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

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:

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

Covered Here

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

Size Spectra

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

Size Spectra

- 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)

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

- **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:
    - 0°C or warmer: VERY LITTLE chance of ice
    - -4°C: 5% 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

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

More Habit Diagrams

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

International

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

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)

Accretion

• Growth of a hydrometeor by collision with supercooled cloud drops that freeze on contact
• Graupel – heavily rimed snow particles
  • Rod: core, hexagonal, lump

Accretion

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

• 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, fall speed, 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

Microphysics Summary

- Condensational growth of cloud droplets
- Some accretional growth of cloud droplets
- Development of mixed phase cloud as cloud base is activated and ice multiplication process occurs
- Crystal growth through Bergeron-Findeisen process
  - Most effective at ~ -10°C
- Other possible effects
  - Accretion of supercooled cloud droplets onto falling ice crystals or snowflakes
  - Crystals will be less pristine or evolve into graupel
    - Favored by
      - Stronger updrafts and/or more cloud liquid water
      - Maritime clouds with more cloud droplets
      - Stronger updrafts
      - Aggregation

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 evaporation contrasts
- Upslope release of potential instability
- Terrain-driven convergence
- Terrain-driven thunderstorm initiation

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"
  - 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

Flow Over/Potential Instability

- Upstream environment is potentially unstable (\(\partial q_e / \partial z < 0\))
- 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/strategic locations
  - Warm sector within 300 km of cold front: British Isles, CA coastal mts (left)
  - Post-cold front: Most ranges of western North America (right)

Flow Over/Seeder Feeder

- Hydrometeors (snow or rain) generated in "seeder" clouds drift 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

- Cox et al. (2005)
- Northern Wasatch Front
- Cox et al. (2005)
**Other Flow Around Effects**

McDonald and Calmes (2003), Andretta and Hazen (2008)

**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)

**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**

ORs

*Different ways to look at dry*
**Importance of Synoptic Forcing**

- PostFront II  
- Lakeband  
- PostFront I  
- Frontal  
- UPF  
- Stable

**Paradoxes of Big Terrain**

- 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)

**Wide vs. Narrow Barriers**
Regional Terrain Effects

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

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.

Terrain Shape

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

Many storms over the western US evolve through stable (prefrontal), transitional, and unstable (postfrontal) stages.

Prefrontal Stage

- Synoptic conditions:
  - Layered clouds from 500-1000 m
  - Air may be stratified to below 1500 m
  - 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 (<0.5 g/m³)

- Riming - Limited
  - Limited observed at levels above 7-10°C
  - Some riming occurs at warmer temperatures near the surface
  - Main riming observed on east slopes that wind drops (perhaps due to low-level easterly flow)
  - Precipitation Rate - Steady, 1.3-2.6 mm/h (0.05-0.10 in/h)

- Orographic effects:
  - Increased ice crystals and aggregates on wind directions, less on west slope
  - Higher precipitation rate on western slopes

Transitional Stage

- Synoptic conditions:
  - Air becomes increasingly unstable
  - Cloud tops decrease with height as low air moves aloft
  - Layered clouds from 1000-1500 m 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

- Precipitation Rate - Showery, 0-7.6 mm/h (0-0.30 in/h)

- Orographic effects:
  - Heavy showers on western slopes, rapid clearing on eastern slopes

- Riming - Quite common
  - Graupel occasionally falls

- Liquid water concentration:
  - High (0.5 to 2.0 g/m³)
Postfrontal Stage

- Synoptic conditions
  - Unstable conditions predominate
  - Cumulus connection 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/m$^3$)
- Rimming
  - Heavy
  - Few ice particles that are present are heavily rimed
  - Graupel common
- Precipitation Rate - Showery, 0.5-3 mm/h (0.2-1.2 in/h) on western slopes
- Orographic effects
  - Scattered heavy orographic rain/snow showers western slopes
  - Near zero precip rate on eastern slopes

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 snowfall
    - 40”, Tamarack, Mar 1911
    - Monthly snowfall
      - 24”, Bear Valley, Dec 1911
- Sierra Nevada record
  - Seasonal snowfall
    - 68”, Tamarack, Apr 2011

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

Prefrontal Stage

- Microphysics
  - Deep clouds with cloud top temperatures near –35°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 (<9 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
**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

**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 4,364 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

**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

**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
Orographic precipitation processes vary depending on geography, atmospheric stability, and temperature. Storms in coastal ranges (e.g., Cascades, Coast range) generally warm and feature:

- More maritime cloud droplet sizes and spectra
- More continental cloud droplet sizes and spectra
- More accumulational growth, particularly during unstable post-frontal flow

Storms in interior ranges (e.g., Rockies) are colder and typically:

- More continental cloud droplet sizes and spectra
- More accumulational growth, with depositional growth dominant

All generalizations are wrong.

Events are ultimately dependent on storm environment and processes can lead to wide variations in orographic precipitation enhancement.

### References