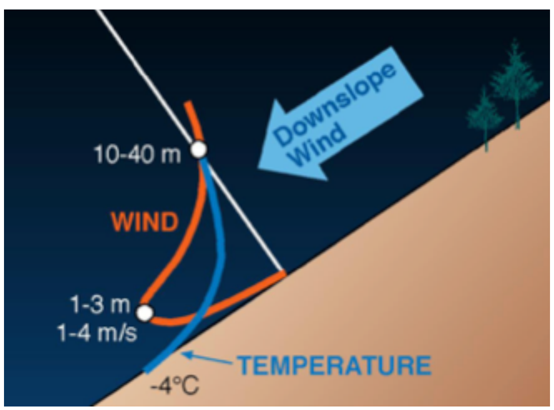
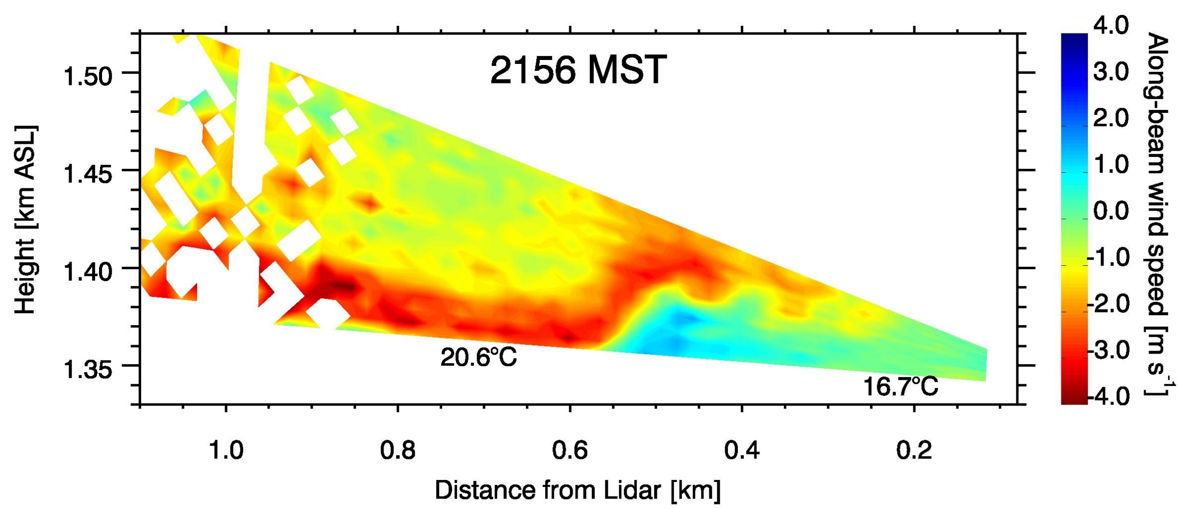
Thermally Driven Flows / Diurnal Mountain Winds

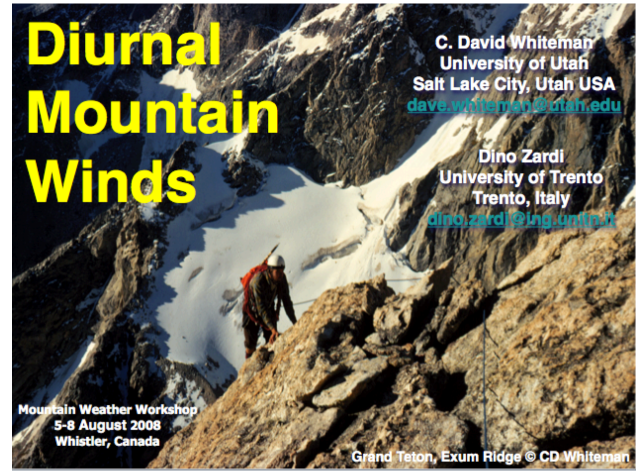
Sebastian W. Hoch

C. David Whiteman

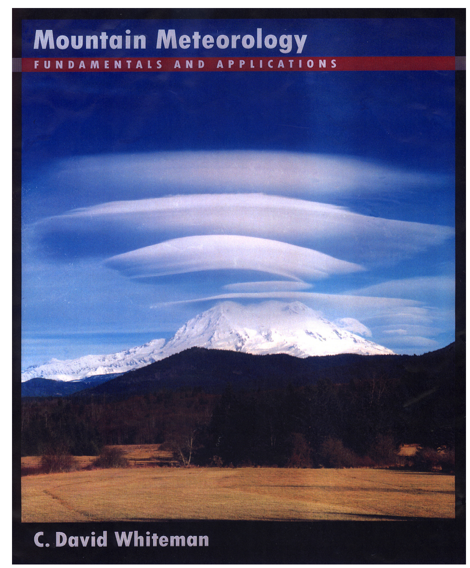




C. David Whiteman



Mountain Weather Workshop
5-8 August 2008
Whistler, Canada



Figures: Whiteman (2000)
unless otherwise indicated

Thermally Driven Flows / Diurnal Mountain Winds

- Mountain-Plain Wind System
- Slope Wind System
- Valley Wind System
- Cross-Valley Winds
- The Diurnal Cycle of Mountain Winds
  - Evening Transition
  - Morning Transition
- ~~Plateau and Basin Meteorology~~
- Summary

Discussion Questions

- What in your experience supports or contradicts the material in this presentation?
- What aspects of diurnal wind systems do you find to be especially important for your forecasting situation?

North Foehn © Reudi Wyss

Introduction

Dolomite Mtns, Italy © CD Whiteman

Diurnal Mountain Winds

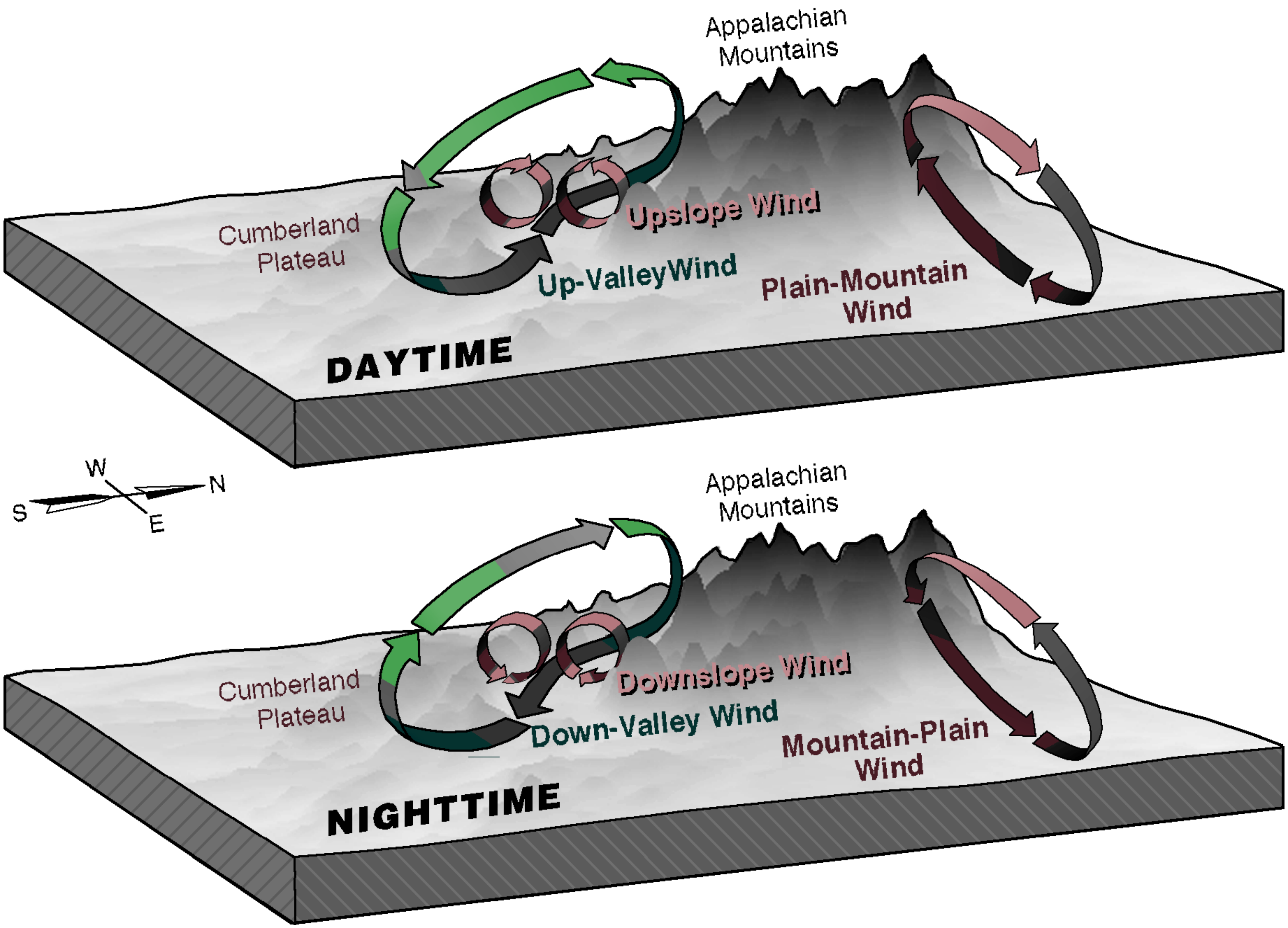
- Develop over complex terrain of all scales.
- Characterized by a reversal of wind direction twice per day.
- Strongest with clear skies when winds aloft are weak.
- As a rule, upslope, up-valley and flow from plain to mountains during daytime and in the opposite direction during nighttime.
- Produced *by horizontal pressure differences* (resulting from *horizontal temperature differences*).
- Circulations are *closed* by *return or compensatory* circulations aloft.

The Mountain Wind System

- Four interacting wind systems are found over mountain terrain:
- Slope wind system (upslope and downslope winds)
- Along-valley wind system (up-valley and down-valley winds)
- Cross-valley wind system (from the cold to warm slope)
- Mountain-plain wind system (plain-mountain and mountain-plain winds)

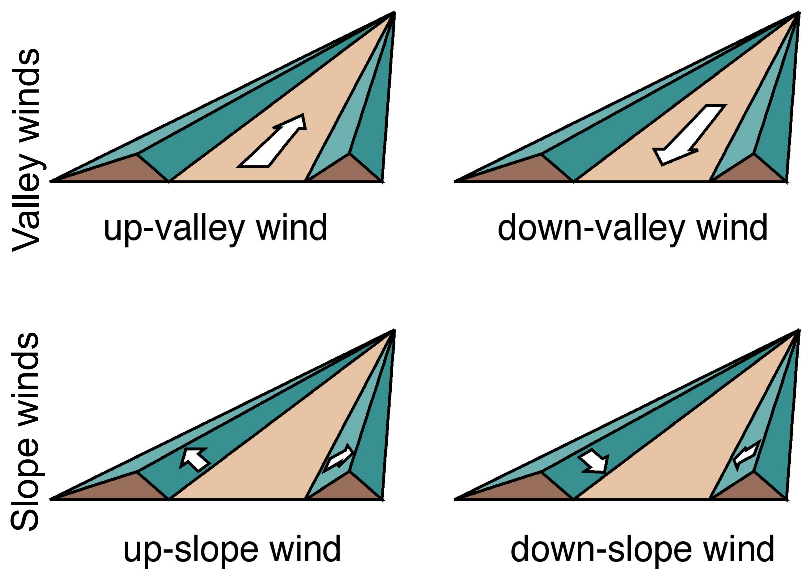
Because diurnal mountain winds are driven by horizontal temperature differences, the regular evolution of the winds in a given valley is closely tied to the thermal structure of the atmospheric boundary layer within the valley, which is characterized by a diurnal cycle of buildup and breakdown of a temperature inversion.

Diurnal mountain winds



Diurnal Mountain Winds

Diurnal mountain winds are winds within topography that reverse twice per day. They are seen in all mountain areas and are best developed on undisturbed ‘radiation’ days.



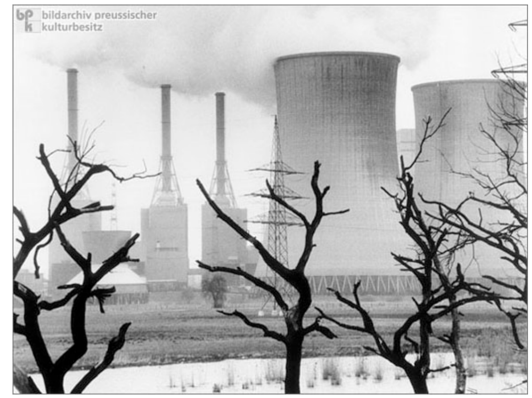
Terminology

- valley wind = up-valley wind (day)
- mountain wind = down-valley wind (night)
- anabatic flow = up-slope wind (day)
- katabatic flow = down-slope wind (night)
- drainage flows = down-slope & down-valley
- cross-valley flow = toward heated hillside
- mountain-plain circulation
- anti-winds

Improper terminology is widespread in mountain meteorology literature!

The continuum concept …

Diurnal Mountain Winds



Forecasting and Applications

- **General forecasting**
- **Fog forecasting**
- **Minimum temperatures**
- **Fire weather**
- **Air pollution**
- **Mountain aviation**

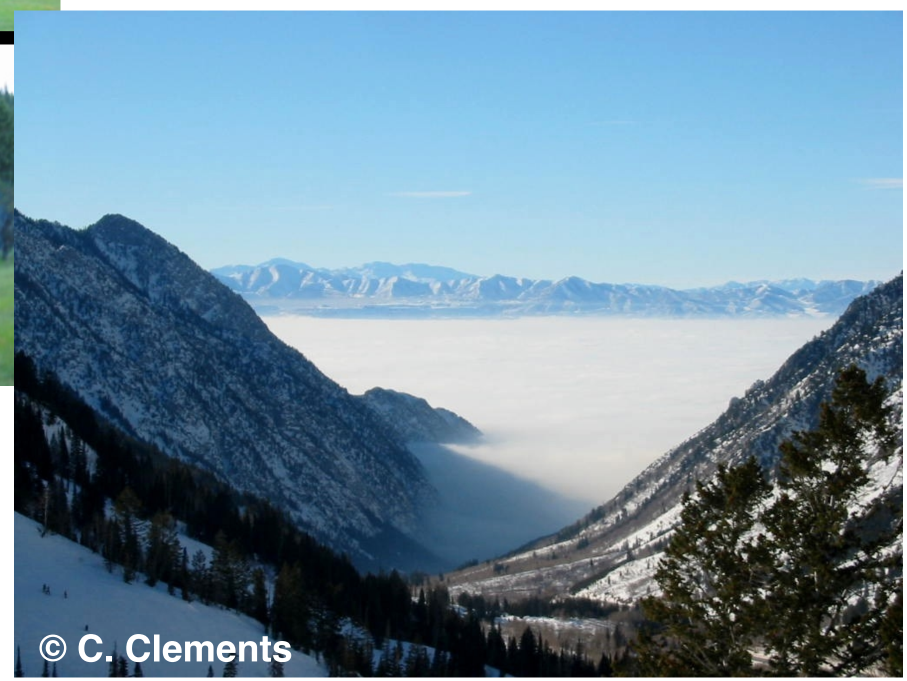
- **Agriculture (vineyards, orchards, crops)**
- **Urban planning**
- **Wind energy**
- **Propagation of light, sound, RF**
- **Ecosystems**
- **Winter Olympics**

Diurnal wind systems

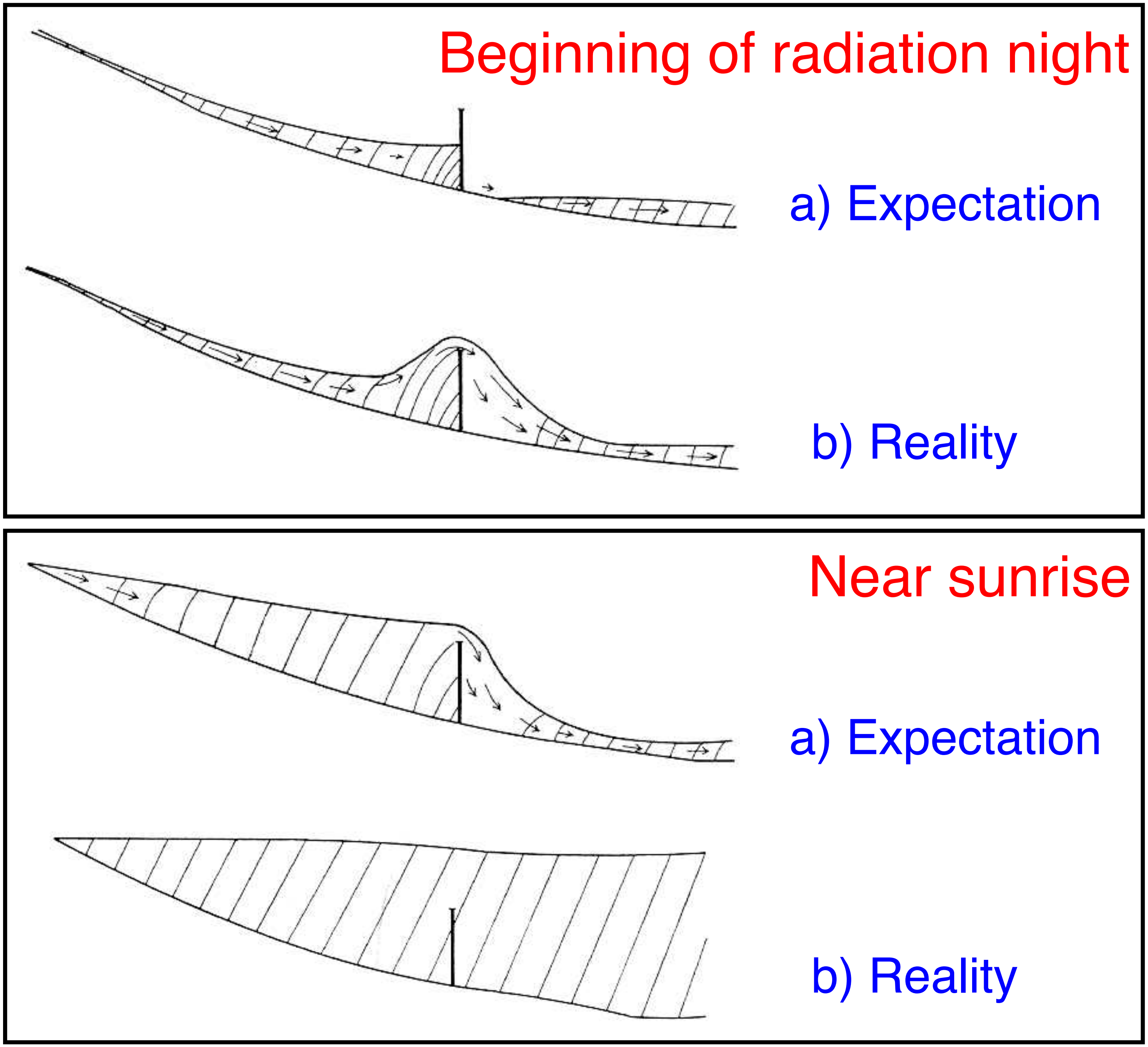
You can observe an awful lot
just by watchin'.

- Lawrence (Yogi) Berra.

Campfire smoke Cayuse Valley, ID



Salt Lake Valley
from Snowbird, UT

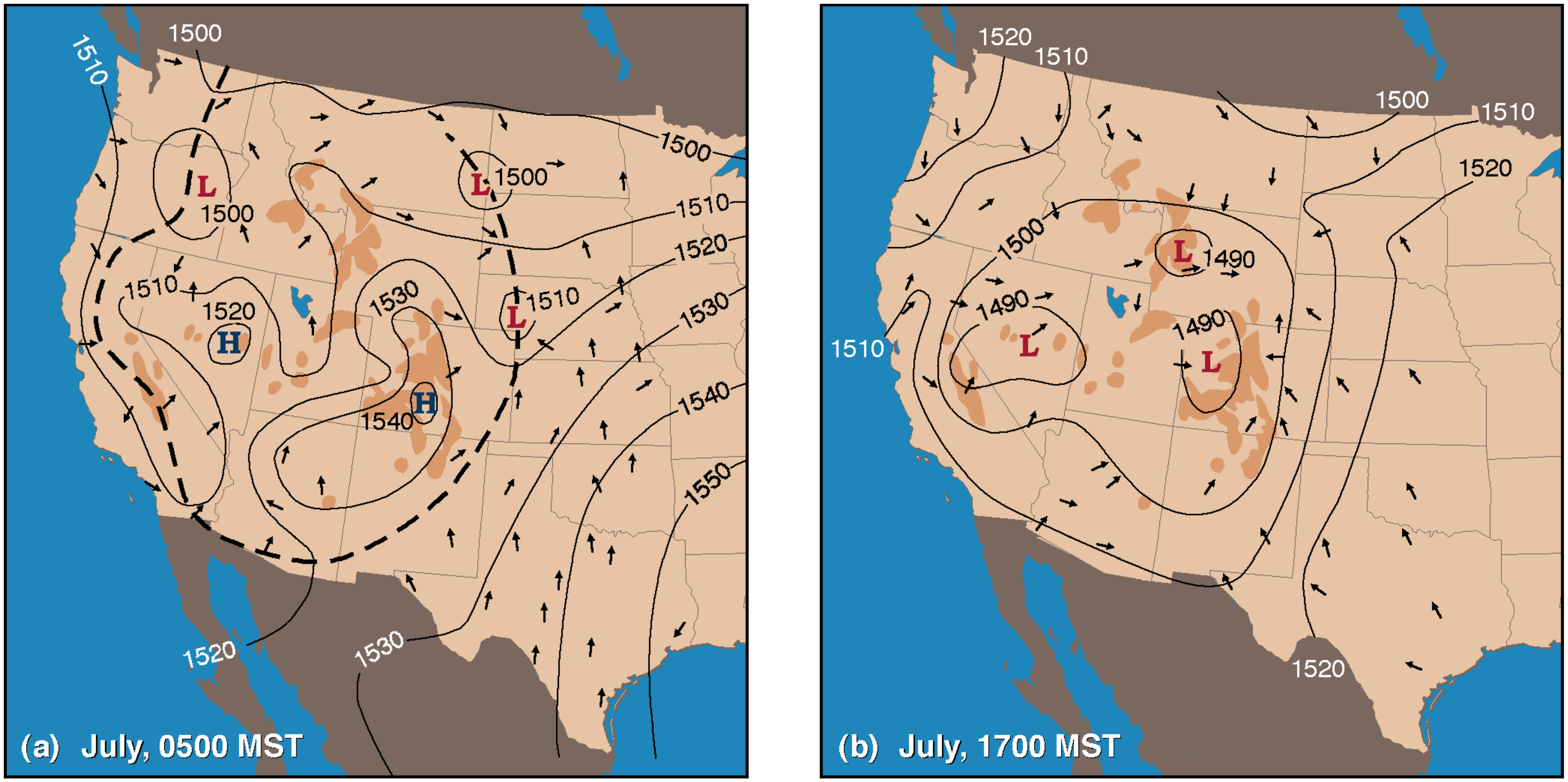

Beginning of radiation night
a) Expectation
b) Reality
Near sunrise
a) Expectation
b) Reality

King
(1973)


Mountain-Plain
Wind System
© Adam Naisbitt

Diurnal

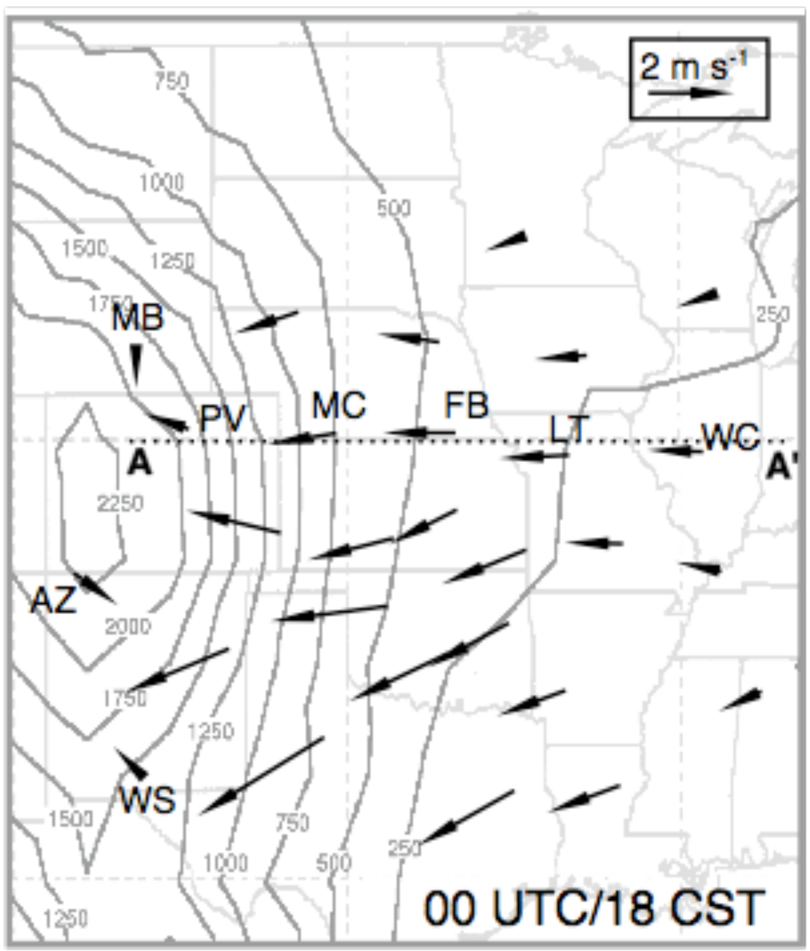
Mean 850 mb pressure and wind patterns



adapted from Reiter & Tang (1984)

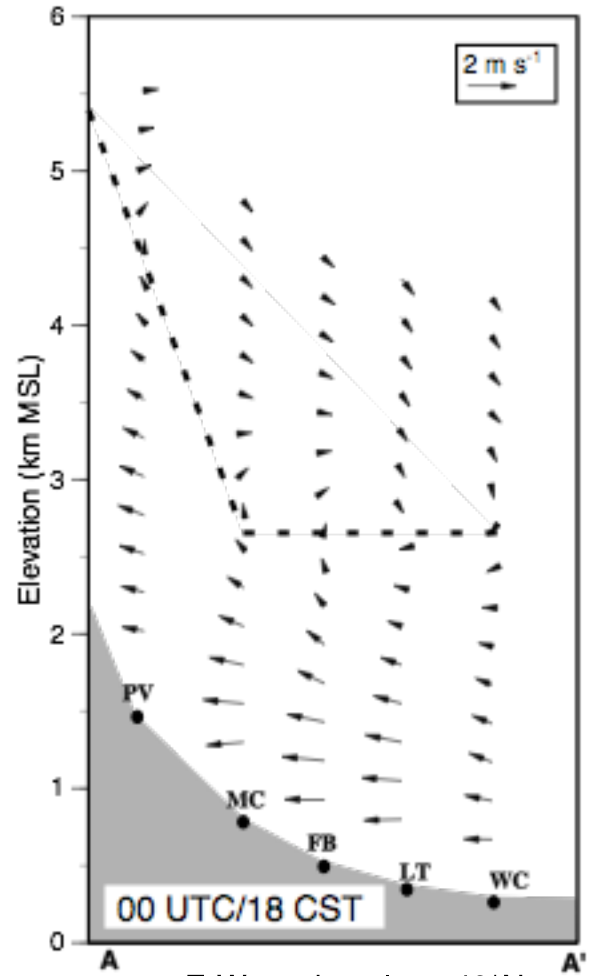
Diurnal mountain-plain wind system

… from 915 MHz radar wind profiler data



Daytime

Winds at 500 m AGL

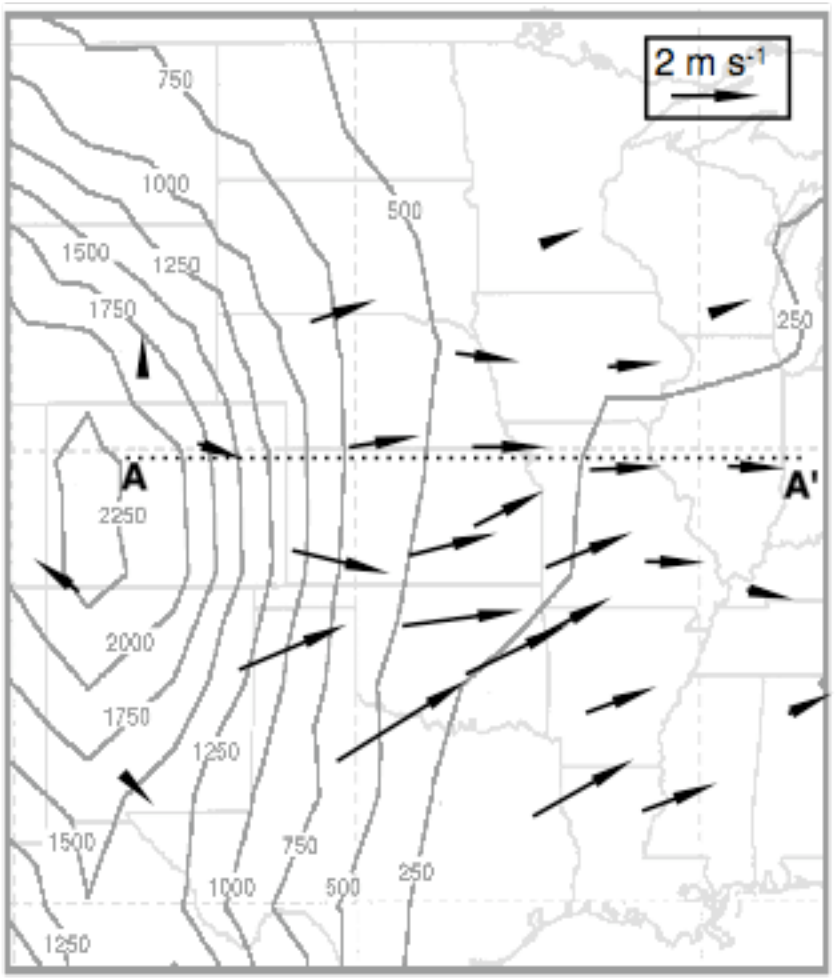


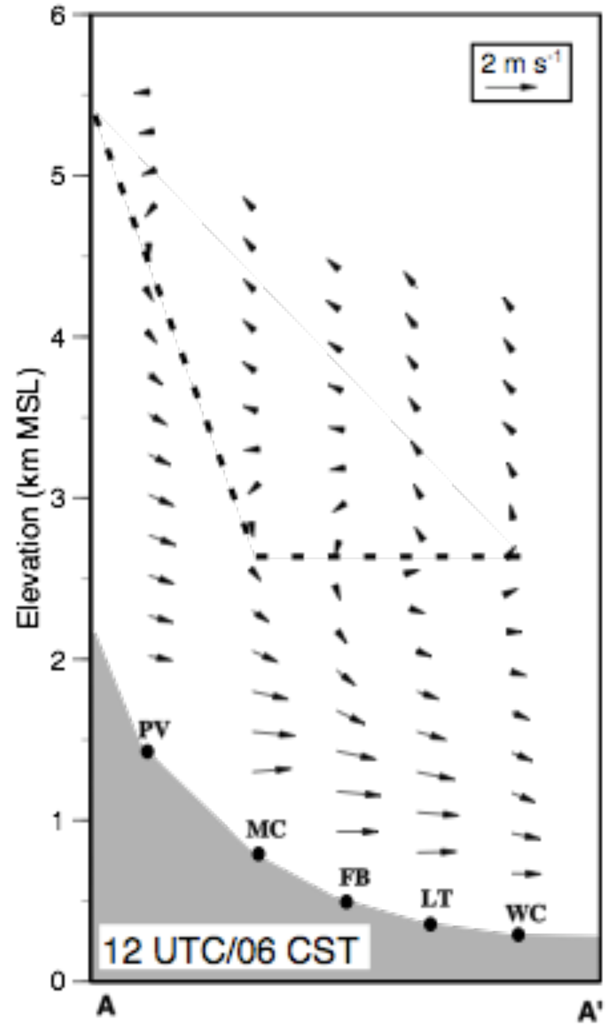
E-W section along 40*N

Whiteman & Bian (1998)

Diurnal mountain-plain wind system

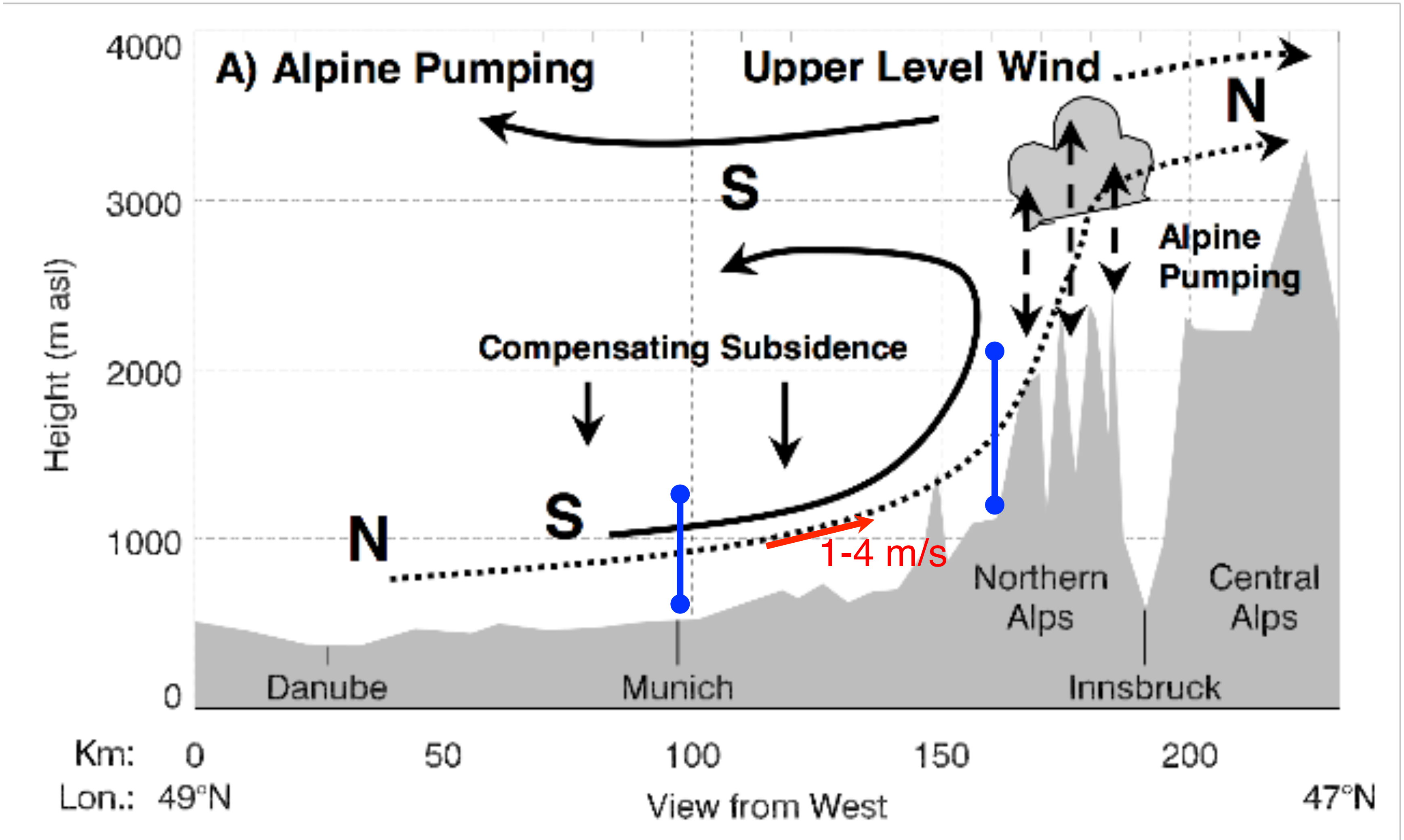
…from 915 MHz radar wind profiler data, continued





Nighttime

Whiteman & Bian (1998)

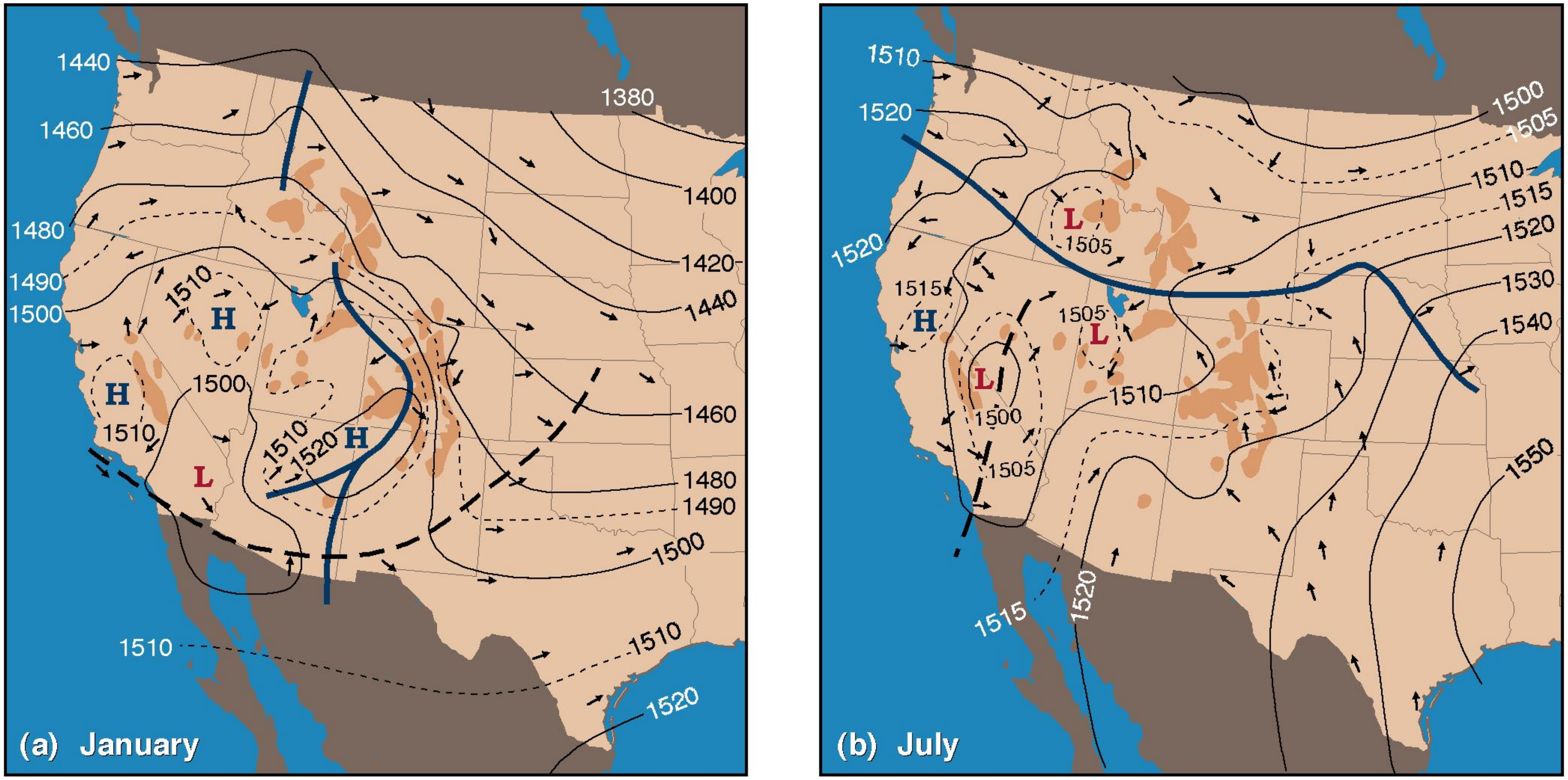


Late morning through afternoon

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

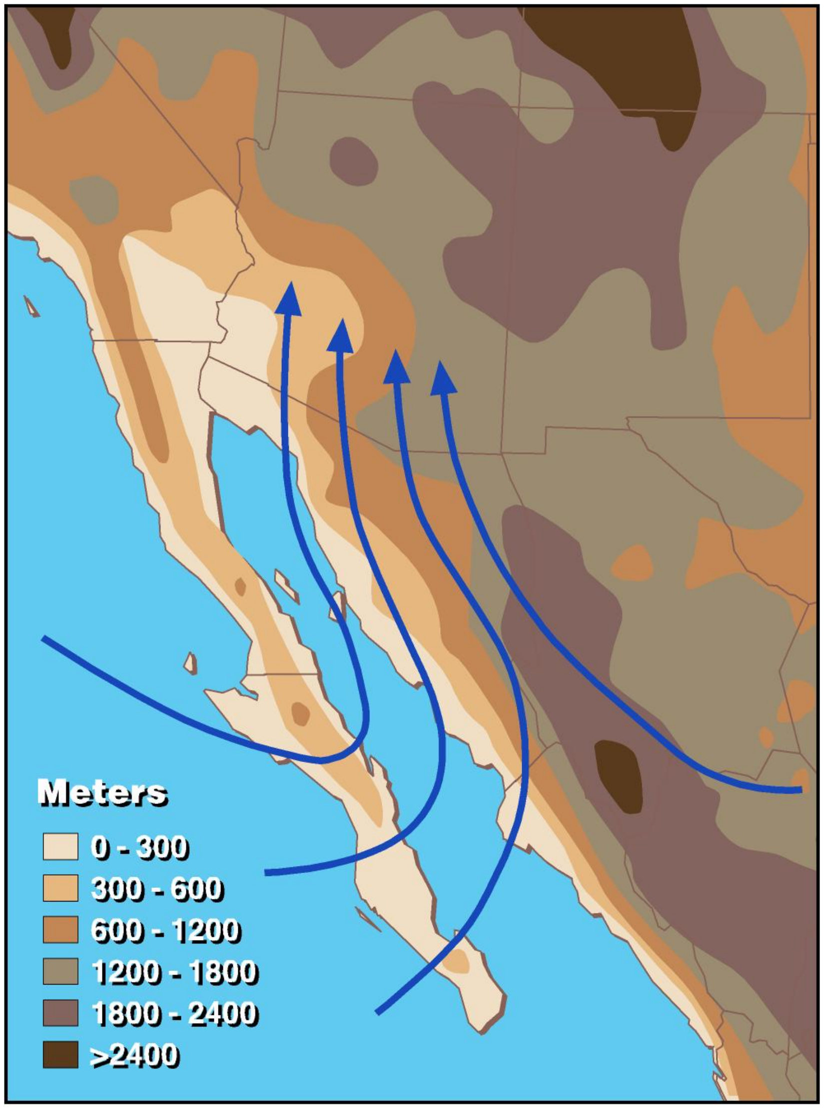
Seasonal

Mean 850 mb pressure and wind patterns



adapted from Reiter & Tang (1984)

The Southwest or Mexican Monsoon

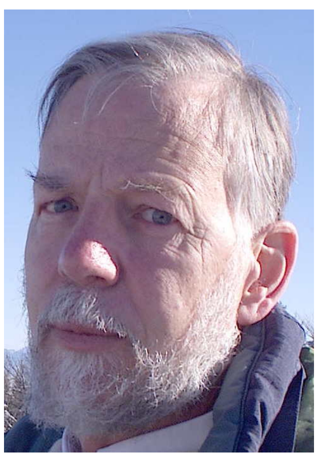


adapted from Stensrud et al. (1995)

... a seasonally varying thermal circulation

Mountain-plain wind system references

GEWEX Asian Monsoon Experiment (http://game.suiri.tsukuba.ac.jp/literature/lists/pubs.htm)
North American Monsoon Experiment (http://www.eol.ucar.edu/projects/name/)
Henne et al. (2005) Mountain venting
Sasaki et al. (2004) Effect of mtns on moisture transport to free troposphere in Sumatra
Weigel et al. (2007b) Effect of mtns on moisture transport to free troposphere in Alps
Weissmann et al. (2003) Alpine pumping (daytime case study using airborne Doppler lidar)
Lugauer and Winkler (2005)
Winkler et al. (2006) Alpine pumping [in German]


Peter Winkler


Martin Weissmann

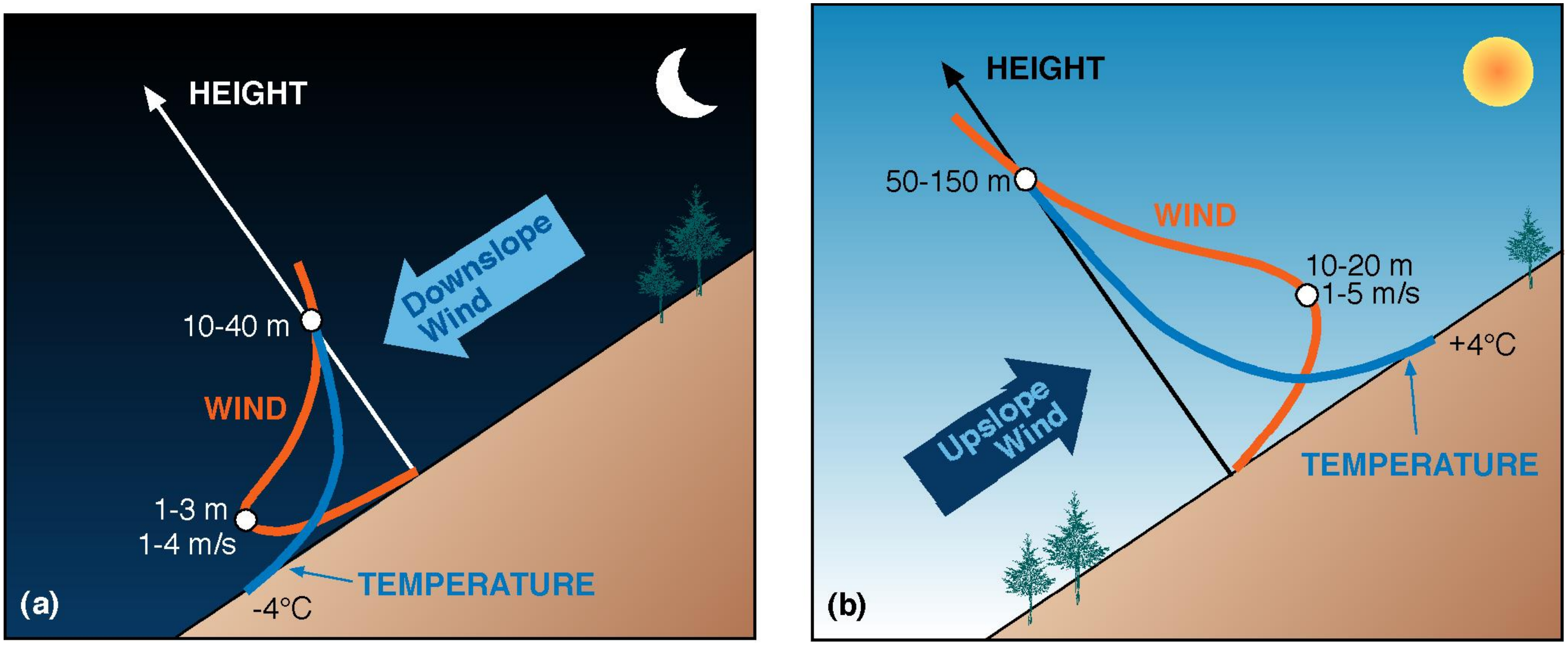

Matthias Lugauer


Stefan Henne

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.

Radiation Budget, Heat Budget & Turbulence

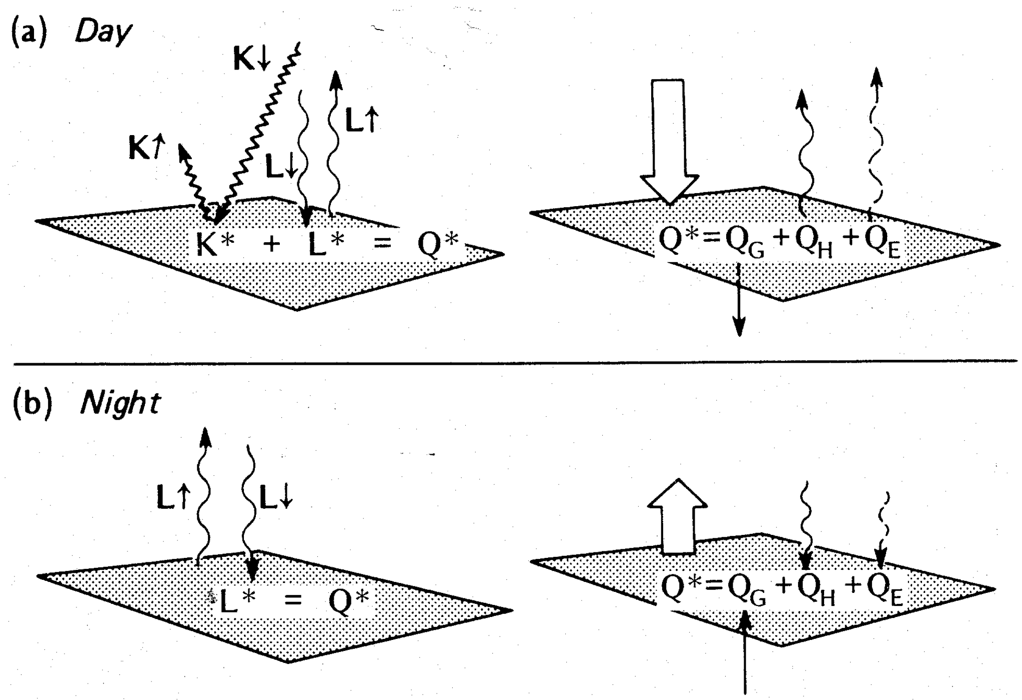
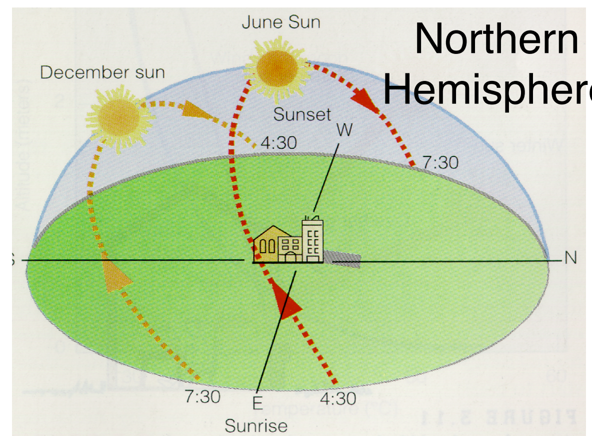


Figure 1.11 Schematic summary of the fluxes involved in the radiation budget and energy balance of an 'ideal' site, (a) by day and (b) at night.

Oke (1978)

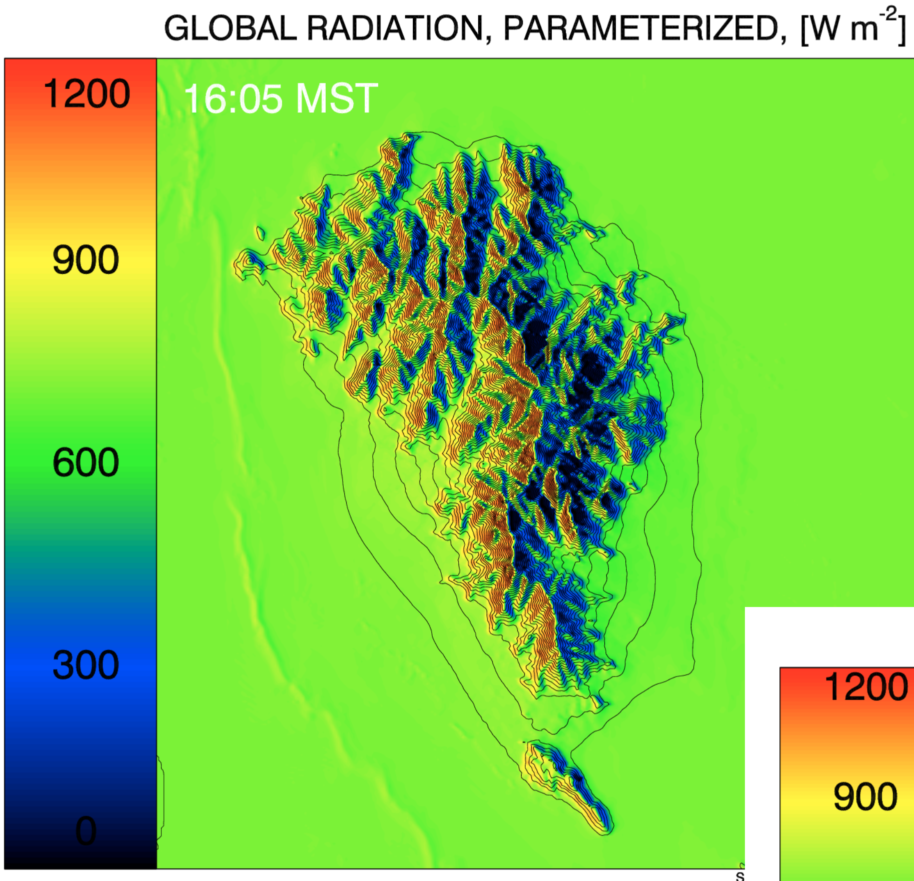
Sun path
summer & winter

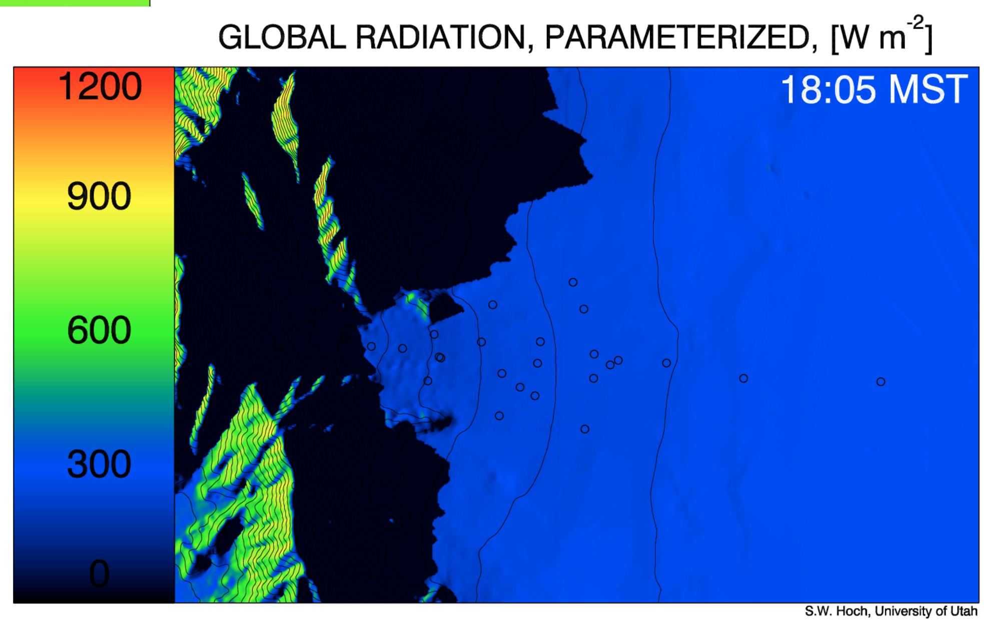


Northern Hemisphere

Ahrens (1994)

Drivers for Slope Wind Systems

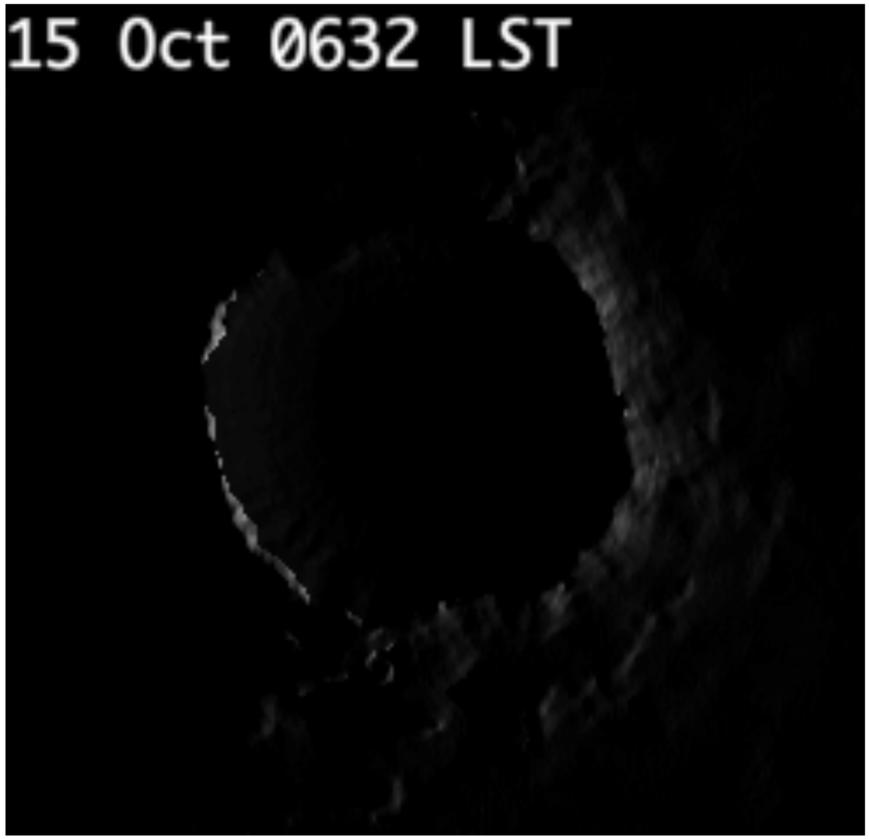




METCRAX - 2006 / METCRAX-II (2013)

Upslope-Downslope Flow Transition

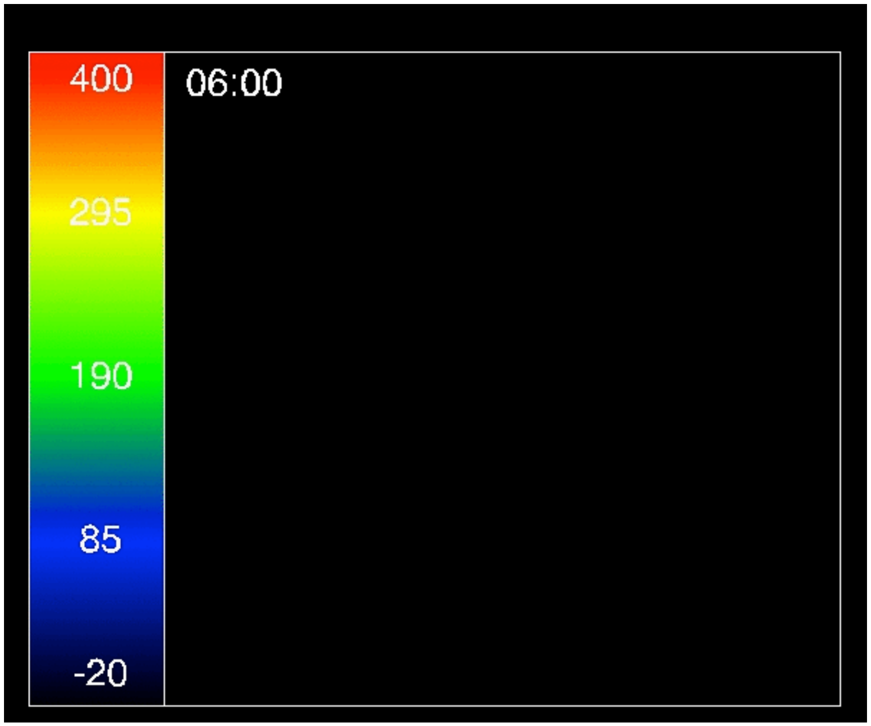
Propagation of shadows and insolation patterns

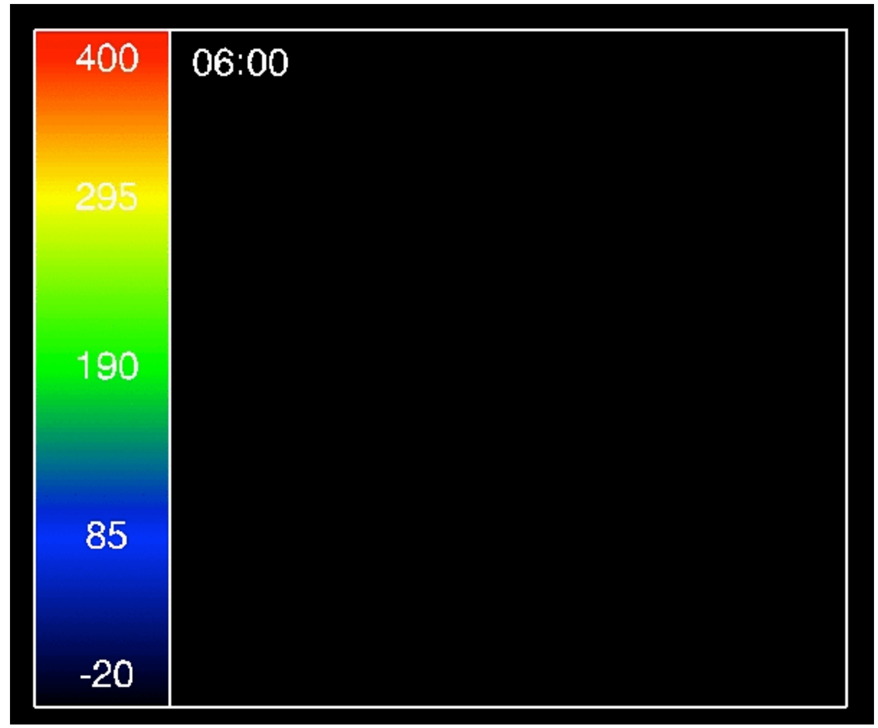


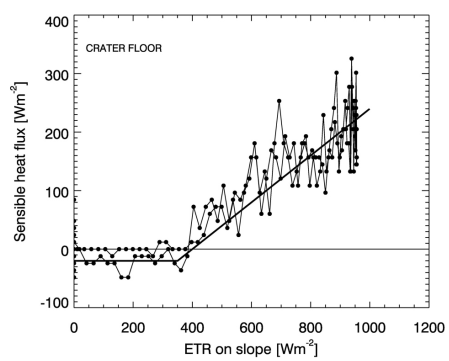
Meteor Crater, Arizona

Whiteman & Kahler (2006)

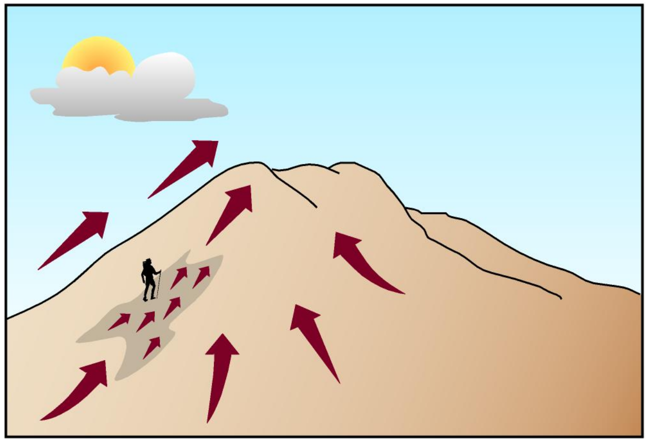
Sensible heat flux, 21 Oct 2006

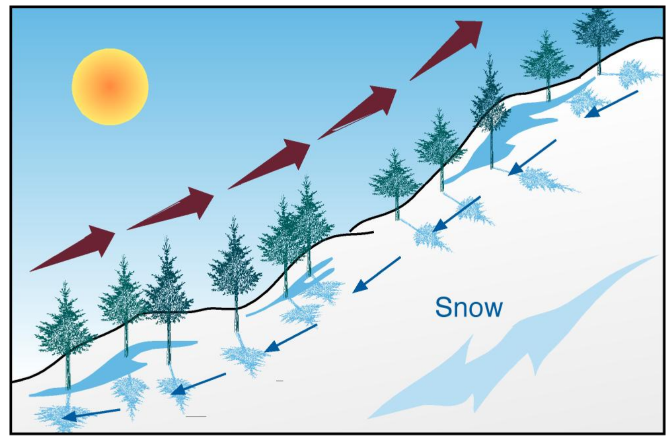






Upslope flows





During daytime, upslope flows occur on mountainsides. The climber might notice them only when they suddenly stop or weaken as a cloud drifts in front of the sun.

In winter, an upslope flow can occur over a forest, even when the ground is snow-covered.

Upslope flow references

Mahrt (1982) Momentum balance of gravity flows
Kuwagata & Kondo (1989) Observation and modeling of upslope flows
Schumann (1990) LES of up-slope flows
Reuten (2006) Scaling and kinematics of upslope flows
Reuten et al. (2005) Water tank studies of upslope flows
Reuten et al. (2007) Lidar observation of odd u-s/d-s recirculation within CBL over slope
Princevac & Fernando (2007)


Larry Mahrt

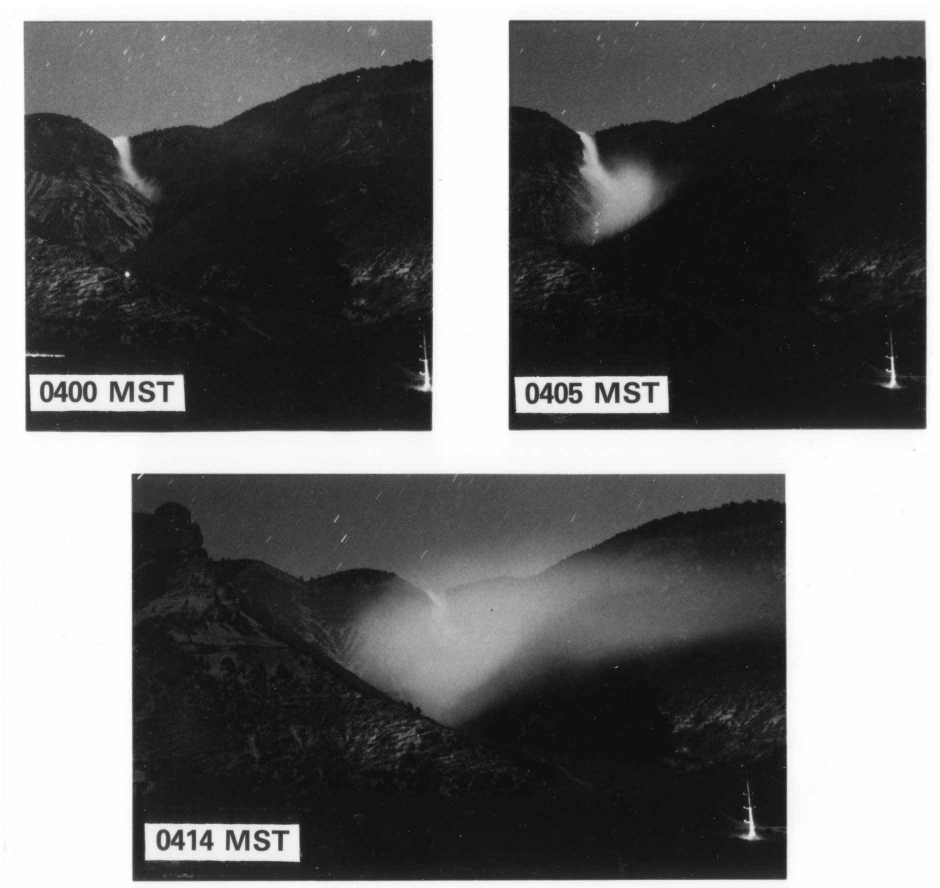

Ulrich Schumann


Joe Fernando


Christian Reuten


Douw Steyn

Downslope Flows



During nighttime, weak downslope flows are often most noticeable when they start on shaded slopes in the late afternoon or early evening. They can also be visualized by smoke drift (left).

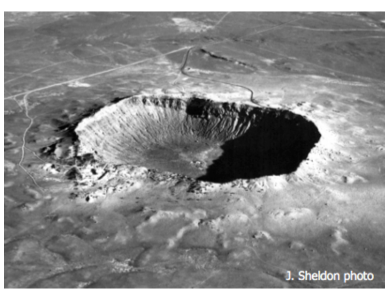
Brush Creek Valley tracer plume.
Photos by Thorp and Orgill

Downslope Flows

Gruenloch Basin sidewall
2051 UTC 2 June 2002

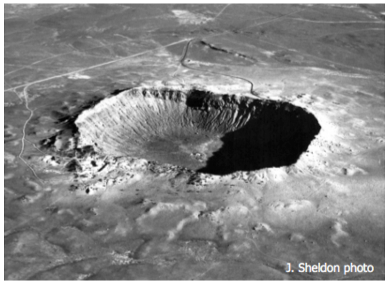
From R. Steinacker

Upslope flow, 1518 MST



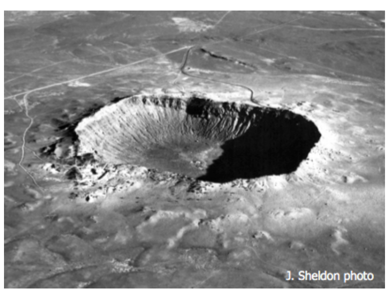
IOP 4

Flow reversal, 1538 MST

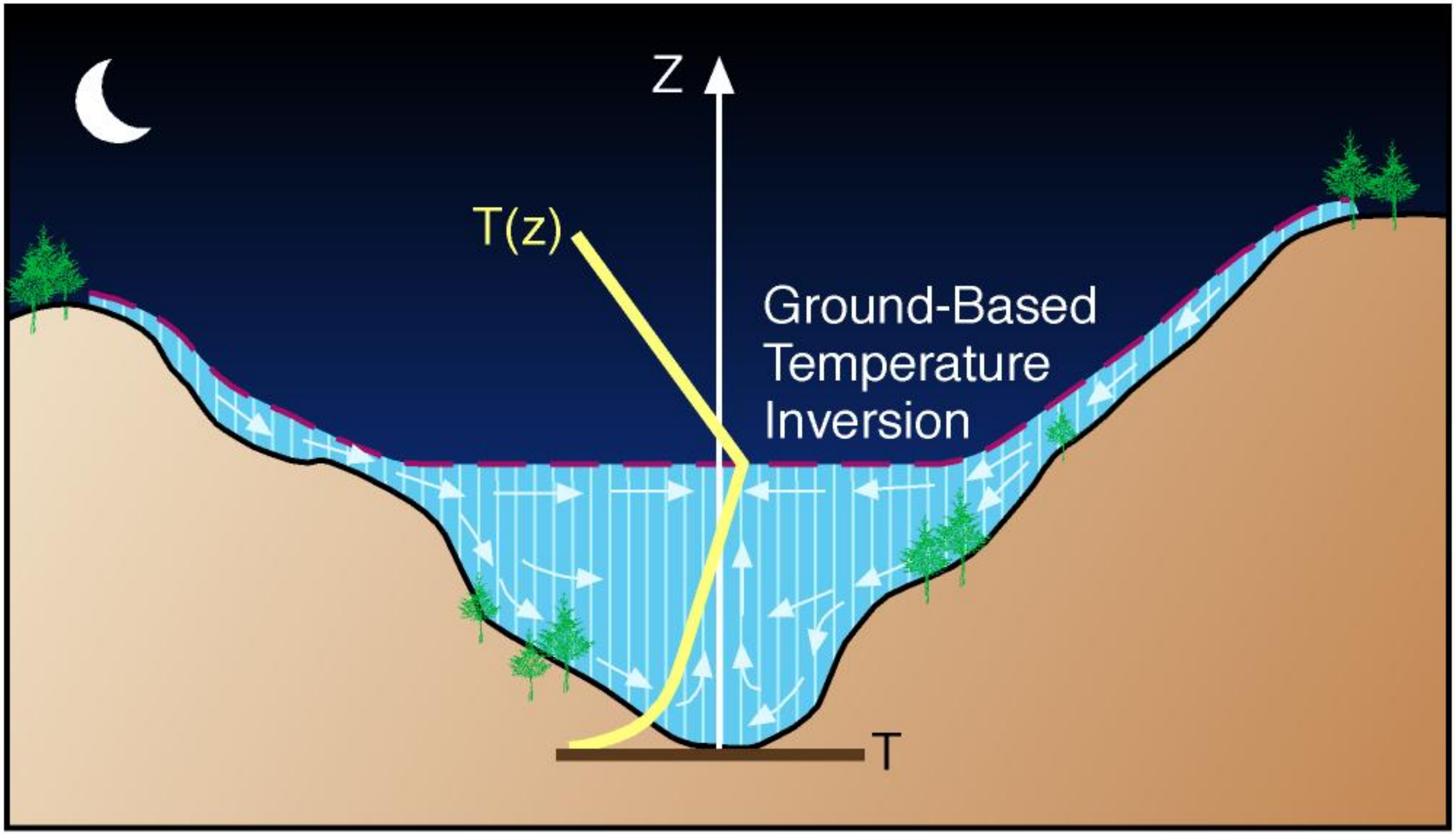


IOP 4

Downslope flow, 1558 MST

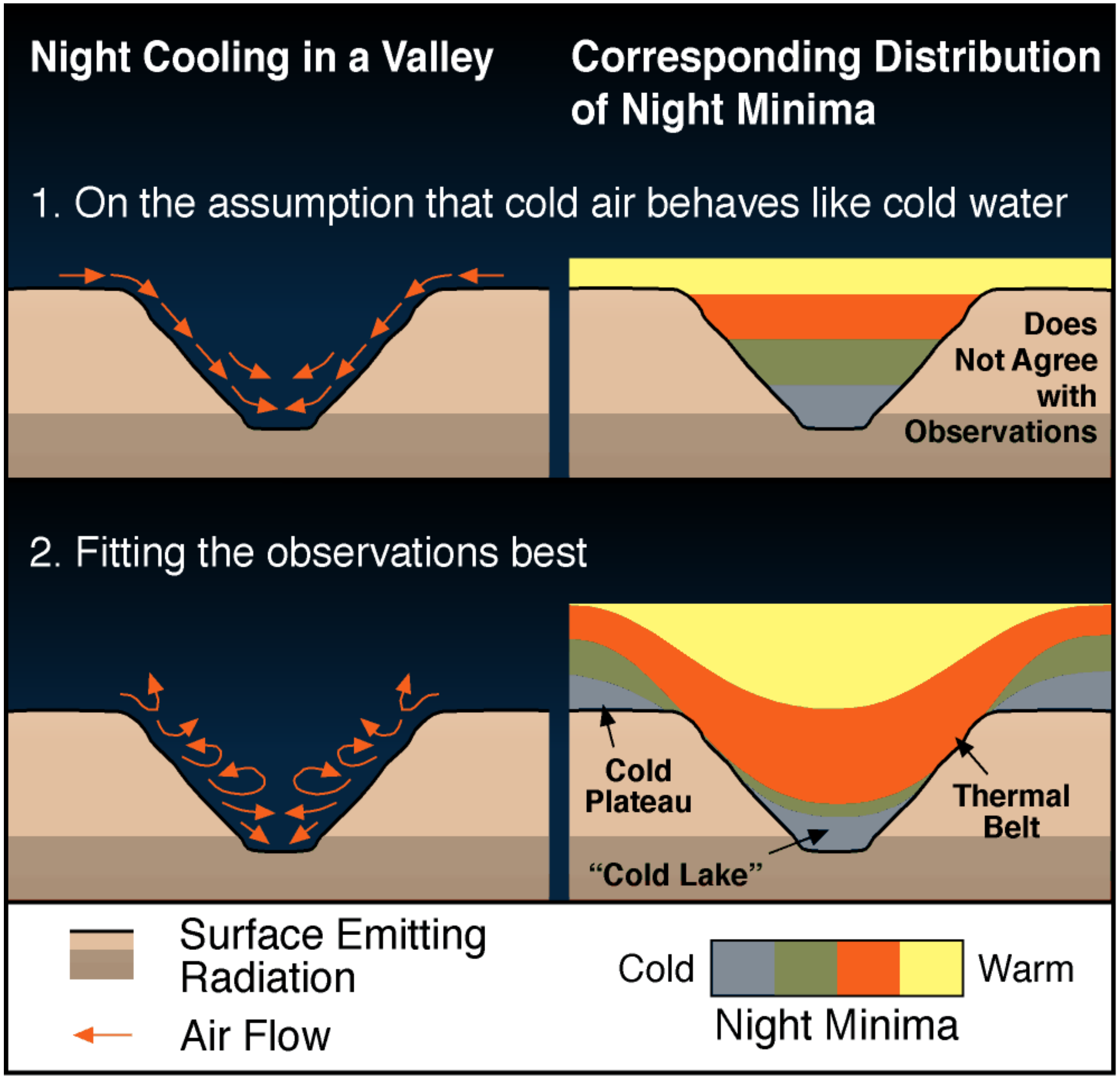


IOP 4

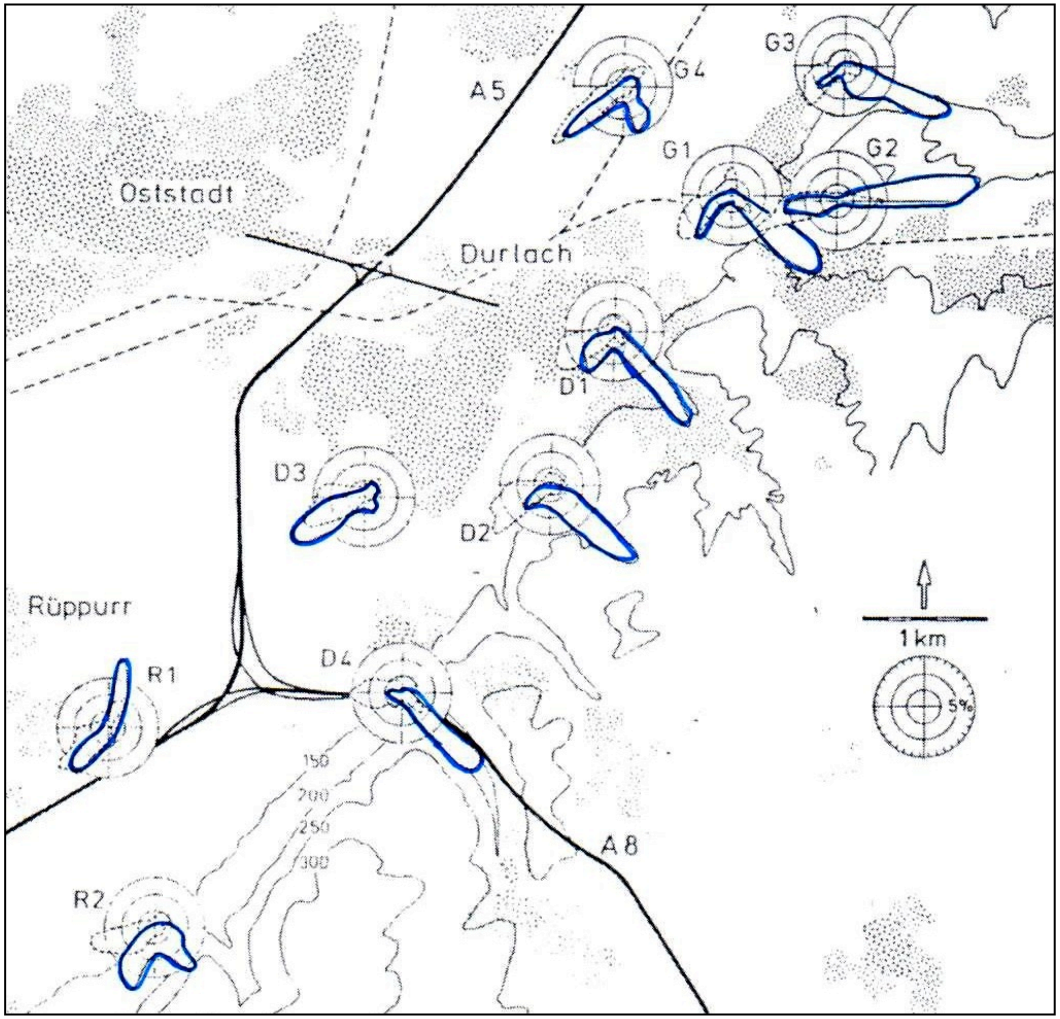


Early in the evening when the atmosphere is near-neutral, downslope flows are strong and they converge on the valley floor. As the ambient stability (valley inversion) builds later in the evening, the downslope flows cannot penetrate readily to the valley floor and converge at higher altitudes.

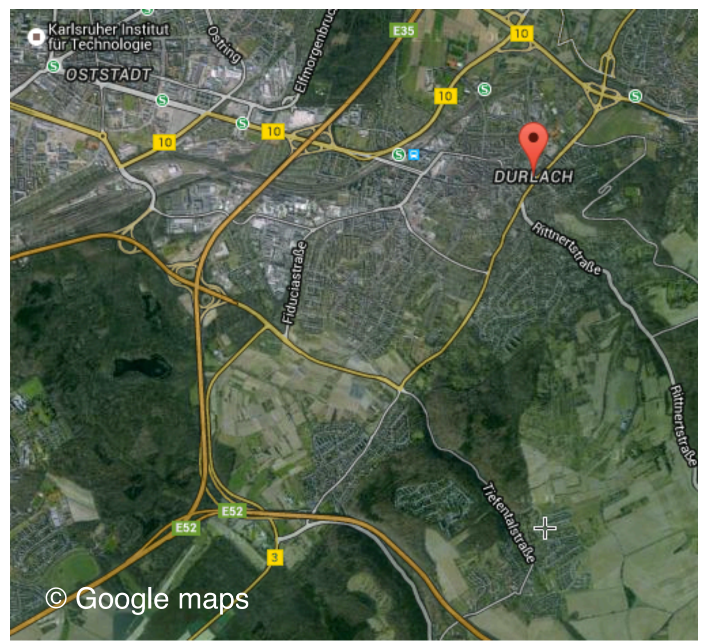
Thermal belt



Geiger et al. (1995)



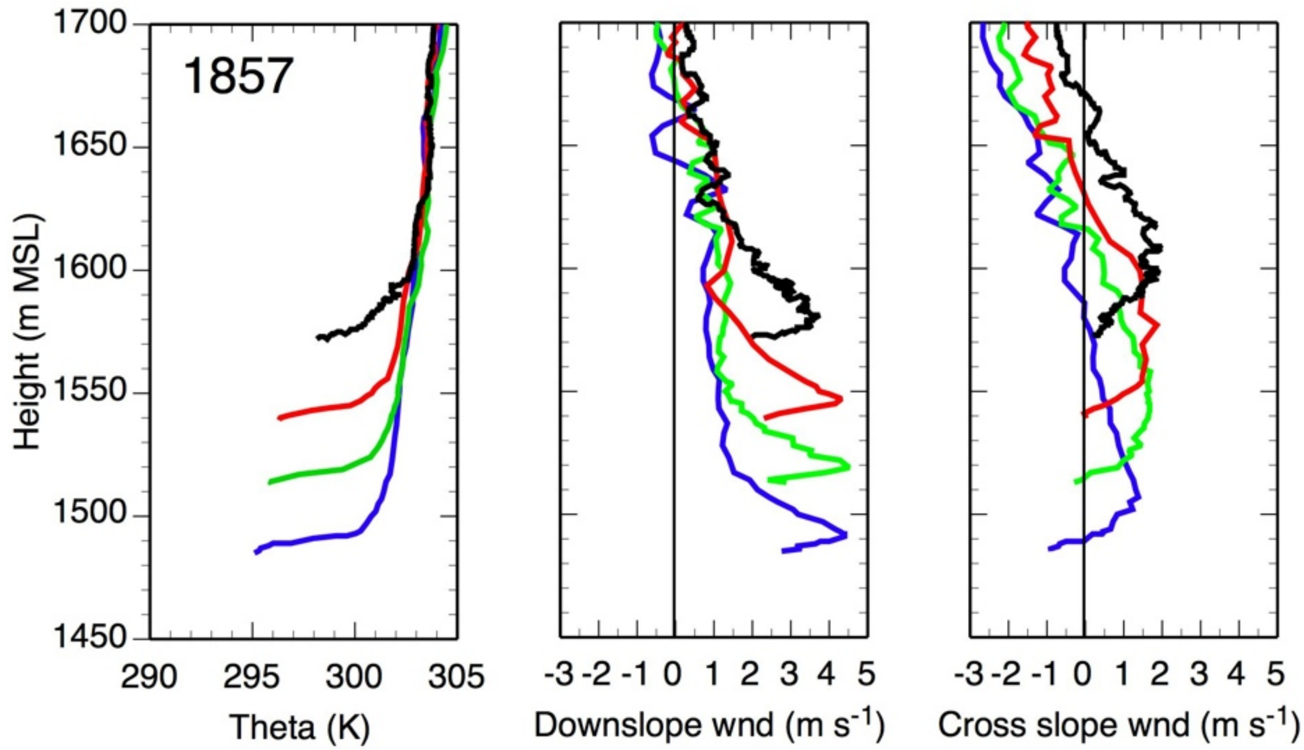
Cold air outflows can **travel some distance** out over an adjacent plain. Here tributary flows run out into the Rhine Valley. The Rhine River flows northward.



Heldt and Höschele, 1989
Höschele, 1980

Downslope flow example

VTMX, 8 Oct 2000



Whiteman & Zhong (2008)

- Jet profile max velocity ~ 15m 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

Downslope flow references

Prandtl (1942) Analytical model laminar d-s flow, constant eddy diffusivity
Doran et al. (1990) Effect of down-valley flow on downslope flow
Banta & Gannon (1995) Effect of soil moisture on katabatic flows
Poulos (1996) Effect of gravity waves on downslope flow
Mahrt et al. (2001) Shallow nighttime drainage flows
Monti et al. (2002) Observations of d-s flow and turbulence
Haiden (2003) Relation between pressure and buoyancy forces in slope layer
Skyllingstad (2003) LES of d-s flows
Smith & Skyllingstad (2005) LES simulation, changing slope angle
Haiden & Whiteman (2005) Slope flow momentum and thermal energy balance
Whiteman & Zhong (2008) Observations of d-s flow on low-angle slope
Zhong & Whiteman (2008) Numerical model: slope angle, stability, ambient winds
Zhong and Poulos (2008) Review of small-scale katabatic flows
De Wekker (2008) Depression of slope flow at mountain base


Greg Poulos


Ignaz Vergeiner

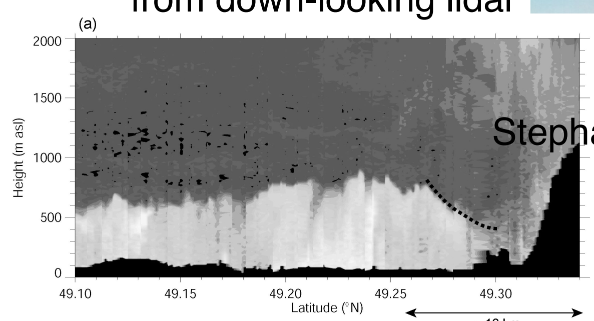

Stephan De Wekker


Thomas Haiden


Eric Skyllingstad

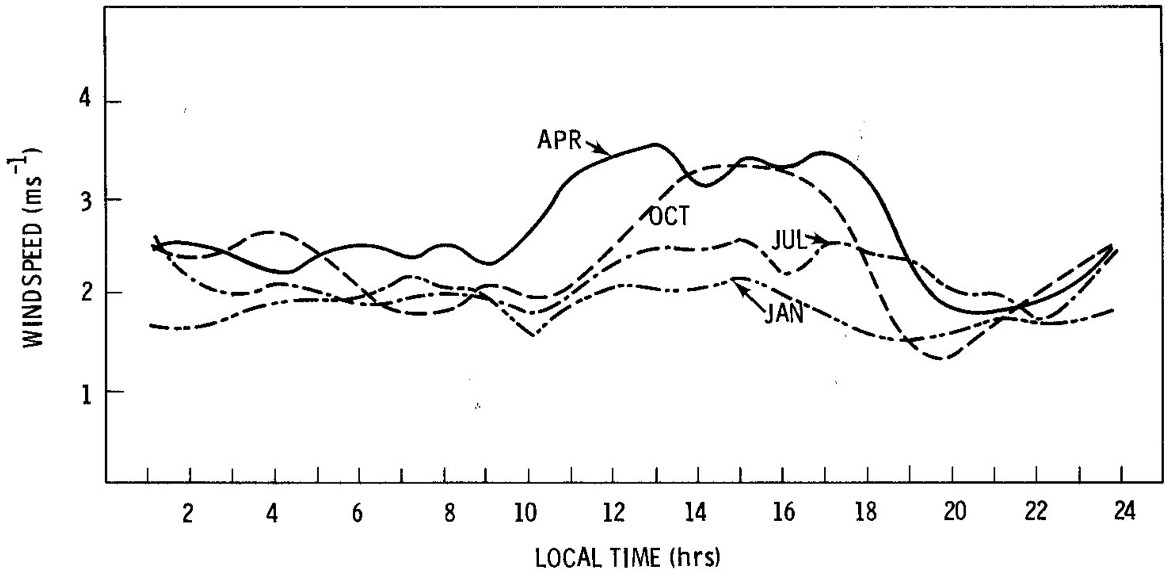

Sharon Zhong

aerosol backscatter
from down-looking lidar

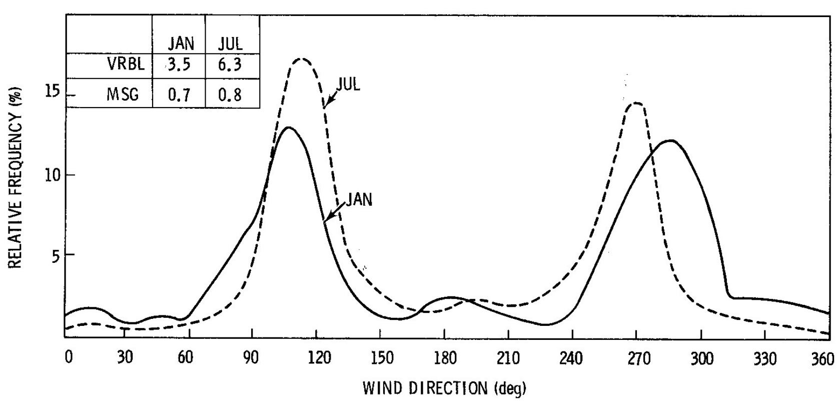


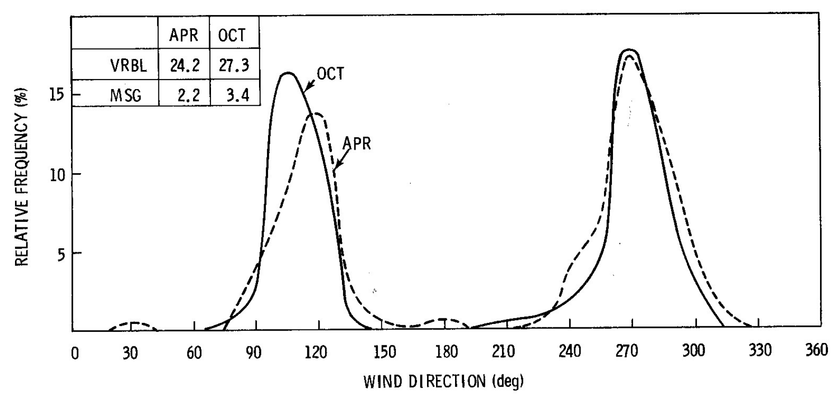

Valley Wind System
COMAP
Boulder, CO
Brush Creek Valley © CD Whiteman

Valley wind system



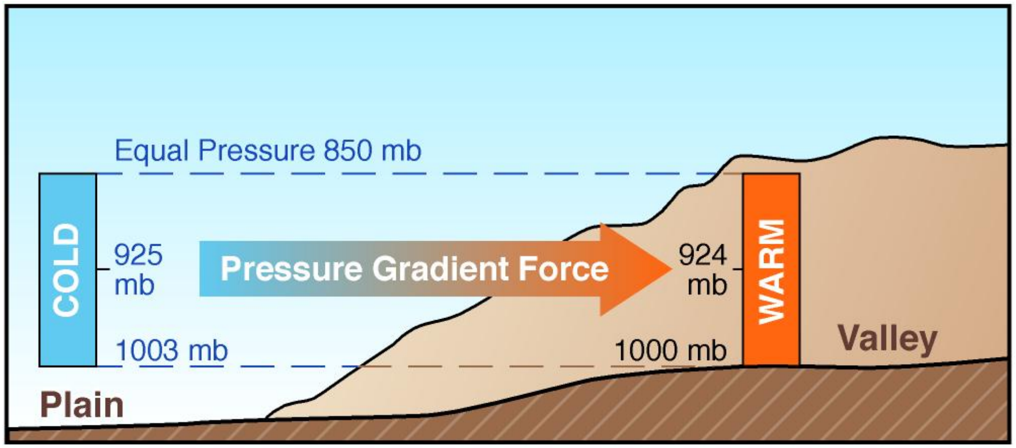
Avon, CO is in the Eagle Valley below the Vail/ Beaver Creek ski area. The observations come from an automatic weather station operated in the early 1980s before the ski resort was built.



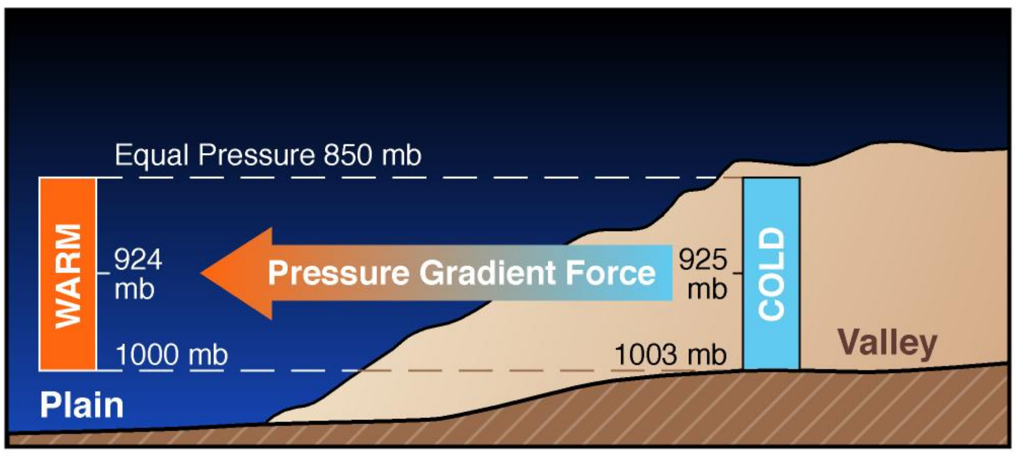


Whiteman

Valley wind system



Daytime

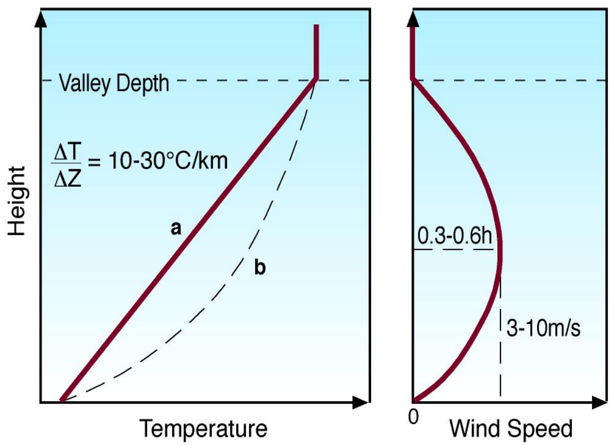


Nighttime

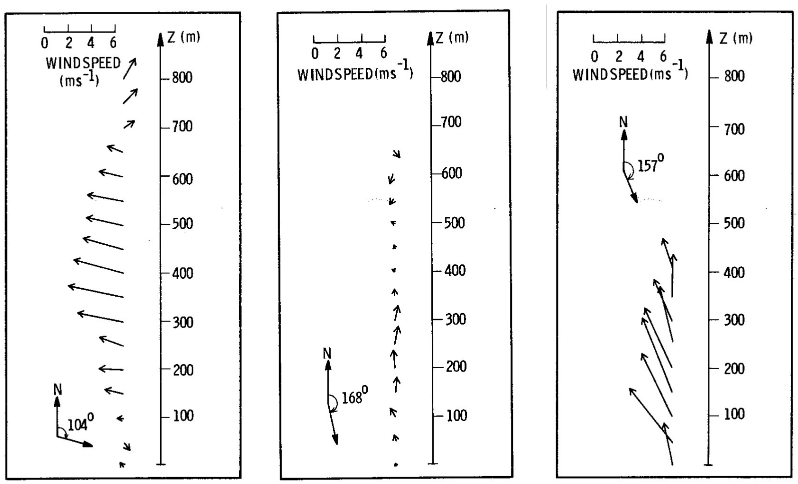
Valley winds are closed circulations that attempt to equalize horizontal pressure gradients that are built up hydrostatically between the valley and plain caused by the greater temperature range of a column of air within the valley compared to a similar column of air over the plain at the same elevation.

Adapted from Hawkes (1947)

Typical T and wind profiles near sunrise



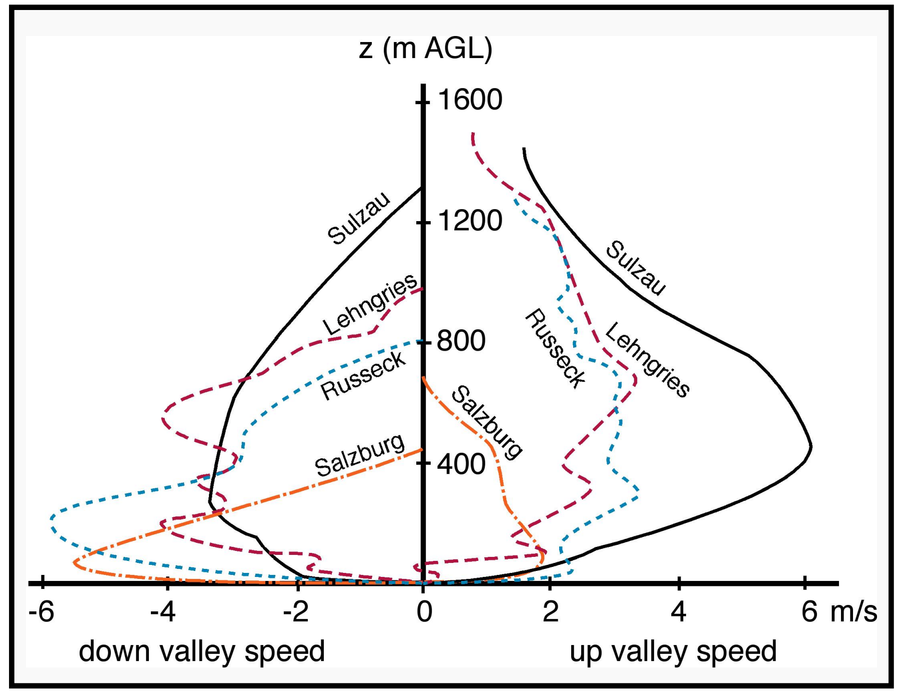
down-valley flows near sunrise



Eagle Valley
700 m deep

Yampa Valley
450 m deep

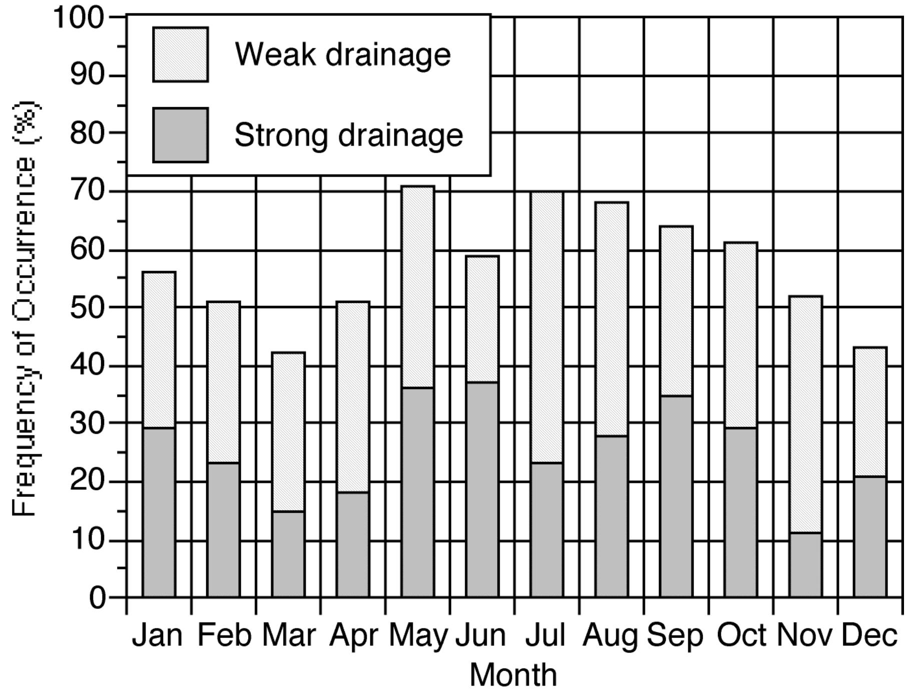
S. Fk. White R.
750 m deep



from Ekhart (1944)

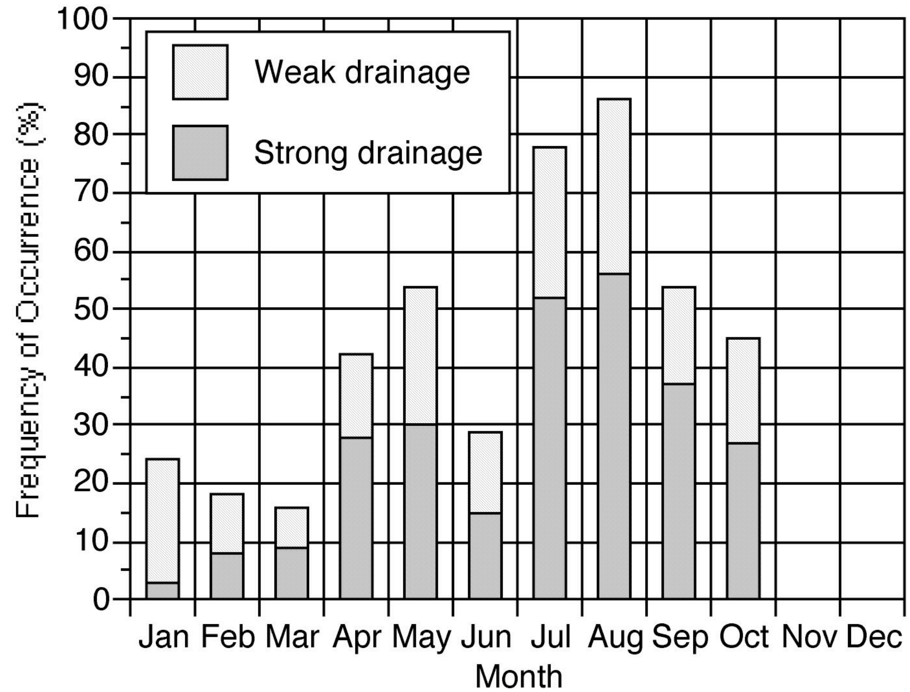
average of all ascents during up-valley and down-valley periods.

Diurnal Wind Frequencies



Brush Creek Valley, CO

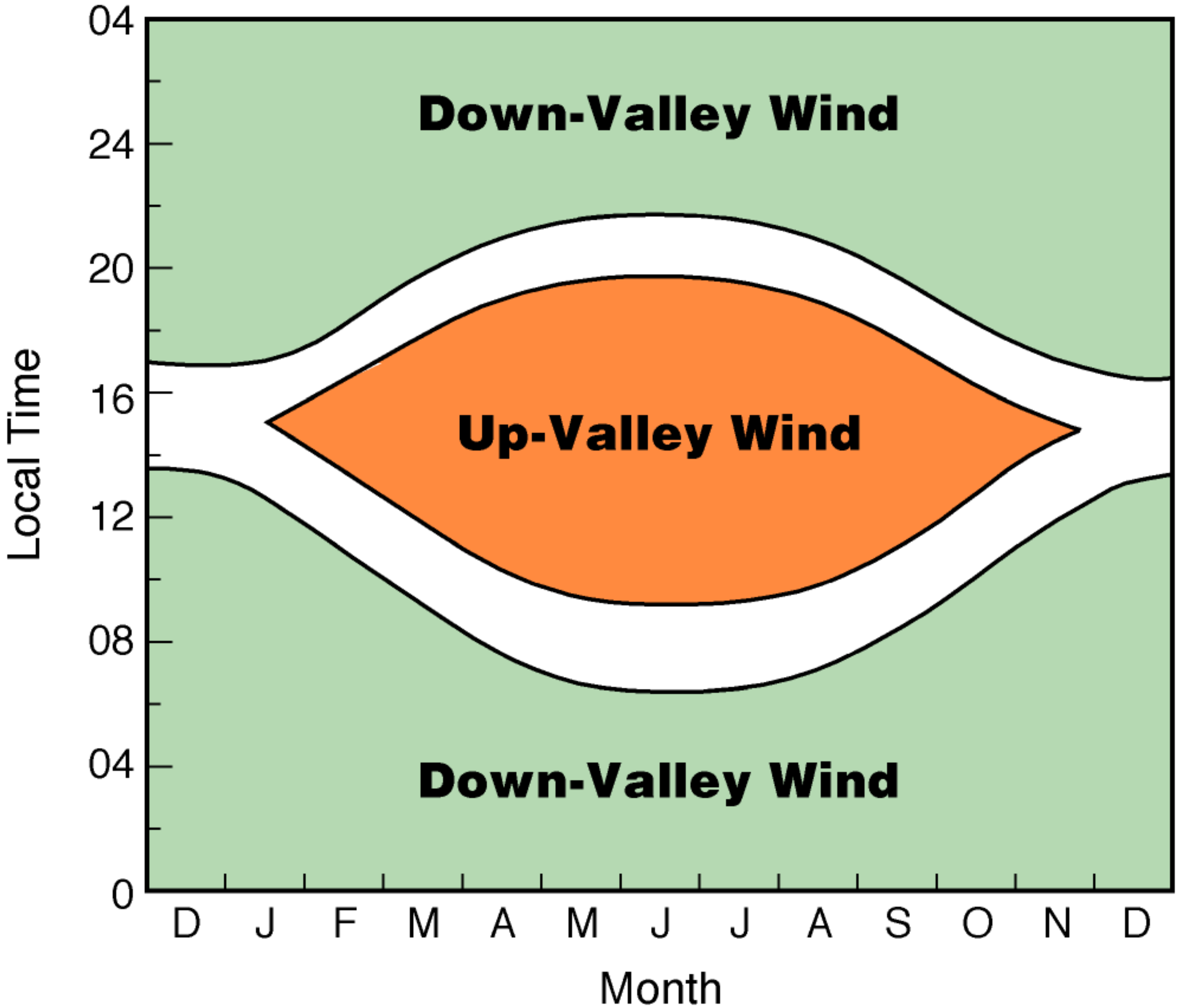
Gudiksen (1989)



Anderson Creek Valley, CA

Gudiksen and Walton (1981)

Seasonal Variation of Diurnal Wind Frequencies

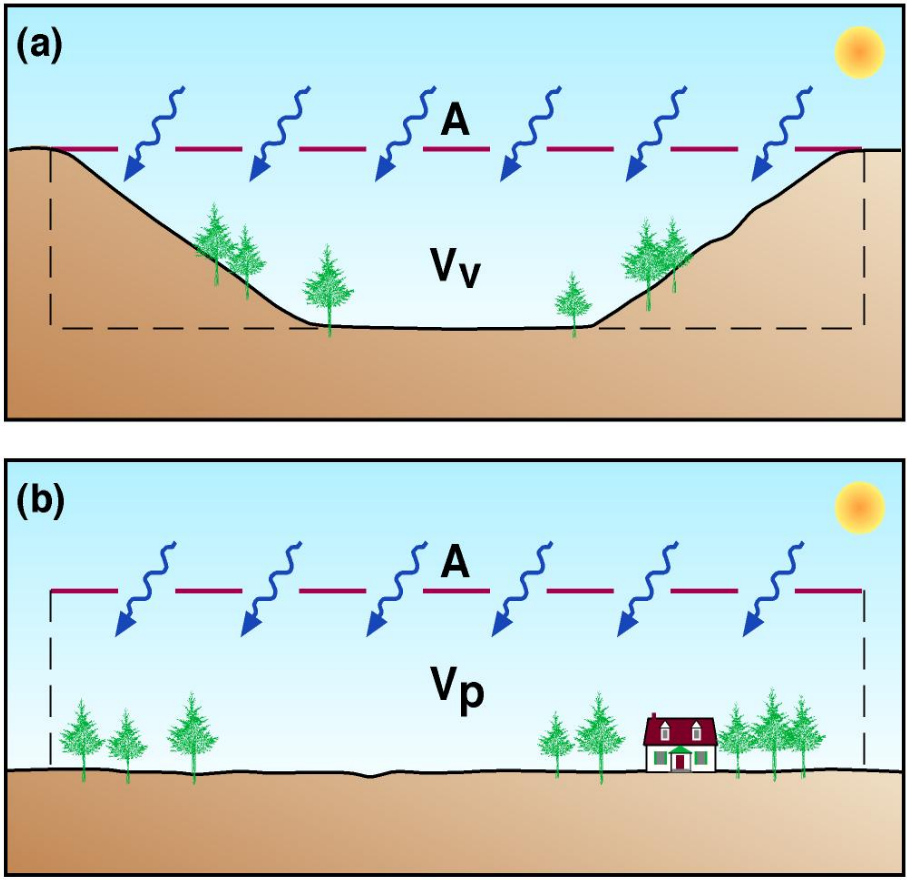


Leusach Tal

Reiter et al. (1983)

What causes the temperature range difference – Plain vs. Valley?

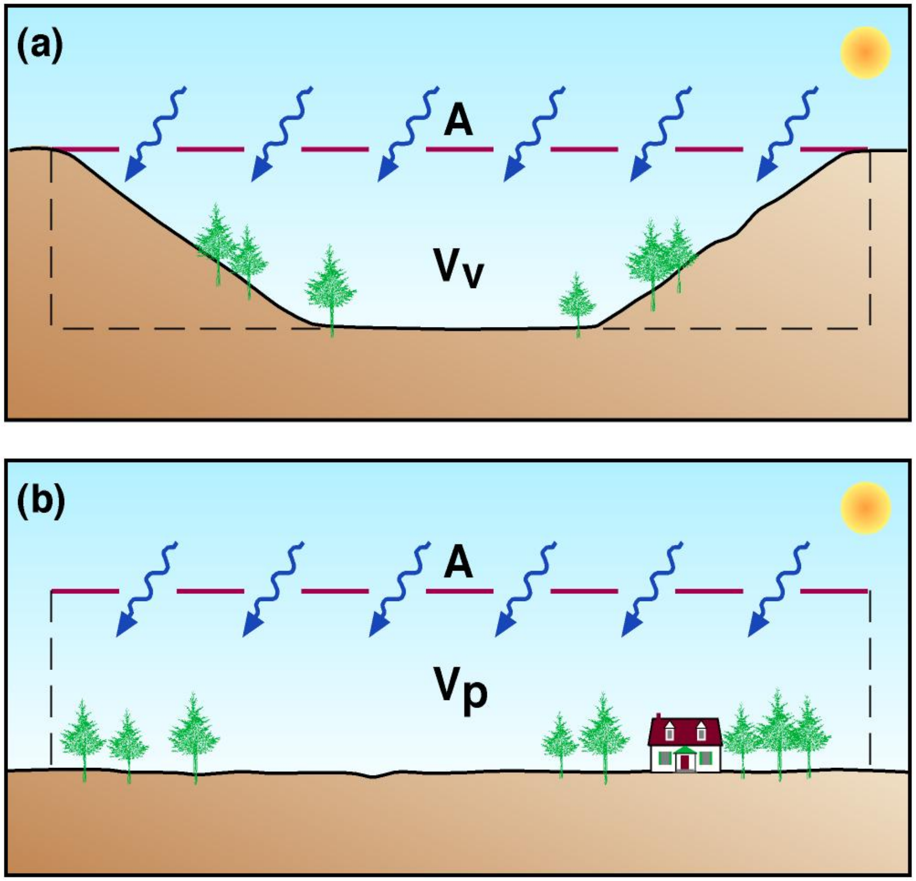
- Horizontal cross section? – Same insolation!
- Radiation heats ground surface; heat is redistributed to the air above
- Equal amount of energy is applied to a smaller mass of air within valley.
- Larger temperature response in the smaller volume.
- Similarly, at night loss of heat by radiation is applied to the smaller volume.
- Topographic amplification factor, TAF; area-height relationship).



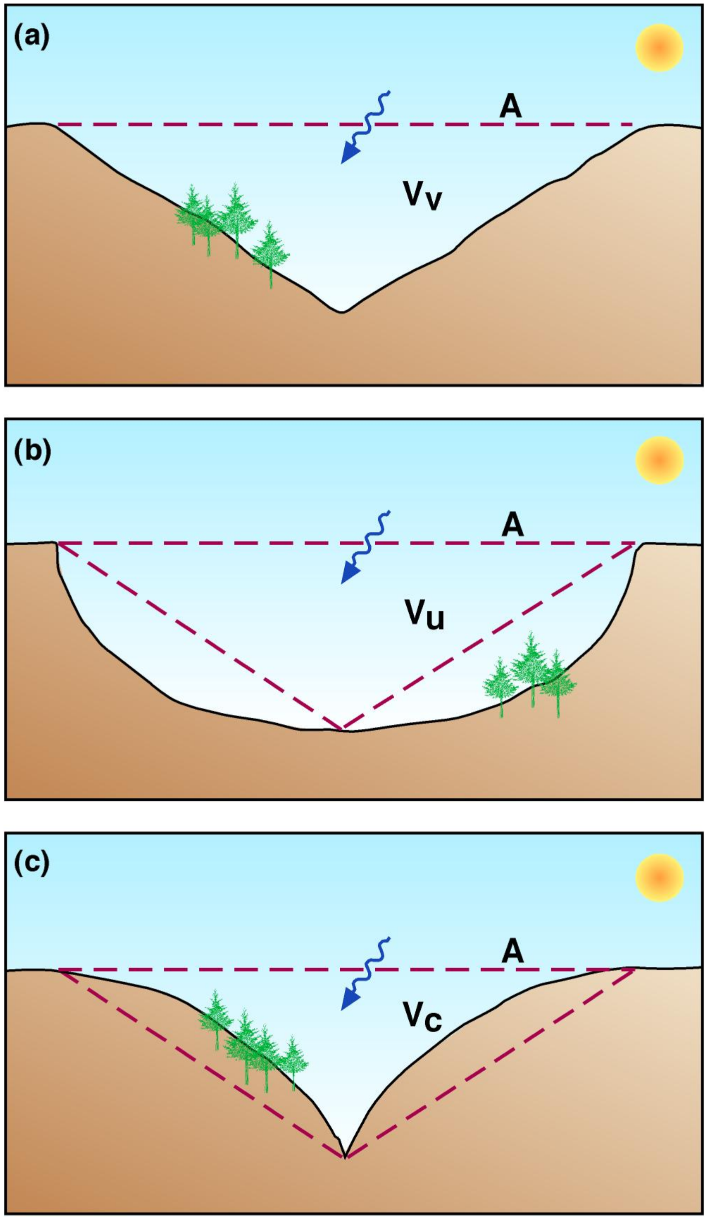
What causes the temperature range difference – Plain vs. Valley?

Valleys: Efficient distribution of heat!

- 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.

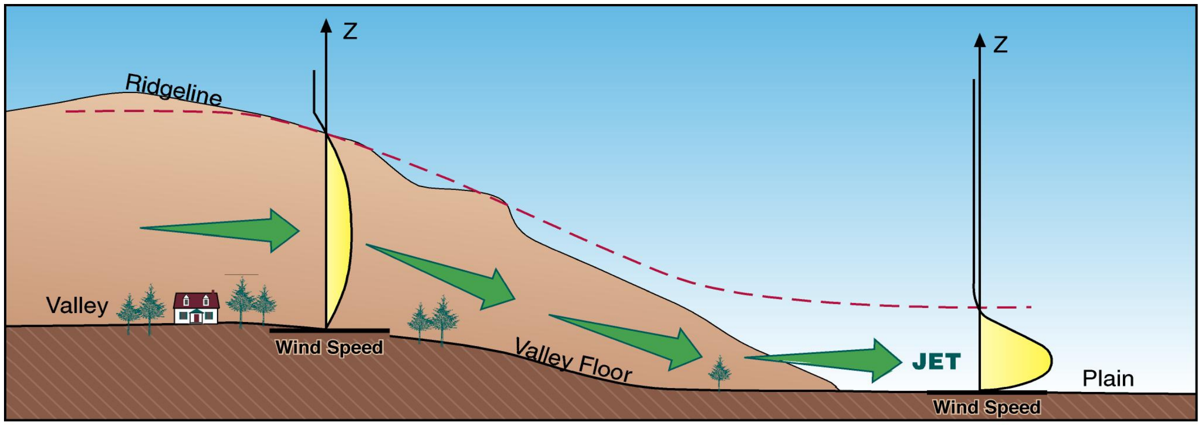


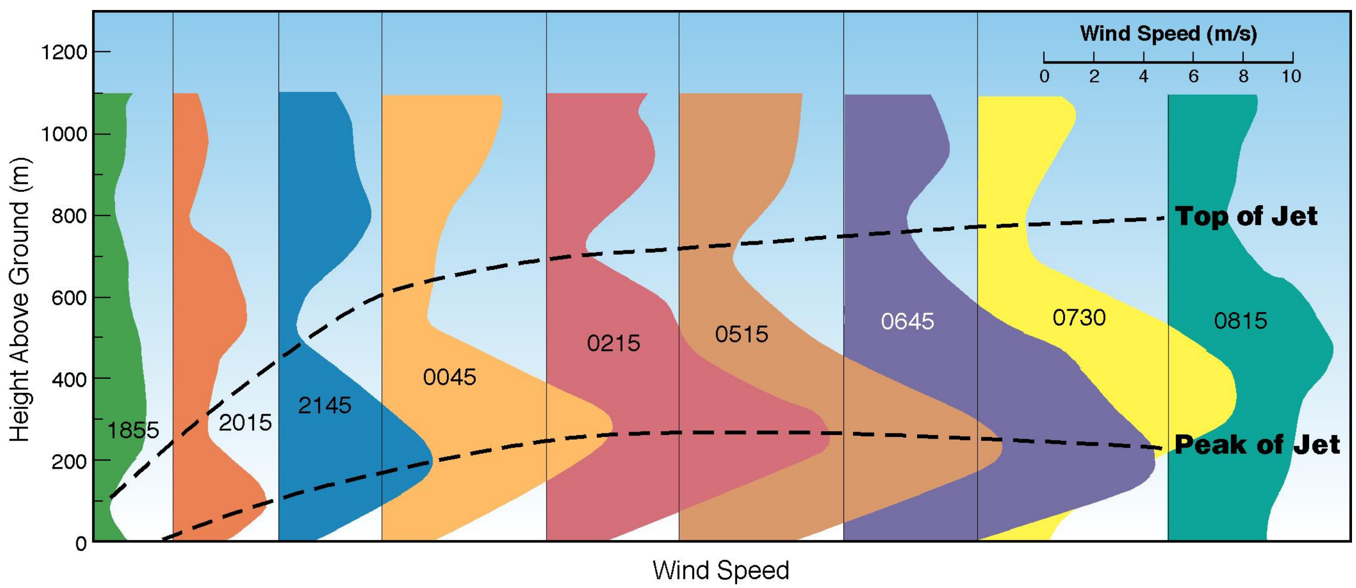
Sheltering: Valley air is somewhat protected from gradient winds by surrounding topography. Heated air by day and cooled air by night is stored up within the valley.



- 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.
- TAF is more for a convex-sidewall valley.

The valley exit jet





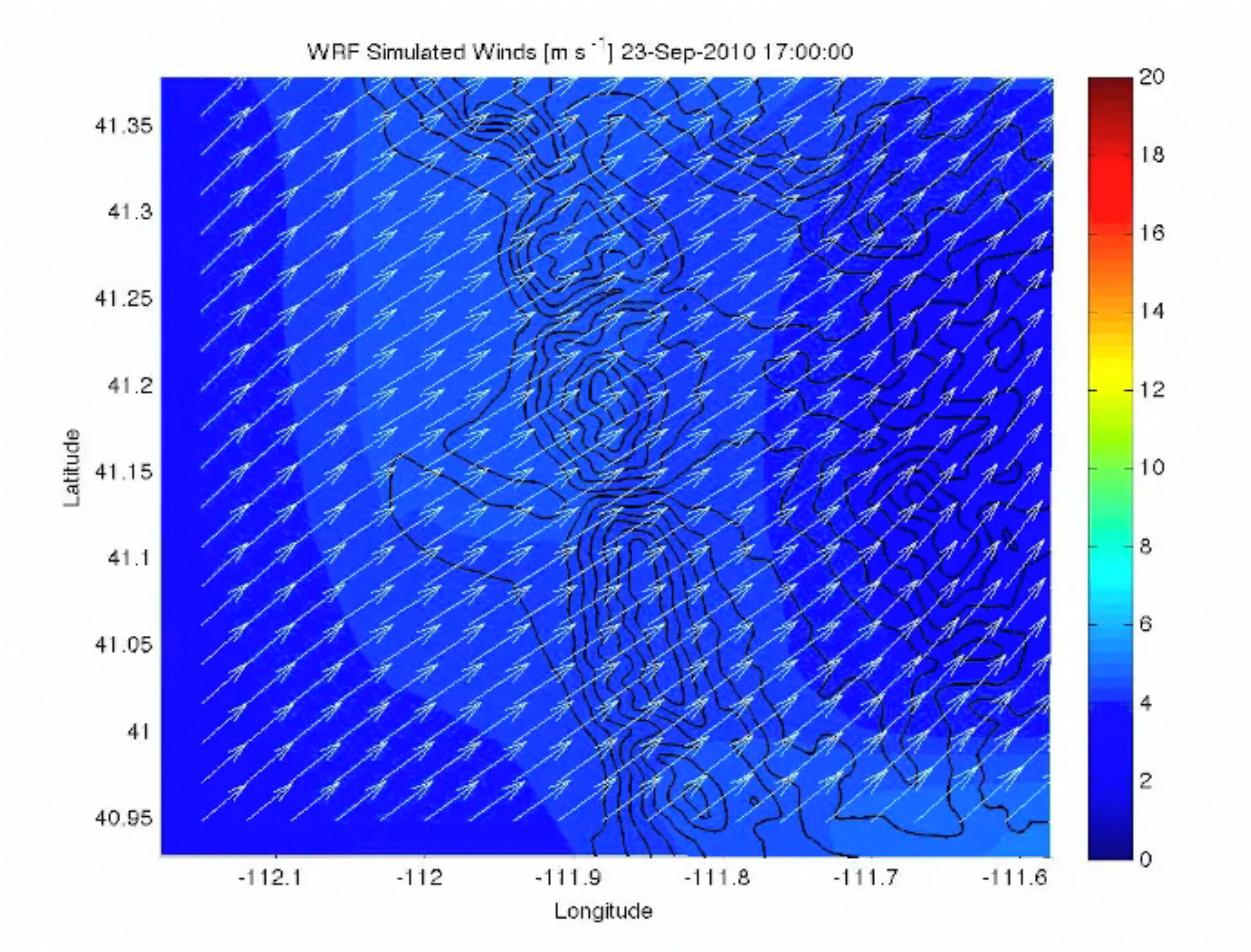
Adapted from Pamperin & Stilke (1985)

Exit jet at Weber Canyon, UT

Exit jet at Weber Canyon, UT

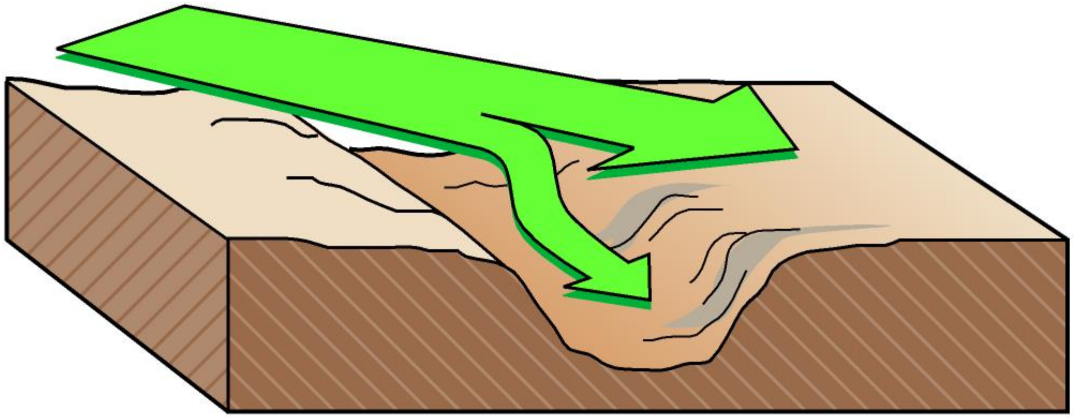
Chrust et al. 2013

WRF model results, Weber Canyon, UT

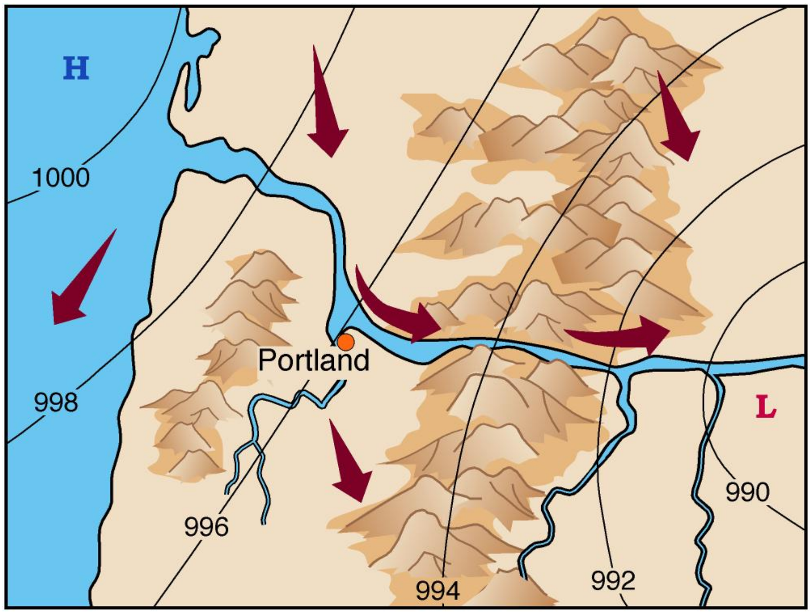


Chrust et al. 2013

Channeling (see next lecture)



Forced Channeling



Pressure Driven Channeling

Selected valley flow references

1989 special ASCOT issue of *JAM*
2000 special *Theor. Appli. Climatol.* issue (Ed.: Ruffieux)
2003 special MAP issue of *QJRMS*:
See references in other sections (e.g., Riviera Valley modeling in Turbulence section)

Neff and Ruffieux (1990) Radiative flux divergence and crosswinds.
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Bader & McKee (1992) Complex terrain BL evolution.
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Kossmann & Sturman (2003) Pressure driven channeling in curved valleys.
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Rucker et al. (2008) Along-valley structure of daytime flows in Wipp Valley.
Etc. (**see complete list of references**)

Bob Banta

Magdalena Rucker

Lisa Darby

References: Turbulence

Doran et al. (1989) Brush Creek Valley turbulence measurements.
Andretta et al. (2001, 2002) Momentum flux, flux measurements.
Rotach et al. (2003, 2004, 2008) SEB closure & turbulence.
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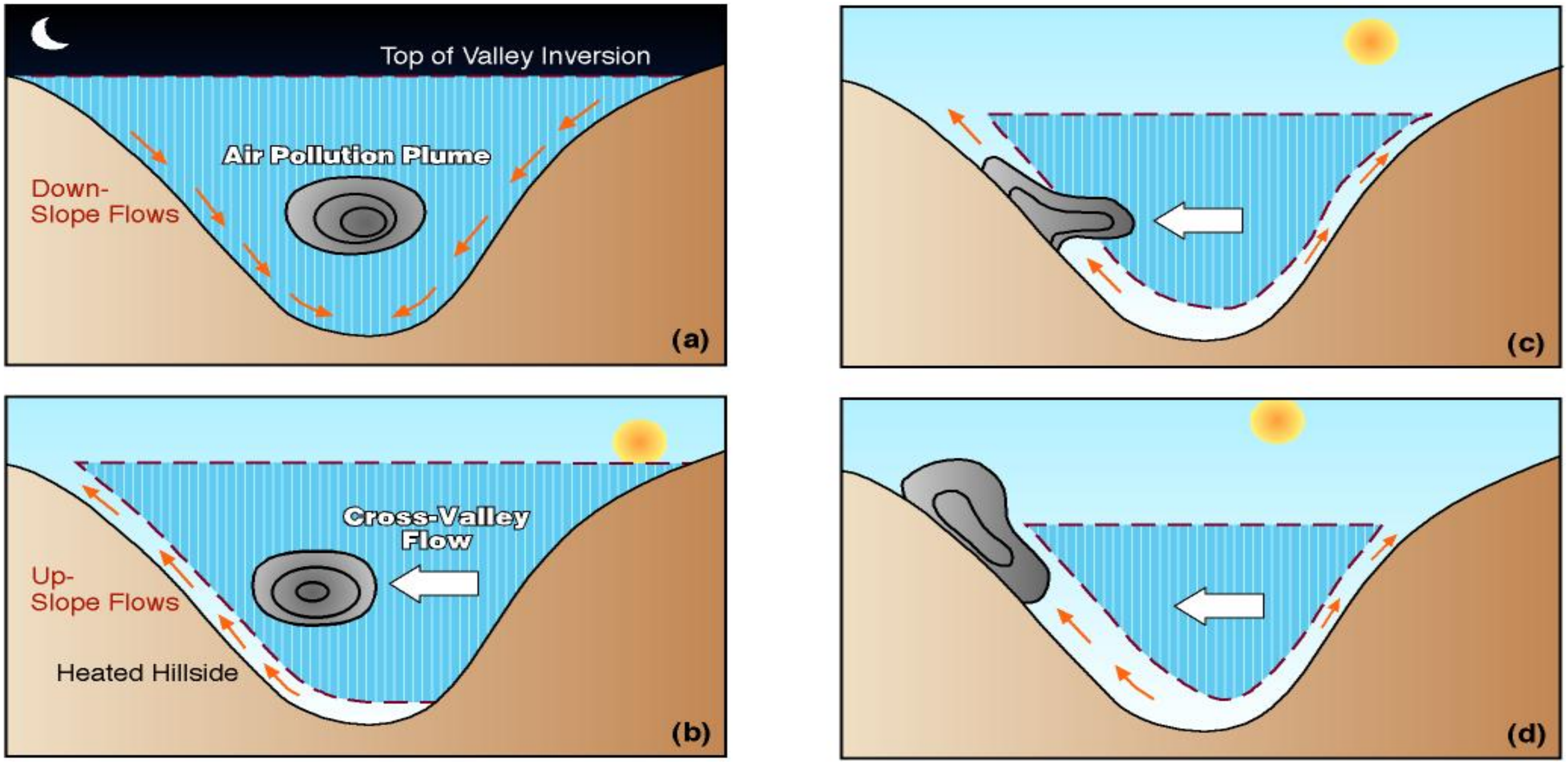
Tina Chow

Andreas Weigel

Mathias Rotach

Cross-Valley Wind System

Bugaboo Spire © Adam Naisbitt



Adapted from Bader & Whiteman (1989)

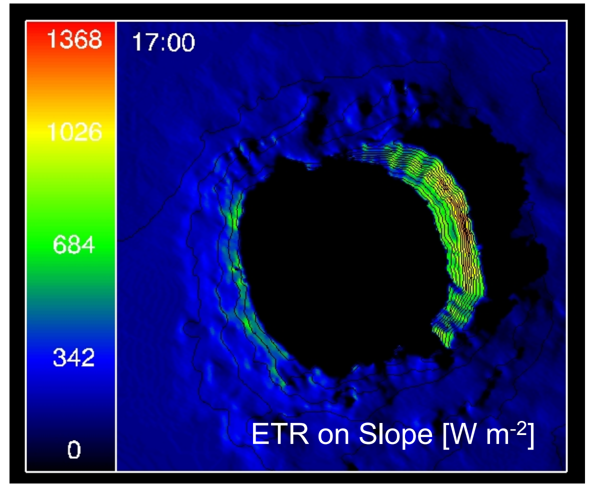
Manuela Lehner

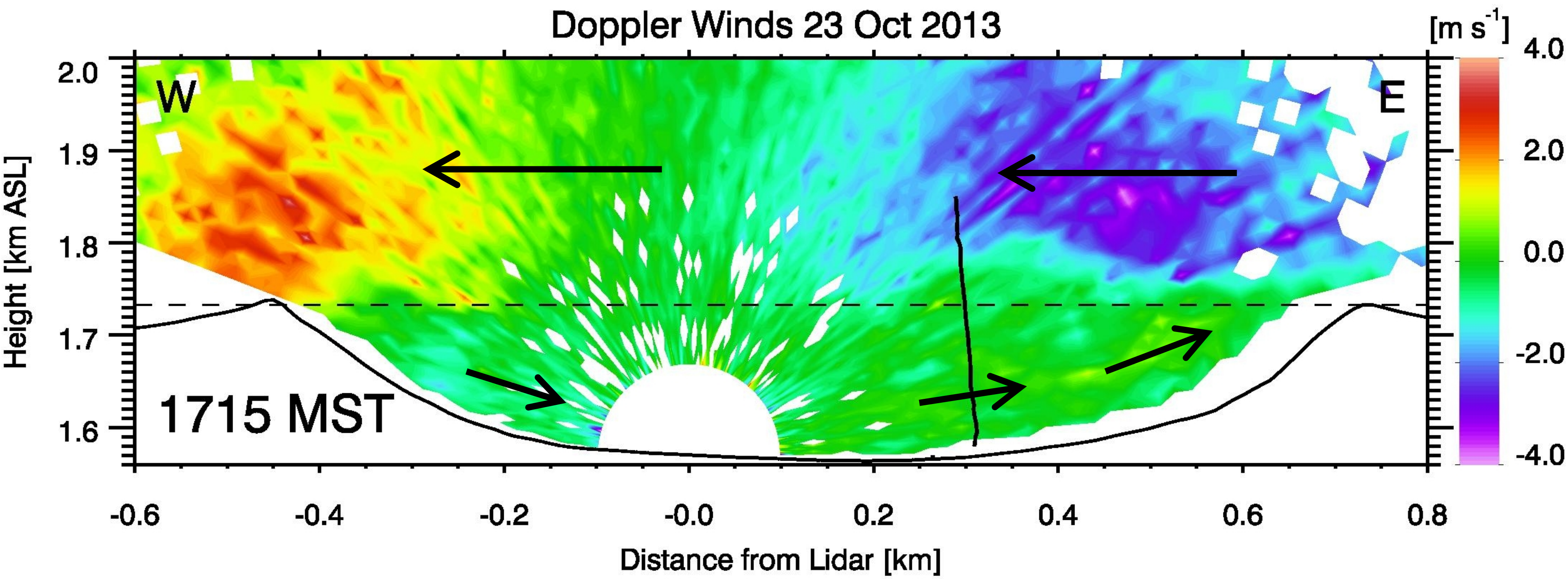
Lehner and Whiteman 2012, 2014
Lehner et al. 2012
Lehner and Gohm 2010

Cross-Basin Circulations

Evening ~17:00 MST

Insolation on west-facing inner crater sidewall crater leads to flow from west to east within the crater basin.



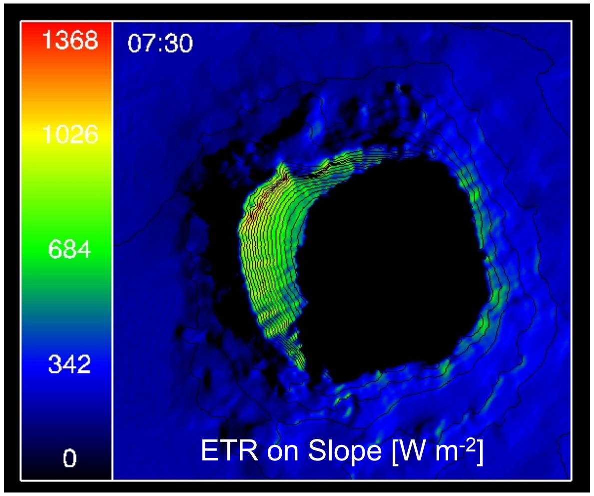


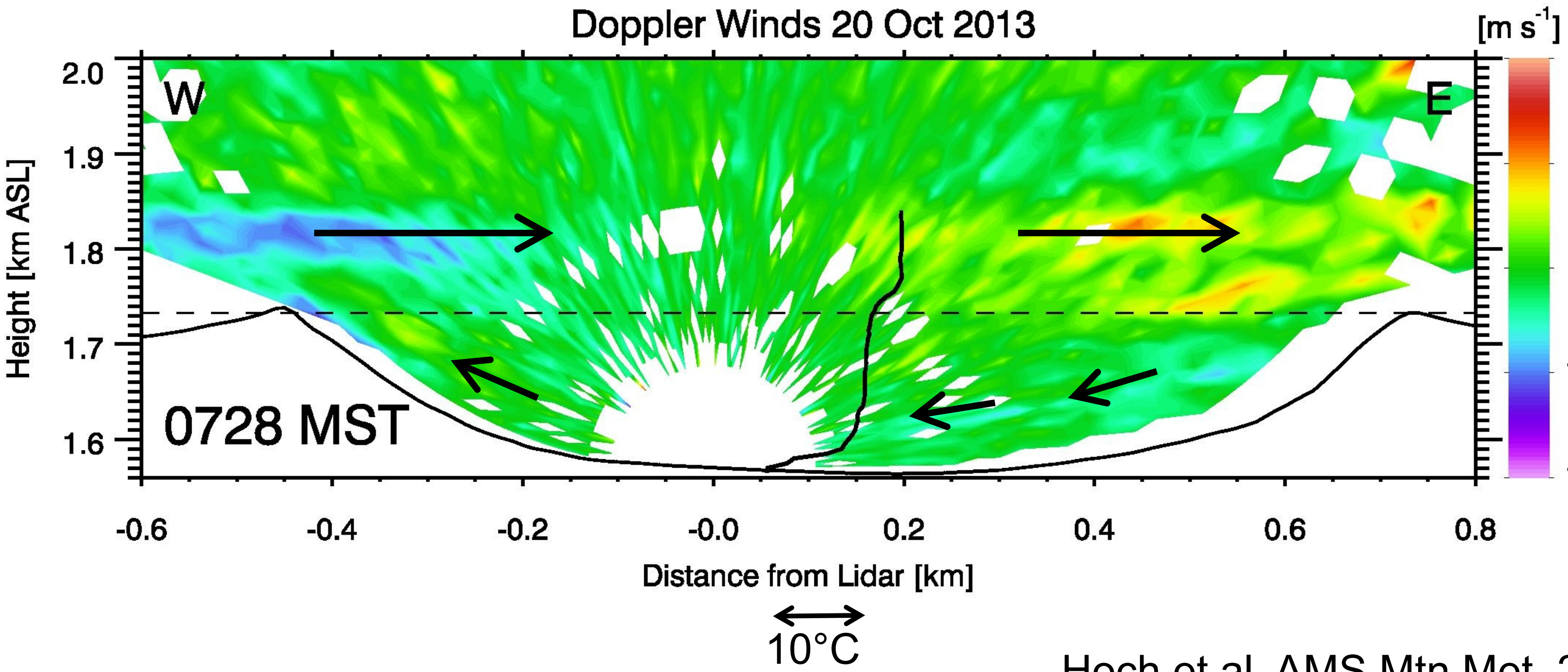
Hoch et al. AMS Mtn Met, 2014

Cross-Basin Circulations

Morning ~07:30 MST

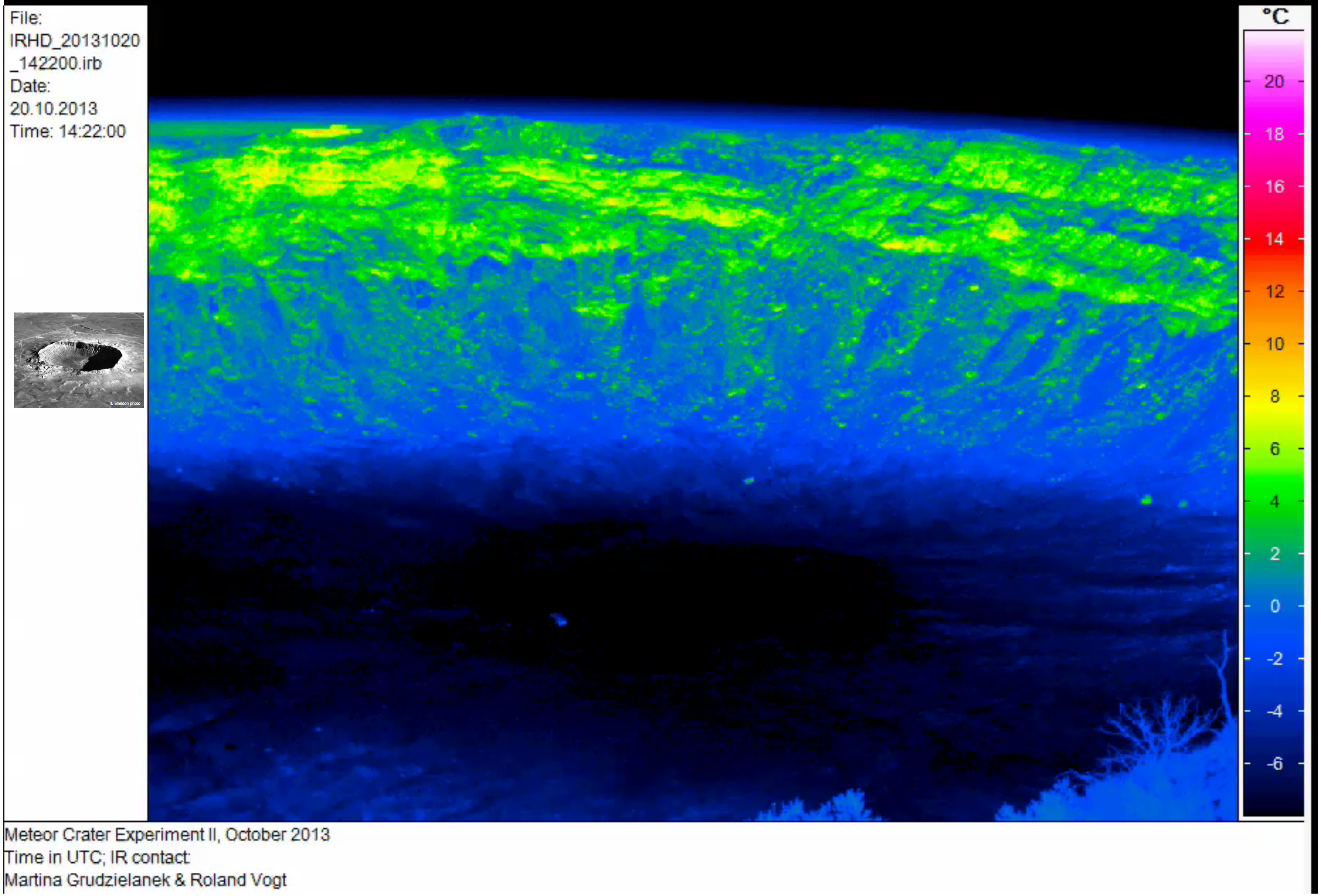
Insolation on east-facing inner crater sidewall crater leads to flow from east to west within the crater basin.





Hoch et al. AMS Mtn Met, 2014

METCRAX-II : Martina Grudzielanek, Iris Feigenwinter, and Roland Vogt



The Diurnal Cycle of Mountain Winds

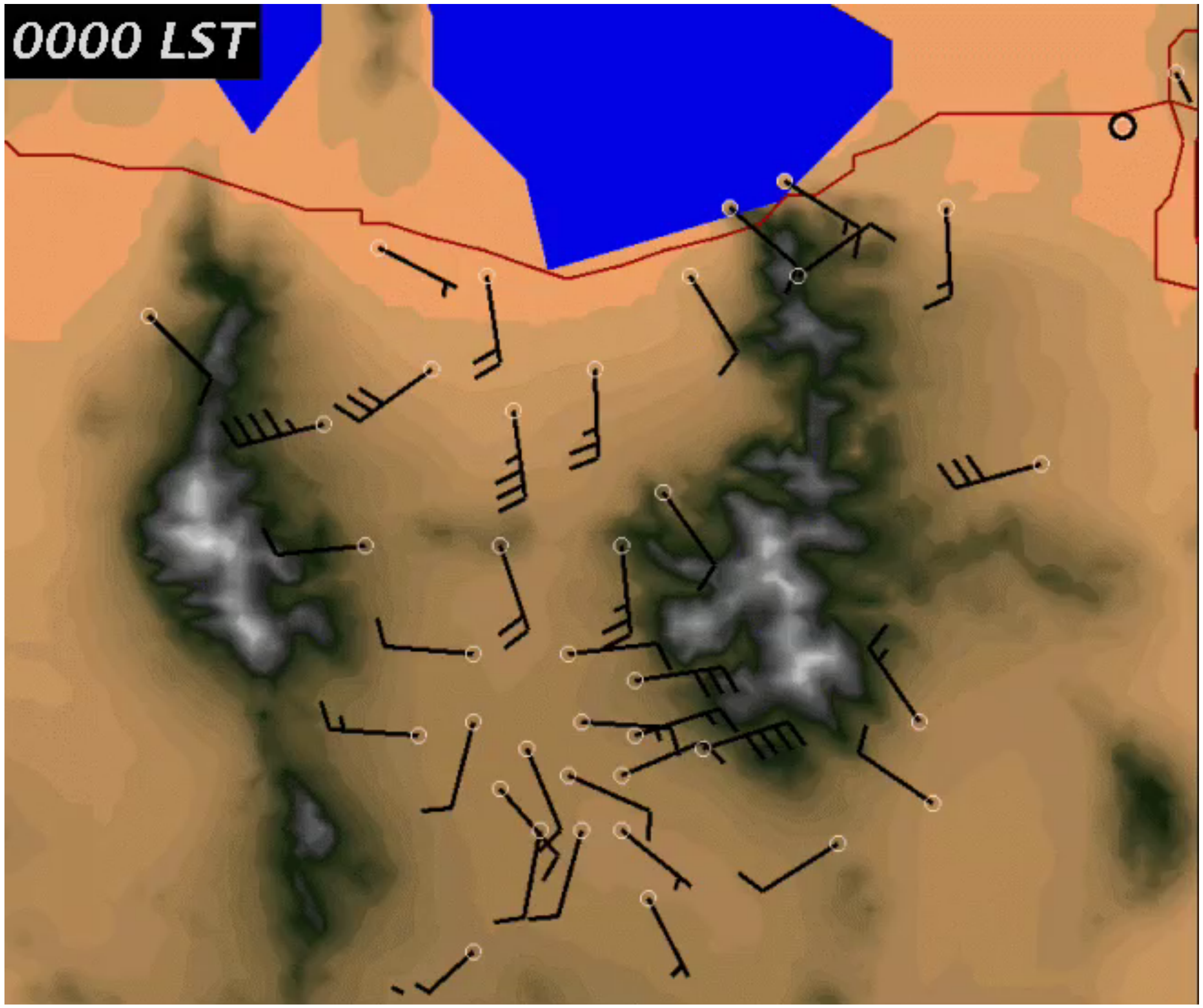
Example: Rush Valley winds

Jebb Stewart

Fletch=1 m/s

Tooele Valley

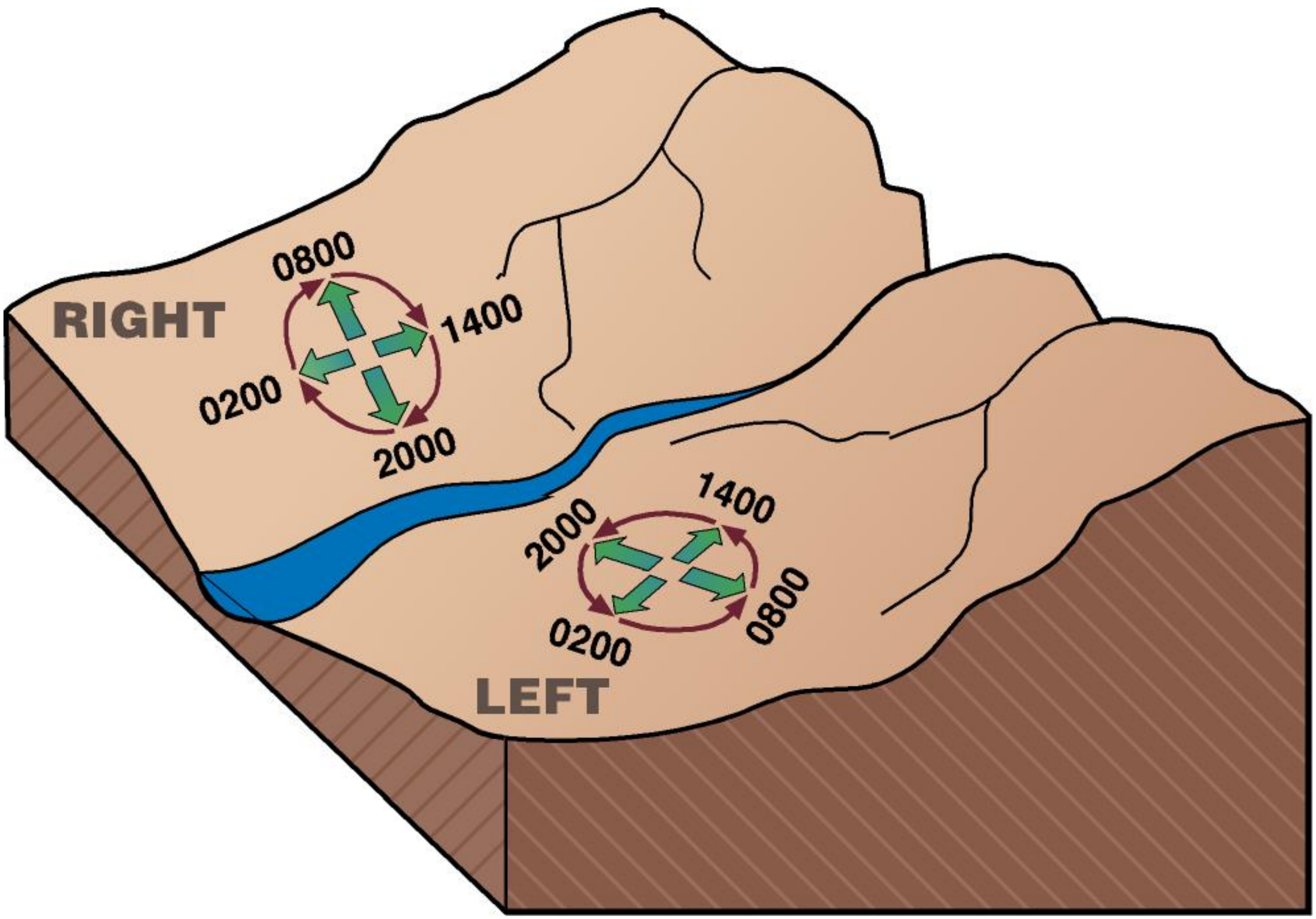
Rush Valley



Salt Lake Valley

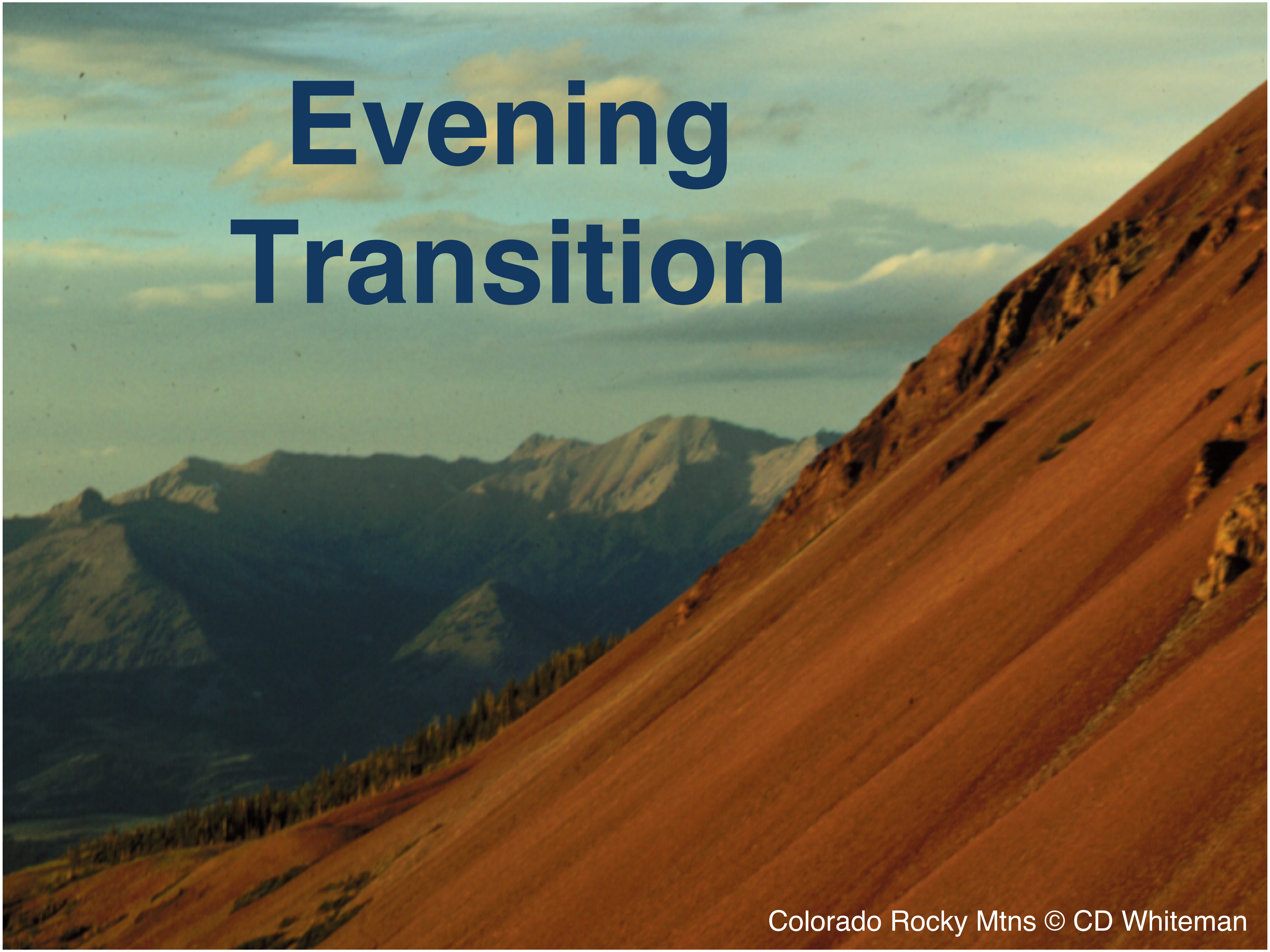
adapted from Stewart et al. (2002)

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



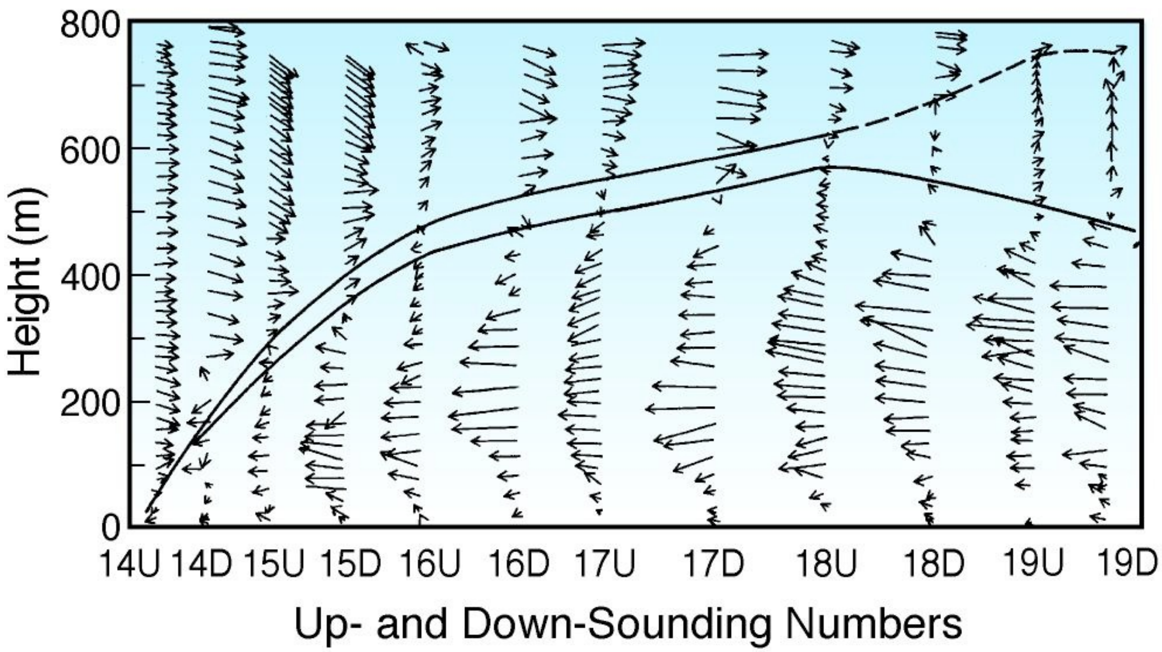
Adapted from Hawkes (1947)

Evening Transition

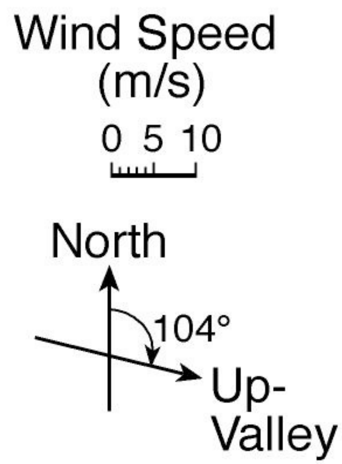


Colorado Rocky Mtns © CD Whiteman

The evening transition winds



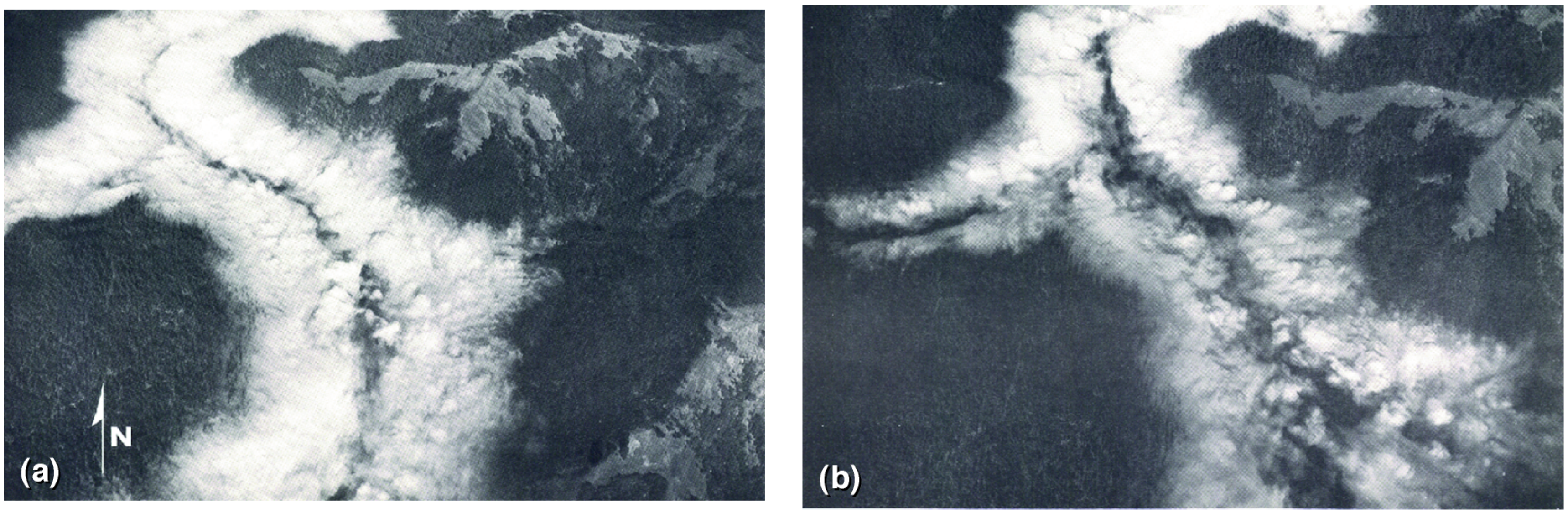
#	Time (MST)	#	Time (MST)
14U	1702-1720	17U	1914-1931
14D	1720-1736	17D	1931-1945
15U	1746-1803	18U	2000-2018
15D	1803-1822	18D	2018-2033
16U	1831-1847	19U	2043-2102
16D	1847-1901	19D	2102-2116



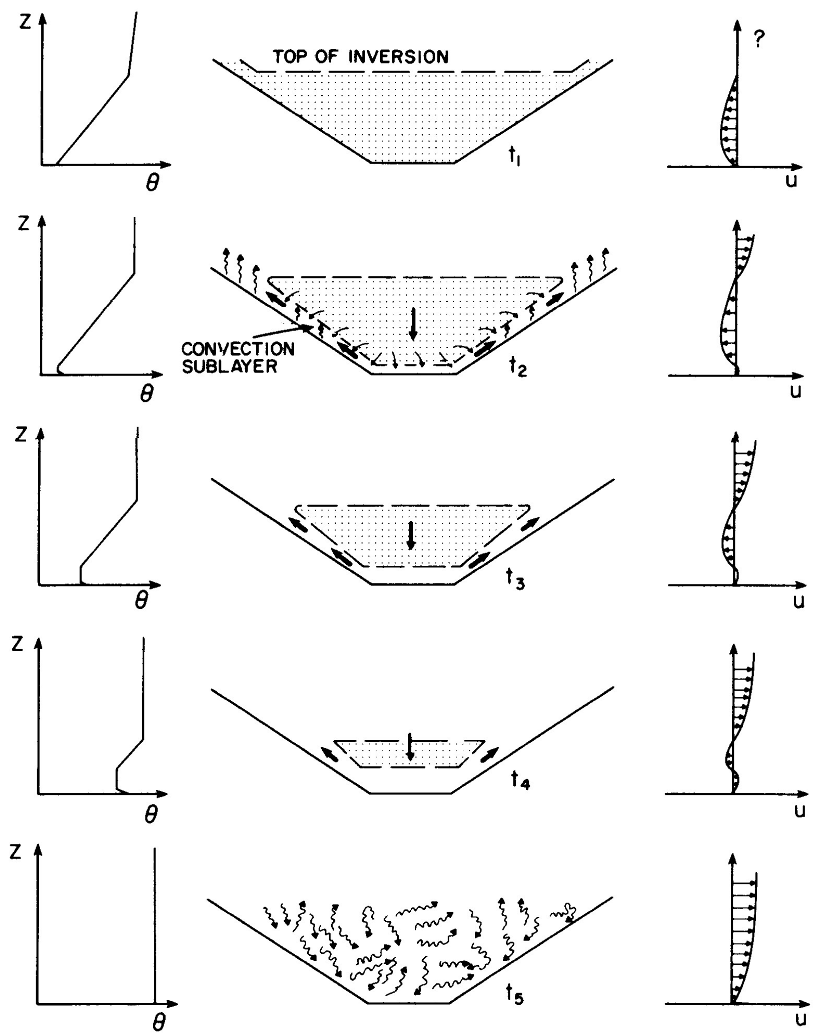
Whiteman (1986)


Morning
Transition
Eastern Alps © Georg Pistotnik

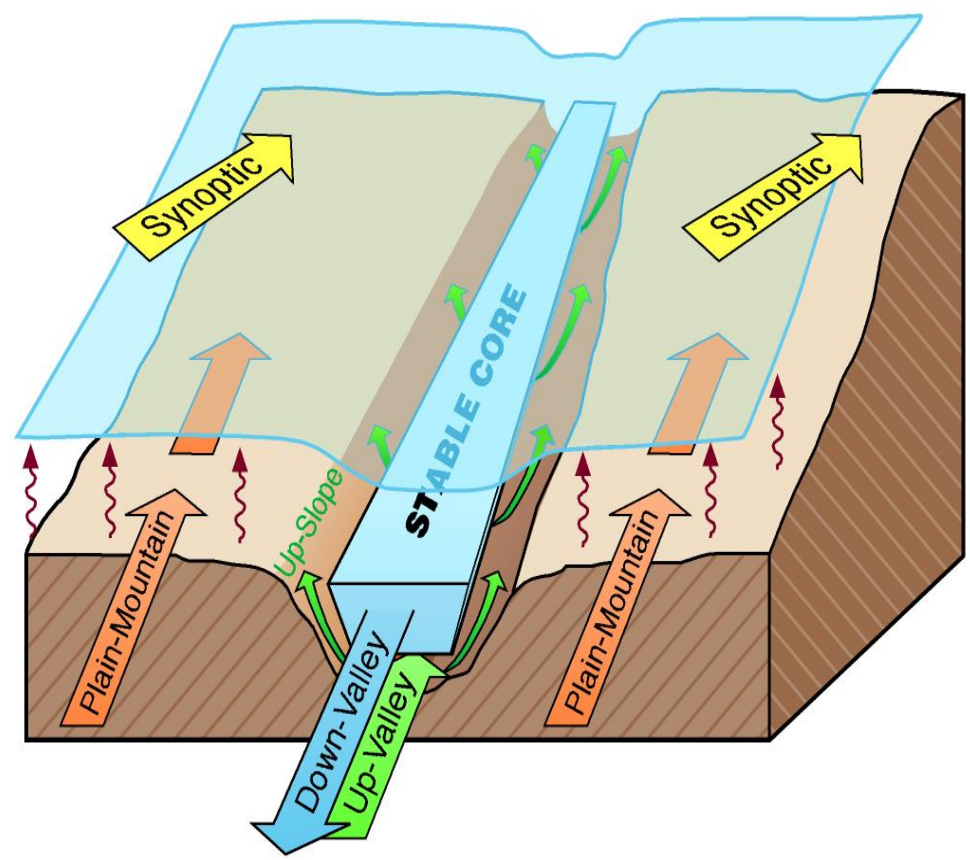
Morning breakup of stratus, Redwood Valley, CA



Hindman (1973)



Whiteman (1980)



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

Subsidence!

Evening transition references

De Wekker and Whiteman (2006) Time scale of BL cooling in valleys basins and plains.
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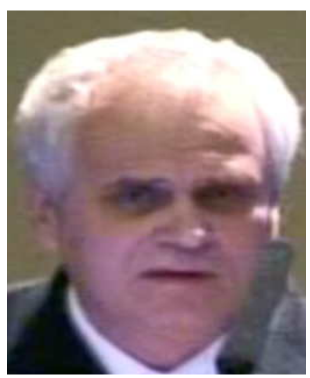
Rotach & Zardi (2007) Summary of MAP/Rivieras results, including non B-U.
Princevac & Fernando (2008) Water tank simulations of inversion B-U.

Sandrine Anquetin



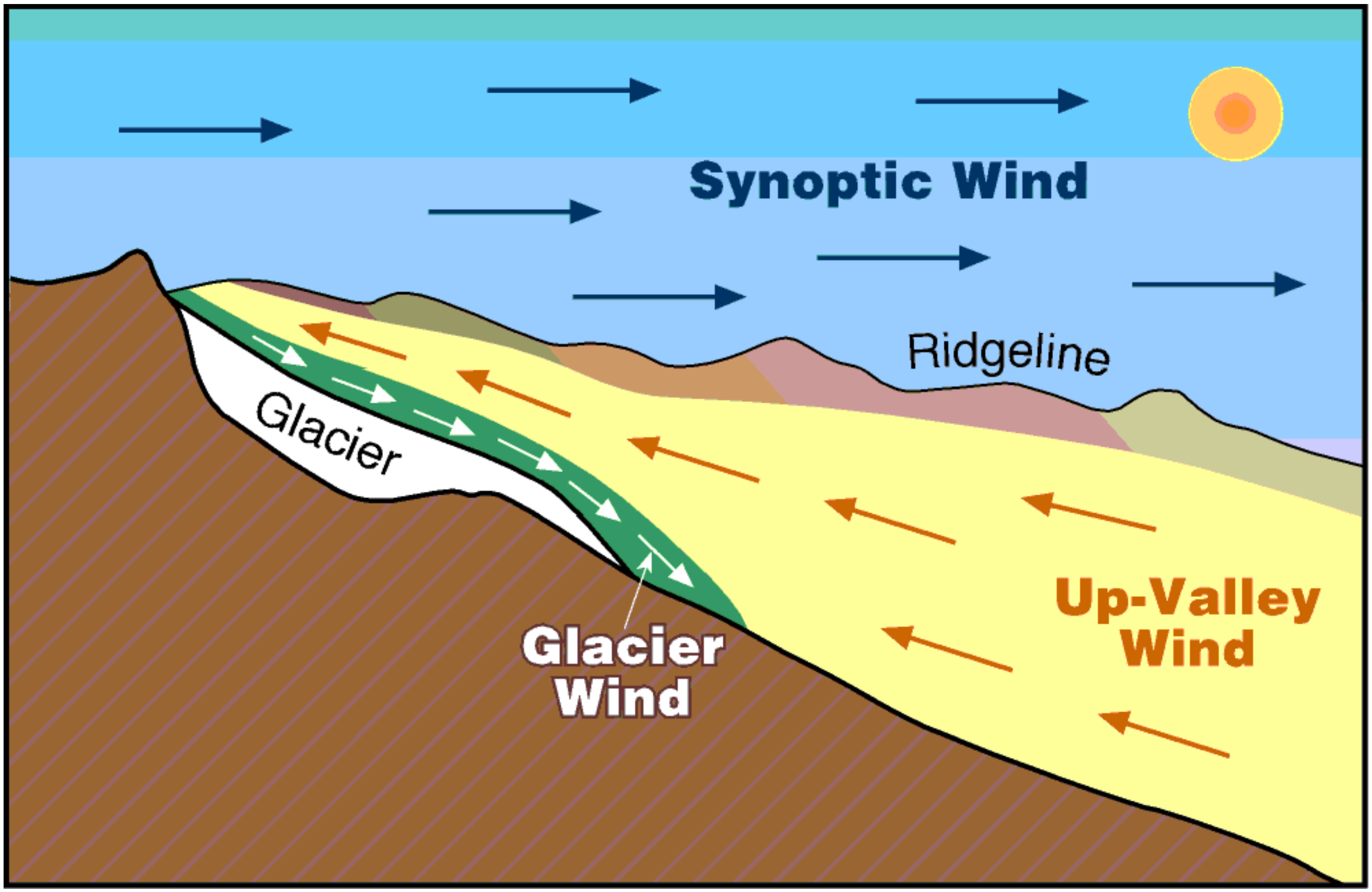
Zoumakis

Tom McKee

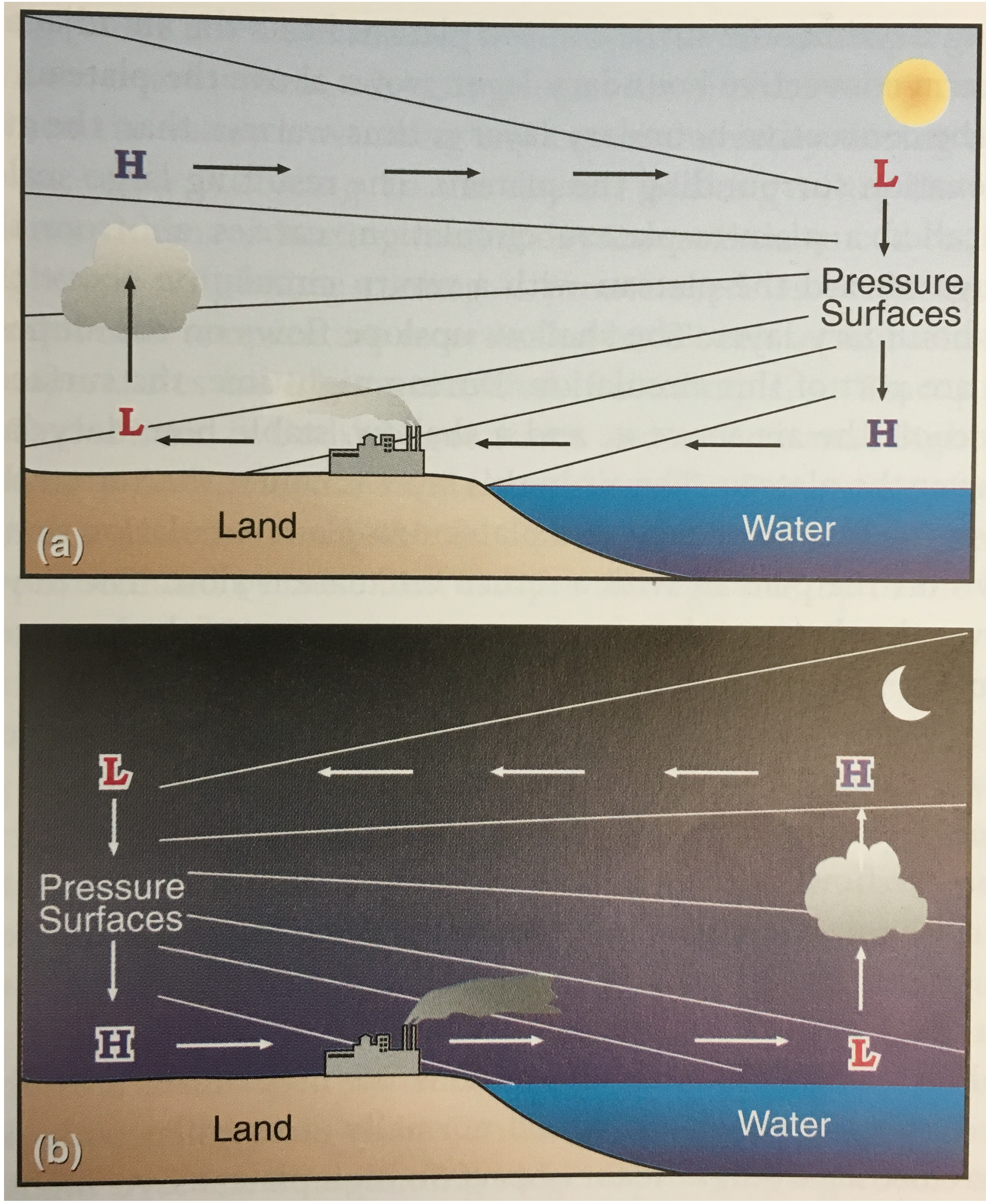
Marko Princevac


Glacier Wind
Pigeon Spire, Bugaboo Mtns © Adam Naisbitt

Glacier wind



Sea and Lake Breeze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Land
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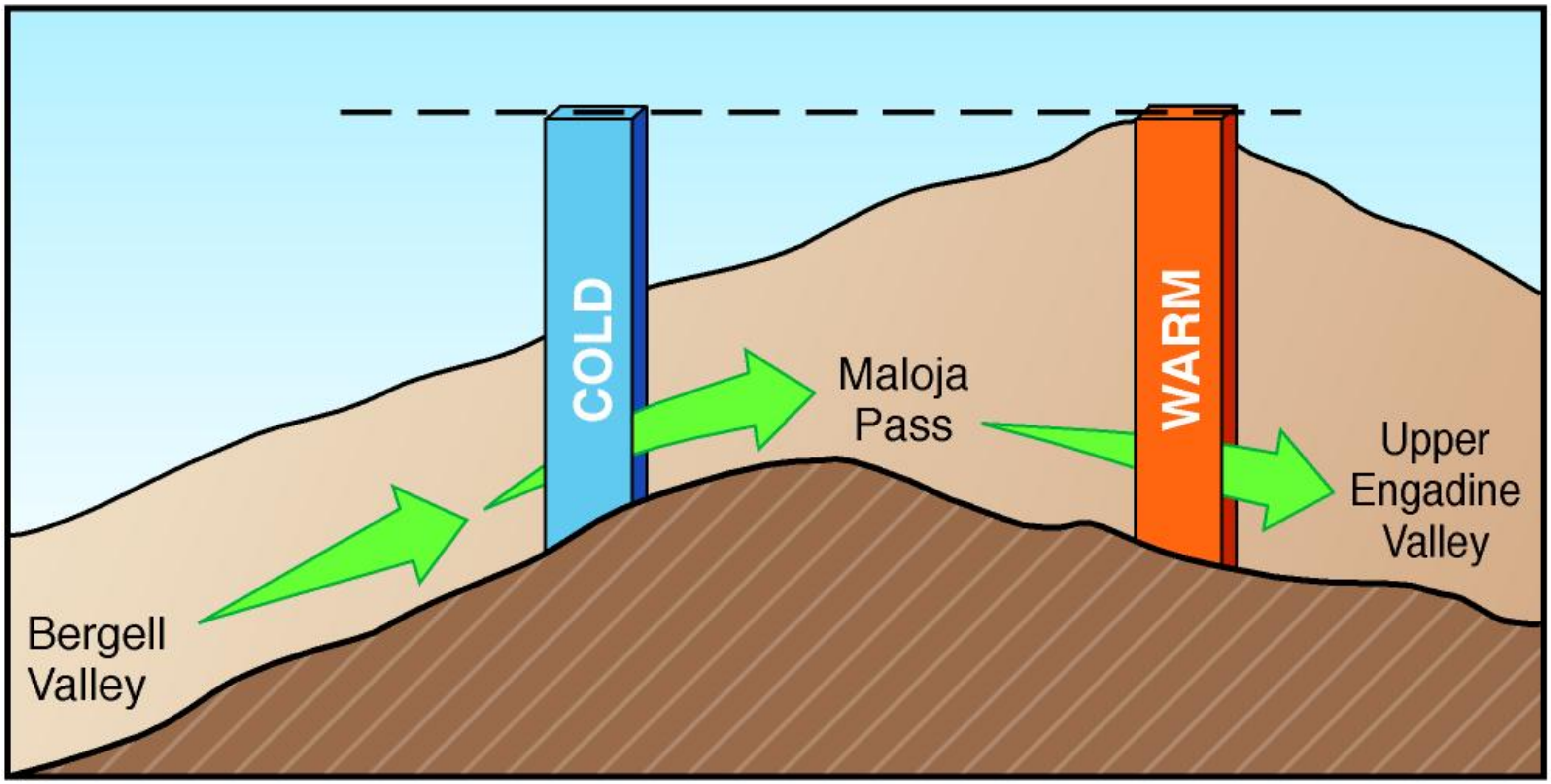
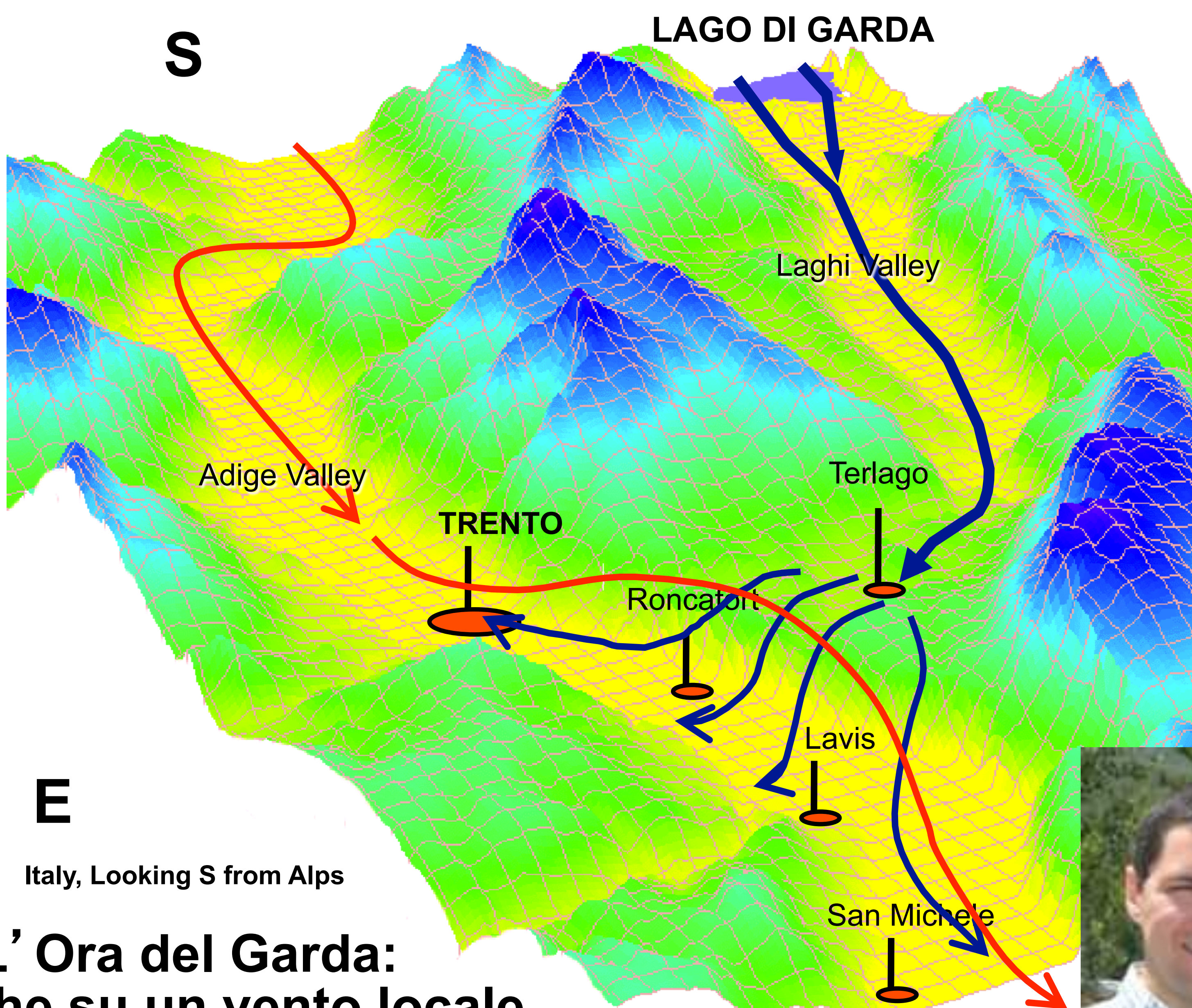
(b)


Special Wind
System

Odd Wind Systems - Maloja Wind





Italy, Looking S from Alps

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

Dino Zardi


Summary
Torres del Paine © Sigrid & Ron Smith

- Summarized mountain-plain, slope, and valley circulations, their interactions, & their aberrations. We have largely omitted the effects of larger scale flows on them.
- There are many meteorological applications: forecasting of diurnal winds, cold-air pools, CBL heights, wind break-ins, air pollution transport and dispersion etc.
- The talk has been descriptive and broad with many missing topics, but there are many quantitative meteorological, climatological and numerical modeling approaches that can be applied to individual problems..

Past and Future

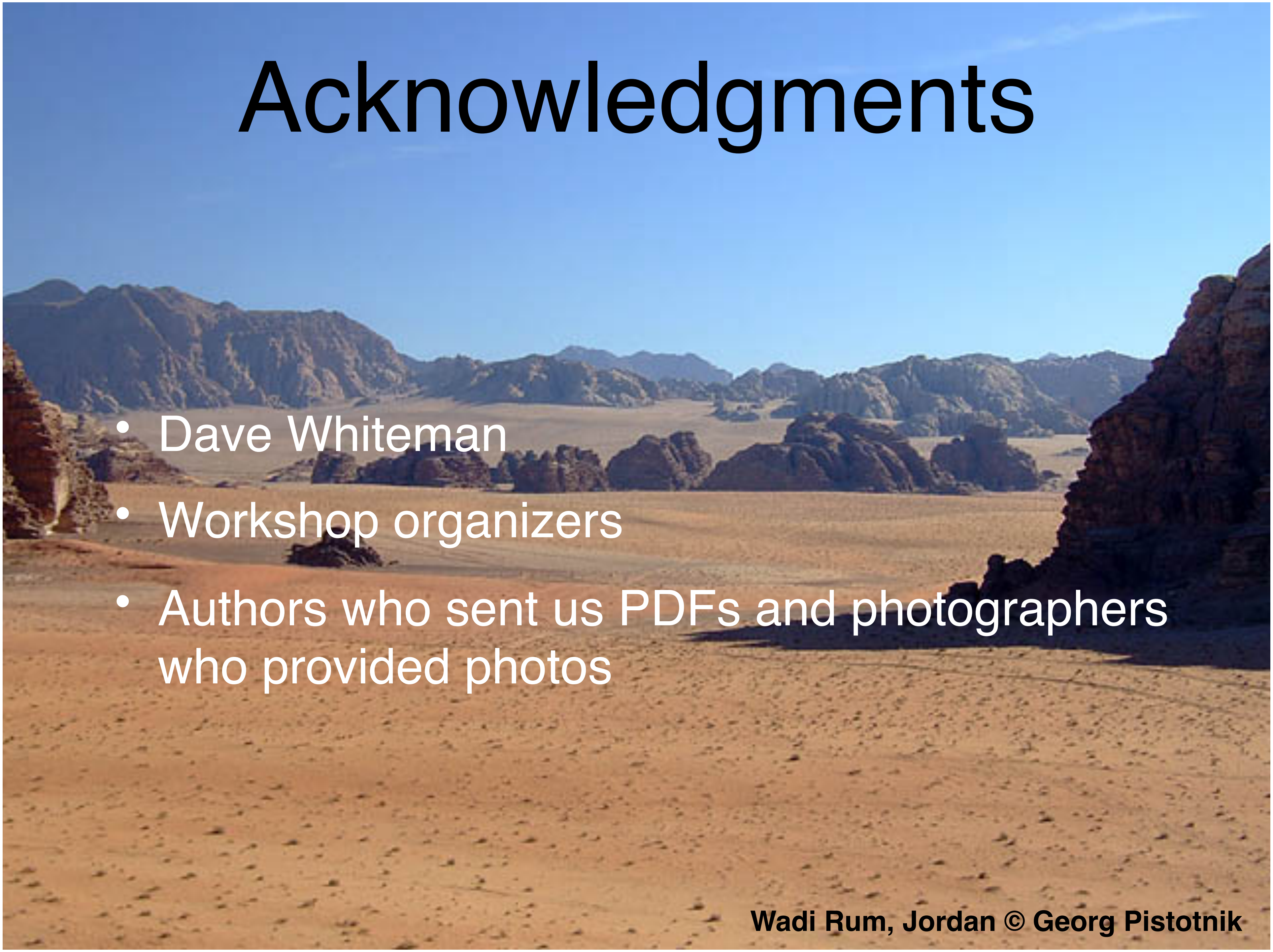
- Much research progress in last 20 years: numerical modeling, turbulence, basin meteorology, plateau meteorology.

- More work needed: applications, radiative transfer, turbulence, regional heat & moisture transfer mechanisms, measurements and processing of turbulence data, upslope flows, mountain-plain circulation, climatology, surface and CB layer parameterizations, LES, observations to test models, new instruments.


The End
Flagstaff wx radar © Michael Staudenmaier

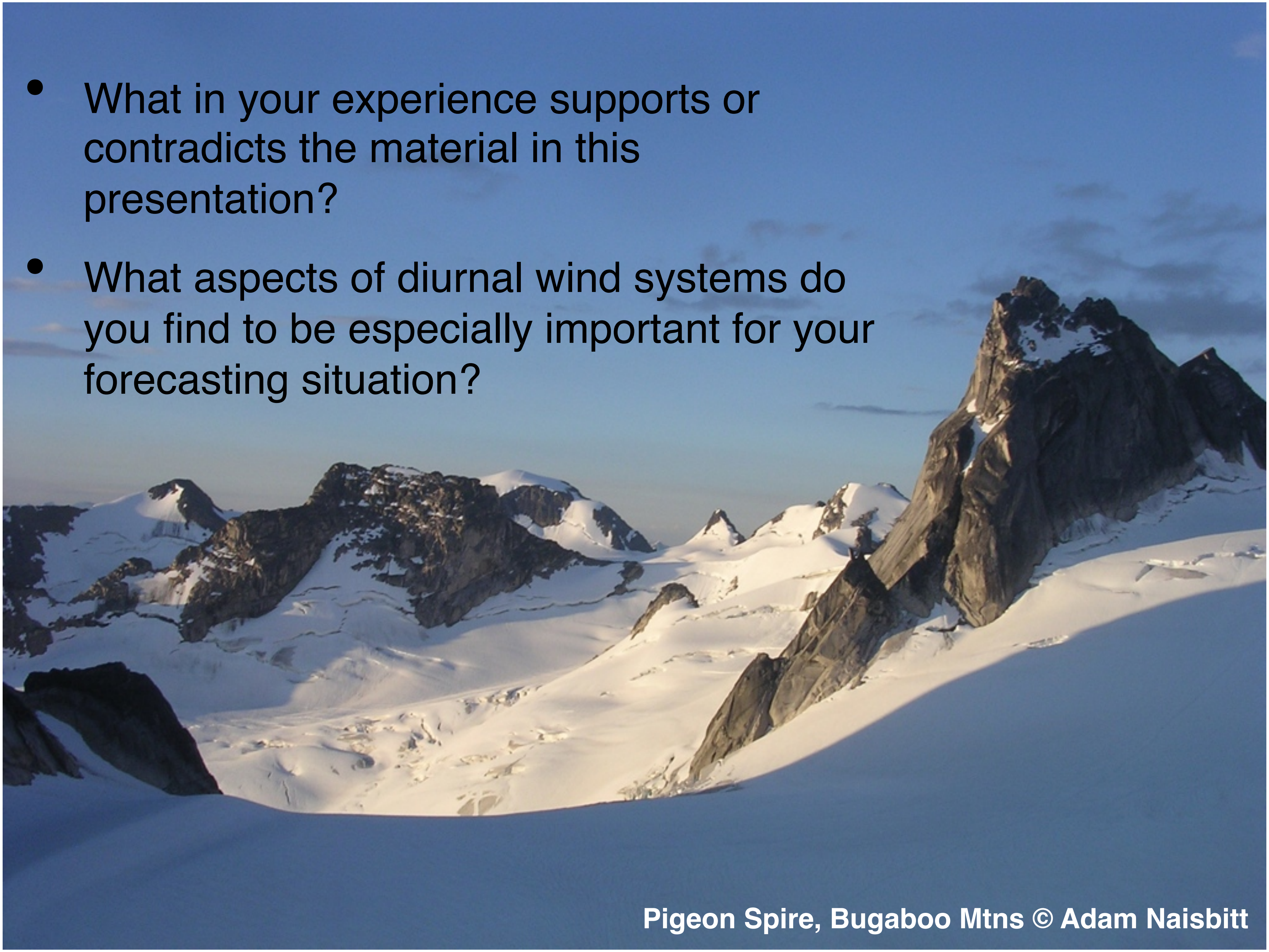
Acknowledgments

- Dave Whiteman
- Workshop organizers
- Authors who sent us PDFs and photographers who provided photos



Wadi Rum, Jordan © Georg Pistotnik

- What in your experience supports or contradicts the material in this presentation?
- What aspects of diurnal wind systems do you find to be especially important for your forecasting situation?



Pigeon Spire, Bugaboo Mtns © Adam Naisbitt