Orographic Precipitation

Atmos 6250: Mountain Meteorology

Jim Steenburgh
Department of Atmospheric Sciences
University of Utah
Jim.Steenburgh@utah.edu

Learning Objectives

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

Reading Materials


OROGRAPHIC EFFECTS ON PRECIPITATING CLOUDS

Chapter 6
Theory, Observations, and Predictions of Orographic Precipitation

Chapter 7
Microphysical Processes Within Winter Orographic Cloud and Precipitation Systems

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

Definitions

- Orographic Precipitation – Precipitation caused or enhanced by one of the mechanisms of orographic lifting of moist air
- Why we care:

D. Strohm

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)

Covered Here

- Microphysical Processes
- Enhancement mechanisms
- Impacts on precipitation
- Storm characteristics

J. Steenburgh

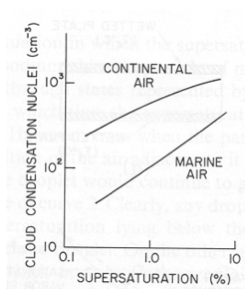
Microphysical Processes

Microphysical Processes

- Cloud droplet formation
  - CCN and droplet size spectra
- Warm cloud processes
  - Collision-coalescence
- Mixed-phase processes
  - Ice nucleation
  - Ice multiplication
  - Depositional growth (a.k.a., the Bergeron-Findeisen Process
  - Accretional growth
  - Aggregation

Droplet Formation

- Cloud droplets form on soluble atmospheric aerosols
  - *Heterogeneous nucleation*
- *Cloud condensation nuclei (CCN)*
  - Aerosol which serve as nuclei for water vapor condensation
- On *average*, there is an order of magnitude more CCN in continental air than maritime air

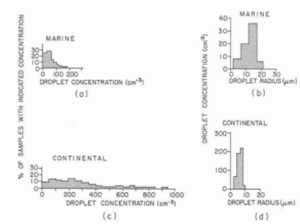


Wallace and Hobbs (1977)

Size Spectra

Marine

Continental



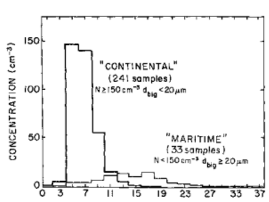
- Continental clouds frequently feature
  - Large cloud droplet number concentrations & smaller cloud droplets
- Maritime clouds frequently feature
  - Smaller cloud droplet number concentrations & larger cloud droplets

Wallace and Hobbs (1977)

Size Spectra

Cloud droplet spectra

Storm Peak Lab
Steamboat, CO



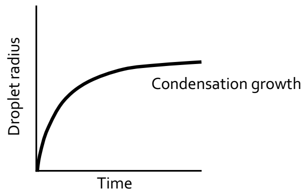
- In continental areas, however, there are large intra- and inter-storm variations depending on aerosol characteristics
  - Maritime size spectra are rare, but possible
- Significance: Impacts hydrometeor growth (more later)

Hindman et al. (1994)

Warm Cloud Processes

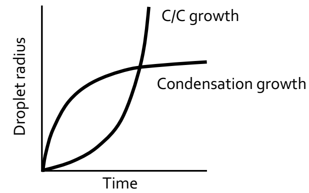
- "Warm Cloud"
  - Clouds that lie entirely below the 0°C level
- Mechanisms for warm cloud hydrometeor growth
  - Condensation
  - Collision-coalescence

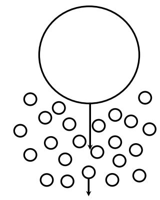
Condensation



- Droplet growth by condensation is initially rapid, but slows with time
- Condensational growth too slow to produce large raindrops

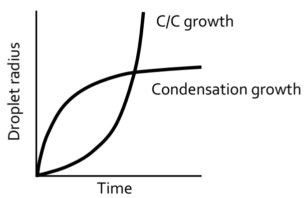
Collision–Coalescence

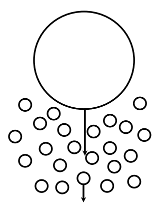




- Growth of small droplets into raindrops is achieved by *collision-coalescence*
- Fall velocity of droplet increases with size
- Larger particles sweep out smaller cloud droplets and grow
- Becomes more efficient as radius increases
- Turbulence may contribute to this growth mechanism

Warm Cloud Processes





- Cloud droplet growth initially dominated by condensation
- Growth into raindrops dominated by collision-coalescence
- Most effective in maritime clouds due to presence of larger cloud droplets (due to fewer CCN)

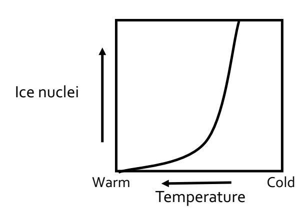
Mixed-Phase Cloud Processes

- Glaciation
  – Ice nucleation & multiplication
- Depositional growth
- Accretion
- Aggregation

Ice Nucleation

- Water does not freeze at 0°C
  – Pure water does not freeze until almost -40°C (homogeneous nucleation)
  – Supercooled liquid water (SLW) – water (rain or cloud droplets) that exists at temperatures below 0°C
  – Ice nuclei – enable water to freeze at temperatures above -40°C
- The effectiveness of potential ice nuclei is dependent on
  – Molecular spacing and crystal structure - similar to ice is best
  – Temperature – Activation is more likely as temperature decreases
- Ice nuclei concentration increases as temperature decreases

Ice Nucleation



Ice nuclei increase by an order of magnitude for every 4°C drop in temperature

Wallace and Hobbs (1977)

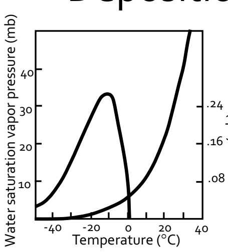
Ice Nucleation

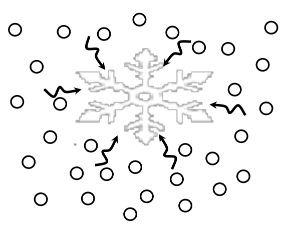
- Significance?
  - Cloud will not necessarily glaciate at temperatures below 0°C
  - Want snow (or even rain in many cases)? Need ice!
  - If temperatures in cloud are
    - -4°C or warmer VERY LITTLE chance of ice
    - -10°C 60% chance of ice
    - -12°C 70% chance of ice
    - -15°C 90% chance of ice
    - 20°C VERY GOOD chance of ice

Ice Multiplication

- Still have a few problems
  - There are still very few ice nuclei even at cold temperatures
  - Ice particle concentrations greatly exceed ice nuclei concentrations in most mixed phase clouds
  - How do we get so much ice?
- Ice multiplication – creation of large numbers of ice particles through
  - Mechanical fracturing of ice crystals during evaporation
  - Shattering of large drops during freezing
  - Splintering of ice during riming (Hallet-Mossop Process)

Deposition (WBF Process)

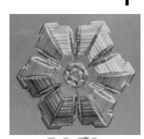




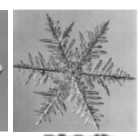
- Saturation vapor pressure for ice is lower than that for water
- Air is near saturation for water, but is supersaturated for ice
- Ice crystals/snowflakes grow by vapor deposition
- Cloud droplets may lose mass to evaporation

Wegener-Bergeron-Findeisen Process

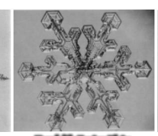
Deposition (WBF Process)



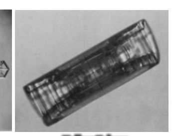
Sector Plate



Stellar Dendrite

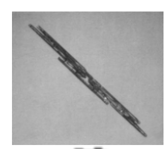


Dendritic Sector Plate



Hollow Column

Habits – types of ice crystal shapes created by vapor deposition

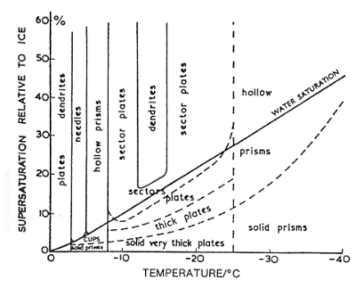


Needle

Snowcrystals.com

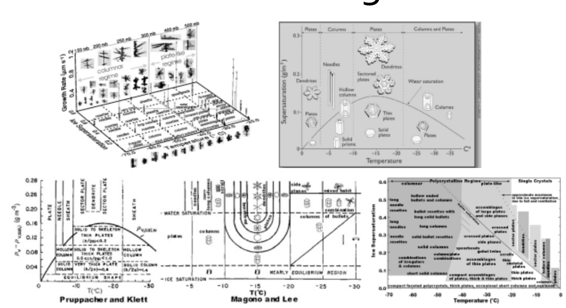
Deposition (WBF Process)

Habit is a function of temperature and supersaturation with respect to ice



Snowcrystals.com

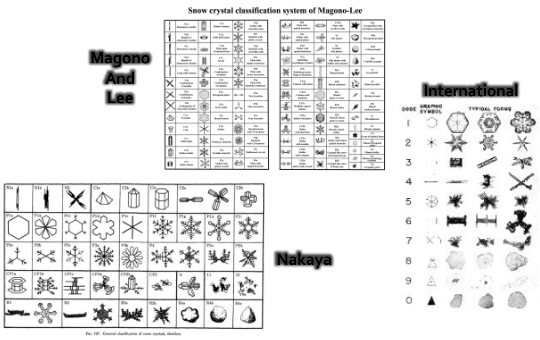
More Habit Diagrams



"A review of over 70 years of ice crystal studies reveals a bewildering variety of habit diagrams" - Bailey and Hallett (2009)

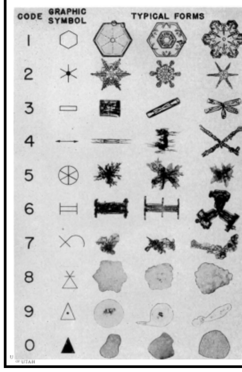
Magono and Lee (1966), Pruppacher and Klett (1997), Bailey and Hallett (2009), Snowcrystals.com

Classification Systems



Magono and Lee (1966), storyofsnow.com, snowcrystals.com

International



- Plates
- Stellar crystals
- Columns
- Needles
- Spatial dendrites
- Capped columns
- Irregular particles
- Graupel
- Sleet
- Hail

Depositional Growth (Plates – Capped columns)

Aggregation/ Accretion (Irregular particles, Graupel)

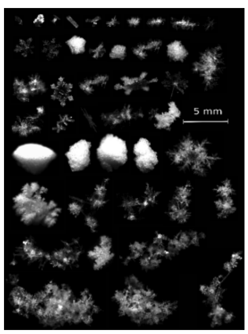
Sleet: **Refreezing of melting snow**

Hail: **"Big Time" accretion**

Reality

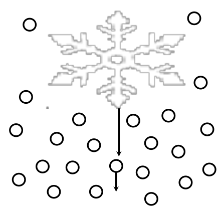
"While aesthetically appealing and offering a striking subject for photography, the fact is that most ice crystals are defective and irregular in shape"

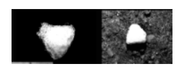
- Bailey and Hallett (2009)



Bailey and Hallett (2009), Garrett et al. (2012)

Accretion





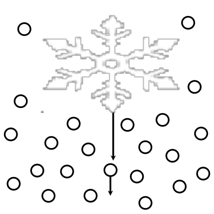
Graupel (UCLA)

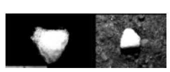
Hexagonal Lump Cone

Magono and Lee (1966)

- Growth of a hydrometeor by collision with supercooled cloud drops that freeze on contact
- Graupel – Heavily rimed snow particles
  - 3 types: cone, hexagonal, lump

Accretion





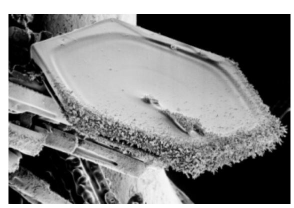
Graupel (UCLA)

Hexagonal Lump Cone

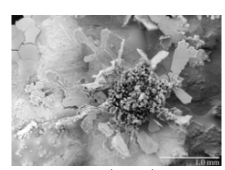
Magono and Lee (1966)

- Favored by
  - Warmer temperatures (more cloud liquid water, less ice)
  - Maritime clouds (fewer, but bigger, cloud droplets)
  - Strong vertical motion (larger cloud droplets lofted, less time for droplet cooling and ice nuclei activation)

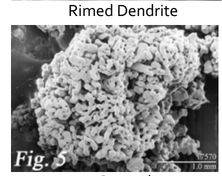
Accretion



Rimed Plate



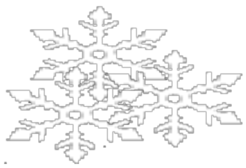
Rimed Dendrite



Graupel

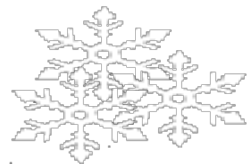
USDA Beltsville Agricultural Research Center

Aggregation



- Ice particles colliding and adhering with each other
- Can occur if their fall speeds are different
- Adhering is a function of crystal type and temperature
  - Dendrites tend to adhere because they become entwined
  - Plates and columns tend to rebound
  - Crystal surfaces become stickier above –5°C

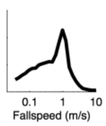
Aggregation



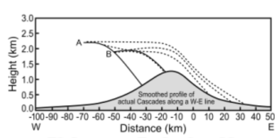
- Bigger particles
- Impact on precipitation rate is probably small
  - May impact crystal transport and fallout across mountain barriers
  - May affect mass loss from sublimation/evaporation below cloud base

Growth, Transport, & Fallout

- Growth, fallspeed, transport, and terrain scale affect precip rate and distribution
- Typical fall speeds
  - Small ice particles: << 1 m/s
  - Snow: ~1 m/s
  - Graupel: ~3 m/s
  - Rain ~ 7 ms^{-1}



Fallspeed of particles @ Alta



Solid Lines = Heavily Rimed Particles
Dashed Lines = Lightly Rimed Particles

Hobbs et al. (1973), Houze (2012), Garrett et al. (2012)

Microphysics Summary

- Condensational growth of cloud droplets
- Some accretional growth of cloud droplets
- Development of mixed phase cloud as ice nuclei are activated and ice multiplication process occurs
- Crystal growth through Bergeron-Findeisen process
  - Most effective at –10 to –15 C
- Other possible effects
  - Accretion of supercooled cloud droplets onto falling ice crystals or snowflakes
    - Snowflakes will be less pristine or evolve into graupel
    - Favored by
      - Warm temperatures (more cloud liquid water)
      - Maritime clouds (bigger cloud droplets)
      - Strong vertical motion
  - Aggregation
    - Entwining or sticking of ice crystals
- Growth rate, fallspeed, transport, and terrain scale affect precipitation rate and distribution

Discussion

What evidence is there that these microphysical processes operate in the Wasatch Mountains?

Do you have a "microphysical experience" you could share with the group?

Mechanisms

Primary Mechanisms

- Stable upslope
- Seeder-Feeder
- Sub-cloud evapoaration contrasts
- Upslope release of potential instability
- Terrain-driven convergence
- Terrain-driven thunderstorm initation

***Mechanisms are not necessarily mutually exclusive and may act in concert**

Photo: J Shafer

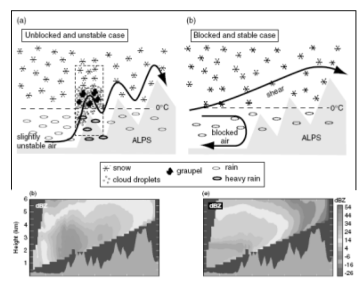
Role of Terrain Induced Flow

- Determines distribution and intensity of orographically induced ascent/descent
- Influences precipitation dynamics/microphysics
- Can strongly influence transport of moisture (e.g., Sierra barrier jet)

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
  - Bocked valley flow, but unblocked flow at mid-mountain and crest level

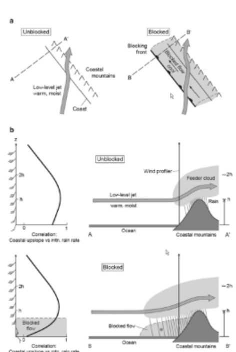
Flow Over vs. Flow Around



Unstable MAP IOP2b **Stable IOP8**

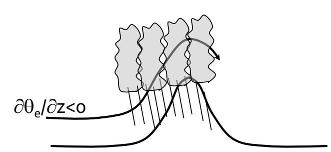
Medina and Houze (2003), Rotunno and Houze (2007)

Flow Over vs. Flow Around



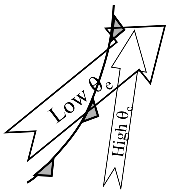
Neiman et al. (2002), Colle et al. (2012)

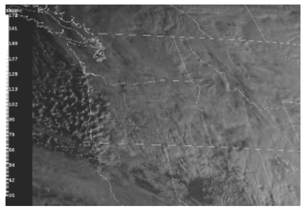
Flow Over/Potential Instability



- Upstream environment is potentially unstable ($\partial\theta_e/\partial z<0$)
- Orographic uplift triggers convection
- Convection may be deep or shallow - both can result in substantial precipitation enhancement
- Can produce large orographic precip rates and ORs

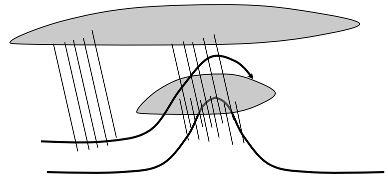
Flow Over/Potential Instability





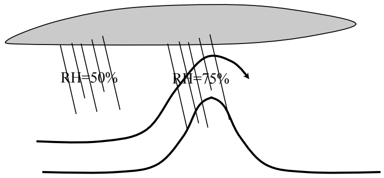
- Also effective over small hills or large barriers
- Favorable synoptic settings/geographic locations
  - Warm sector within 300 km of cold front: British Isles, CA coastal mts (left)
  - Post-cold-frontal: Most ranges of western North America (right)

Flow Over/Seeder Feeder



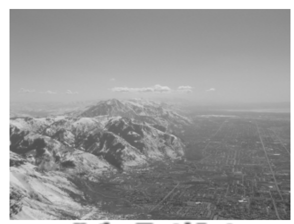
- Hydrometeors (snow or rain) generated in "seeder" clouds aloft fall through low-level orographic "feeder" clouds
- Feeder cloud might not precipitate otherwise
- Precipitation enhanced in feeder cloud primarily by
  - Collision-coalescence
  - Accretion
- Can occur when low-level flow is blocked

Flow Over/RH Contrasts

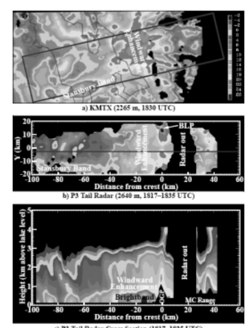


- Orographic ascent doesn't produce feeder cloud, but it does increase RH over Mountains
- Results in less loss from evaporation and sublimation

Blocking

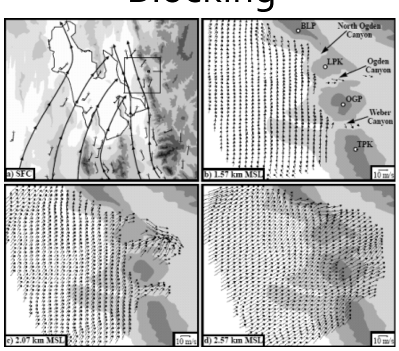


Northern Wasatch Front



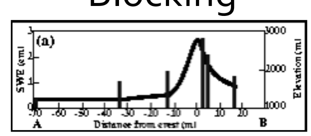
Cox et al. (2005)

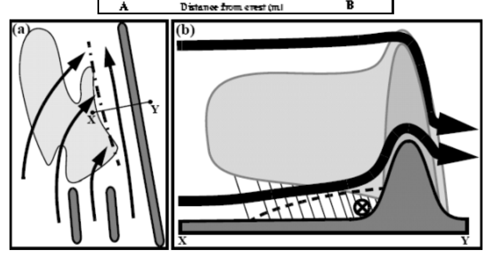
Blocking



Cox et al. (2005)

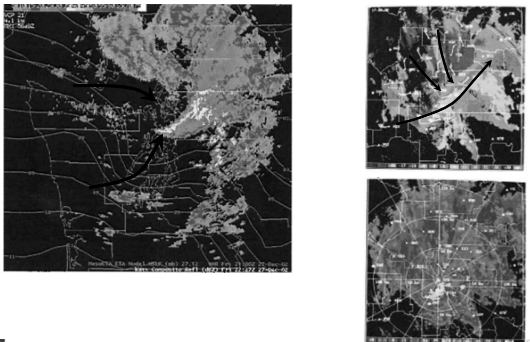
Blocking





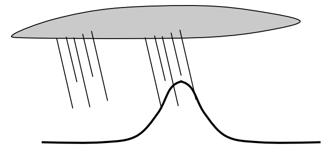
Cox et al. (2005)

Other Flow Around Effects



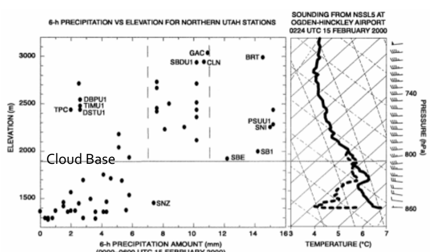
McDonnal and Colman (2003), Andretta and Hazen (1998)

Sub-Cloud Effects



- Decreasing precipitation with distance below cloud base
- Vertical distribution of moisture strongly influences OR in stable events
  - The drier the low-levels, the larger the OR

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)

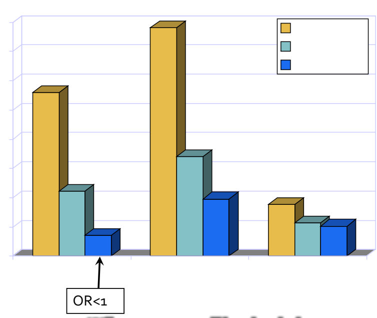
Impacts on Precipitation

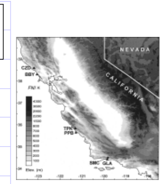
Orographic Ratio

- Favoring Large OR
  - Flow over barrier
  - Strong cross-barrier flow
  - Sub-cloud sublimation & evaporation
  - Weak frontal/synoptic forcing
  - Potential instability release
- Favoring Small OR
  - Flow around/along barrier
  - Weak cross-barrier flow
  - Shallow, moist airflow toward barrier
  - Strong frontal/synoptic forcing

***Interactions between these factors create a wide spectrum of possibilities**

Orographic Ratio

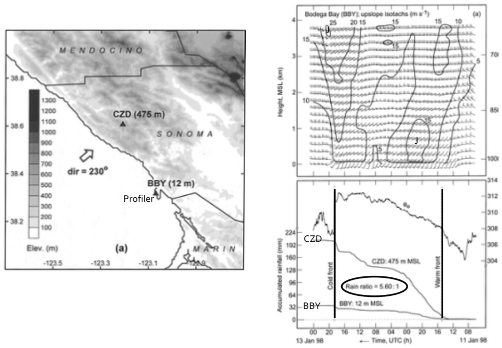




***Mileage may vary if low-levels dry**

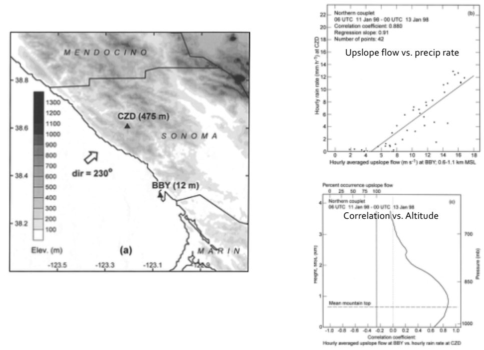
Neiman et al. (2002)

Flow Over Precip Rates



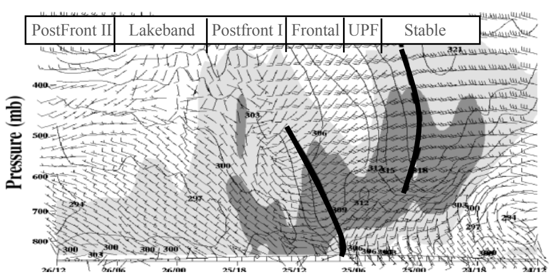
Neiman et al. (2002)

Flow Over Precip Rates



Neiman et al. (2002)

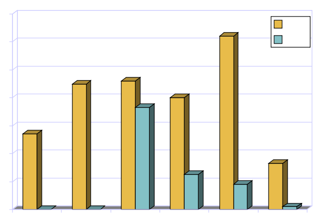
Importance of Synoptic Forcing



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

Steenburgh (2003, 2004)

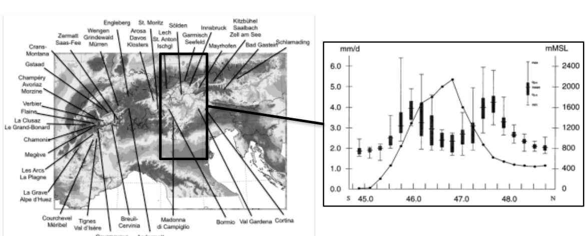
Importance of Synoptic Forcing



OR smallest during frontal passage

Steenburgh (2003, 2004)

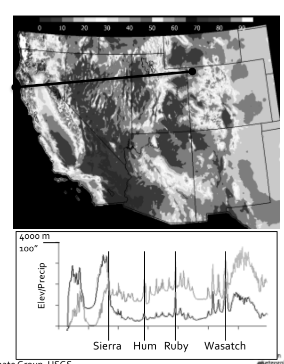
Paradoxes of Big Terrain



Steenburgh (in prep), Frei and Schar (1998)

Wide vs. Narrow Barriers

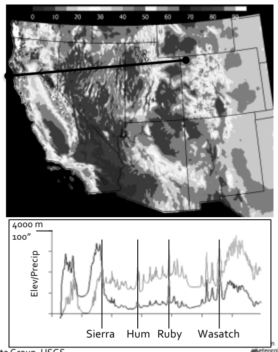
- Asymmetrical precipitation distribution with broad windward-to-near crest max across wide barriers (e.g., Coast Range, Sierra)
- Symmetrical distribution with near-crest max over narrow barriers (e.g., Ruby, Wasatch)



OSU/PRISM Climate Group, USGS

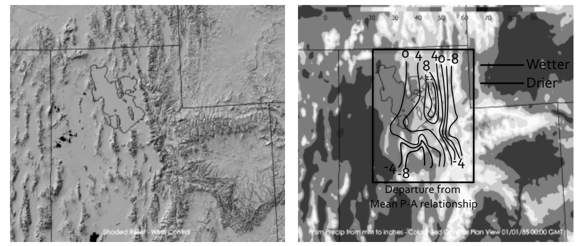
Regional Terrain Effects

- At a given elevation, mountain precip increases eastward from Sierra
  - Sierra/Cascade shadowing strongest in direct lee



OSU/PRISM Climate Group, USGS

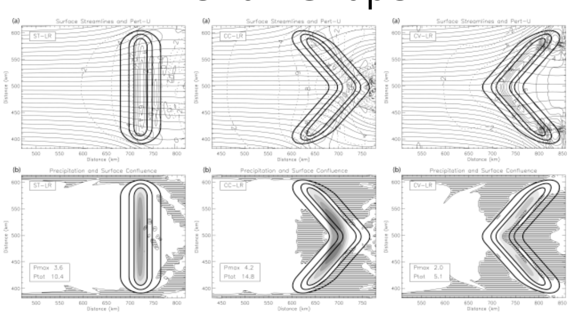
Sub-Regional Terrain Effects



On sub-regional scale, adjusting for mean precipitation-altitude relationship reveals areas that are locally wet or dry for their elevation
Mean PRISM precip masks these subtleties

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

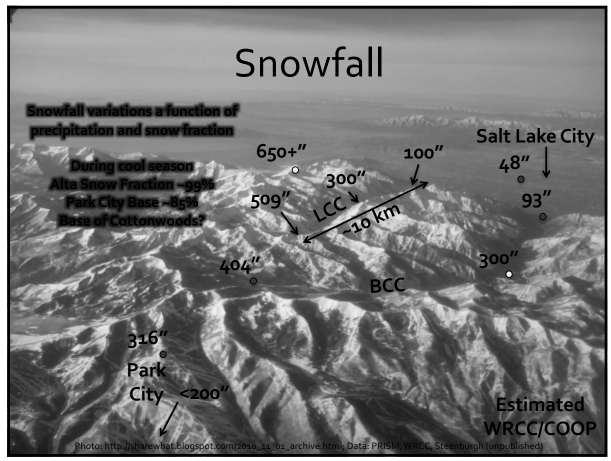
Terrain Shape



Dry Froude Number ~1

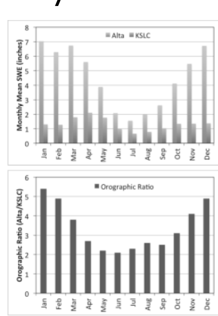
Watson and Lane (2012)

Snowfall



Seasonality

- Climatological orographic ratio varies seasonally
  - Jan Alta/SLC ~ 7
  - Jun Alta/SLC ~2

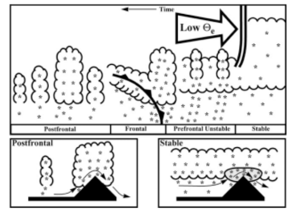


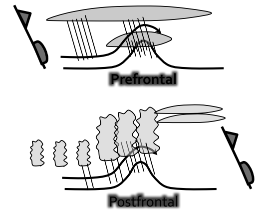
Discussion

What are the causes of the seasonality in orographic ratio over northern Utah?

Storm Characteristics

Storm Stages



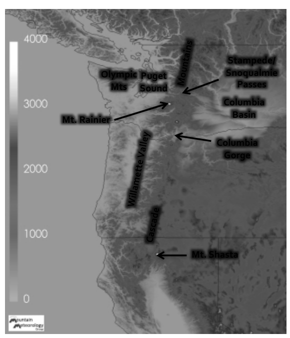


- Many storms over the western US evolve through stable (prefrontal), transitional, and unstable (postfrontal) stages
- The transitional stage can feature the passage of a surface cold or occluded front and/or a destabilizing surge of low-θ_e air aloft

Hobbs (1975), Steenburgh (2003)

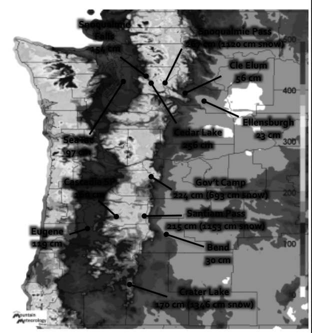
Cascade Mountains

- Crest height 1750–2500 m
- Width O(100 km)
- Separate Columbia Basin from Puget Sound lowlands and Willamette Valley
- Major passes/gaps
  - Columbia River Gorge (MSL)
  - Stampede/Snoqualmie Passes (~1000 m)
  - Stevens Pass (~1200 m)
- Two 14er volcanoes: Mt. Rainier & Mt. Shasta
- Other volcanoes: Mt. Adams, Mt. Baker, Glacier Peak, Mt. St Helens, Mt. Hood, Mt. Jefferson, Mt. Bachelor, Three Sisters, Lassen Peak



Annual Precipitation (cm)

- SWE 150–450 cm
- Heavy snowfall in upper elevations
  - Mt. Baker Ski Area (1400 m)
    - 1650 cm average
    - WR 3109 cm in 1998/99
  - Paradise Ranger Station (1650 m)
    - 1600 cm average
    - 3105 cm in 1971/72
- Oregon Cascades drier than Washington Cascades
  - Relief less formidable
  - Storm track not as favorable



WRCC, OSU/PRISM Climate Group

Prefrontal Stage

- Synoptic conditions
  - Layered clouds from sfc-9 km with clear layers
  - Air may be subsaturated to below 1500-2000 m MSL
  - Easterly winds over crest as frontal trough approaches
- Ice/water particle concentrations
  - Ice particles dominate over water droplets
  - More ice crystals over western than eastern slopes
- Liquid water concentration
  - Low (0-0.5 g/m^3)
- Riming - Limited
  - Seldom observed at levels above T=-10°C
  - Some riming occurs at warmer temperatures near the surface
  - More riming is observed on east slopes than west slopes (perhaps due to low-level easterly flow)
- Precipitation Rate - Steady, 1.3-2.6 mm/h (.05-.10 in/h)
- Orographic effects
  - Increased ice crystals and aggregates on west slope, less ice on east slope
  - Higher precipitation rate on western slopes

Hobbs (1975)

Transitional Stage

- Synoptic conditions
  - Air becomes increasingly unstable
  - Cloud tops decrease with height as drier air moves aloft
  - Layered clouds from sfc-5.4 km with embedded cumulus
  - Crest level winds become westerly except in passes
- Ice/water particle concentrations
  - Ice particles become less common due to lowering cloud tops
  - Water droplets become increasingly common
- Liquid water concentration
  - High (0.5 to 2.0 g/m^3)
- Riming - Quite common
  - Graupel occasionally falls
  - Ice crystals tend to be rimed
- Precipitation Rate - Showery, 0-7.6 mm/h (0-.30 in/h)
- Orographic effects
  - Heavy showers on western slopes, rapid clearing on eastern slopes
  - More riming and graupel on western slopes
  - Higher precipitation rate on western slopes

Hobbs (1975)

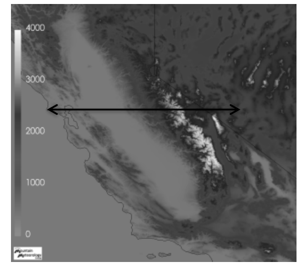
Postfrontal Stage

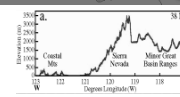
- Synoptic conditions
  - Unstable conditions predominate
  - Cumulus convection with heavy rain/snow showers
  - Crest level winds become westerly over crest and in passes
- Ice/water particle concentrations
  - Large water particle concentrations (many small drops)
- Liquid water concentration
  - Moderate (0.1 to 1.0 g/m³)
- Riming – Heavy
  - Few ice particles that are present are heavily rimed
  - Graupel common
- Precipitation Rate - Showery, 0-5.2 mm/h (0-.20 in/h) on western slopes
- Orographic effects
  - Scattered heavy orographic rain/snow showers western slopes
  - Near zero precip rate on eastern slopes

Hobbs (1975)

Sierra Nevada

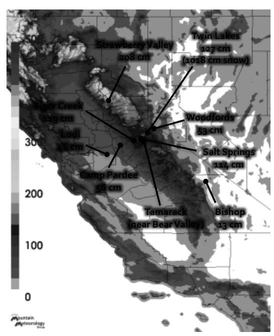
- Crest height 2000–4000 m
- Width O(100km)
- Gradual (3%) windward slope
- Abrupt lee slope
- Numerous Peaks over 3500 m
  - Mt. Whitney 4421 m
- 11 14ers





Annual Precipitation

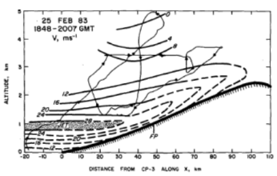
- Increases to north (storm track/barrier jet)
- Dramatic lee-side rain shadow
- U.S. snowfall records
  - Seasonal snow depth
    - 454", Tamarack, Mar 1911 (???)
  - Monthly snowfall
    - 390", Tamarack, Jan 1911 (???)
  - Snowfall from single storm
    - 189", Mt. Shasta Ski Bowl, 13-19 Feb 1959
  - 24-h snowfall (2nd greatest)
    - 67", Echo Summit 4-5 Jan 89
- Sierra Nevada record
  - Seasonal snowfall
  - 884", Tamarack, 1906-07 (???)



WRCC, OSU/PRISM Climate Group

Prefrontal Stage

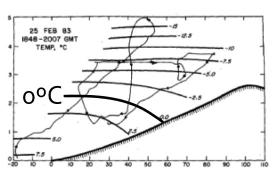
- Synoptic conditions
  - Cyclone approaches from SW-NW
  - Low-level advection of warm moist air ahead of warm/occluded front
  - Cyclone may tap into subtropical moisture (atmospheric river)
- Barrier Jet – dominant kinematic feature over windward slopes
  - Approaching flow is blocked and becomes along-barrier
  - Barrier jet speeds are up to twice as strong as approaching winds
  - Centered 0.5-1.5 km above ground (would be at ground if not for friction)
  - Transports large quantities of heat and moisture to northern Sierra



Marwitz (1986), Marwitz (1987a,b)

Prefrontal Stage

- Diabatic effects
  - Precipitation rate is higher over windward slopes
  - Forced ascent (adiabatic cooling), and melting and evaporation of hydrometeors causes isotherms to descend near the barrier
  - Lower freezing/snow levels over windward slopes than upstream



Marwitz (1986), Marwitz (1987a,b)

Prefrontal Stage

- Microphysics
  - Deep clouds with cloud top temperatures near –25°C
  - Maritime cloud droplet concentrations (< 100 cm-3) with larger droplet radii (10-15 μm) observed above melting level
  - More continental cloud droplet concentrations (100-200 cm-3) with smaller droplet radii (<5 μm) observed below melting level
  - Droplet concentrations are still smaller than that found over continental ranges like San Juans
  - Ice crystal growth by accretion (riming) appeared to be greater (more than double) than that produced by deposition

Marwitz (1986), Marwitz (1987a,b)

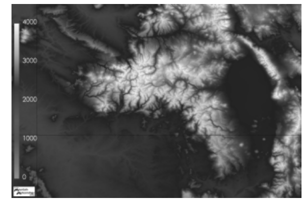
Transitional/Post-Frontal Stages

- Similar to that found in Cascades
- Synoptic conditions
  - Air becomes increasingly unstable
  - Cloud tops decrease with height
  - Cumulus convection becomes increasingly important
- Ice/water particle concentrations
  - Ice particles become less common due to lowering cloud tops
  - Water droplets become increasingly common
- Hydrometeor growth
  - Increased riming and more graupel or heavily rimed ice crystals
- Orographic effects
  - Heavy showers on western slopes, that gradually become increasingly scattered
  - Rapid clearing on eastern slopes, with precip rate becoming zero

Marwitz (1986), Marwitz (1987a,b)

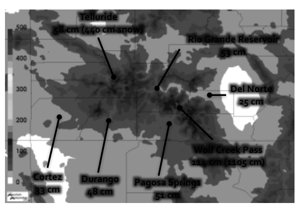
San Juan Mountains

- Crescent-shaped range in southwest Colorado
- Mean crest height varies from 3 km at NM-CO border to 4 km at its westernmost extent
- Foothills 100 km upwind reach ~1.5 km MSL
- Mountains rise abruptly in last 25 km to crest (continental divide)
- Numerous peaks over 3500 m
- Uncompahgre Peak 4361 m



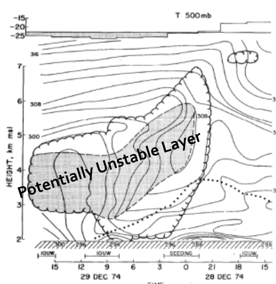
Annual Precipitation

- Greatest near or at crest
- Precipitation increases slightly toward southeast
- Contrast between windward and leeward precipitation not as great as Sierra/Cascades



Stages

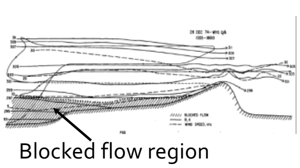
- Stable
  - Flow below mountain-top level is blocked
- Neutral
  - Storm is deep and extends through troposphere
- Unstable
  - Convergence at base of San Juans with convection
- Dissipation
  - Subsidence at mountain top level dissipates storm



Marwitz (1980)

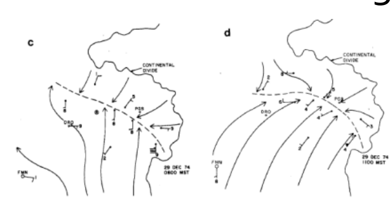
Stable Stage

- Flow is blocked by San Juans and is diverted to the west
- Storm is predominantly glaciated with little liquid water
- Diffusional growth dominates
  - Snow crystals are unrimed or lightly rimed



Marwitz (1980), Cooper and Saunders (1980)

Neutral to Unstable Stages



- Blocked flow ends and a convergence develops at base of the mountains
- Extensive regions of supercooled water develop
  - Produced by convection
- Snow crystals lightly rimed in neutral stage, heavily rimed in unstable stage
- Accretional growth becomes important and may be dominant in unstable stage

Marwitz (1980), Cooper and Saunders (1980)

Summary

- Orographic precipitation processes vary depending on geography, atmospheric stability, and temperature
  - Storms in coastal ranges (e.g., Cascades, Coast range) are generally warmer and feature
    - more maritime cloud droplet sizes and spectra
    - large cloud liquid water concentrations
    - and more accretional growth, particularly during unstable post-frontal flow
  - Storms in interior ranges (e.g., Rockies) are colder and typically feature
    - more continental cloud droplet sizes and spectra
    - small cloud liquid water concentrations
    - and less accretional growth, with depositional growth dominant
- All generalizations are wrong
  - Events are ultimately dependent on storm environment

Summary

- The relative role of accretion relative to deposition
  - increases with decreasing stability
  - increases with increasing vertical velocity
  - decreases as air becomes more continental and/or polluted
- Many orographic storms evolve from stable to unstable stages
  - Beware of surges of low-θe aloft
  - Can occur ahead of surface front
- Storm characteristics and processes can lead to wide variations in orographic precipitation enhancement

References

Andretta, T. A., and D. S. Hazen, 1998: Doppler radar analysis of a Snake River Plain convergence event. *Wea. Forecasting*, **13**, 482–491.

Bailey, M. P., and J. Hallett, 2009: A comprehensive habit diagram for atmospheric ice crystals: confirmation from the laboratory, AIRS II, and other field studies. *J. Atmos. Sci.*, **66**, 2888–2899.

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.

Cooper, W. A., and C. P. R. Saunders, 1980: Winter storms over the San Juan Mountains. Part II: Microphysical processes. *J. Appl. Meteor.*, **19,** 927–941.

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.

Frei, C., and C. Schär, 1998: A precipitation climatology of the Alps from high-resolution rain-gauge observations. *Int. J. Climatol.*, **18**, 873–900,

Garrett, T. J., C. Fallgatter, K. Shkurko, and D. Howlett, 2012: Fallspeed measurment and high-resolution-multi-angle photography of hydrometeors in freefall. In press. [http://www.inscc.utah.edu/~tgarrett/Snowflakes/Snowflakes_files/MASCdescrip.pdf].

Hindman, E. E., M. A. Campbell, and R. D. Borys, 1994: A ten-winter record of cloud-droplet physical and chemical properties at a mountaintop site in Colorado. *J. Appl. Meteor.*, **33**, 797-807.

Hobbs, P. V., 1975: The nature of winter clouds and precipitation in the Cascade Mountains and their modification by artificial seeding. Part I: Natural conditions. *J. Appl. Meteor.*, **14,** 783–804.

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.

Magono, C., and C. W. Lee, 1966: Meteorological classification of natural snow crystals. *J. Faculty Sci.*, **II**, 321–335.

References

Marwitz, J., 1980: Winter storms over the San Juan Mountains. Part I: Dynamical processes. *J. Appl. Meteor.*, **19,** 913–926.

Marwitz, J., 1986: A comparison of winter orographic storms over the San Juan Mountains and the Sierra Nevada. *Precipitation Enhancement—A Scientific Challenge, Meteor. Monogr.*, No. 43, Amer. Meteor. Soc., 109– 113.

Marwitz, J. D., 1987a: Deep orographic storms over the Sierra Nevada. Part I: Thermodynamic and kinematic structure. *J. Atmos. Sci.*, **44**, 159–173.

Marwitz, J. D., 1987b: Deep orographic storms over the Sierra Nevada. Part II: The precipitation processes. *J. Atmos. Sci.*, **44**, 174–185.

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.

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.

Pruppacher, H. R., and J. D. Klett, 1997: *Microphysics of Clouds and Precipitation*. Kluwer Academic, 954 pp.

Rotunno, R. and R. A. Houze, 2007: Lessons on orographic precipitation from the Mesoscale Alpine Programme. *Quart. J. Roy. Meteor. Soc.*, **133**, 811–830.

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.

References

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.

Wallace, J. M., and P. V. Hobbs, 1977: *Atmospheric Science: An Introductory Survey*. Academic Press, 467 pp.