Thermally Driven Flows

Atmos 6250: Mountain Meteorology
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Photo: greatmontanabeertrek.com

Reading


Chapter 2
Diurnal Mountain Wind Systems

Dino Zardi and C. David Whiteman

Zardi, D., and C. D. Whiteman, 2013: Diurnal mountain wind systems. *Mountain Weather Research and Forecasting: Recent Progress and Current Challenges*. T. Chow, S. de Wekker, and B. Snyder, Eds., Springer, 35–119.

Discussion

- Why do terrain heterogeneities (mountains, valleys, slopes) lead to circulations in the presence of uniform surface heating or cooling?
- Can you provide some examples of thermally driven mountain, valley, or slope circulations in Utah?

Types of Mountain Winds

- *Dynamically driven flows* produced by the interaction of the large-scale flow with topography
- *Thermally driven flows* (a.k.a. diurnal mountain winds) produced by horizontal contrasts in heating and cooling that arise from topographic and land-surface contrasts
- Frequently combined to some extent

Types of Mountain Winds

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This Lecture

- *Thermally driven flows* (a.k.a. diurnal mountain winds) produced by horizontal contrasts in heating and cooling that arise from topographic and land-surface contrasts
- Frequently combined to some extent

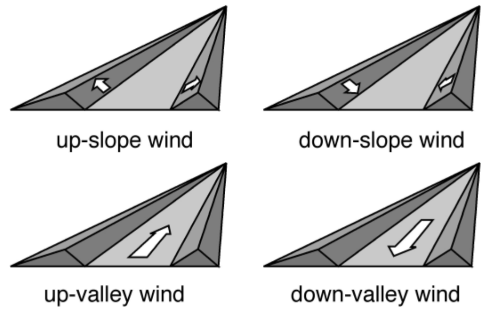
Thermally Driven Mountain Winds

- *Slope flows (upslope and downslope)*
  - Produced by horizontal temperature contrasts between air over a valley and air over its sidewalls
- *Valley flows (up-valley and down-valley)*
  - Produced by horizontal temperature contrasts along a valley axis or between air in the valley and over an adjacent plain
- *Cross-valley flows*
  - Produced by horizontal temperature differences between two opposing valley sidewalls
- *Mountain-plain wind system*
  - Produced by horizontal temperature differences between air over a mountain massif and air over the surrounding plains

Thermally Driven Mountain Winds

- *Diurnal mountain wind systems*
  - Thermally driven wind systems associated with the diurnal cycle of heating and cooling at the Earth's surface
  - Exhibit diurnal reversal
- *Anabatic flows*
  - Upslope, upvalley
- *Katabatic flows*
  - Downslope, downvalley
- Anabatic and katabatic flows do not necessarily exhibit diurnal reversal
  - Katabatic more commonly than anabatic

Slope and Valley Flows

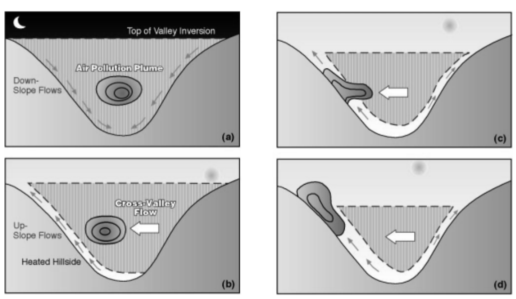


Daytime Nighttime

*Diurnal reversal common, but not required (e.g., glacial flows)

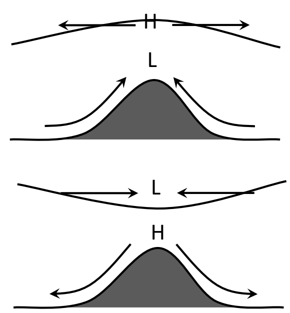
Whiteman (2000)

Cross Valley Flow



Bader and Whiteman (1989), Whiteman (2000)

Mountain-Plain Wind System

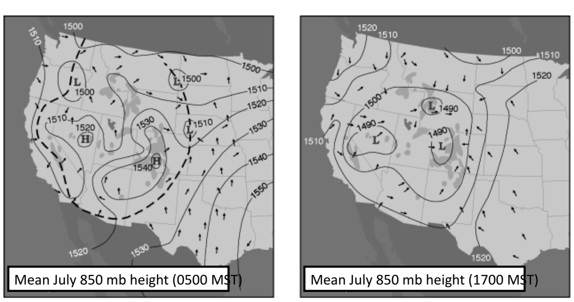


Regional-scale circulation between mountain/plateau massiff and surrounding lowlands

Daytime

Nighttime

Mountain-Plain Wind System

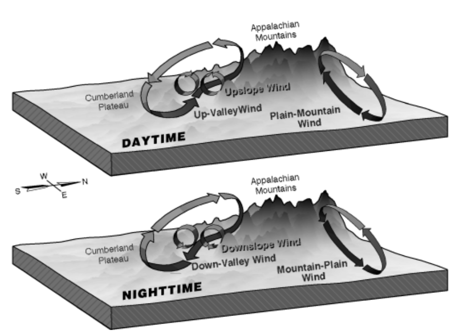


Mean July 850 mb height (0500 MST) Mean July 850 mb height (1700 MST)

Reiter & Tang (1984); Whiteman (2000)

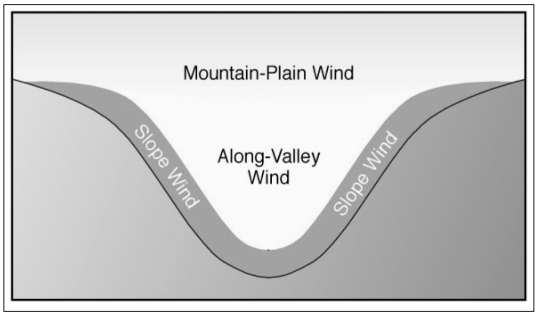
Reiter and Tang (1984), Whiteman (2000)

Multiscale Interactions



Whiteman (2000)

Multiscale Interactions



Whiteman (2000)

Slope Flows

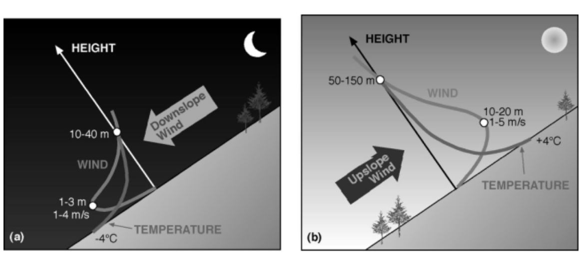
Discussion

- Late in the day, flows that move directly down the terrain gradient typically develop along slopes
- What mechanisms drive these flows?
- Why don't they continue to get stronger during the night (in most instances, they don't)

Slope Flows

- Gravity or buoyancy flows that follow the terrain gradient
- Driving force is buoyancy generated by the cooling or warming of air adjacent to the slope
- Best developed in clear, undisturbed weather
- Difficult to find in pure form

Slope Flows



Whiteman (2000)

Along-Slope Force Balance

$$\frac{Du}{Dt} = -g\frac{\theta'}{\theta_0}\sin\alpha - \frac{1}{\rho_0}\frac{\partial(p-p_a)}{\partial s} - \frac{\partial(\overline{u'w'})}{\partial n}$$

u = velocity parallel to slope (along s), positive downslope

ρ_0 = reference density without cooling

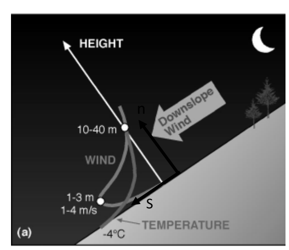
P_a = Ambient pressure

θ' = perturbation θ near slope

θ_0 = reference θ

α = slope angle

$\overline{u'w'}$ = turbulent momentum flux

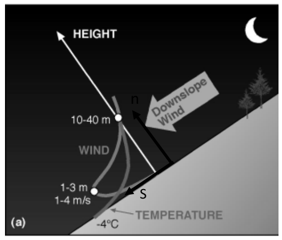


Horst and Doran (1986), Whiteman (2000)

Along-Slope Force Balance

$$\frac{Du}{Dt} = -g\frac{\theta'}{\theta_0}\sin\alpha - \frac{1}{\rho_0}\frac{\partial(p-p_a)}{\partial s} - \frac{\partial(\overline{u'w'})}{\partial n}$$

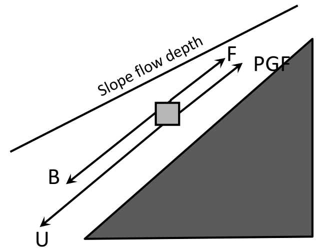
$\frac{Du}{Dt}$	Along-slope acceleration
$-g\frac{\theta'}{\theta_0}\sin\alpha$	Buoyancy component along slope
$-\frac{1}{\rho_0}\frac{\partial(p-p_a)}{\partial s}$	Along-slope pressure difference gradient (difference relative to ambient)
$-\frac{\partial(u'w')}{\partial n}$	Turbulent momentum flux (a.k.a., friction)



Horst and Doran (1986), Whiteman (2000)

Slope Flows

$$\frac{Du}{Dt} = -g\frac{\theta'}{\theta_0}\sin\alpha - \frac{1}{\rho_0}\frac{\partial(p-p_a)}{\partial s} - \frac{\partial(\overline{u'w'})}{\partial n}$$



Assuming steady state, buoyancy balanced by:

1. Friction/entrainment
2. Pressure gradient (relative to ambient) produced by changes in depth of cold pool along slope

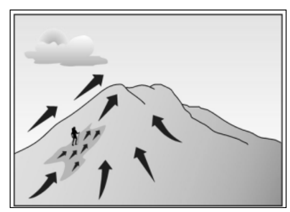
Horst and Doran (1986), Whiteman (2000)

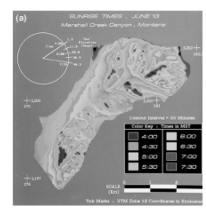
Slope Flows

- Typically 1–5 ms^{-1}, but speed increases with slope length
  – Antarctica 15–30 ms^{-1}
- Decrease in depth with increasing static stability
- Downslope flows
  – Strongest at or just following sunset
    - Deepening cold pool creates adverse PGF later at night and limits buoyancy effect
    - Converge into gullies, basins, etc.
- Upslope flows
  – Strongest midmorning
  – Increase in depth as one moves upslope
  – Converge over higher ground (e.g., ridges, plateaus, etc.)

Slope Flows

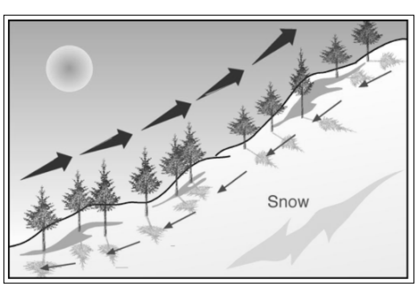
- Very sensitive to spatial variations in surface radiation
  – Persistent cloud cover, time of sunrise/sunset
  – Slope aspect, topographic shading, etc.





Whiteman (2000)

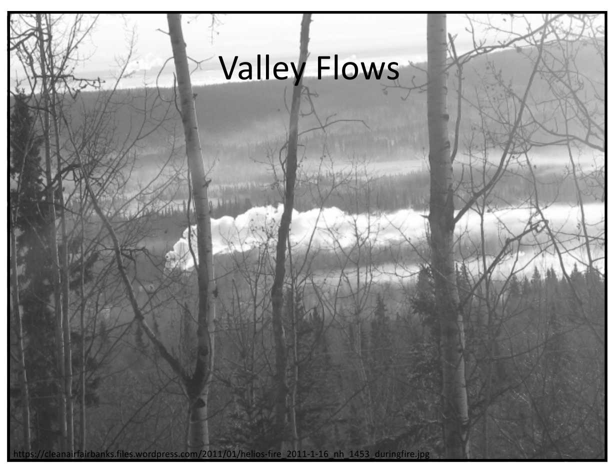
Upslope Flow above Forest



Heating in canopy layer can produce upslope flow above shallow downslope in the snow-cooled sub-canopy layer

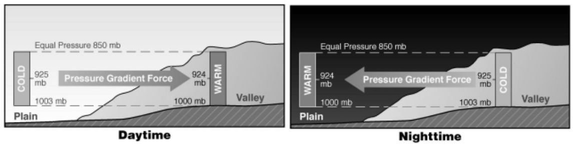
Whiteman (2000)

Valley Flows



https://cleanairfairbanks.files.wordpress.com/2011/01/helios-fire_2011-1-16_nh_1453_duringfire.jpg

Valley Flows

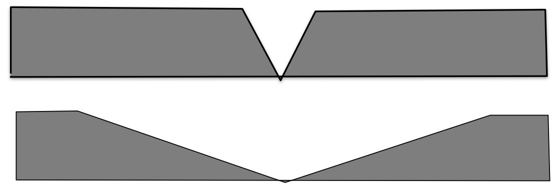


- Driven by stronger heating and cooling of the valley atmosphere compared to the adjacent plain
- Best developed in clear, undisturbed weather

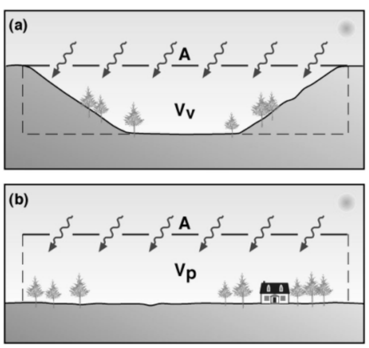
Whiteman (2000)

Discussion

- Based on the cross sections pictured, which of the valleys below would have a stronger daytime up-valley flow?



Valley Winds

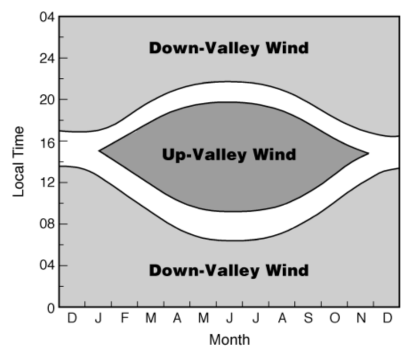


Valley Volume Effect
Valley-to-plain temperature contrasts develop because air volume in valley is smaller than that in plain

Valley doesn't have to slope to produce along-valley winds

Whiteman (2000)

Seasonal Effect on Diurnal Reversal

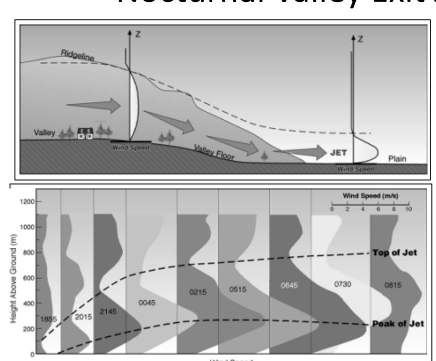


Reiter et al. (1983), Whiteman (2000)

Nocturnal Valley Exit Jet

- Winds tend to be higher near mouth of a valley because
  - Winds accelerate with distance down the valley
  - Horizontal pressure gradient largest near exit where there is an abrupt transition from high pressure in valley to low pressure over plain
  - By continuity, wind speed increases as cold valley air sinks and fans out over plain
- Greatest impact for deep valleys that end abruptly at a plain

Nocturnal Valley Exit Jet

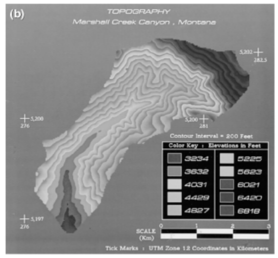


Exit jet from Austria's Inn Valley

Pamperin and Stilke (1985), Whiteman (2000)

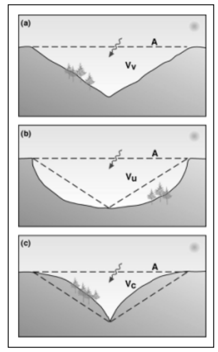
Valley Wind Variability

- Along-valley temperature and wind variability can be produced by
  - Contrast in short- or lon-wave radiation losses or gains along valley
  - Rate of conversion of net radiation to sensible heat
    - Concerns: Heterogeneous snow cover, soil moisture, vegetation



Whiteman (2000)

Valley Shape



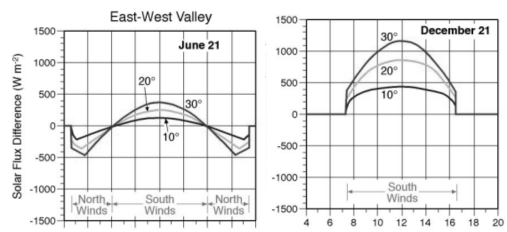
- Along-valley temperature and wind variability can be produced by changes in valley volume
  - Heating of air in valley is proportional to valley volume (Whiteman 1990)
  - Areas with convex valley sidewalls heat more quickly than U-shaped areas

Whiteman (2000)

Discussion

This photo of upper Little Cottonwood Canyon was taken shortly after sunrise
Assuming calm large-scale winds, what local flows do you expect?

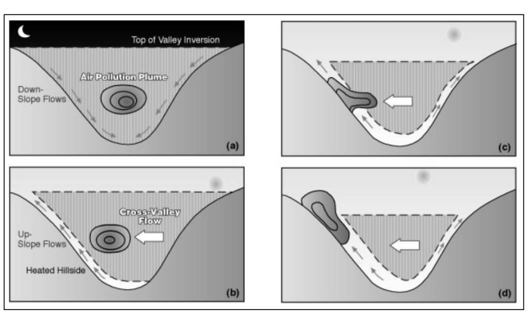
Cross-Valley Winds



- Blow across valley when air on one side becomes warmer than other sid)
- Compensatory flows in opposite direction aloft
- Culprits: Unequal sidewall exposure to sun, heterogeneous snow cover, vegetation, soil moisture

Whiteman (2000)

Cross-Valley Winds

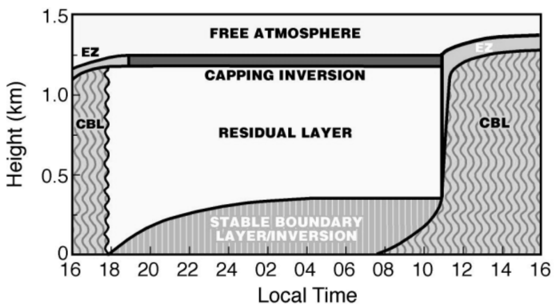


Bader and Whiteman (1989), Whiteman (2000)

The Diurnal PBL Cycle

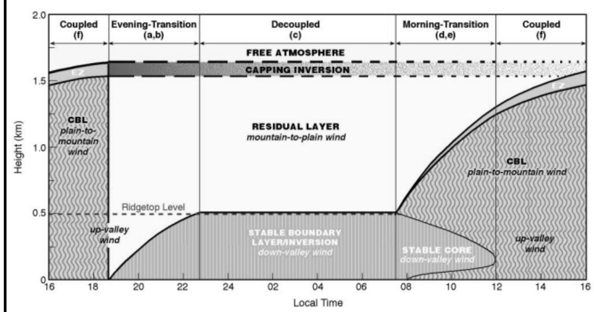
- Nighttime (decoupled) period
- Morning transition
- Daytime CBL
- Evening transition

Diurnal PBL Evolution over a Plain



Whiteman (2000)

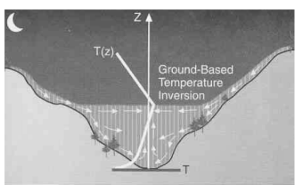
Diurnal PBL Evolution over Valley

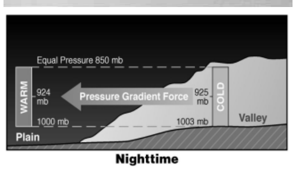


Whiteman (2000)

Nighttime Decoupled Period

- Valley flow decoupled from residual CBL aloft
- Down valley and downslope winds prevail





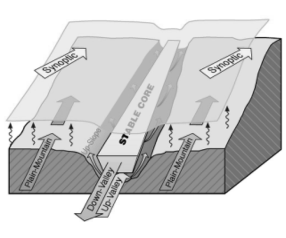
Whiteman (2000)

Discussion

- What is going on in the Wasatch Weather Weenies banner below? Describe the clouds and hypothesize why they look the way they do

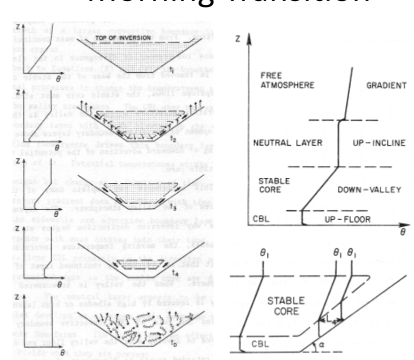
Morning Transition

- CBL begins to develop over *heated* slopes
- Upslope flows develop along valley sidewals, then shallow up-valley flow along valley axis
- Top of inversion sinks due to compensating subsidence
- Downvalley flow persists in shrinking stable-core aloft
- Stable core eventually destroyed by CBL growth and up-valley flow extends through valley depth
- Valley may eventually couple with ambient synoptic flow or plain-mountain circulation



Whiteman (2000)

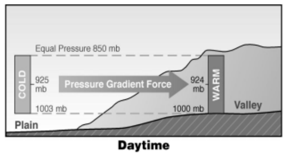
Morning Transition

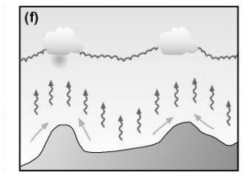


Whiteman (1980)

Daytime CBL

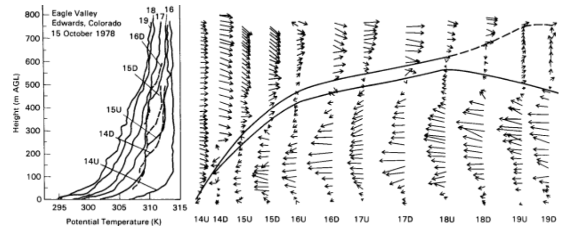
- Convection occurs above all slopes
- Upslope and up-valley flows predominate within valley
- Winds transition to the large-scale flow above the valley
- Winds in the valley may become turbulent and upper winds may occasionally channel into valley





Whiteman (2000)

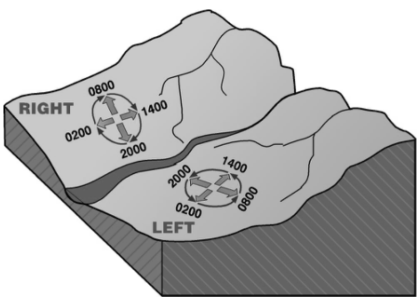
Evening Transition



- Begins in late afternoon
- Downslope flows begin first in shaded areas on sidwalls and valley floor, then over all sidewals
- Valley inversion with down-valley flow grows in depth

Whiteman (1986)

Diurnal Cycle Hodograms

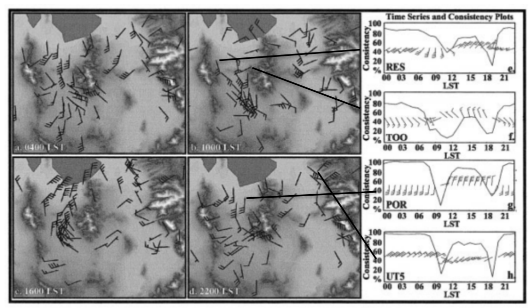


Right Bank winds turn clockwise

Left Bank winds turn counterclockwise

Hawkes (1947), Whiteman (2000)

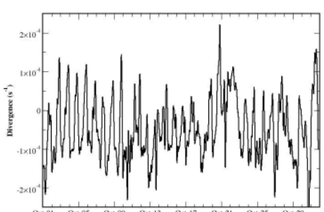
Discussion



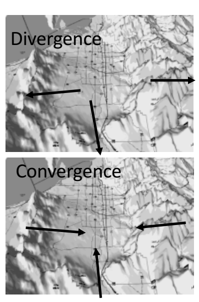
How well do the mean summer winds at the stations above match the theory on the prior slide? Explain discrepancies (Full and half barb denote 1 and 0.5 ms^{-1}, respectively)

Stewart et al. (2002)

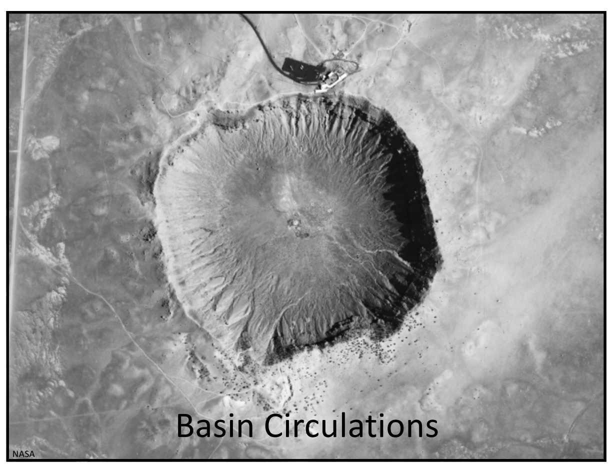
Diurnal Cycle of Valley Divergence



October 2000

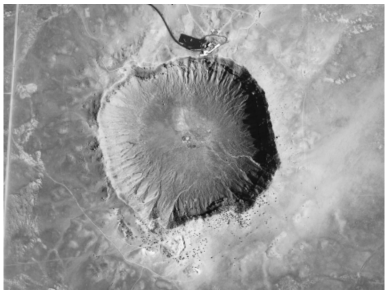


Courtesy Mike Splitt



NASA

Discussion



Describe the diurnal evolution of winds you expect in a basin. How are they Different than in a valley? Why?

NASA

Basin Circulations

- Unless perturbed by the larger-scale flow, enclosed terrain features develop slope flows but weak along-basin circulations
  - Slope flows typically weaken as basin cold pool deepens
- The absence of along-basin advection and associated turbulence results in a larger diurnal temperature range
  - Overnight minimums are especially low
- Basin cold pools can be diurnal (i.e., develop at night) or persist for days or weeks

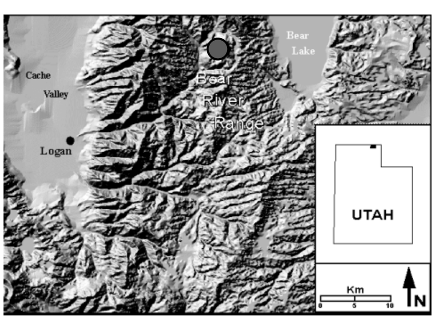
Examples

Whiteman (2000)

Examples

Courtesy Dave Whiteman

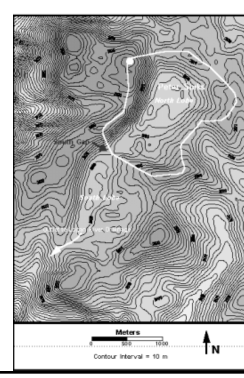
Peter Sinks



Utah all-time record low of -57°C

Clements (2001)

North Sink



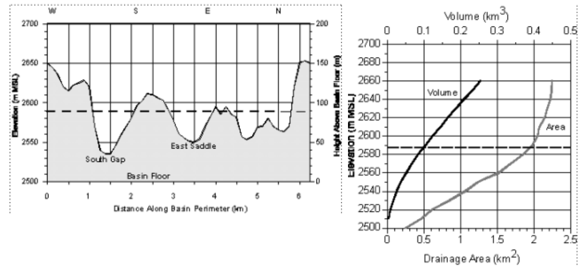
Clements (2001)

North Sink

Vegetation "inversion"

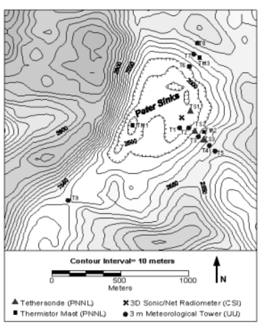
Clements (2001)

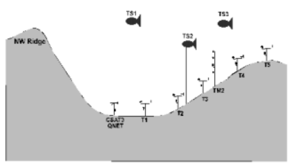
Perimeter



Clements (2001)

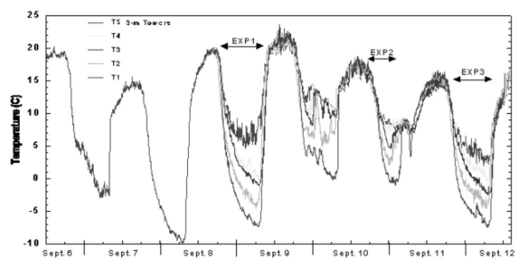
Instrumentation





Clements (2001)

Surface Temperature

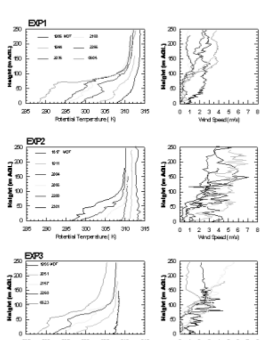


Big diurnal cycle
Coldest air in bottom of basin
Air temperature increases upward along basin sidewalls

Clements (2001)

Vertical Structure

- Gradual cooling of basin airmass through night
- Downslope flow early, then winds become weak
- Inversion at top of basin strengthens



Clements (2001)

Summary

- Large spectrum of thermally driven flows in complex terrain
  - Slope flows
  - Valley flows
  - Cross-valley flows
  - Mountain-plain circulations
- Typical diurnal evolution under light forcing includes
  - Nocturnal regime
    - Downslope and down-valley flows
  - Morning transition
    - Rapid development of slope and shallow up-valley flows
    - Gradual erosion of elevated down-valley flow and stable core aloft
  - Afternoon regime
    - Upslope and up-valley; possible coupling with large-scale flow aloft
  - Evening regime
    - Rapid onset of downslope then downvalley with gradual deepening of cold core
- Basins
  - Weak slope flows initially in evening that weaken
  - Attain very cold nocturnal temperatures due to limited flows and turbulence

References

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