Session 3

Mountain meteorology

Mountains have an impact on atmospheric flow, hence on local weather and climate.

We will cover today:

1. Stability of the atmosphere
2. Thermally driven circulation
3. Flow interaction with topography
4. Orographic precipitation
5. Downslope winds and mountain waves
6. Frontal passage
7. *A local wind: Joran*

Book:
Barry, “Mountain weather and climate”, 2008
Thillet, “La météo de montagne”, 1997

Internet:
COMET-Meted: https://www.meted.ucar.edu/education_training/course/4

1. Stability

Atmospheric static (only buoyancy) stability

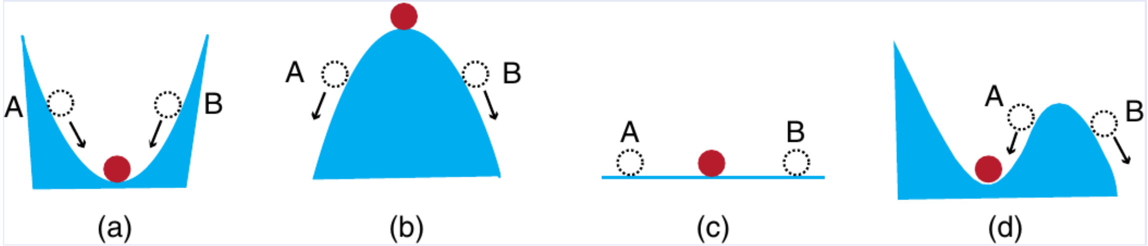
Stability refers to the motions of air parcel in the atm.

a) Absolutely stable atm:
Env. lapse rate < moist adiabatic lapse rate → air is sinking

b) Absolutely unstable atm:
Env. lapse rate > dry adiabatic lapse rate → air is rising

c) Neutral atm:
Env. lapse rate = adiabatic dry or moist, no buoyancy

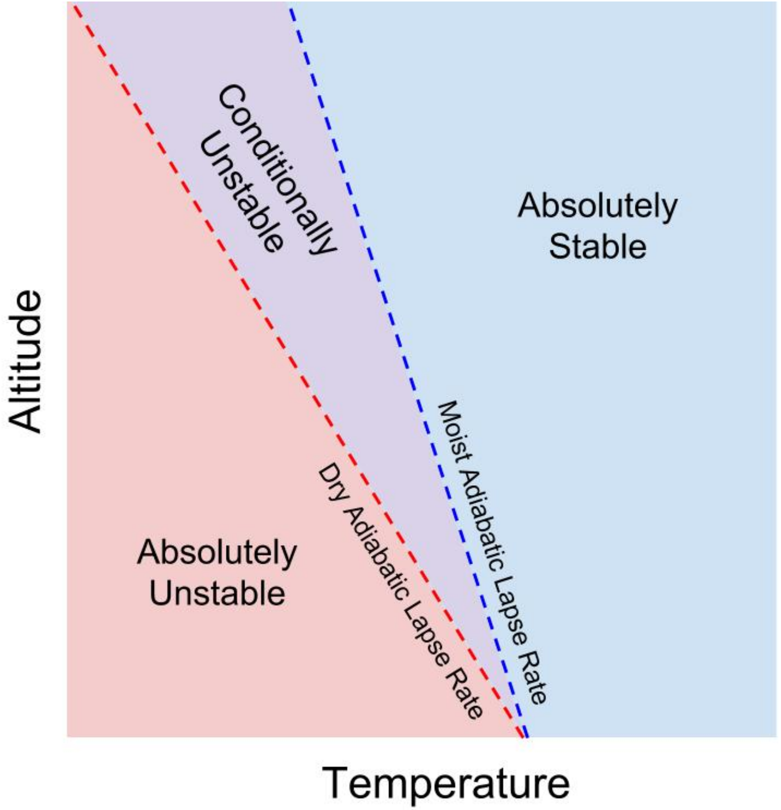
d) Conditionally unstable atm:
Moist adiabatic < env. lapse rate < dry adiabatic
→ stable if unsaturated, unstable if saturated (lifting)



(a) (b) (c) (d)

Wallace&Hobbs, fig3.12

Dry adiabatic lapse rate = $9.8 K\ km^{-1}$
Moist adiabatic lapse rate = $6\text{-}7\ K\ km^{-1}$



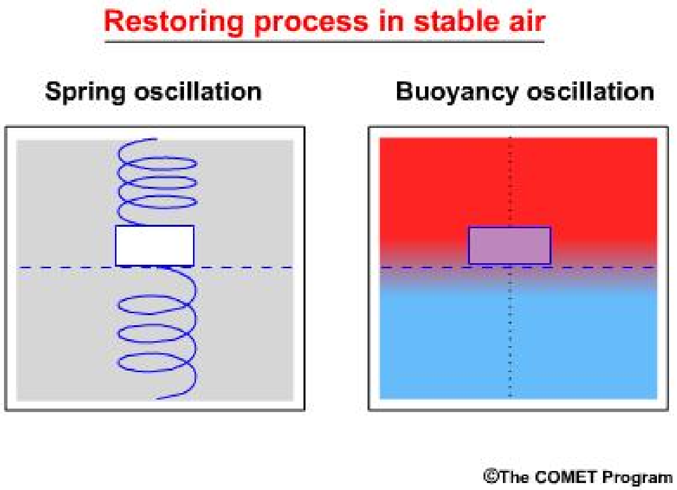
http://pressbooks-dev.oer.hawaii.edu/atmo/chapter/chapter-5-atmospheric-stability/

Statically stable atmosphere

When an air parcel is moved up (or down) in a statically stable atm, it will oscillate (pushed down when up, pushed up when down).

Frequency of those oscillations = Brunt-Väisälä frequency

$$N_{BV} = \sqrt{\frac{|g|}{T_v}\left(\frac{\Delta T_v}{\Delta z} + \Gamma_{d/s}\right)} \sim \sqrt{\frac{|g|}{\theta}\frac{\Delta \theta}{\Delta z}}$$



N_{BV}	Brunt-Väisälä freq [rad s^{-1}]
T_v	virtual temperature [K] ~ T dry air
Γ_d	dry adiabatic lapse rate [K m^{-1}]
Γ_s	saturated adiabatic lapse rate [K m^{-1}]
θ	potential temperature [K] of the parcel (or layer)

Dynamic stability - Turbulence kinetic energy (TKE)

Reynolds decomposition of kinetic energy → mean kinetic energy + turbulence kinetic energy (TKE)

$$TKE = \frac{1}{m}\frac{1}{2}\left[\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right]$$

m mass of the air parcel [kg]

u', v', w' fluctuations around mean [ms^{-1}]

The evolution of TKE can be described: $$\frac{\partial(TKE/m)}{\partial t} = Ad + M + B + Tr - \epsilon$$

Ad	TKE advection by mean wind
Tr	TKE transport by pressure gradient
ϵ	TKE dissipation by viscosity
$M = -\overline{u'w'}\frac{\partial\bar{u}}{\partial z} - \overline{v'w'}\frac{\partial\bar{v}}{\partial z}$	TKE mechanical production by vertical wind shear
$B = \frac{g}{\overline{T_v}}\overline{w'\theta_v'}$	TKE production/suppression by vertical buoyancy θ_v is the virtual potential temperature

(in horizontally homogeneous flow)

Richardson numbers

In horizontally homogeneous flow, Ad and Tr are negligible, so M and B are the key terms for TKE

We can define the flux Richardson number Ri_f (= B / M)
Ri_f = ratio between buoyant and mechanical production of TKE

$$Ri_f = \frac{\frac{|g|}{\overline{T}_v}\overline{w'\theta'_v}}{\overline{u'w'}\frac{\partial \bar{u}}{\partial z} + \overline{v'w'}\frac{\partial \bar{v}}{\partial z}}$$

The flux Richardson number Ri_f can be approximated using the K-theory (fluxes proportional to gradients) as the gradient Richardson number Ri_g

$$Ri_g = \frac{\frac{|g|}{\overline{T}_v}\frac{\partial \bar{\theta}_v}{\partial z}}{\left(\frac{\partial \bar{u}}{\partial z}\right)^2 + \left(\frac{\partial \bar{v}}{\partial z}\right)^2}$$

The gradient Richardson number can be approximated using finite difference as the bulk Richardson number Ri_b

$$Ri_b = \frac{\frac{|g|}{\overline{T}_v}\frac{\Delta\theta_v}{\Delta z}}{\left(\frac{\Delta U}{\Delta z}\right)^2 + \left(\frac{\Delta V}{\Delta z}\right)^2}$$

$$Ri_b \sim \frac{N_{BV}^2(\Delta z)^2}{(\Delta U)^2 + (\Delta V)^2}$$

$\Delta U, \Delta V$ horizontal wind speed differences [m s^{-1}]

1. Stability

Dynamic stability

When $Ri_b > Ri_t = 1$ → flow is statically and dynamically stable
→ flow is less turbulent (possibly laminar)

When $Ri_b < Ri_c = 0.25$ → flow is statically stable but dynamically unstable because of shear
→ flow is increasingly turbulent (may form Kelvin-Helmholtz waves)

Washington Post

When $Ri_b < 0$ → flow is statically unstable

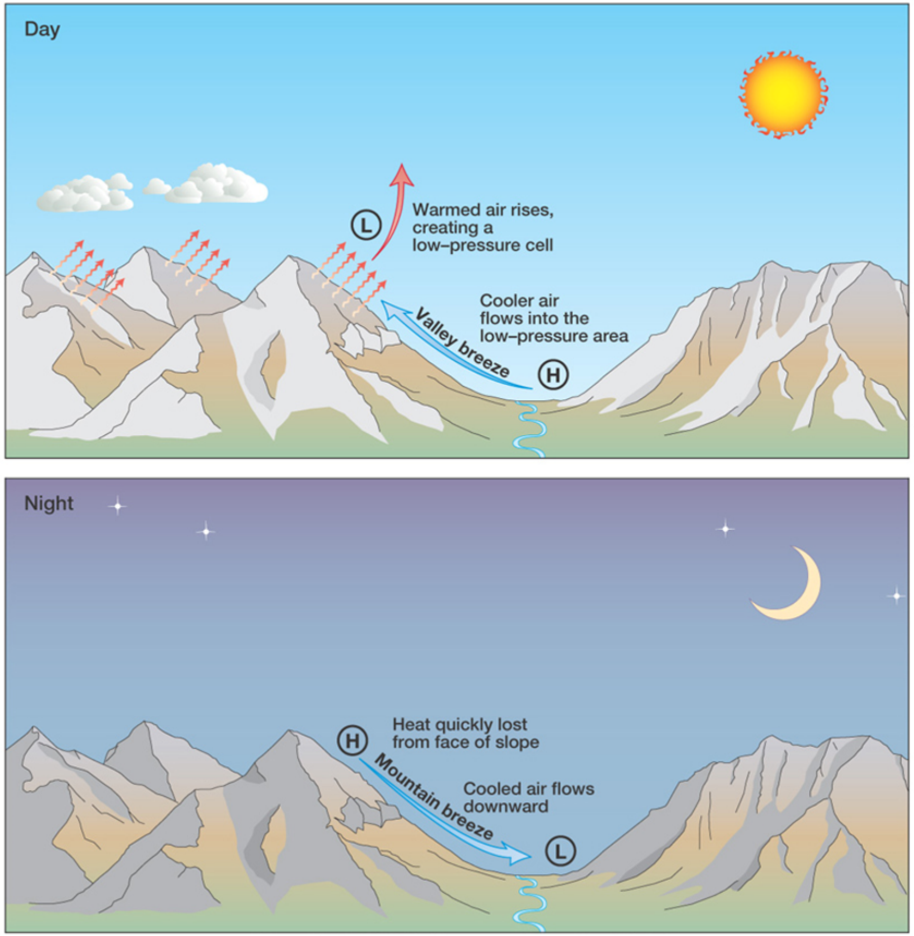
$$Ri_b = \frac{\frac{|g|}{T_v}\frac{\Delta\theta_v}{\Delta z}}{\left(\frac{\Delta U}{\Delta z}\right)^2 + \left(\frac{\Delta V}{\Delta z}\right)^2}$$

2. Thermally driven circulation

Slope winds

Anabatic winds: upslope winds when sun is heating mountain slopes (day)

Katabatic winds: downslope winds due to denser cold air (night)



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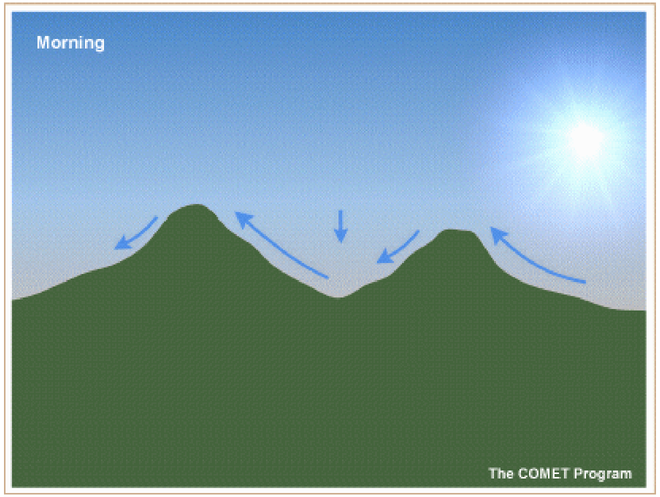
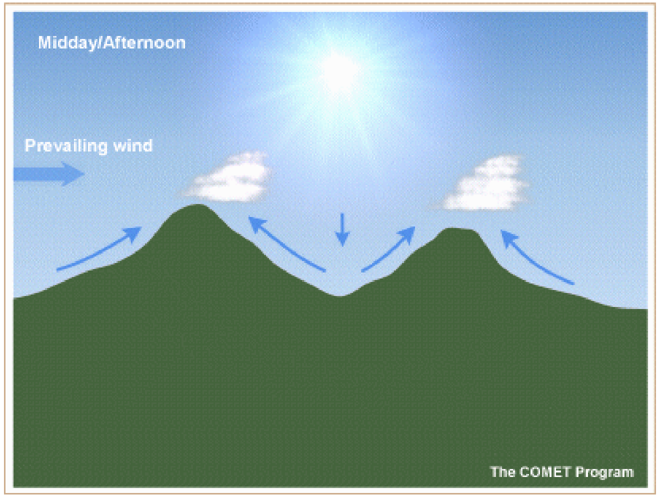
2. Thermally driven circulation

Slope winds – diurnal cycle

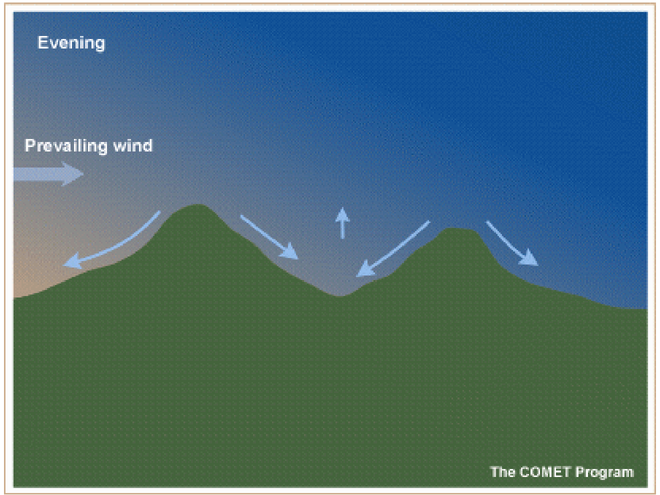
Morning



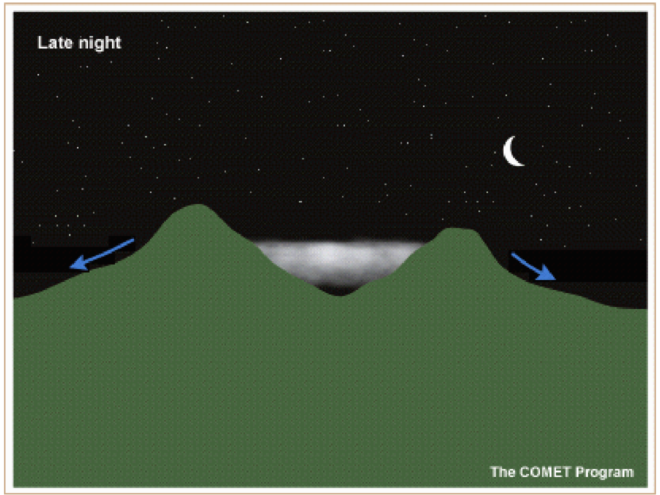
Afternoon



Evening



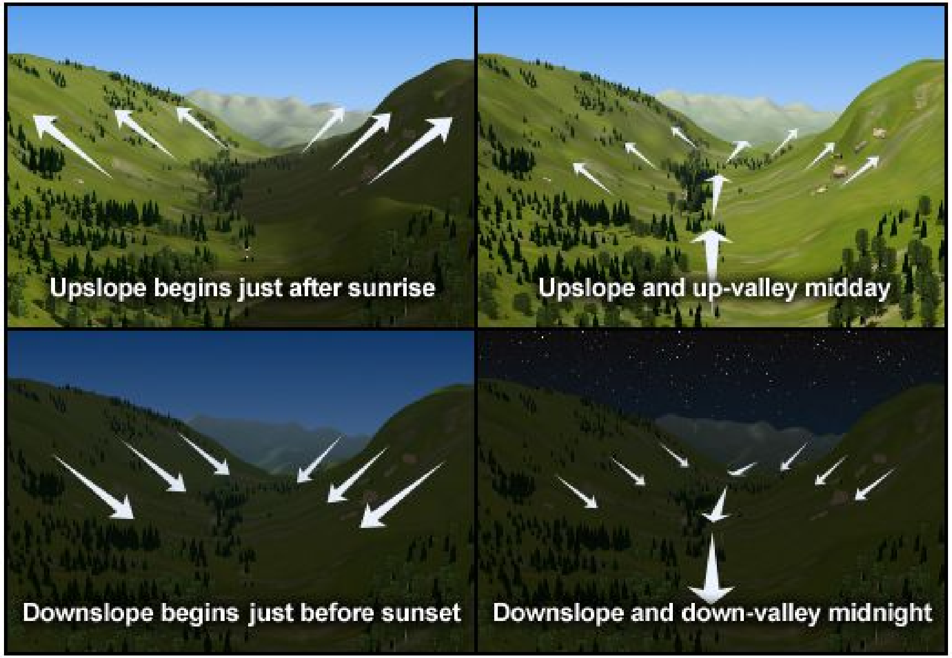
Night

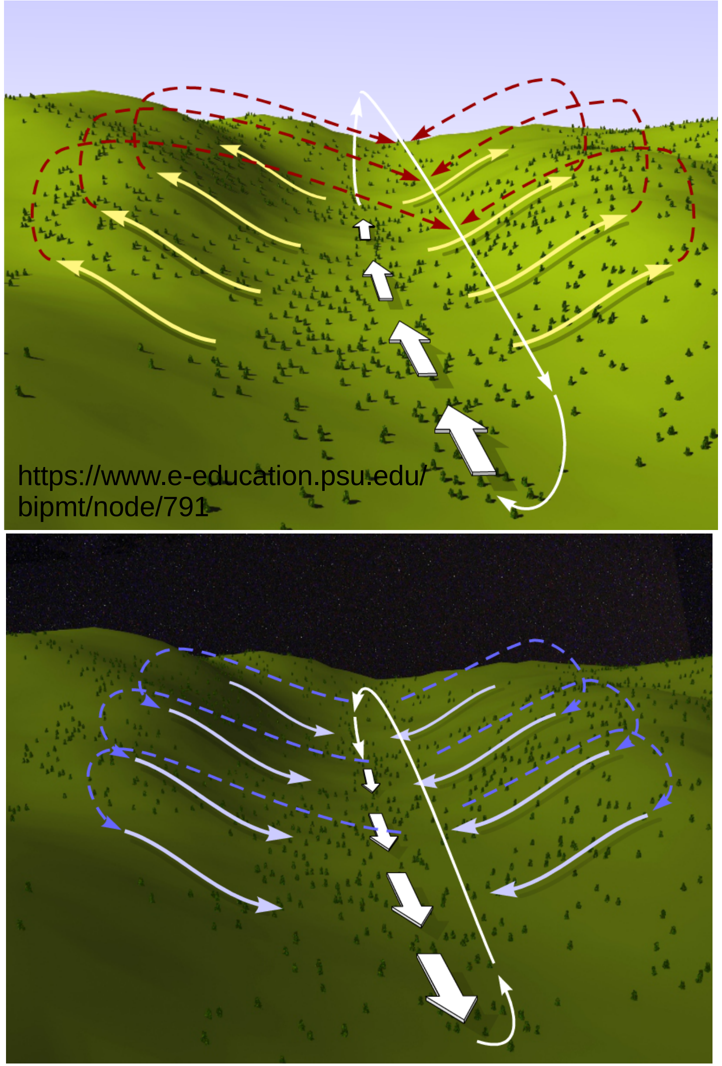


2. Thermally driven circulation

Valley winds

Slope winds combined with valley circulation.
Diurnal cycle as well...




https://www.e-education.psu.edu/bipmt/node/791

2. Thermally driven circulation

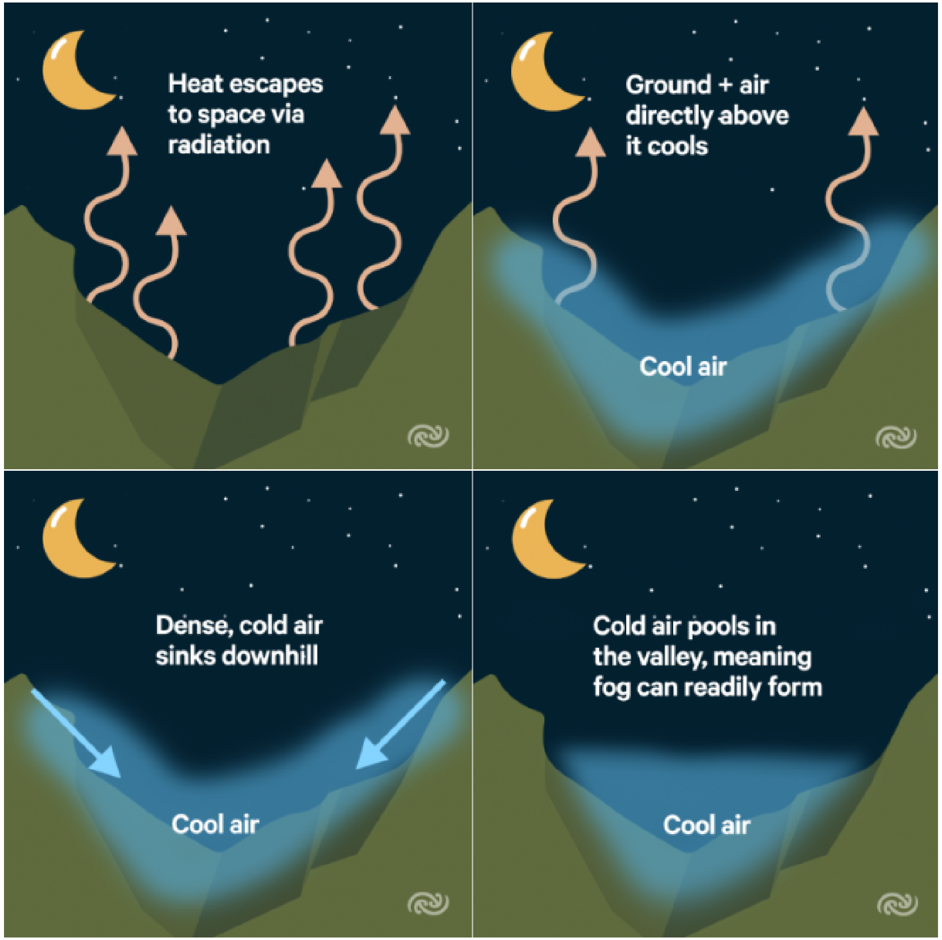
Cold air pooling

Air cools down by radiative cooling

It hence becomes denser and flows to lower flatter regions.

→ cold air pool in the valleys
(with temperature inversion at the top).

→ Frequently associated with stratus/fog



https://www.facebook.com/MetService/photos/pcb.2252370754824970/2252364851492227/?type=3&theater

3. Flow interactions with topography

Flow encountering a mountain - Context

What happens? Is the flow going above or around (or both) the mountain?

Important factors: mountain shape (height, width…), wind speed and flow stability

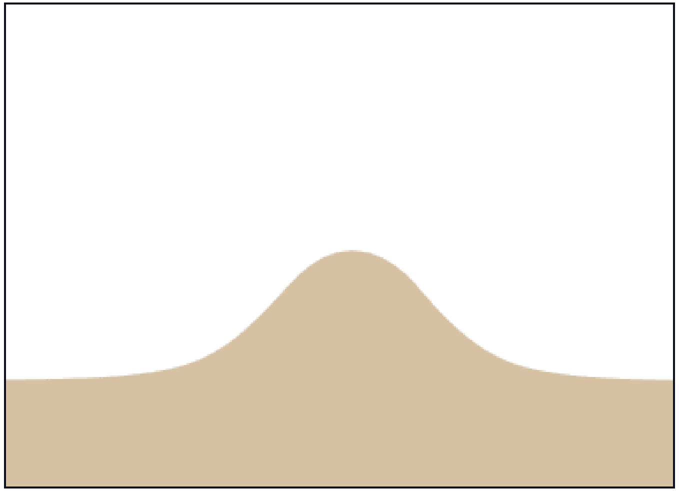
https://france.altaibasecamp.com/en/home

Flow encountering a mountain - Analogy

Flow goes above or around: kinetic energy (KE) vs gravitational potential energy (PE)

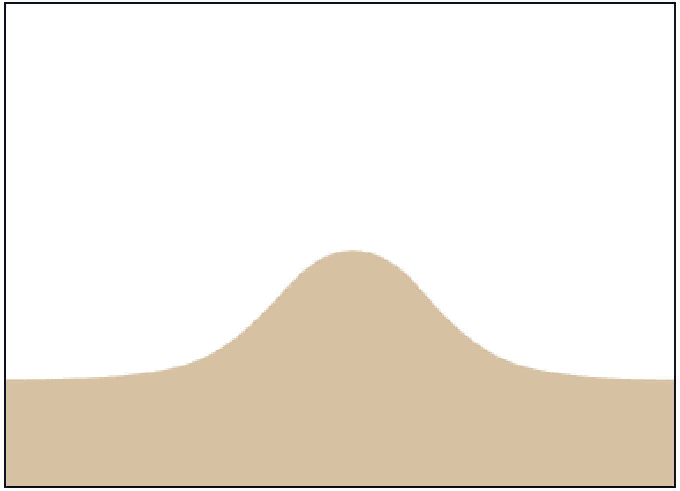
Analogy of a marble: (1) KE < PE ; (2) KE = PE ; (3) KE > PE

(a)



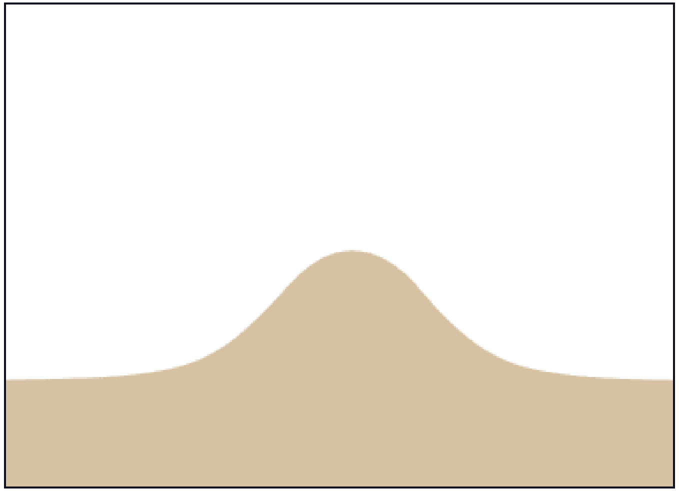
The COMET Program

(b)



The COMET Program

(c)



The COMET Program

(1,2,3) → (a,b,c)?

Flow encountering a mountain – (static) Stability

Wave propagation in general → Froude number = ratio between inertial and gravitational forces.

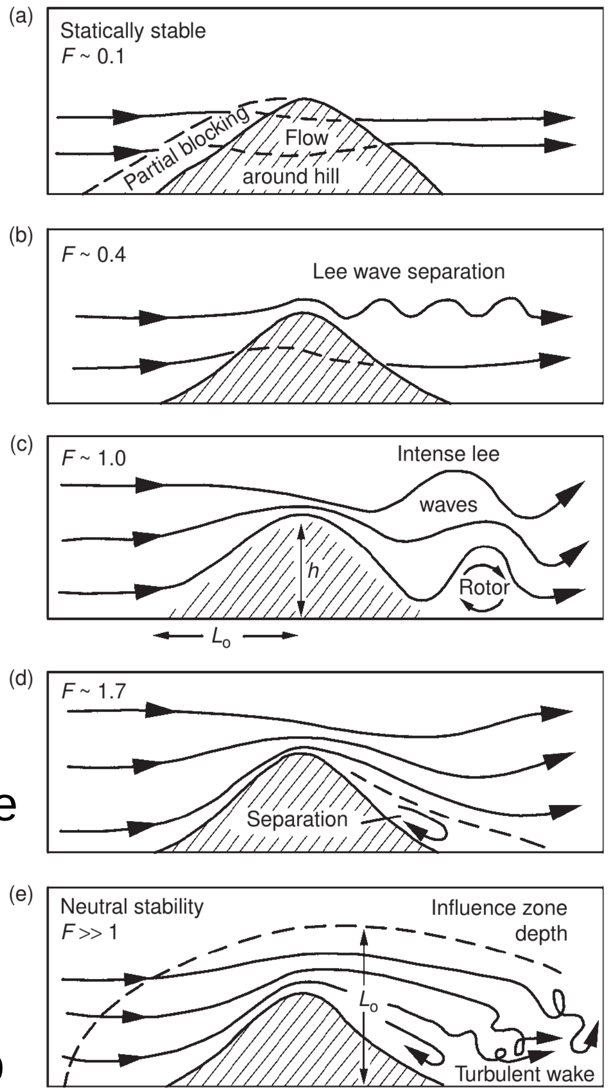
For atm flow, Froude = ratio between kinetic energy and gravitational potential energy:

$$Fr = \frac{U}{N_{BV}h}$$

Dimensionless mountain height H

$$H = \frac{1}{Fr} = \frac{N_{BV}h}{U}$$

Fr << 1 (H >>1)	flow goes around the mountain, limited waves + (partial) blocking
Fr ~1 (H~1)	flow resonates with mountain → large wave amplitude + rotor / lenticular clouds
Fr >> 1 (H << 1)	flow goes above mountain + recirculation cavity in the lee + turbulent wake



Barry 2008, fig2.29

3. Flow interactions with topography

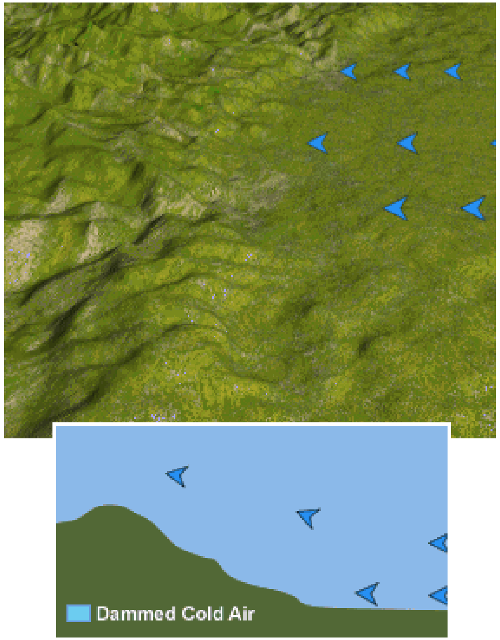
Flow encountering a mountain - Blocking

If Fr << 1 (strong stratification and/or weak wind), there is total or partial blocking of the flow by the mountain.

What does it imply for the large-scale and local circulation?

Large scale: flow does not feel the mountain, geostrophic

Near mountain barrier, the air parcel has to rise, velocity decreases:
- not enough kinetic energy to go over the mountain
- no more geostrophic balance → wind turns toward lower pressure

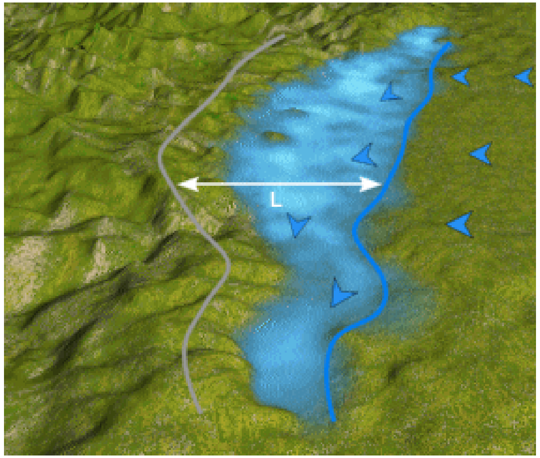


The COMET Program

Flow encountering a mountain – Blocking extension

How far back upstream does the blocking extend?

The upstream distance depends on:
- height of the barrier
- incoming flow speed
- stratification.



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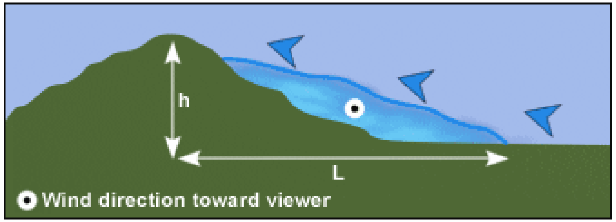
Distance $L = (N_{BV}h-U)/f$

h mountain height
f Coriolis parameter



The COMET Program

The stronger the stratification (N_{BV}) for a given h, the further upstream the influence is seen

Questions

1. What is the Brunt-Väisälä frequency?

2. Explain the valley winds during day and night.

3. What dimensionless numbers are relevant to predict the behavior of a flow impinging a mountain?

4. Orographic precipitation

Orographic precipitation

Airflow interacting with orography:

- Leads to a given dynamic response (function of wind direction and terrain features)
- Which controls the lower boundary conditions in the area
- In turn sets the 3D-pattern of condensation and subsequently of precipitation
- Also influences the microphysical processes (seeder-feeder, evaporation, riming…)

Flow is also influenced by condensation/precipitation processes (latent heating)!

Orographic clouds on
Table Mountain (SA)

https://ekayasolutions.blogspot.com/2011/01/orographic-cloud-formation-on-table.html?_escaped_fragment_

4. Orographic precipitation

Orographic lifting mechanisms

Mechanical lifting
(a) Stable up-slope ascent

(b) Blocked flow → upstream ascent

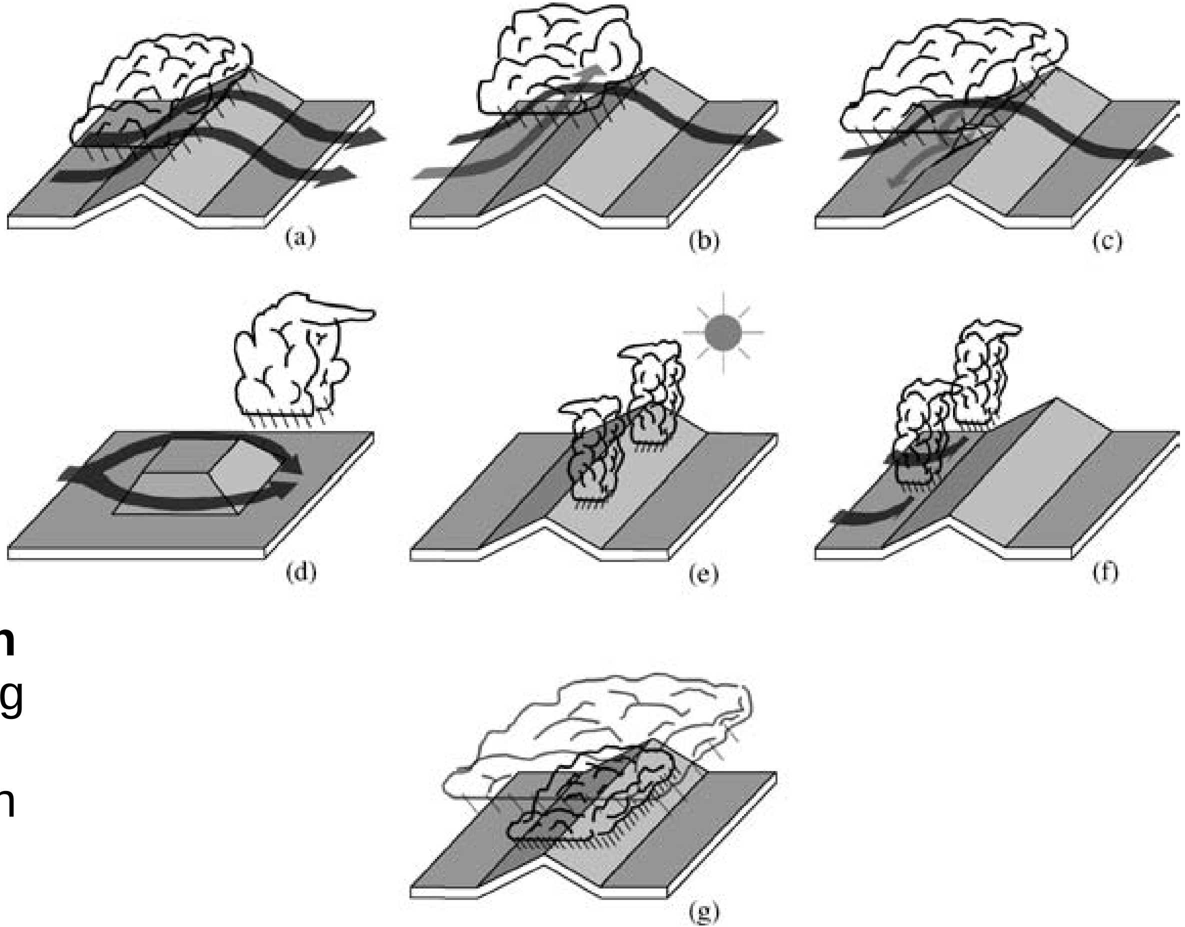
(c) Precip melting/evap → cooling
→ wind valley
→ ascent

(d) Convergence → ascent

Orographically triggered Convection
(e) Sun-facing slopes radiative warming

(f) Lifting above level of free convection

(g) **Seeder-Feeder**

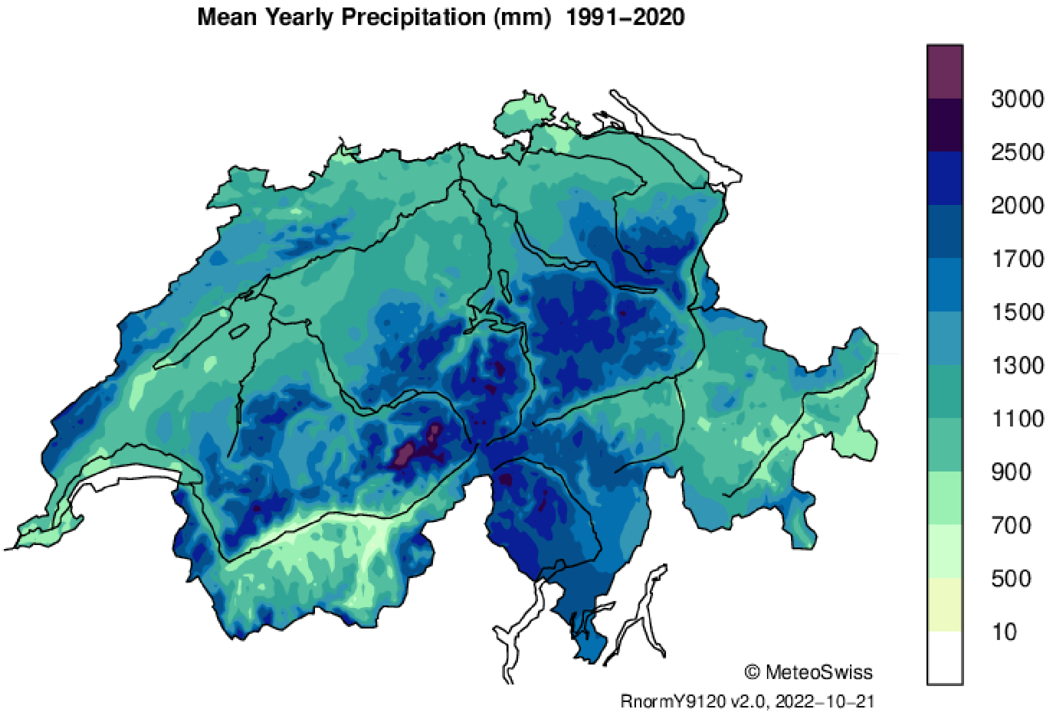


Roe 2005

4. Orographic precipitation

In Switzerland

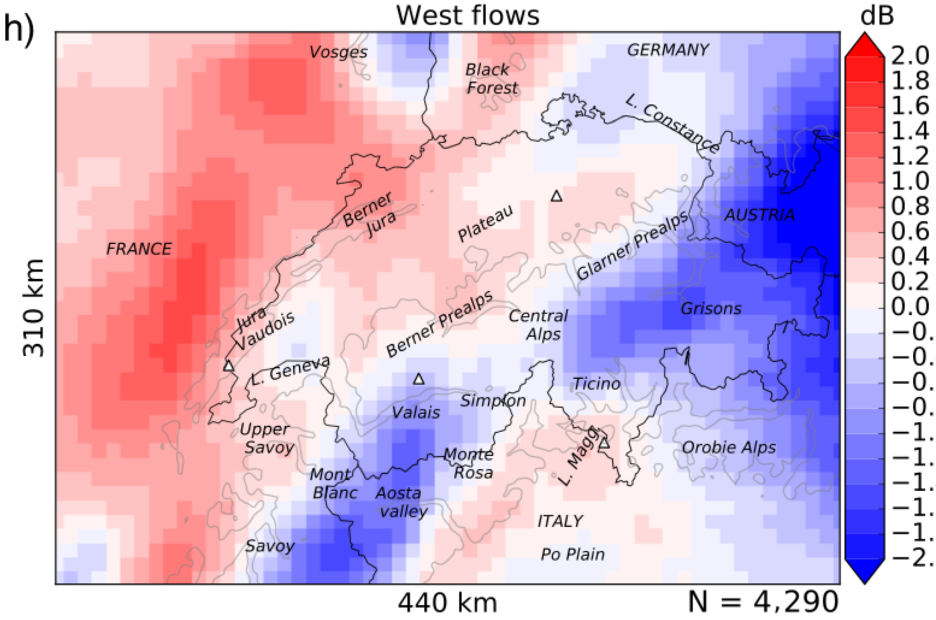
Orographic mechanisms reflected in annual precipitation amount



Mean Yearly Precipitation (mm) 1991–2020

https://www.meteosuisse.admin.ch/services-et-publications/applications/ext/climate-norm-maps-public.html

Growth and decay in precip for west flow (from radar)



Foresti et al., QJRMS, 2018

5. Downslope winds and mountain waves

Downslope winds

Depending on synoptic conditions, flow over the lee side of a mountain (→ downslope) may be very strong, dry and warm or cold: Föhn, Bora, katabatic (meso-scale) winds.

https://imaggeo.egu.eu/view/5054/

https://www.meteorologiaenred.com/en/foehn-effect.html

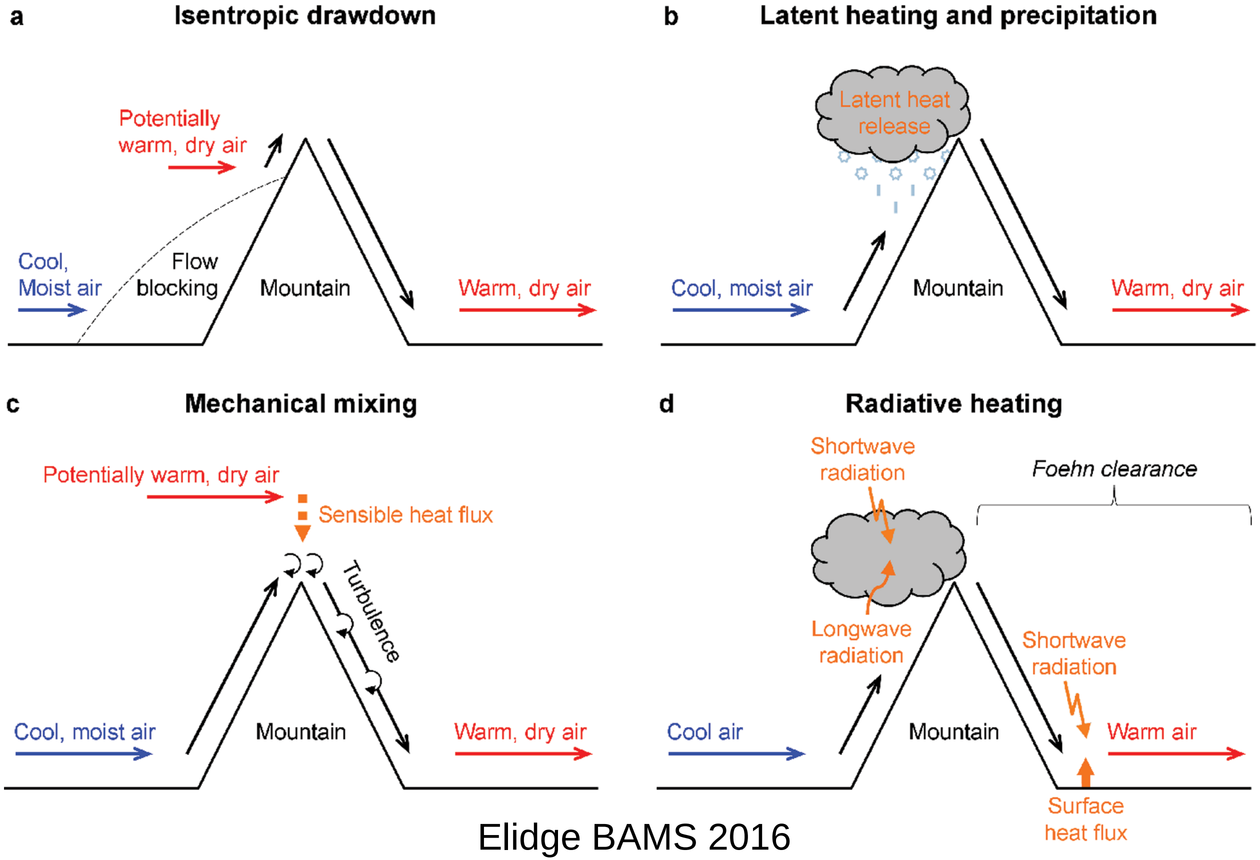
Downslope winds – Föhn (Chinook in North Am., Zonda in Argentina)

4 main mechanisms:

a) **Isentropic drawdown**
Blocking → upper air goes down on lee side → dry adiabatic warming

b) **Latent heating + precip**
Orographic ascent → cooling + condensation on windward side
Descent on lee side → dry adiabatic warming

c) Mechanical mixing
Turbulent mixing of lower (cool+moist) and upper (warm+dry) air at top → warmer dryer air on lee side.

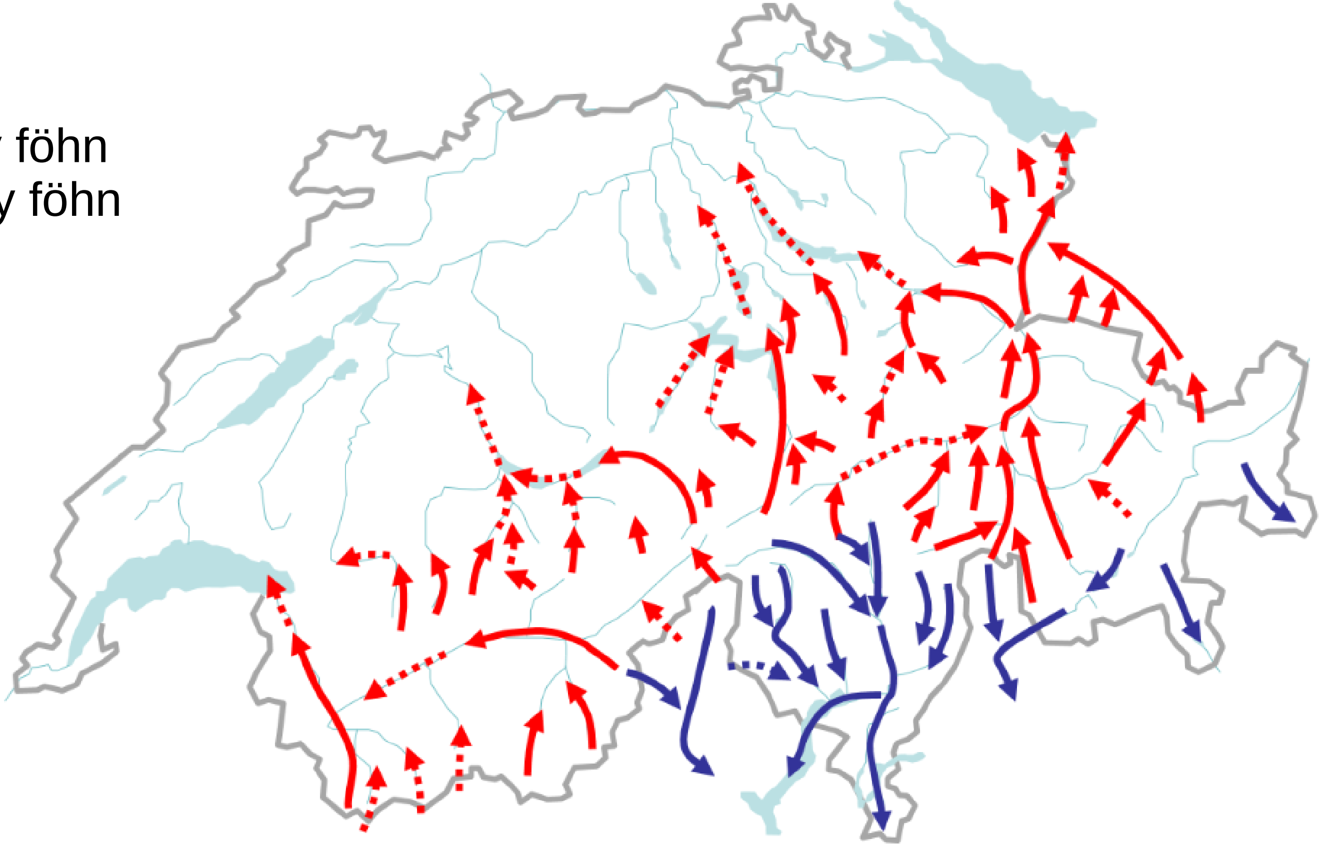


Elidge BAMS 2016

d) Radiative heating → less clouds on lee side → more sun radiation → warming

Downslope winds - Föhn

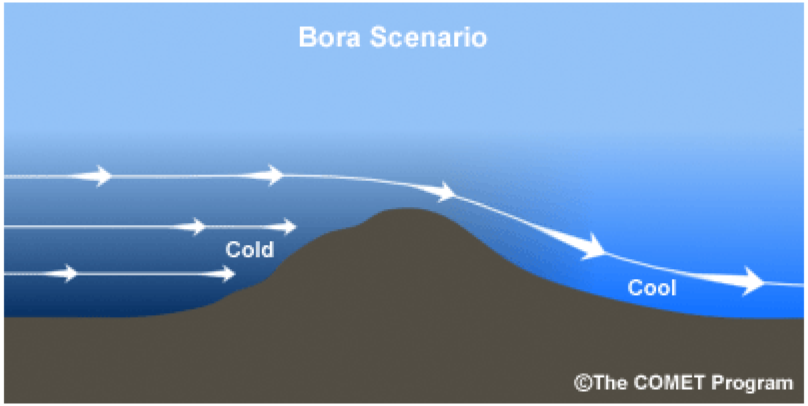
Föhn valleys in CH:
- red arrows = southerly föhn
- blue arrows = northerly föhn



5. Downslope winds and mountain waves

Downslope winds - Bora

Cold air + large-scale pressure gradients + low mountain range
→ lower cold air goes over (partial blocking) + orographic wave
→ katabatic flow + wave breaking + complex 3D flow...
→ cold and dry wind on the lee slope



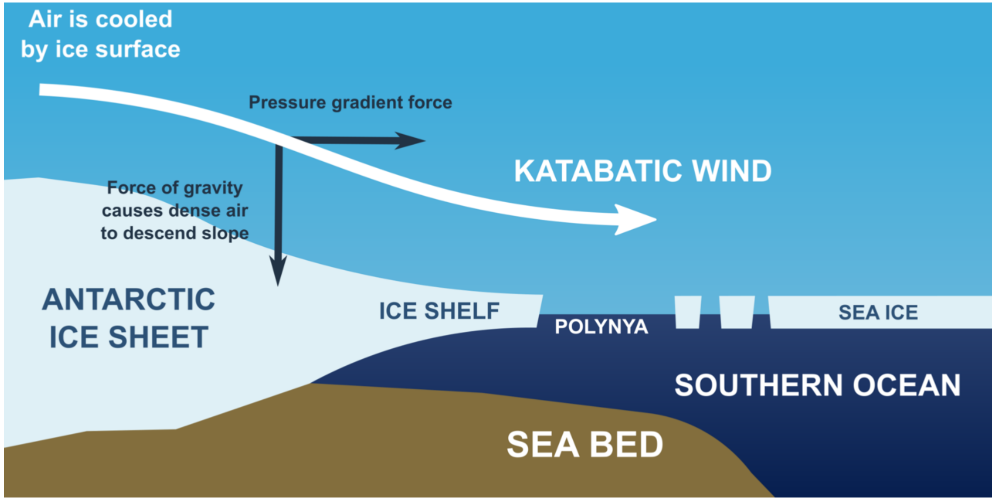
Bora in Croatia (Wikipedia)

Downslope winds – Katabatic winds

Gravity driven winds, can occur at much larger scales than the slope winds seen earlier

Those winds take place on polar ice caps:
- Coriolis force becomes significant
- Adiabatic warming and drying
- Confined layer (100s m)

→ Fierce dry winds at the coast.

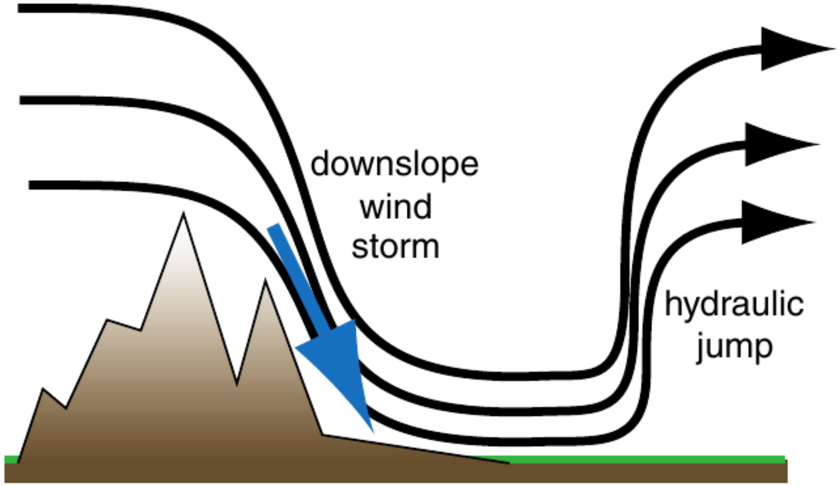


https://commons.wikimedia.org/wiki/File:Katabatic-winds-antarctica.png

Mawson’s camp, 1913 (@F. Hurley)

Downslope winds – Hydraulic jump

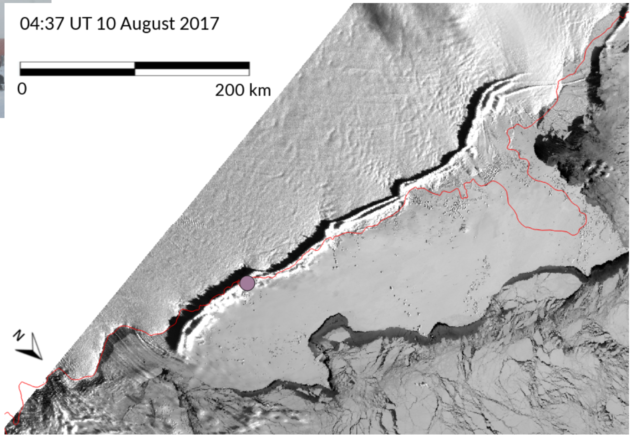
When strong downslope winds reach flatter area, they may create a hydraulic jump



WH2006, fig9.33

Frequent over Antarctic coast

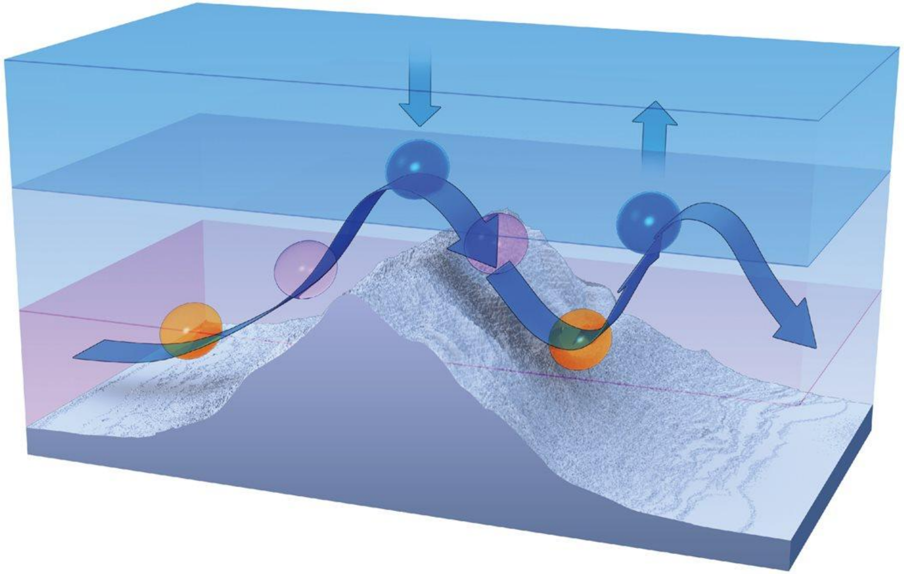
DDU, 10 Aug 2017



Vignon, JAS, 2020

Mountain waves – Gravity waves

In stable atm, the buoyancy and gravity forces are balanced, so an air parcel going up (down) will be pushed back down (up) → gravity wave.



https://www.aopa.org/news-and-media/all-news/2017/march/flight-training-magazine/weather-gravity-wave

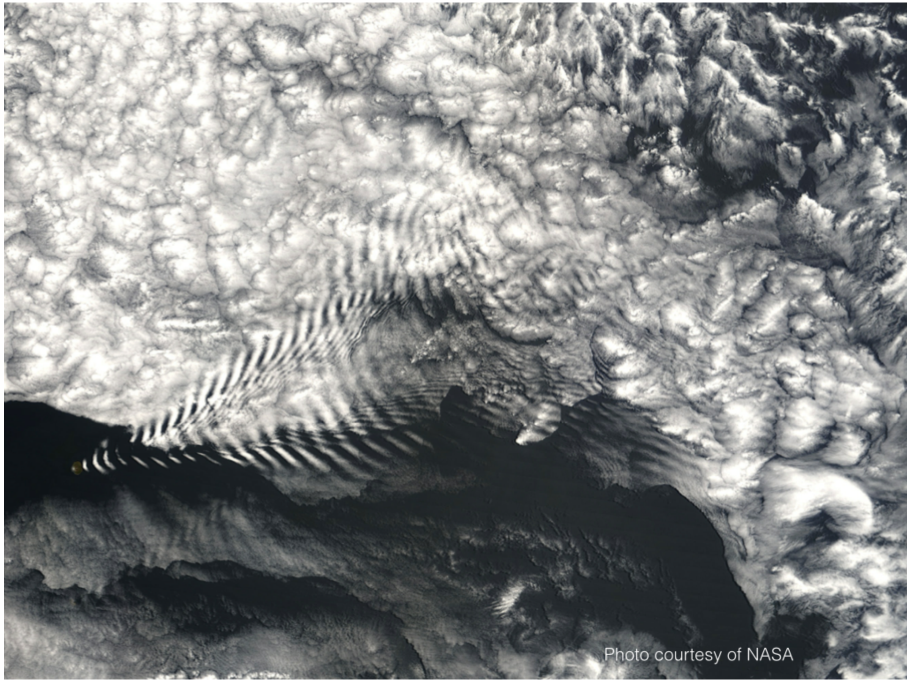
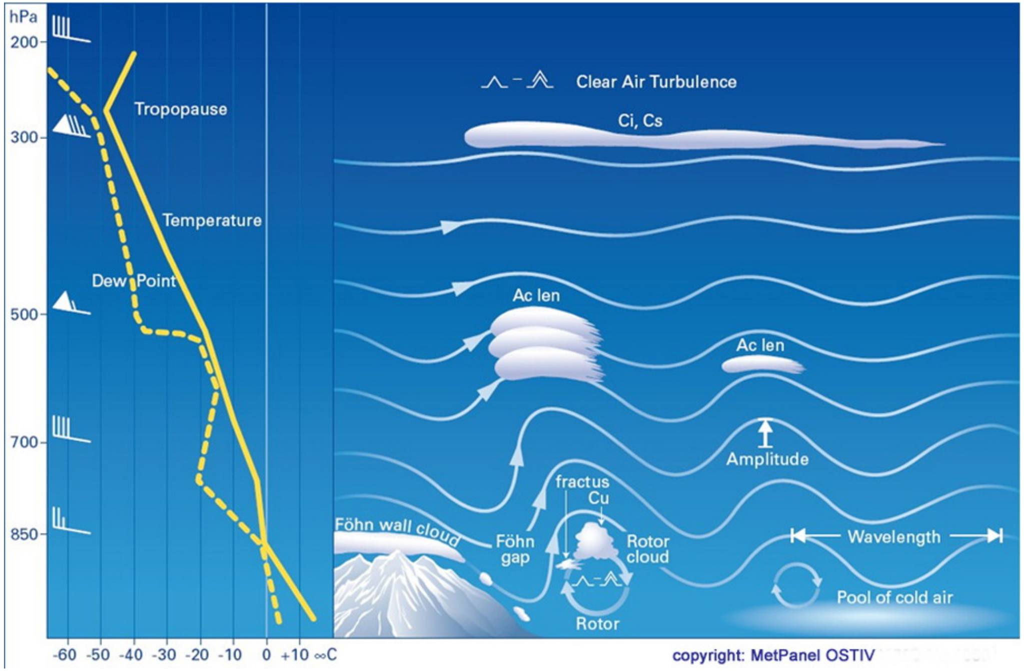


Photo courtesy of NASA

Mountain waves can be dangerous because of intense turbulence and high wind speed...

Mountain waves – Clouds

Clouds typically associated to mountain waves: cap, lenticular and rotor clouds

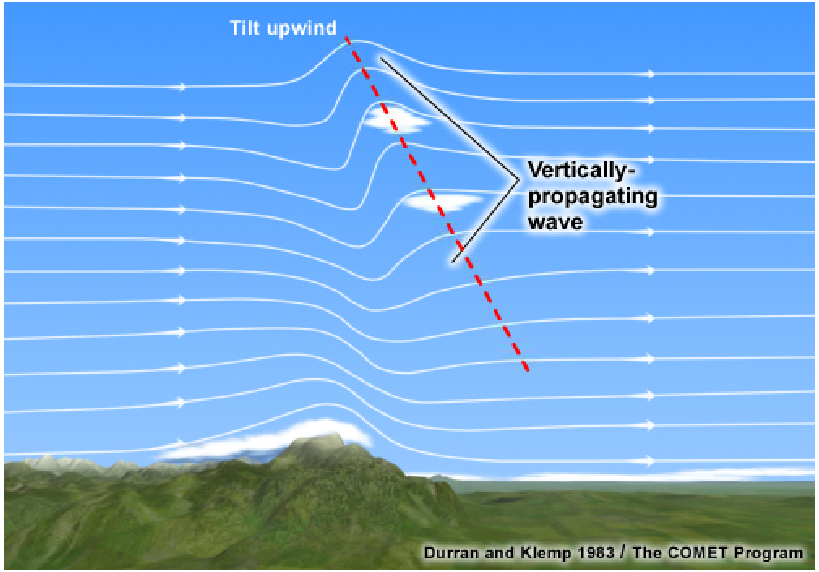


copyright: MetPanel OSTIV

https://rescueservice.sk/?p=9390

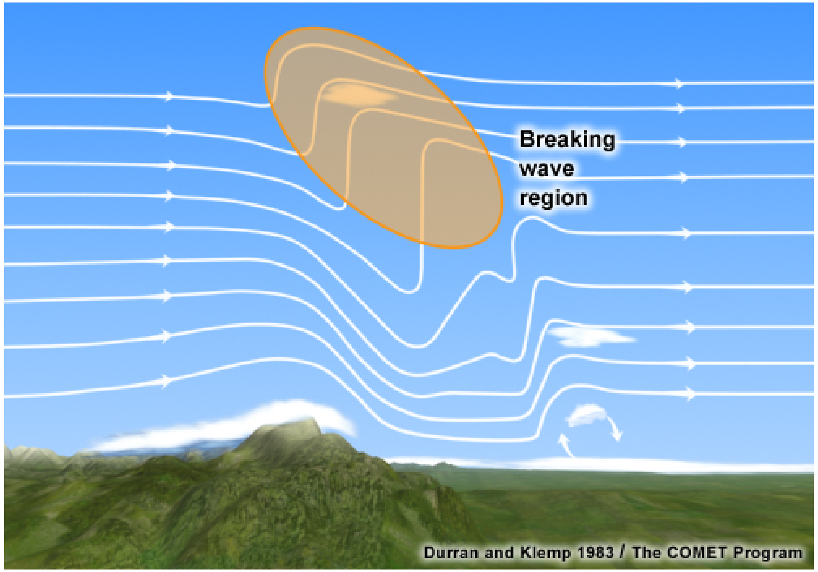
Mountain waves – Vertical propagation

Amplitude is increasing with height
→ upwind tilt of the wave.



Durran and Klemp 1983 / The COMET Program

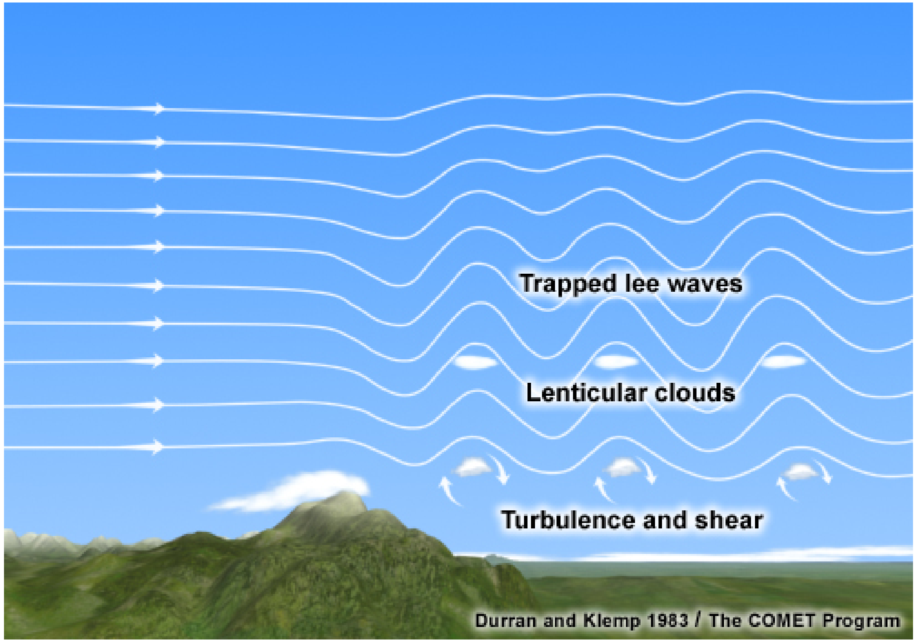
Vertical wave may break:
→ dissipation of a lot of energy
→ strong turbulence, danger for aircraft!



Durran and Klemp 1983 / The COMET Program

Mountain waves – Trapped waves

If there is strong wind shear or a less stable layer above, the waves will be trapped
→ vertical propagation is blocked so the waves are confined in the atm below
→ horizontal extension can be larger...



Durran and Klemp 1983 / The COMET Program

Questions

1. What is the key mechanism leading to orographic precipitation?

2. What are the three main types of downslope winds?

3. What is a gravity wave?

4. In which region of the atm potentially associated with gravity waves is turbulence very strong and potentially dangerous?

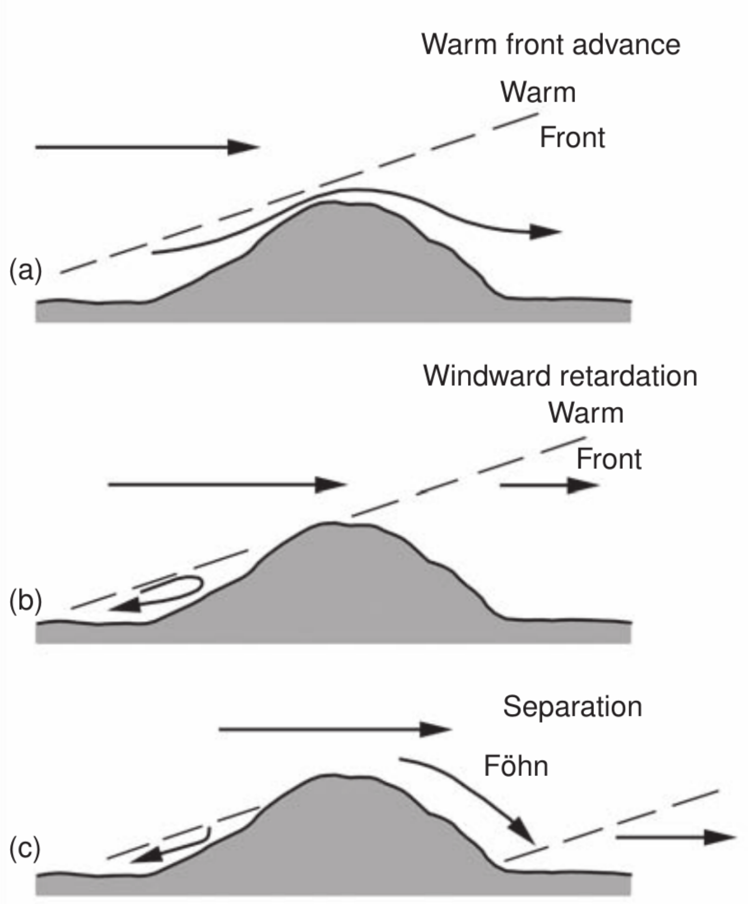
6. Frontal passage

Warm front over a mountain

(a) The warm front approaches.

(b) The lower part is retarded because of blocking.

(c) Separation (possibly strengthened by Föhn) leading to 2 cloudy/rainy regions.



Barry 2008, fig3.8

6. Frontal passage

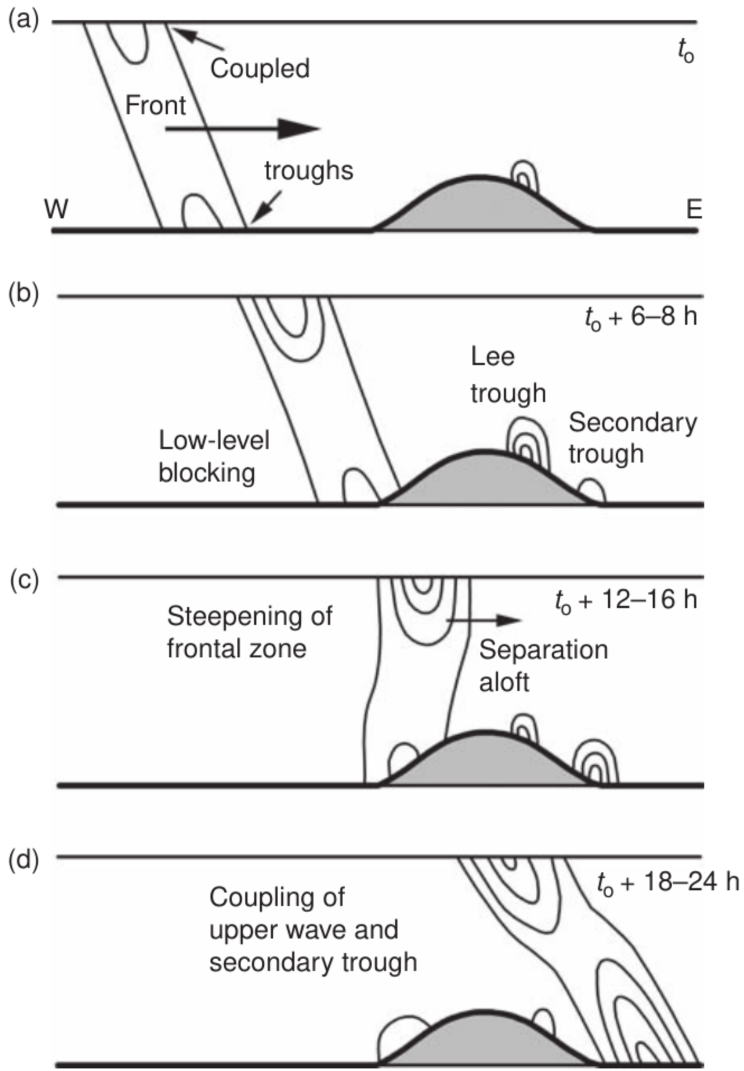
Cold front over a mountain

(a) The cold front approaches.

(b) The lower part is retarded because of blocking.

(c) The front steepens because of the blocking.

(d) New coupling after the mountain.



Barry 2008, fig3.9

7. A local wind: Joran

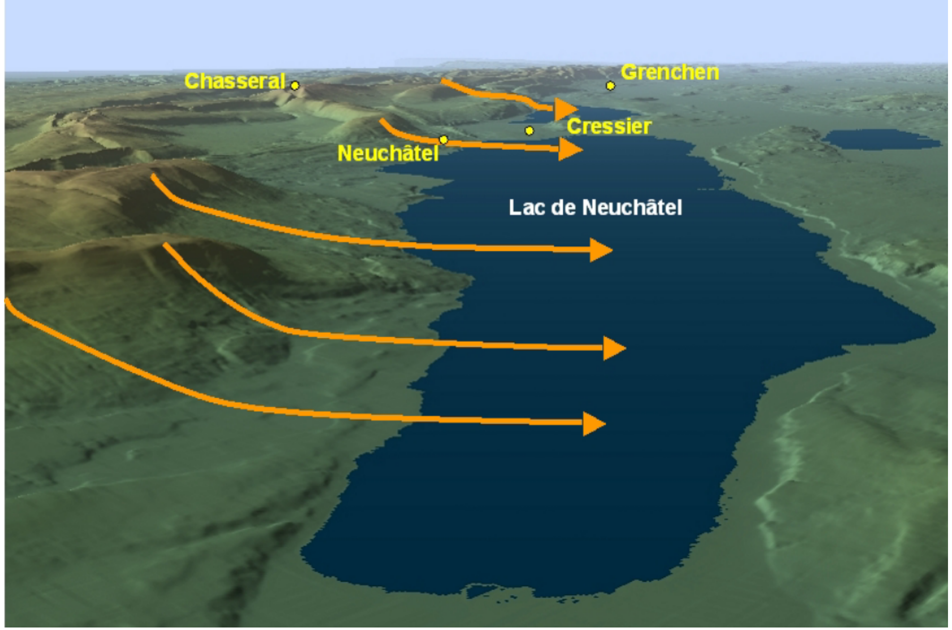
Joran

Joran is a downslope wind on the eastern slopes of the Jura range.

Joran “dynamique”: related to cold air overspilling from ridge/France, associated with cap clouds on Jura.

Joran “d’orage”: cold air associated to local thunderstorms.

Joran “beau temps”: common katabatic wind in the evening.

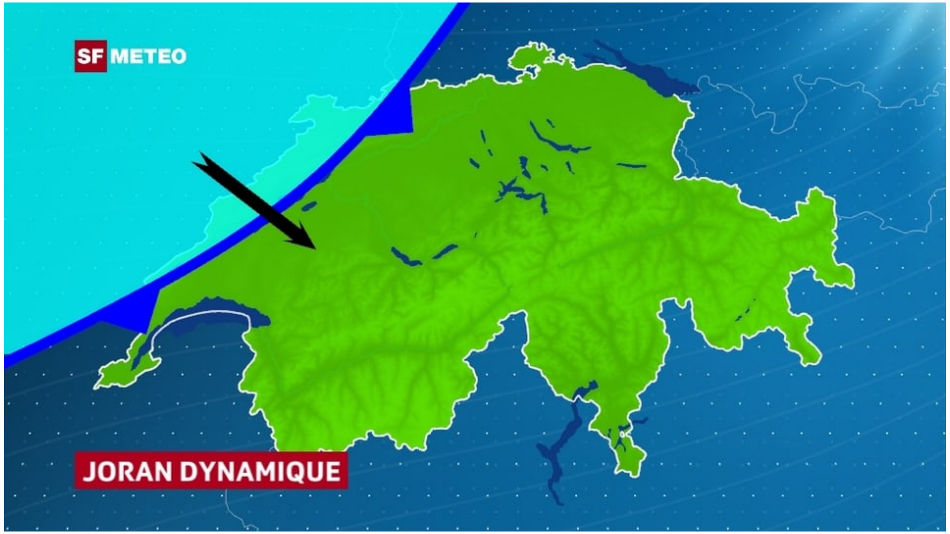


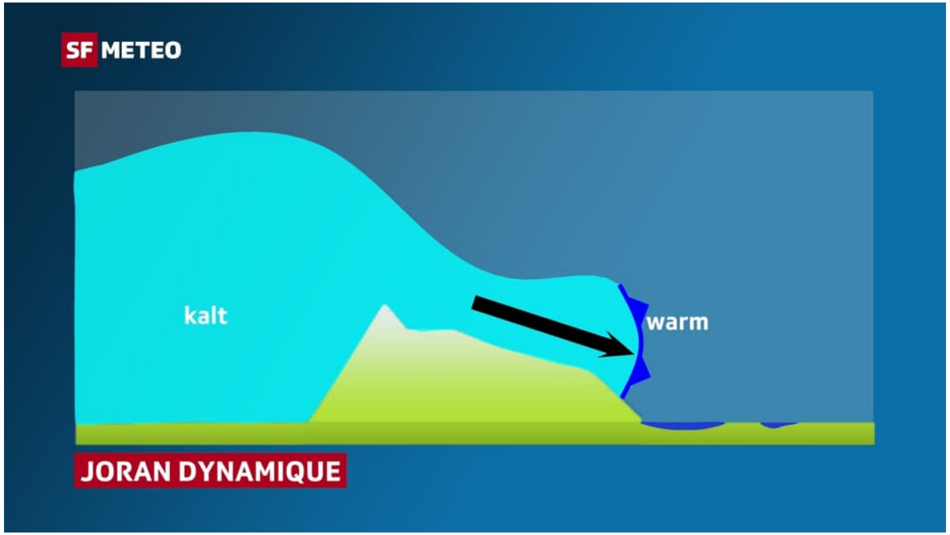
https://myclimbrate.files.wordpress.com/2013/09/joran.pdf

7. A local wind: Joran

Joran dynamique

Related to a cold front approaching from west, blocking by Jura then overspilling to CH.





https://www.srf.ch/meteo/meteo-news/joran-fallwind-am-jurasuedfuss-mit-ueberraschenden-gesichtern

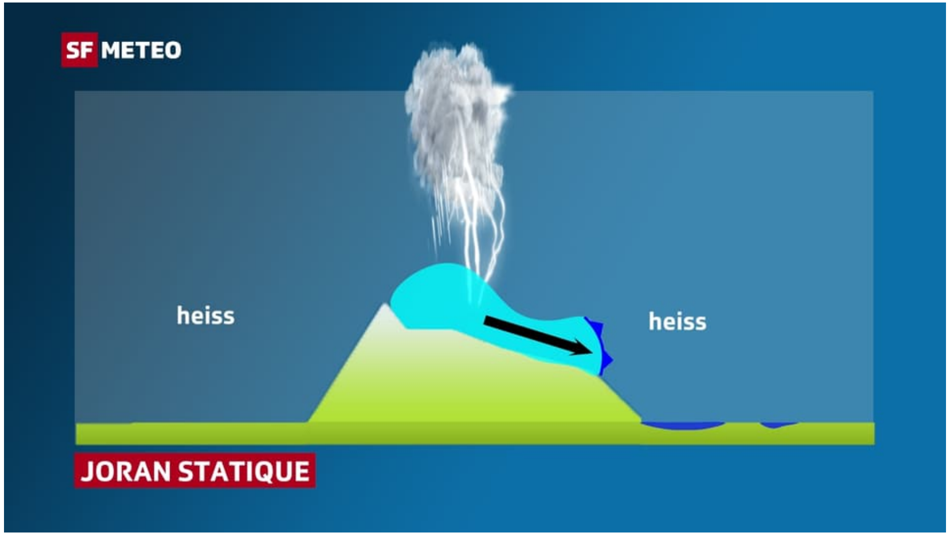
Which downslope wind is it similar to?

7. A local wind: Joran

Joran d’orage

Storms in the Jura generate cold outflow, combined with eastern slopes.

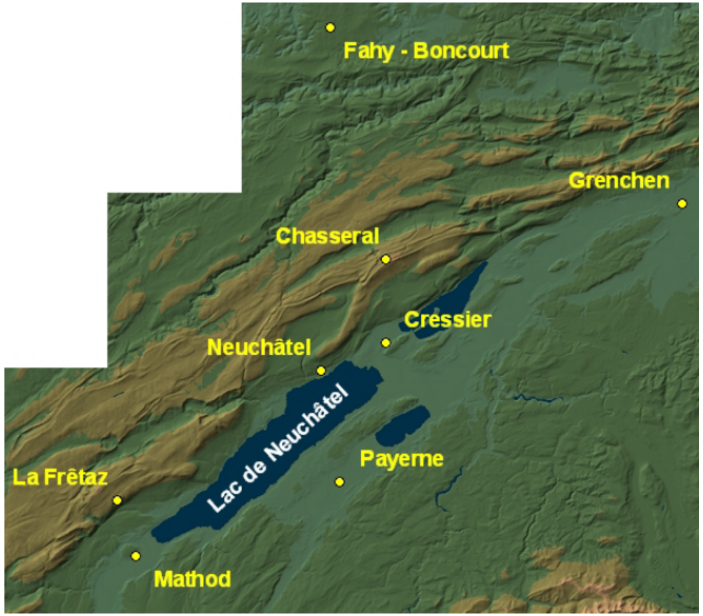
Can be very sudden and intense (gust > 100 km/h).



https://www.srf.ch/meteo/meteo-news/joran-fallwind-am-jurasuedfuss-mit-ueberraschenden-gesichtern

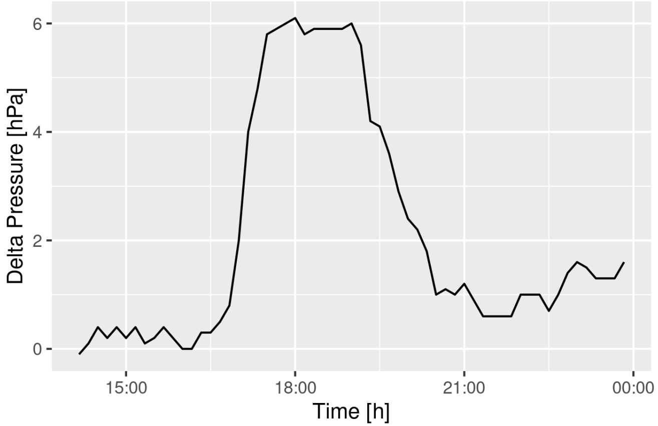
7. A local wind: Joran

Ex of Joran case – 13 Jun 2013

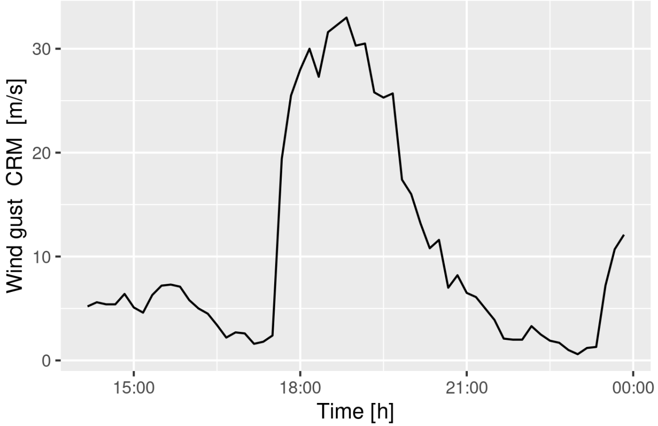


https://myclimbrate.files.wordpress.com/2013/09/joran.pdf

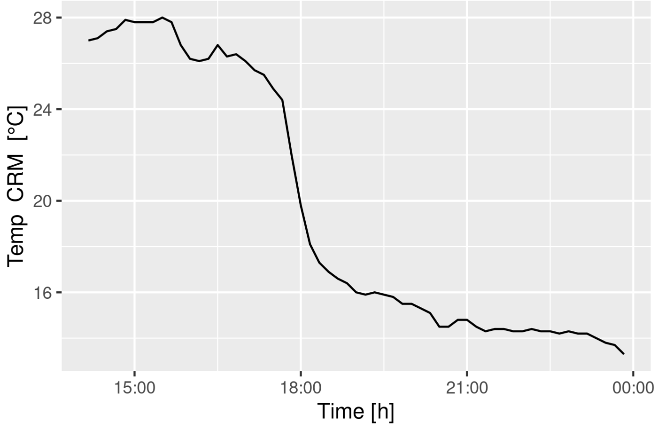
Δ pressure Fahy / Cressier



Wind gust (max 1s) at Cressier



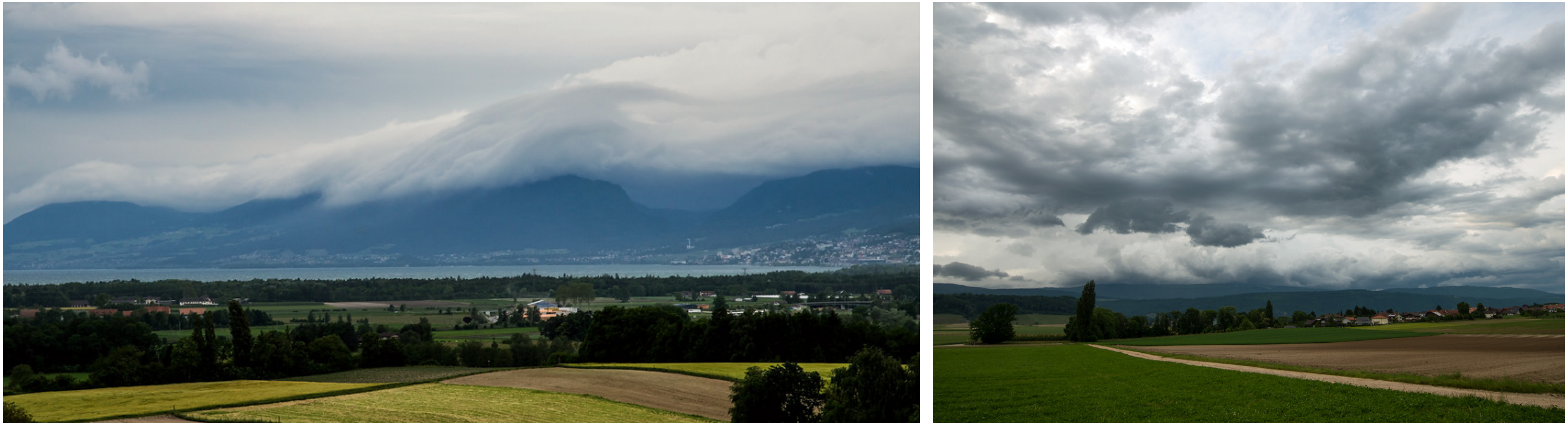
Temperature at Cressier



7. A local wind: Joran

Ex of Joran case – 13 Jun 2013

Pictures taken in the area between Lakes Neuchâtel and Bienne



https://www.fotometeo.ch/lokale-wetterphaenomene-i-der-joran/

Summary

Mountain meteorology

1. Stability → Static stability = function of buoyancy so lapse rate is crucial.
   → Brunt-Vaisala frequency: oscillation of air parcel in stable atm.
   → Dynamic stability: effect of wind shear and turbulence.
2. Thermal circ. → Slope winds (anabatic / katabatic).
   → Valley winds.
   → Cold air pooling.
3. Flow interactions → Stability and Froude number.
   → Blocking.
4. Orographic precip → Lifting due to mountains leads to saturation and precipitation
5. Winds and waves → Downslope winds: Föhn, Bora, katabatic
   → Mountain waves: gravity waves, associated clouds and turbulence.
6. Frontal passage → Mountain influence on passing warm and cold fronts.
7. Local wind: Joran → definition and example.