Observational Studies of Mesoscale Flows in Complex Topography

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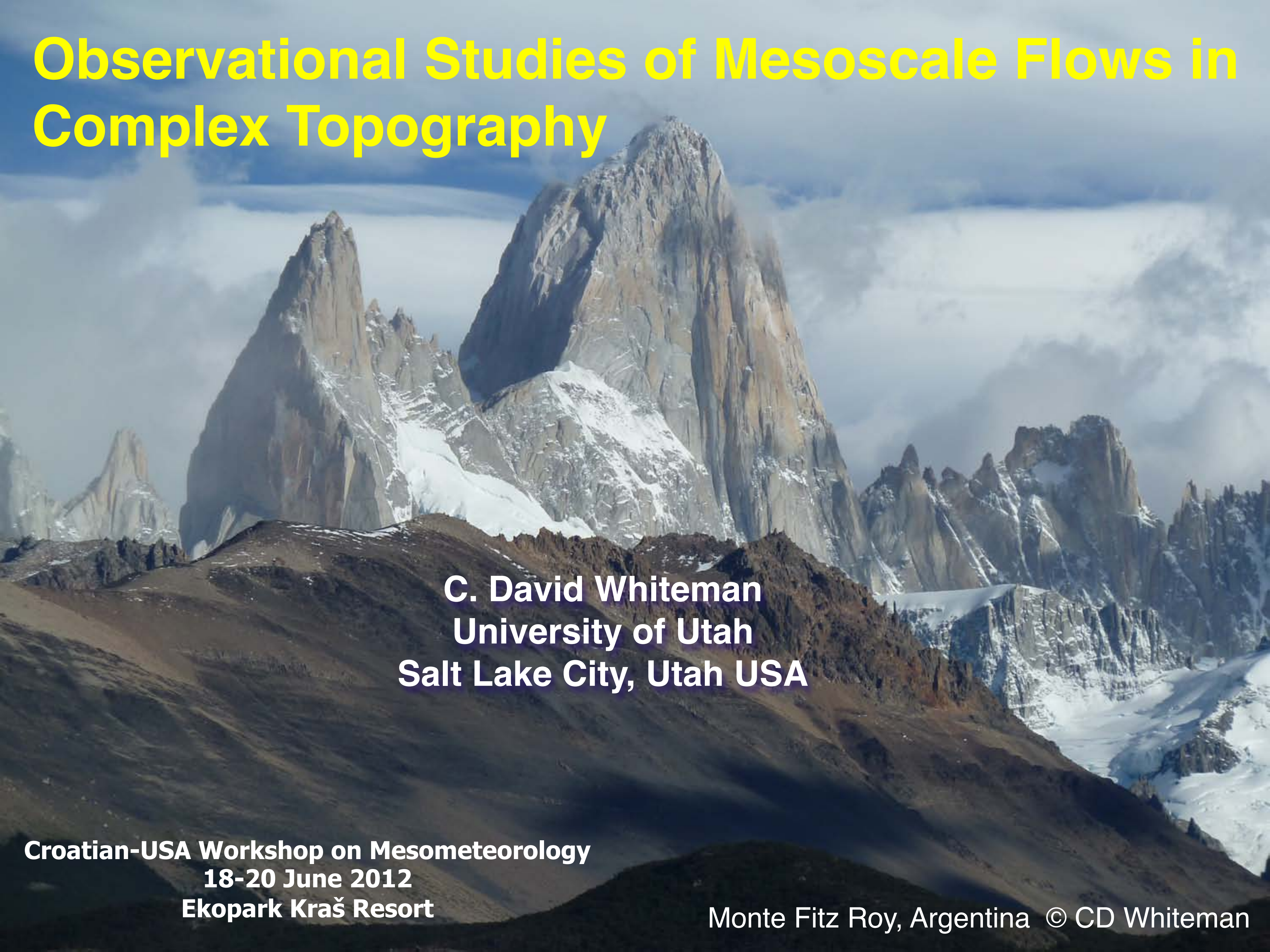
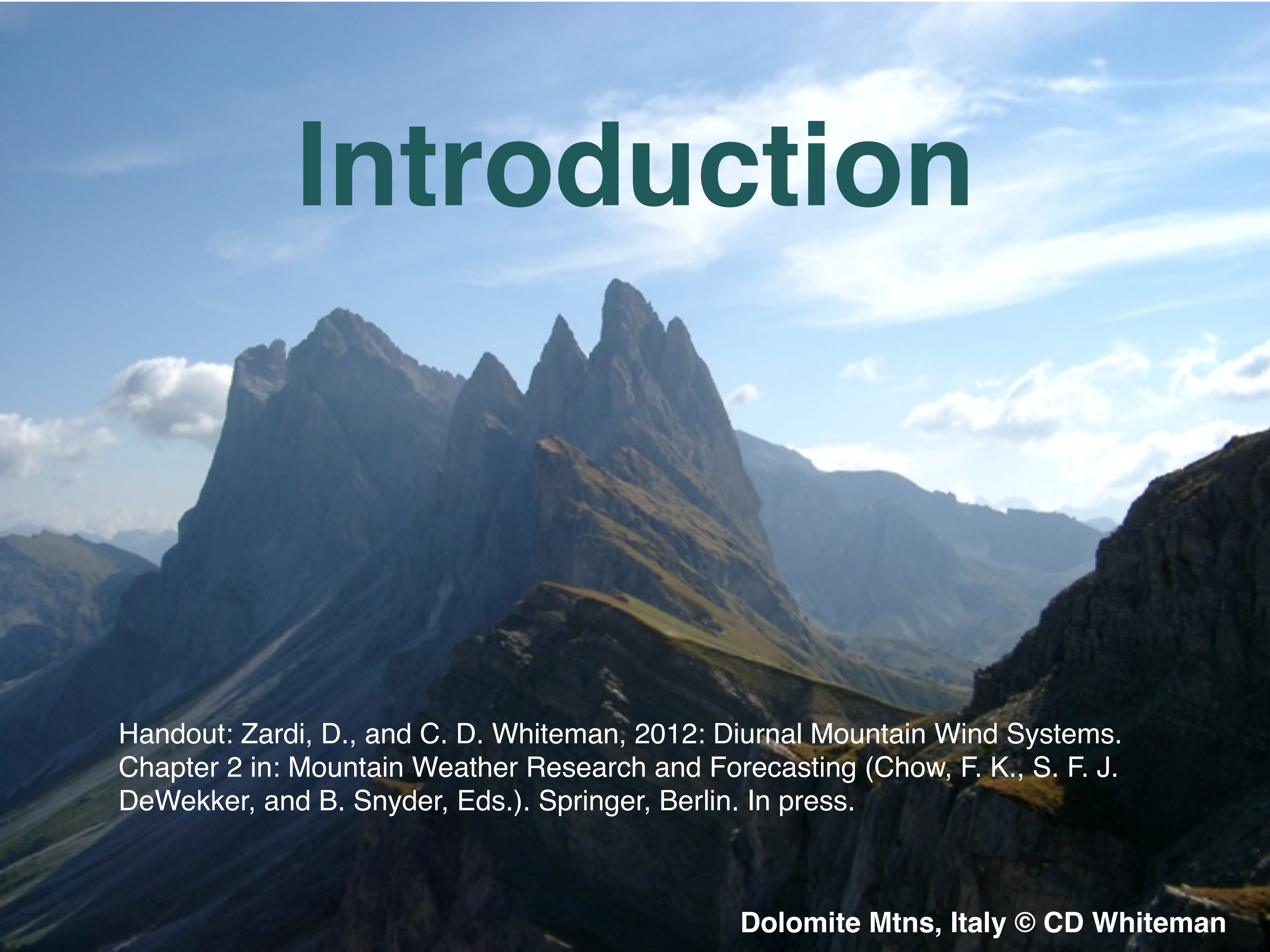
Croatian-USA Workshop on Mesometeorology
18-20 June 2012
Ekopark Kraš Resort



Monte Fitz Roy, Argentina © CD Whiteman

Introduction

Handout: Zardi, D., and C. D. Whiteman, 2012: Diurnal Mountain Wind Systems. Chapter 2 in: Mountain Weather Research and Forecasting (Chow, F. K., S. F. J. DeWekker, and B. Snyder, Eds.). Springer, Berlin. In press.



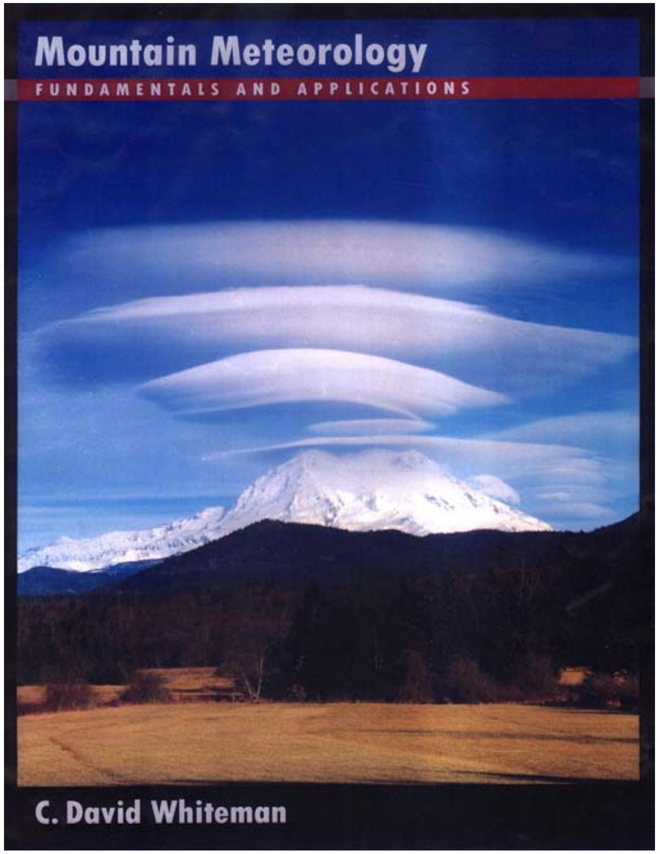
Dolomite Mtns, Italy © CD Whiteman

Outline

Introduction

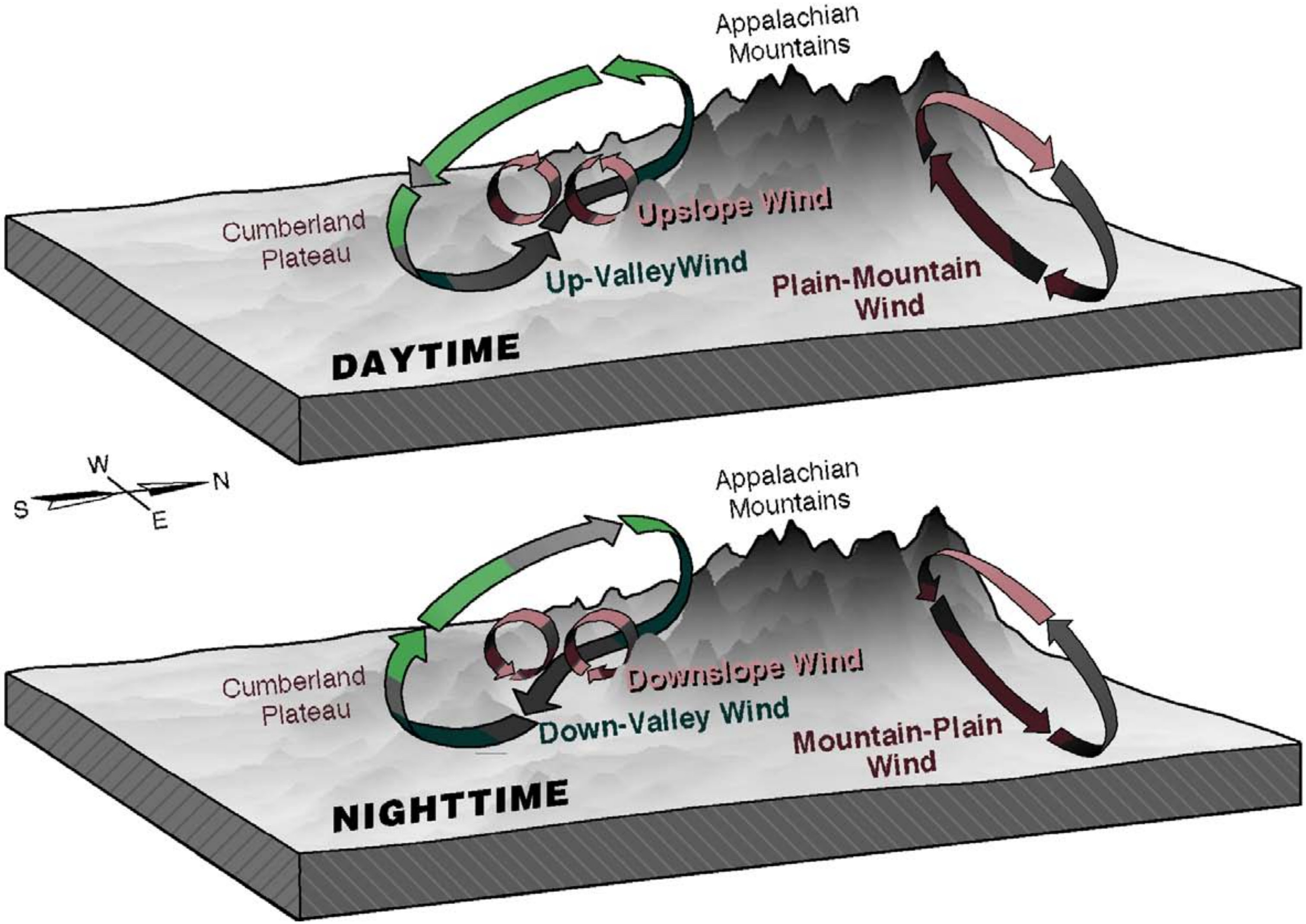
- Mountain-Plain Wind System
- Slope Wind System
- Valley Wind System
- Diurnal Cycle of Mountain Winds
- Valley Exit Jets
- Basin Meteorology
- Rime Mushrooms

Summary



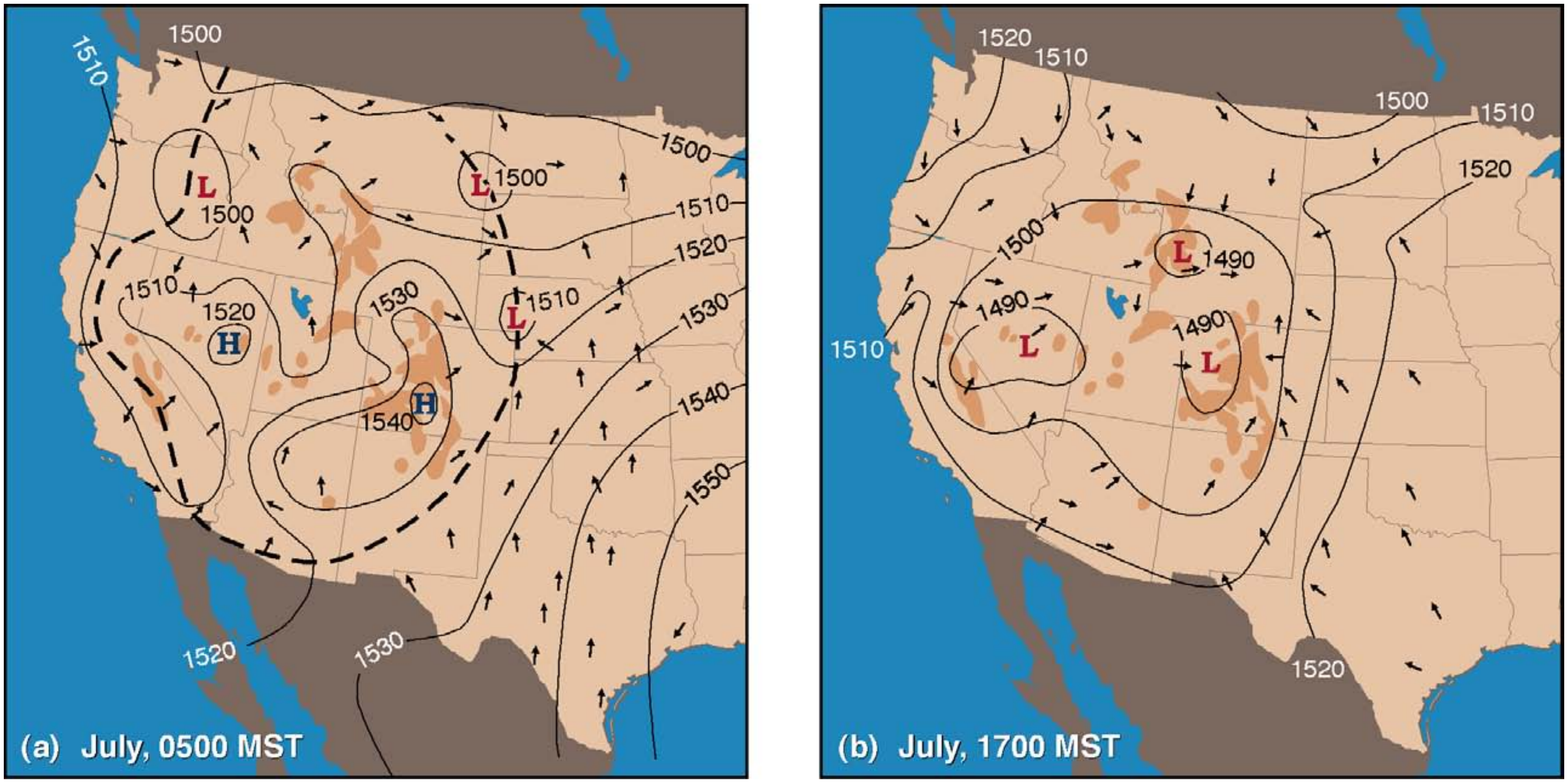
Figures: Whiteman (2000)
unless otherwise indicated

Diurnal mountain winds



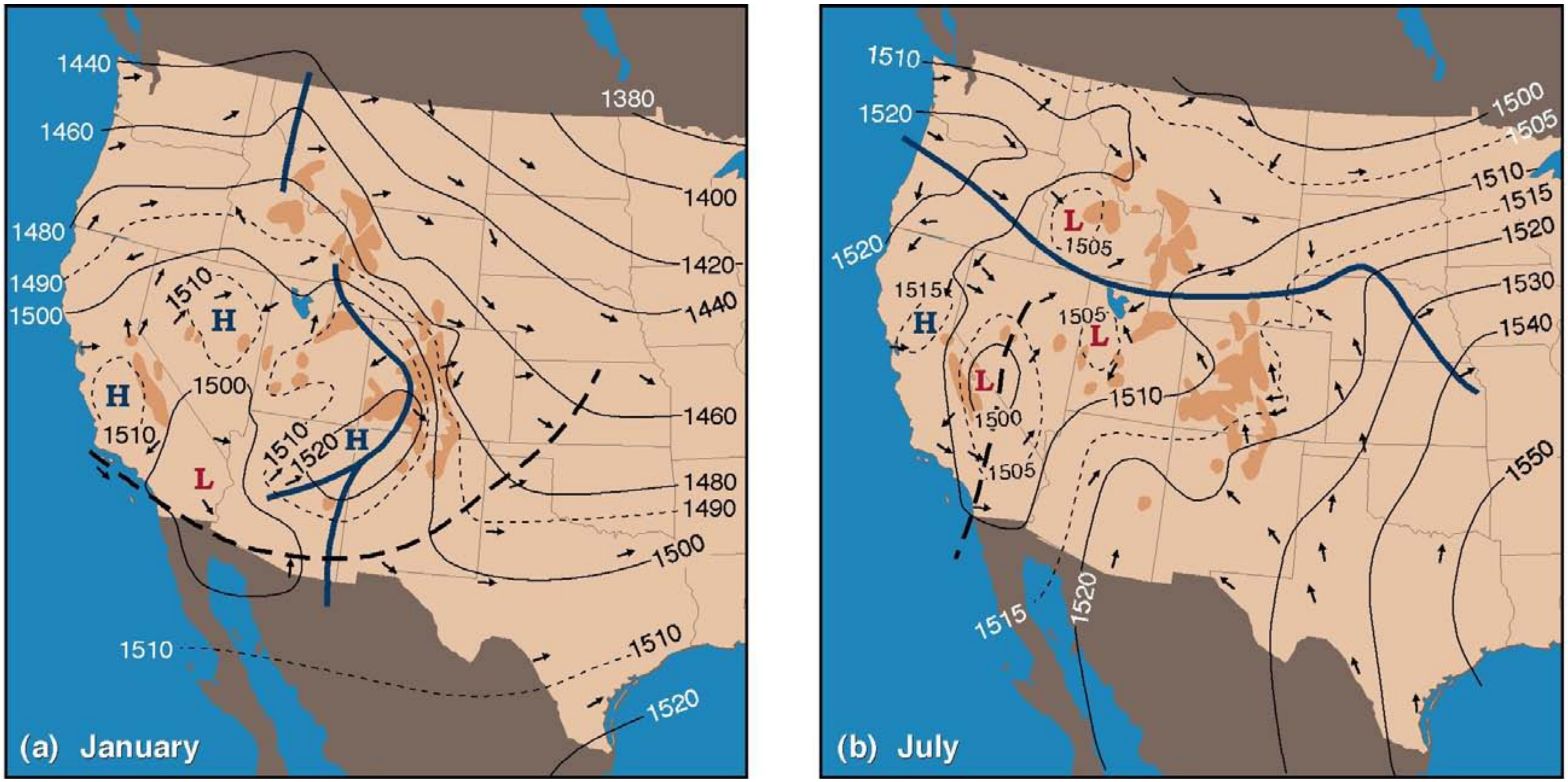
Mountain-Plain
Wind System
© Adam Naisbitt

Mean 850 mb pressure and wind patterns



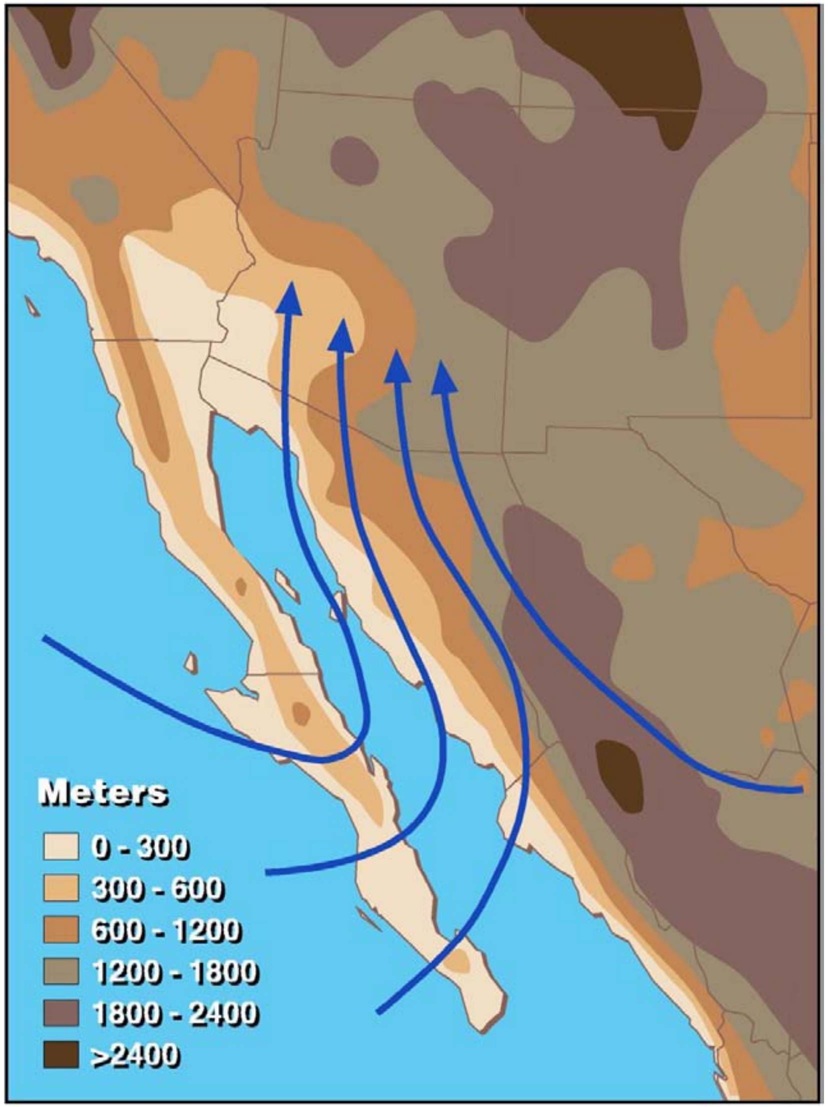
adapted from Reiter & Tang (1984)

Mean 850 mb pressure and wind patterns

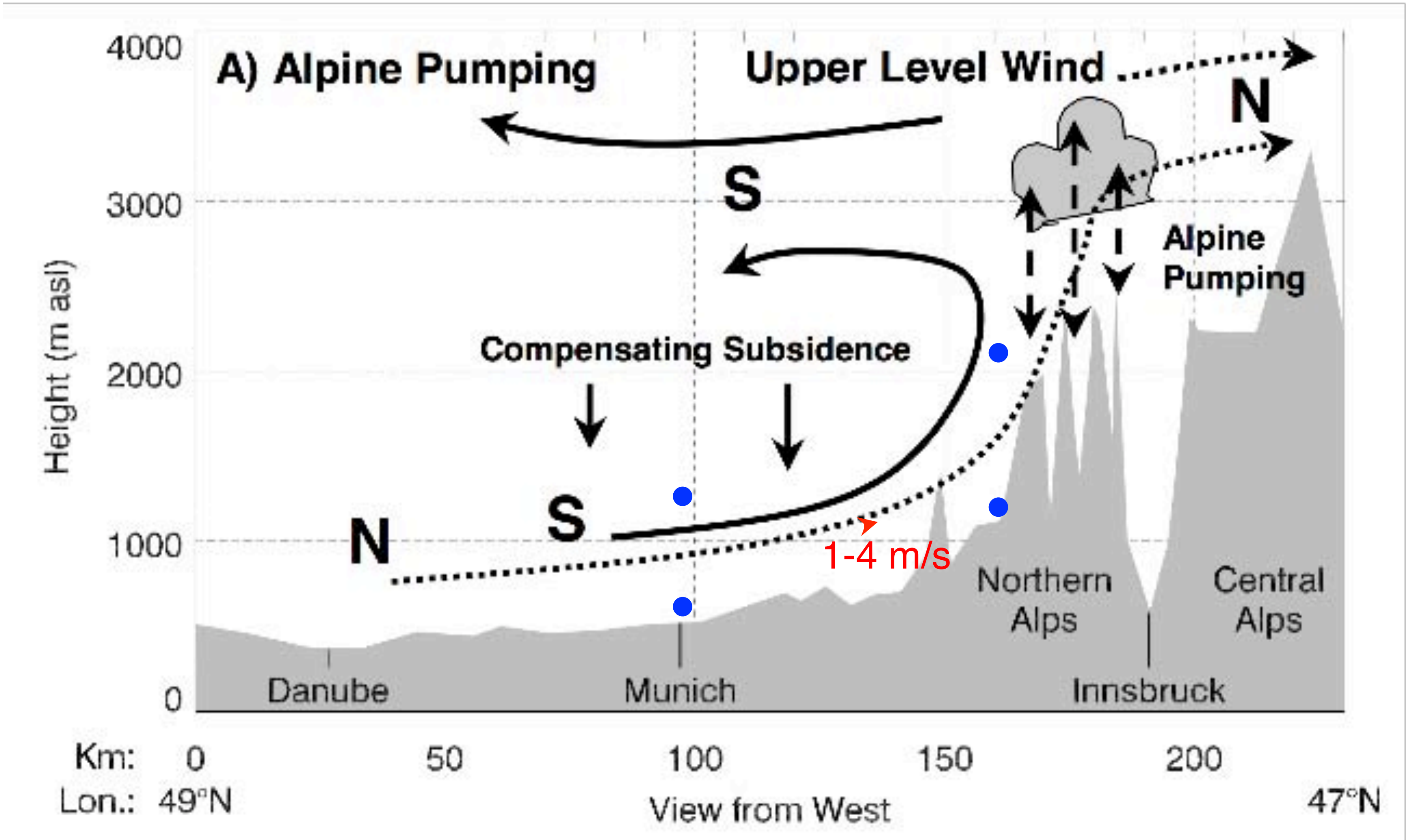


adapted from Reiter & Tang (1984)

The Southwest or Mexican Monsoon



adapted from Stensrud et al. (1995)



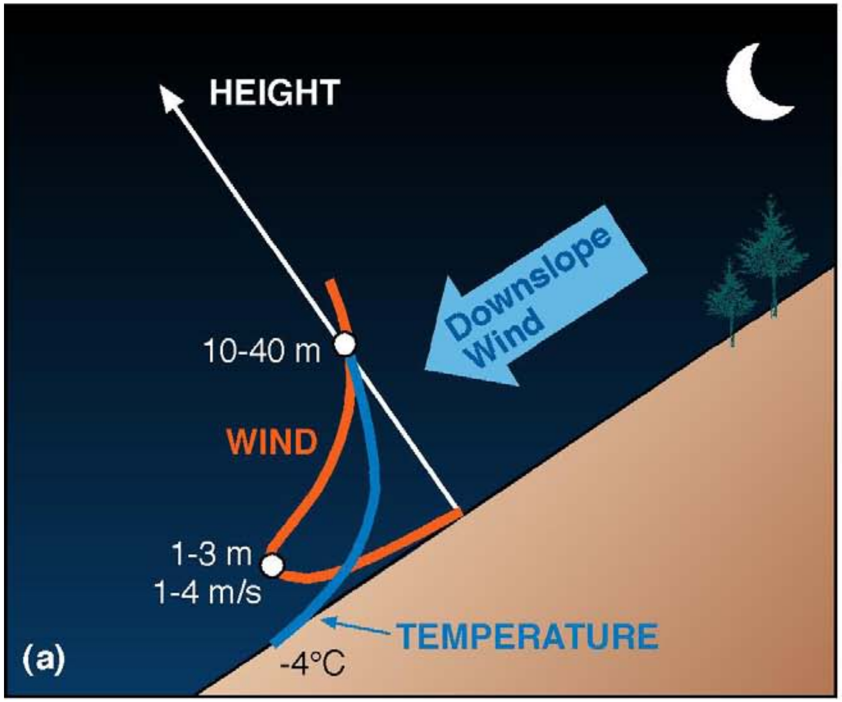
Late morning through afternoon

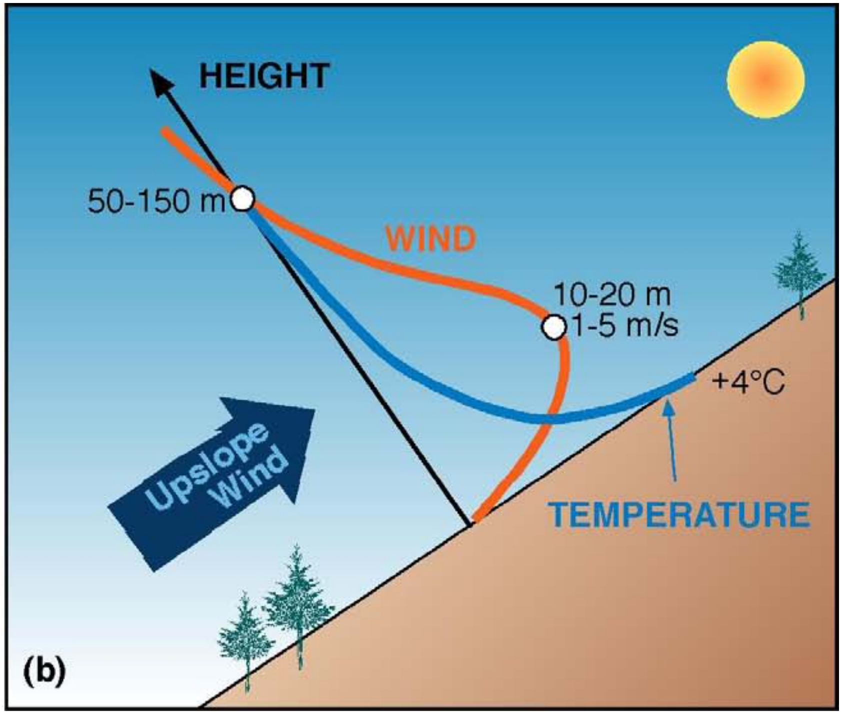
Winkler et al. (2006)
Weissmann et al. (2006)

Slope Wind System

Roundtop Pk from Carson Pass, Sierra Nevada © Craig Clements

Slope flows





Slope winds are gravity or buoyancy circulations following the dip of the underlying slope and caused by differences in temperature between air heated or cooled over the mountain slopes and air at the same altitude over the valley center. Quick response. Affected by along-valley wind system, weather (SEB and radiation budget, ambient flows), changing topography/surface cover, obstacles. --- Difficult to find in a pure form.

Downslope flows

Gruenloch Basin sidewall
2051 UTC 2 June 2002

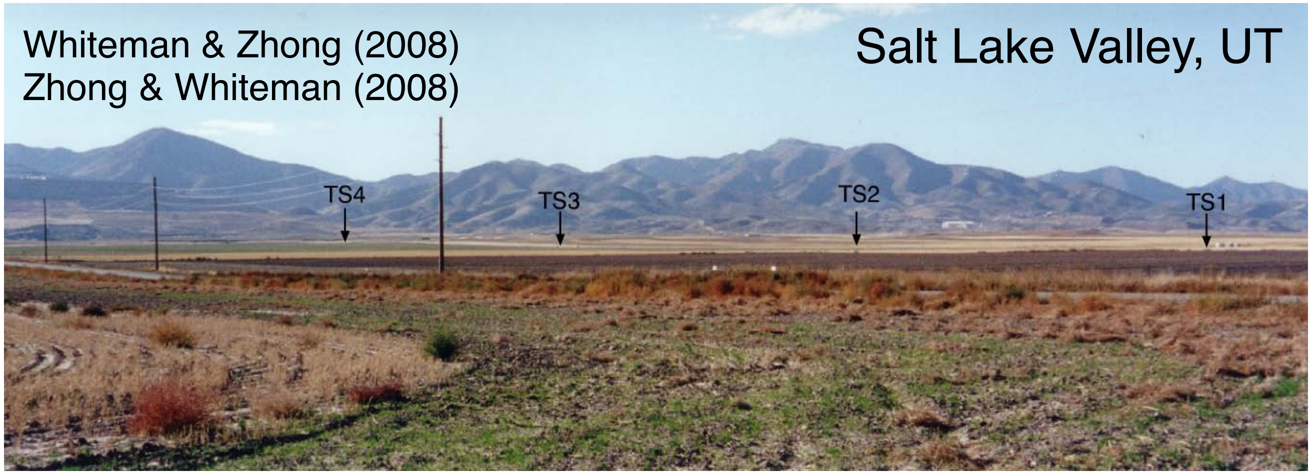
From R. Steinacker

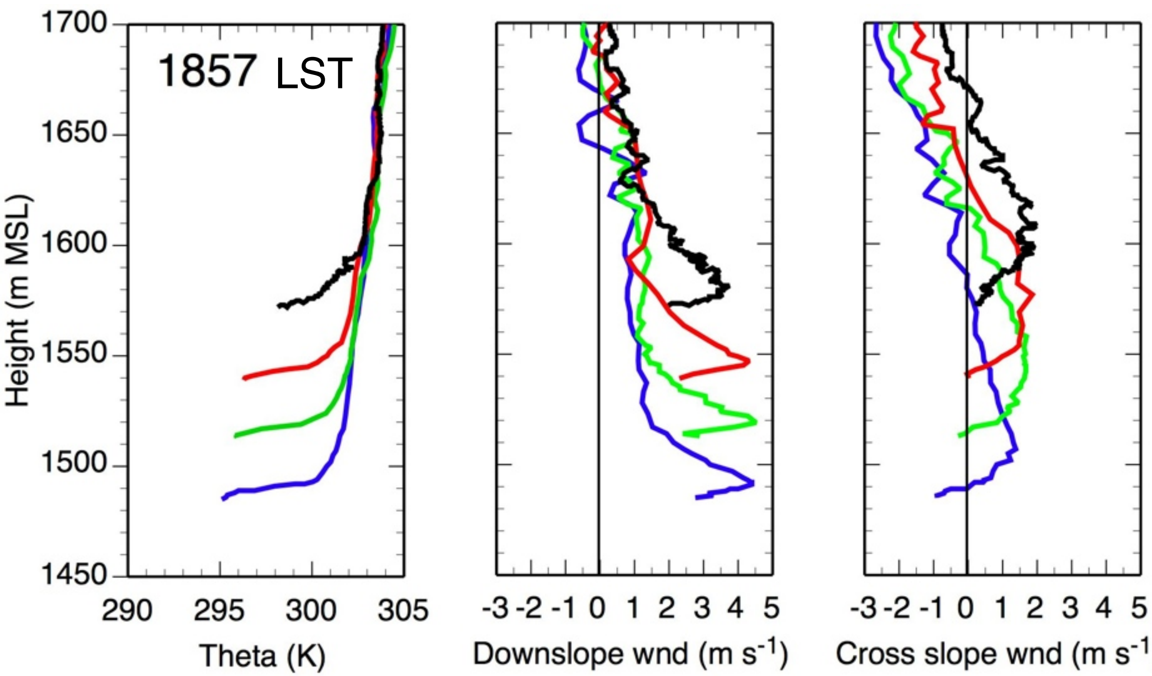
Open questions - slope flows

- Models developed and run with little comparison to scarce data
- Numerical models often overemphasize speeds
- Work needed:
  - Interactions of thermal circulations
  - Effects of ambient stability ("simple slopes")
  - No radiative flux divergence models
  - Intermittency
- Representativeness of observations on slopes

Downslope flow

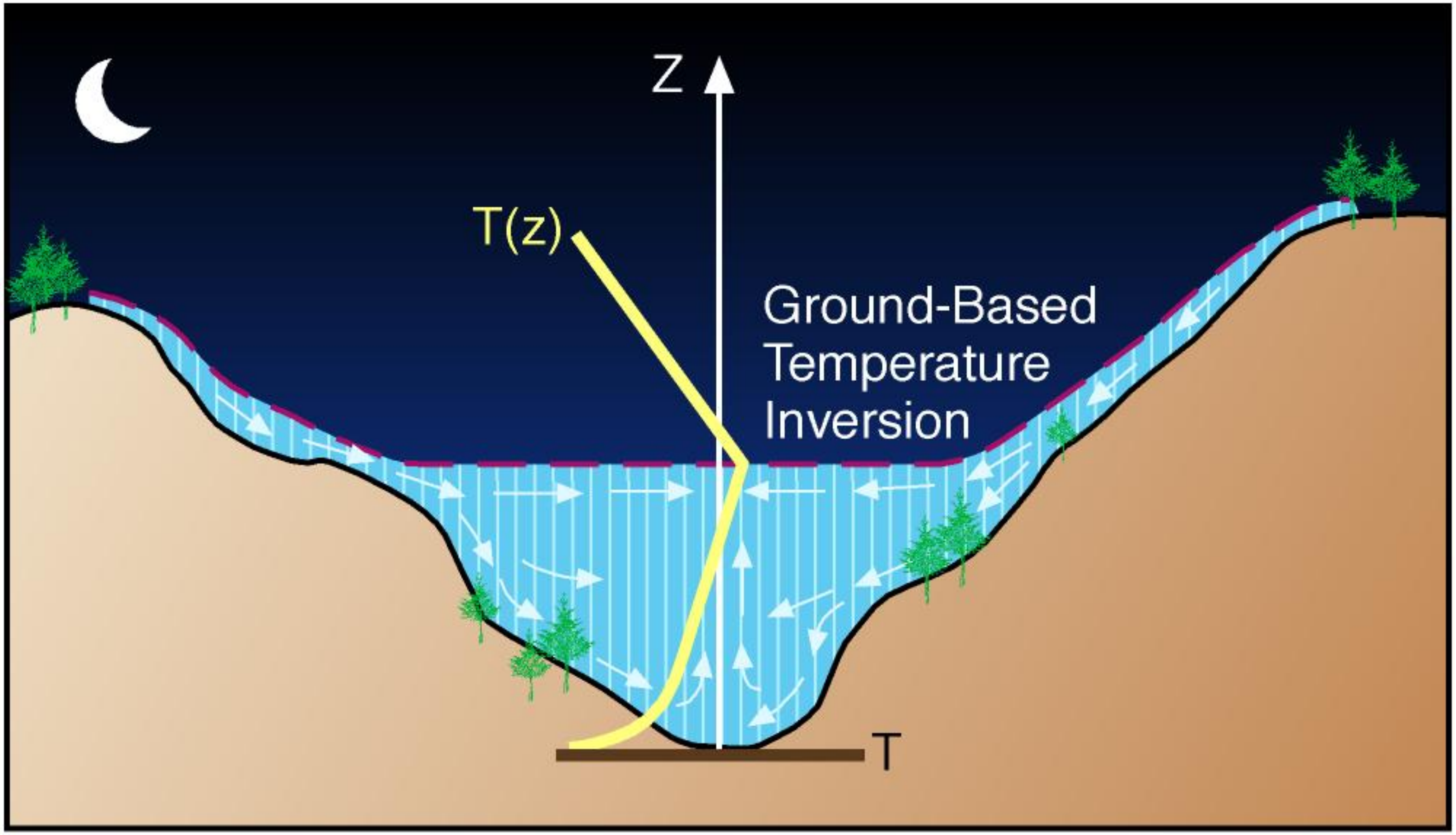
VTMX, 8 Oct 2000





- Jet profile max velocity ~ 15 m AGL increases with downslope distance, reaching 7 m/s
- Temperature deficit increases with downslope distance, reaching 7 K
- Downslope flow layer extends to ~150 m AGL
- Volume (mass) flux increase with downslope distance

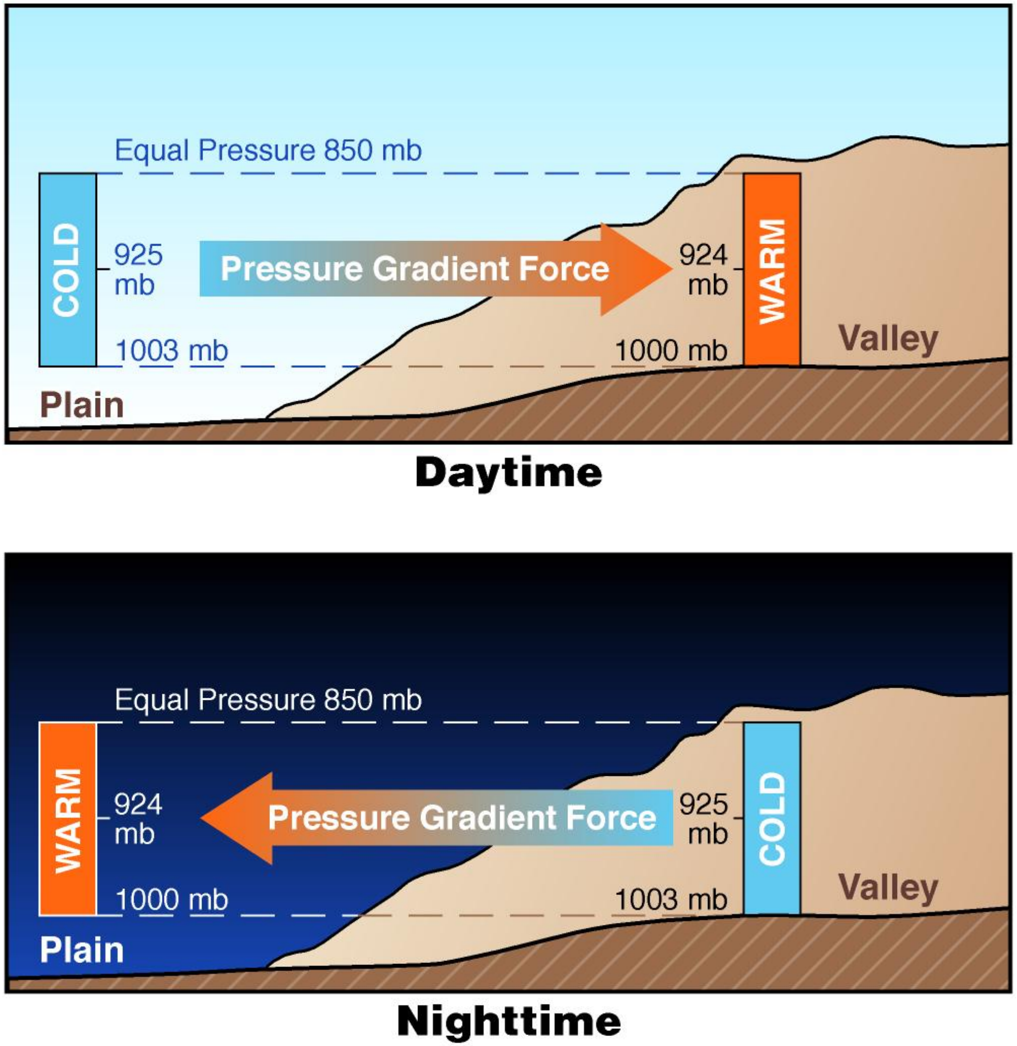
Haiden, T., and C. D. Whiteman, 2005: Katabatic flow mechanisms on a low-angle slope. *J. Appl. Meteor.*, **44**, 113-126.



Early in the evening when the atmosphere is near-neutral, downslope flows are strong and they converge on the valley floor. As the ambient stability (valley inversion) builds later in the evening, the downslope flows cannot penetrate readily to the valley floor and converge at higher altitudes.


Valley Wind
System
COMAP
Boulder, CO
Brush Creek Valley © CD Whiteman

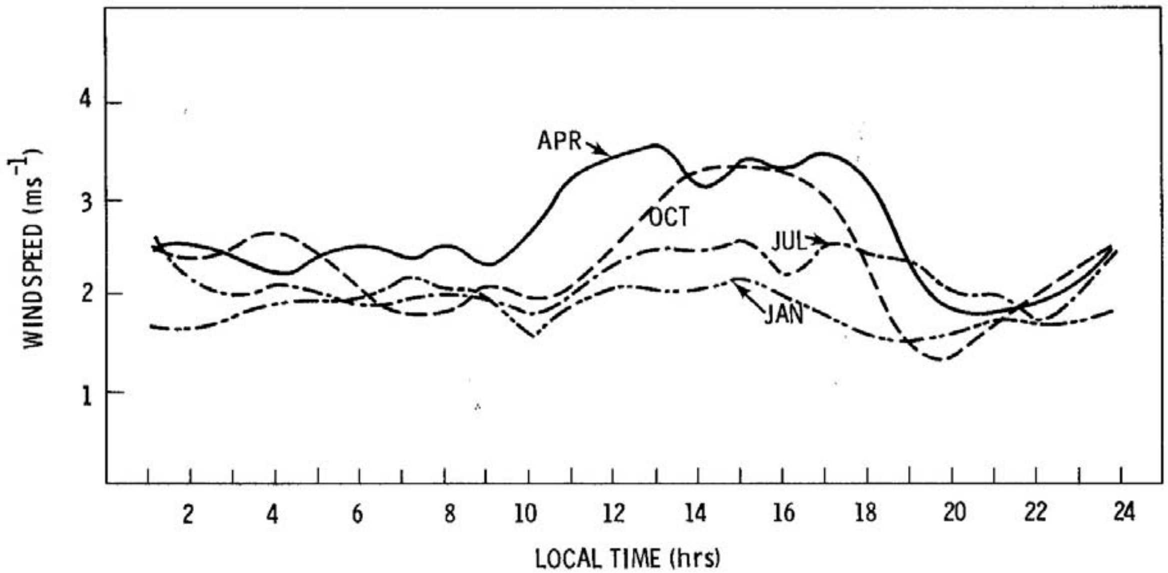
Valley wind system



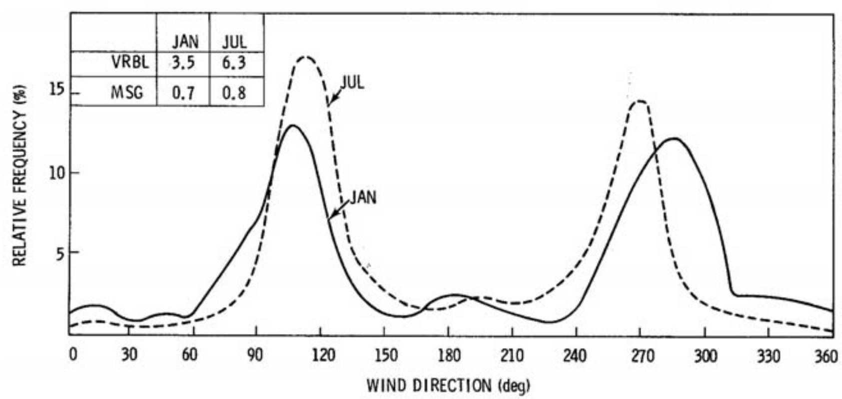
Whiteman (2000), adapted from Hawkes (1947)

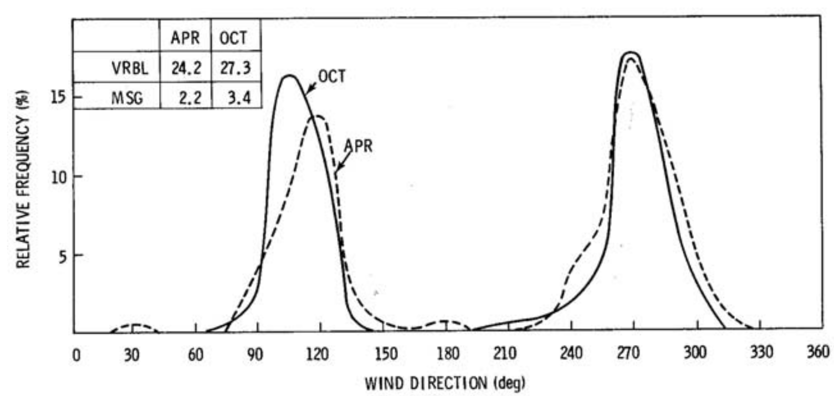
Valley winds are closed circulations that attempt to equalize horizontal pressure gradients that are built up hydrostatically between the valley and plain caused by the greater temperature range of a column of air within the valley compared to a similar column of air over the plain at the same elevation.

Valley wind system



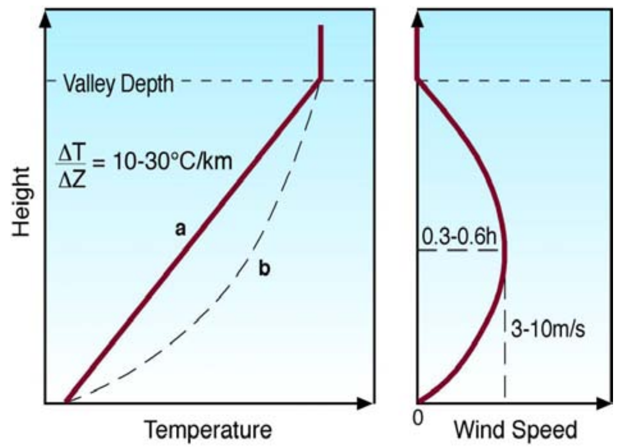
Avon, CO is in the Eagle Valley below the Vail/Beaver Creek ski area. The observations come from an automatic weather station operated in the early 1980s before the ski resort was built.



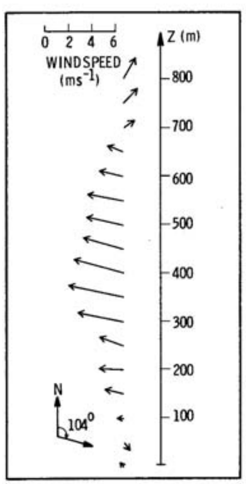


Whiteman

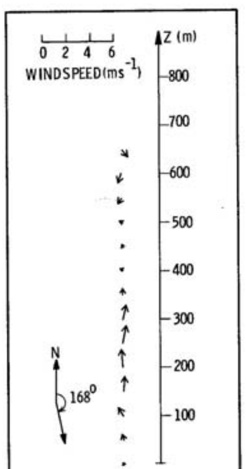
Typical T and wind profiles near sunrise



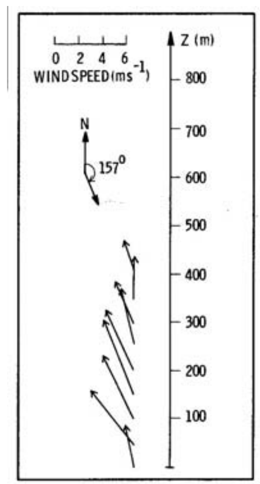
down-valley flows near sunrise



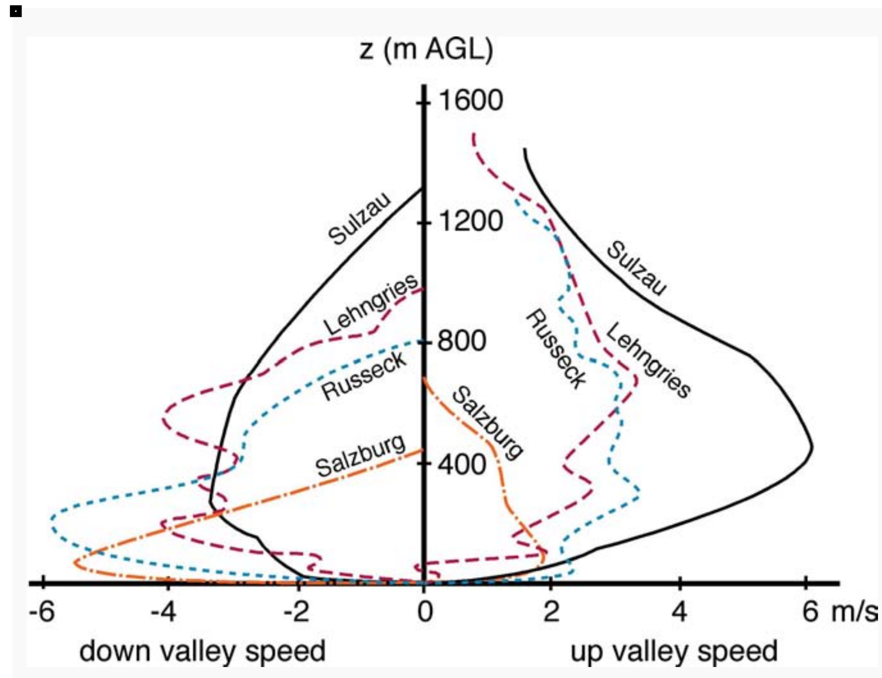
Eagle Valley
700 m deep



Yampa Valley
450 m deep



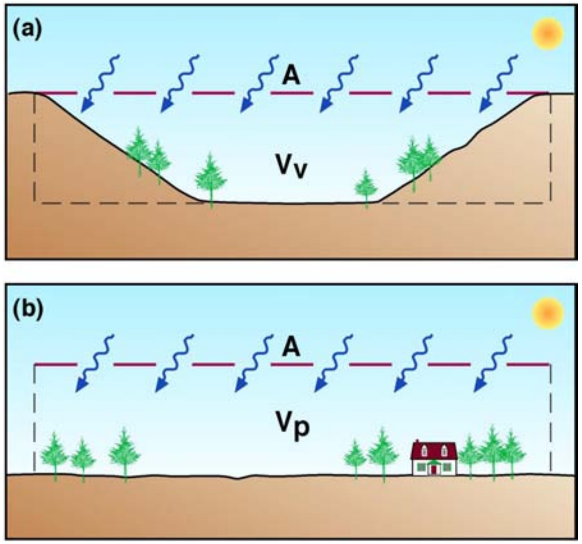
S. Fk. White R.
750 m deep



from Ekhart (1944)

average of all ascents during up-valley and down-valley periods.

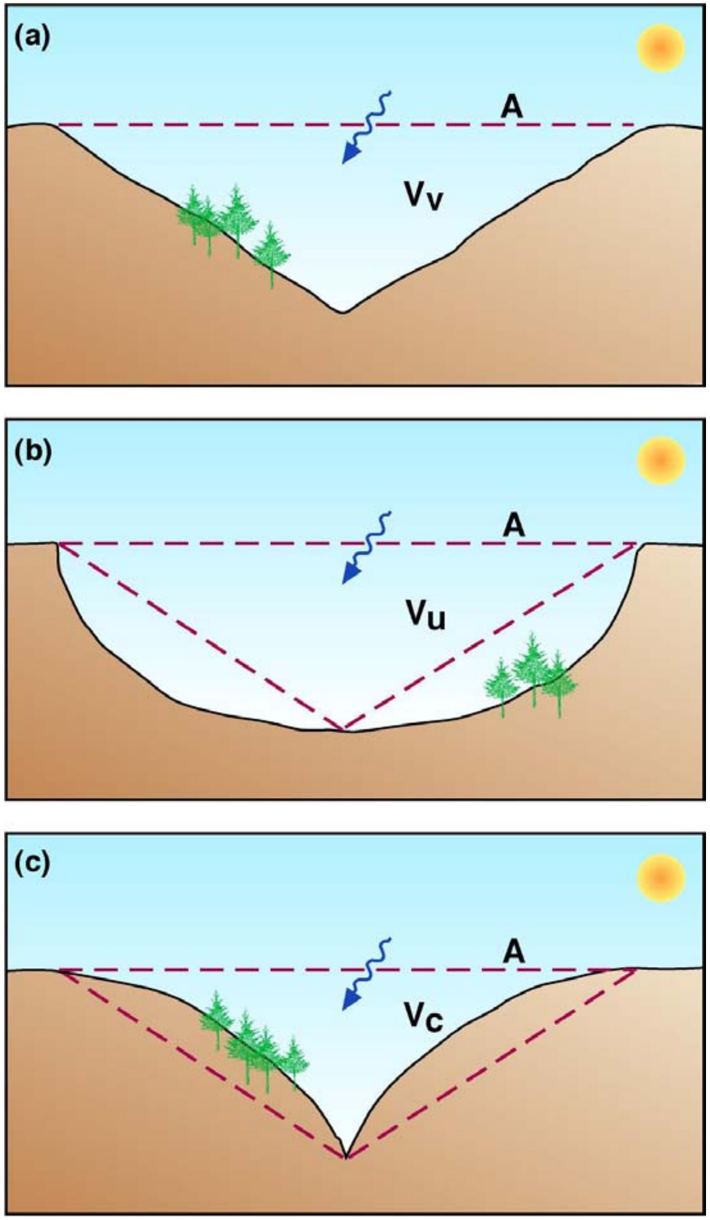
What causes the temperature range difference?



1. Horizontal area over valley receives same insolation as that over the plain. Insolation heats ground surface and a portion is redistributed to the air above by radiation, conduction, and convection. An equal amount of energy is applied to a smaller mass of air within valley, producing a larger temperature response in the smaller volume (FLT). Similarly, at night loss of heat by radiation is applied to the smaller volume (topographic amplification factor, TAF; area-height relationship).

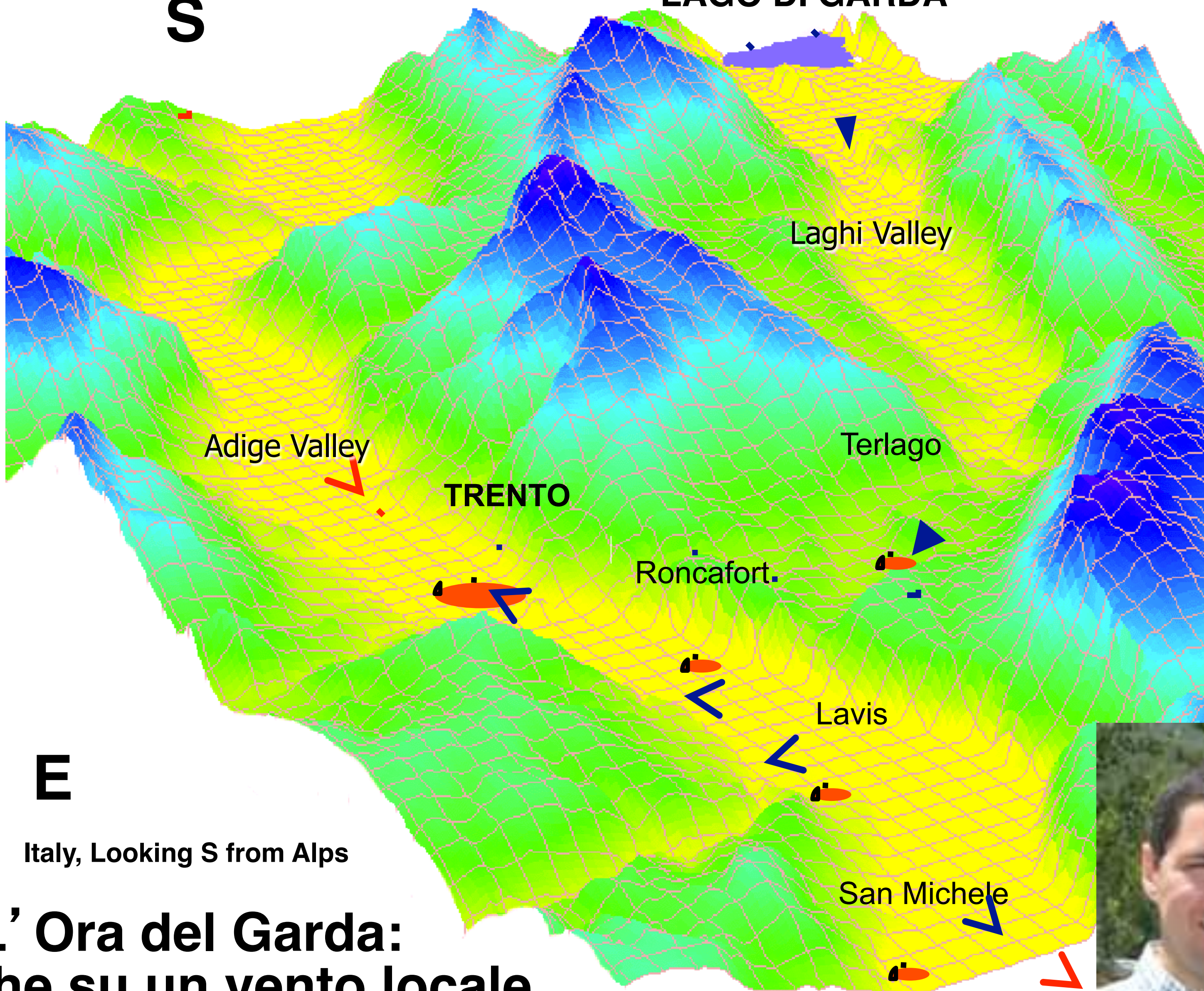
2. There is an efficient distribution of heat in the valley, where slopes are good heat exchange surfaces. During day, heat is transferred efficiently to cross section by sinking motions that compensate for upslope flows on sidewalls. During night, downslope flows continually cause new air to contact the cold radiating slopes and fill valley with cold air, whereas over plain only a shallow layer is cooled near the surface.

3. Valley air is somewhat protected from gradient winds by surrounding topography. Heated air by day and cooled air by night is stored up within the valley.



TAF depends on valley geometry. Heating in a V-shaped valley produces an amplification of 2 relative to a plane (or vertical sidewall valley). TAF is less for a U-shaped valley and more for a convex-sidewall valley.

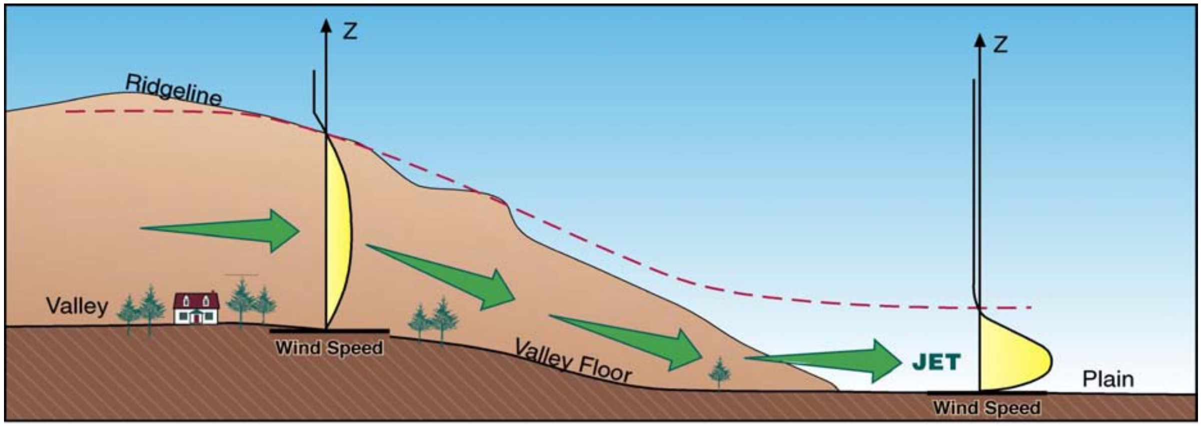
Problems with TAF concept:
• a *static* concept (doesn't account for advection)
• requires heat exchange to be *confined* to volume



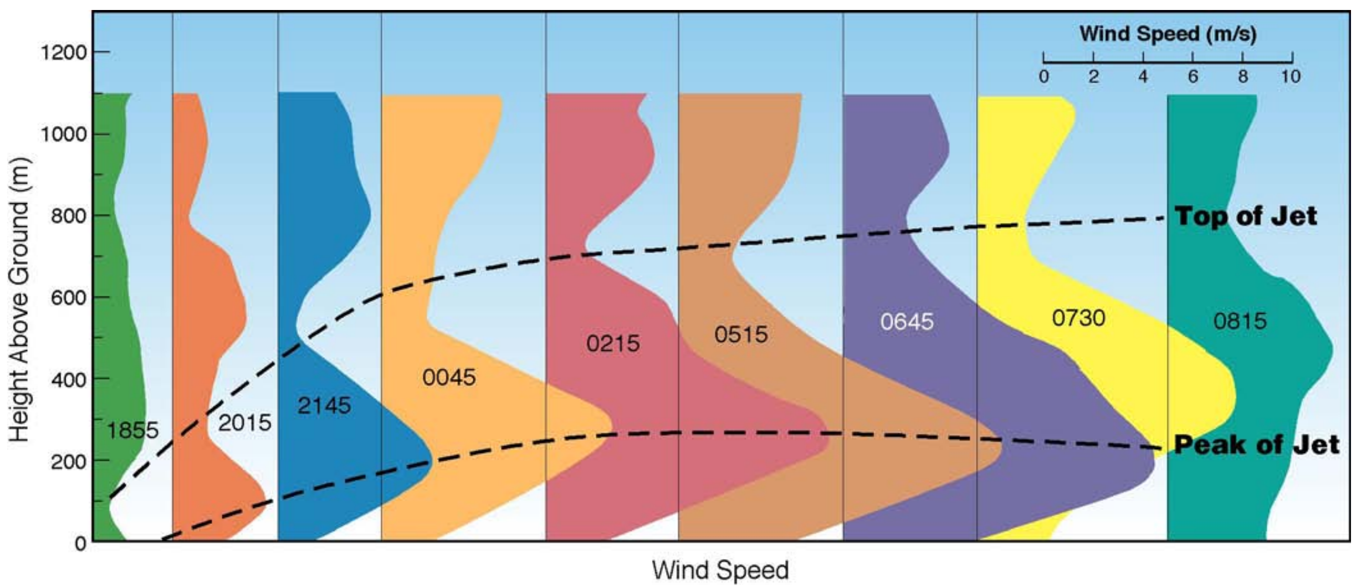
L' Ora del Garda: ricerche su un vento locale molto particolare

Dino Zardi

The valley exit jet

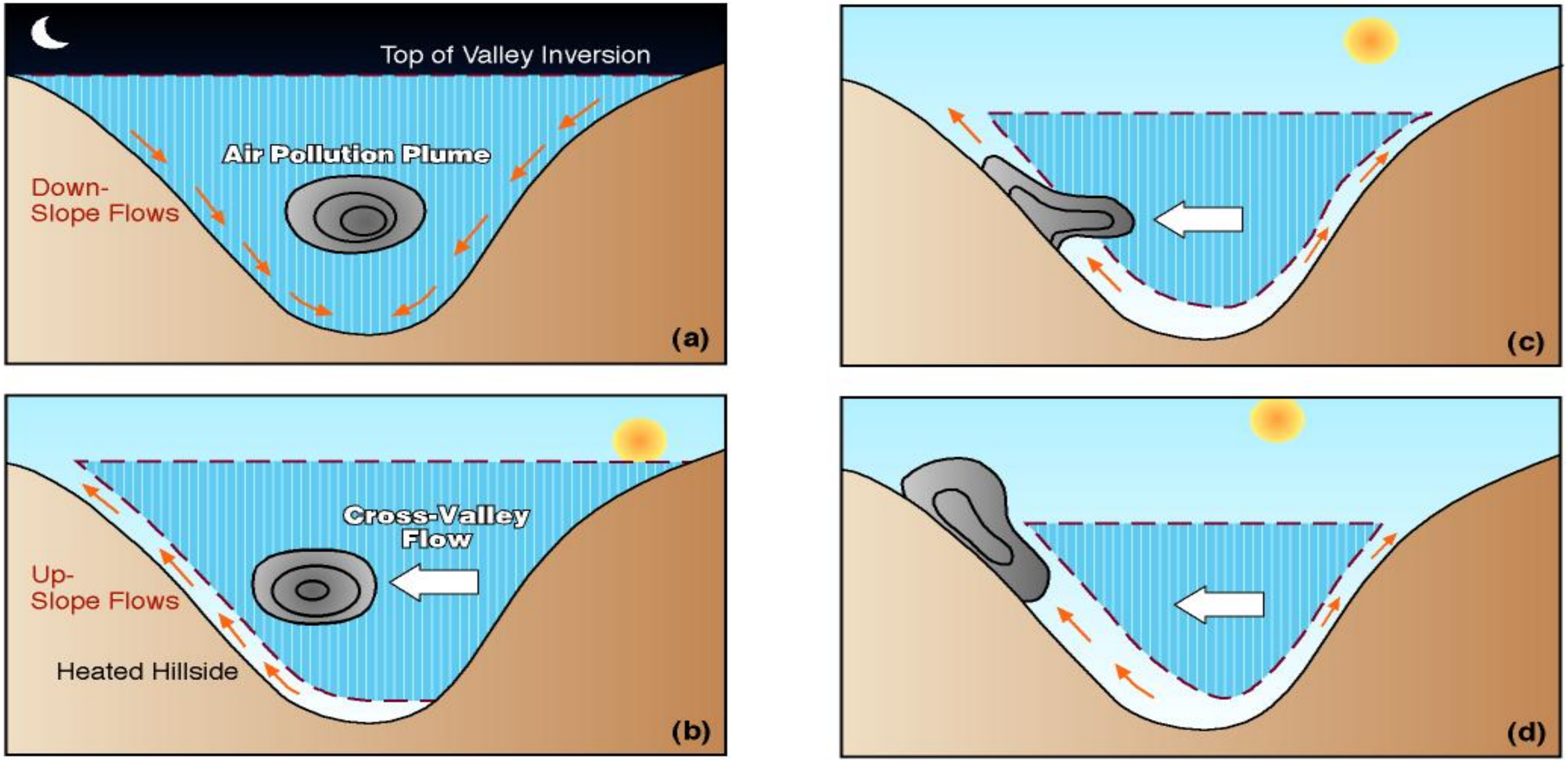


adapted from Pamperin & Stilke (1985)




Cross-Valley
Wind System
Bugaboo Spire © Adam Naisbitt

Brush Creek, CO tracer experiment



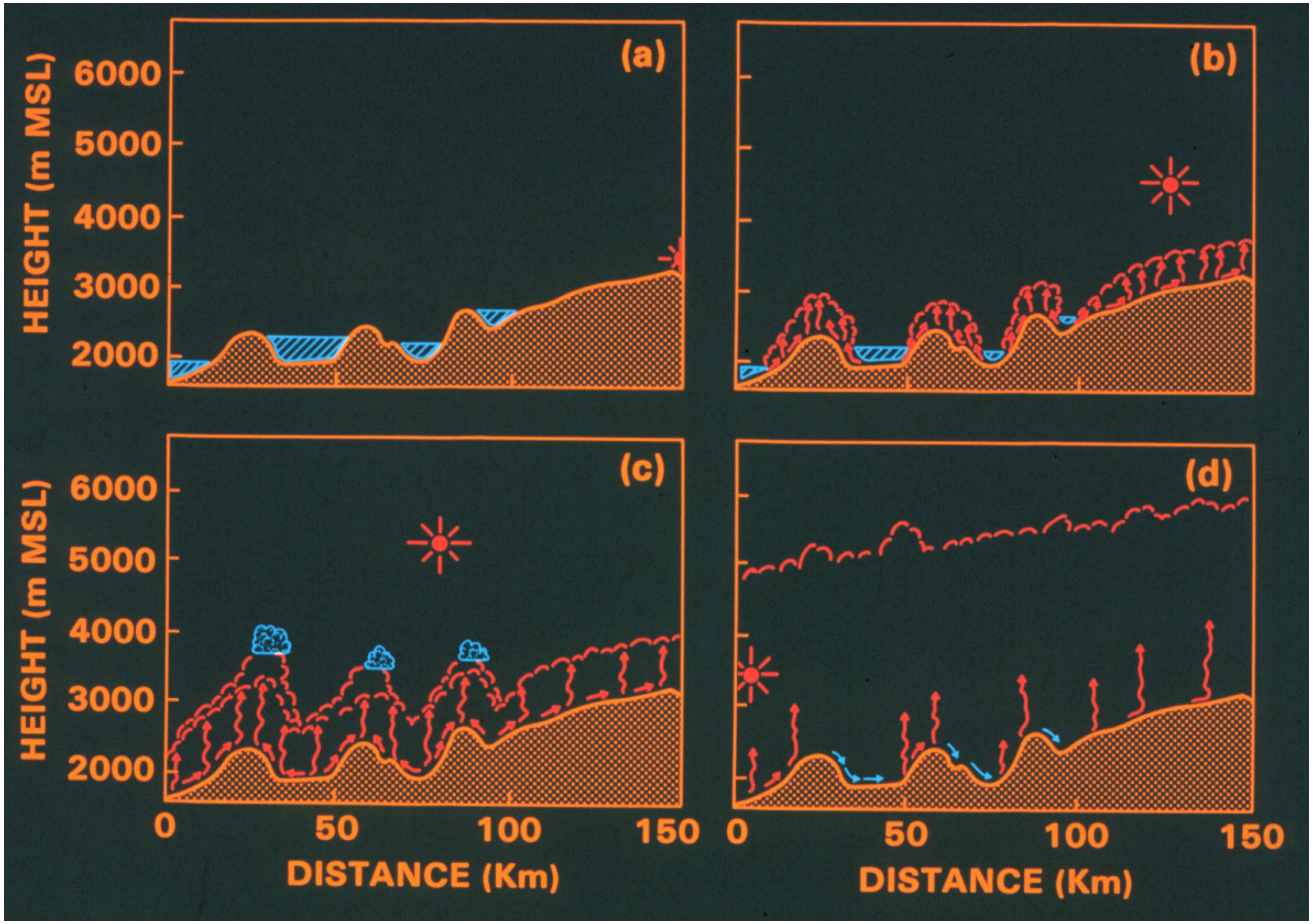
adapted from Bader & Whiteman (1989)

Lehner, M., C. D. Whiteman, and S. W. Hoch, 2011: Diurnal cycle of thermally driven cross-basin winds in Arizona's Meteor Crater. *J. Appl. Meteor. Climatol.*, **50**, 729-744.

Lehner, M., and C. D. Whiteman, 2012: The thermally driven cross-basin circulation in idealized basins under varying wind conditions. *J. Appl. Meteor. Climatol.*, **51**, 1026-1045.

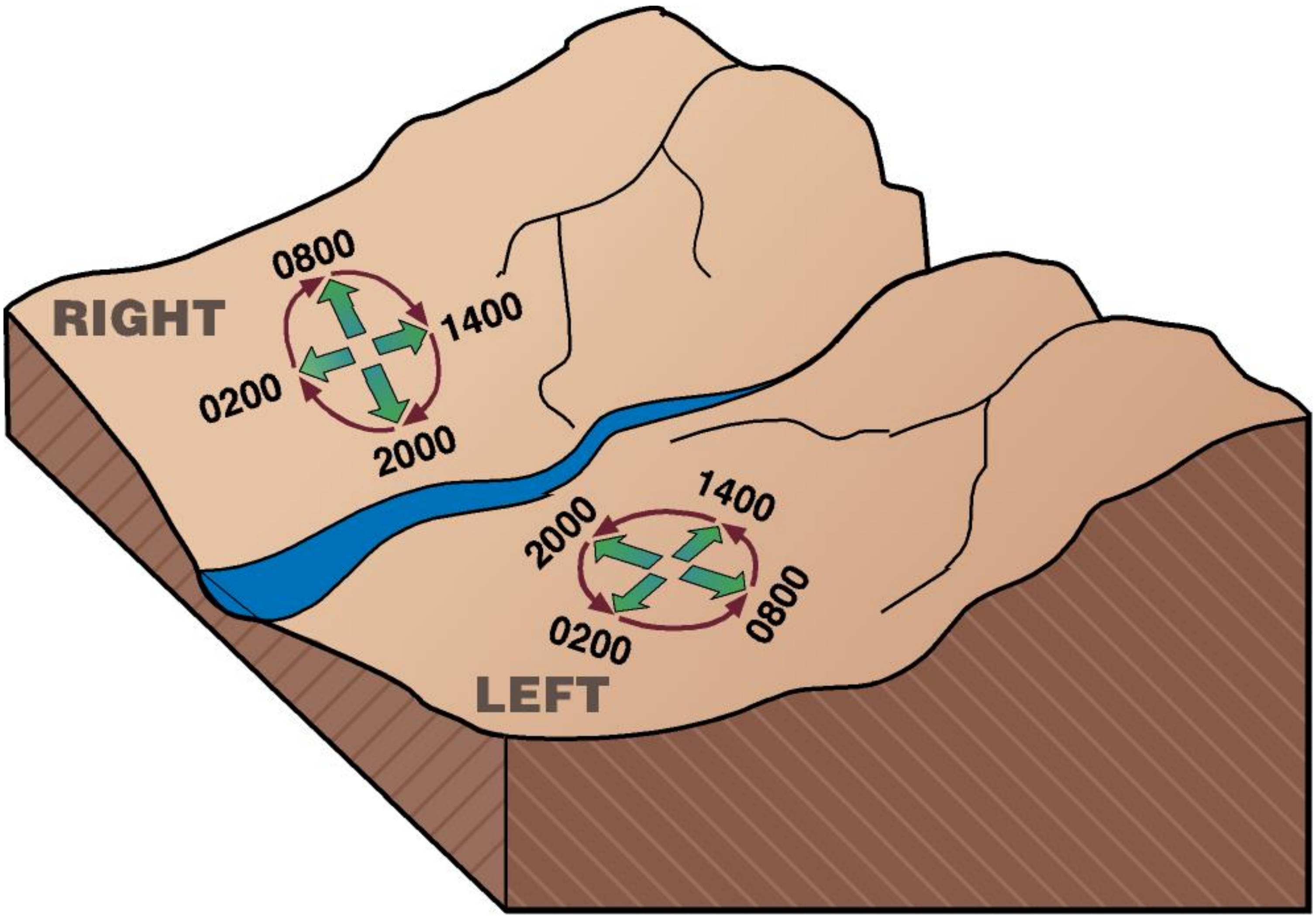
The Diurnal Cycle of Mountain Winds

The diurnal cycle



Whiteman, adapted from Fiedler (1987)

Wind turning: Left bank - CCW; Right bank - CW



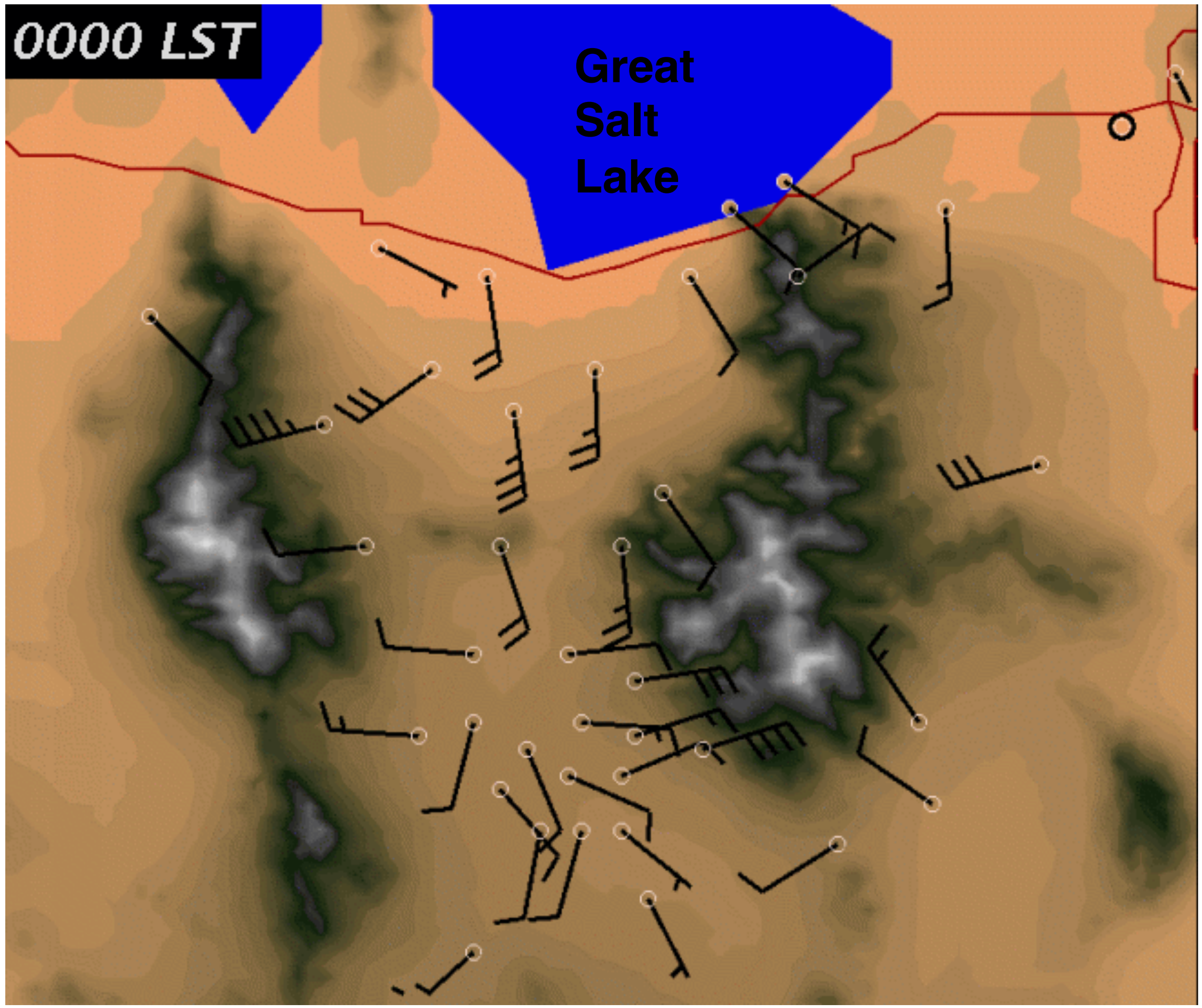
adapted from Hawkes (1947)

Example: Rush Valley winds

Fletch=1 m/s

Tooele Valley

Rush Valley



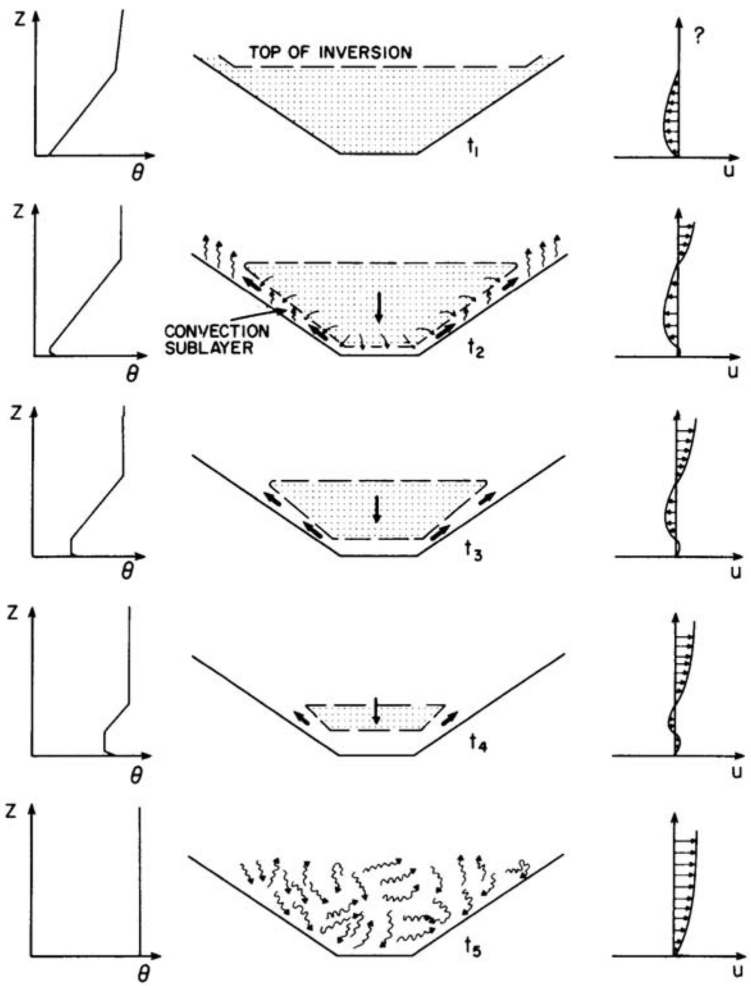
Salt Lake Valley

adapted from Stewart et al. (2002)

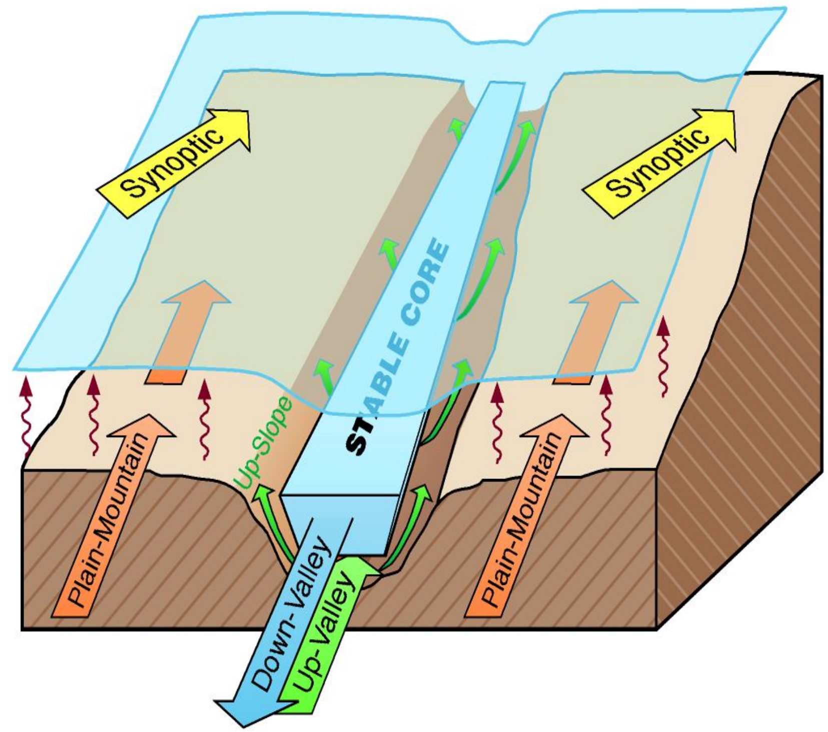

Evening
Transition
Colorado Rocky Mtns © CD Whiteman

Morning Transition

Eastern Alps © Georg Pistotnik



Whiteman (1980)

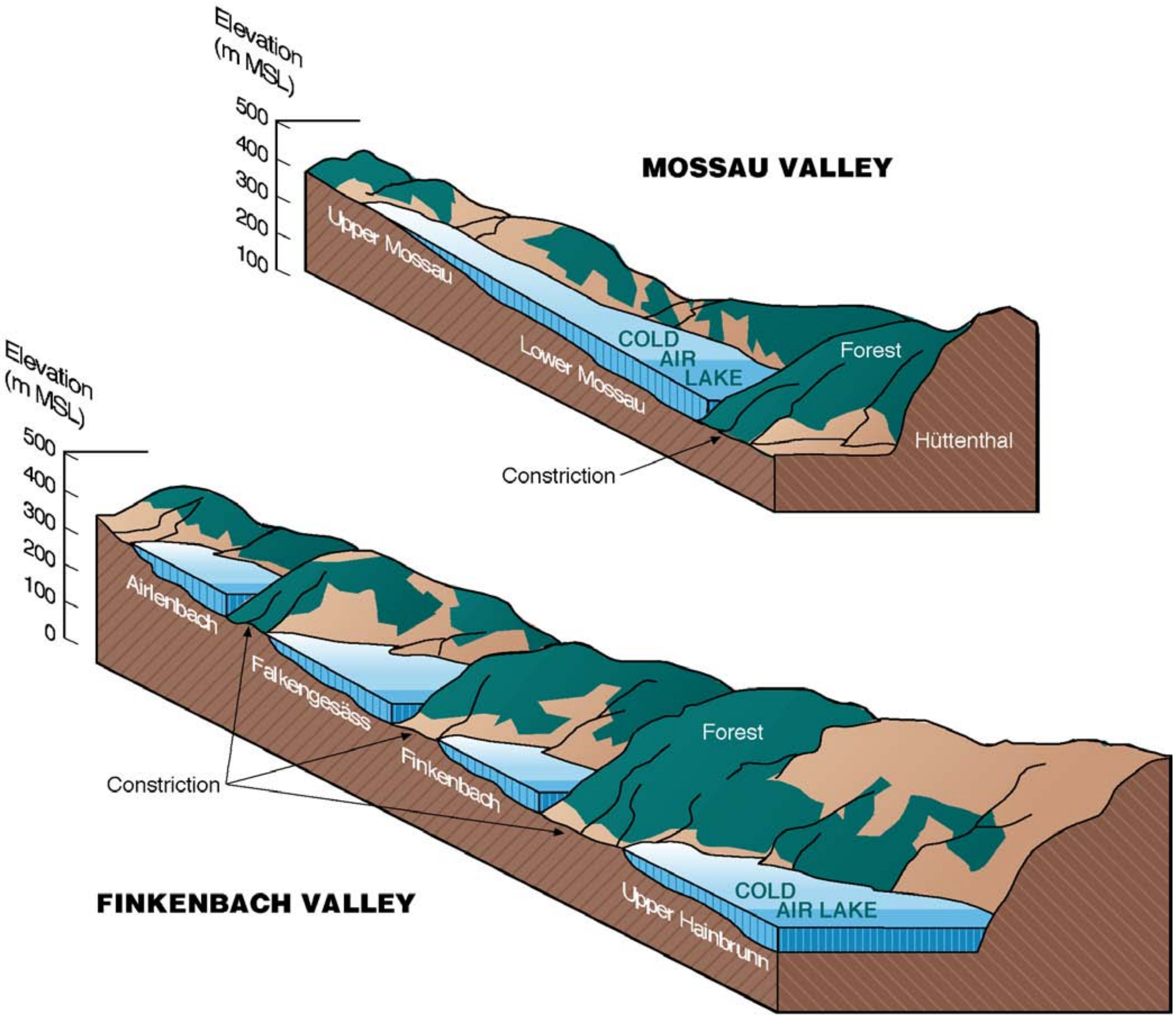


Temperature and wind structure layers at a time midway through the transition

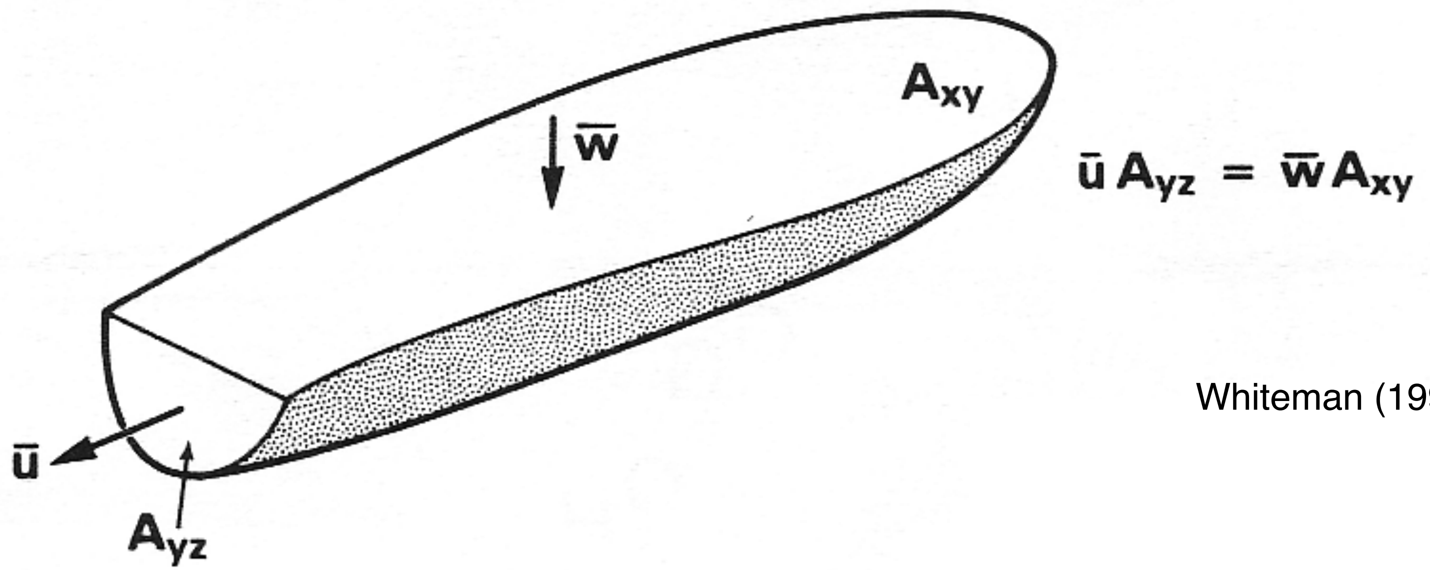
Subsidence!


Basin Meteorology
Southern Bolivia Altiplano © Jochen Reuder

Cold air pools in valleys



Basin Meteorology



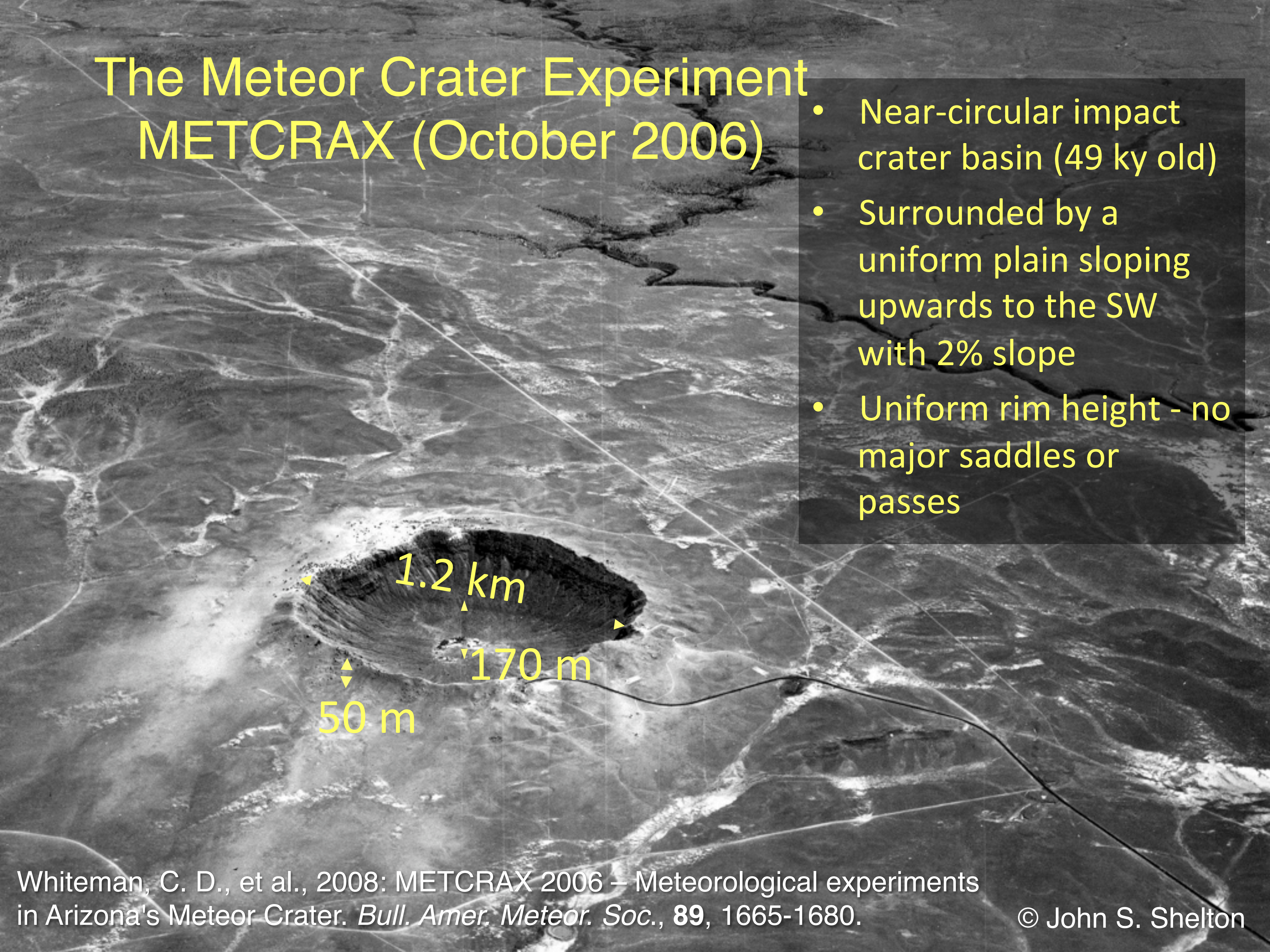
Whiteman (1990)

Extreme minimum temperatures usually occur in mountain basins, rather than in valleys:

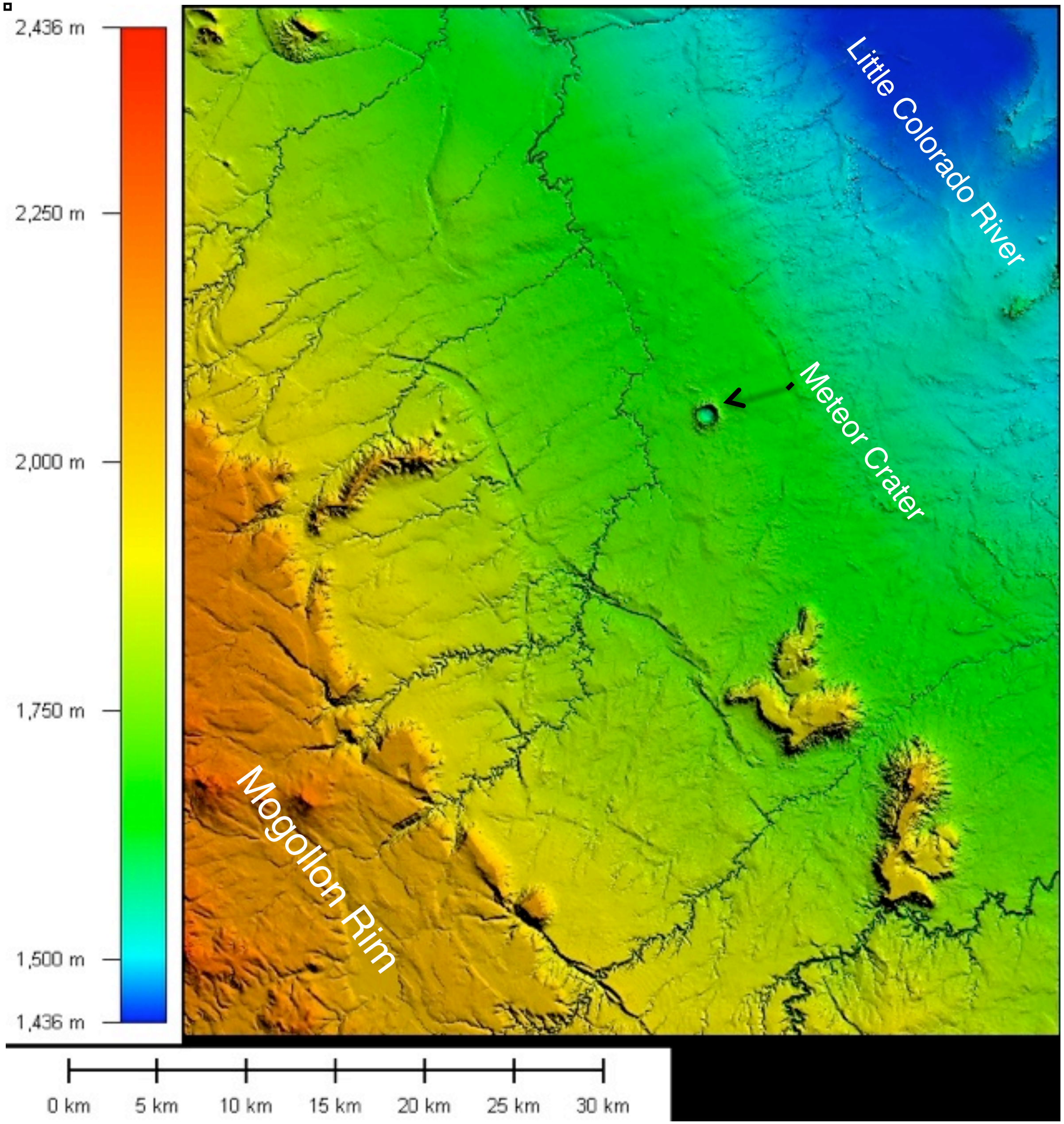
Peter Sink, UT -69.3°F (-56.3°C) Feb 1, 1985
West Yellowstone, MT -66°F (-54°C) Feb 1933
Taylor Park, CO -60°F (-51°C) Feb 1951
Fraser, CO -53°F (-47°C) Jan 1962
Stanley, ID -54°F (-48°C) Dec 1983
Gruenloch Basin, Austria -63°F (-52.6°C) between 19 Feb and 4 Mar 1932

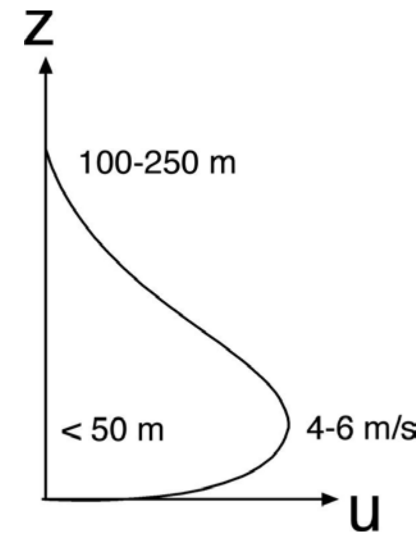
The Meteor Crater Experiment
METCRAX (October 2006)

- Near-circular impact crater basin (49 ky old)
- Surrounded by a uniform plain sloping upwards to the SW with 2% slope
- Uniform rim height - no major saddles or passes



Whiteman, C. D., et al., 2008: METCRAX 2006 – Meteorological experiments in Arizona's Meteor Crater. *Bull. Amer. Meteor. Soc.*, **89**, 1665-1680.





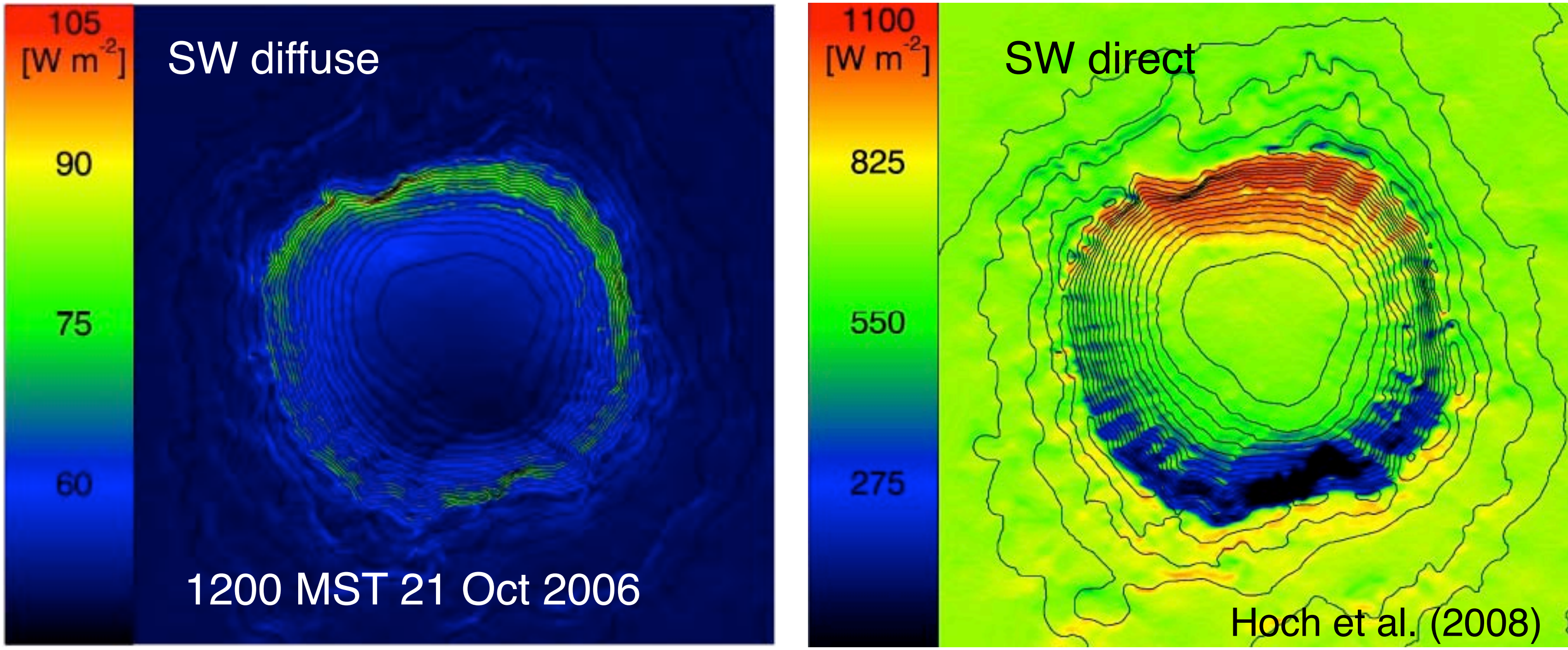
Savage et al. (2008)

Propagation of shadows and insolation patterns

Meteor Crater, Arizona

Whiteman & Kahler (2006)

Radiative transfer modeling within topography



Hoch, S. W., C. D. Whiteman, and B. Mayer, 2011: A systematic study of longwave radiative heating and cooling within valleys and basins using a three-dimensional radiative transfer model. *J. Appl. Meteor. Climatol.*, **50**, 2473-2489.

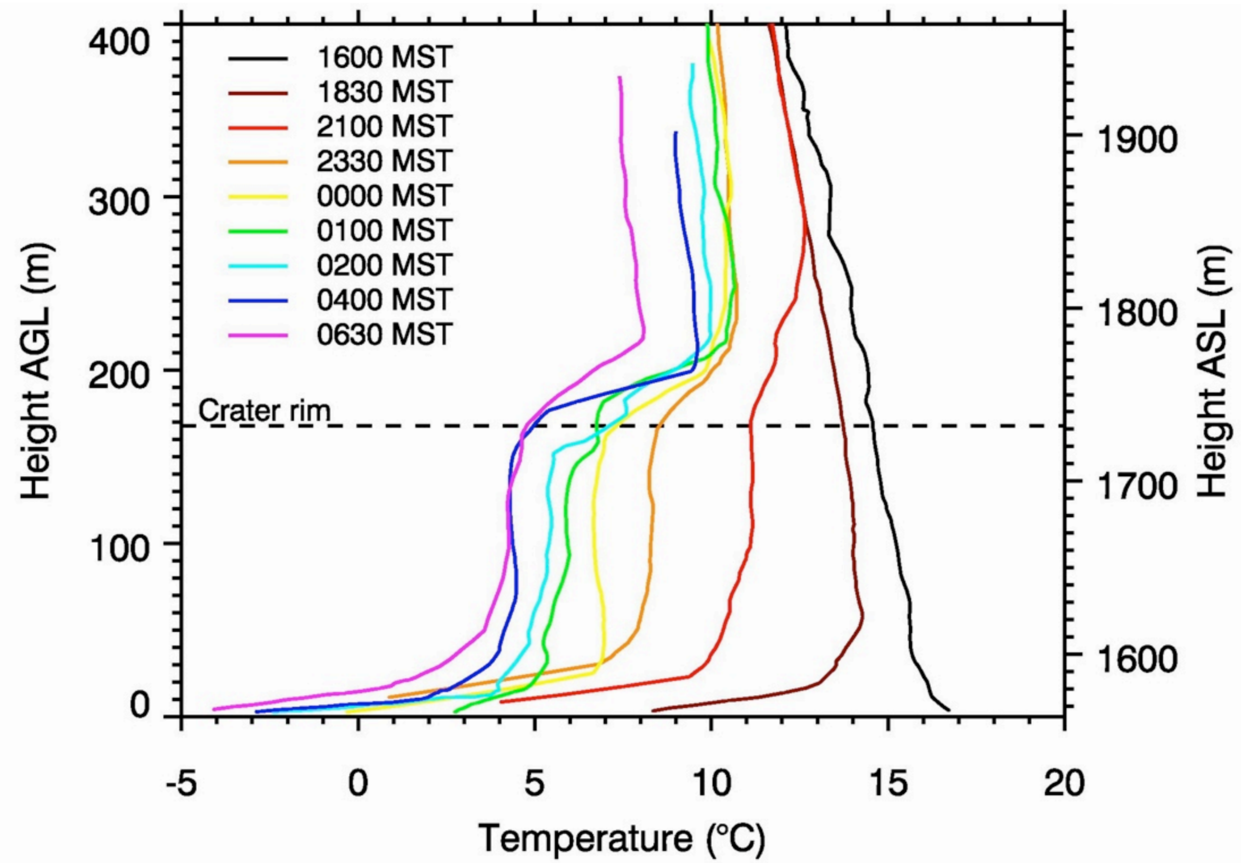
Mayer, B., S. W. Hoch, and C. D. Whiteman, 2010: Validating the MYSTIC three-dimensional radiative transfer model with observations from the complex topography of Arizona's Meteor Crater. *Atmos. Chem. Phys.*, **10**, 8685-8696. doi:10.5194/acp-10-8685-2010.

Hoch, S. W., and C. D. Whiteman, 2010: Topographic effects on the surface radiation balance in and around Arizona's Meteor Crater. *J. Appl. Meteor. Climatol.*, **49**, 1114-1128.

Sebastian Hoch

Temperature evolution

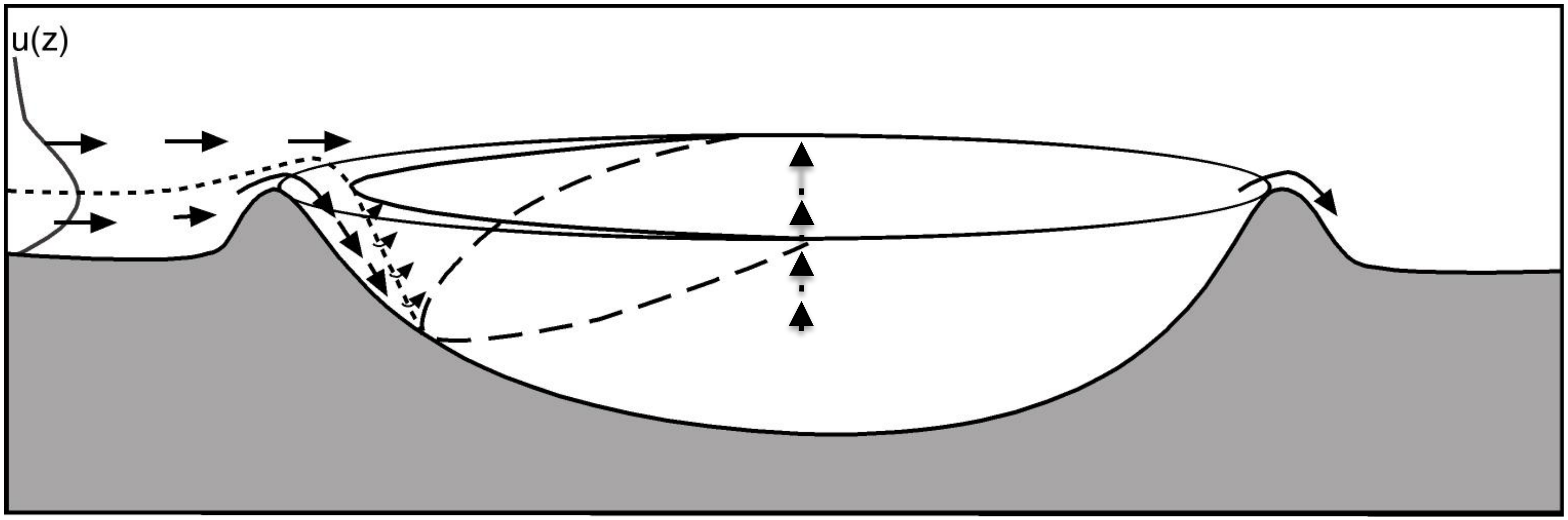
Meteor Crater, 22-23 Oct 2006



- Strong 30-m deep inversion on crater floor
- Isothermal atmosphere in remaining 75% of crater depth
- Temperature jump develops at rim level
- Crater cools while remaining isothermal
- Horizontally homogeneous

What physical process(es) produce the isothermalcy?

Cold air intrusions

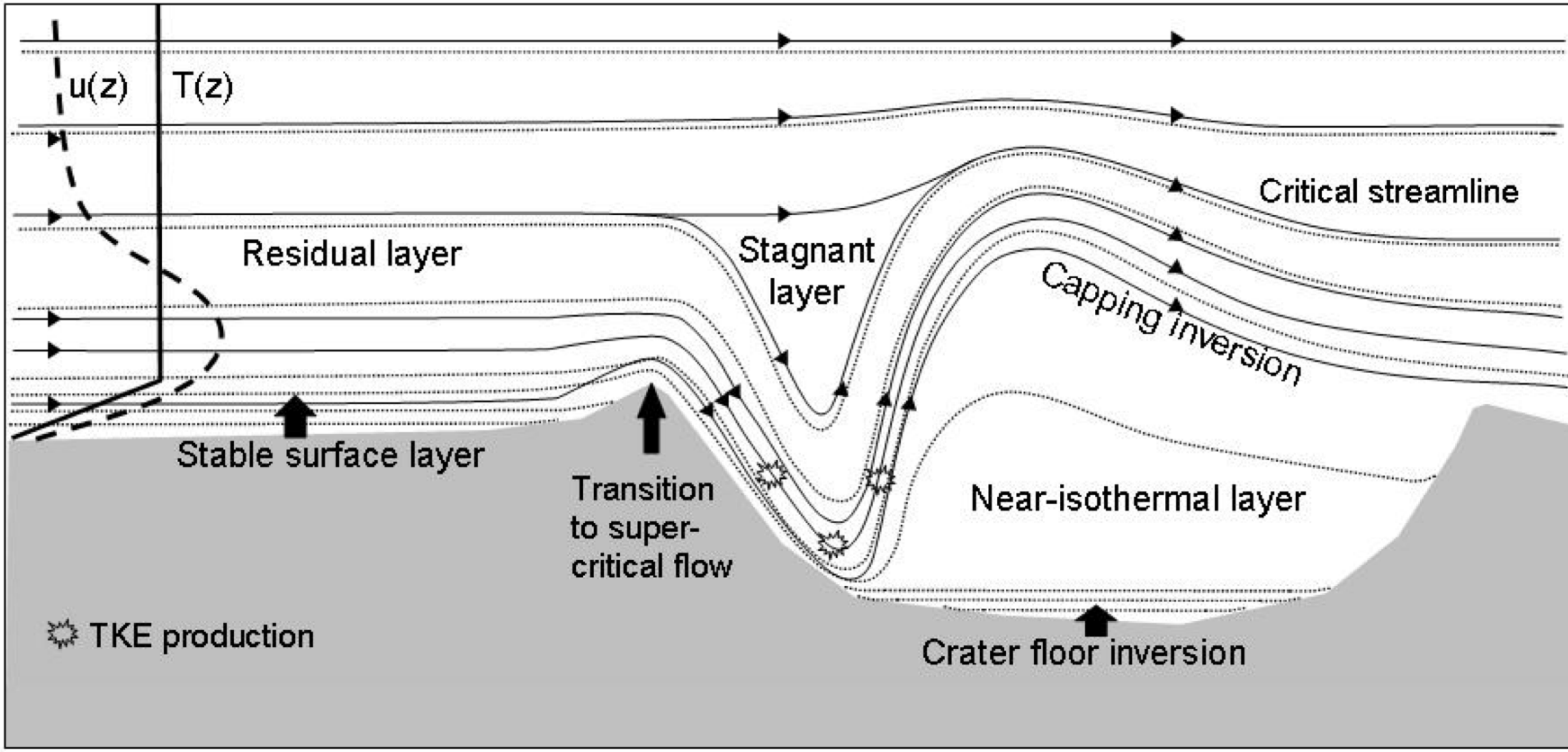


A **southwesterly drainage flow** comes down the Colorado Plateau. A cold air mass builds up on the front side of the crater, the flow splits around the crater, and some of the **cold air spills over** the rim. The cold air flows down the upwind inner sidewall, **detraining cold air** into the basin atmosphere. This horizontal mixing into the crater atmosphere, which decreases with distance down the sidewall and the **compensatory rising motion**, destabilizes the basin atmosphere driving it towards isothermalcy.

Whiteman, C. D., S. W. Hoch, M. Lehner, and T. Haiden, 2010: Nocturnal cold air intrusions into Arizona's Meteor Crater: Observational evidence and conceptual model. *J. Appl. Meteor. Climatol.*, **49**, 1894-1905.

Haiden, T., C. D. Whiteman, S. W. Hoch, and M. Lehner, 2011: A mass-flux model of nocturnal cold air intrusions into a closed basin. *J. Appl. Meteor. Climatol.*, **50**, 933-943.

Warm air intrusions



Adler, Bianca, C. David Whiteman, Sebastian W. Hoch, and Manuela Lehner, 2012: Warm air intrusions in Arizona's Meteor Crater. *JAMC*, **51***,* 1010-1025*.*

Temperature inversions in Bingham Canyon Mine

Rime mushrooms

R. Garibotti

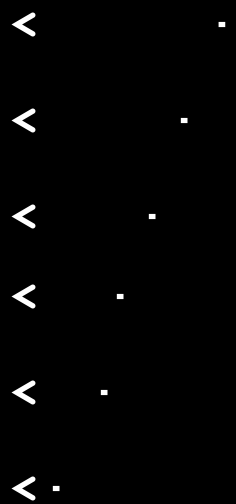
Rime mushroom

- *Rime mushroom*: A *hard rime* accretion on a surface-based obstacle in the form of a bulge or mushroom-shaped projection.
- *Hard rime*: white ice that forms when super-cooled cloud droplets freeze on the windward side of sub-freezing ground-based obstacles, usually with high wind velocities and air temperatures between -2 and -10°C.
- Extreme semi-permanent or permanent rime mushrooms can occur in some mountain ranges, presenting a significant impediment to mountain climbers.

note the ‘overhang’

hard rime

wind direction



Rime mushrooms

Monte Sarmiento, Tierra del Fuego

Rate of accretion of super-cooled liquid water mass on a sub-freezing structure:

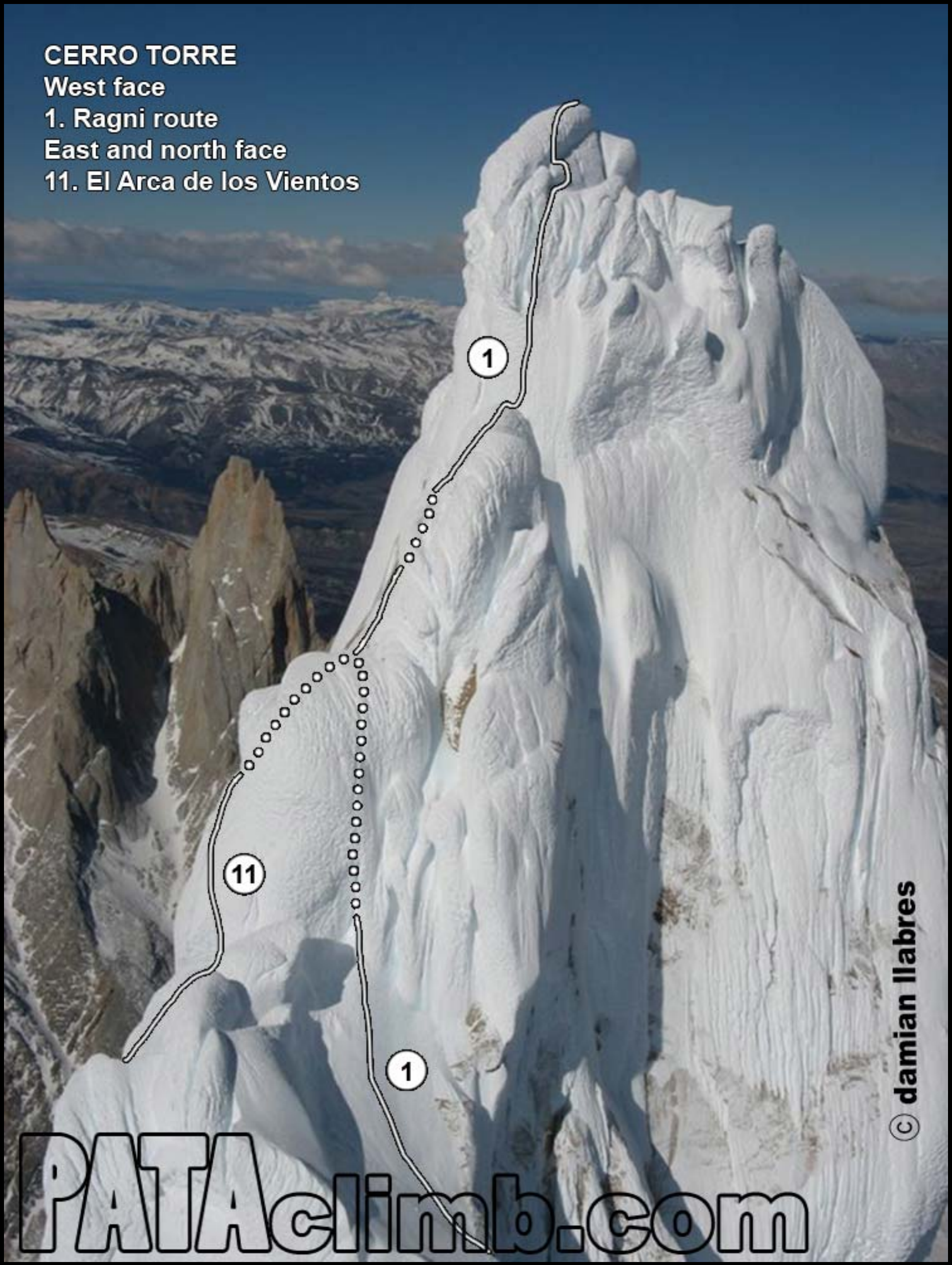
$$dM/dt = \alpha \text{ w U A} \quad [\text{kg s}^{-1}]$$

w = super-cooled liquid water content
U = wind speed normal to surface
A = surface area
α = collision coefficient (0 - 1)

The skiing analogy

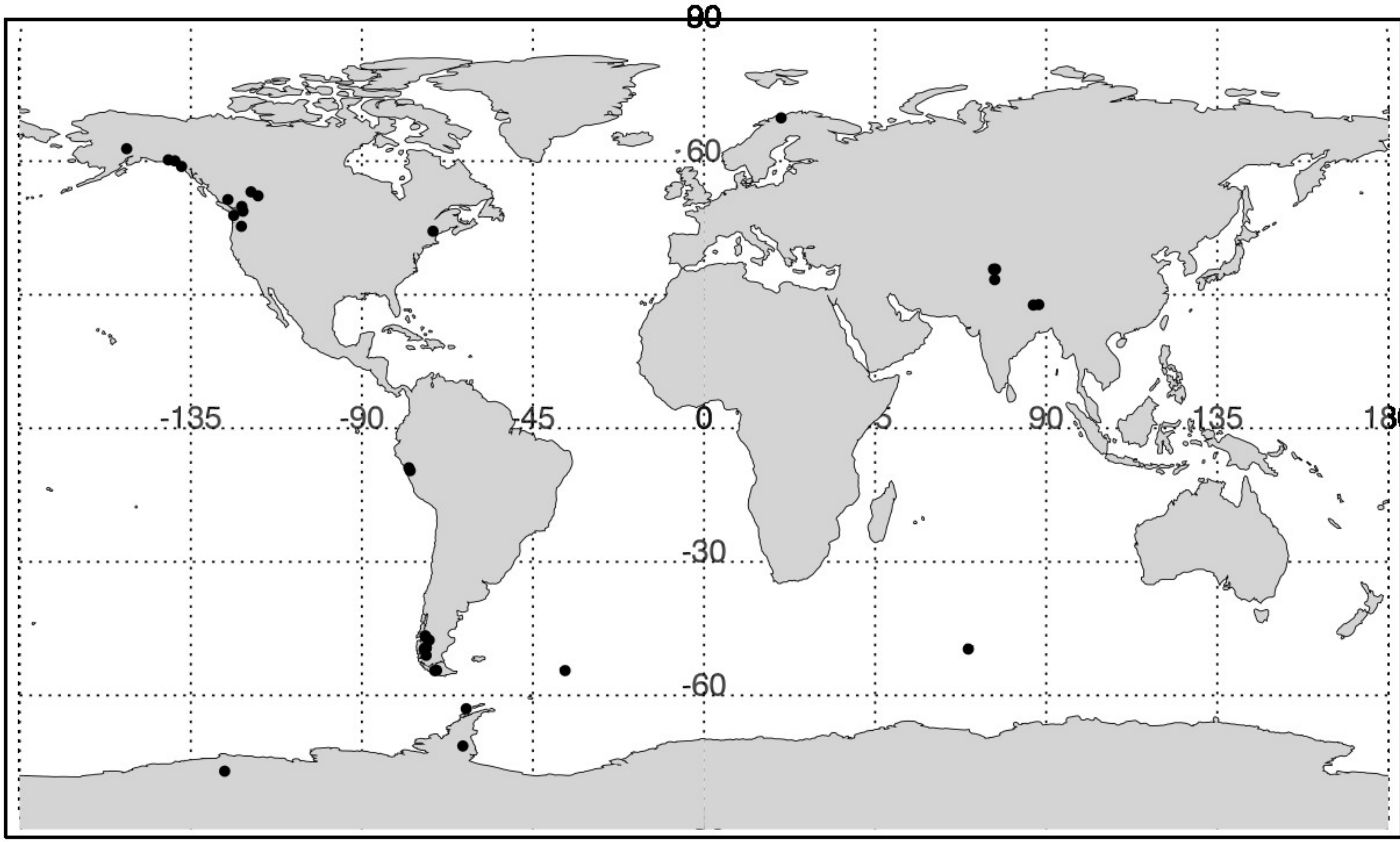
Rime Mushroom Examples


© Rolando Garibotti


CERRO TORRE
West face
1. Ragni route
East and north face
11. El Arca de los Vientos
1
11
1
© damian llabres
PATAclimb.com

Cerro Paine Grande
SW ridge

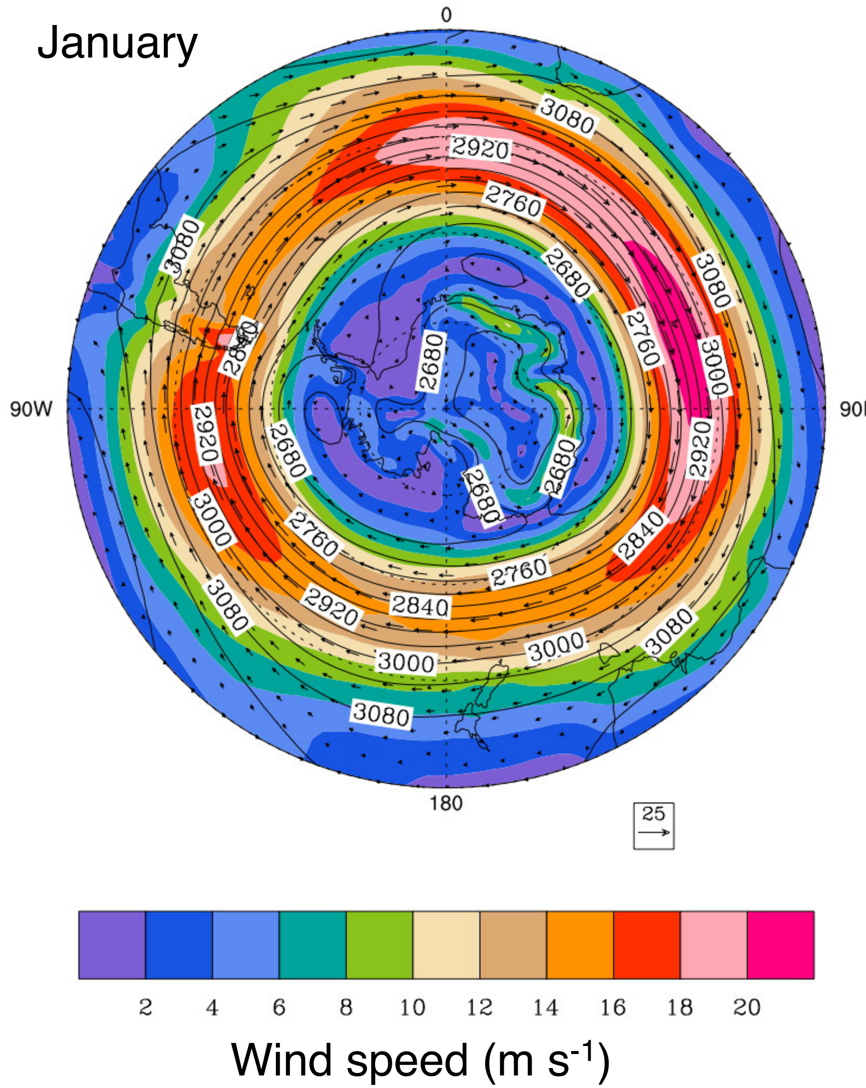
Cerro Standhardt
N Ridge
30 m
© Rolando Garibotti



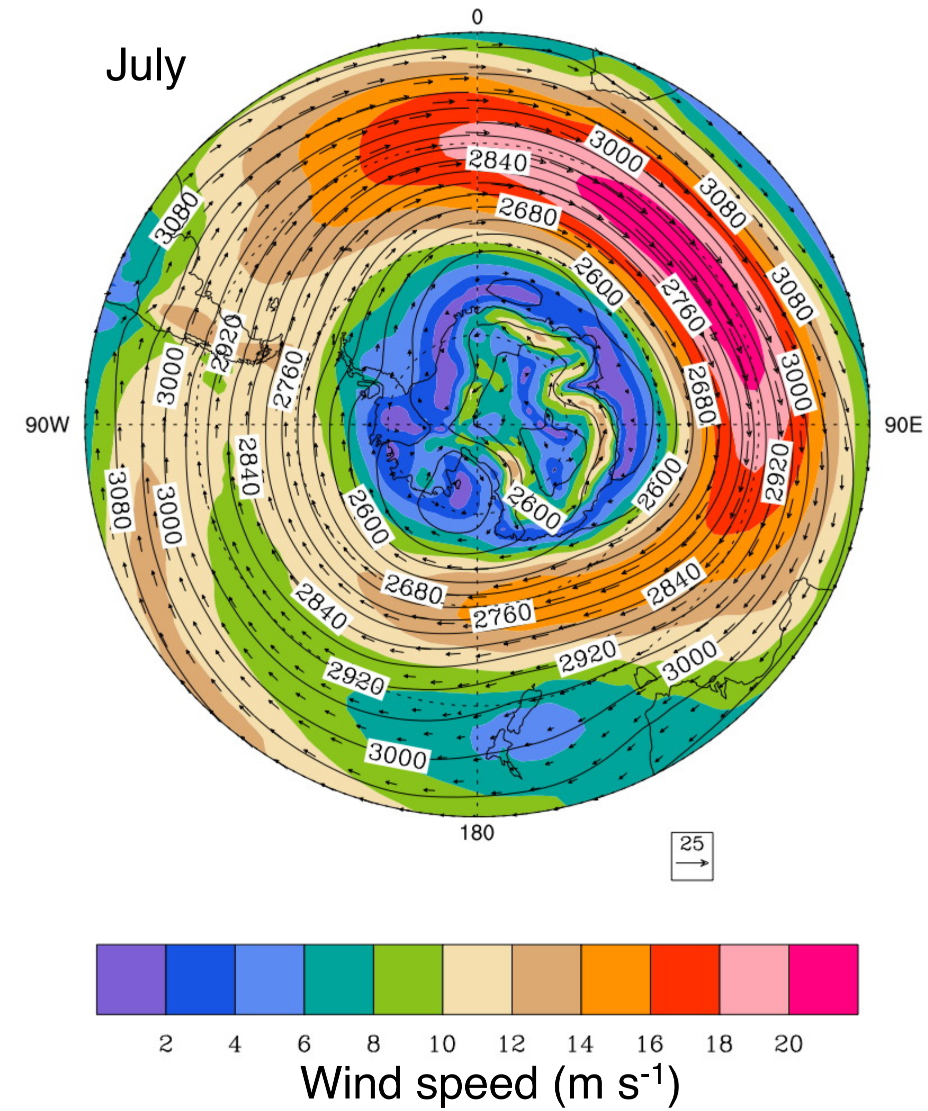
Locations where rime mushrooms have been reported

Meteorology of Rime Mushrooms - Patagonia

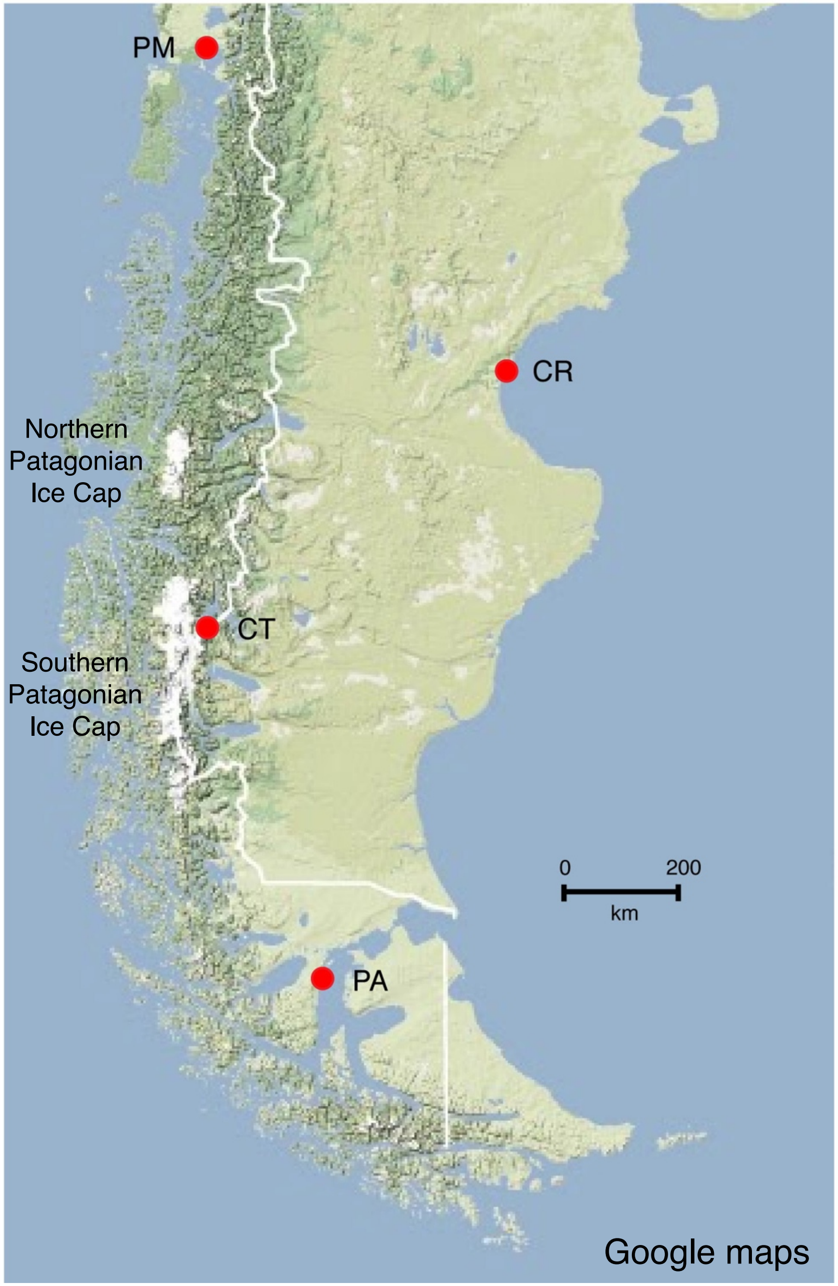
70 kPa



January
0
90W
90E
180
25
2 4 6 8 10 12 14 16 18 20
Wind speed ($m\ s^{-1}$)



July
0
90W
90E
180
25
2 4 6 8 10 12 14 16 18 20
Wind speed ($m\ s^{-1}$)



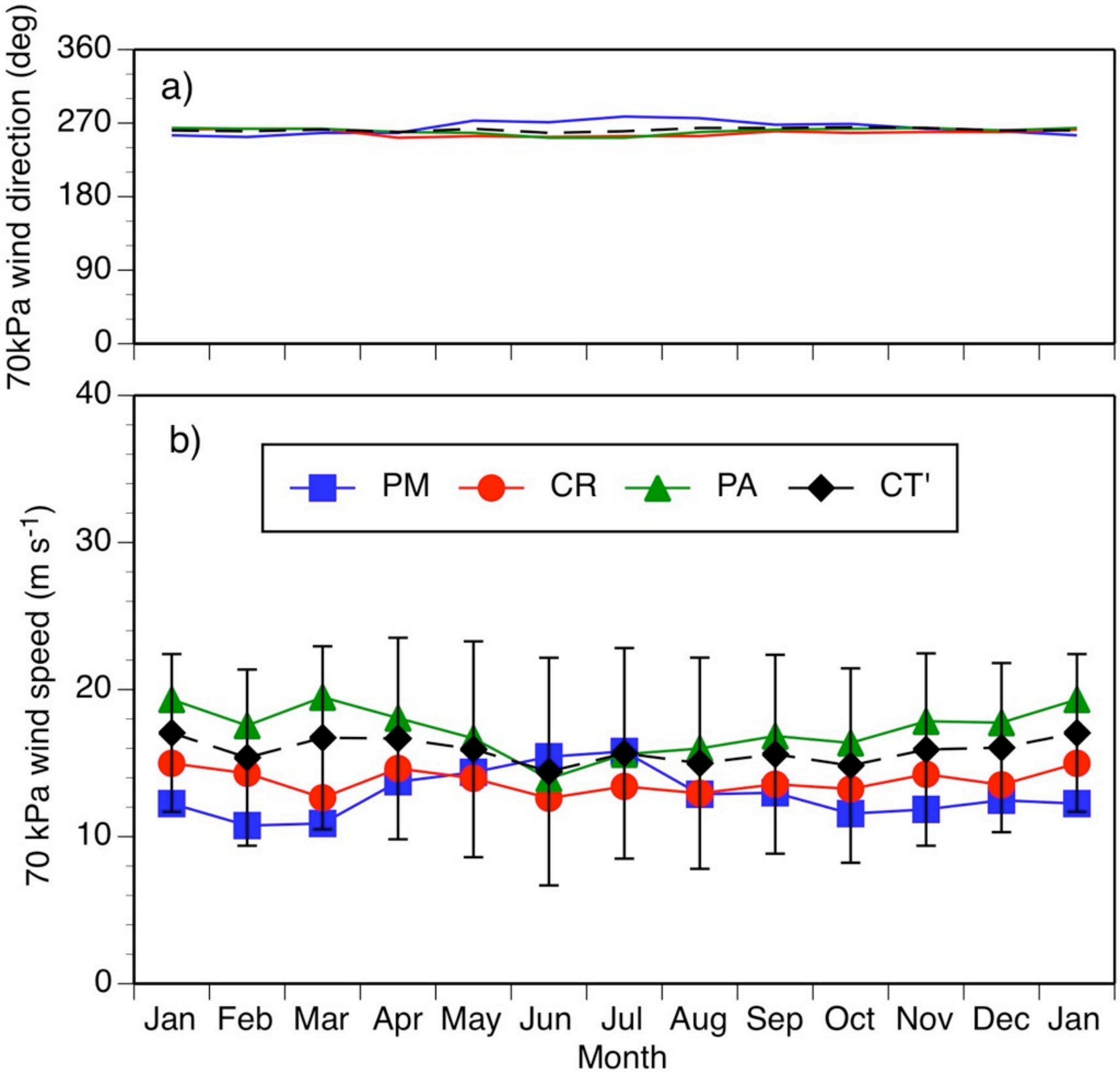
PM = Puerto Montt
CR = Comodoro Rivadavia
CT = Cerro Torre
PA = Punta Arenas

Radiosondes 1975 -Apr 2012

Cerro Torre is in the Monte Fitz Roy Massif

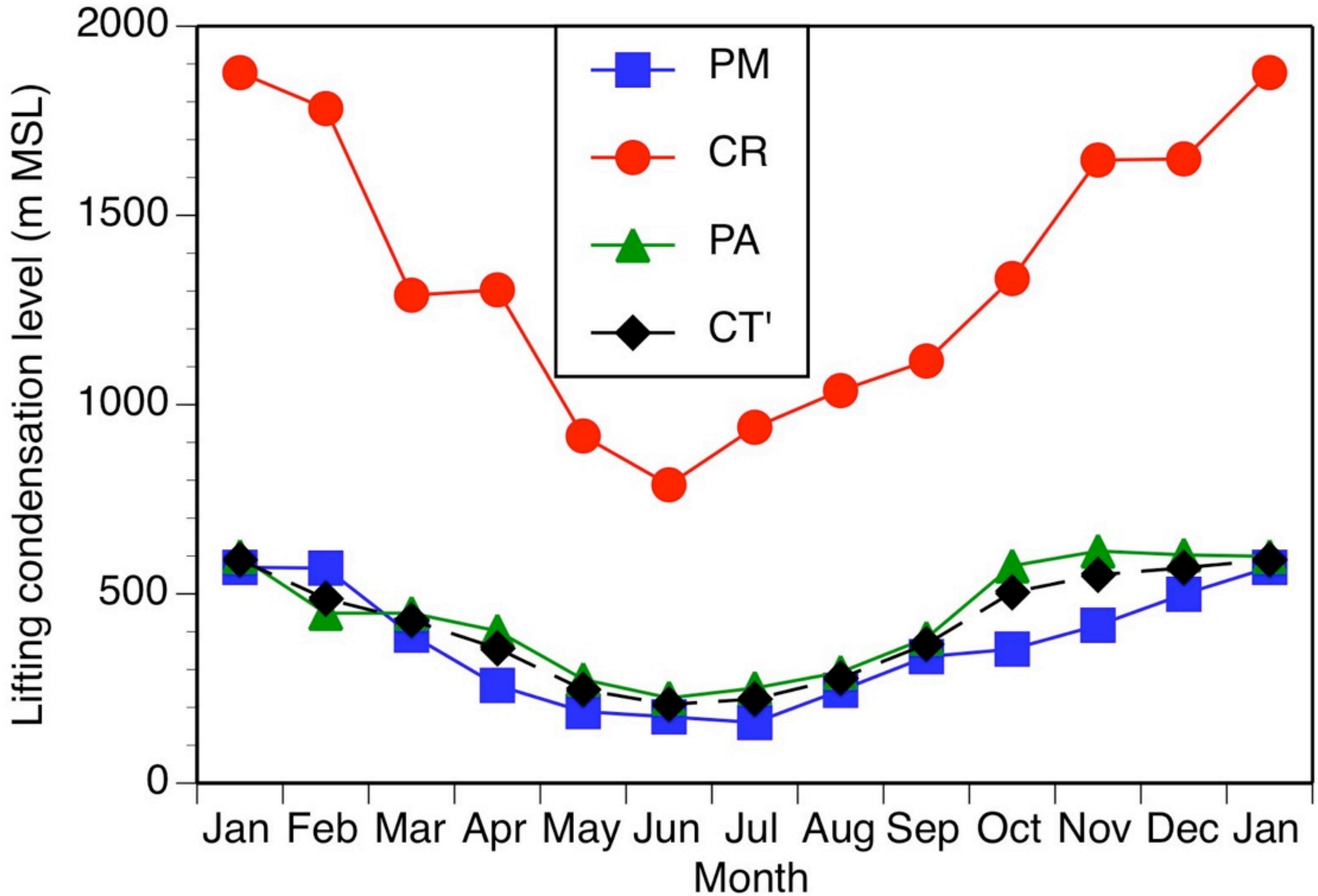
NCDC: Global radosonde archive

70 kPa winds

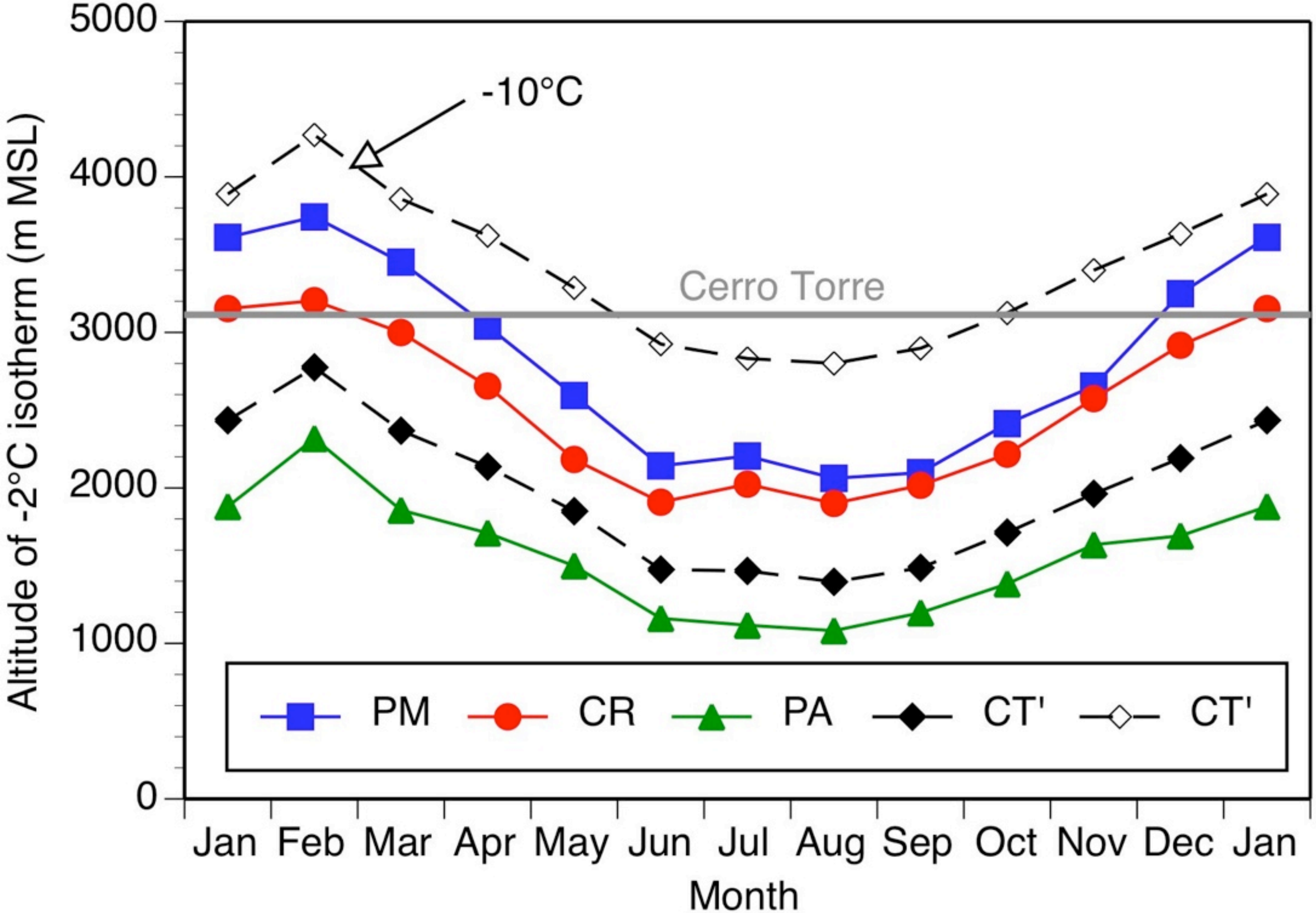


a)
b)
70kPa wind direction (deg)
360
270
180
90
0
70 kPa wind speed (m s^{-1})
40
30
20
10
0
PM
CR
PA
CT'
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Month

Lifting condensation level



Height of -2° and -10°C isotherms



Climbing Ice Mushrooms


Cerro Torre
© Rolando Garibotti


Punta Herron
W Ridge
Ice mushrooms form on this ridge. They grow and then break off.
© Rolando Garibotti


W Face Cerro Torre natural tunnel was climbable 2005-2008+. Absent in 2011.
Reports of such tunnels date back to mid-1980s.
Natural tunnels
Colin Haley entering 50-m long natural tunnel
© Rolando Garibotti


W face Cerro Torre
50 m natural
mushroom tunnel
© Bjørn-Eivind Årtun
A similar tunnel was climbed in 1993 by Jay Smith and partners

Cerro Torre

Jorge Ackermann digging upper part of a tunnel/half pipe in CT's last mushroom

© Rolando Garibotti

© Cullen Kirk


January 2012
climbers
Cerro Torre
© Colin Haley

Summary

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Torres del Paine © Sigrid & Ron Smith