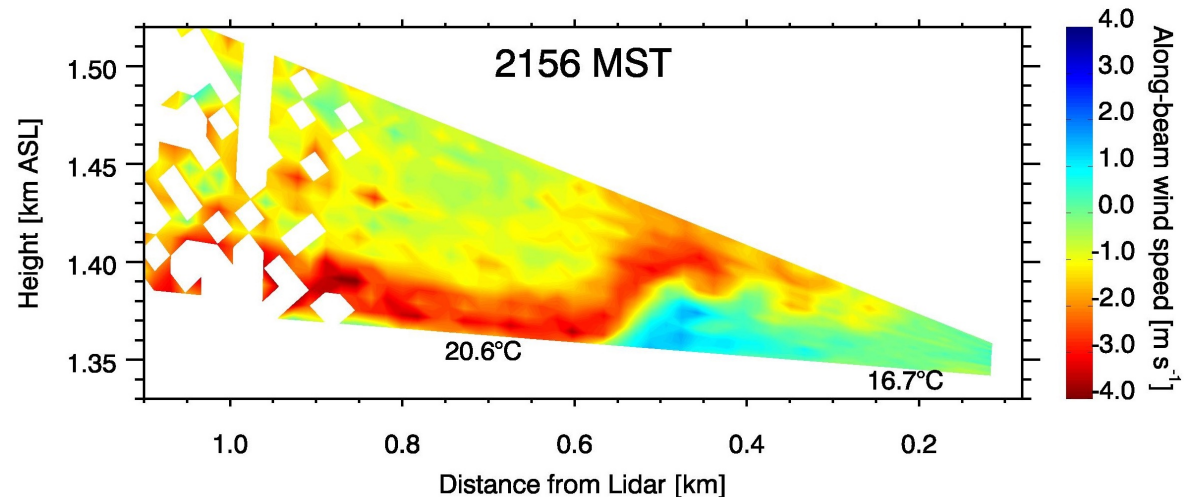
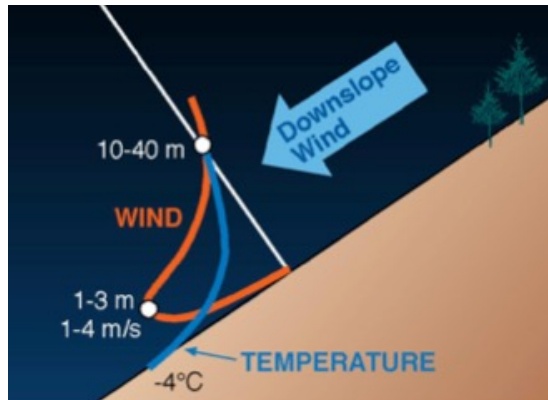


# Thermally Driven Flows / Diurnal Mountain Winds

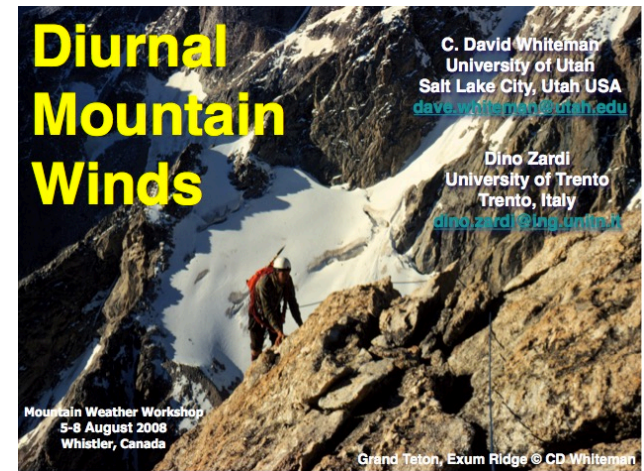
Sebastian W. Hoch

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

Summary

# Introduction



# Diurnal Mountain Winds

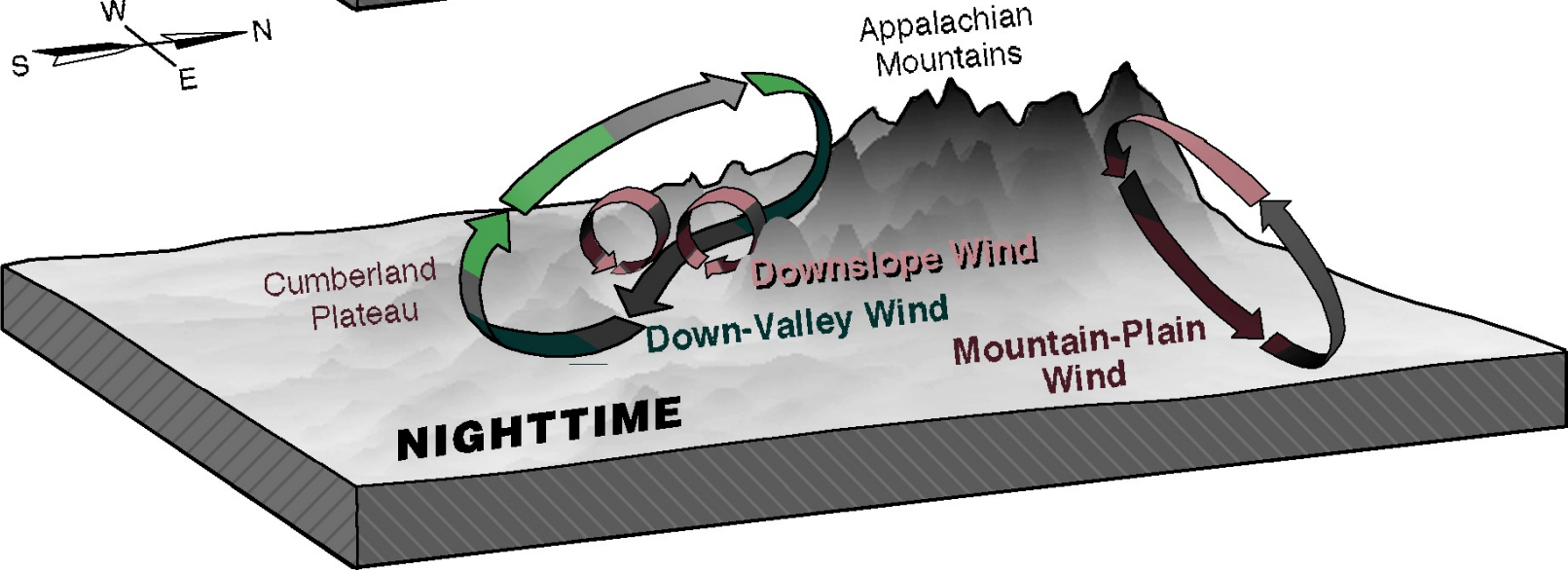
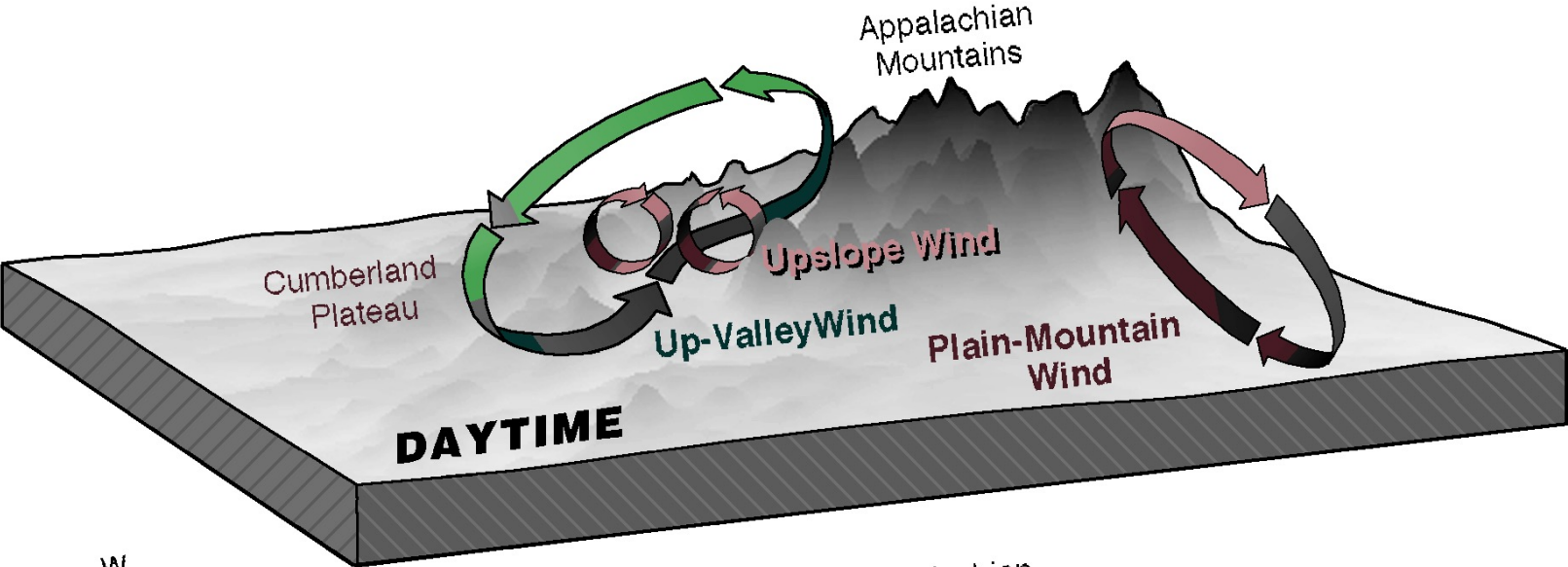
- Develop over complex terrain of all scales.
- Characterized by a reversal of wind direction twice per day.
- Strongest with clear skies when winds aloft are weak.
- As a rule, **upslope, up-valley** and flow from **plain to mountains** during **daytime** and in the **opposite** direction during **nighttime**.
- 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**.

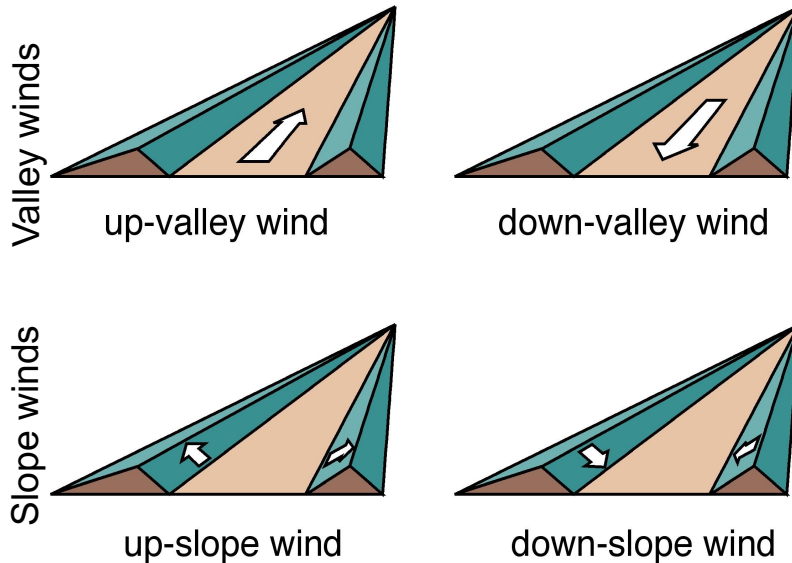
# Diurnal mountain winds



# 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



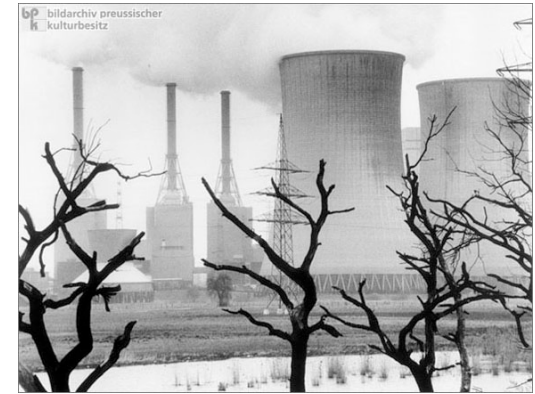
- valley wind = up-valley wind (day)
- mountain wind = down-valley wind (night)
- anabatic flow = up-slope wind (day)
- katabatic flow = down-slope wind (night)
- drainage flows = down-slope & down-valley
- cross-valley flow = toward heated hillside
- mountain-plain circulation
- anti-winds

Improper terminology is widespread in mountain meteorology literature!

The continuum concept ...



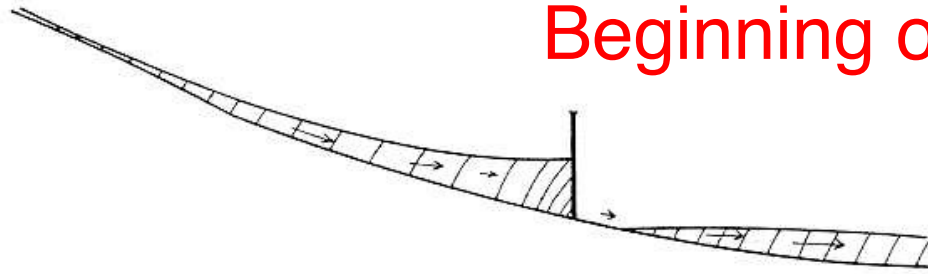
# Diurnal Mountain Winds



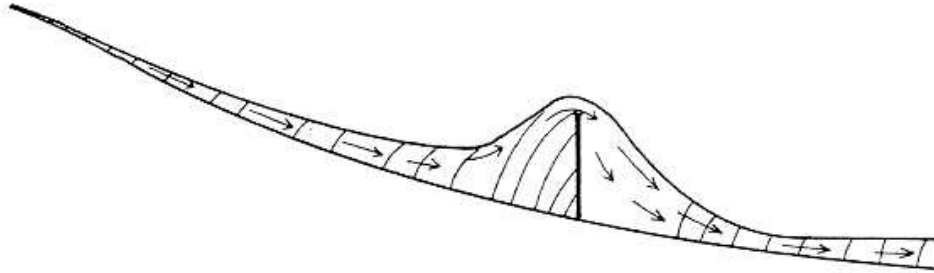
## Forecasting and Applications

- **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**

# Beginning of radiation night

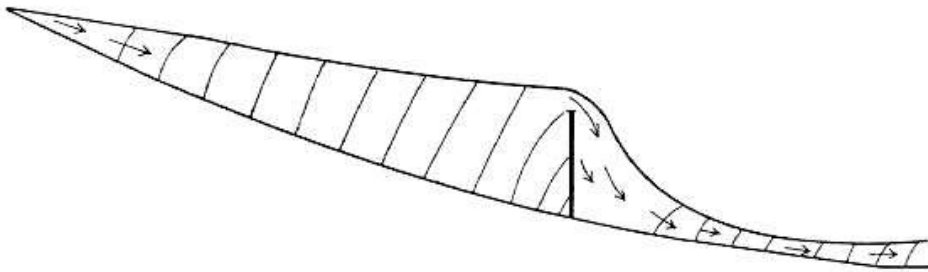


a) Expectation

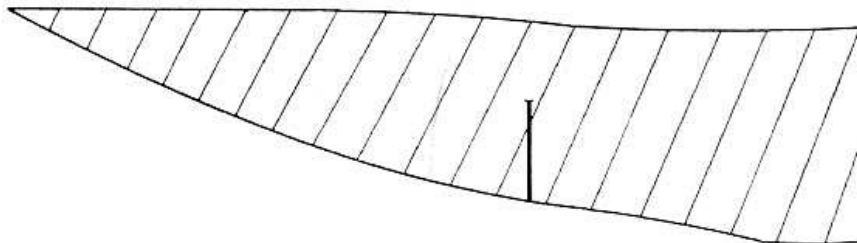


b) Reality

# Near sunrise




a) Expectation



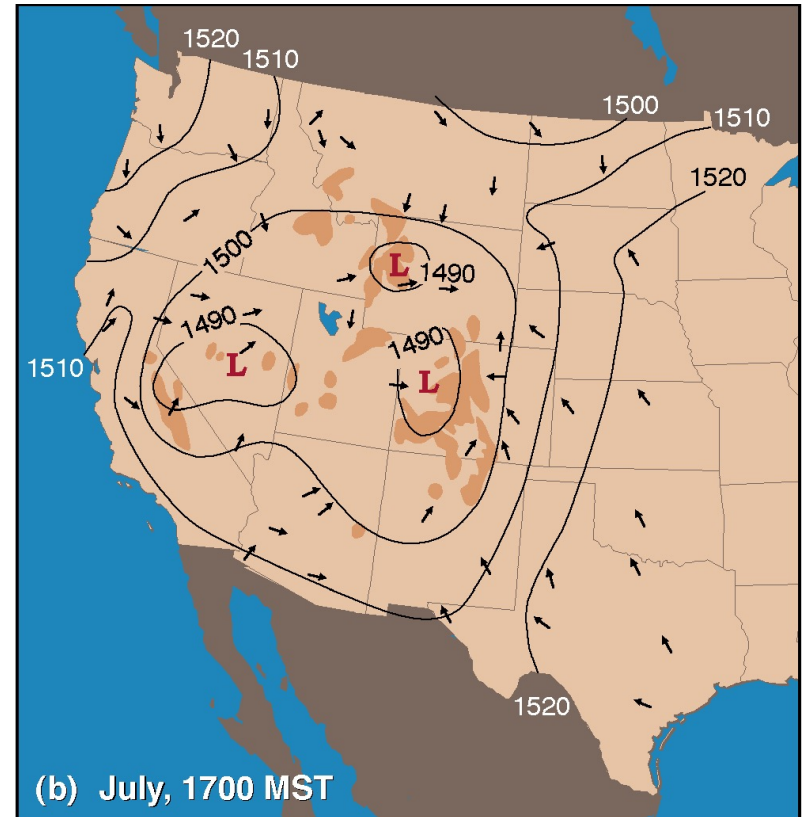
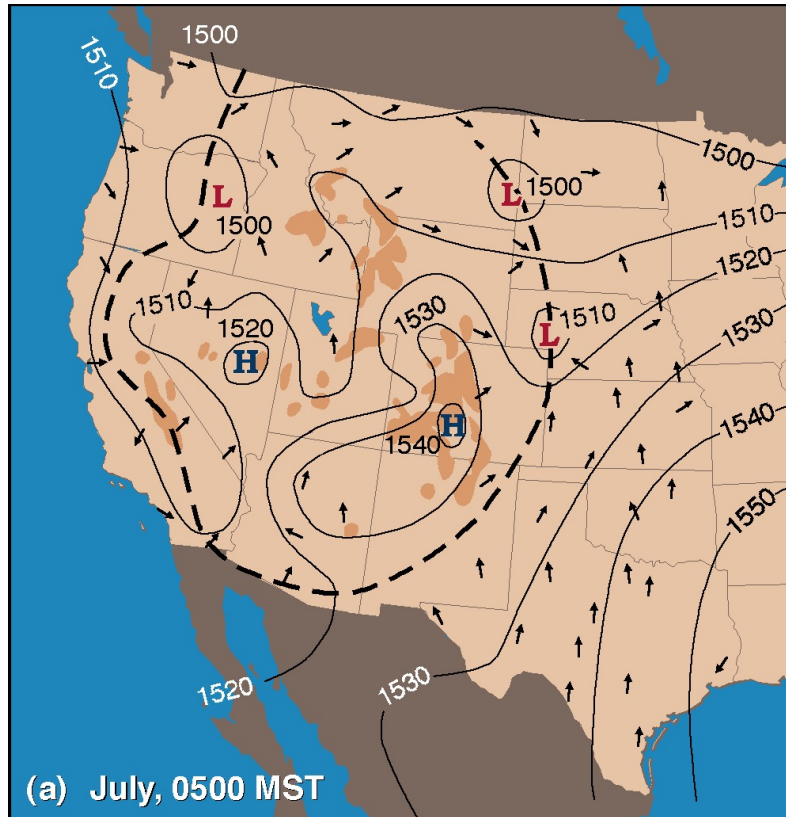
b) Reality

# Mountain-Plain Wind System



# Diurnal

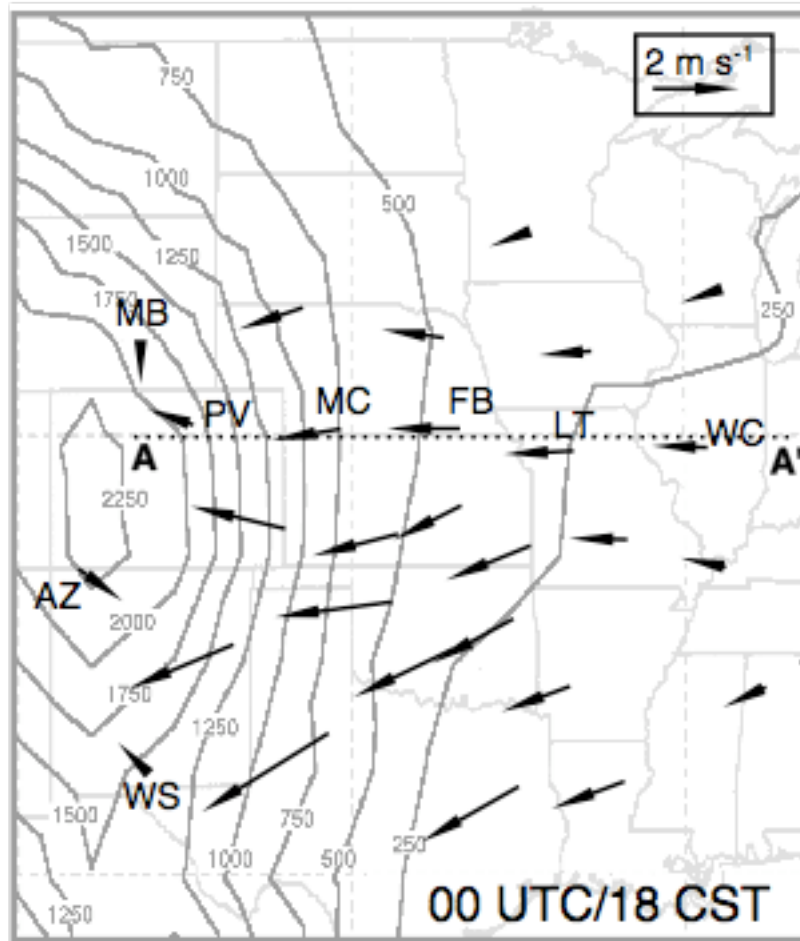
## Mean 850 mb pressure and wind patterns



adapted from Reiter & Tang (1984)

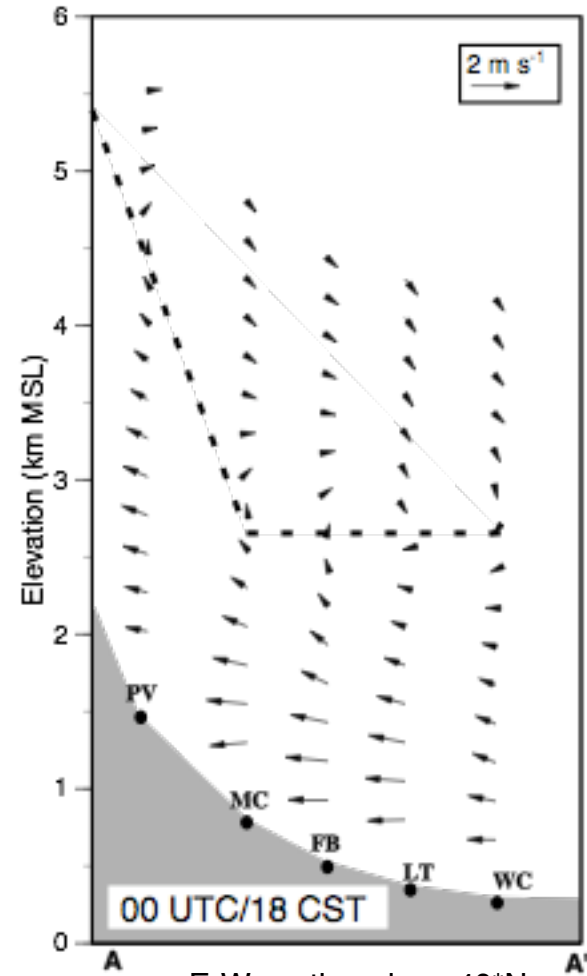
# Diurnal mountain-plain wind system

... from 915 MHz radar wind profiler data



Daytime

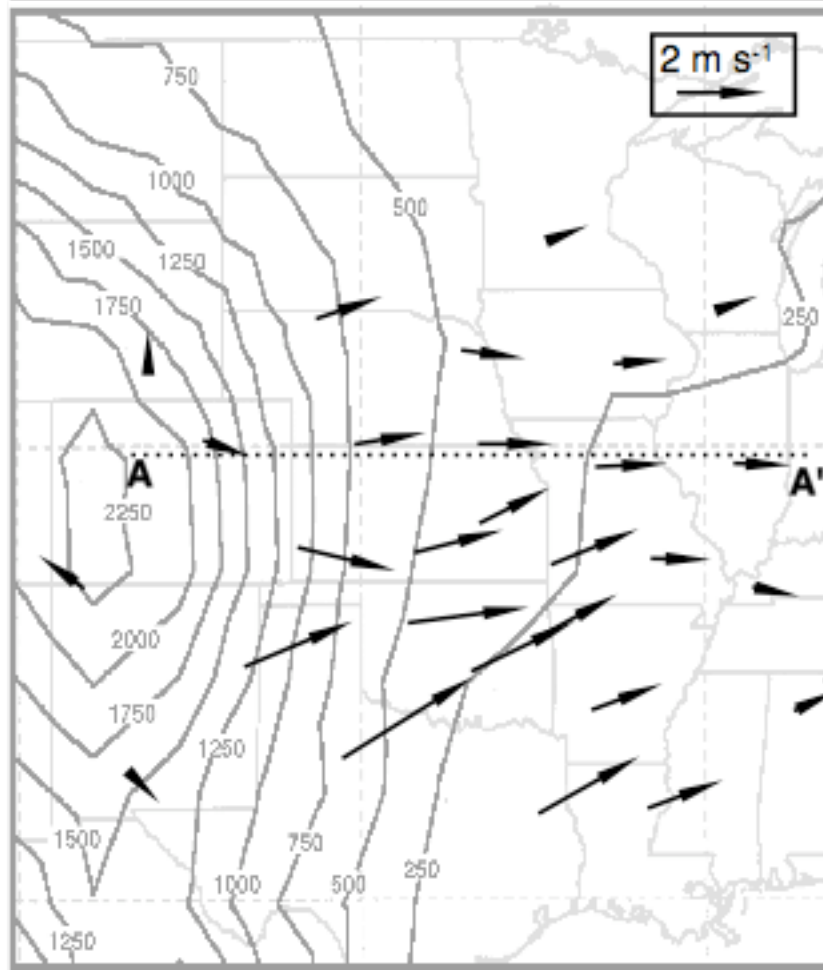
Winds at 500 m AGL



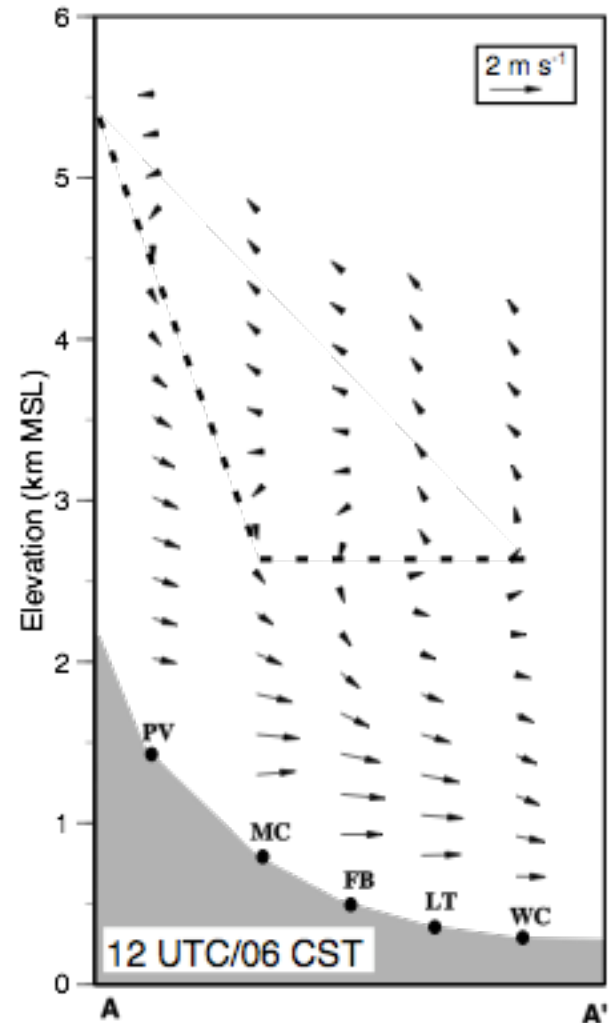
Whiteman & Bian (1998)

# Diurnal mountain-plain wind system

...from 915 MHz radar wind profiler data, continued



Nighttime



Whiteman & Bian (1998)

# 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

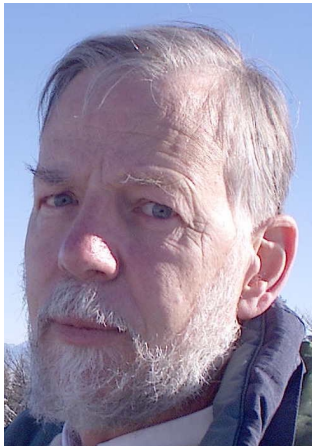
Sasaki et al. (2004) Effect of mtns on moisture transport to free troposphere in Sumatra

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



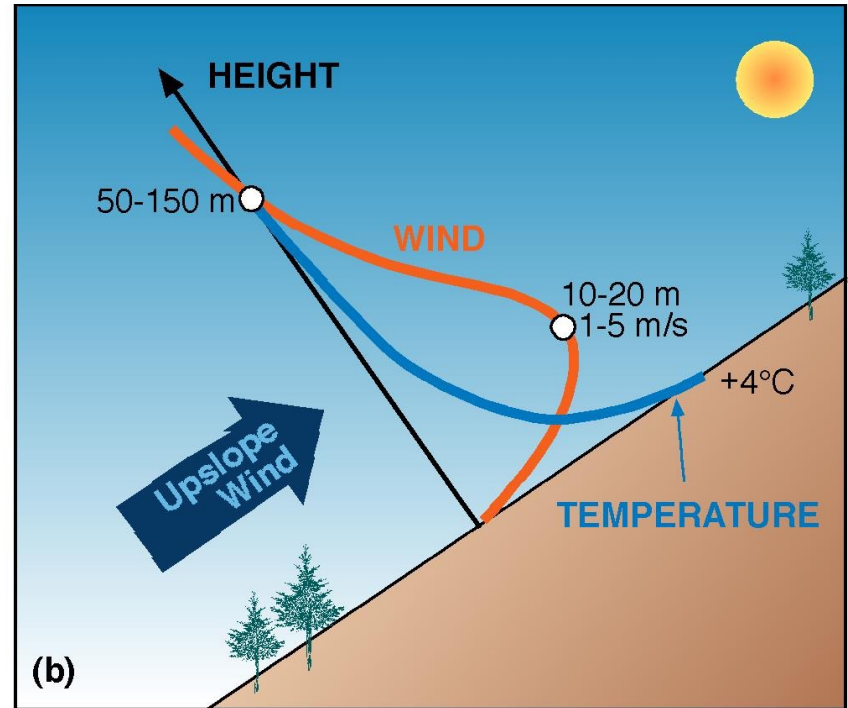
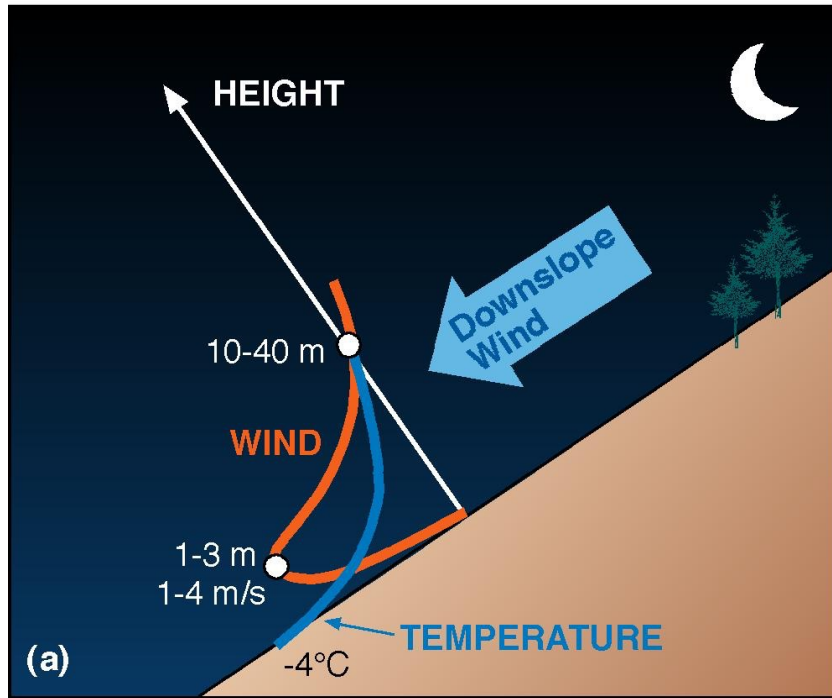
Stefan Henne

# Slope Wind System





# 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**. They are affected by the **surface energy and radiation budget** and ambient flows (such as synoptic and along-valley winds), changing topography/surface cover, obstacles.

- Quick response
- Difficult to find in pure form

# Radiation Budget, Heat Budget & Turbulence

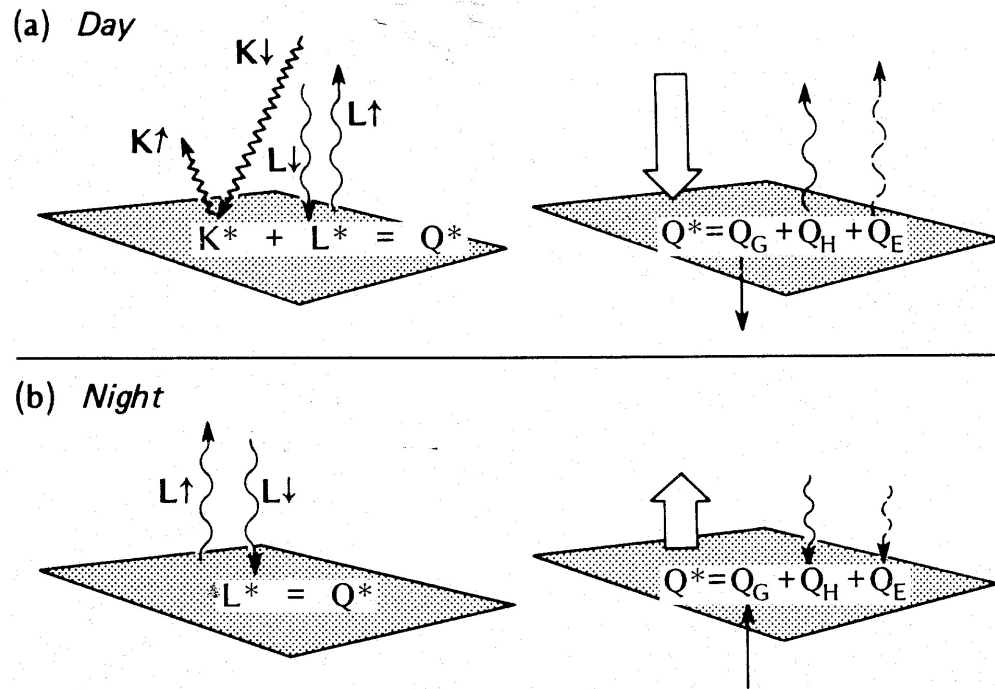
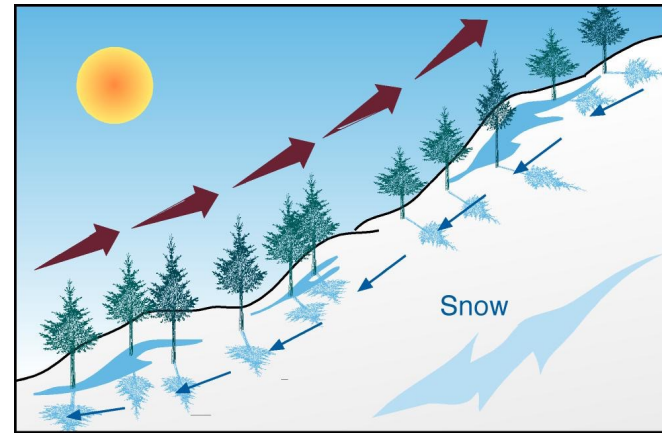
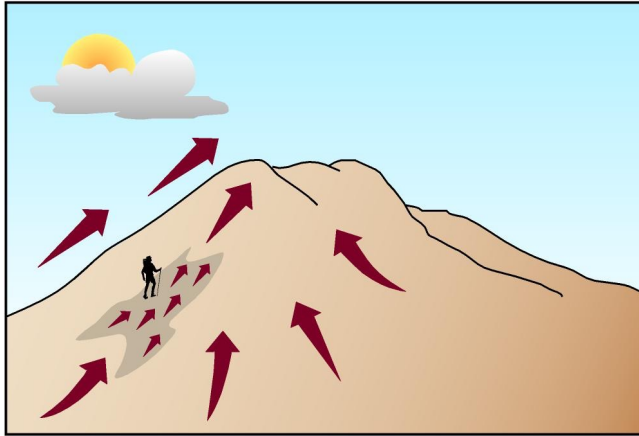


Figure 1.11 Schematic summary of the fluxes involved in the radiation budget and energy balance of an 'ideal' site, (a) by day and (b) at night.

Oke (1978)

# 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



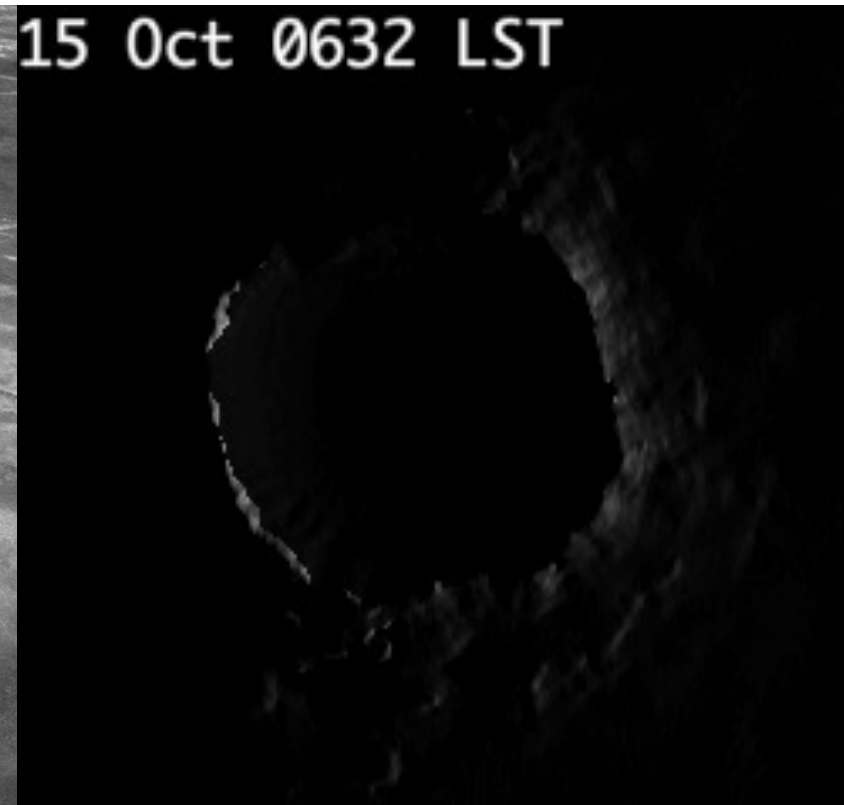
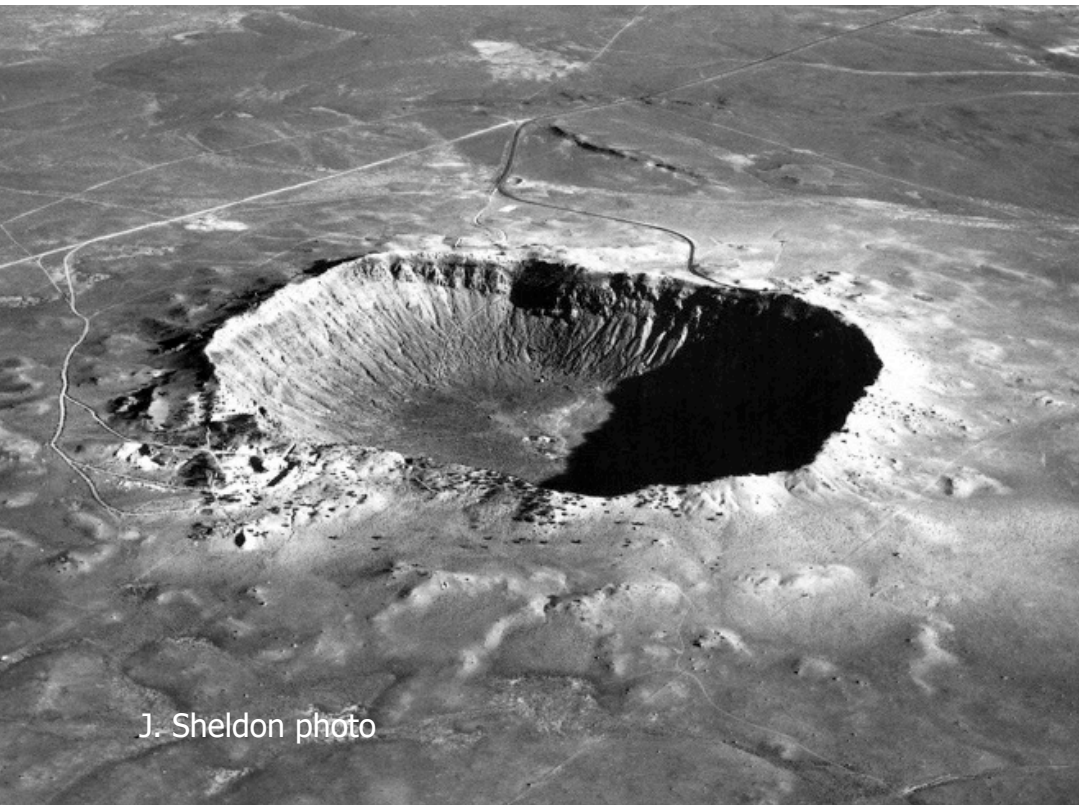
Christian Reuten



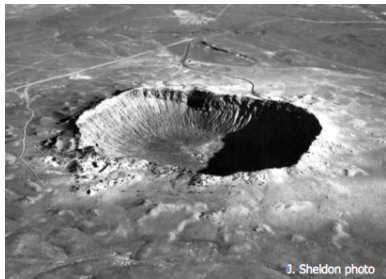
Douw Steyn

# METCRAX - 2006 / METCRAX-II (2013)

## Upslope-Downslope Flow Transition

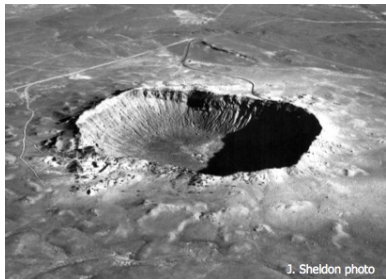


# Upslope flow, 1518 MST



**IOP 4**

# Flow reversal, 1538 MST

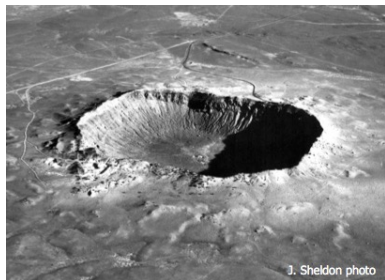


**IOP 4**

# Downslope flow, 1558 MST



**IOP 4**





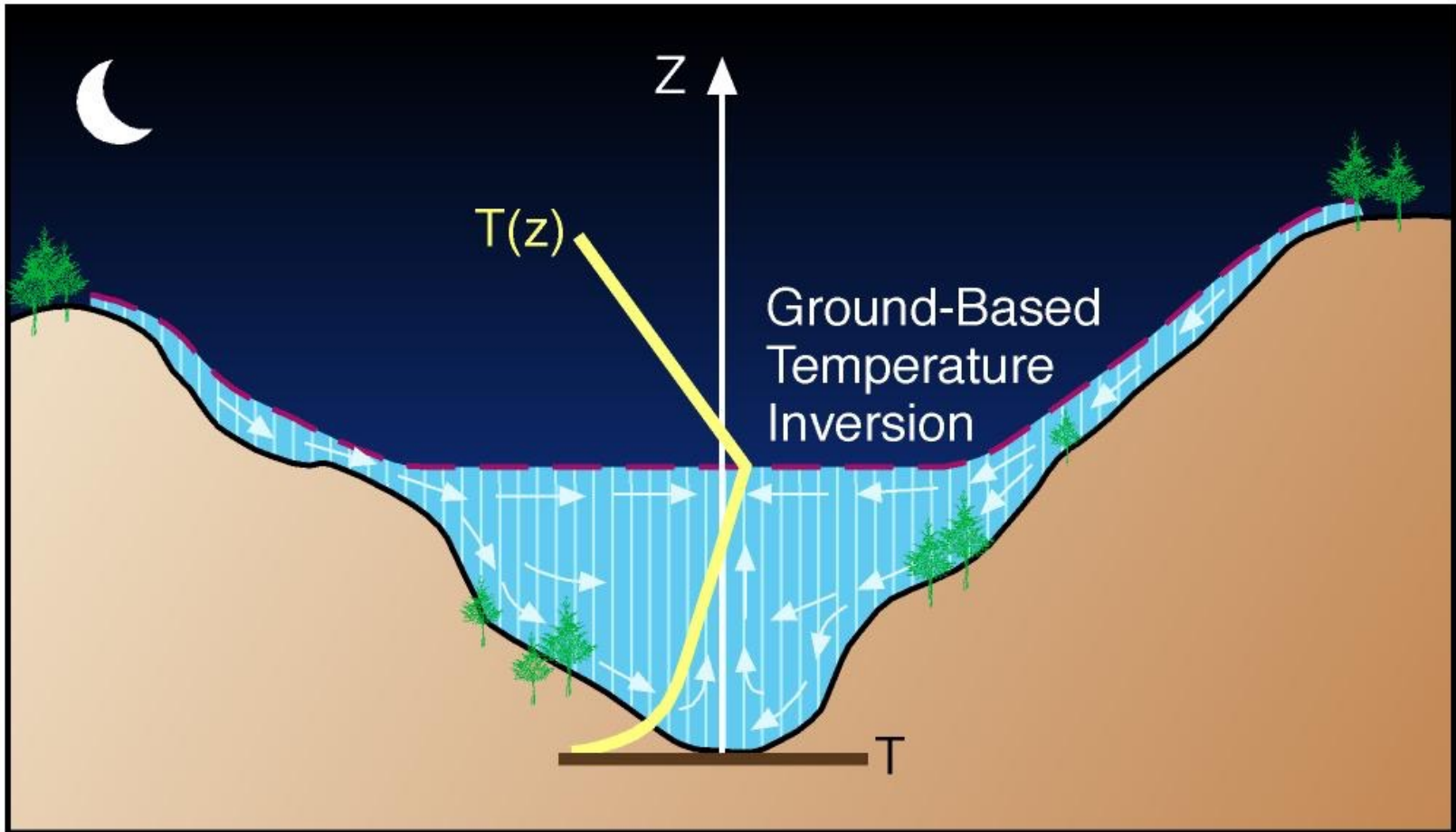
# Downslope Flows



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.

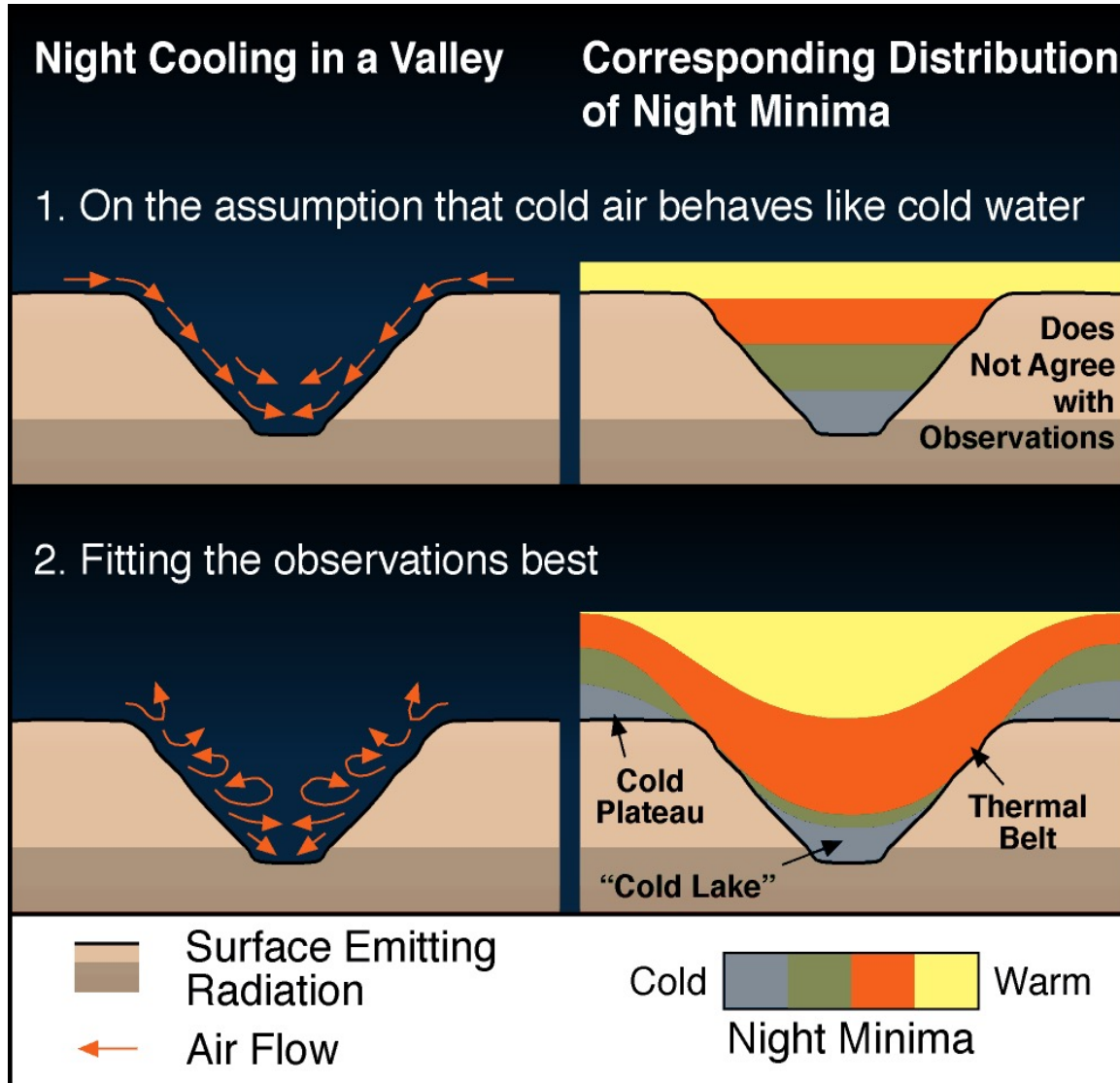
Grünloch Basin sidewall  
2051 UTC 2 June 2002

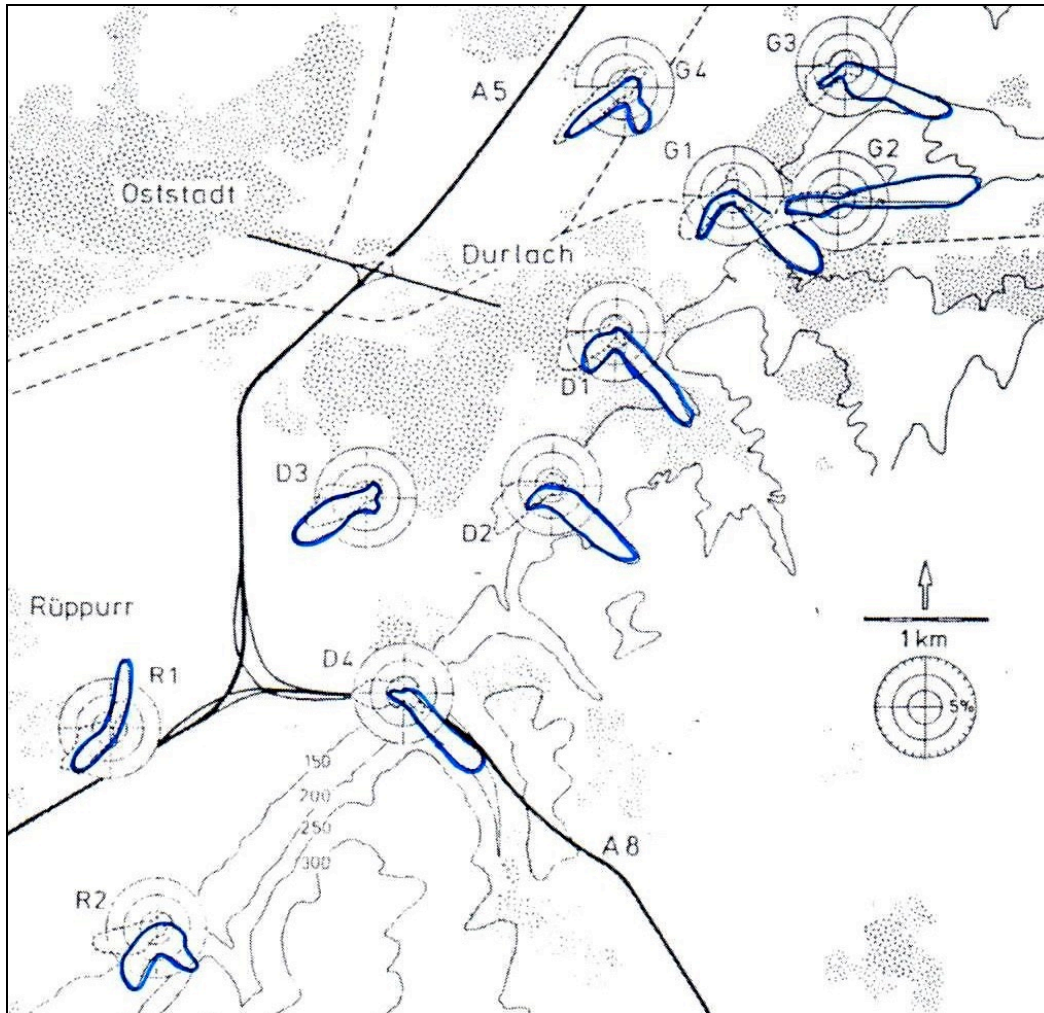
From R. Steinacker



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.

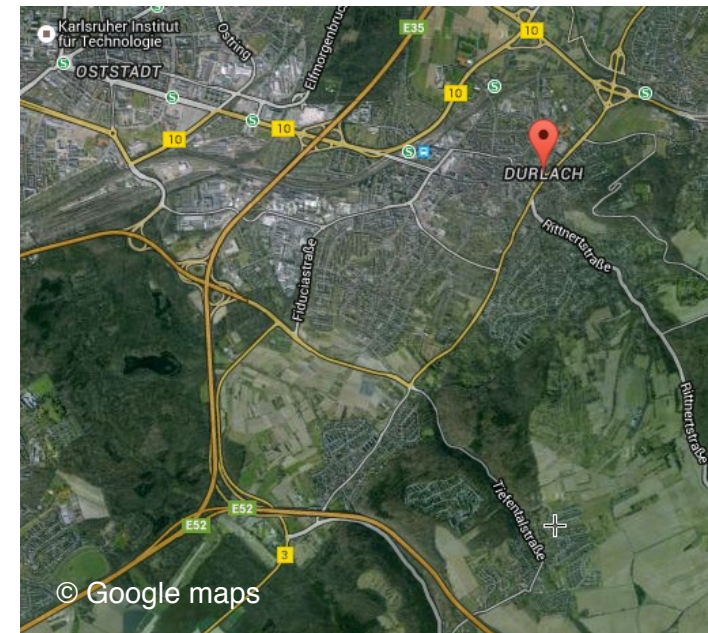
# Thermal belt





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

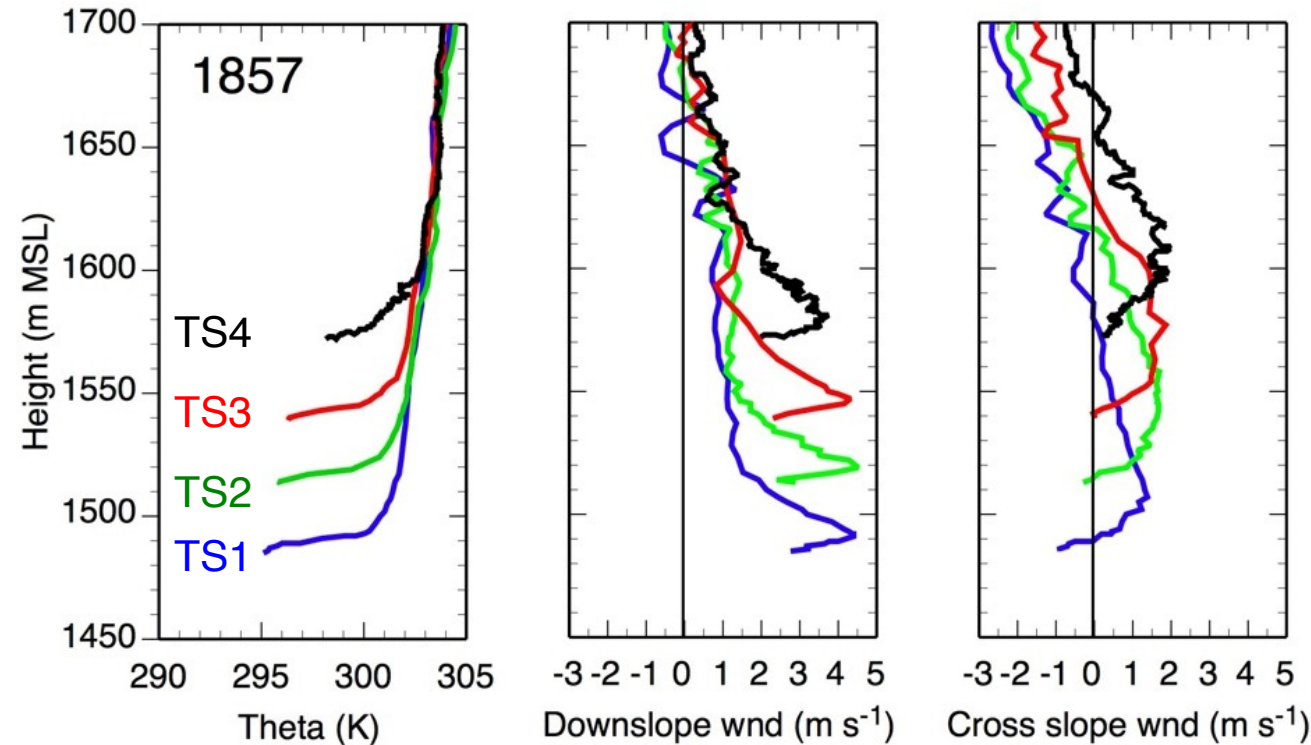


## Salt Lake Valley, UT



# Downslope flow example

VTMX, 8 Oct 2000



- Jet profile max velocity  $\sim 15$  m AGL increases with downslope distance, reaching 7 m/s
- Temperature deficit increases with downslope distance, reaching 7 K
- Downslope flow layer extends to  $\sim 150$  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

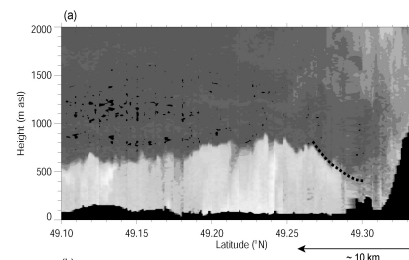


Eric Skyllingstad



Sharon Zhong

aerosol backscatter  
from down-looking lidar



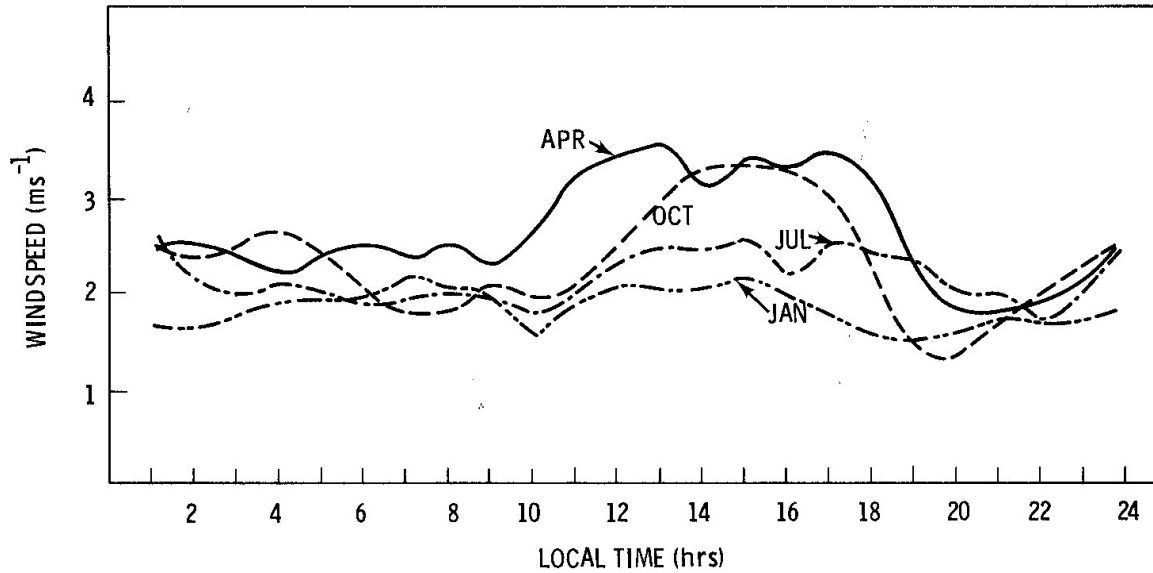
An aerial photograph of a deep, rugged valley. The valley floor is a mix of green fields and brownish terrain, with a winding river or road visible. The surrounding mountains are dark and rocky, with distinct horizontal layers of sedimentary rock. The sky is filled with white and grey clouds.

# Valley Wind System

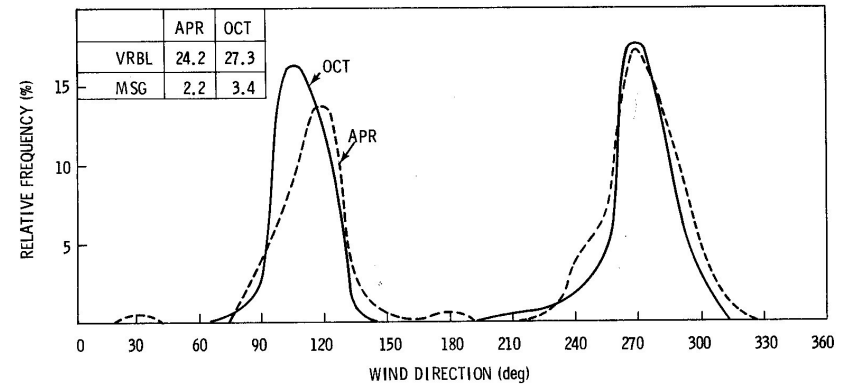
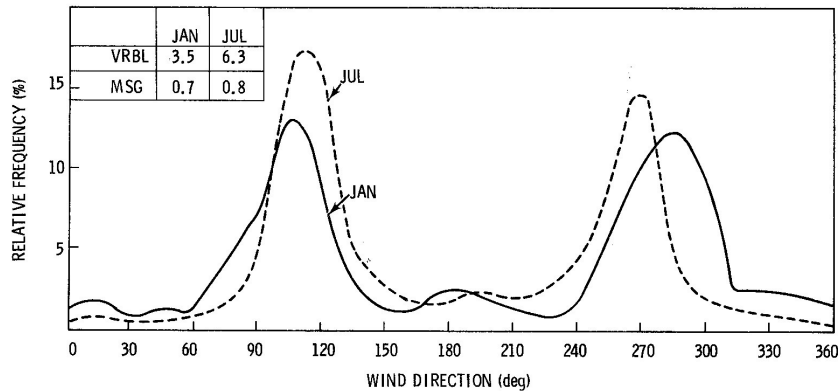
COMAP  
Boulder, CO

Brush Creek Valley © CD Whiteman

# Valley wind system

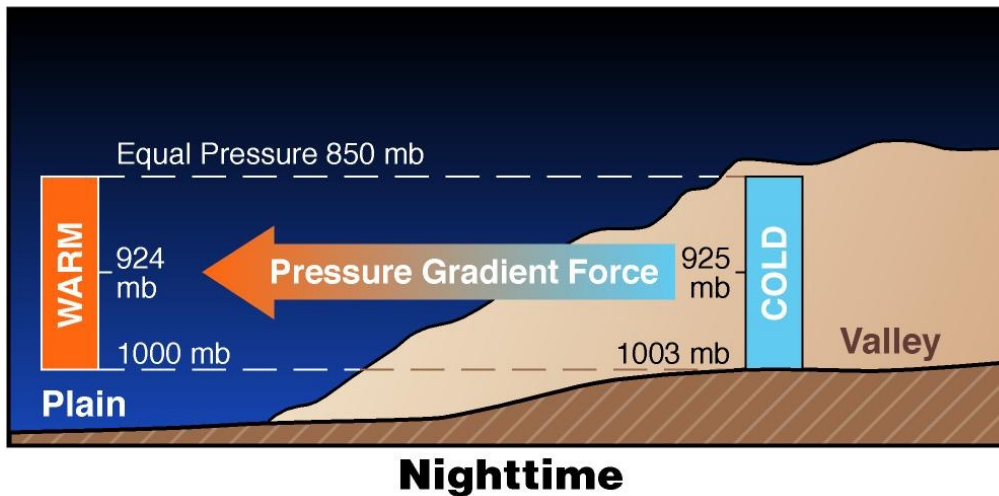
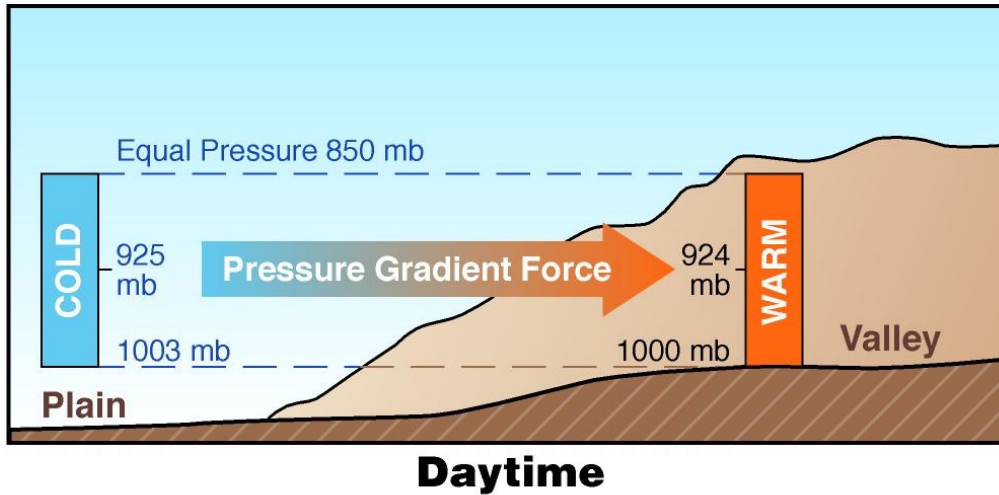


Avon, CO is in the Eagle Valley below the Vail /Beaver Creek ski area. The observations come from an automatic weather station operated in the early 1980s before the ski resort was built.





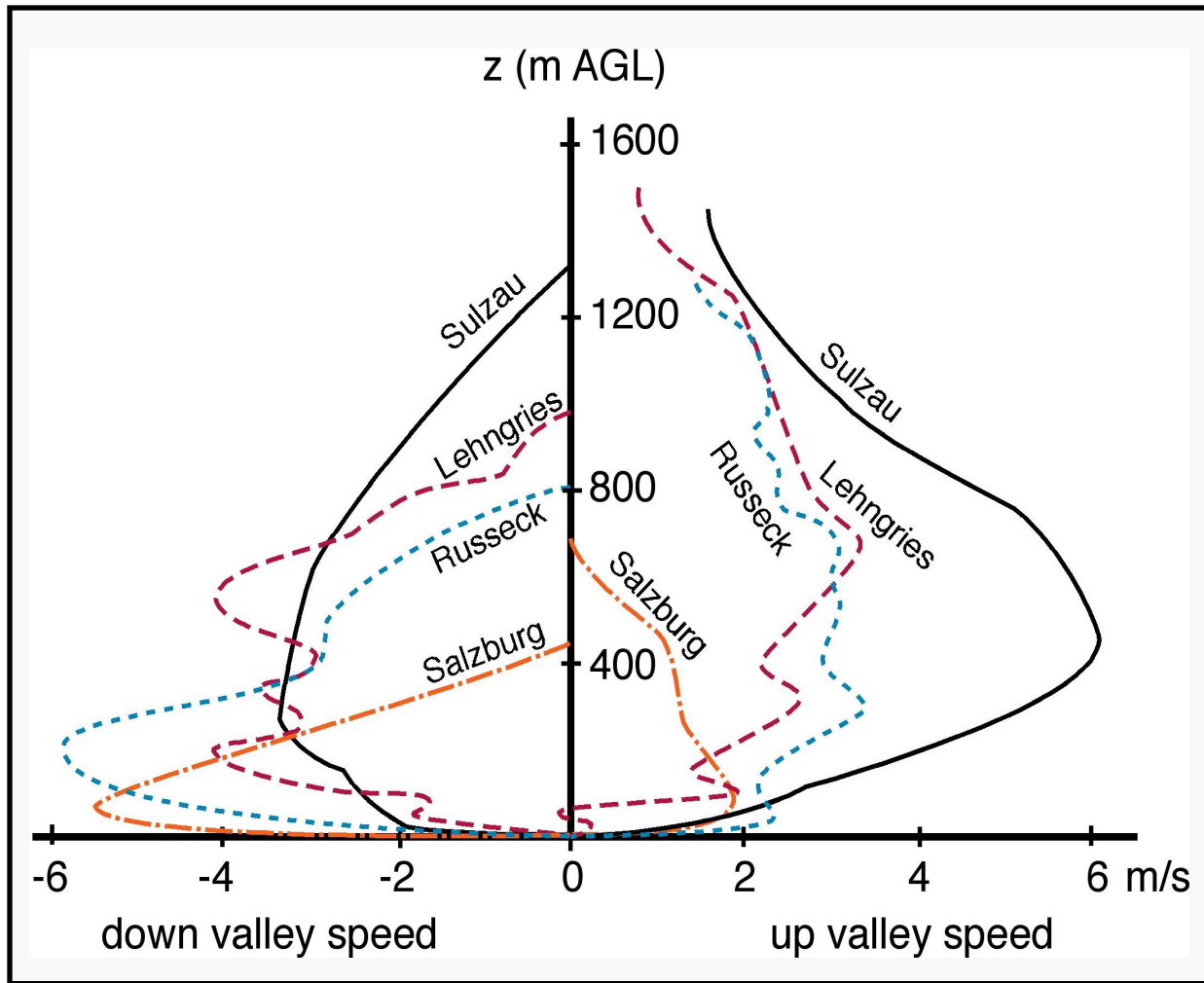
# Valley wind system



**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)

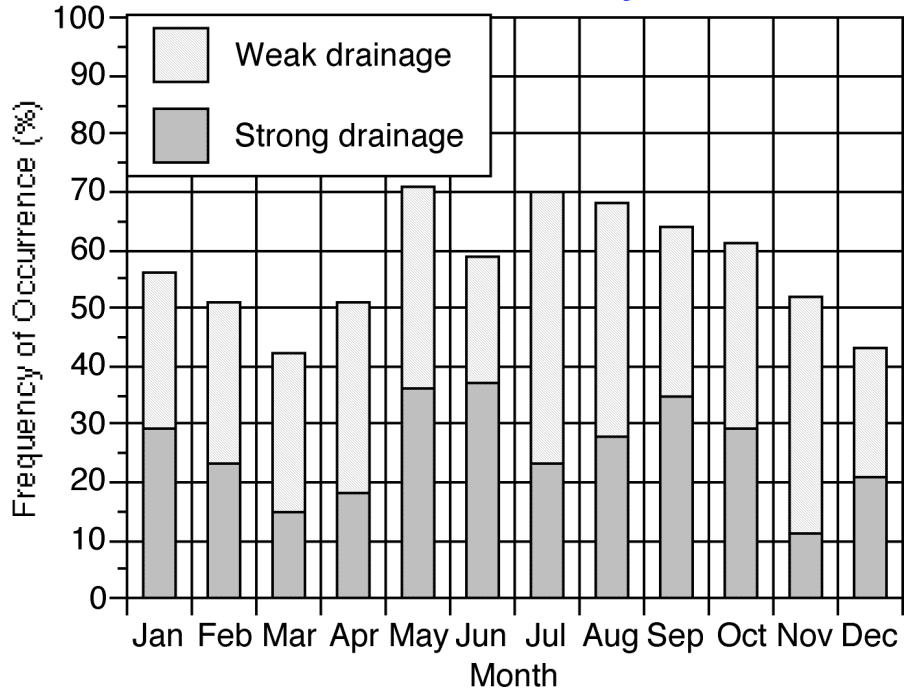
# Up- and Downvalley wind profiles



from Ekhart (1944)

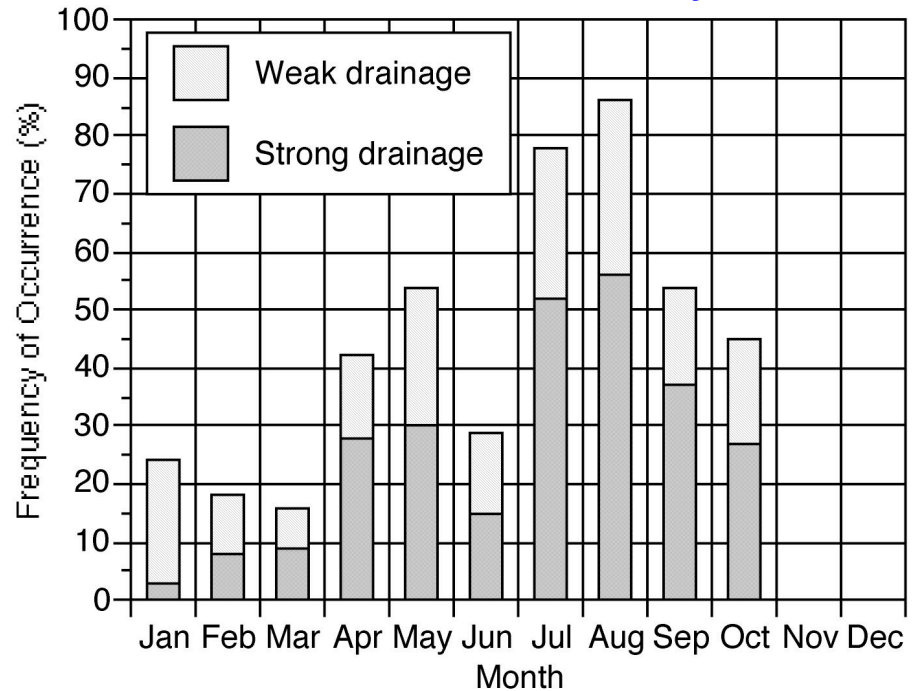
# Diurnal Wind Frequencies

## Brush Creek Valley, CO



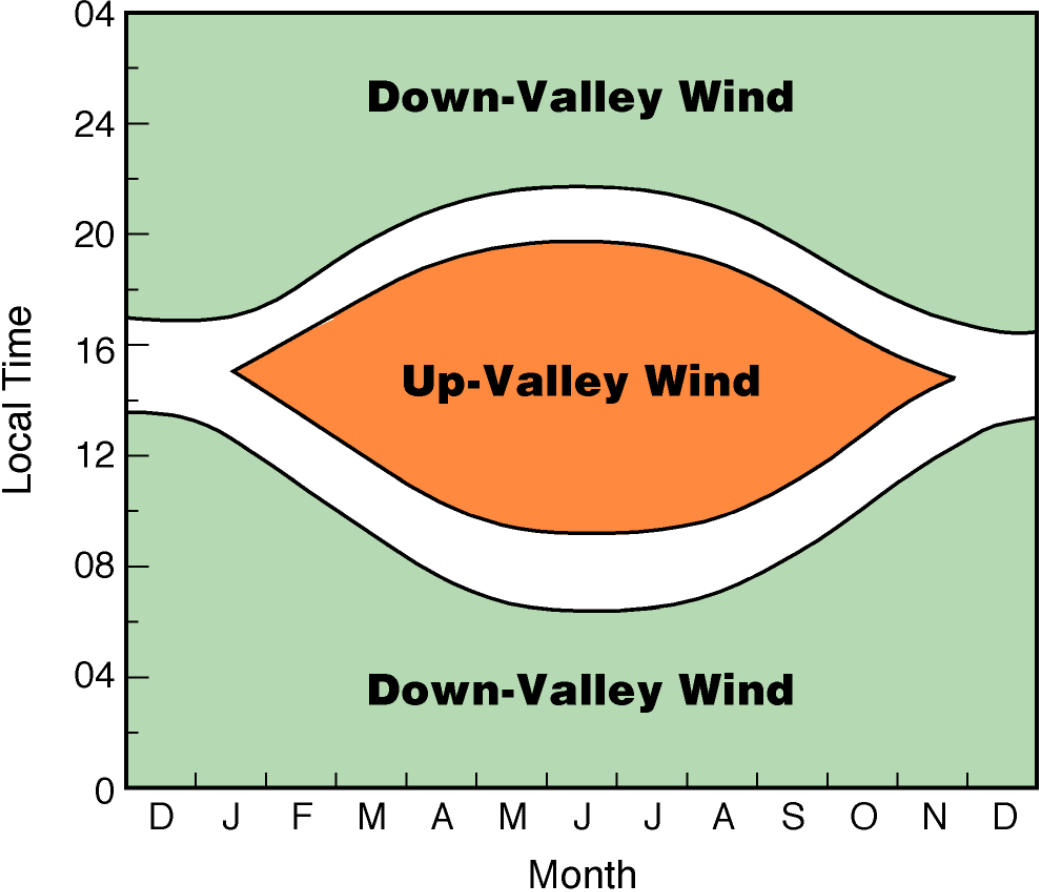
Gudiksen (1989)

## Anderson Creek Valley, CA



Gudiksen and Walton (1981)

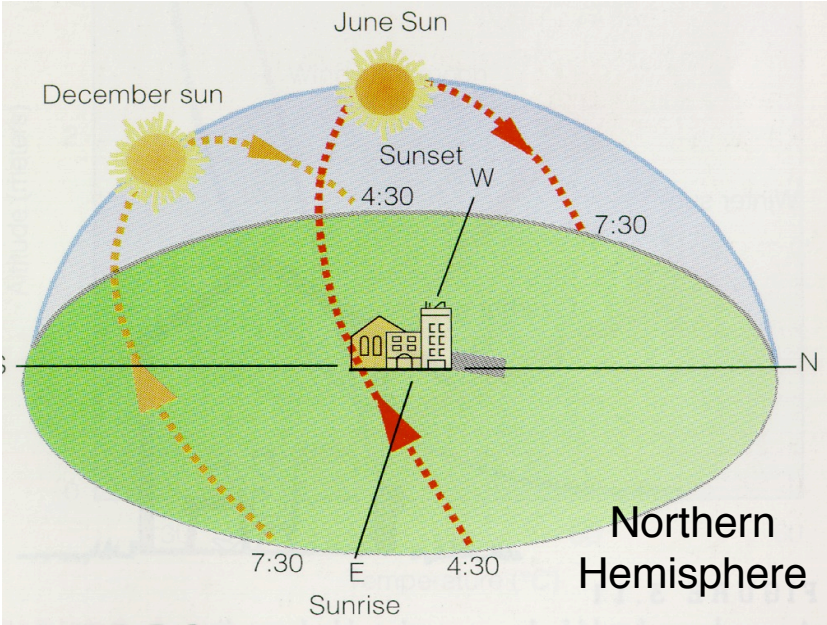
# Seasonal Variation of Diurnal Wind Frequencies



Leusach Tal

Reiter et al. (1983)

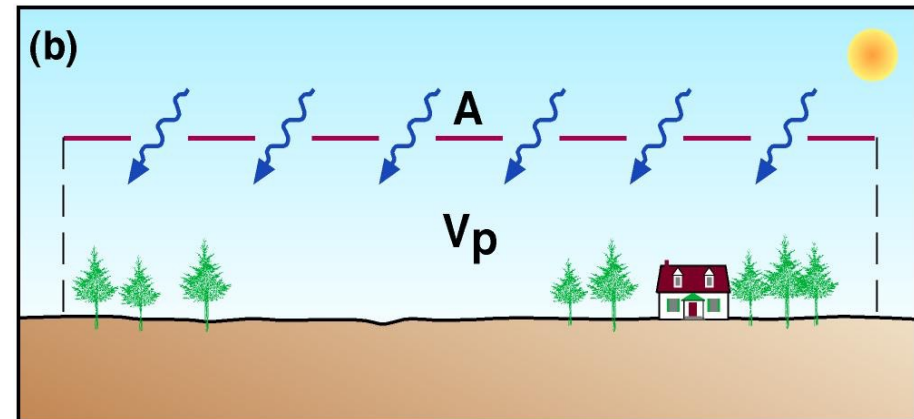
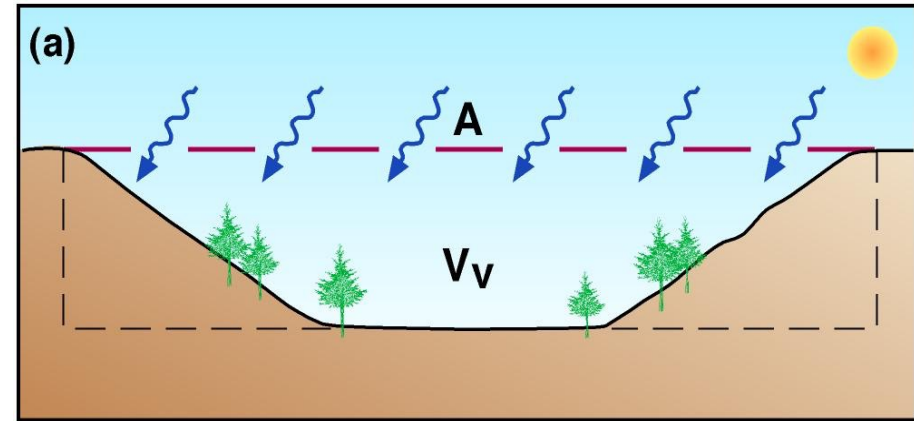
## Sun path summer & winter



Ahrens (1994)

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

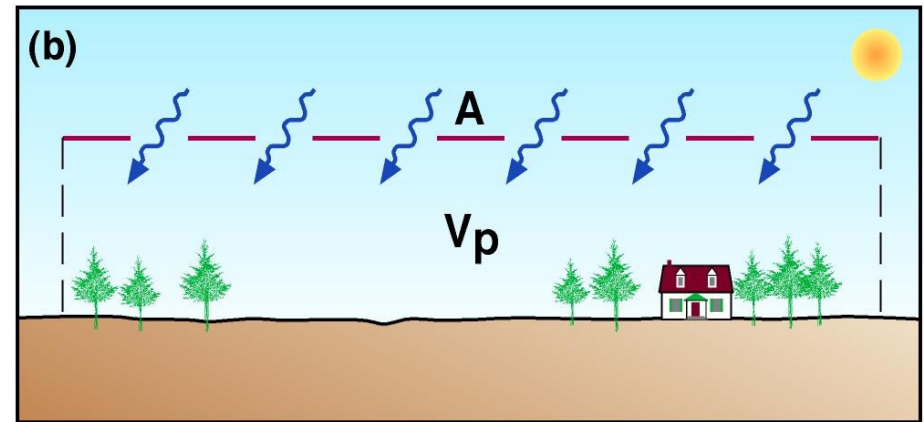
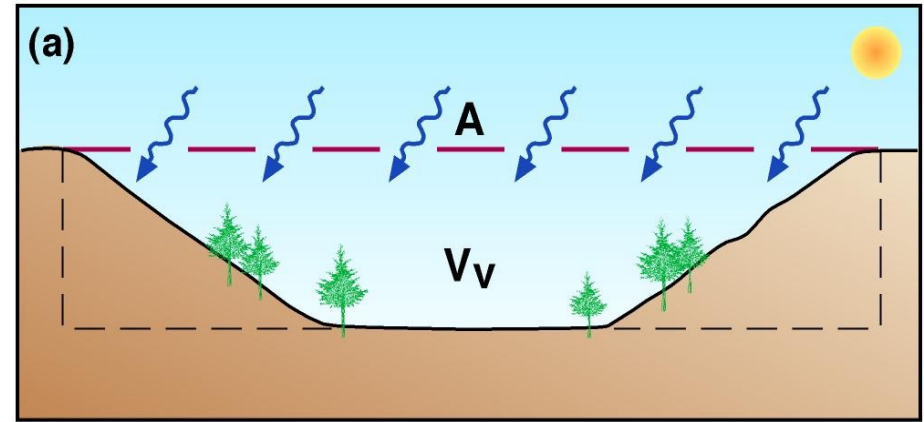
- Horizontal cross section? – Same insolation!
- Radiation heats ground surface; heat is redistributed to the air above
- Equal amount of energy is applied to a smaller mass of air within valley.
- Larger temperature response in the smaller volume.
- Similarly, at night loss of heat by radiation is applied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



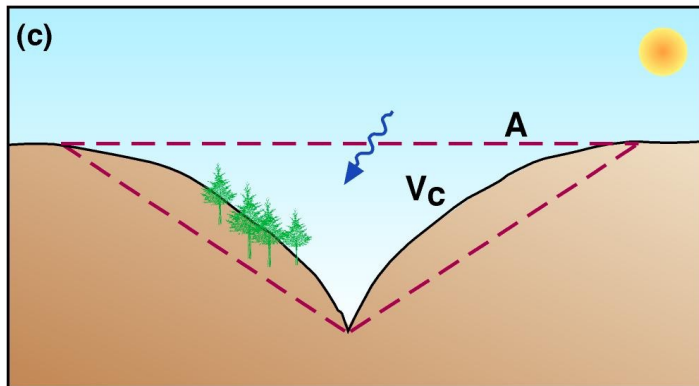
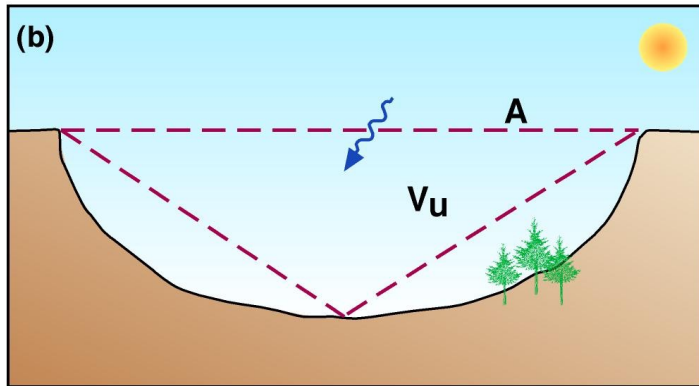
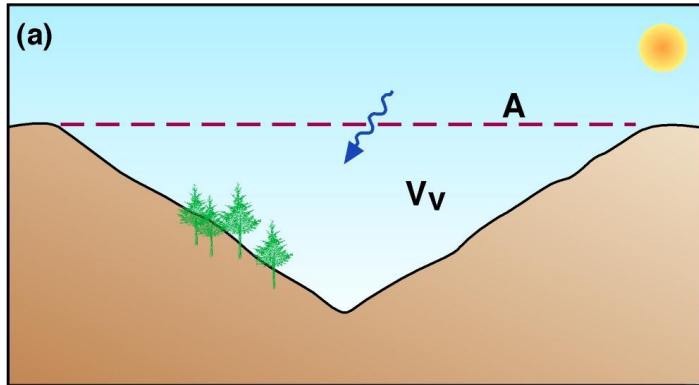
# What causes the temperature range difference – Plain vs. Valley?

## 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.

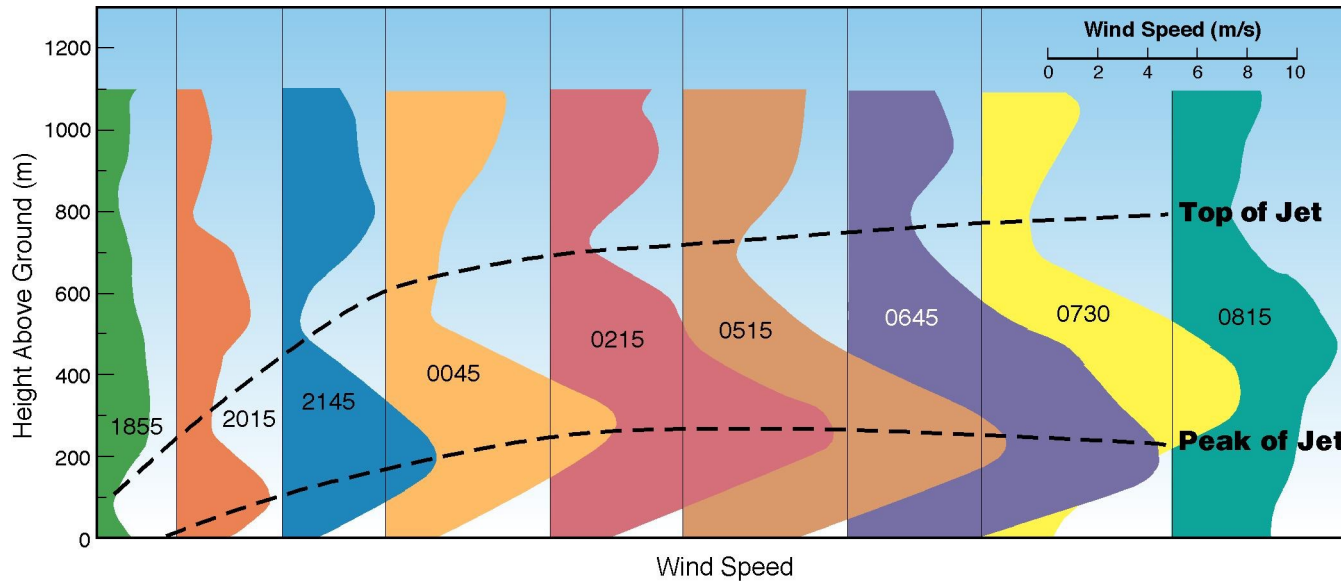
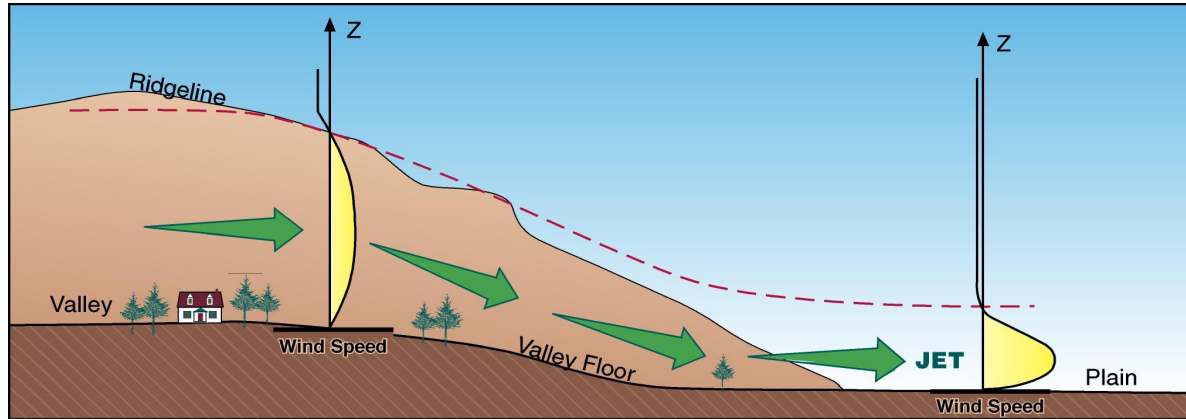


Sheltering: Valley air is somewhat **protected** from gradient winds **by surrounding topography**. Heated air by day and cooled air by night is stored up within the valley.



- 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-sided valley.

# The valley exit jet



Adapted from  
Pamperin &  
Stilke (1985)



# Exit jet at Weber Canyon, UT



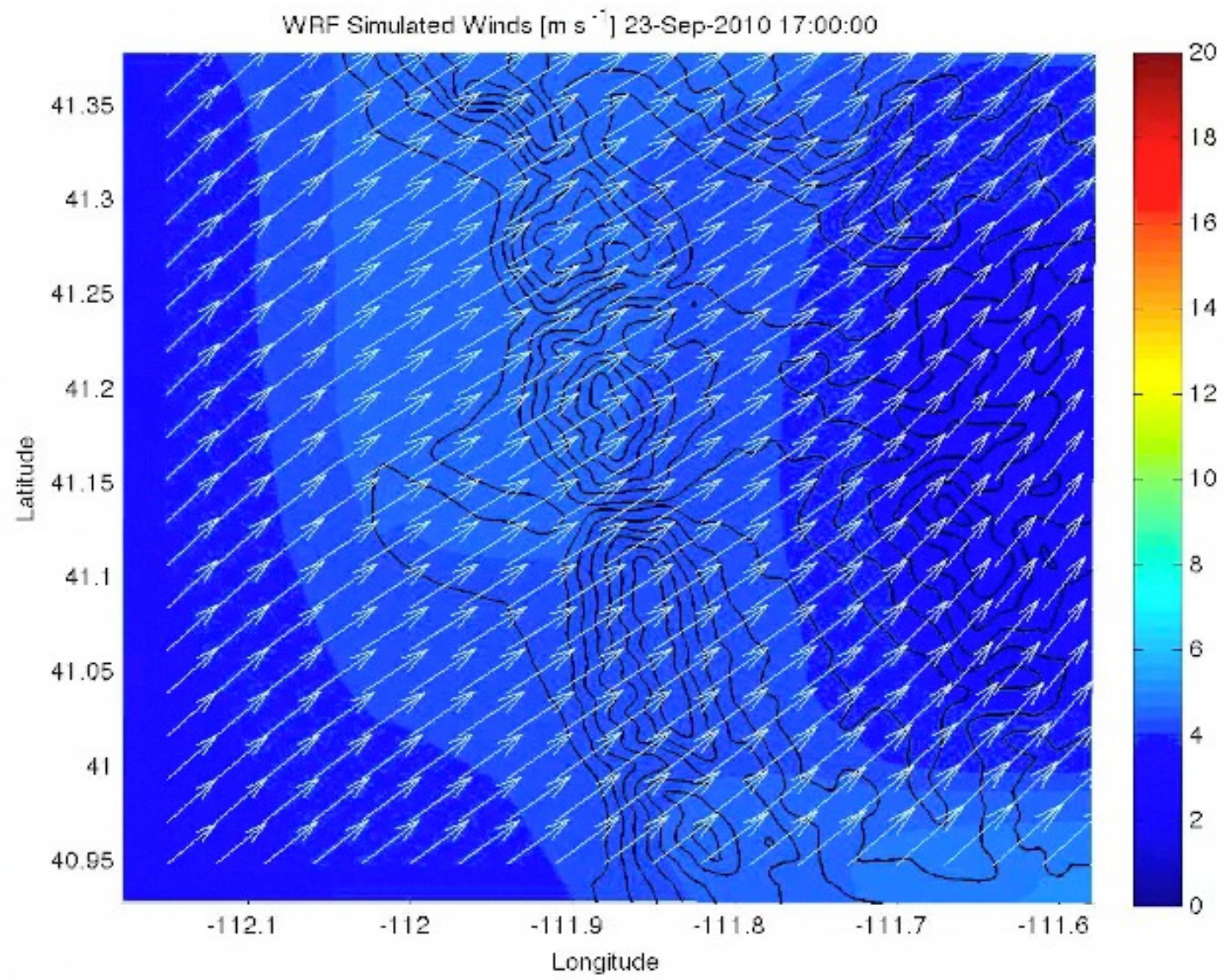
# Exit jet at Weber Canyon, UT



© M. Farley-Chrust

Chrust et al. 2013

# WRF model results, Weber Canyon, UT



# Selected valley flow references

1989 special ASCOT issue of *JAM*

2000 special *Theor. Appl. 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.

Doran (1991) Effect of ambient winds on valley flows.

Bader & McKee (1992) Complex terrain BL evolution.

Whiteman and Doran (1993) Pressure driven channeling in Tennessee Valley.

Banta et al. (1997, 1999, 2004) Tributary valley; Wind flow in Grand Canyon, d-v LLJ.

King (1997) Climatology of valley winds in two oppositely oriented valleys.

Eckman (1998) Pressure driven channeling in Tennessee Valley.

Rife et al. (2002) Diurnal BL circulations in Great Basin Desert.

DeFranceschi et al. (2002) DeFranceschi (2006) Ora del Garda wind; ABL dynamics.

Zhong and fast (2003) Comparison of model performance in Salt Lake Valley.

Kossmann & Sturman (2003) Pressure driven channeling in curved valleys.

Rampanelli et al. (2004) Mechanisms of upvalley winds (model)

Zhong et al. (2004) Wind system in California's Central Valley

Chen et al. (2004) Stratified downvalley flows over transverse ridge in Salt Lake Valley.

Cox (2005) Dissertation: winds and BL development in Salt Lake Valley.

Chemel & Chollet (2006) Obs of daytime BLs in deep Alpine valleys.

Pinto et al. (2006) Downvalley flow and nocturnal BL, Salt Lake Valley.

Bergström & Juuso (2006) Valley wind modeling.

Darby and Banta (2006); Darby et al. (2006) Canyon flows and LLJ in Salt lake Valley

Bischoff-Gauß et al. (2008) BL evolution of arid Andes Valley.

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.

Weigel & Rotach (2004) Daytime turbulence characteristics in Riviera valley.

Weigel (2005) Dissertation on MAP/Riviera Valley observations and modeling.

Weigel et al. (2006, 2007a,b,c) TKE, moisture exchange, trbc characteristics.

Rotach & Zardi (2007) Key findings from MAP.

DeFranceschi et al. (2008) Second order trbc moments in SL of Alpine valley



Tina Chow



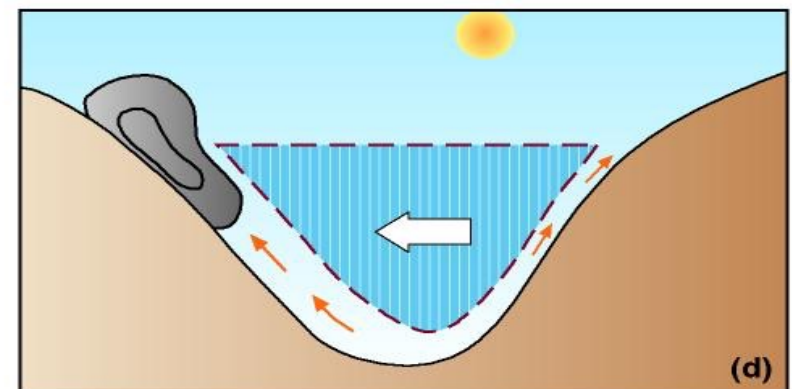
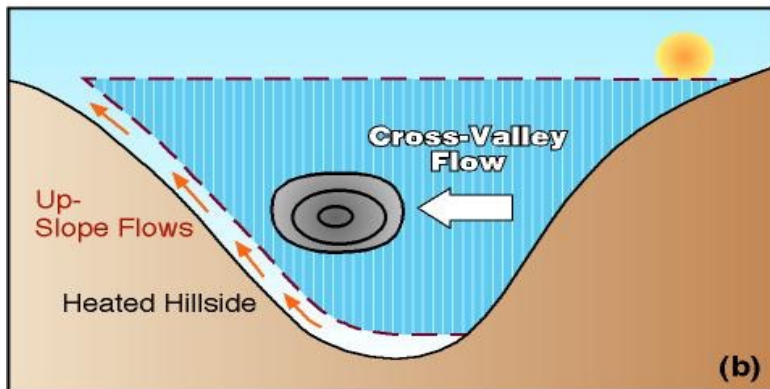
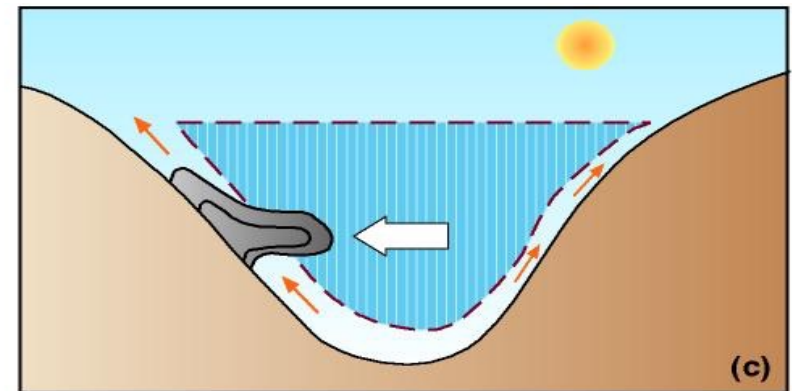
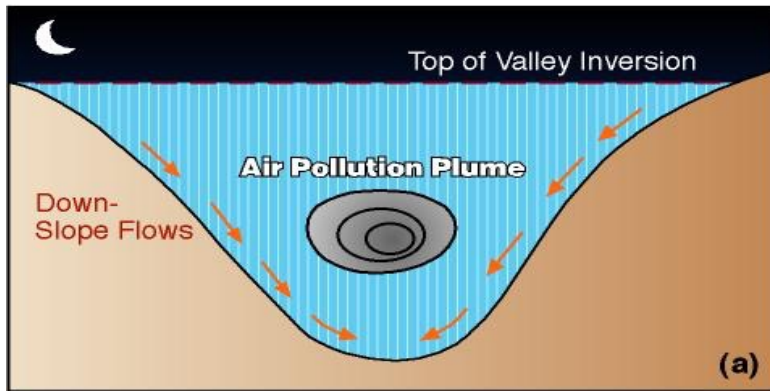
Andreas Weigel



Mathias Rotach

# Cross-Valley Wind System





Adapted from Bader & Whiteman (1989)



Manuela Lehner

Lehner and Whiteman 2012, 2014

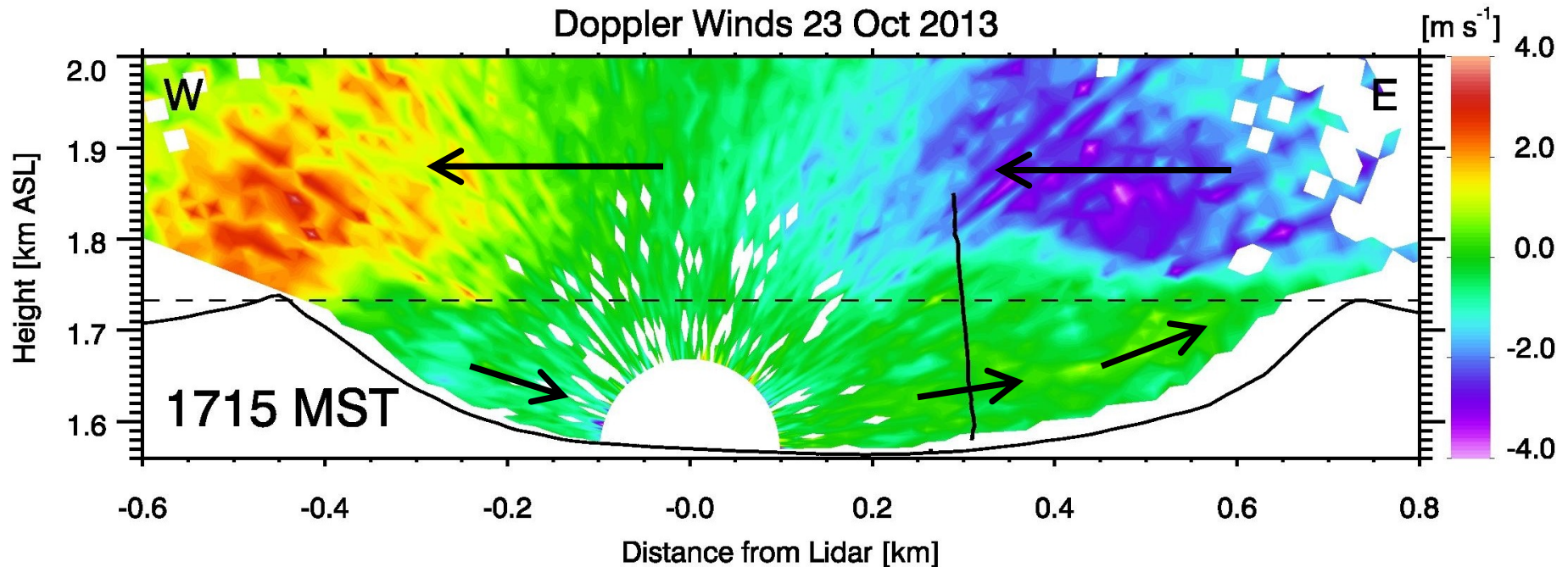
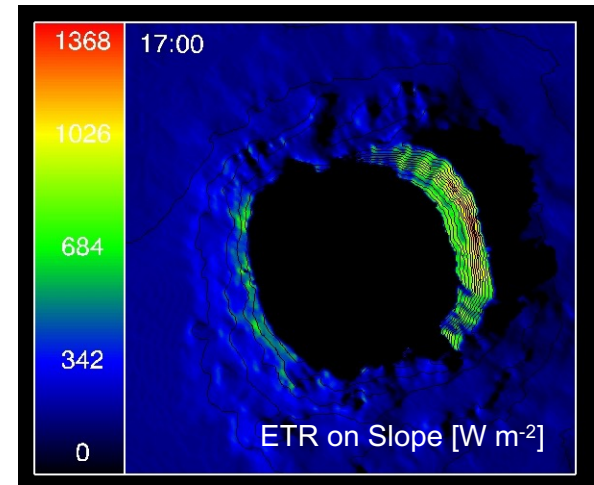
Lehner et al. 2012

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.

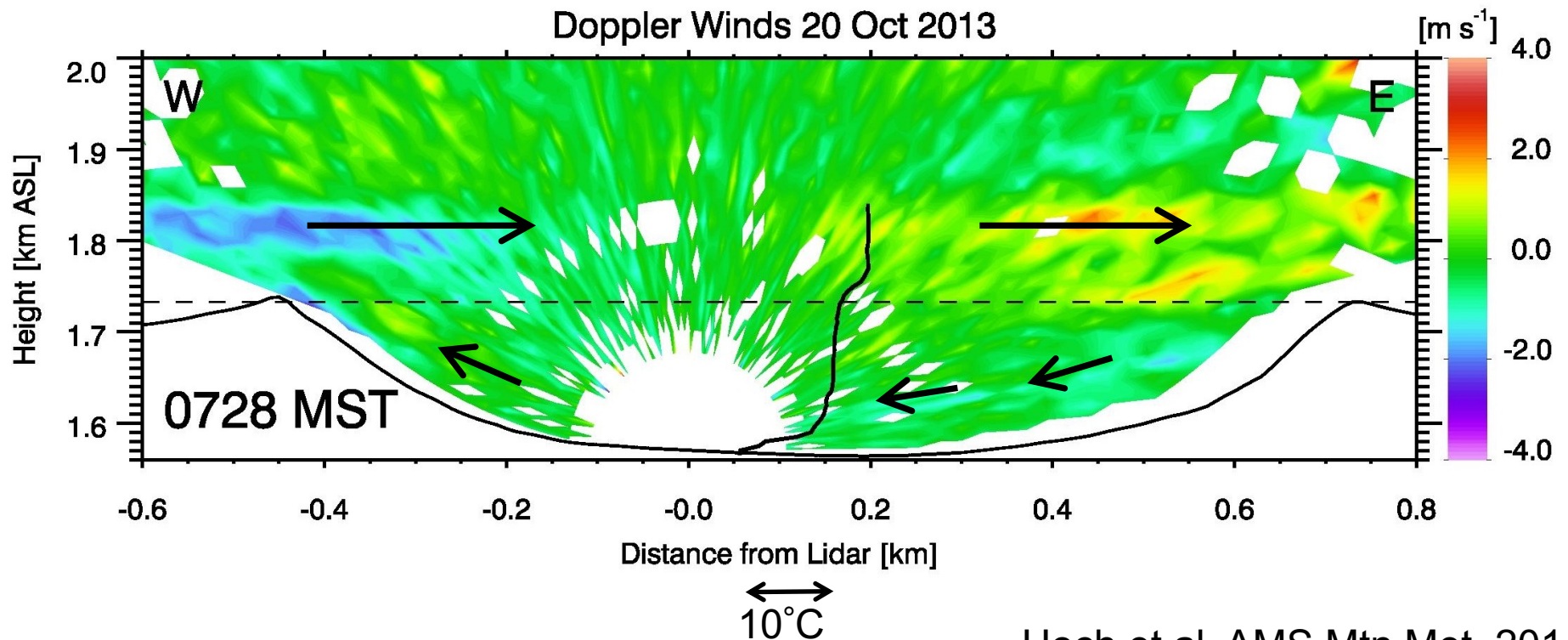
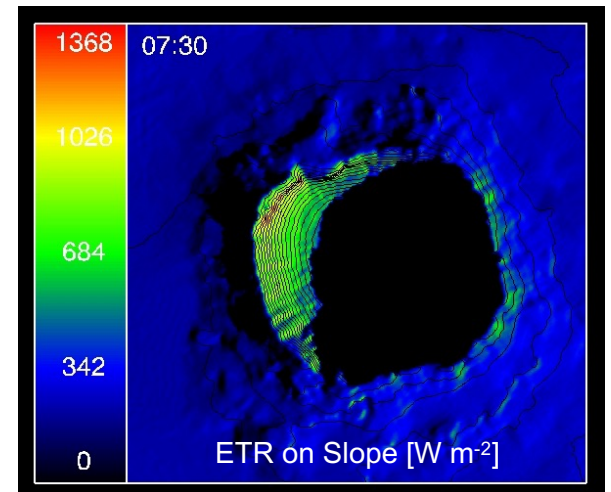




# Cross-Basin Circulations

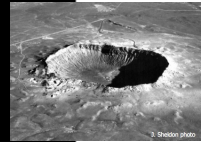
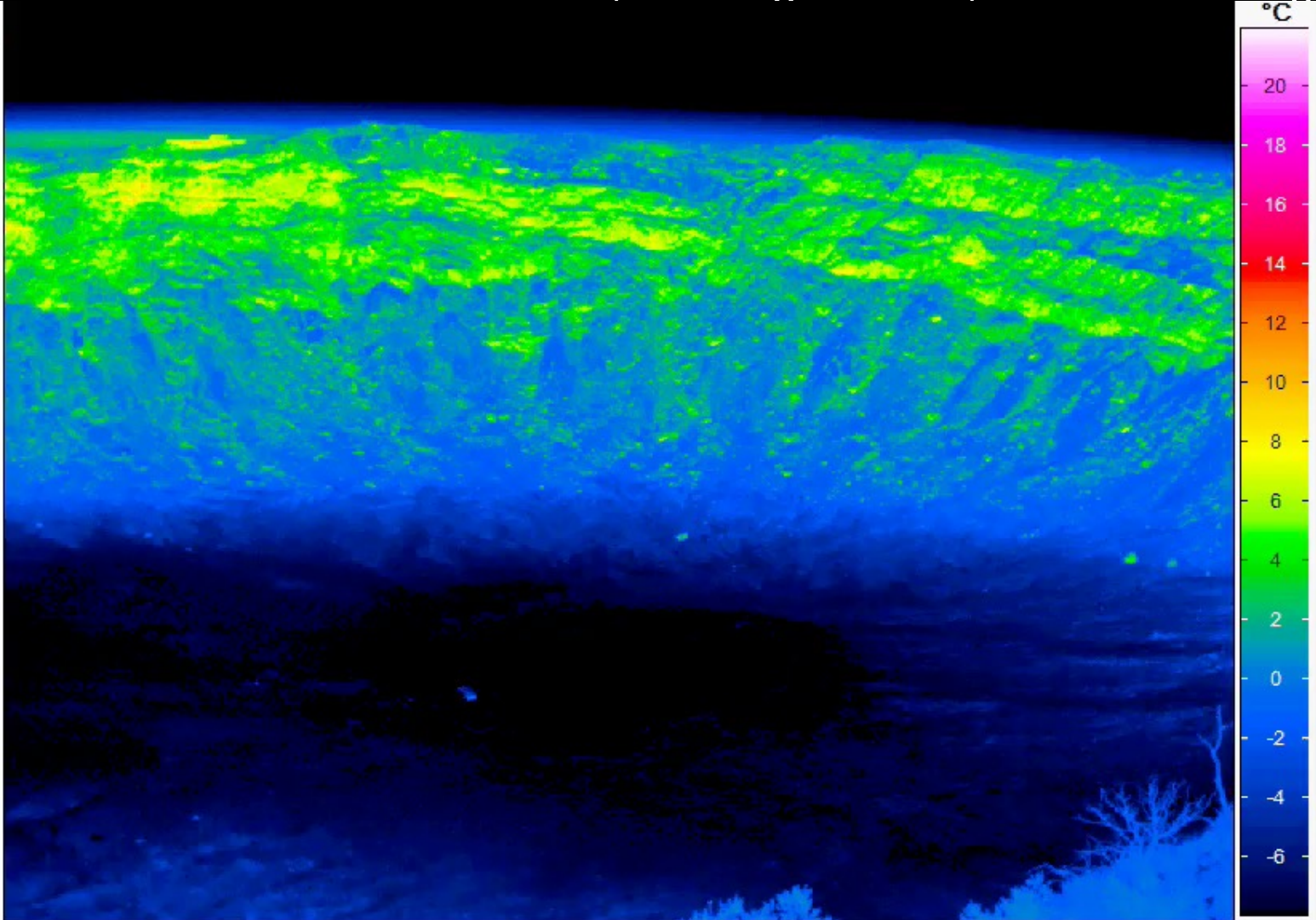
Morning ~07:30 MST

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



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

File:  
IRHD\_20131020  
\_142200.irb  
Date:  
20.10.2013  
Time: 14:22:00



Meteor Crater Experiment II, October 2013  
Time in UTC; IR contact  
Martina Grudzielanek & Roland Vogt

# The Diurnal Cycle of Mountain Winds

The background of the slide is a photograph of a mountain range. The mountains are silhouetted against a sky that transitions from a deep purple at the top to a lighter, hazy blue near the horizon. The foreground shows dark, jagged rock formations. The title text is centered over the upper half of the image.

# Example: Rush Valley winds

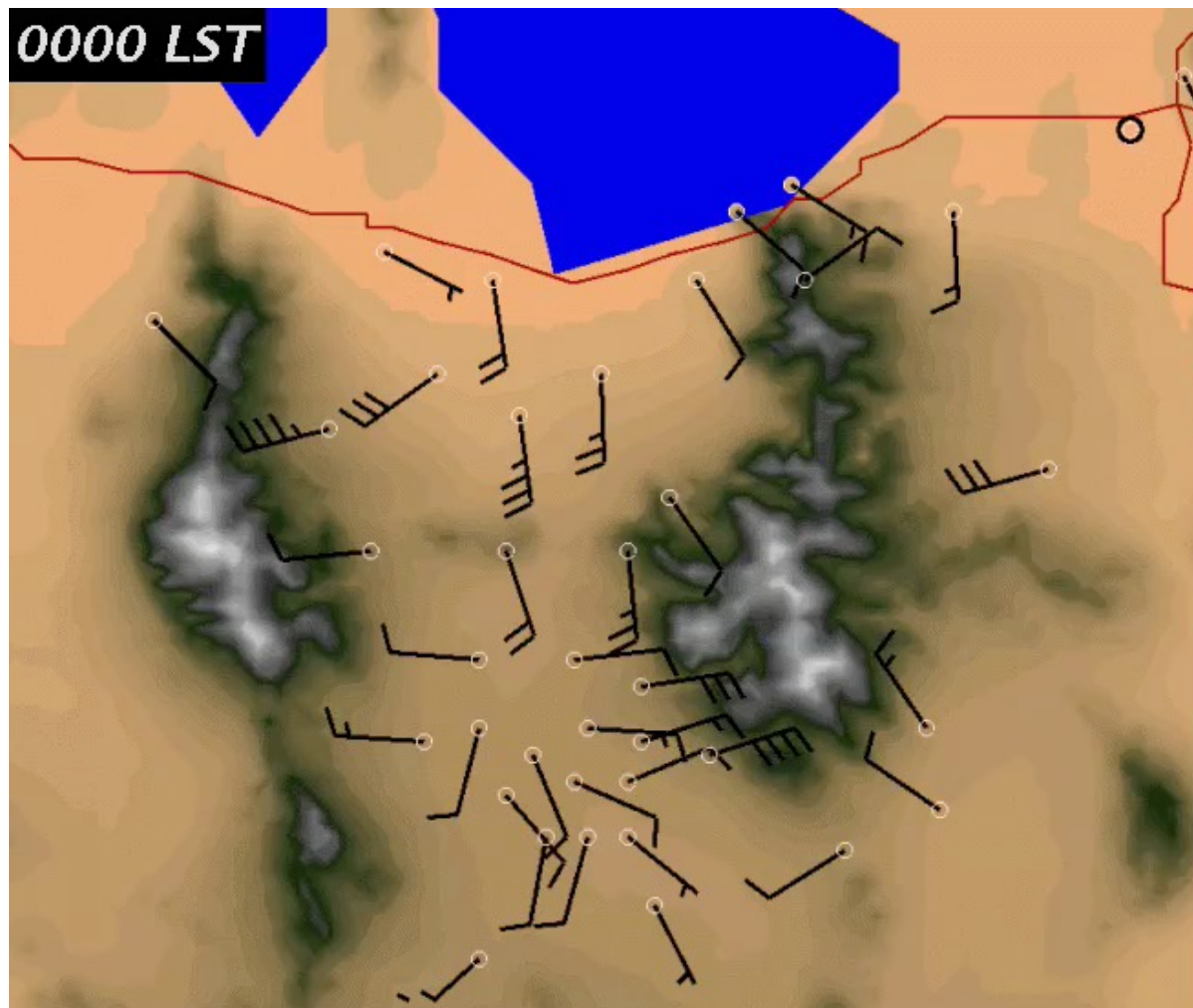
Fletcher=1 m/s



Jebb Stewart

Tooele Valley

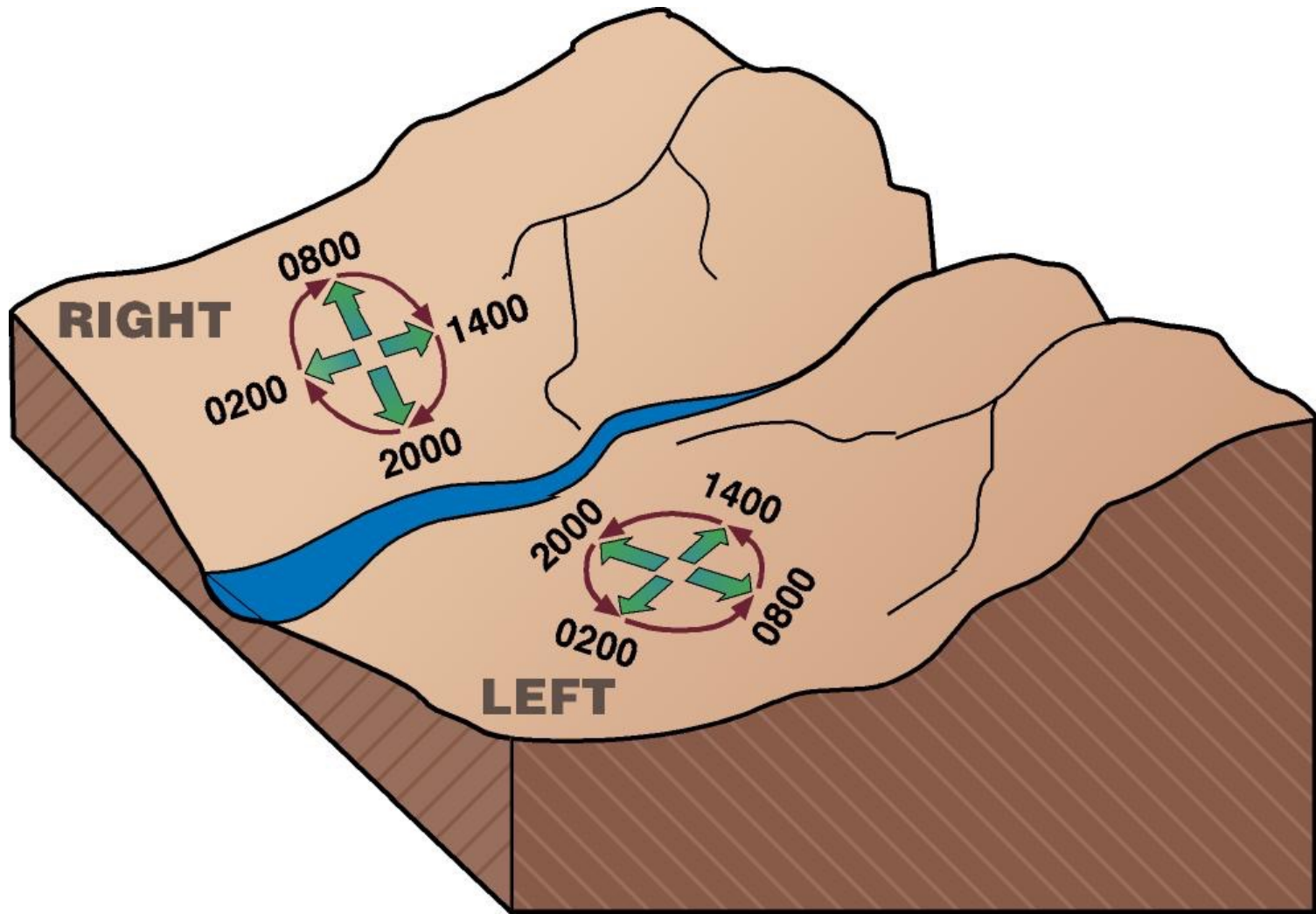
Rush Valley



Salt  
Lake  
Valley

adapted from Stewart et al. (2002)

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



Adapted from Hawkes (1947)

What is the diurnal variation of thermally driven flows that you expect at the Olympic venues?



Image Landsat / Copernicus  
Image © 2018 CNES / Airbus  
Image © 2018 DigitalGlobe

Google Earth

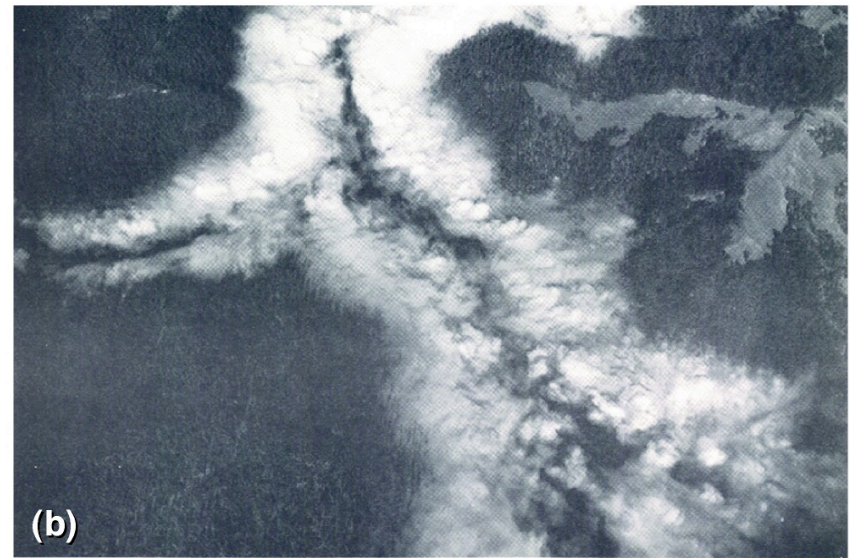
2009

eye alt 2.02 km

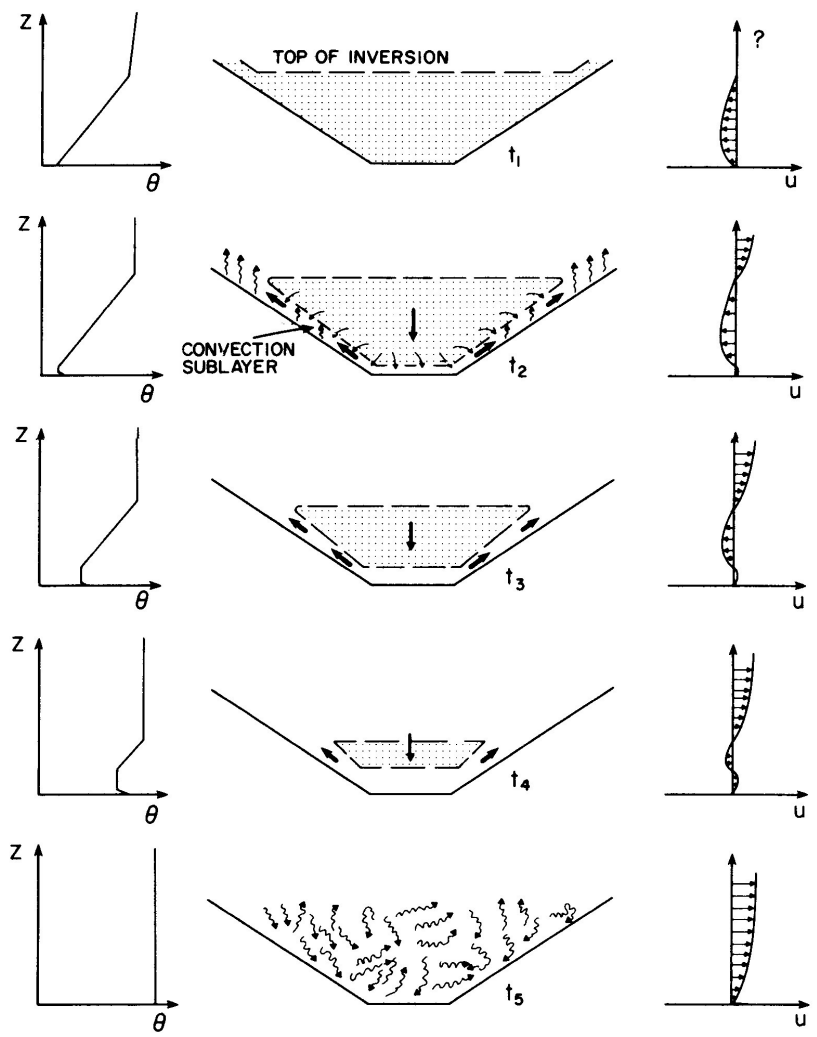
# Morning Transition

A photograph of a mountain range in the Eastern Alps, showing multiple layers of peaks receding into the distance under a hazy, overcast sky. The foreground shows dark, forested slopes, while the background peaks are shrouded in mist, creating a sense of depth and atmosphere.

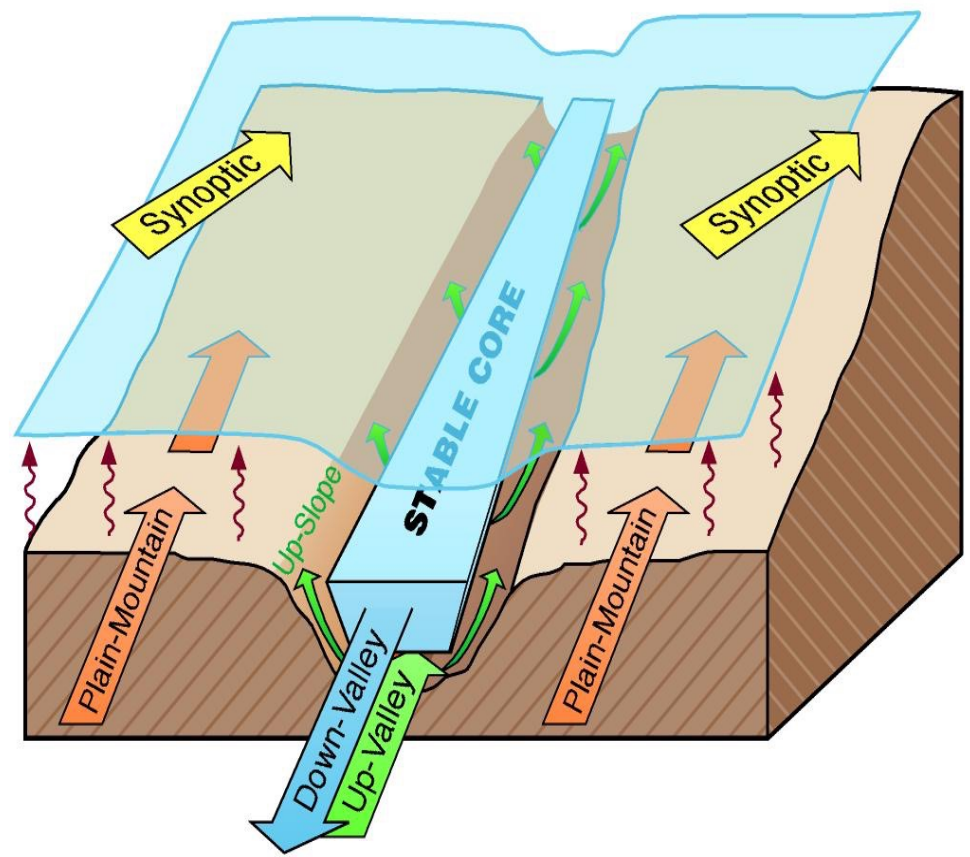
# Morning breakup of stratus, Redwood Valley, CA







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.  
Whiteman et al. (1999c) Comparison of integrated nighttime cooling in multiple valleys.  
Mahrt (2006) Variation of surface air temperature in complex terrain.  
Mahrt et al. (2001) Shallow drainage flows.

# Morning transition references

Bader & McKee (1985) Effects of shear, stability and topo characteristics on B-U.  
Sakiyama (1990) Breakup of inversions in two Canadian valleys.  
Kuwagata & Kimura (1994, 1997) Obs/sims of B-U in deep Japanese valley.  
Vrhovec & Hrabar (1996) Simulation of inversion B-U in Slovenian basin.  
Haiden (1998) Modify analytical model for differential vertical advection.  
Anquetin et al. (1998) LES simulation of diurnal cycle in idealized valley.  
Colette et al. (2003) Effects on B-U of valley width and depth and topo shading.  
Whiteman et al. (2004) Comparison of B-U between a European and a US basin.  
Zoumakis & Efsthathiou (2006a,b) Parameterization of B-U, thermodynamic model.  
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

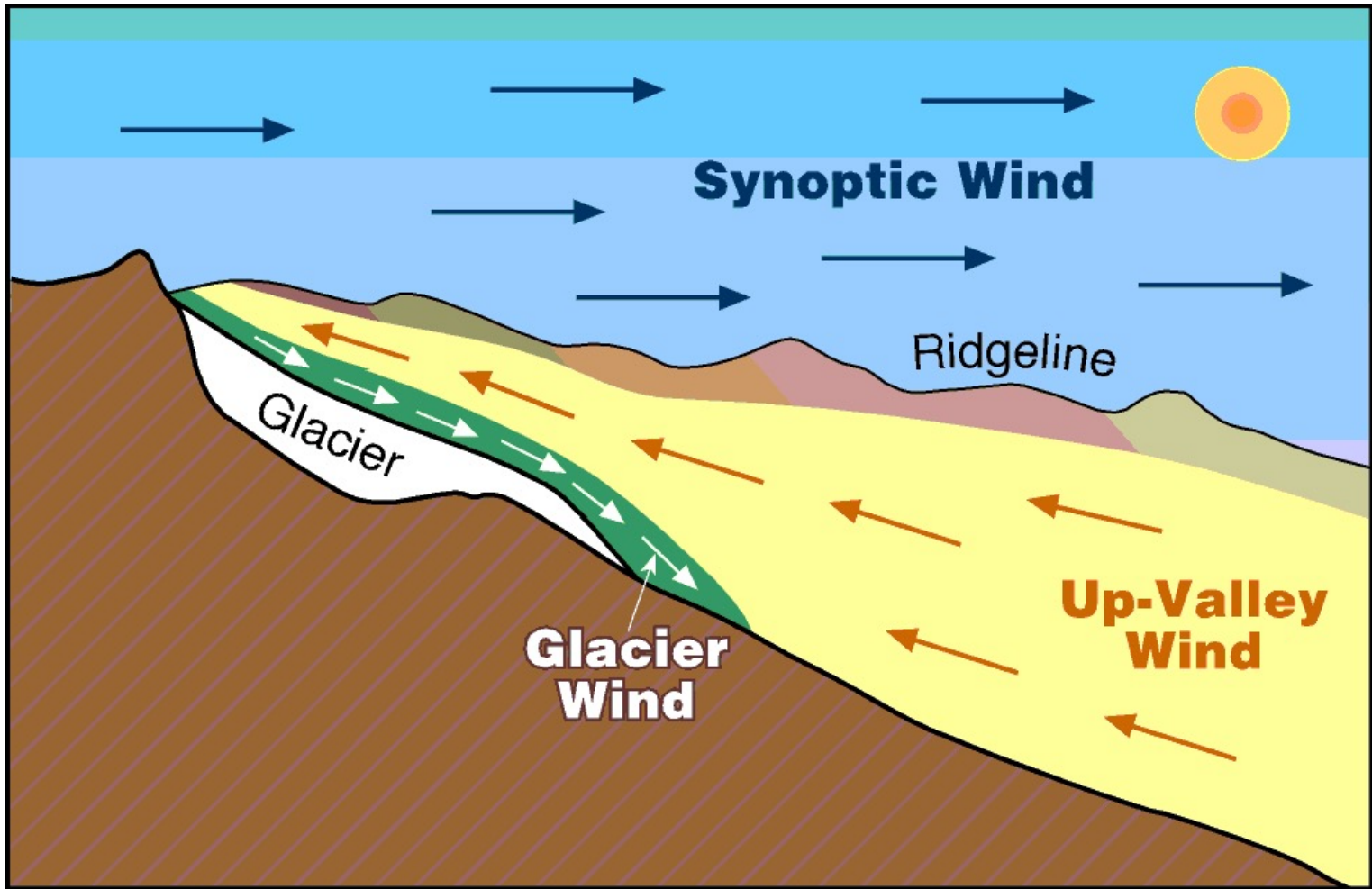


Marko Princevac

# Glacier Wind

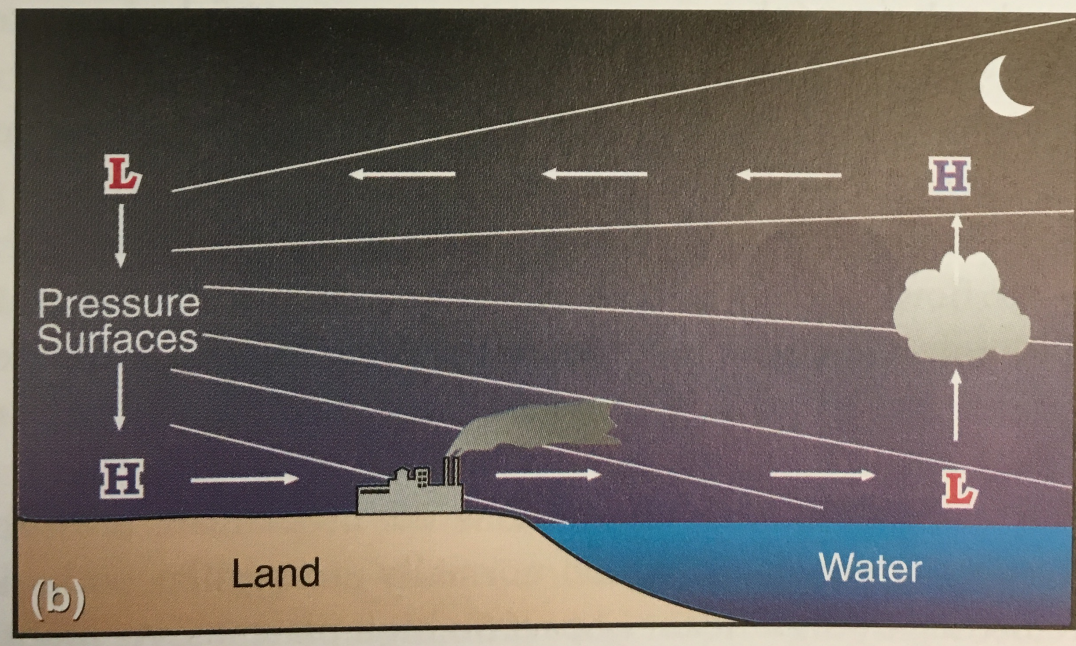
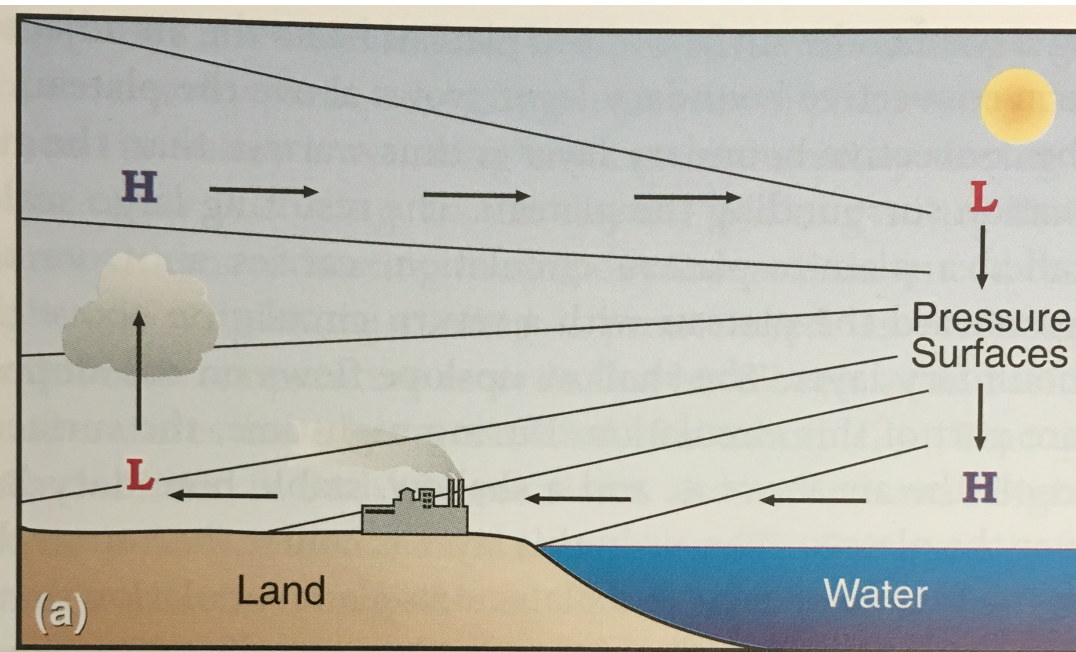


# Glacier wind



# Sea and Lake Breeze

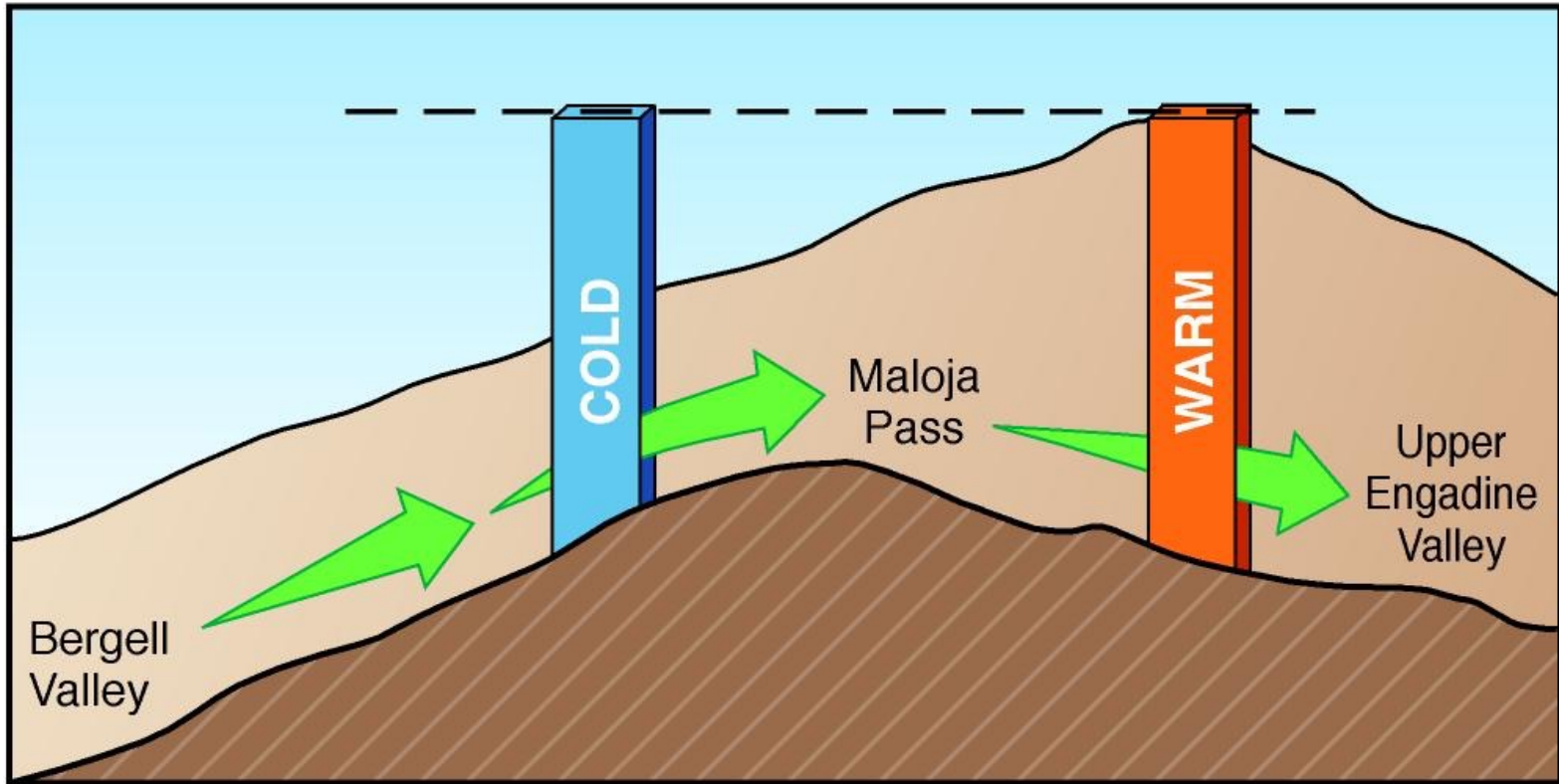




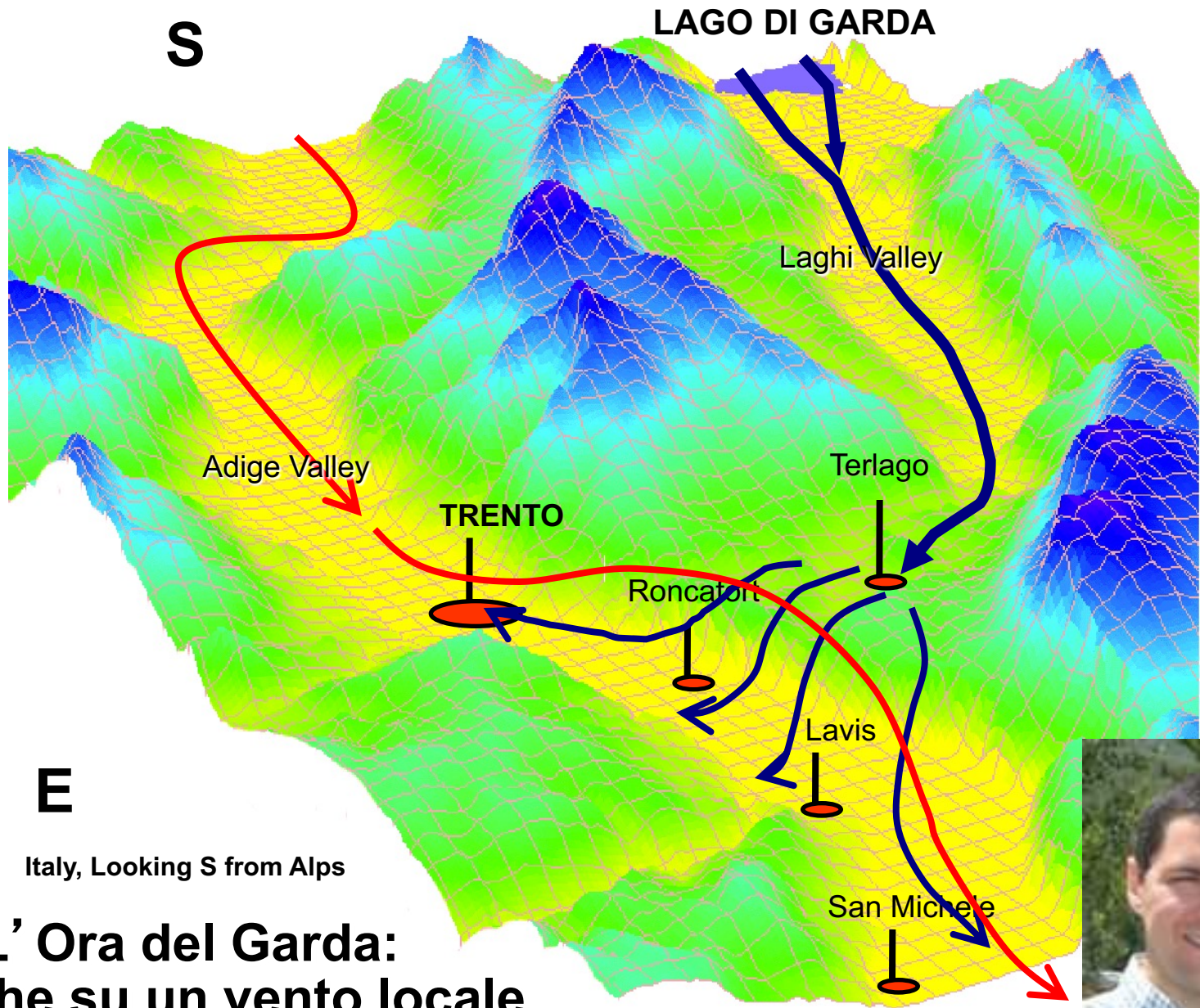
An aerial photograph of a desert landscape with sparse green and yellow vegetation. In the center, a white SUV is parked on a dirt road. Several tall, slender metal towers are visible, some with horizontal arms extending from them. The towers are spaced out across the terrain. The sky is clear and blue. The text "Special Wind System" is overlaid in large, bold, yellow letters in the lower half of the image.

# 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



# Thank you

Torres del Paine © Sigrid & Ron Smith