significance shown in Figure 2a.

Source: Dennison et al. (2014), GRL

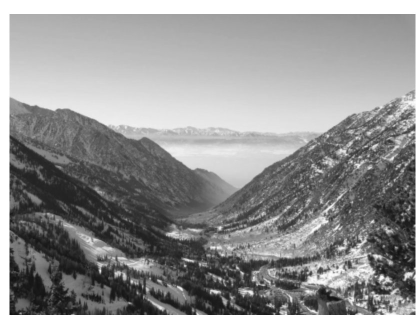
Billion Dollar Wildfire Disasters

- Oakland 1991
- California Fall 1993
- Western US 1994
- Western US 2000
- Western US 2002
- California 2003
- Western US 2006
- Western US 2007
- Western US 2008
- Western US 2009
- TX–NM-AZ 2011
- Western US 2012
- Valley-Butte Fires CA 2015
- Western US 2015
- Gatlinburg, TN 2016

San Diego, CA, Oct 2003

Source: https://www.ncdc.noaa.gov/billions/, Photo: http://interwork.sdsu.edu/fire/purpose.htm

Air Quality



Pollutants frequently trapped in basins and valleys, leading to poor air quality episodes

Most Polluted Cities (PM2.5 Episodes)

By Short-Term Particle Pollution

- #1: Bakersfield, CA
- #2: Fresno-Madera, CA
- #2: Visalia-Porterville-Hanford, CA
- #4: Modesto-Merced, CA
- #5: Fairbanks, AK
- #6: San Jose-San Francisco-Oakland, CA
- #7: Salt Lake City-Provo-Orem, UT
- #8: Logan, UT-ID
- #9: Los Angeles-Long Beach, CA
- #10: Reno-Carson City-Fernley, NV
- #11: El Centro, CA
- #12: Lancaster, PA
- #13: Missoula, MT
- #14: Sacramento-Roseville, CA
- #14: Anchorage, AK
- #16: Yakima, WA
- #17: Seattle-Tacoma, WA
- #17: Pittsburgh-New Castle-Weirton, PA-OH-WV
- #19: Medford-Grants Pass, OR
- #20: Philadelphia-Reading-Camden, PA-NJ-DE-MD
- #21: Harrisburg-York-Lebanon, PA
- #21: South Bend-Elkhart-Mishawaka, IN-MI
- #23: Eugene, OR
- #24: Phoenix-Mesa-Scottsdale, AZ
- #25: Bend-Redmond-Prineville, OR

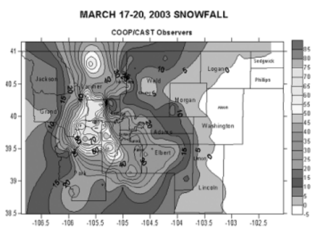
Western US Basins and Valleys

Source: http://www.lung.org/our-initiatives/healthy-air/sota/city-rankings/most-polluted-cities.html

Snowstorms

- Mountains affect intensity and distribution of snowfall, as well as snow levels through the blocking and channeling of airmasses
- Can be widespread or highly localized

2003 Front Range Blizzard



March 16–20, 2003
Up to 5 feet of snow, losses of > $300 million due largely to roof collapses

Source: http://www.pieglobal.com/statistics-and-observations-on-the-colorado-blizzard-of-2003/
http://www.ucar.edu/communications/newsreleases/2004/blizzard.html (photo by Carlye Calvin)

Ice Storms

- Mountains affect the blocking, damming, and channeling of shallow, cold airmasses, contributing to the development of thermodynamic profiles favorable for sleet or freezing rain

North American Ice Storm of 1998

January 5–9 1998
Northeast US and eastern Canada
100+ mm of freezing rain in some areas
$4+ Billion in damage
Channeling by orography critical (Roebber and Gyakum 2003, MWR)

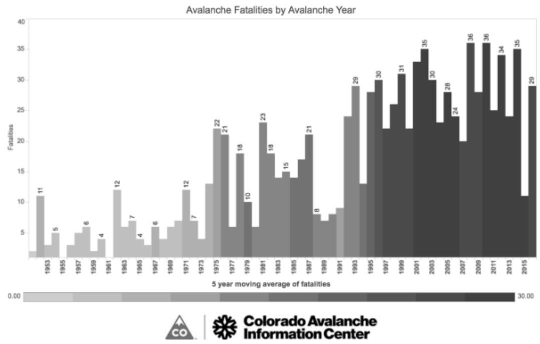
Photos: John Ferguson and Environment Canada

Avalanches

Weather and topography form two sides of the avalanche triangle

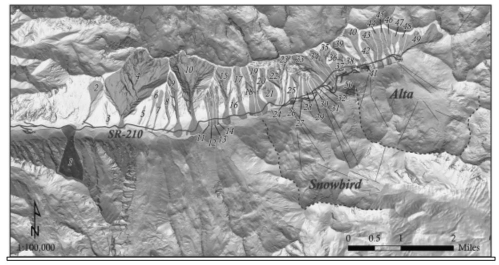
Source: http://www.avalanche-center.org/

Avalanches



Source: http://avalanche.state.co.us/accidents/statistics-and-reporting/

Little Cottonwood Canyon



"Based on data from the 1991/92 ski season, the estimated revenue loss for ski resorts in upper LCC during the closure of SR-210 for avalanche hazard is \$1.4million day^{-1} [\$2.3 million day^{-1} in 2013 dollars (Blattenberger and Fowles 1995)]"
– Campbell and Steenburgh (2014)

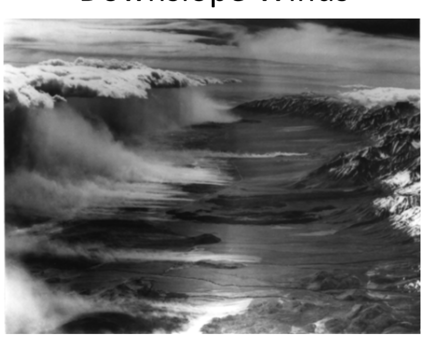
Image: Steenburgh (2014), Courtesy Adam Naisbitt

Little Cottonwood Canyon, 23 Dec 1988 (Courtesy National Weather Service)

High Winds

- Mountains can produce local flow accelerations and damaging winds
- Examples include gap winds and downslope winds
- In addition to concerns for structures, terrain-induced turbulence and rotors are a major hazard for aircraft

Downslope Winds



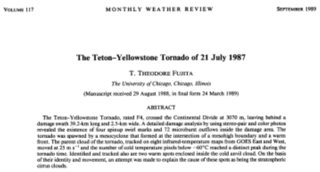
Downslope wind and rotor cloud over the Owens Valley east of the Sierra Nevada

Source: http://www.atmos.washington.edu/Atlas/phot_oro09.html, Photo taken by Robert Symons & courtesy Morton G. Wurtele

Severe Convective Storms

- Yes, these occur in the mountains too
- In addition, the severe storm environment of the high plains and portions of Europe and South America are strongly influenced by regional topographic effects

Teton Tornado


Volume 117 MONTHLY WEATHER REVIEW September 1989

The Teton–Yellowstone Tornado of 21 July 1987

T. Theodore Fujita

The University of Chicago, Chicago, Illinois

(Manuscript received 29 August 1988, in final form 24 March 1989)

ABSTRACT

The Teton–Yellowstone Tornado, rated F4, crossed the Continental Divide at 3070 m, leaving behind a damage swath 39.2-km long and 2.5-km wide. A detailed damage analysis by using stereo-pair and color photos revealed the existence of four spinup swirl marks and 72 microburst outflows inside the damage area. The tornado was spawned by a mesocyclone that formed at the intersection of a mesohigh boundary and a warm front. The parent cloud of the tornado, tracked on eight infrared-temperature maps from GOES East and West, moved at 25 m s^{-1} and the number of cold temperature pixels below −60°C reached a distinct peak during the tornado time. Identified and tracked also are two warm spots enclosed inside the cold anvil cloud. On the basis of their identity and movement, an attempt was made to explain the cause of these spots as being the stratospheric cirrus clouds.

F4
Crossed Continental Divide @ 3070 m
Damage swath 39.2 km long and 2.5 km wide

Source: Fujita (1989, MWR)

Transportation and Road Maintenance

- 70% of US roads in snowy regions that receive 13 cm or more of snow a year
- 24% of US weather-related vehicle crashes occur on snowy, slushy, or icy pavement
- 15% occur during snowfall or sleet
- 1,300 fatalites/yr on snowy, slushy, or icy pavement
- 116,800 injuries per year on snowy, slushy, or icy pavement
- Winter road maintenance accounts for 20% of state DOT maintenance budgets
- State and local agencies spend more than $2.3 billion on snow and ice control
- Not all mountain weather related, but illustrates importance of winter weather

Source: http://www.ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm

Mountain Weather Not All Bad!

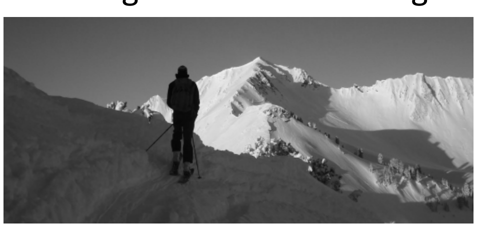
Avenues Foothills, 29 November 2010

Mountain Weather Economics

- Outdoor recreation generates
  - In the US
    - $646 billion in consumer spending
    - 6.1 million direct jobs
  - In the western US including Alaska and Hawaii
    - 197.5 billion in consumer spending
    - 1.8 million direct jobs
    - $61.1 billion in salaries and wages

Source: https://outdoorindustry.org/research-tools/outdoor-recreation-economy/, 16 Aug 2015

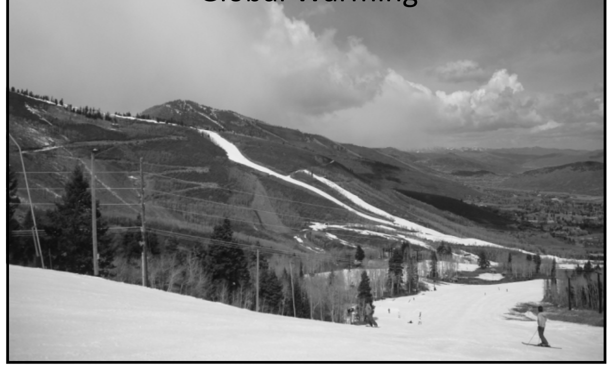
Skiing and Snowboarding



- $7.5 Billion in direct spending at US resorts
- 57 million US resort visits per year
- Backcountry gear now ~8% of equipment sales
- Highly sensitive to weather and climate variability

Source: https://www.nsaa.org/, http://www.snowsports.org/research-surveys/snow-sports-fact-sheet/, 16 Aug 2015

Mountains Regions and Global Warming



Questions

Why do we care about climate change in the mountains?

What do you think some of the impacts of climate change will be in mountainous regions?

Importance of Mountains

- 40% of the global population lives in watersheds originating from mountains
- Mountains are often ecological islands with unique species and strong ecosystem gradients
- Mountains are popular areas for ecotourism

Source: Beniston (2003)

Potential Impacts of Climate Change in Mountainous Regions

- Hydrology: Shifts in distribution, seasonality, amount, and type (e.g., rain or snow) of precipitation and runoff
- Ecology: Shifts and losses of vegetation, forests, and biodiversity
- Human Health: Shifts in vector-borne diseases
- Tourism: Beneficial and adverse effects

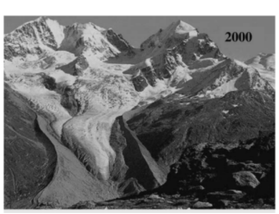
Source: Beniston (2003)

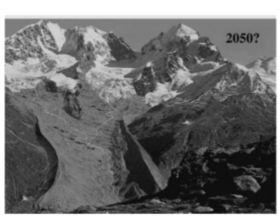
Hydrologic Consequences

- More precipitation falling as rain instead of snow in areas near the melting point during winter
- More snowfall in some colder, high altitude and high latitude areas with first few degrees of warming
  - Eventually nearly all altitudes lose
- Substantial losses of most mountain glaciers
- Runoff changes that requiring mitigation and adaption (easier for advanced than developing countries)

Source: Beniston (2003)

Projections for Tschierva Glacier, Switzerland





Source: Beniston (2003), Courtesy: Max Maisch, University of Zurich

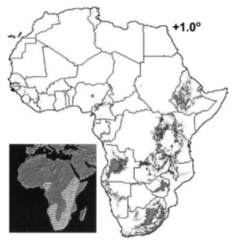
Ecosystem Consequences

- Multifaceted
  - Likely loss of coldest climate/ecosystem zones at mountain peaks
  - Migration of some species higher
  - Loss of some species due to adverse climatic change and invasive species
    - E.g., trout can only go so high
  - Survival of some species in existing habitat areas due to lower climate-change sensitivity
- In some instances, ecosystem disturbance is or will have a stronger influence than climate change

Source: Beniston (2003)

Human Health

- Vector-borne diseases like malaria may become more prevalent in some mountainous and highland regions



Changes in the incidence rate of Malaria for a 1°C temperature increase Grey denotes invasion areas that are currently malaria free

Source: Beniston (2003)

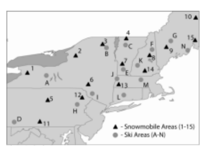
Tourism

- Direct impacts: Changes in the climatic conditions necessary for recreation activities
- Indirect impacts: Changes to mountain landscapes and socio-economic shifts in demand for activities and destinations
- These vary geographically and by sector
- May be adverse (loss of snow for skiing) and beneficial (e.g., longer hiking season)

Source: Beniston (2003)

Winter Sports in Northeast US

- Under A1Fi scenario (fossil-fuel intensive) by 2070–2099
  - Reliable snowmobile seasons (>50 days) virtually eliminated
  - Only 4 of 14 geographically distributed ski areas can maintain a 100-day ski season (with much greater snowmaking requirements)
  - Consider analysis to be conservative



Source: Scott (2008, Mitig. Adapt. Strat. Glob. Change)

Summary

- Mountain weather impacts are diverse and extend away from mountainous regions
- Global warming will have important impacts on mountain climate, ecology, human health, and tourism that are mainly adverse, but in some cases beneficial
- More in the lectures to come!

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