Front–Mountain Interactions

Atmos 6250: Mountain Meteorology
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Learning Objectives

- After this class you should be able to
  - Recognize several ways that mountains influence frontal structure, evolution, and processes
  - Use this recognition to better analyze and predict the evolution of fronts over complex terrain
  - Better utilize multi-elevation surface observations, including data from non-conventional observing sites and networks, for weather analysis and forecasting

What Is a Front?

- An elongated zone of strong temperature gradient (>10˚C/1000 km) and relatively large static stability and cyclonic vorticity (Bluestein 1986)
- A boundary between two airmasses (Bluestein 1993)
- The interface or transition zone between two airmasses of different density (Glossary of Meteorology 2000)
- I can't define front, but I know one when I see one (Steenburgh 2017)

Our Working Definition

- A front is an *well-defined but imaginary* boundary between two *large-scale* airmasses of differing *density*
- This does not include topographically trapped cold pools, convective outflows, dry lines, etc., although this lecture may be useful for understanding the evolution of these features as well

Fronts in Complex Terrain

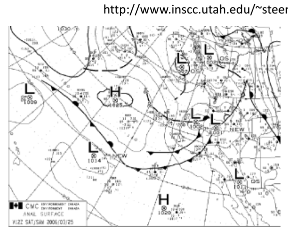
- Mountains aren't necessarily "bad" for fronts
- Depending on the situation, mountains can
  - strengthen or weaken fronts
  - accelerate or decelerate fronts
  - make fronts harder or easier to analyze and predict
- Front-mountain interactions are important, but avoid "mountain myopia"
  - excessive reliance on mountain meteorology when the large-scale and other non-orographic processes may be important

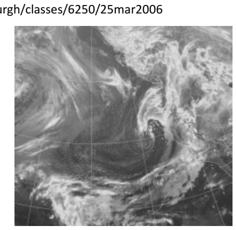
Opening Challenge

You are working a forecast shift at 1500 UTC 25 March 2006 as a surface cyclone penetrates inland into interior North America

What surface fronts or troughs can you identify at 1500 UTC?
What do you expect to see over the Intermountain West as the system moves inland?

http://www.inscc.utah.edu/~steenburgh/classes/6250/25mar2006





Analysis Time

What Surface Fronts or Troughs Can You Identify at 1500 UTC?

a) Two cold fronts identified in the 1200 UTC analysis moving inland

b) One cold front and one baroclinic trough moving inland

c) Only one cold front/baroclinic trough moving inland (i.e., the other has weakened)

d) No surface fronts or baroclinic troughs (i.e., both have dissipated)

What Do You Expect to See over the Intermountain West?

a) An intense cold-frontal passage

b) A typical cold-frontal passage

c) A weak transition from continental to cooler Pacific Air (or two weak cold-frontal passages)

a) No major airmass change

And the Answers Are…

Challenges of 25 Mar 2006 Event

- Analysis of weak, decaying front(s) in complex terrain of northern California
- Lack of a conceptual model of frontal evolution over complex terrain & the Intermountain West
- Mountain myopia?

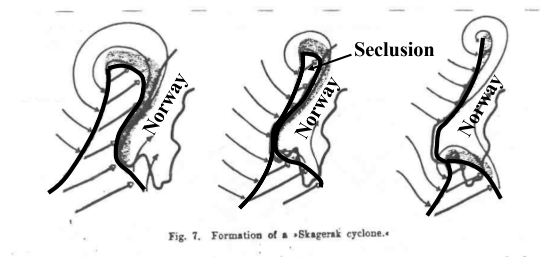
Outline

- Front-mountain interactions
  - Movement
    - Retardation or acceleration by blocking, channeling, and other terrain induced flows
    - Distortion of frontal shape & frontal fragmentation
  - Strength
    - Frontogenesis or frontolysis produced by terrain-induced deformation, divergence, and vertical motion
    - Diabatic effects arising from orographic precipitation, airmass transformation, and cloud and precipitation shadowing
  - Vertical Structure
    - Changes in frontal slope due to terrain induced horizontal flow and vertical motion
    - Decoupling of surface and upper-level fronts due to low-level blocking
- Frontal analysis in complex terrain
  - Challenges & approaches, including hands on lab

Front-Mountain Interactions

Frontal Movement

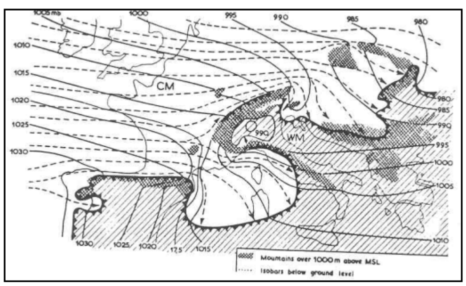
Frontal Movement



Warm frontal retardation and formation of the topographic seclusion and Skagerak cyclone

Bjerknes and Solberg 1922

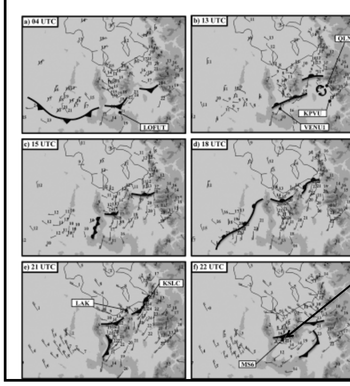
Frontal Movement



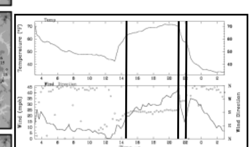
Orographic cold-frontal distortion by the orography of Europe including blocking/retardation by the Alps, Pyrenees, & Dinaric Alps and acceleration through Rhone Gap (Mistral) and Adelsberger Saddle

Bergeron 1928, Godske et al. 1957

Frontal Movement



Frontal distortion and fragmentation by basin-and-range topography



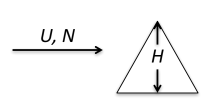
West and Steenburgh (2010)

Movement Conceptual Model

- The mountain-induced flow advects and distorts the front (Egger and Hoinka 1992)
  - Consider how the front will move in the absence of orography
  - Superimpose the terrain induced flow
  - Adjust the frontal movement accordingly
- Useful *if* frontal motion is controlled primarily by large-scale advection
  - Not always the case; Frontal Speed = Advection + Propagation
- Likelihood of blocking and around/along-mountain flow increases with increasing stability and mountain height

Movement Conceptual Model

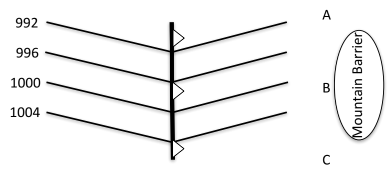
$$\mathrm{Fr} = \frac{U}{NH}, N = \left(\frac{g}{\theta}\frac{d\theta}{dz}\right)^{1/2}$$



U = Cross-barrier flow
N = Buoyancy frequency
H = Barrier height

- Flow around (i.e., blocking) favored for Fr < 1
  - More likely with increasing stability (N) and mountain height (H)
- Keep it simple as use of Fr is difficult in practice (e.g., Reinecke and Durran 2008)
  - Usually U and N are not constant with height and differ in pre-and post-frontal airmasses
  - Moist-diabatic processes are also important, but quite messy to deal with

Where Will the Front Move Fastest?



a) Point A

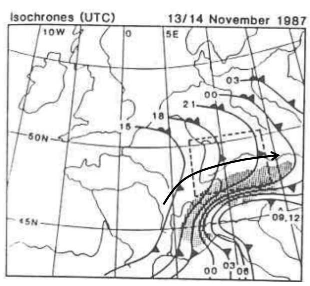
b) Point B

c) Point C

d) Points A and C

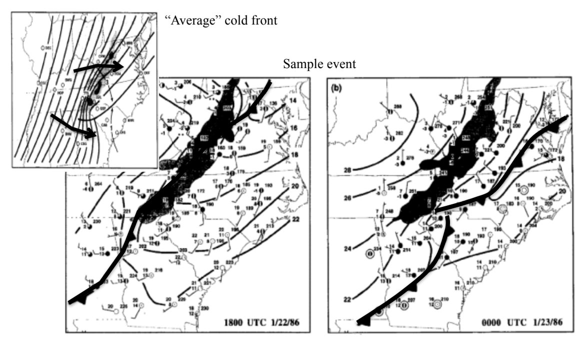
Where Will the Front Move Fastest?

Real-World Example



Hoinka and Volkert (1982)

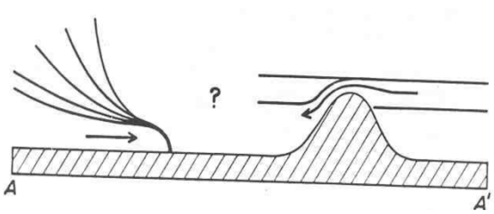
Real-World Example



O'Handley and Bosart (1996)

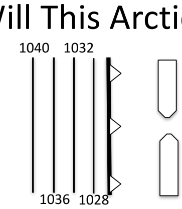
Additional Contributing Factor

Competition with pre-frontal downslope flow
May be enhanced by frontal trough, cold-air damming on downstream side of barrier, and related "ageostrophic suck"



Smith (1986)

What Will This Arctic Front Do?



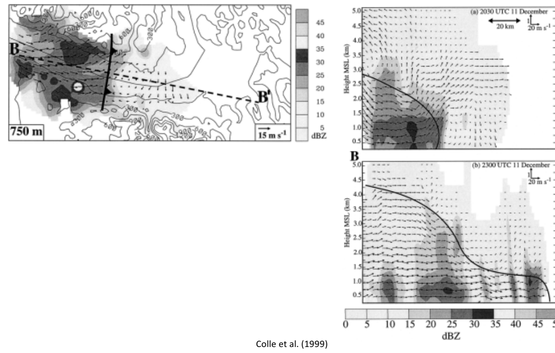
a) Move unimpeded over the mountain barrier

b) Stall on the windward slope and at the gap

c) Stall on the windward slope, but accelerate into the gap

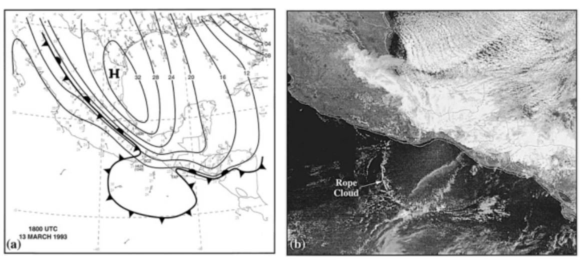
Terrain Channeling

Real-World Example



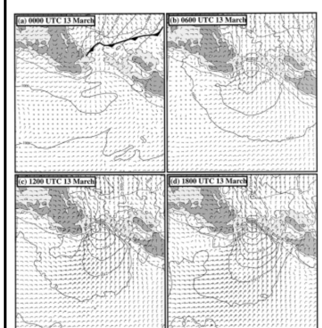
Colle et al. (1999)

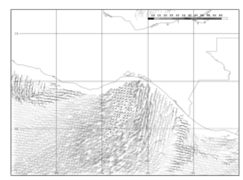
Real-World Example



Steenburgh et al. (1998)

Real-World Example





QuikSCAT wind (kt)
0300 UTC 22 Nov 2006

Superstorm 1993 Cold Surge
MM5 Simulation

Steenburgh et al. (1998), Brennan et al. (2010)

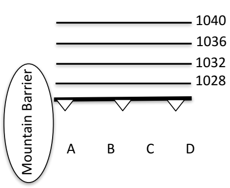
Which Will Experience Fropa First?

a) Point A

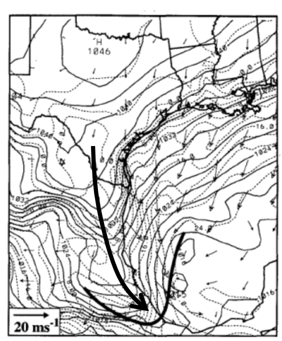
b) Point B

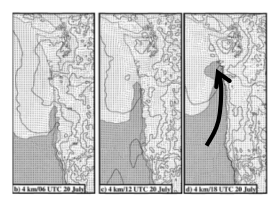
c) Point C

d) Point D



Real-World Examples





Cold surges, marine pushes, cold-air damming, etc.

Colle and Mass (1995), Steenburgh and Mass (2000)

Front-Mountain Interactions

Frontal Strength

Frontogenesis Review

Defined mathematically as the rate of change of the *magnitude* of the *horizontal* potential temperature gradient

$$F = \frac{D}{Dt}\left|\nabla_p \theta\right|$$

$$F > 0 \Rightarrow \text{Frontogenesis}$$

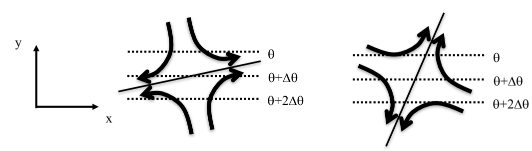
$$F < 0 \Rightarrow \text{Frontolysis}$$

Frontogenesis Review

- In the presence of a horizontal potential temperature gradient
  - <u>Convergence</u> is always frontogenetical; <u>divergence</u> is always frontolytical
  - The influence of <u>deformation</u>, <u>differential diabatic heating</u>, and <u>differential vertical motion</u> depend on their orientation relative to the horizontal θ gradient
  - <u>Vorticity</u> does not directly contribute to frontogenesis, but can play an indirect role

Deformation and Frontogenesis

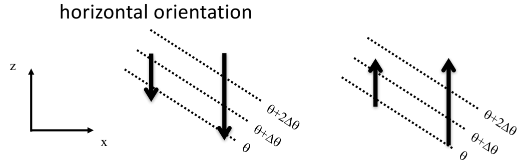
- Deformation is
  - Frontogenetical if the angle between the axis of dilatation and isentropes is < 45º
  - Frontolytical if the angle is > 45º



Frontogenetical Frontolytical

Tilting and Frontogenesis

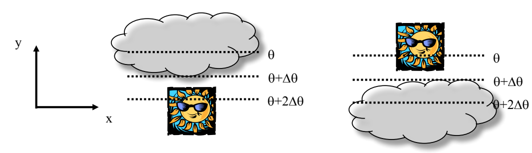
- Differential vertical motion is
  - Frontogenetical if it rotates the isentropes into a more vertical orientation
  - Frontolytical if it rotates the isentropes into a more horizontal orientation



Frontogenetical Frontolytical

Diabatic Effects & Frontogenesis

- Differential diabatic temperature tendencies are
  - Frontogenetical if they reinforce the temperature gradient
  - Frontolytical if the oppose the temperature gradient

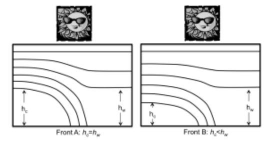


Frontogenetical Frontolytical

Limitations of "F"

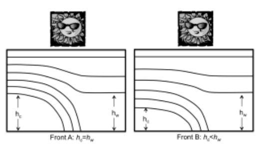
- Only an instantaneous calculation
- Does not account for interactions between terms
  - E.g., diabatic heating gradients can generate a thermally driven flow that affects the divergence or deformation frontogenesis
- Strongly influenced by magnitude of horizontal θ gradient
  - To isolate kinematic changes, some have argued for use of normalized F (e.g., Schultz 2004)

Which Statement Is True?



a) Front B strengthens at the same rate as A
b) Front B weakens at the same rate as A
c) Front B strengthens faster than A
d) Front B weakens faster than A

The Thermally Driven Flow

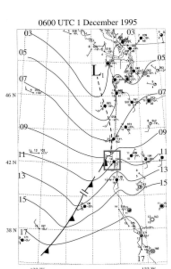


a) Has no impact on the strength of Front B
b) Strengthens Front B
c) Weakens Front B

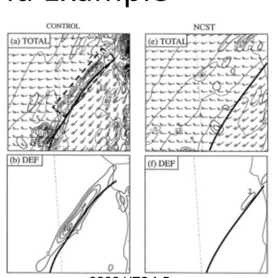
Strength Conceptual Model

- Mountains influence frontogenesis or frontoloysis through
  - Terrain-induced divergence and deformation
  - Terrain-induced vertical motion and tilting effects
  - Diabatic processes
    - Orographically induced clouds & precipitation
    - Orographic cloud and precipitation shadowing
    - Effects can be direct or indirect

Real-World Example



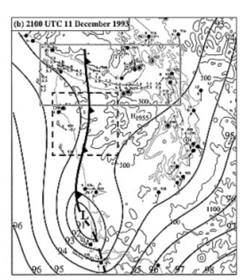
0600 UTC 1 Dec

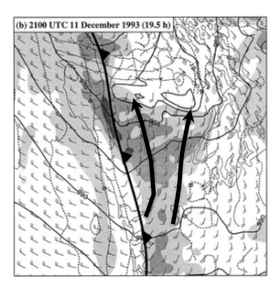


0800 UTC 1 Dec

"The coastal topography helped to further enhance and collapse the thermal gradient and associated cold-frontal rainband through enhanced deformation frontogenesis associated with the prefrontal terrain-enhanced flow"
- Colle et al. (2002)

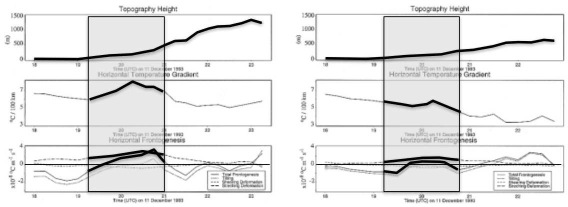
Real-World Example





"Prefrontal flow splitting around the Olympics intensified the front by enhanced stretching deformation as it approached the barrier"
- Colle et al. (1999)

Real-World Example



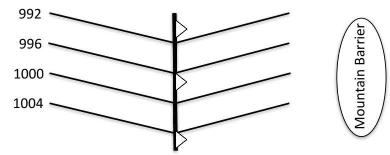
With Olympics
Stronger Stretching Deformation Fr
Less negative or slightly positive tilting Fr (prefrontal downslope)
Stronger Front

Half Olympics
Weaker Stretching Deformation Fr
More negative tilting Fr
Weaker Front

Temp Gradient
Stretching Def Fr
Tilting Fr

Colle et al. (1999)

What Will Happen to This Front?

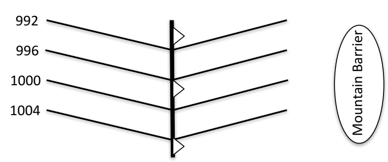


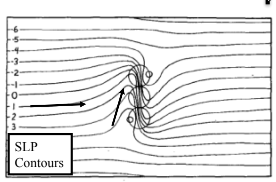
a) It will be strengthened by the mountain-induced horizontal flow

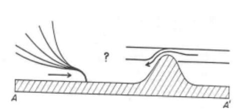
b) It will be weakened by the mountain-induced horizontal flow

c) It will not strengthen or weaken

What will happen to this front?

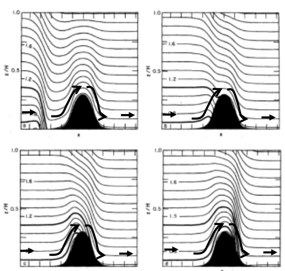






Smith (1982, 1986)

Idealized Tilting



Windward Side
Tilting Effects Weaken

Leeward Side
Tilting Effects Strengthen

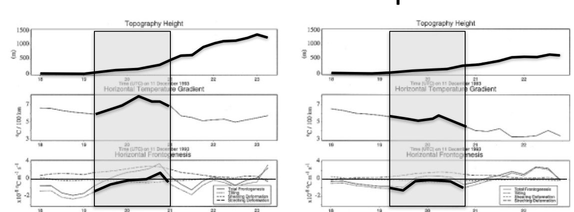
Blumen and Gross (1987)

Great, but…"*Windward accleration (frontolysis) and leeside retardation (frontogenesis) as predicted by the 2-D passive scalar approach are rarely if ever observed*"
- Egger and Hoinka (1992)

Tilting in the Real World

- 2-D uniform flows are oversimplifications
- In practice, consider the full 3-D flow field as a cyclone and attendant fronts approach or move through an area of complex terrain
- Frontal trough, blocking, and "ageostrophic suck" often retard and contribute to frontogenesis as a front approaches a mountain barrier

Real-World Example



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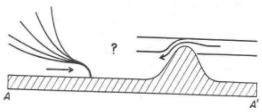
Temp Gradient
Stretching Def Fr
Tilting Fr

Colle et al. (1999)

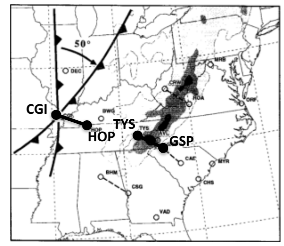
What Will Tilting Do to This Front?

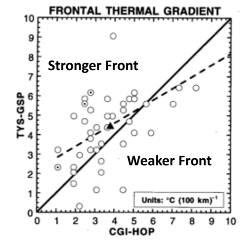


a) Strengthen it
b) Weaken it
c) Nothing

Smith (1986)

Putting It All Together





Mean CGI-HOP=3.8C/100km; Mean TYS-GSP=4.5C/100km

"Over the mountains the cross-front thermal [gradient is] enhanced by about 25%...Once past the mountains, fronts are weaker and often difficult to locate."

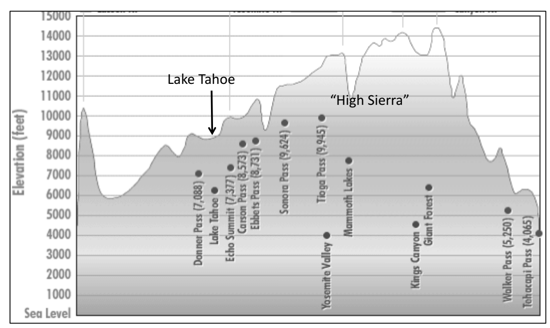
- O'Handley and Bosart (1996)

Mountains aren't everything, so there are some fronts that weaken (large-scale or diabatic processes)

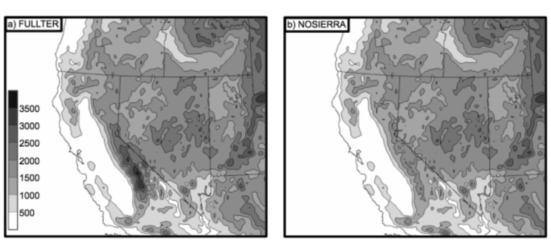
Diabatic Effects

- Orographic precipitation & related airmass transformation
- Cloud and precipitation shadowing
- Effects are direct and indirect, as well as local and remote

Example: Sierra Nevada

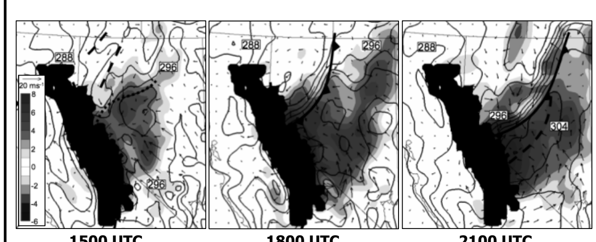


Example: Sierra Nevada



West and Steenburgh (2010)

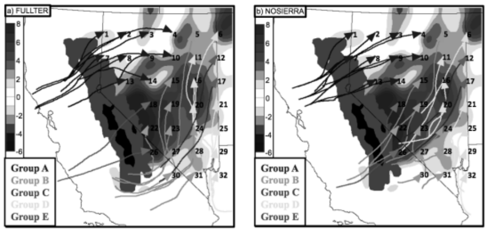
Example: Sierra Nevada



FULLTER Lowest-Level Temperature
FULLTER-NOSIERRA Wind and Lowest-Level Pot. Temperature Anomalies

West and Steenburgh (2010)

Example: Sierra Nevada

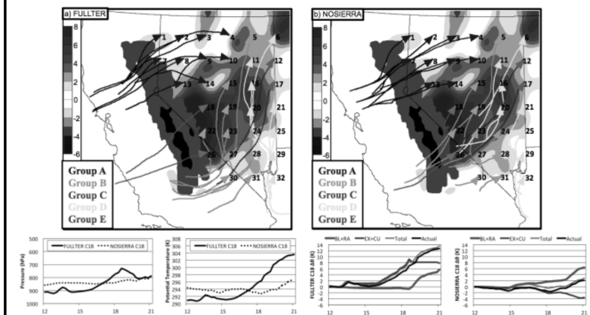


Prefrontal trajectories experience substantial differences in path and thermodynamic histories

Postfrontal trajectories move relatively unimpeded across Northern Sierra/Southern Cascades in FULLTER and NOSIERRA

West and Steenburgh (2010)

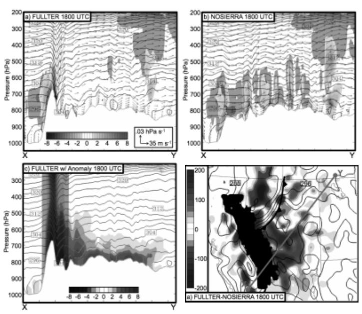
Example: Sierra Nevada



C18: Warmer in FULLTER due to warming in windward orographic cloud (airmass transformation) and leeward cloud/rain shadowing

West and Steenburgh (2010)

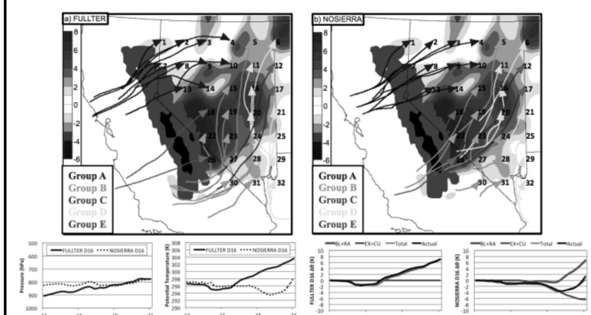
Example: Sierra Nevada



- Greater airmass transformation
  - Warming and drying
- Cloud and precipitation shadowing
  - Less low-level evaporative cooling
  - More sensible heating during day

West and Steenburgh (2010)

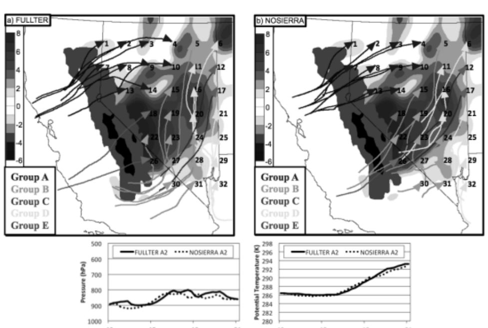
Example: Sierra Nevada



D16: Warmer in FULLTER since it originates over Mohave (higher initial θ despite lower altitude) and cloud/rain shadowing

West and Steenburgh (2010)

Example: Sierra Nevada



A2: Virtually the same in FULLTER and NOSIERRA

West and Steenburgh (2010)

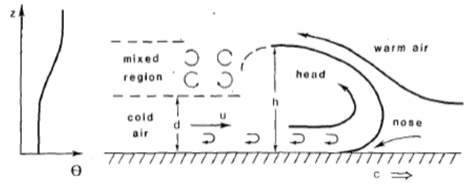
Front-Mountain Interactions

Vertical Structure

Vertical Structure

- Channeling and gravity current-like structures
- Blocking, forward tilting, and decoupling of lower and upper-portions of front

Terrain Channeling

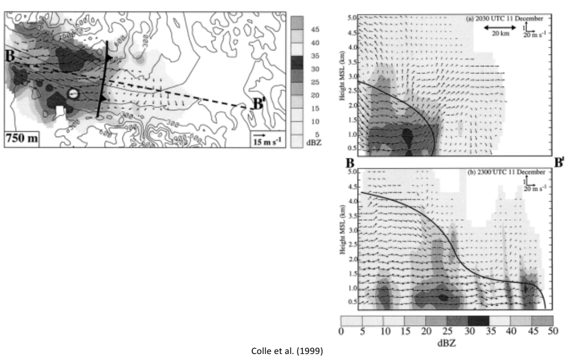


Can enhance frontal collapse and shallow, gravity current-like structure
Can occur along a barrier as well as within gaps and valleys

Pronounced frontal nose
Low-level rear-to-front flow w/ prefrontal warm air ascending nose
Possible narrow cold-frontal rainband or convective initiation

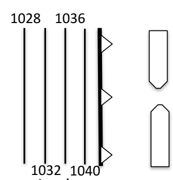
Simpson (1982), Smith and Reeder (1988)

Real-World Example



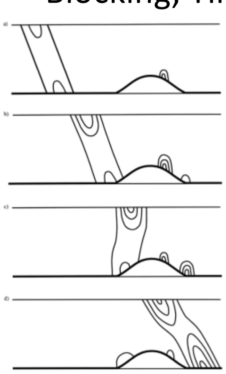
Colle et al. (1999)

What Will This Arctic Front Do?



a) Become shallower in the gap
b) Become deeper in the gap
c) Tilt forward in the gap
d) Have the same slope and depth in the gap as upstream

Blocking, Tilting, and Decoupling



"The mountain retards and blocks the approaching front at the surface while the upper-level PV anomaly…moves across the domain unaffected. When upstream blocking is strong, frontal propagation is discontinuous across the ridge."
- Dickinson and Knight (1999)

Real World Example
"Terrain-front interactions resulted in a slowing of the front as the system made landfall, and blocking contributed to a tipped-forward baroclinic structure below 800 mb"
- Colle et al. (2002)

Possible Real-World Examples

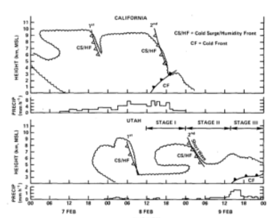
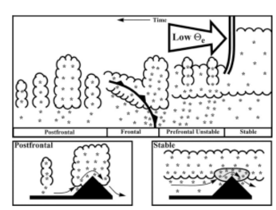


FIG. 2. Diagram of cloud, precipitation and synoptic features for storms passing through Sheridan, California (top panel) and Beaver, Utah (bottom panel) between 0000 UTC (7 Feb) and 0000 UTC (10 Feb). Top panel taken from Reynolds and Kuciauskas (1988). Note precipitation scales are not the same.

Reynolds and Kuciauskas (1988)
Long et al. (1990)



Steenburgh (2003)

Issue: Observed, but role of front-mountain interactions not examined
Does topography increase the frequency and vertical separation of split-front-like features?

Leeside Effects

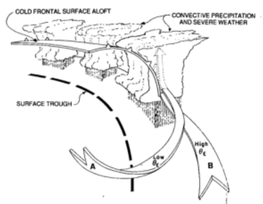
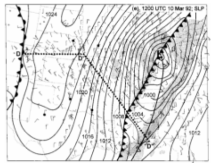
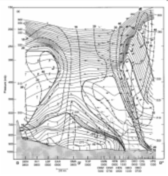


FIG. 17. Schematic of the process by which a CFA can trigger severe weather. The arrow A shows the flow of dry air that initially descends along the eastern slopes of the Rockies. The arrow B shows the flow of warm, moist air from the Gulf of Mexico.

Hobbs et al. (1990)

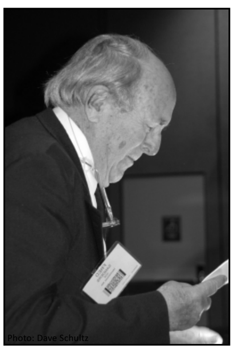




Neiman et al. (1998)

Frontal Analysis in Complex Terrain

The Challenge

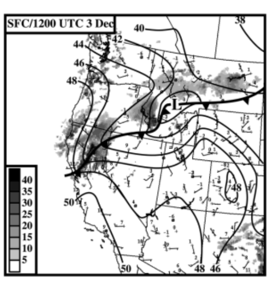


"Dick [Reed] and I believed there were no fronts in the Intermountain West and used brown lines to identify surface troughs"
- Fred Sanders

Why So Difficult?

- Sea level pressure reduction
- Conventional observing stations poorly resolving key topographic scales and phenomenon
- Conventional observing stations sited primarily in valleys and basins
- Variations in station elevation complicating the analysis of horizontal temperature gradients
- Diabatic & boundary layer processes obscuring large-scale airmass changes
  - Diurnal and persistent cold pools
  - Terrain-induced flows (thermally or dynamically driven)
- Lack of appropriate conceptual models for areas of complex terrain
- Etc…

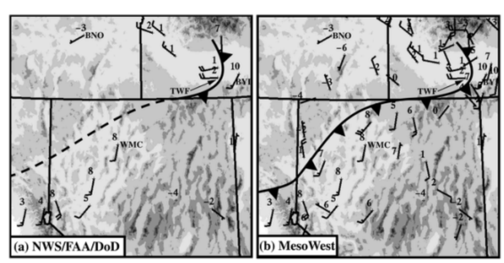
Suggested Approaches



Consider using altimeter setting to reduce/extrapolate pressure to the mean elevation of the observing sites in your region (e.g., above, 1500 m AMSL)

Steenburgh and Blazek (2001)

Suggested Approaches



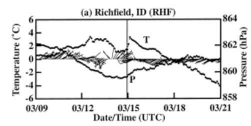
Use non-conventional data

Steenburgh and Blazek (2001)

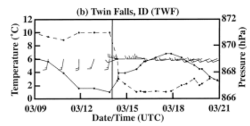
Non-Conventional Data

- “All observations are bad, some are useful”
- More data makes outliers easier to identify – get all you can
- Mesoscale is a space *and time* scale
  - Get data at the highest frequency possible
  - Time series at high resolution are your best friend in complex terrain

Suggested Approaches



Site with nocturnal inversion
(frontal temperature change masked)

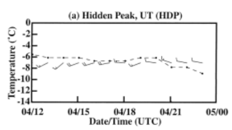


Site without nocturnal inversion
(frontal temperature change evident)

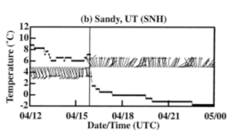
Take advantage of multi-elevation, multi-exposure nature of observational data
Can be helpful to deal with cold pools

Steenburgh and Blazek (2001)

Suggested Approaches



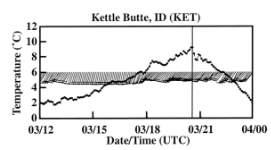
Intense surface front at Sandy (4800 ft)
not evident at Snowbird (11,000 ft)
despite being only 20 km away



Take advantage of multi-elevation, multi-exposure nature of observational data
Can be helpful for diagnosing vertical frontal structure

Steenburgh and Blazek (2001)

Suggested Approaches



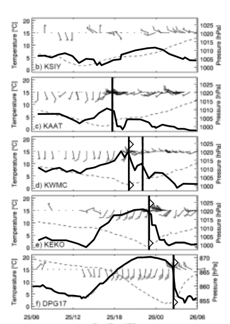
Terrain channeling – no wind shift with FROPA

Develop quick-access wind-rose climatologies for stations and
identify those with unique circulations

Steenburgh and Blazek (2001)

Suggested Approaches

- Time series analysis
  - Your best friend in areas of complex terrain
  - Best way to identify frontal intensity
  - Potential temperature analyses can be helpful, but many non-conventional stations don’t report pressure (or don’t do so reliably)



Steenburgh and Blazek (2001), Steenburgh et al. (2009)

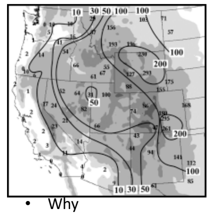
Conceptual Models

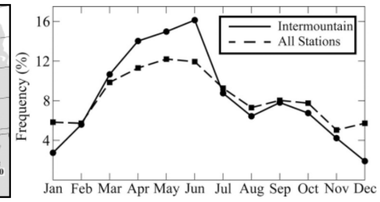
- Stand on the shoulders of giants
  - Glean what can be learned from other areas of complex terrain
  - Build from this foundation to develop them for your area of complex terrain

Summary

- A rich spectrum of processes influence Front–Mountain interactions
  - Recognize potential topographic effects, but be leery of "mountain myopia" as large-scale processes are also important
- Multi-elevation surface observations, including data from non-conventional observing sites and networks, can be used to improve weather analysis and forecasting in areas of complex terrain

Class Discussion





- Why
  - Is the number of strong cold-front passages smallest on the Pacific Coast?
  - Is there a maximum in strong cold front passages at KSLC?
  - Is the number of strong cold-front passages largest east of the Rockies?
  - Is the frequency of strong cold-front passages largest in the spring?
  - Is the spring frequency in the Intermountain West larger than elsewhere?

References

Bergeron, T., 1928: Über die dreidimensional verknüpfende Wetteranalysee. *Geofys. Publ.*, **5** (6), 1-111.

Bjerknes, J., and H. Solberg, 1922: Life cycle of cyclones and the polar front theory of atmospheric circulation. *Geofys. Publ.*, **2**, 1-60.

Bluestein, H. B., 1993: *Synoptic-Dynamic Meteorology in Midlatitudes, Vol. II*. Oxford University Press, 608 pp.

Blumen, W., and B. Gross, 1987: Semigeostrophic flow over orography in a stratified rotating atmosphere. Part I: Steady three-dimensional solutions over finite ridges. *J. Atmos. Sci.*, **44**, 3007-3019.

Brennan, M. J., H. D. Cobb, and R. D. Knabb, 2010: Observations of Gulf of Tehuantepec gap wind events from QuikSCAT: An updated event climatology and operational model evaluation. *Wea. Forecasting*, **25**, 646–658.

Colle, B. A., and C. F. Mass, 1995: The structure and evolution of cold surges east of the Rocky Mountains. *Mon. Wea. Rev.*, **123**, 2577–2610.

Colle, B. A., C. F. Mass, and B. F. Smull, 1999: An observational and numerical study of a cold front interacting with the Olympic Mountains during COAST IOP5. *Mon. Wea. Rev.*, **127**, 1310–1334.

Colle, B. A., B. F. Smull, and M.-J. Yang, 2002: Numerical simulations of a landfalling cold front observed during COAST: Rapid evolution and responsible mechanisms. *Mon. Wea. Rev.*, **130**, 1945–1966.

Egger, J., and K. P. Hoinka, 1992: Fronts and orography. *Meteor. Atmos. Phys*., 48, 3-36.

Godske, C. L., T. Bergeron, J. Bjerknes, and R. C. Bundgaard, 1957: *Dynamic Meteorology and Weather Forecasting*. American Meteorological Society and Carnegie Institution of Washington, 800 pp.

Hobbs, P. V., J. D. Locatelli, and J. E. Martin, 1990: Cold fronts aloft and the forecasting of precipitation and severe weather east of the Rocky Mountains. *Wea. Forecasting*, **5**, 614-626.

Hoinka, K. P., and H. Volkert, 1992: Fronts and the Alps: Findings from the Front Experiment 1987. *Meteor. Atmos. Phys.*, **48,** 51–75.

Long, A. B., A. W. Huggins, and B. A. Campistron, 1990: Investigations of a winter mountain storm in Utah. Part I: Synoptic analyses, mesoscale kinematics, and water release rates. *J. Atmos. Sci.*, **47**, 1302–1322.

References

Mass, C. F., and W. J. Steenburgh, 2000: An observational and numerical study of an orographically trapped wind reversal along the west coast of the United States. *Mon. Wea. Rev.*, **128**, 2363–2397.

Neiman, P. J., and Coauthors, 1998: An observational study of fronts and frontal mergers over the continental United States. *Mon. Wea. Rev.*, **126**, 2521–2554.

O'Handley, C., and L. F. Bosart, 1996: The impact of the Appalachian Mountains on cyclonic weather systems. Part I: A climatology. *Mon. Wea. Rev.*, **124**, 1353–1373.

Reinecke, P. A., and D. R. Durran, 2008: Estimating topographic blocking using a Froude number when the static stability is nonuniform. *J. Atmos. Sci.*, **65**, 1035-1048.

Reynolds, D. W., and A. P. Kuciauskas, 1988: Remote and in situ observations of Sierra Nevada winter mountain clouds: Relationships between mesoscale sructure, precipitation and liquid ater. *J. Appl. Meteor.*, **27**, 140–156.

Schultz, D. M., 2004: Cold fronts with and without prefrontal wind shifts in the central United States. *Mon. Wea. Rev.*, **132**, 2040–2053.

Simpson, J. E., 1982: Gravity currents in the laboratory, atmosphere, and ocean. *Ann. Rev. Fluid Mech.,* **14**, 213-234.

Smith, R.B., 1982. Synoptic observations and theory of orographically disturbed wind and pressure. *J. Atmos. Sci.,* **39**, 60-70.

Smith, R.B., 1986. Mesoscale mountain meteorology in the Alps. *Scientific Results of the Alpine Experiment*. Vol. II, GARP Publications Series No. 27, World Meteor. Soc., 407-423.

Smith, R. K., and M. J. Reeder, 1988: On the movement and low-level structure of cold fronts. *Mon. Wea. Rev.*, **116**, 1927–1944.

Steenburgh, W. J., 2003: One hundred inches in one hudred hours: Evolution of a Wasatch Mountain winter storm cycle. *Wea. Forecasting*, **18**, 1018-1036.

Steenburgh, W. J., and T. R. Blazek, 2001: Topographic distortion of a cold front over the Snake River Plain and central Idaho Mountains. *Wea. Forecasting*, **16**, 301-314.

References

Steenburgh, W. J., D. M. Schultz, and B. A. Colle, 1998: The structure and evolution of gap outflow over the Gulf of Tehuantepec, Mexico. *Mon. Wea. Rev.*, **126**, 2673–2691.

Steenburgh, W. J., C. R. Neuman, G. L. West, and L. F. Bosart, 2009: Discrete frontal propagation over the Sierra-Cascade Mountains and Intermountain West. *Mon. Wea. Rev*., **137**, 2000-2020.

West, G. L., and W. J. Steenburgh, 2010: Life cycle and mesoscale frontal structure of an Intermountain cyclone. *Mon. Wea. Rev*., **138**, 2528-2545.