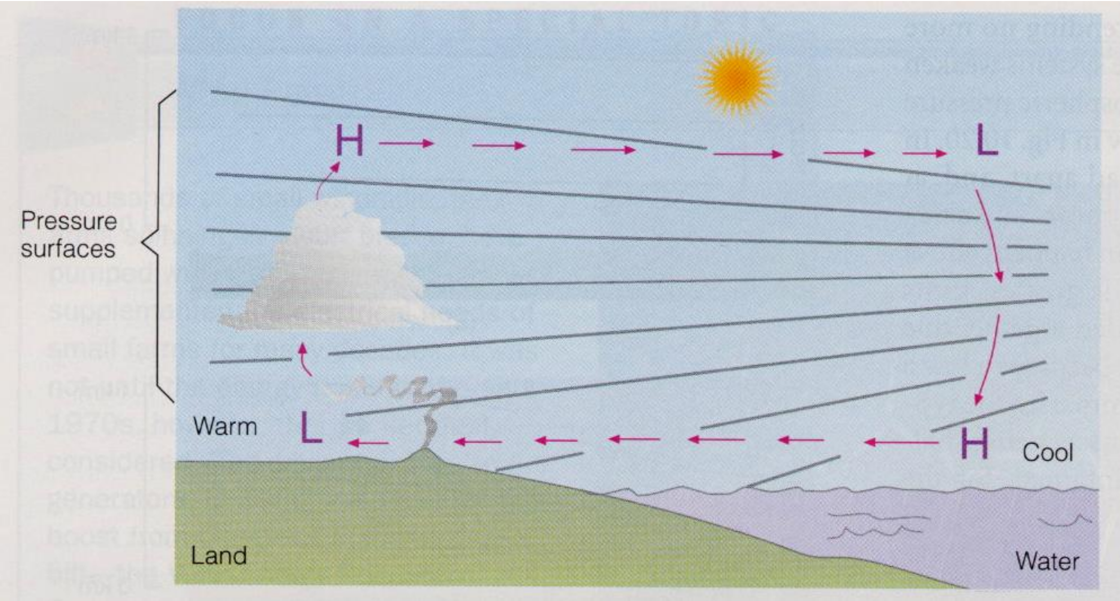
Local wind systems

Textbooks and web sites references for this lecture:

- Dennis L. Hartmann, Global Physics Climatology, Academic Press, 1994, ISBN 0-12-328530-5 (§ 6)
- Robert McIlveen, Fundamentals of Weather and Climate, Chapman & Hall, 1995, ISBN 0-412-41160-1 (§ 11)
- Joseph M. Moran e Michael D. Morgan, Meteorology, The Atmosphere and the Science of Weather, Mc Millan College Publishing Company, 1994, ISBN 0-02-383341-6 (§ 10)
- James R. Holton, An Introduction to Dynamic Meteorology, Academic Press, 1992, ISBN 0-12-354355-X (§ 9.5-9.6)

Sea and Land Breezes

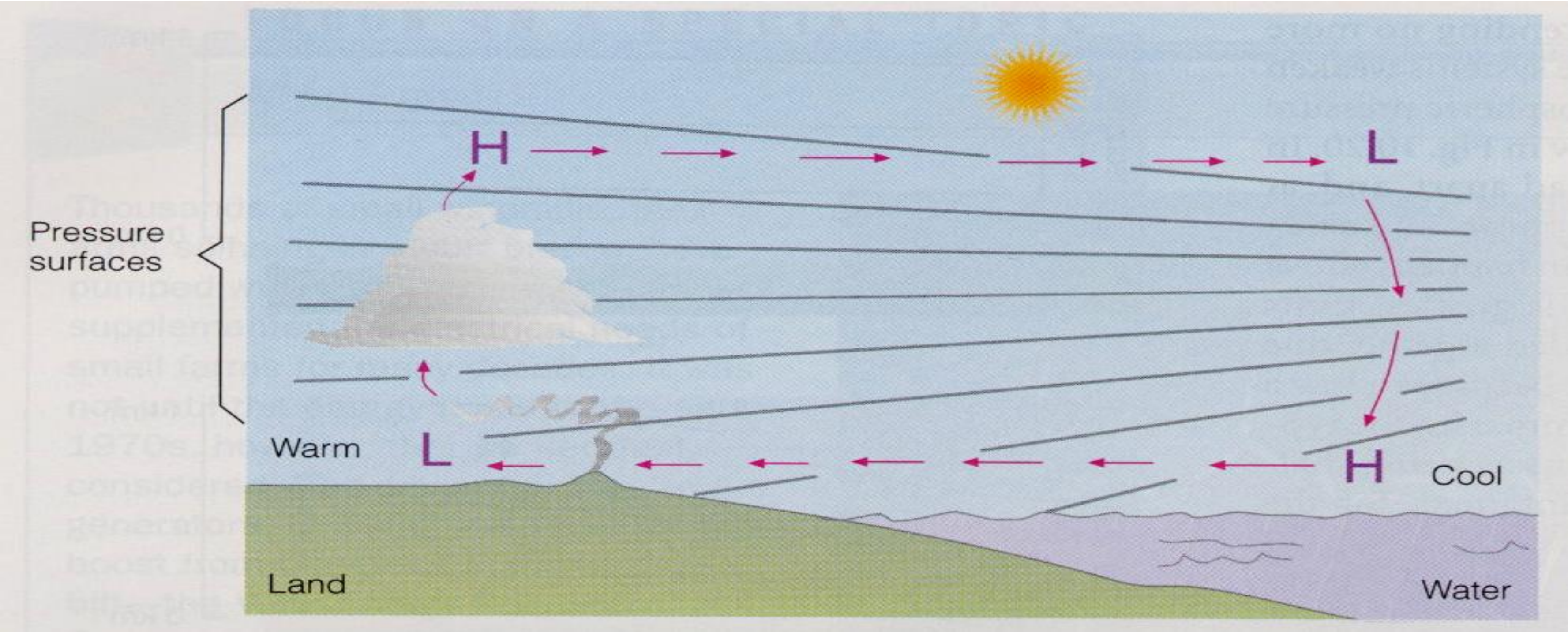
- Sea and land breezes are
  - Mesoscale coastal winds
  - Thermal circulations driven by differential heating/cooling of adjacent land and water surfaces
  - Most prevalent when/where solar heating is strong
- Sea breeze development
  - Solar heating raises land temperature more than water
  - Air in contact with land warms and rises
  - Cooler (denser) sea air moves in to replace rising air over land
  - Air sinks over the water in response to surface air movement, producing return circulation (land-to-sea breeze) aloft



- Sea breezes
  - Cool coastal communities
  - Bring more humid air
    - Haze
    - Fog
  - Often produce summer thunderstorms inland from the coast

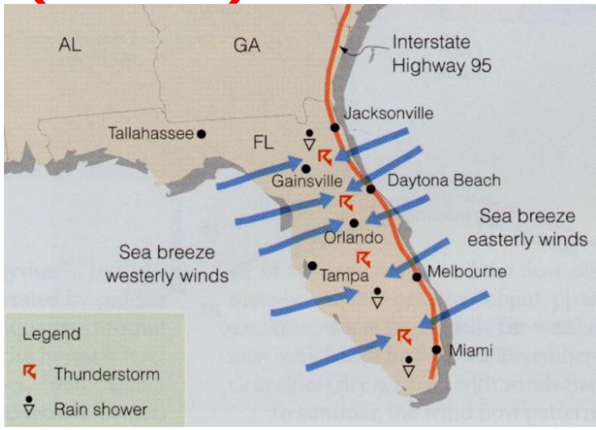
Six Steps in Sea Breeze Development

- We can also describe sea breeze in terms of pressure gradients
  - Land is heated creating “bulging” pressure surfaces
  - Heated column produces “**H**” aloft over land
  - Air aloft flows outward from land to ocean
  - Upper flow creates surface “**H**” over water
  - Surface flow responds with flow toward land at low levels
  - Large scale ascent over land destabilizes column - enhances cloud development - thunderstorms
    - » descent over ocean stabilizes oceanic column



Sea and Land Breezes (cont)

- Converging Gulf of Mexico and Atlantic sea breezes produce uplift and thunderstorm development in Florida
  - Disruption of sea breezes reduces rainfall and can lead to a bad fire season



- Land breezes form at night due to stronger radiative cooling of land surface leading to sinking and offshore flow of this cooler air mass with return flow aloft

Brezze: analisi quantitativa

- Let consider Navier-Stokes equation: $\frac{d\bar{u}}{dt} = -\frac{\overline{\nabla p}}{\rho} - 2\bar{\Omega} \times \bar{u} + \bar{g} + \frac{\bar{F}}{\rho}$

- As circulation of u can be seen as vorticity $\bar{\omega} = \bar{\nabla} \times \bar{u}$ flux, we have:

$$\Gamma = \int_S \bar{\omega} \bullet \bar{n}\, dS = \oint_\gamma \bar{u} \bullet d\bar{r}$$

- And the time derivative of the above expression is:

$$\frac{d\Gamma}{dt} = \frac{d}{dt}\oint_\gamma \bar{u} \bullet d\bar{r} = \oint_\gamma \frac{d\bar{u}}{dt} \bullet d\bar{r} + \oint_\gamma \bar{u} \bullet d\bar{u} = \oint_\gamma \frac{d\bar{u}}{dt} \bullet d\bar{r}$$

because $\oint_\gamma \bar{u} \bullet d\bar{u} = \oint_\gamma du^2 = 0$

- Then, substituting: $\frac{d\Gamma}{dt} = -\oint_\gamma \frac{\overline{\nabla p}}{\rho} \bullet d\bar{r} - 2\oint_\gamma \bar{\Omega} \times \bar{u} \bullet d\bar{r} + \oint_\gamma \frac{\bar{F}}{\rho} \bullet d\bar{r}$

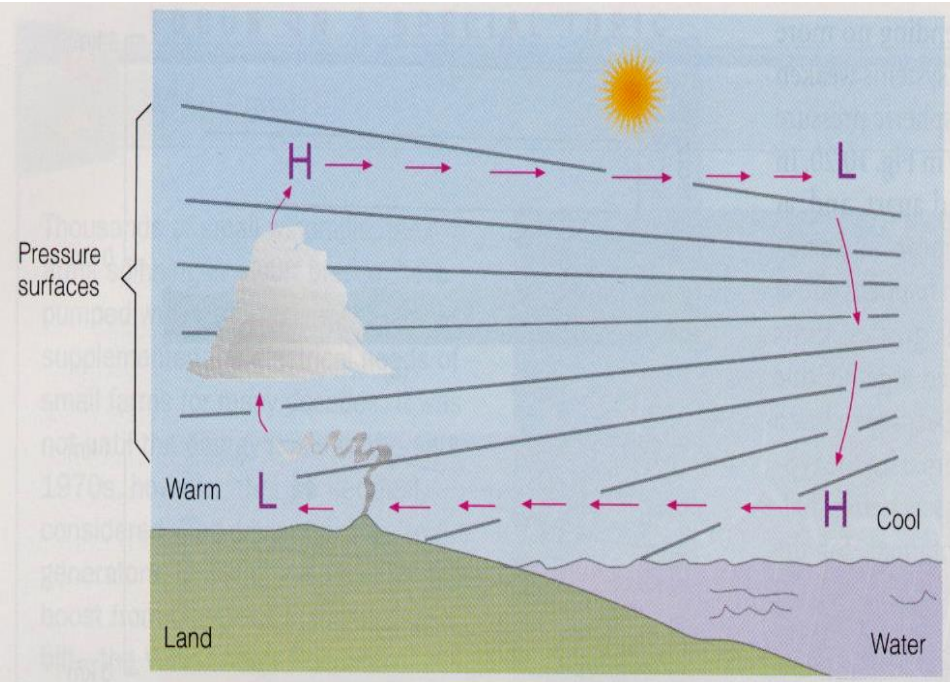
- Let consider, of these terms, only pressure gradient: we can write:

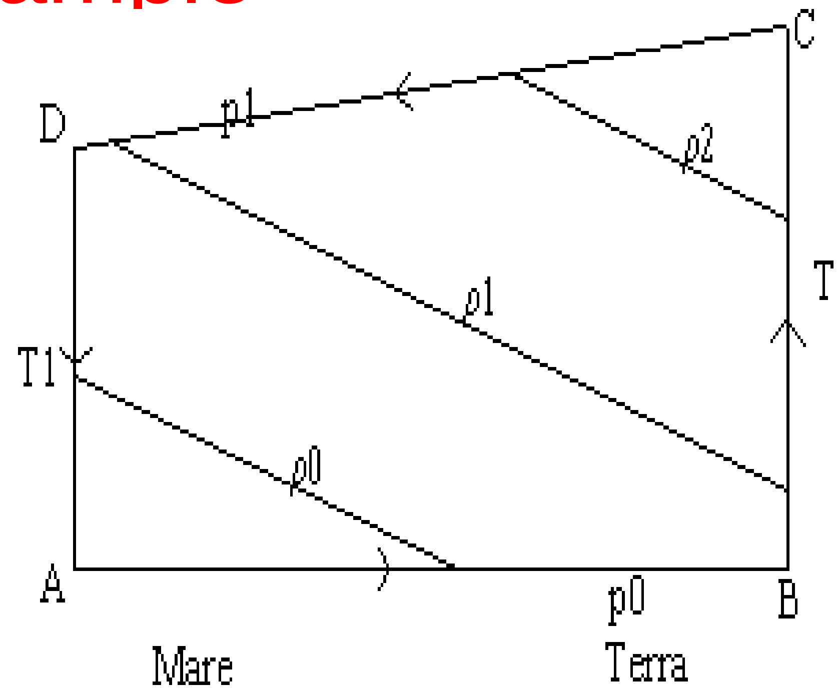
$$\frac{\overline{\nabla p}}{\rho} \bullet d\bar{r} = \frac{dp}{\rho} = R_d T d\, ln\, p$$

from which

$$\frac{d\Gamma}{dt} \cong R_d \ln \frac{p_1}{p_0} (T_2 - T_1)$$

Breeze example





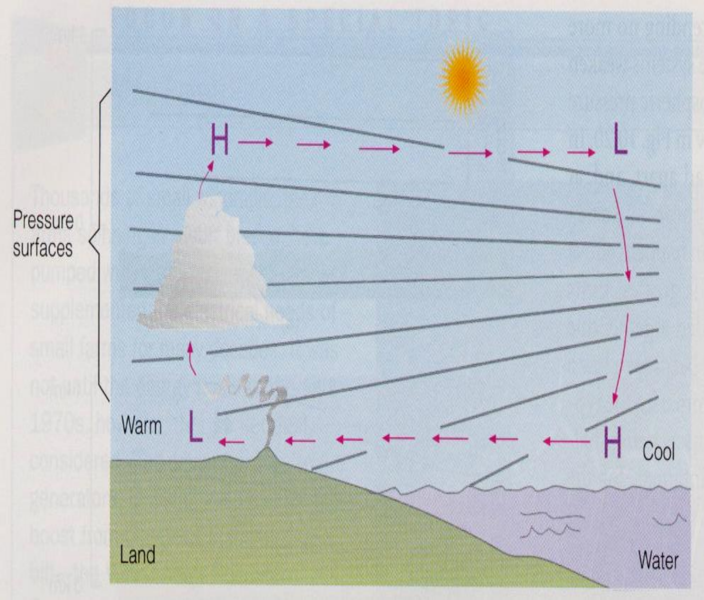
- Let consider diurnal breeze case; let take as integration path Γ the ABCD path of the air along the cell; this path is constituted by the two isobaric lines p_0 and p_1 and by the two vertical lines AD and BC; Γ=AB+BC+CD+DA
- The only segments giving non-null contribution to the integral are AD and BC, because along the two isobaric lines p_0 and p_1 dp is zero; integral is then:

$$\frac{d\Gamma}{dt} \cong R_d \ln\frac{p_1}{p_0}\left(T_2 - T_1\right)$$

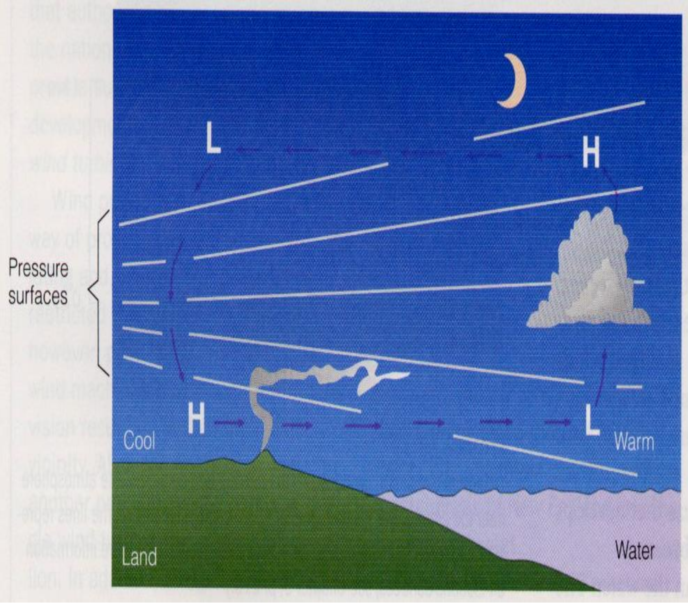
$$\frac{d\Gamma}{dt} = \frac{d}{dt}\oint_\gamma \bar{u}\bullet d\bar{r} \approx \frac{d\bar{u}}{dt}\bullet\oint_\gamma d\bar{r} = \frac{d\bar{u}}{dt}\left[2(h+L)\right]$$

$$\frac{d\bar{u}}{dt} \cong R_d \ln\left(\frac{p_1}{p_0}\right)\frac{\left(T_2 - T_1\right)}{2(h+L)}$$

Breeze numerical example



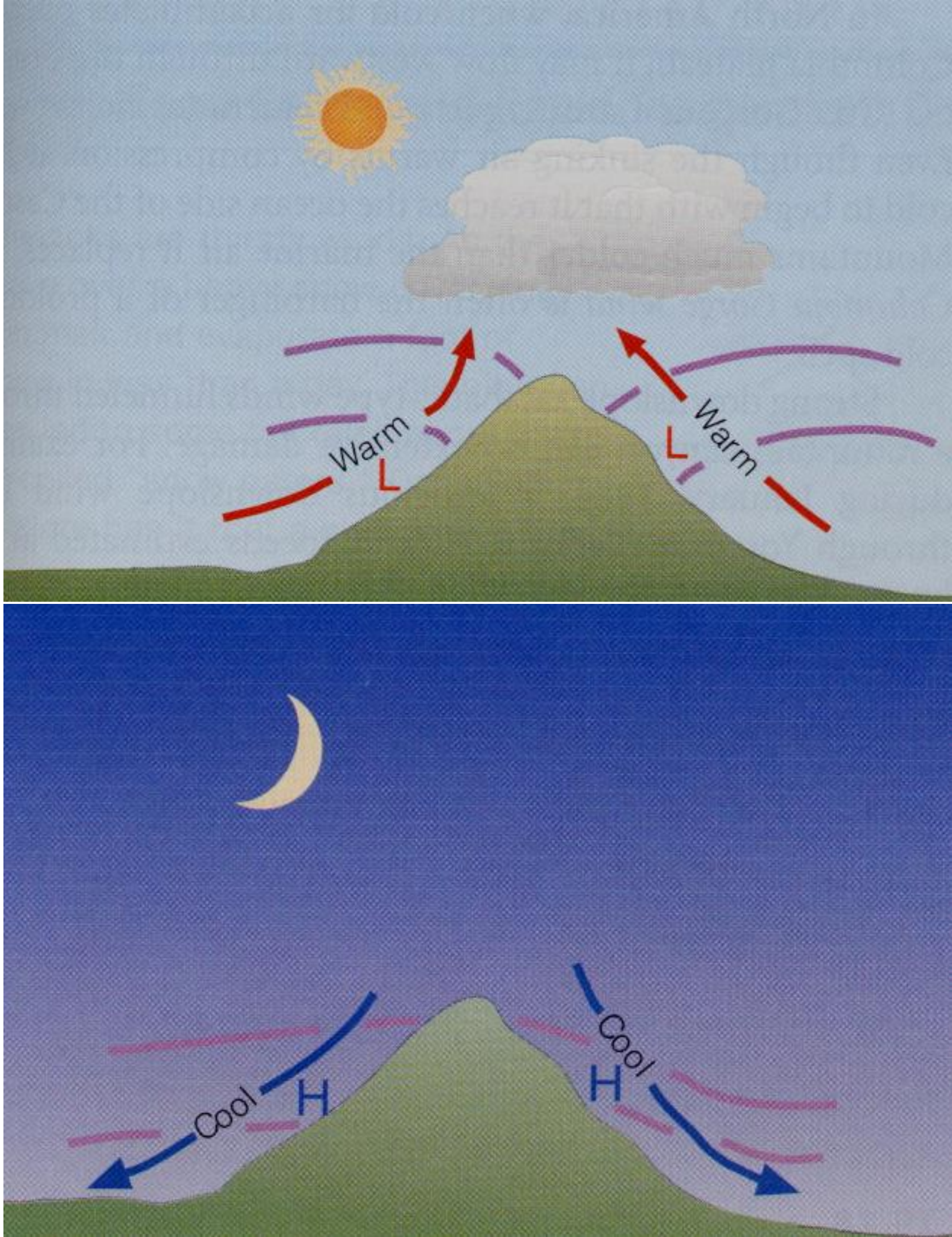
$$\frac{d\bar{u}}{dt} \cong R_d \ln\left(\frac{p_1}{p_0}\right)\frac{(T_2 - T_1)}{2(h+L)}$$



- Then, if $T_2 > T_1$ we have $d\Gamma/dt > 0$ i.e. the resulting circuitation is disposed in way that wind flows from sea to land (diurnal situation), while during nighttime, when $T_2 < T_1$ and then $d\Gamma/dt < 0$, the wind flows from land to sea
- This equation is approximated as all destructive terms have been neglected, so the velocity <u> is considered accelerated
- Considering <u> constant along line ABCD, by naming L=AB≈CD and h≈AD≈BC, we have that, considering typical values p_0≈1000 hPa, p_1≈900 hPa, $(T_2 - T_1)$≈10 °C, L=20 Km e h=1 Km, the mean acceleration is 7 10^{-3} ms^{-2}, corresponding to about 25 ms^{-1} in 1 hour in absence of friction

Mountain/Valley winds

- Sunlight heats mountain slopes during the day and they cool by radiation at night
- Air in contact with surface is heated/cooled in response
- A difference in air density is produced between air next to the mountainside and air at the same altitude away from the mountain
- Density difference produces upslope (day) or downslope (night) flow
- Daily upslope/downslope wind cycle is strongest in clear summer weather when prevailing winds are light

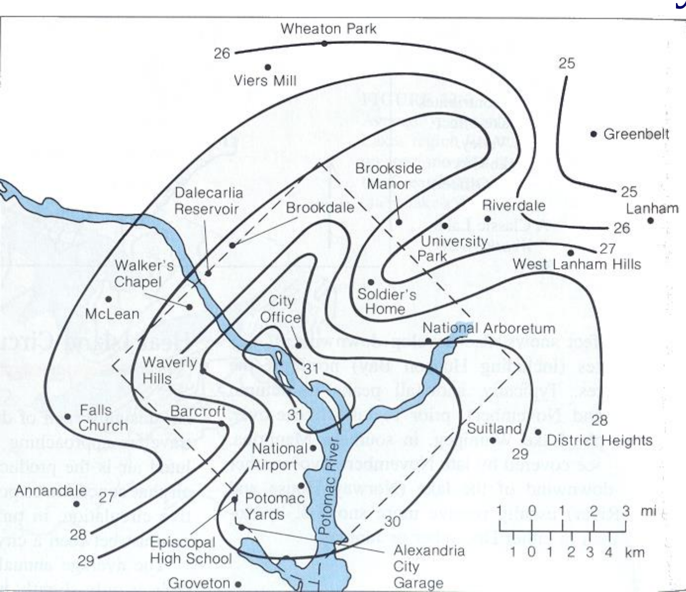


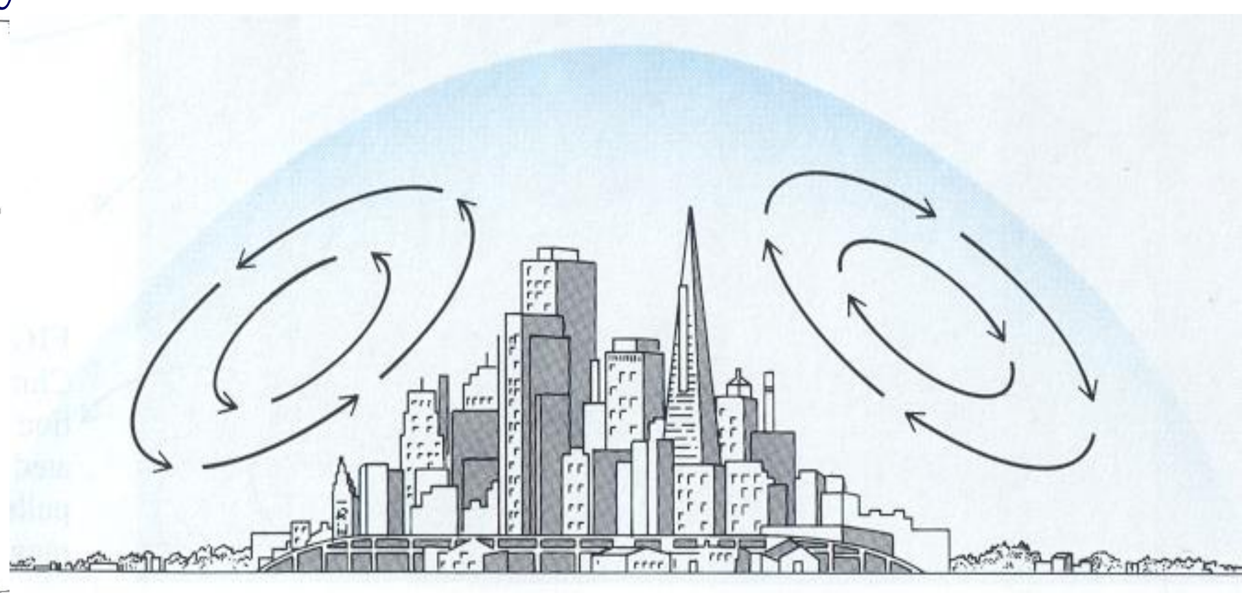
Consequences of Mountain/Valley winds

- Upslope flow during the day leads to formation of clouds and precipitation along mountain ranges
  - When is the best time for hiking and climbing?
- Breezes transport pollutants from the urban area into the mountain areas (Susa valley, Aosta valley, …)

Urban heat islands

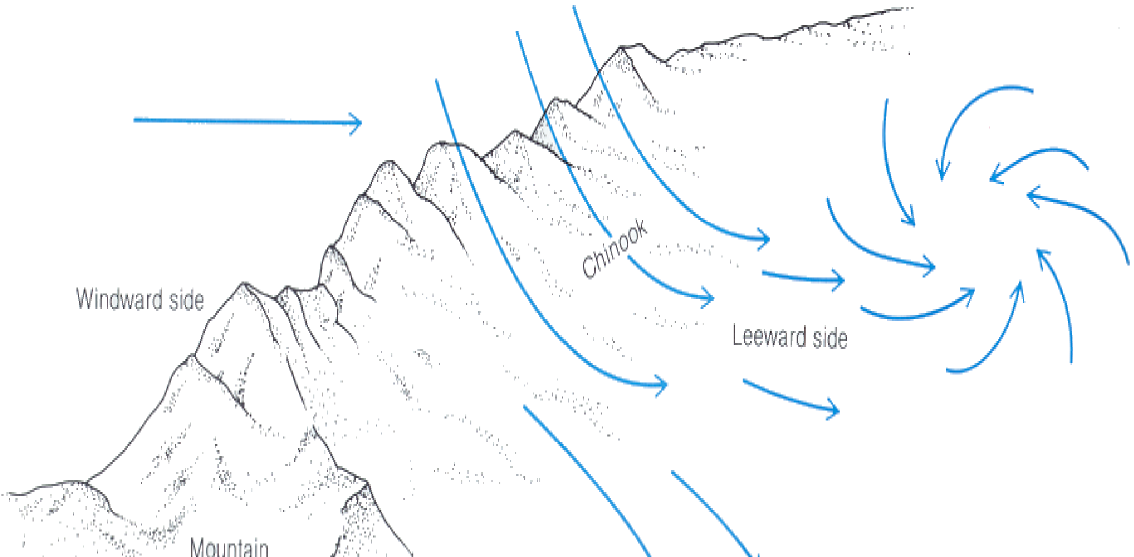
- Presence of a veil of dust, smoke, smog, haze over the city with weak winds
- Normally $\Delta T = T_{downtown} - T_{suburban} \sim 1\ ^{\circ}C$ but sometimes $\Delta T \sim 10\ ^{\circ}C$
- $\Delta T \propto$ urbanization → there is a growth rate of ΔT in the years
- $T_{downtown} > T_{suburban}$ because of multiple reflections between buildings, heat capacity of concrete and asphalt, the heat emitted by houses, industries and cars (even 100 W/m^2)
- Because in urban area there is lower evapotranspiration, there is also a moisture gradient between downtown and the suburban area → development of toroidal convective cells on the city

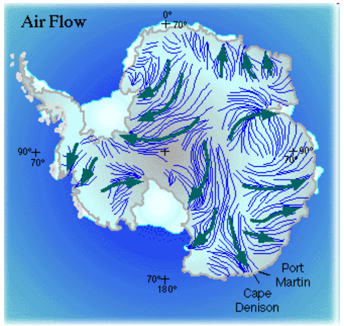




Katabatic winds

- Cold air is heavy → falls along mountain sides (it remains cold despite the adiabatic compression)
- Usually they are weak winds (≤ 5 m/s) but in some cases they are channeled into narrow valleys and, for the Bernoulli theorem, they can gain considerable speed





Examples of katabatic winds:

- **Mistral** (from the Rhone Valley in France towards the Ligurian Sea)
- **Bora** (from Dalmatia, Slovenia and Croatia towards the Adriatic Sea)
- **Antarctic** catabatic winds (from the cold highlands toward the ocean)

"Warm" downslope winds

- When an air mass is forced to cross a mountain range, after crossing it tends to return to the initial level
- When the vertical depth is considerable (≥ 1000 m), the effect of adiabatic heating is significant: $\gamma_a \sim 1.0^\circ C/100m \rightarrow \Delta T = 10^\circ C/Km$
- In this case, wind speeds can be very intense ($\propto g\Delta Z$ where ΔZ is the vertical displacement)
- When the phenomenon began in leeward locations, there may be sudden heating of 5-20 °C (max: 40 °C)

Examples of warm downslope winds

- **Foehn (Alps, Italy and Switzerland)**
- **Chinook (Rocky Mountains, USA)**
- **Zonda (Andes, Argentina)**
- **Santa Aña (California, USA)**

The *foehn* theories

- Foehn (name of German origin) was known to the Romans as "favonius“ (Pliny described it as a spring wind characterizing the period of the year from mid-February) and to the Greeks (Homer, Pindar and Aristotle) as zefiro (zefuritis, ζεφυριτης), west wind causing violent rainfalls
- Two theories are well known for the generation of the foehn
- Julius (von) Hann (1839 – 1921) is the author of the oldest (1866) theory about the foehn onset
- **The Hann theory** describes the foehn as a downslope wind in which the warming is caused by the adiabatic compression
- In the time, the Hann theory has been adapted and simplified, and the classical mechanism used to account for foehn winds involves the forced ascent of moist air over a mountain barrier: the latent heat release due to the condensation process raises the temperature of the air
- This last theory has replaced the Hann one and has become known as **the thermodynamic theory**

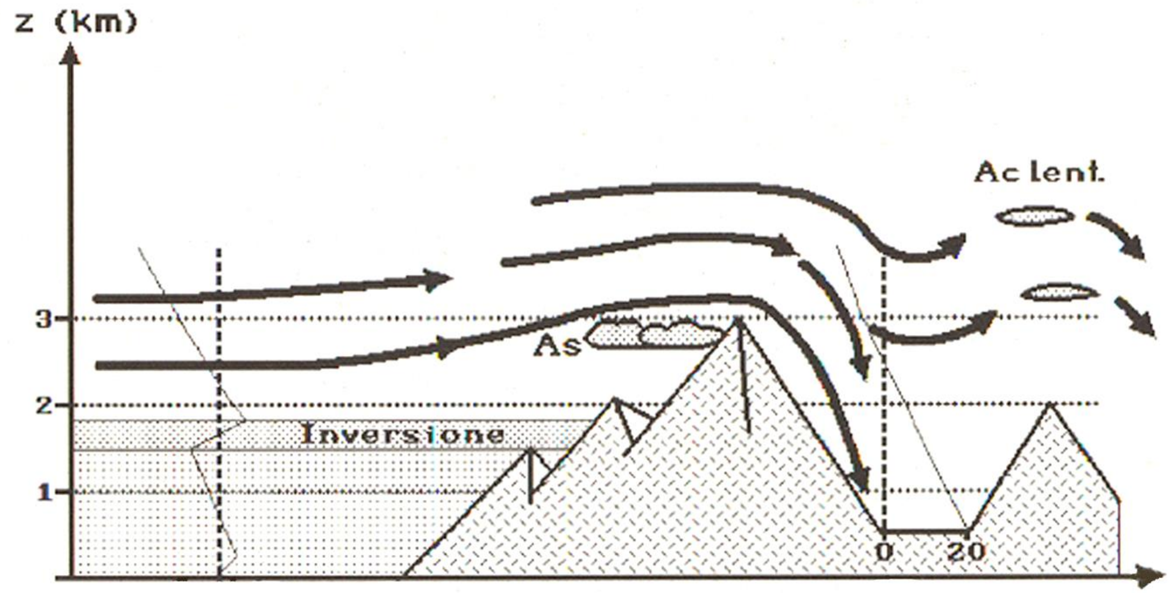
The Hann theory of the *foehn*

- Foehn winds can occur when moist lower-level air is blocked by a mountain barrier, allowing drier upper air to replace it in the lee of the mountains
- As the drier air from above flows down the lee slopes it gains strength and is warmed by adiabatic compression
- This type of foehn occurrence is a consequence of blocking of air flows by the mountains, which is essentially a mechanical effect, and so could be described as mechanically driven

The heating (and drying) of the air mass is proportional to the layer in which the air mass is falling down: $\Delta T = \gamma_{ad} \Delta z$

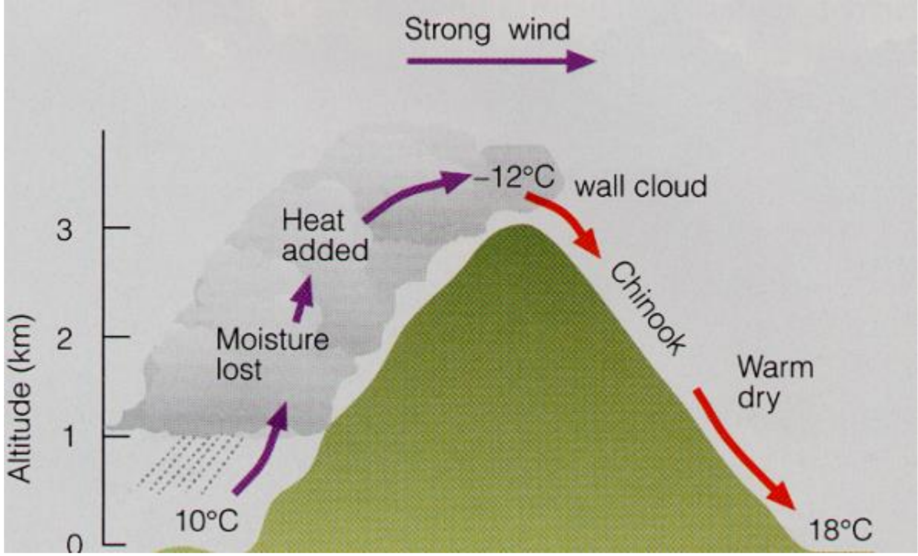
Being $\gamma_{ad} \sim 0.1°C/Km$, if $\Delta z = z_{upwind} - z_{downwind} = 1$ Km

→ $\Delta T = 10°C$



The thermodynamic theory of the *foehn*

- The classical mechanism used to account for foehn winds involves the forced ascent of moist air over a mountain barrier
- The ascending moist air cools at the saturated adiabatic lapse rate, ultimately resulting in condensation and precipitation (*stau* effect), which removes much of the moisture from the air mass
- The mechanism described is thermodynamic in nature and so this type of foehn occurrence could be described as thermodynamically driven
- The latent heat release due to the condensation process raises the temperature of the air. The drier air is then warmed further due to adiabatic compression as it descends down the lee slopes
- Since the saturated adiabatic lapse rate is lower than the dry adiabatic lapse rate the process results in a net heating of the air mass, even without the warming due to latent heat release



Most of the heating (and the whole drying) of the air mass is proportional to the upwind layer in which the air mass is saturated: $\Delta T=(\gamma_{ad}-\gamma_{aw})(z_{LCL}-z_{top})$
Being γ_{ad}~0.1°C/Km and usually γ_{aw}~0.06°C/Km, if $\Delta z= z_{LCL}-z_{top}$= 1 Km → ΔT=4°C

Some basic thermodynamic equations

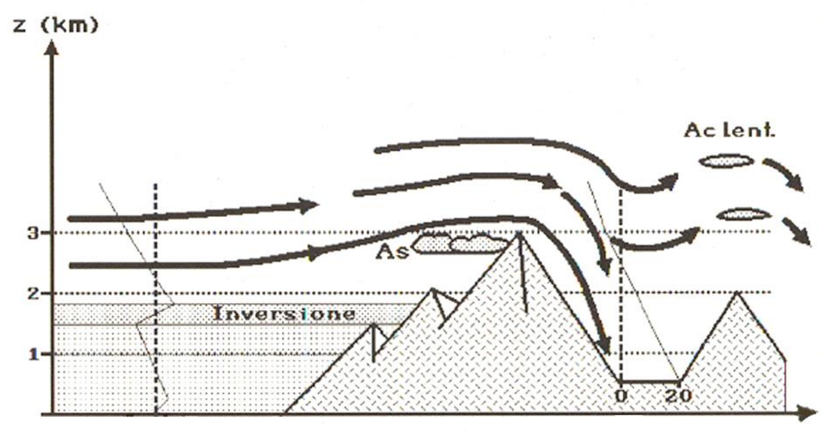
Dry atmosphere		Moist atmosphere
$\delta Q = \delta L + dU$	1^{st} principle of thermodynamics	$\delta Q = \delta L + dU$
$dU = C_V dT$ $\partial L = p d\alpha$	Relations for a perfect gas	$dU = C_V dT$ $\partial L = p d\alpha + L_e ds_m$
$\delta Q = c_P dT - R_d T \dfrac{dp}{p}$	δQ=0 for adiabatic processes	$\delta Q = c_P dT - R_d T \dfrac{dp}{p} + L_e ds_m$
$\dfrac{dp}{p} = -g \dfrac{dz}{R_d T_e}$	Hydrostatic relation	$\dfrac{dp}{p} = -g \dfrac{dz}{R_d T_e}$
$\gamma_{ad} = -\left(\dfrac{dT}{dz}\right) = \dfrac{g}{C_p}\dfrac{T}{T_e} \approx 10^{-2}\dfrac{K}{m}$	Lapse rate	$\gamma_{aw} = -\left(\dfrac{dT}{dz}\right) = \dfrac{g}{C_p}\dfrac{T}{T_e} + \dfrac{L_e}{C_P}\dfrac{ds_m}{dz}$ $\gamma_{aw} = \gamma_{ad} + \dfrac{L_e}{C_P}\dfrac{ds_m}{dz} \approx 0{,}6 \cdot 10^{-2}\dfrac{K}{m}$

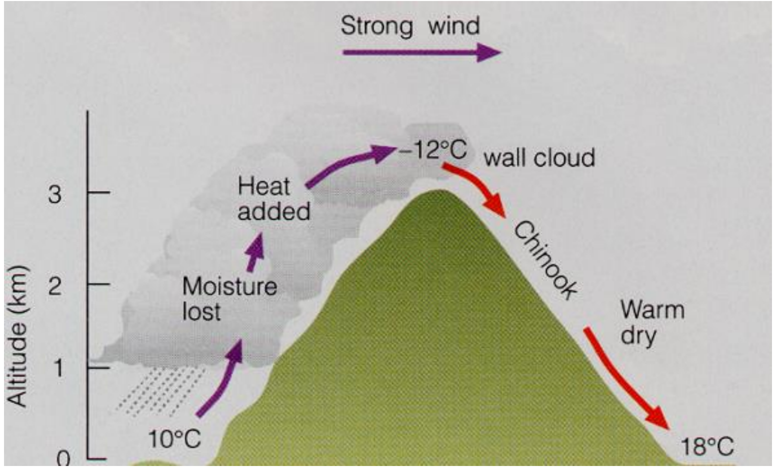
$$\gamma_a > \gamma'_a$$

NB: γ_{aw}~0.6°C/Km means that ds_m/dz=1.6 10^{-6} m^{-1} which is just one of the possible values for this parameter

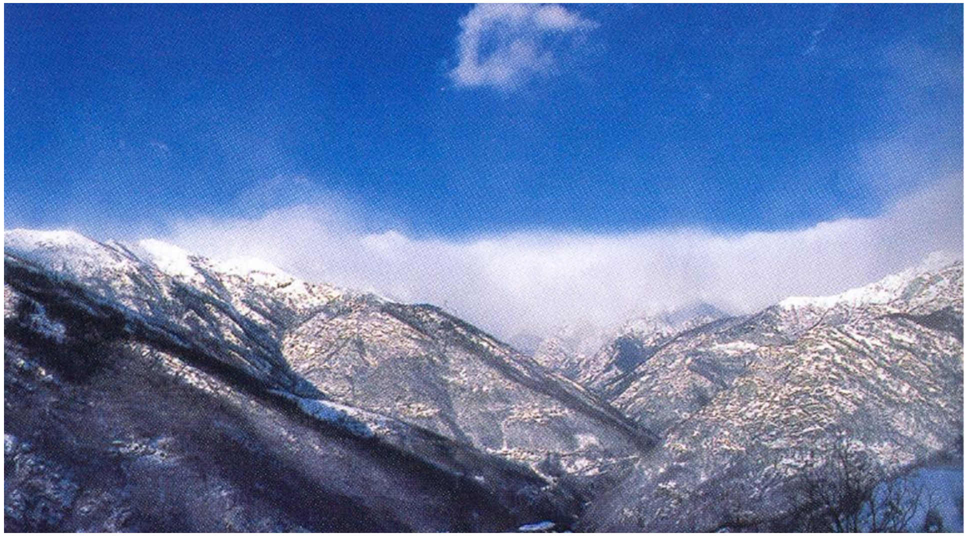
Foehn and *stau*

- For both theories, in the mountain range downwind side an increase of temperature, violent wind gusts and dry and clean air are observed; air is drier, warmer and cleaner for the Hann theory
- In the upwind side the thermodynamic theory predicts a barrier of clouds that can reach a considerable thickness and result in precipitation (*stau* effect – stau means "stagnation, barrier"); this barrier is called "**foehn wall**" as they appear as a wall on the ridges, seen from the downwind side
- According to the thermodynamic theory, precipitations in the upwind side of the mountain occur starting from the lift condensation level; these precipitations remove the liquid water from the air mass, making them drier
- According to the Hann theory, precipitations in the upwinf side of the mountain range can be generated below the inversion layer but do not affect the air mass crossing the mountain
- Eventual oscillations due to atmospheric stability can generate lenticular clouds in the leeward side





The foehn wall



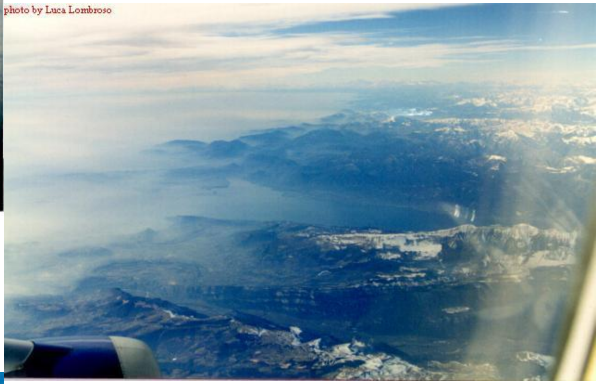

Effects of foehn

Sudden increase in the visibility (over 100 Km) in the downwind area because relative humidity drop to very low values

Sometimes the foehn do not comes to the ground due to the presence of a layer of cold air which, being heavier than the foehn air (warm and dry), remains close to the soil and can be removed gradually (and not always) only by friction

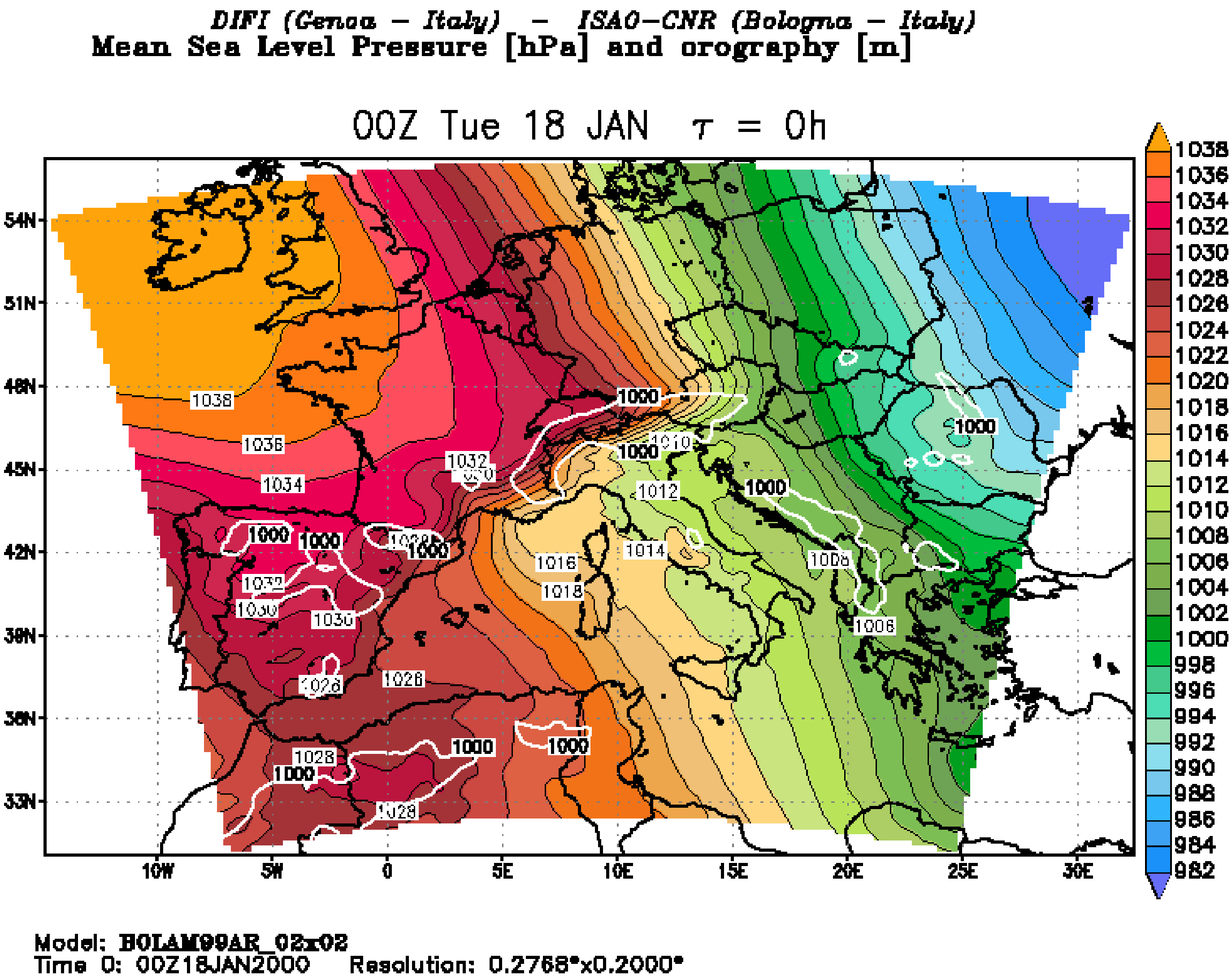
Then, for dynamic effect, gradually foehn removes the cold air layer (and eventually the fog) at the ground

In the intermediate stage the upper zone of the boundary layer is warm and clear from fog with very high visibility, while the bottom of the valleys are still covered by the fog



The situation typical for a foehn event

- Presence of a stronf anticyclone over Atlantic ocean and France and/or Switzerland and of a cyclone located near Ligurian Sea, Northern Italy and Adriatic Sea



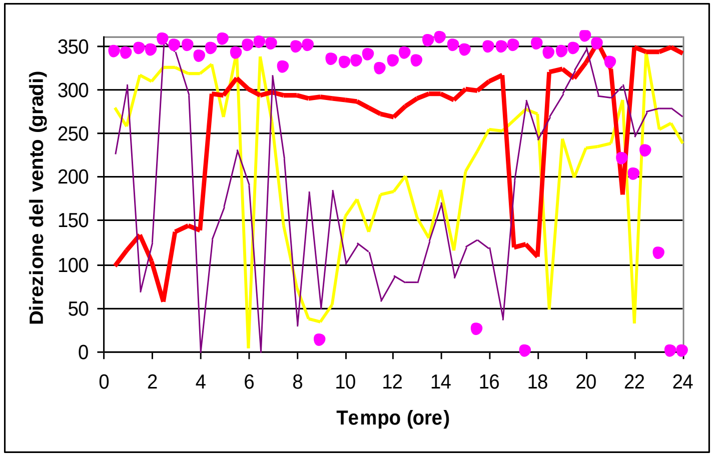
- Pressure differences (W and E, or N and S) of the Alps must be higher than 5 hPa in order to have a foehn event
- With pressure differences larger than 10 hPa, the foehn event is strong
- A characteristic of the foehn onset is the formation of a nose profile along the Alps (foehn nose)
- Isobars disposed parallel to the topography lines

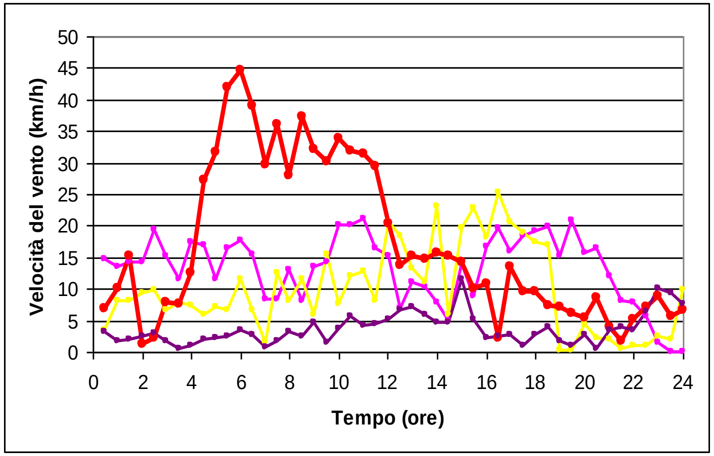
Climatology of foehn on Northern Italy

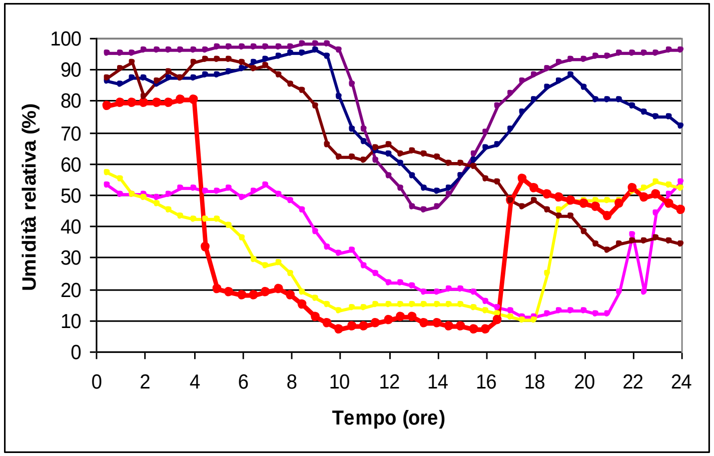
- The annual number of days with strong foehn events, according with Giuliacci and Borghi (which analyzed SYNOP and METAR Italian messages during 1931-1960) ranges 2 to 10
- Maxima in Cuneo province, Lago Maggiore, extreme Venezia Giulia, and also on Appennines

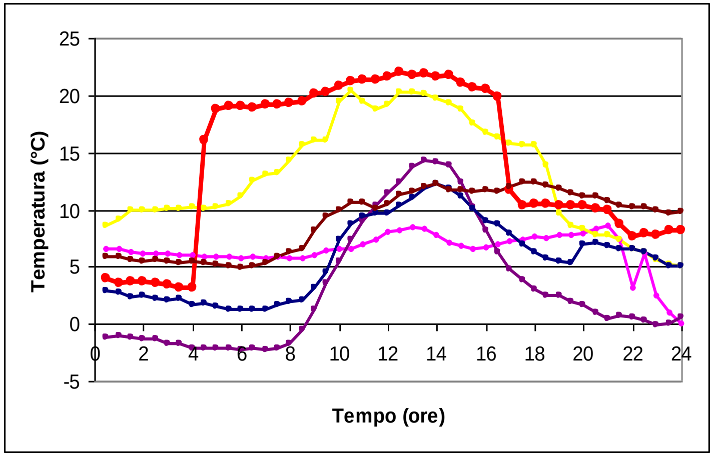
Typical evolution of parameters during a foehn event

Abrupt increase of wind speed and stationariety of wind direction (in Piedmont aligned on NW to N)



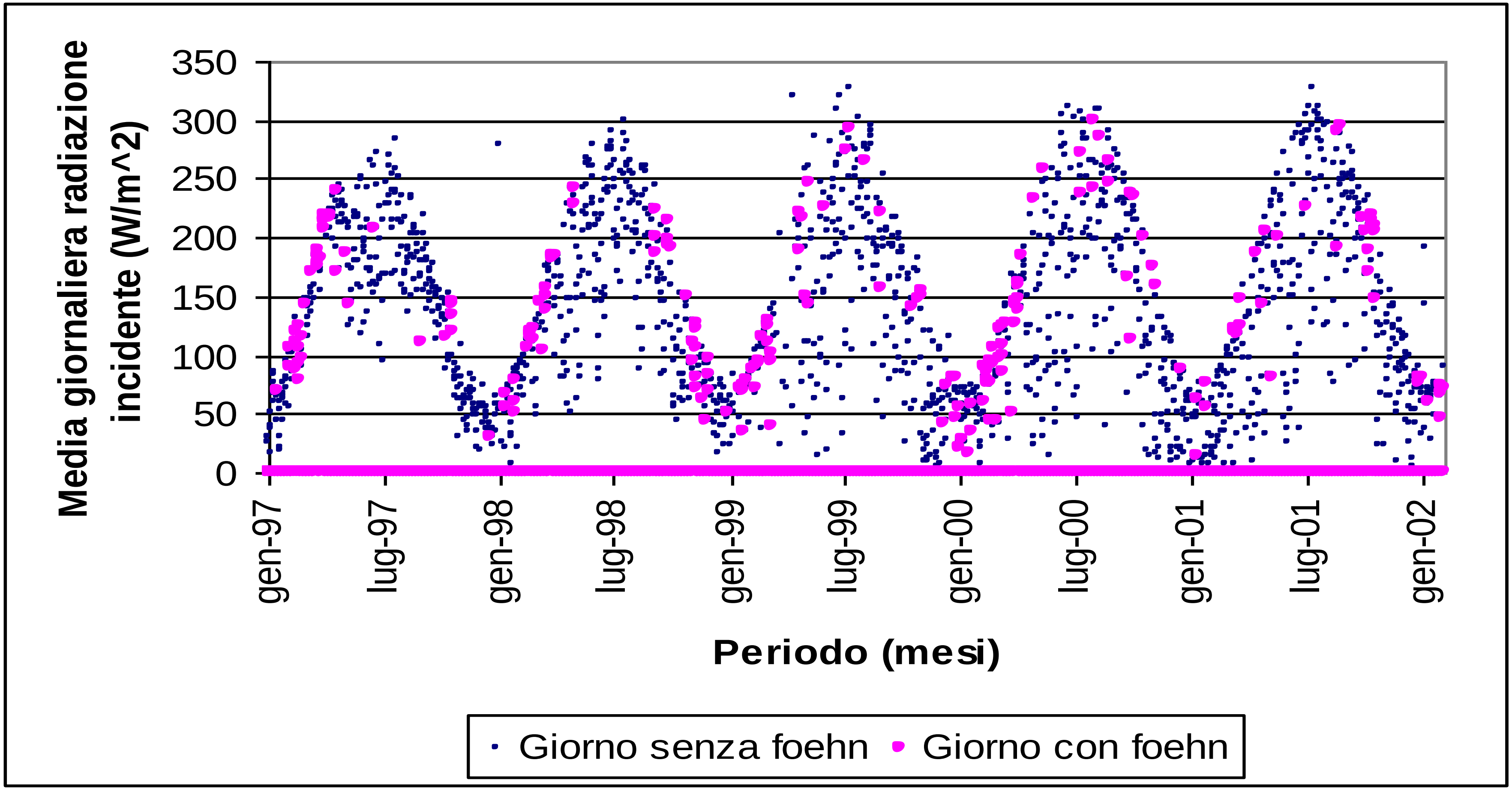






Abrupt drop of the relative humidity (even -95% in 1h) and increase of air temperature (even +16°C in 1h)

Solar radiation during foehn episodes

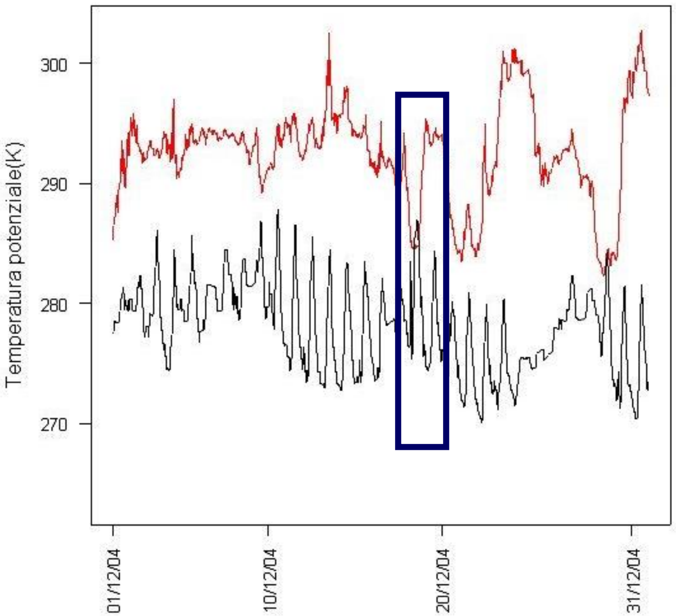


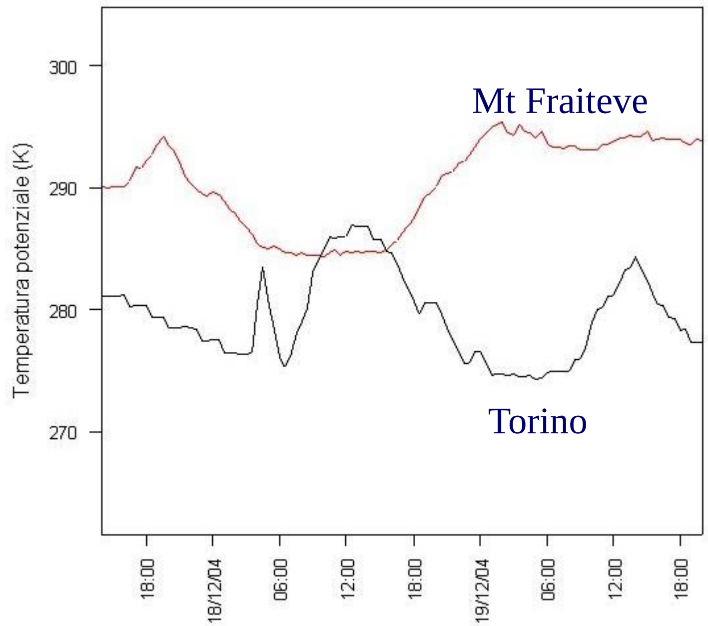
Daily mean solar radiation recorded during the years 1997-2002 at Chiomonte, Susa e Avigliana (in Piedmont): during foehn episodes normally sky is clear, especially during wintertime

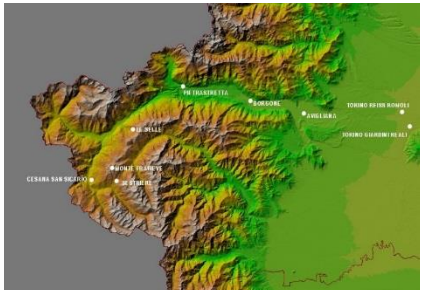
Potential temperature

- Being potential temperature constant for dry adiabatic processes, potential temperature constitutes a tracer for the air mass: when the flow reaches the valley station, the potential temperature equals that of the top mountain station

$$\vartheta = T\left(\frac{1000}{p}\right)^{\frac{R_d}{c_p}}$$





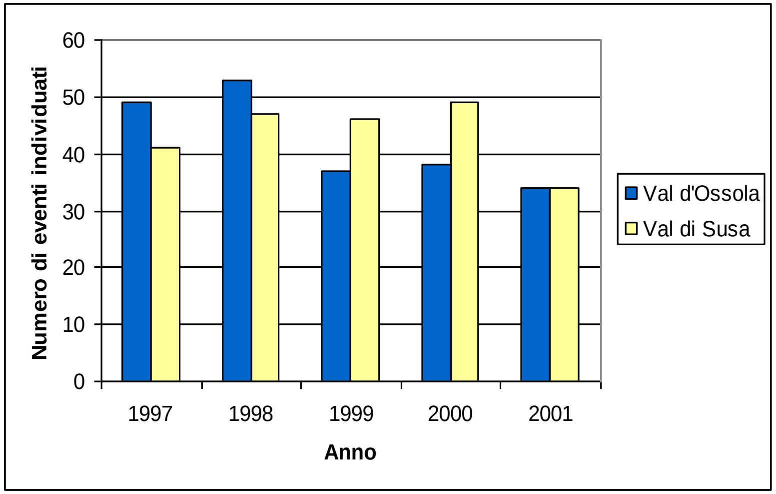


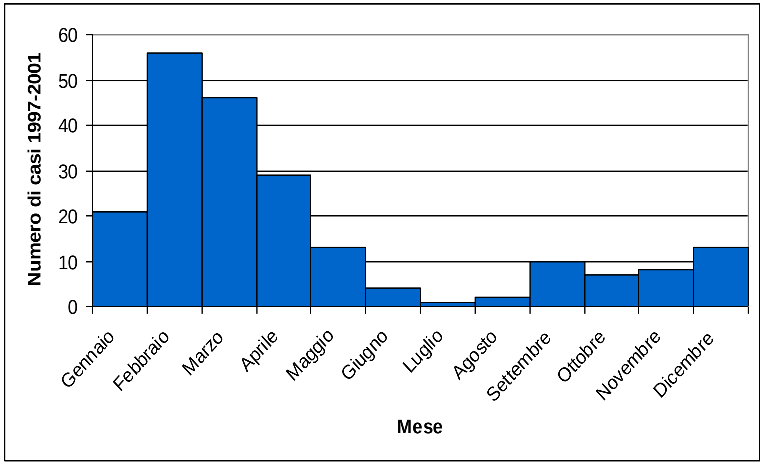
- To include also the upwind side of the mountain, it is necessary to consider the equivalent potential temperature, or pseudopotential temperature, which for definition is invariant for adiabatic processes even with changes of phase

$$\vartheta_p = \vartheta \cdot e^{\left(\frac{xL_e}{c_p T_d}\right)}$$

Foehn climatology in Piedmont (1997-2002)

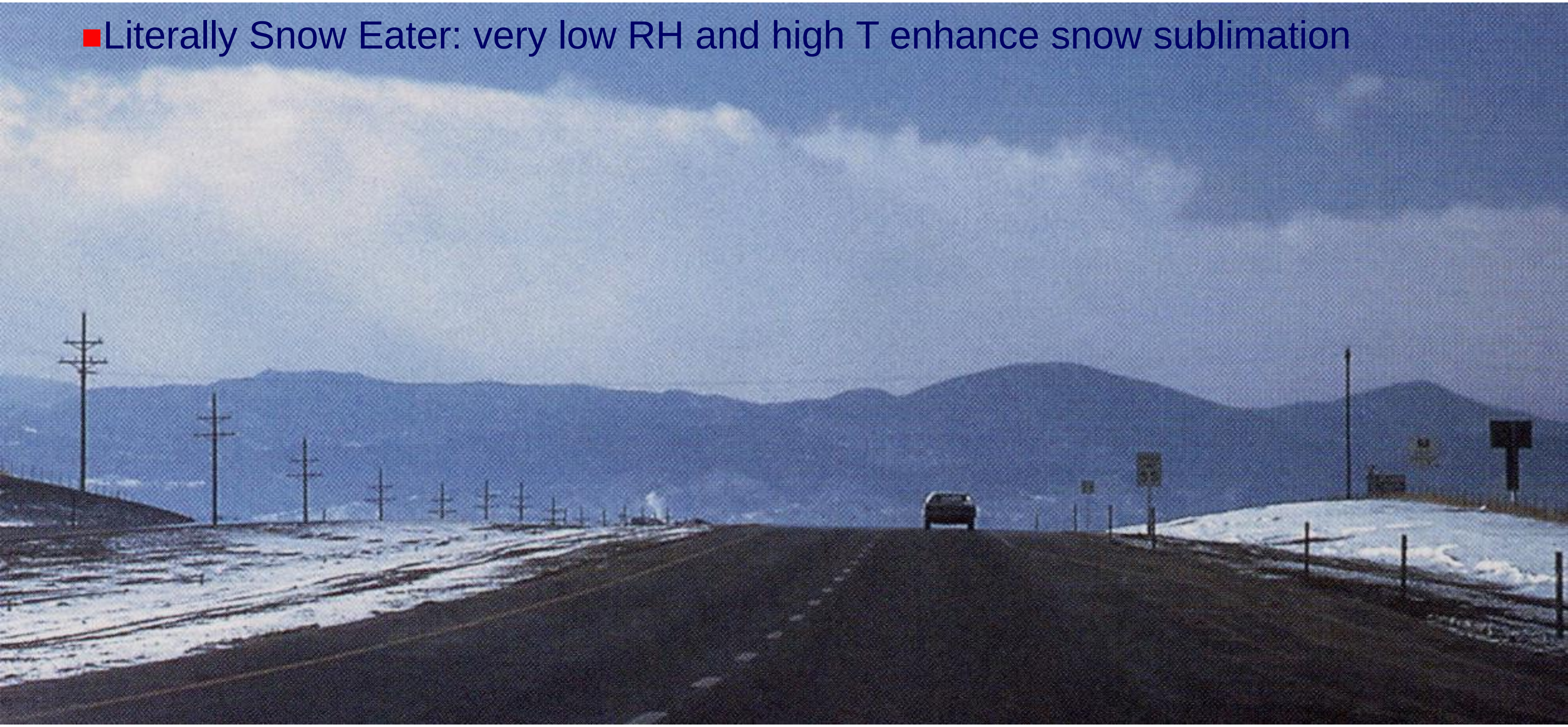
- An average of 44 days of foehn per year
- Highest frequency in February, March, April and January, lower in July, August and June – but never zero
- Strong interannual variability
- Avigliana observes about 80% of cases, Torino only 34%: frequency decreases progressively with the distance from mountains

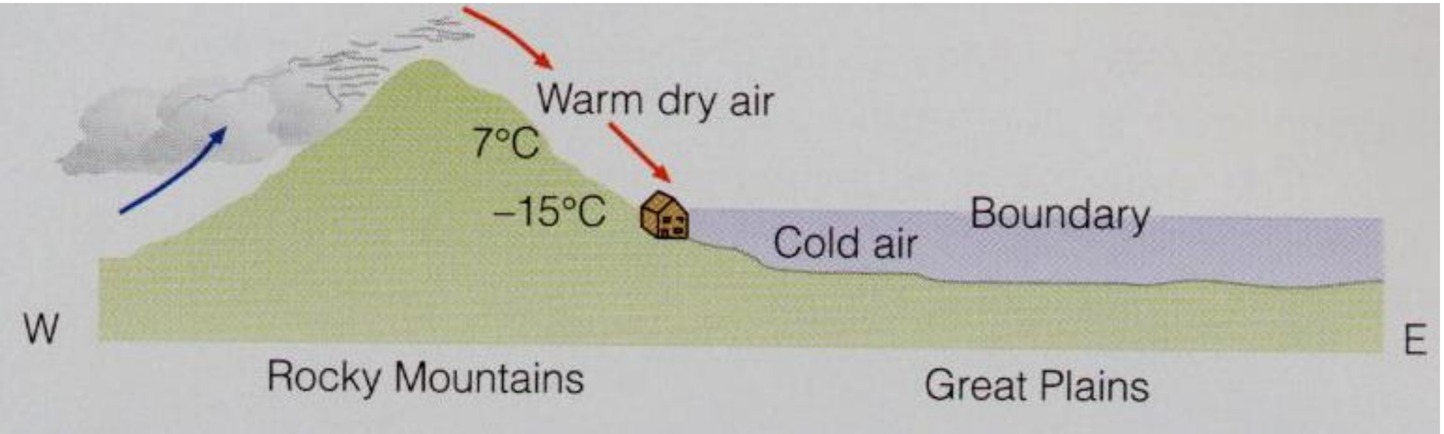




Chinook

- Literally Snow Eater: very low RH and high T enhance snow sublimation





Cold air may pool near surface with warm Chinook flow above