Winter Storm Fundamentals

Cool-Season Precipitation:
Fundamentals and Applications

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Learning Objectives

- After this class you should
  - Understand the processes that affect the depth and height of the transition zone, the height of the snow level, and the development of snow, ice pellets, freezing rain, or freezing drizzle
  - Be able to apply top-down forecast approaches for predicting precipitation type
  - Understand and apply key meteorological variables affecting the snow-to-liquid ratio during snowstorms

Cool-Season Precipitation Types

Ice Particles

- *Ice crystal* – any one of the number of forms in which ice appears
- *Ice pellet* – Transparent or translucent ice pellet less than 5 mm in diameter (sleet in the US)
- *Ice pellet aggregate* – Individual ice particles linked or fused together

Stewart et al. (2015)

Ice Particles

- *Refrozen wet snow* – partially melted snow that refroze
- *Sleet* – In the US, this term refers to ice pellets
- *Snow* – White or translucent ice crystals, chiefly in complex branch hexagonal form and often agglomerated into snowflakes
- *Snow pellet* – White, opaque, approximately round (sometimes conical) ice particles having a snowlike structure, about 2-5 mm in diameter (a.k.a. graupel)

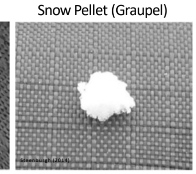
Stewart et al. (2015)

Ice Particle Examples

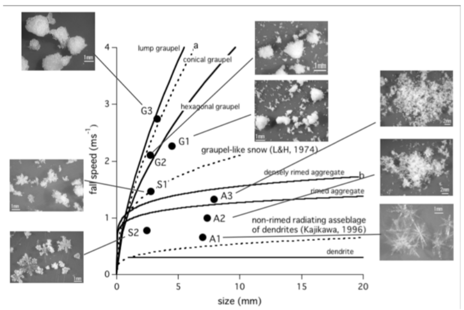
Ice Pellets (sleet)

Snow

Snow Pellet (Graupel)

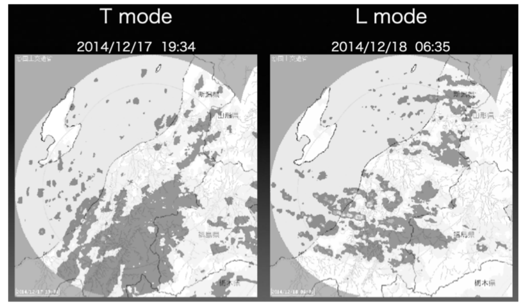


Type, Size, and Fall Speed



Courtesy Dr. Masaaki Ishizaka

Example: Sea Effect of Japan



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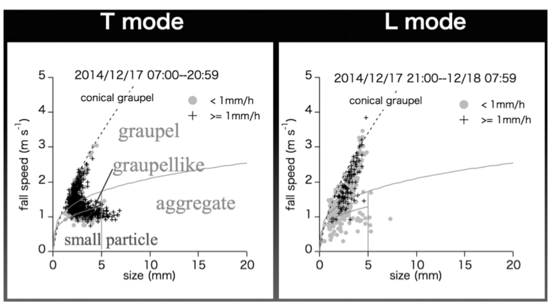

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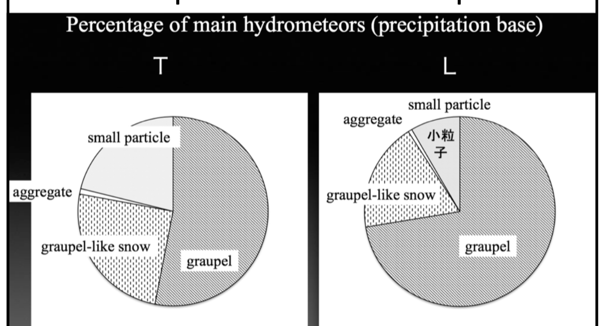


Courtesy Dr. Masaaki Ishizaka

Mixed-Phase Particles

- *Wet snow* – Snow that contains a great deal of liquid water
- Semimelted snow pellet – Snow pellet that has undergone some melting
- *Liquid core pellet* – Partially refrozen particle with ice shell and liquid water core
- *Almost melted particle* – Precipitation composed mainly of liquid water, but with some ice and the shape not discernible
- Typically fall speeds increase as particles melt

Stewart et al. (2015)

Liquid Particles

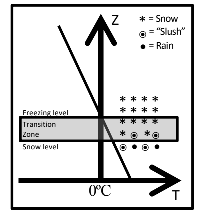
- *Drizzle* – Very small, numerous, and uniformly distributed water drops with diameters < 0.5 mm
- *Freezing drizzle* – Drizzle that falls in liquid form but freezes on impact to form a coating of glaze
- *Freezing rain* – Rain that falls in liquid for, but freezes on impact to form a coating of glaze
- *Rain* – Precipitation in the form of liquid water with diameters > 0.5 mm or, if widely scattered, drops may be smaller
- *Supercooled rain* – Liquid precipitation at temperatures below freezing
- Typical fall speeds for drizzle ~2m/s; freezing rain, rain, or supercooled rain ~7–9 m/s

Stewart et al. (2015)

Rain-Snow Transition Zone

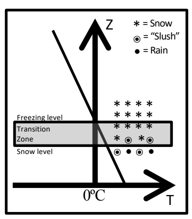
The Rain-Snow Transition Zone

- A region where falling snow is warming, melting, and becoming rain
- May be identified horizontally or quasi horizontally where it intersects the surface, or vertically in soundings or mountainous regions
- Becomes a more complex precipitation type transition zone if there are warm layers > 0˚C, which can lead to freezing rain or ice pellets



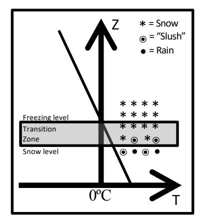
The Rain-Snow Transition Zone

- *Freezing level*
  - Glossary of Meteorology: Lowest altitude at which the air temperature is 0˚C
  - Practical consideration: Critical to also know the highest altitude at which the air temperature is 0˚C
  - Common in aviation to report multiple freezing levels to the highest altitude at which the air temperature is 0˚C



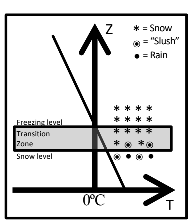
The Rain-Snow Transition Zone

- *Snow level*
  - Glossary of Meteorology: No definition provided
  - Common: Altitude above which snow is accumulating on the ground
  - White et al. (2011): Altitude where falling snow melts to rain
  - Minder et al. (2011): Level at which the precipitation mass is 50% ice

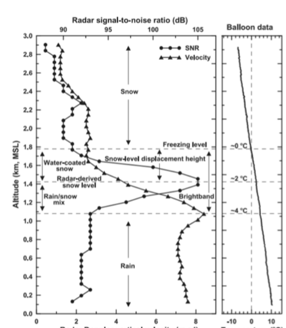


The Rain-Snow Transition Zone

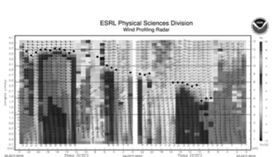
- *Snow level*
  - Rule of thumb: ~300 meters below freezing level
  - Reality: Varies depending on thermodynamic and humidity profile, as well as precipitation intensity
  - As a first guess, some forecasters use the highest level at which the wet bulb temperature is 0.5˚C
  - Typically lower over mountains than in free air upstream



Profiling Radar Examples

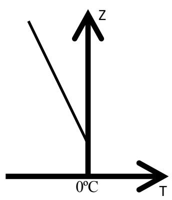


White et al. (2011)



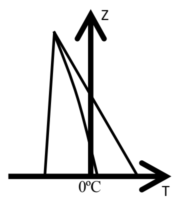
NOAA/ESRL

Diabatic Effects



Melting creates an isothermal layer

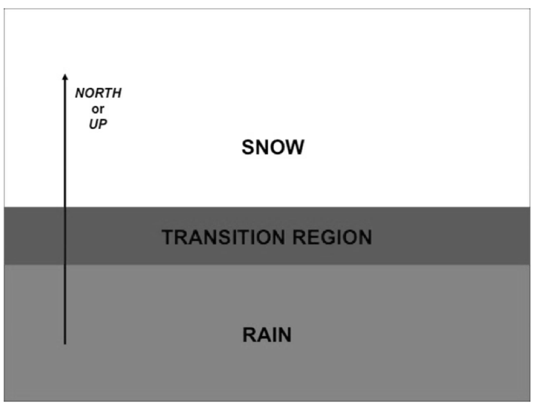
Increased precipitation rates deepen melting layer and lower snow level



Evaporation results in temperatures converging to wet bulb and lower freezing and snow levels than indicated by solely by temperature

Rain/Snow Transition Regions

Dr. Ronald Stewart
University of Manitoba
2008 AMS/COMET/MSC Mountain Weather Workshop
Whistler, British Columbia, Canada



Question

Isothermal layers at 0ºC are normally __________ over topography than over nearby flat regions

a) the same depth
b) shallower
c) deeper

Question

An increase in precipitation rate could _______ the height of the base of the transition region

a) raise
b) maintain
c) lower

Question

As one ascends the Seegrubenbahn through the transition region, which sequence best describes the change in precipitation particles with increasing altitude

a) snow, wet snow, slush, rain
b) rain, slush, wet snow, snow
c) slush, rain, snow, wet snow
d) rain, wet snow, slush, snow

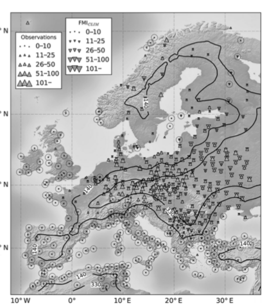
Pathways to Freezing Drizzle (FZDZ), Freezing Rain (FZRA) and Ice Pellets (IP)

Pathways to FZDZ, FZRA, & IP

- FZDZ: Warm-phase processes (no significant ice nucleation)
  - Shallow cloud decks forming over arctic airmasses (eastern 2/3 of US)
  - Cloud top temperatures > -10ºC
  - Poor ice nucleation
  - Common in central US
- FZRA: Deep moist layer and midlevel warm (>0ºC) layer
  - Cold-air damming with overrunning in eastern US
  - Warm-frontal overrunning in central US
  - Cold pools, cold-air damming, and terrain-forced flows a factor in western US
- IP: See FZRA, but add deeper/colder surface-based layer enabling refreeze before rain reaches ground

Rauber et al. (2000)

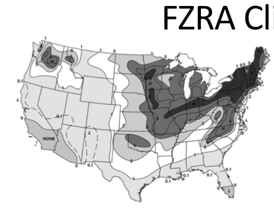
FRZA Climatology: Europe

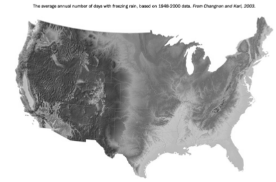


- Discussion: Where and why are freezing rain events most common in Europe
- In plot
  - Orange triangles = number of observed FZRA reports
  - Circles = stations > 2000 m (omitted) or < 10 FZRA observations
  - Contours – distance from coast

Kämäräinen et al. (2017)

FZRA Climatology

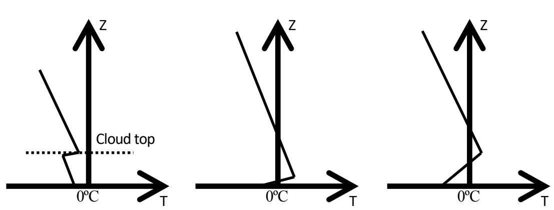




- Discussion: In the continental US, why are freezing rain events most common:
  - In the Columbia Basin
  - In the north-central and northeast states?
  - East of the southern Appalachian Mountains?

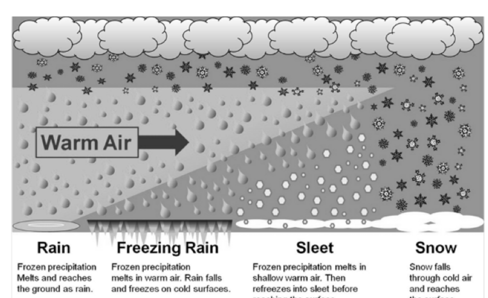
http://mcc.sws.uiuc.edu/living_wx/icestorms/index.html, https://www.reddit.com/r/MapPorn/

Example Temperature Profiles



Freezing Drizzle	Freezing Rain	Sleet
Poor ice nucleation + warm-phase processes	Snow melts in >0˚C layer; Rain doesn't refreeze until contacting ground or other objects	Snow melts in >0˚C layer; Rain refreezes before reaching ground

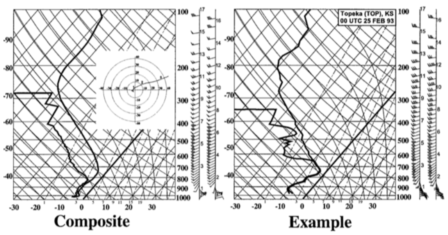
Transition Zone with Melting Layer Aloft



NOAA/NWS

You Decide: FZDZ or FZRA?

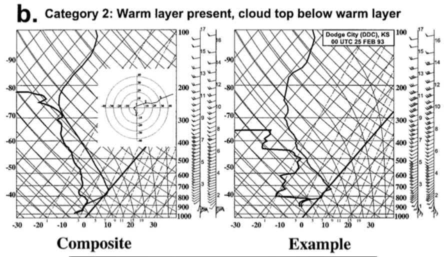
a. Category 1: No warm layer

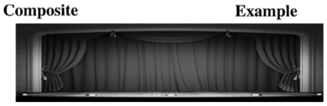


Rauber et al. (2000)

You Decide: FZDZ or FZRA?

b. Category 2: Warm layer present, cloud top below warm layer

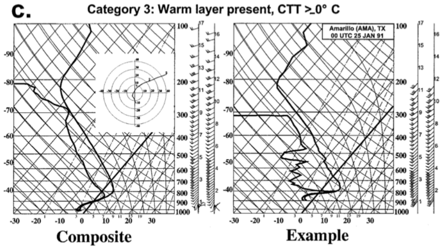




Rauber et al. (2000)

You Decide: FZDZ or FZRA?

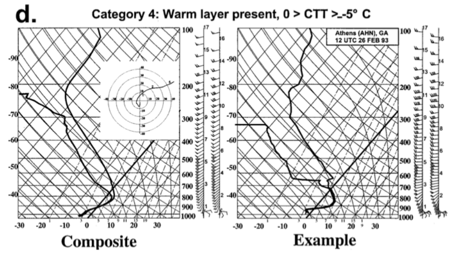
c. Category 3: Warm layer present, CTT ≥ 0° C

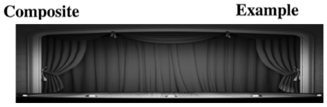


Rauber et al. (2000)

You Decide: FZDZ or FZRA?

d. Category 4: Warm layer present, 0 > CTT ≥ -5° C

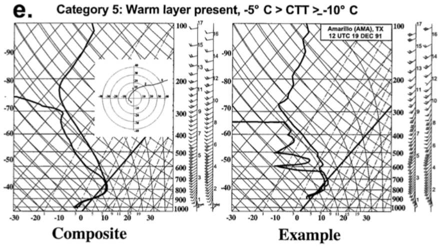


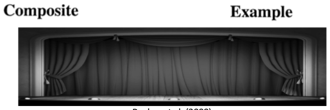


Rauber et al. (2000)

You Decide: FZDZ or FZRA?

e. Category 5: Warm layer present, -5° C > CTT ≥ -10° C

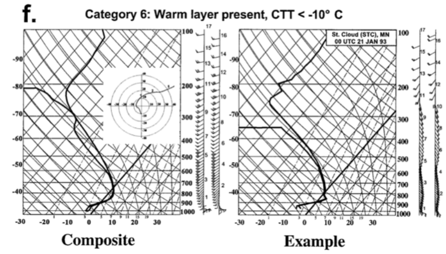


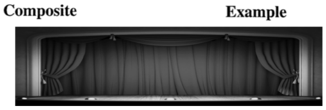


Rauber et al. (2000)

You Decide: FZDZ or FZRA?

f. Category 6: Warm layer present, CTT < -10° C





Rauber et al. (2000)

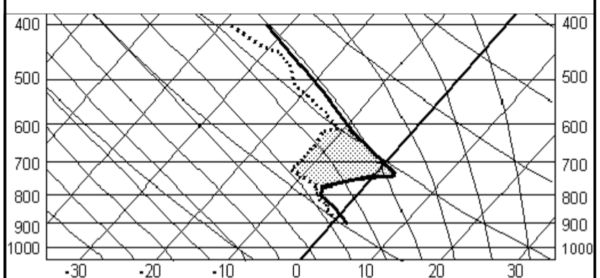
Top Down Forecasting

- A way to assess what hydrometeors will form and their evolution as they fall to the surface
- Frequently based on model or observed soundings
- Start at cloud top
  - Mixed phase or warm phase processes?
    - CTT ~ -4˚C: Little or no ice
    - CTT ~ -10˚C: Commonly used cutoff temp for warm phase
  - Beware of seeder-feeder from higher clouds

Top Down Forecasting

- Diagnose potential for melting and freezing during fallout
  - Melting in warm layer?
  - Freezing in near-surface sub-freezing layer?
  - Consider diabatic effects (melting, evaporation)
- What precipitation will occur at the surface
  - Snow, FZRA, FZDZ, IP?

You Decide: SN, FZDZ, FZRA, or IP?



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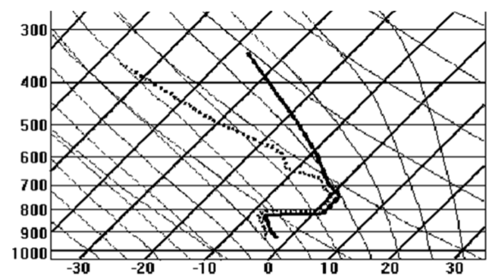

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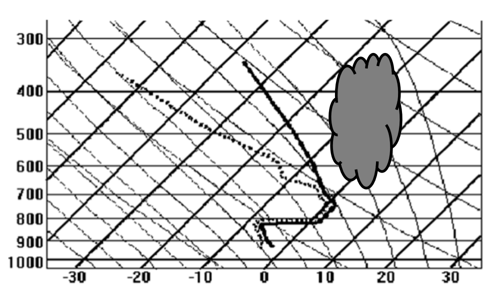
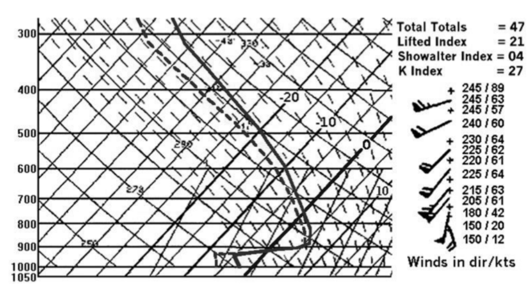


What if elevated convection develops?

You Decide: SN, FZDZ, FZRA, or IP?



Snow Levels in Mountainous Terrain

Questions

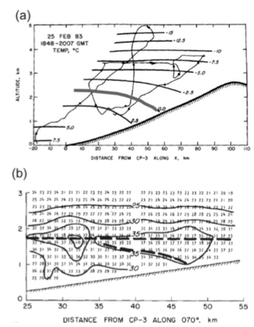
Compared to the free atmospheric upstream, the snow level over the mountains is usually

a) the same height
b) lower
c) higher

Why?

The Mountainside Snow Level

- Compared to free air upstream, usually near mountains the
  - Freezing level is lower
  - Bright-band is deeper
  - Snow level is lower



Marwitz (1983), Minder et al. (2011)

The Mountainside Snow Level

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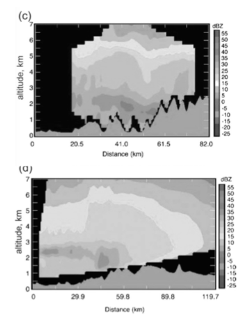


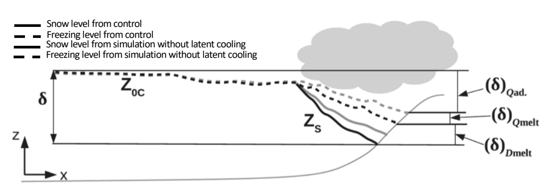
Medina et al. (2005), Minder et al. (2011)

Mechanisms

- Latent cooling from melting precipitation
  - More effective over mountains where ground limits depth of convective overturning
  - Precipitation rates frequently higher over mountains
- Microphysical melting distance
  - Ice crystals over mountains comprised in a way that they take longer to melt (e.g., denser, more rimed)
- Adiabatic cooling from forced ascent

Minder et al. (2011)

Idealized Modeling



Each of these mechanisms makes important contributions
$(\delta)_{Qad}$ = Change in snow level from adiabatic cooling
$(\delta)_{Qmelt}$ = Change in snow level from latent cooling of precipitation
$(\delta)_{Dmelt}$ = Change in snow level from microphysical melting distance

Minder et al. (2011)

Additional Details from Modeling

- Magnitude of snow level decrease depends on characteristics of incident flow and terrain geometry
- Depression of snow level increases with increasing temperature
  - Might act as a modest buffer for mountain hydroclimates against global warming
- Results dependent on cloud microphysics parameterization
  - An important source of uncertainty

Minder et al. (2011)

Snow-to-Liquid Ratio (SLR)

Definition

- Snow-to-liquid ratio (SLR) = New snow depth / New snow water equivalent (SWE)
- Related measures include snow density, water content, and specific gravity
  - snow density = ρ_{water} / SLR
  - water content (%) = 100/SLR
  - specific gravity = 1/SLR (rarely used)

SLR vs. Related Measures

	Heavy	Average	Light
SLR	7:1	14:1	25:1
Snow density	143 kg m^{-3}	71 kg m^{-3}	40 kg m^{-3}
Water content	14.3%	7.1%	4.0%
Snow character	"Sierra cement"	Utah average	"Champagne powder"

Low SLR High Density | **High SLR Low Density**

Why Is SLR Important?

- Contemporary winter precipitation forecasting typically involves three steps:
  - Quantitative precipitation forecast (QPF)
  - Determination of precipitation type
  - Application of SLR when precipitation type is snow
    - Snowfall amount = QPF x SLR

Why Is SLR Important?

- Snow clearing operations often based on specific amount thresholds, where perfect QPF is of limited value if a poor SLR is applied
- In avalanche forecasting, SLR is related to snow shear strength (Casson 2008)
- Accurate SLR and snowfall amount forecasts are critical for mountain communities

The Problem with SLR

- Daily SLR varies considerably in both space and time within storms
- Forecast snowfall amount strongly dependent on SLR
- How much snow from a QPF of 25 mm?



3:1 **10:1** **30:1**

Discussion: What Controls SLR?

Crystal Type and SLR

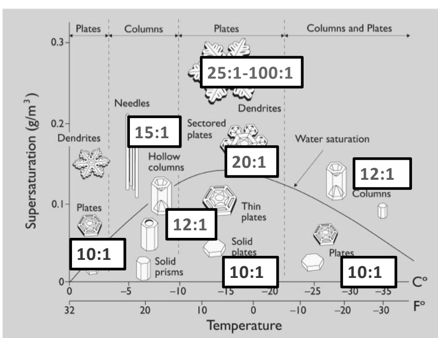
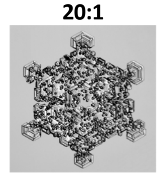
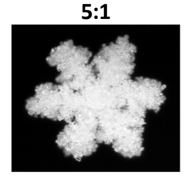


Image: snowcrystals.com; SLR based on Power et. al. 1964, Dubé 2003, Cobb 2006

Riming and SLR

50:1 **20:1** **5:1**

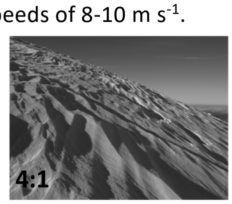
snowcrystals.com

- Riming can decrease SLR by up to 90%.
- Most important for temperatures above −10ºC; supercooled water more likely to be present
- Tends to increase with vertical velocity

Surface Winds and SLR

- Strong winds cause snow crystals to be dislodged and roll along the surface, removing outer features and decreasing SLR.
- Snow transport begins at speeds of 8-10 m s^{-1}.

⟹

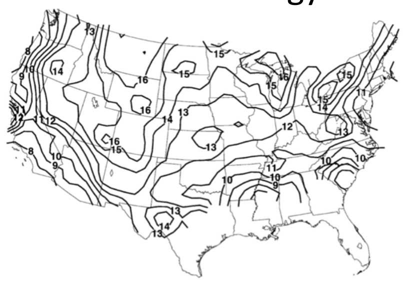


Forecasting – The 10:1 Rule

- "Convenient" but innaccurate approach of multiplying QPF by 10
- Inaccuracy known in the 19th century!
  - "…assuming 10 inches of snow to 1 of water or some other factor, is subject to a large range of error because of the wide variability of this ratio for different kinds of snow."

    – Report of the Chief Signal Officer, 1888

SLR Climatology



10:1 not even a good estimate of mean in many areas!

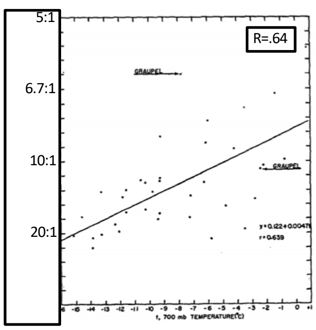
Discussion: Why is the SLR lowest along the coasts and in the south and highest over the western interior and near the Great Lakes?

Baxter et al. (2005)

Improving on the 10:1 Rule

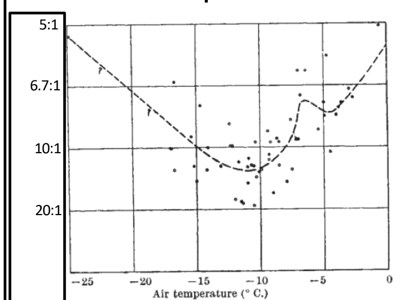
- Empirical techniques have been developed, relying on surface or in-cloud temperature
  - However, many of these techniques have not been verified and challenges remain
- Temperature is one of the strongest predictors, but still only explains about 25-40% of the variance

SLR Temperature Relationship



SLR vs. 700-mb temperature @ Central Sierra Snow Lab (Diamond and Lowry 1954)

SLR Temperature Relationship



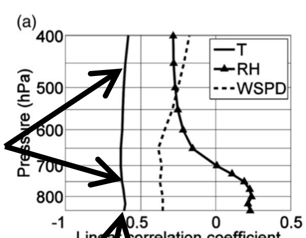
Group Discussion

Why is the SLR largest at about -12°C?

(Values increase downward)

SLR vs. Surface temperature @ Weissfluhjoch, Davos (Bossolasco 1954)

SLR @ Alta, UT

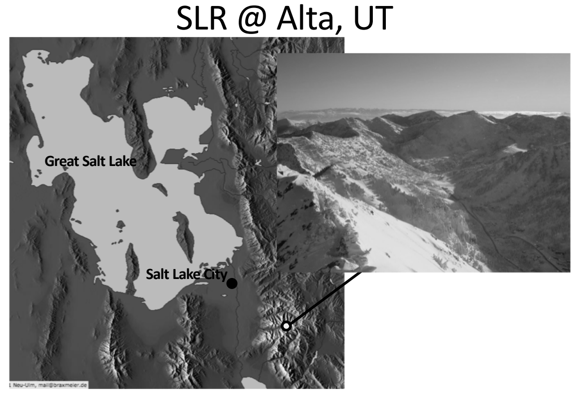


Correlation nearly constant with height (unusual?)

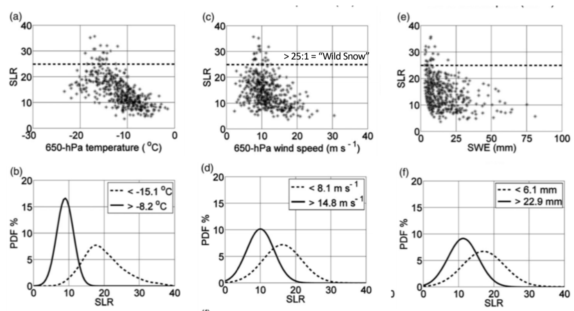
Strongest Relationship With T

Alcott and Steenburgh (2010)

SLR @ Alta, UT



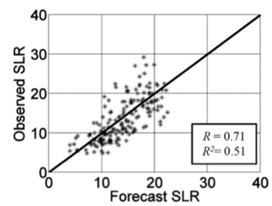
SLR @ Alta, UT



Alcott and Steenburgh (2010)

Prediction @ Alta

- Stepwise Multiple Linear Regression to observed data, then apply to NWP output
- Key variables: Temperature, wind speed, RH, wind direction at multiple levels, plus SWE

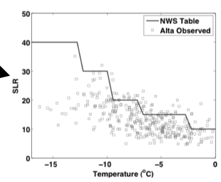


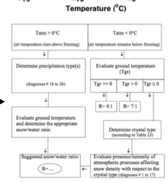
Improvement over other methods, but still scatter

Alcott and Steenburgh (2010)

Other Methods

- Look up tables
- Neural network approaches (Roebber et al. 2003)
  - Arguably a "smarter" version of SMLR approach
- Flowcharts (Dubé 2003)





SLR Summary

- Poor data poses a challenge
- Many methods are ad hoc
- Best methods are probably point specific and based on a long training dataset
- Methods that can be applied broadly geographically are elusive
- Good luck!

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