Orographic Precipitation

VU2: Course Number 707813

Jim Steenburgh
Fulbright Visiting Professor of Natural Sciences
University of Innsbruck
Department of Atmospheric Sciences
University of Utah
jim.steenburgh@utah.edu

Learning Objectives

- After this class you should
  - Recognize the key factors and physical mechanisms that influence the distribution and intensity of precipitation in complex terrain
  - Be able to critically evaluate scientific literature pertaining to orographic precipitation

Useful Papers


OROGRAPHIC EFFECTS ON PRECIPITATING CLOUDS

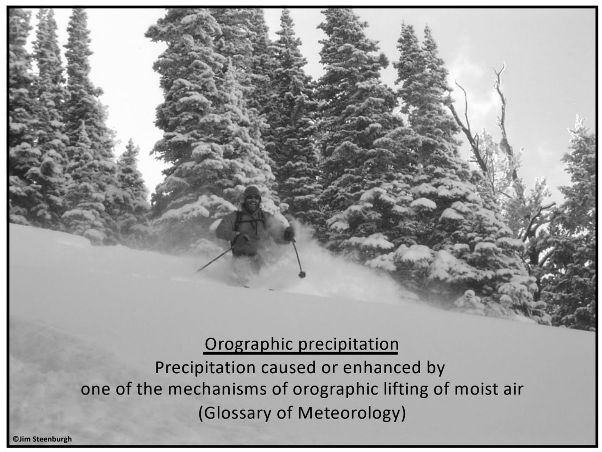
Chapter 6
Theory, Observations, and Predictions of Orographic Precipitation

Brian A. Colle, Ronald B. Smith, and Douglas A. Wesley

Chapter 7
Microphysical Processes Within Winter Orographic Cloud and Precipitation Systems

Pre-class reading

Houze (2012), Colle et al. (2013), Stoelinga et al. (2013)



<u>Orographic precipitation</u>
Precipitation caused or enhanced by
one of the mechanisms of orographic lifting of moist air
(Glossary of Meteorology)

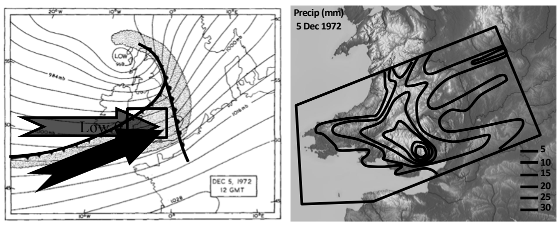
Key Factors

Key Factors

- Synoptic setting
- Size and shape of the topography
- Microphysical processes and time scales
- Dynamics of the terrain-induced flow
- Thermodynamics of orographically lifted air

Houze (2012)

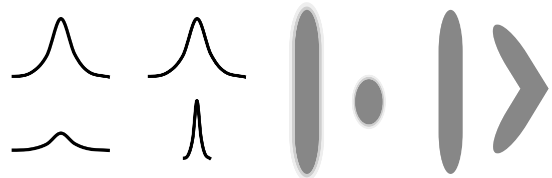
Synoptic Setting



"Large-scale synoptic factors determine the characteristics of the airmass which crosses the hills [and mountains], its wind speed and direction, its stability, and humidity"
– Sawyer (1956)

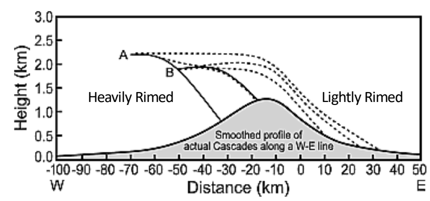
Images adapted from Browning et al. (1974)

Size and Shape of the Topography



Discussion: Why do each of these matter?

Microphysical Process and Time Scales



Hydrometeor growth, transport, and fallout

Hobbs et al. (1973); Houze (2012)

Dynamics of the Terrain-Induced Flow

Flow over or around (i.e. blocked) barrier?

$\hat{H} = NH/U$

- $\hat{H}$: Nondimensional Mountain Height (inverse Froude number)
- N: Brunt–Väsälä Frequency
- H: Mountain Height
- U: Barrier-normal wind speed

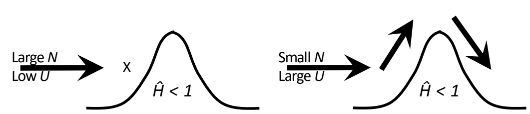
$\hat{H}_m = N_m H/U$

- N_m: Moist Brunt–Väsälä Frequency

Dynamics of the Terrain-Induced Flow

$\hat{H} = NH/U$

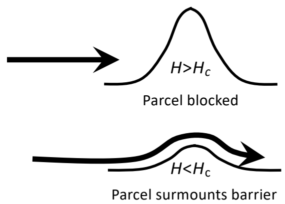
Blocking ($\hat{H}$ > 1) favored by	*Flow over ($\hat{H}$ < 1) favored by*
High stability	Low stability
Large mountain	Small mountain
Weak cross-barrier flow	Strong cross-barrier flow



Dynamics of the Terrain-Induced Flow

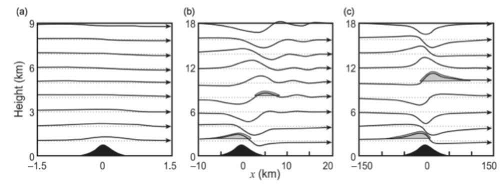
Critical Mountain Height (H_c)

- $H_c = U/N$
- H > H_c: Flow is blocked
- H < H_c: Flow surmounts barrier



Dynamics of the Terrain-Induced Flow

Gravity Wave Structure



Flow response dependent on incident wind speed, wind shear, and static stability as well as width, height, and shape of mountain

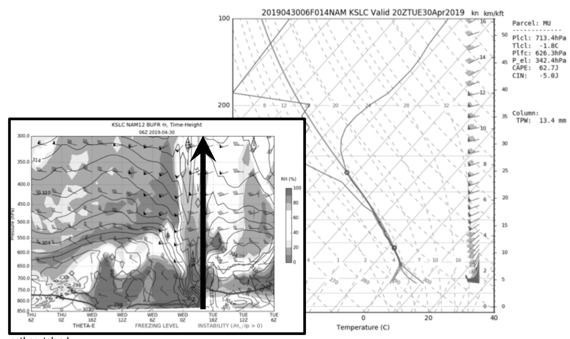
Important for both windward and leeward effects, as well as multiridge effects, including role of trapped waves

Houze (2012), Durran (1986)

Thermodynamics of Orographically Lifted Air

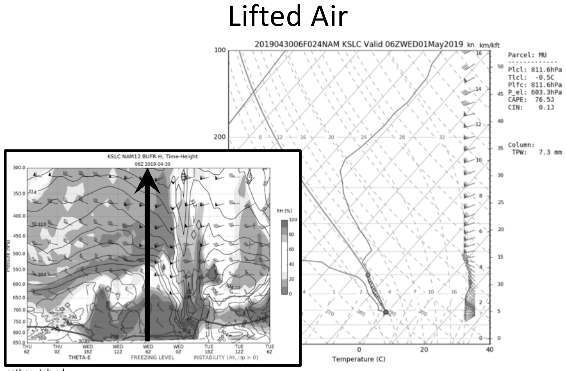
- Vertical profiles of temperature and humidity
- Depth of moisture
- Presence of stable layers, CAPE, potential instability, etc
- Best diagnosed with upstream time-height sections and soundings

Thermodynamics of Orographically Lifted Air



weather.utah.edu

Thermodynamics of Orographically Lifted Air



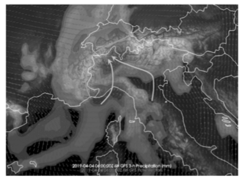
weather.utah.edu

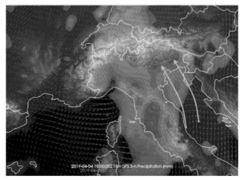
Dynamics of the Terrain-Induced Flow

Implications of flow over vs. flow around

Importance of Terrain-Induced Flow

- Determines location and intensity of orographically induced ascent/descent
- Influences precipitation dynamics/microphysics
- Can strongly influence transport of moisture

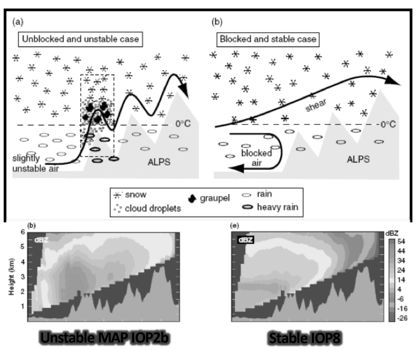




Flow Over vs. Flow Around

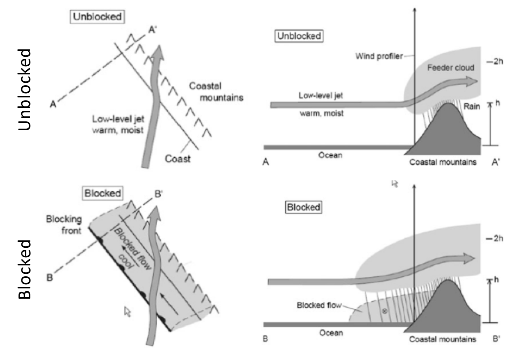
- Flow over ("unblocked")
  - Favored with weak static stability
  - Orographic ascent near barrier
  - Potential instability release (not always)
  - Possibility of Seeder Feeder
  - Can enhance contrasts in sub-cloud evaporation
- Flow Around ("blocked")
  - Favored with high static stability
  - May produce "blocking front"
  - Shifts orographic ascent upwind of barrier
  - Lowland or foothills precip can exceed high elevation precip
  - May result in terrain-induced convergence (windward, leeward, concavity, etc.)
- Both can operate simultaneously
  - Blocked valley flow, but unblocked flow at mid-mountain and crest level
  - Blocked unsaturated flow in one region, unblocked saturated flow in another

Flow Over vs. Flow Around



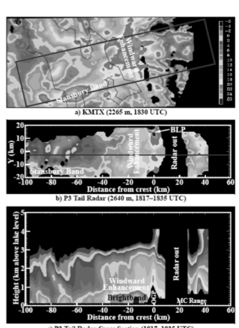
Medina and Houze (2003), Rotunno and Houze (2007)

Flow Over vs. Flow Around



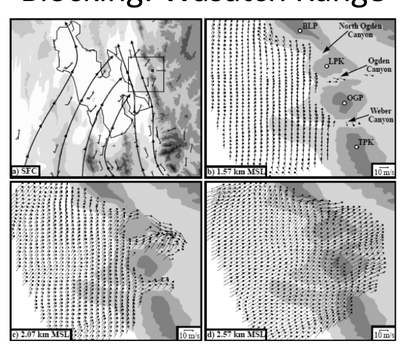
Neiman et al. (2002)

Blocking: Wasatch Range



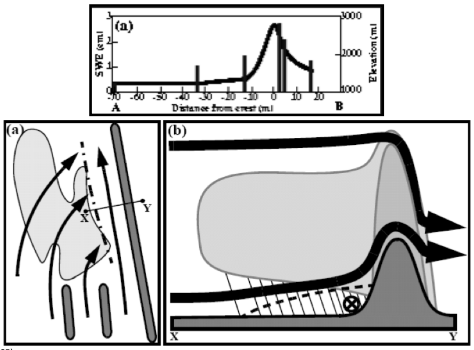
Cox et al. (2005)

Blocking: Wasatch Range



Cox et al. (2005)

Blocking: Wasatch Range

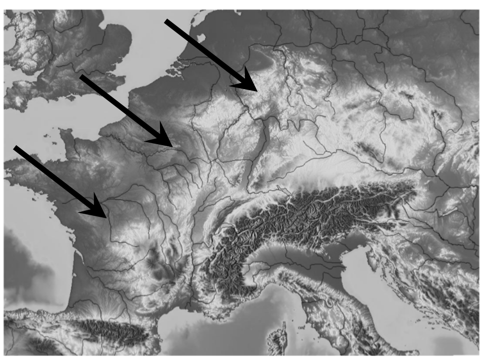


Cox et al. (2005)

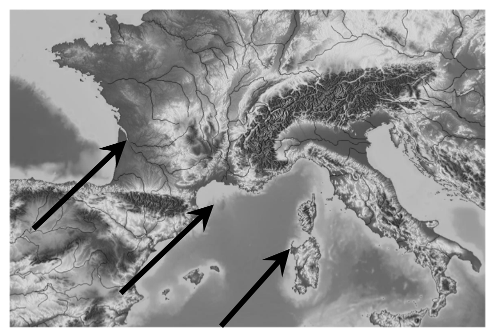
Discussion

Diagnose the possible flow patterns and influence on precipitation for the following idealized flows if low-level blocking occurs upstream of the Alps, but not over surrounding mountain ranges

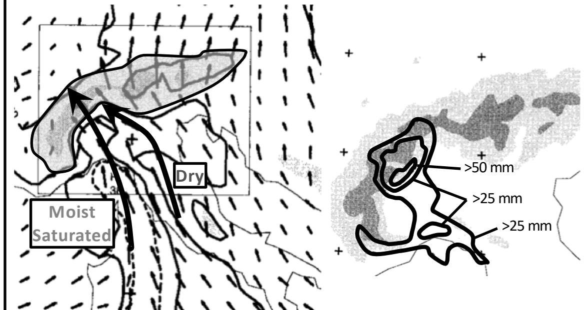
Northwesterly Flow Impinging on Alps



Southwesterly Flow Impinging on Alps

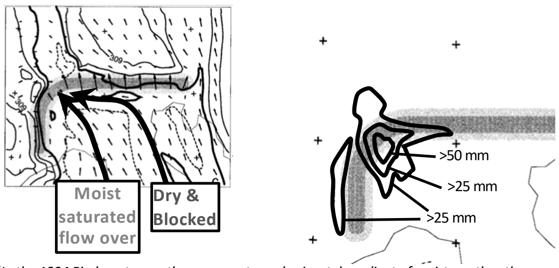


Hybrid: 1994 Piedmont Flood



Rotunno and Ferretti (2001)

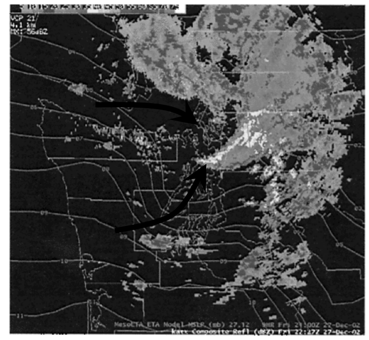
Hybrid: 1994 Piedmont Flood



"In the 1994 Piedmont case, there was a strong horizontal gradient of moisture; thus the western moist part of the airstream flows over, while the eastern drier part is deflected westward around the obstacle, and so a convergence is produced between the airstreams"
– Rotunno and Ferretti (2001)

Rotunno and Ferretti (2001)

Other Flow Around Effects



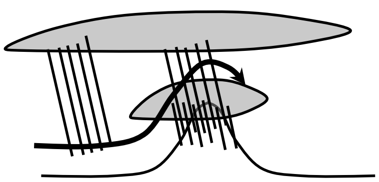
McDonnal and Colman (2003)

Additional Physical Mechanisms

Additional Physical Mechanisms

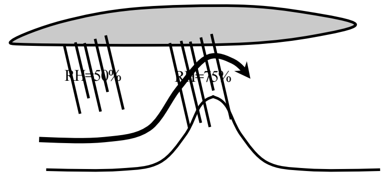
- Seeder-Feeder
- Sub-cloud evaporation contrasts
- Moist orographic convection

Seeder Feeder



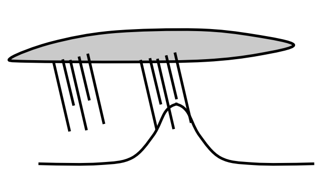
- Hydrometeors (snow or rain) generated in "seeder" clouds aloft fall through low-level orographic "feeder" clouds
- Feeder cloud might not precipitate otherwise
- Precipitation enhanced in feeder cloud primarily by
  - Collision-coalescence
  - Accretion

Sub-Cloud Effects



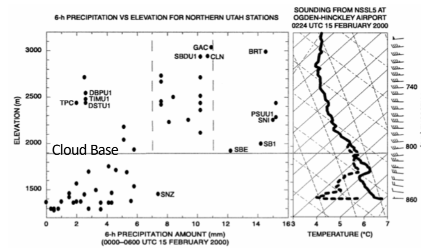
- Orographic ascent doesn't produce feeder cloud, but it does increase RH over Mountains
- Results in less loss from evaporation and sublimation

Sub-Cloud Effects



- Decreasing precipitation with distance below cloud base
- Vertical distribution of moisture strongly influences the strength of this effect
  - The drier the low-levels, the larger decrease below cloud base

Sub-Cloud Effects



"Precipitation amounts decreased with distance below cloud base, consistent with sublimation and evaporation in the dry subcloud air" – Schultz and Trapp (2003)

Schultz and Trapp (2003)

Moist Orographic Convection

"Develops when and where moist instability coincides with sufficient terrain-induced ascent to locally overcome convective inhibition"
– Kirshbaum et al. (2018)

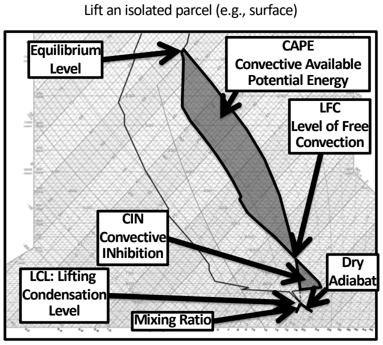
Kirshbaum et al. (2018)

Key Ingredients

- Instability
  - Diagnosed from parcel theory
  - Air parcels, when displaced vertically, become saturated and accelerate away from their initial position
- Moisture
  - Must be sufficient to produce saturation and ultimately precipitation
- Lift
  - Must get parcels to their level of free convection (LFC)

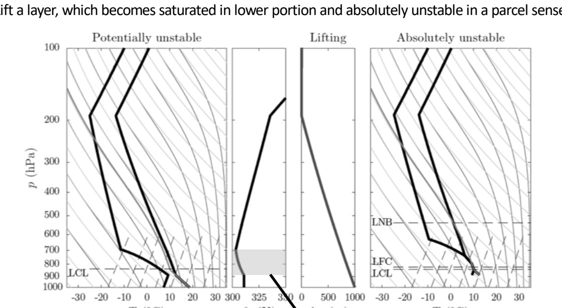
Parcel Theory

Lift an isolated parcel (e.g., surface)



Potential Instability

Lift a layer, which becomes saturated in lower portion and absolutely unstable in a parcel sense



$\partial\theta_e/\partial z<0$ (potentially unstable)

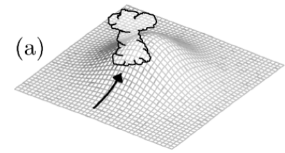
Kirshbaum et al. (2018)

Moist Orographic Convection

- Orographic lift or ascent initiates/triggers convection
- Ascent can be
  - Mechanical: Due to airflow over or around obstacle
  - Thermal: Due to differential heating over sloping terrain)

Kirshbaum et al. (2018)

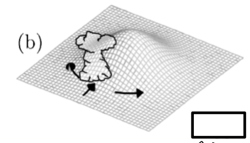
Mechanical Trigger Mechanisms



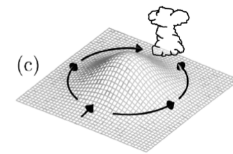
Terrain forced ascent in unblocked flow
Streamlines must be displaced to LFC
or
Potentially unstable air brought to saturation

Convection initiates where flow reaches LFC

Can be low on slope if *H* >> *LFC*



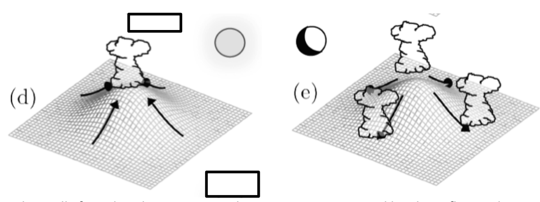
Ascent in blocked flow with $\hat{H} \gtrsim 1$



Lee-side convergence

Kirshbaum et al. (2018)

Thermal Trigger Mechanisms

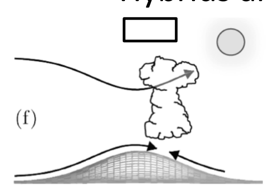


Thermally forced anabatic ascent with convection near crest

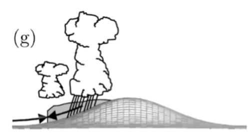
Nocturnal katabatic flow with convection near base

Kirshbaum et al. (2018)

Hybrids and Feedbacks



Lee-side upslope with gravity-wave ascent aloft



Secondary initiation associated with convective cold pool

Kirshbaum et al. (2018)

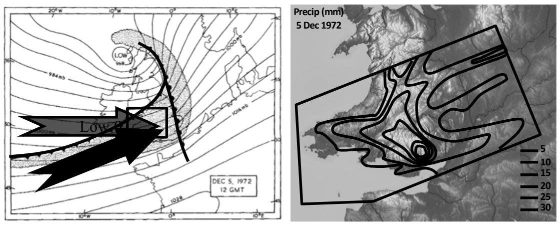
Mechanically Forced

Steenburgh (2014)

Thermally Forced

Brian Blaylock, University of Utah

Potential Instability Release



- Can be effective over small hills or large barriers depending on synoptic setting
  - e.g., low hills of British Isles in warm sector within 300 km of cold front
- Strong enhancement can occur even if convection is shallow

Adapted from Browning et al. (1974)

Impacts on Precipitation

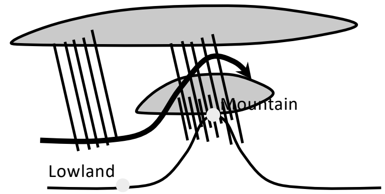
Discussion

What synoptic patterns and physical mechanisms would yield:

a. Large orographic enhancement

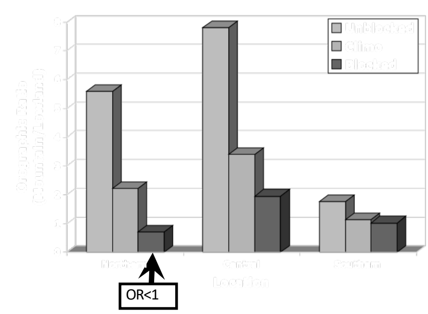
b. Small orographic enhancement (or more lowland than mountain precipitation)

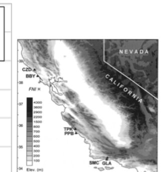
Orographic Ratio



$$OR = \frac{\text{Mountain Precipitation (Water Equivalent)}}{\text{Lowland Precipitation (Water Equivalent)}}$$

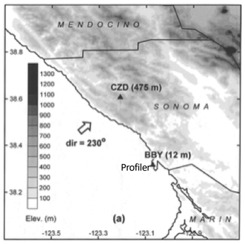
Orographic Ratio

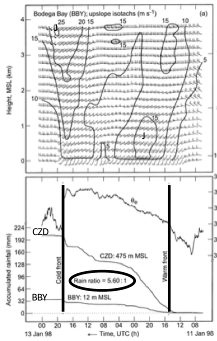




Neiman et al. (2002)

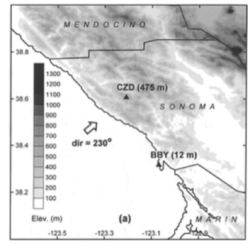
Unblocked Precip Rates

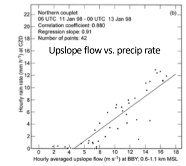


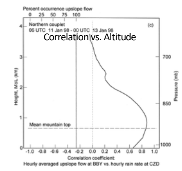


Neiman et al. (2002)

Unblocked Precip Rates

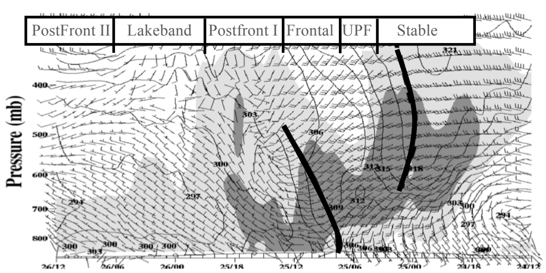






Neiman et al. (2002)

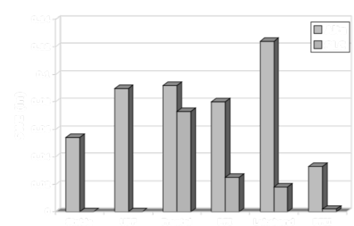
Importance of Synoptic Forcing



SLC Wind/Theta-e/RH Time-Height Section

Steenburgh (2003, 2004)

Importance of Synoptic Forcing

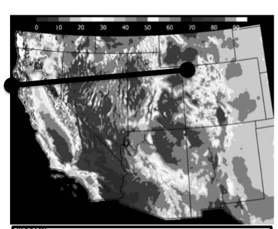


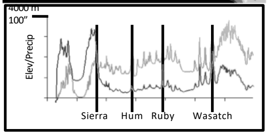
OR smallest during frontal passage

Steenburgh (2003, 2004)

Wide vs. Narrow Barriers

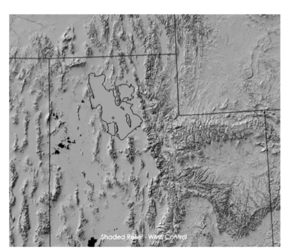
- Asymmetrical precipitation distribution with broad windward-to-near crest max across wide barriers (e.g., Coast Range, Sierra)
- Symmetrical distribution with near-crest max over narrow barriers (e.g., Ruby, Wasatch)

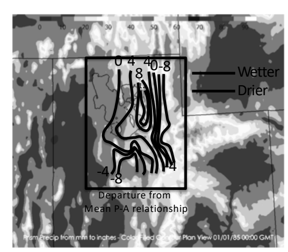




OSU/PRISM Climate Group, USGS

Sub-Regional Terrain Effects

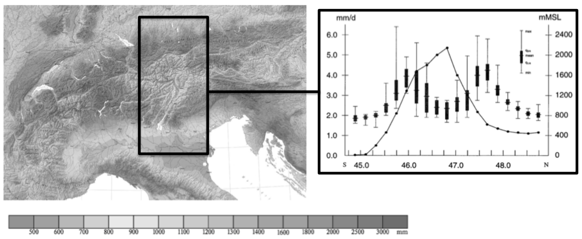




On sub-regional scale, adjusting for mean precipitation-altitude relationship reveals areas that are locally wet or dry for their elevation

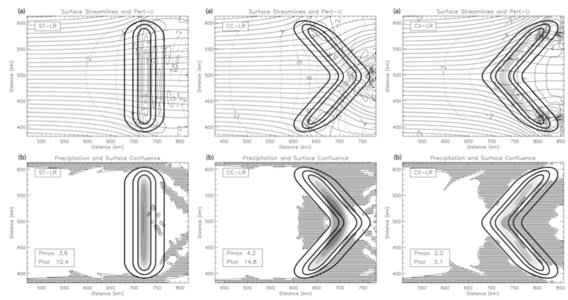
OSU/PRISM Climate Group, USGS, Shafer et al. (2006)

Wide and Sub-Regional Effects in Alps



Frei and Schär (1998); Hydrologic Atlas of Switzerland

Terrain Shape



Dry Froude Number ~1

Watson and Lane (2012)

Snowfall (cm)

Snowfall variations a function of precipitation, snow fraction, SLR

Photo: http://sharewhat.blogspot.com/2010_11_01_archive.html; Data: PRISM, WRCC, Steenburgh (unpublished)

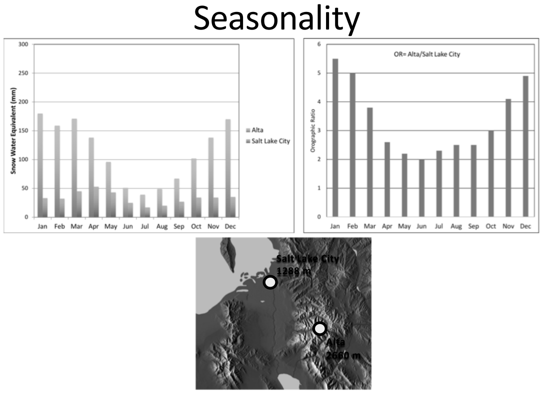
Discussion

The orographic ratio varies depending on climate, terrain characteristics, geography, and season

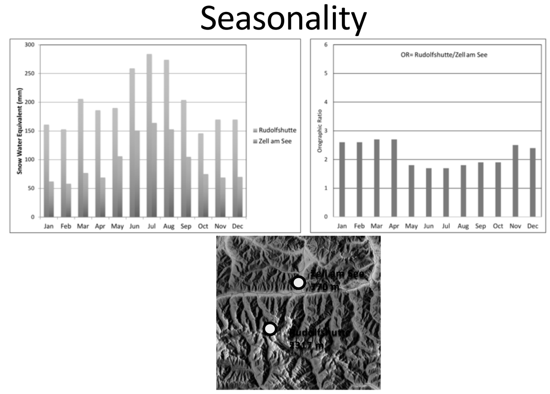
Diagnose and compare the seasonality in OR between northern Utah and three Austrian sites in the next four slides

What are the similarities and differences and why do they exist?

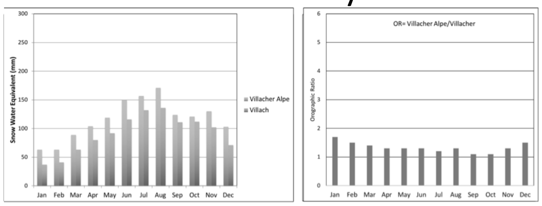
Seasonality

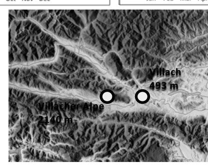


Seasonality

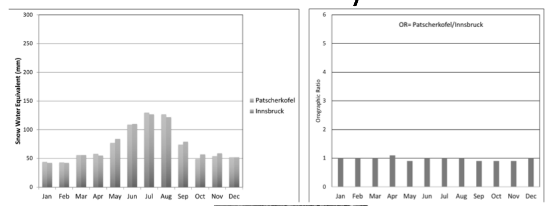


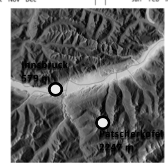
Seasonality





Seasonality





The End…

References

- Browning, K. A., F. F. Hill, and C. W. Pardoe, 1974: Structure and mechanism of precipitation and the effect of orography in a wintertime warm sector. *Quart. J. Roy. Meteor. Soc.*, **100**, 309-330.
- Colle, B. A., R. B. Smith, and D. A. Wesley, 2012: Theory, observations, and predictions of orographic precipitation. *Mountain Weather Research and Forecasting*, F. Chow, S. de Wekker, and B. Snyder, Eds., 291-344.
- Cox, J. A. W., W. J. Steenburgh, D. E. Kingsmill, J. C. Shafer, B. A. Colle, O. Bousquet, B. F. Smull, and H. Cai, 2005: The kinematic structure of a Wasatch Mountain winter storm during IPEX IOP3., *Mon. Wea. Rev*., **133**, 521–542.
- Durran, D. R., 1986: Mountain waves. *Mesoscale Meteorology and Forecasting*. P. S. Ray, Ed., American Meteorological Society, 472-492.
- Frei, C., and C. Schär, 1998: A precipitation climatology of the Alps from high-resolution rain-gauge observations. *Int. J. Climatol*., **18**, 873–900.
- Hobbs, P. V., R. C. Easter, and A. B. Fraser, 1973: A theoretical study of the flow of air and fallout of solid precipitation over mountainous terrain: Part II. Microphysics, *J. Atmos. Sci*., **30**, 813–823.
- Houze, R. A., Jr., 2012: Orographic effects on precipitating clouds. *Rev. Geophys*., **50**, RG1001.
- Kirshbaum, D. J., B. Adler, N. Kalthoff, C. Barthlott, and S. Serafin, 2018: Moist orographic convection: Physical mechanisms and links to surface-exchange processes. *Atmosphere*, **9**, 80; doi:10.3390/atmos9030080.
-
- Medina, S., and R. A. Houze, Jr., 2003: Air motions and precipitation growth in Alpine storms. *Quart. J. Roy. Meteor. Soc*., **129**, 345-371.
- McDonnal, D., and B. Colman, 2003: Unpublished.
- Medina, S. and R. Houze, 2003: Air motions and precipitation growth in alpine storms. *Quart. J. Roy. Meteor. Soc.,* **129**, 345–371.

References

- Neiman P. J., F. M. Ralph, A. B. White, D. E. Kingsmill, and P. O. G. Persson, 2002: The statistical relationship between upslope flow and rainfall in California's coastal mountains: Observations during CALJET. *Mon. Wea. Rev.*, **130**, 1468–1492.
- Rotunno, R., and R. Ferretti, 2001: Mechanisms of intense Alpine rainfall. *J. Atmos. Sci.*, **58**, 1732-1749.
- Rotunno, R. and R. A. Houze, 2007: Lessons on orographic precipitation from the Mesoscale Alpine Programme. *Quart. J. Roy. Meteor. Soc.*, **133**, 811–830.
- Sawyer, J. S., 1956: The physical and dynamical problems of orographic rain. *Weather*, **11**, 375-381.
- Schultz, David M., Robert J. Trapp, 2003: Nonclassical cold-frontal structure caused by dry subcloud air in northern Utah during the Intermountain Precipitation Experiment (IPEX). *Mon. Wea. Rev.*, **131**, 2222–2246.
- Shafer, J. C., W. J. Steenburgh, J. A. W. Cox, and J. P. Monteverdi, 2006: Terrain influences on synoptic storm structure and mesoscale precipitation distribution during IPEX IOP3. *Mon. Wea. Rev.*, **134**, 478–497.
- Steenburgh, W. J., 2003: One hundred inches in one hundred hours: Evolution of a Wasatch Mountain winter storm cycle. *Wea. Forecasting*, **18**, 1018–1036.
- Steenburgh, W. J., 2004: THE MAP ROOM: One hundred inches in one hundred hours. *Bull. Amer. Meteor. Soc.*, **85**, 16–20.
- Steenburgh, J., 2014: Secrets of the Greatest Snow on Earth. Utah State University Press, 186 pp.
- Stoelinga, M. T., R. E. Stewart, G. Thompson, and J. M. Theriault, 2012: Microphysical processes within winter orographic cloud and precipitaiton systems. *Mountain Weather Research and Forecasting*, F. Chow, S. de Wekker, and B. Snyder, Eds., 345-408.
- Watson, C. D., and T. P. Lane, 2012: Sensitivities of orographic precipitation to terrain geometry and upstream conditions in idealized simulations. *J. Atmos. Sci.*, **69**, 1208-1231.