Field Observation in Climatology and Environmental Hydrology

Module: Regional wind systems

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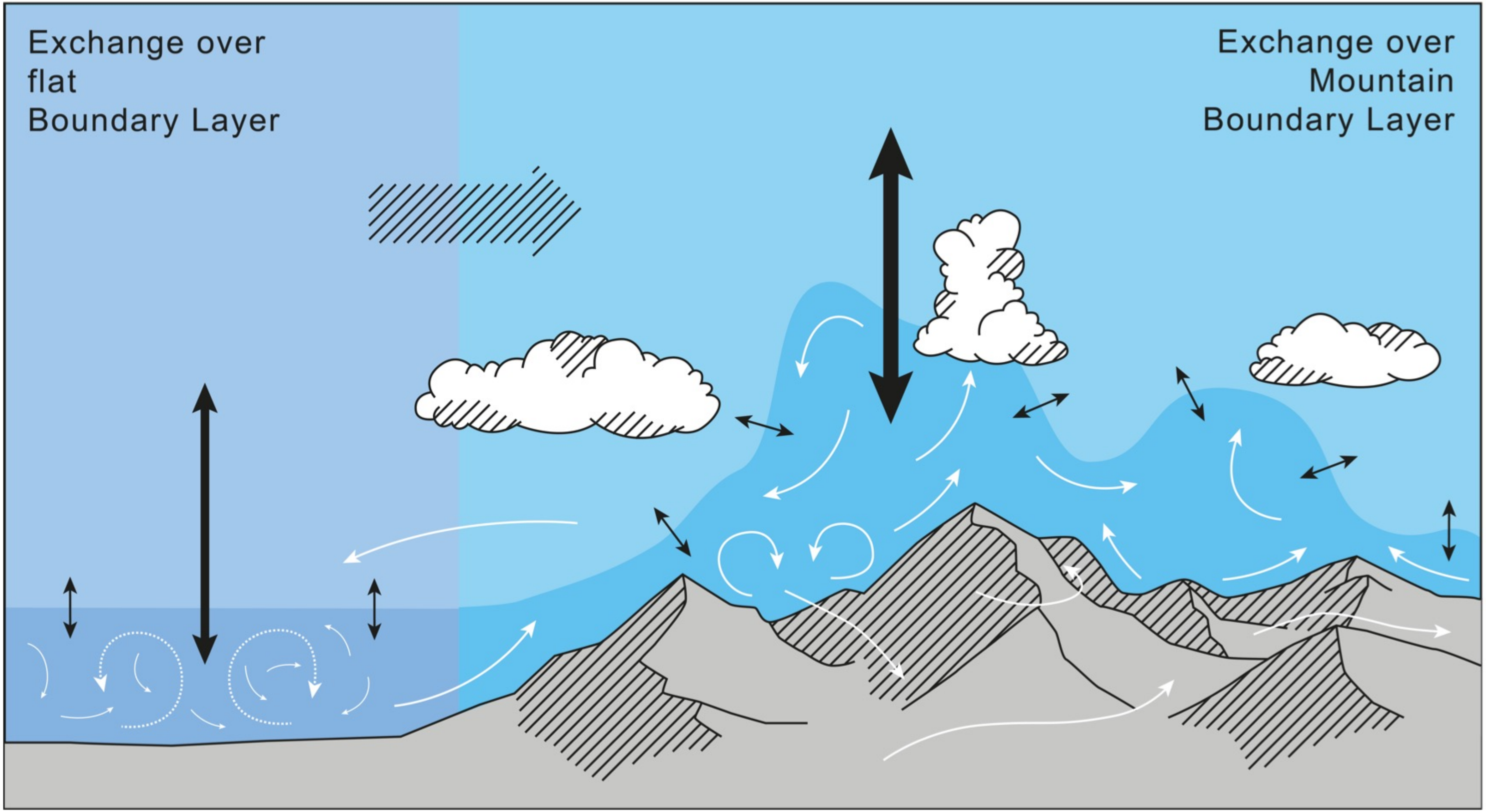
Date 29.06.2023

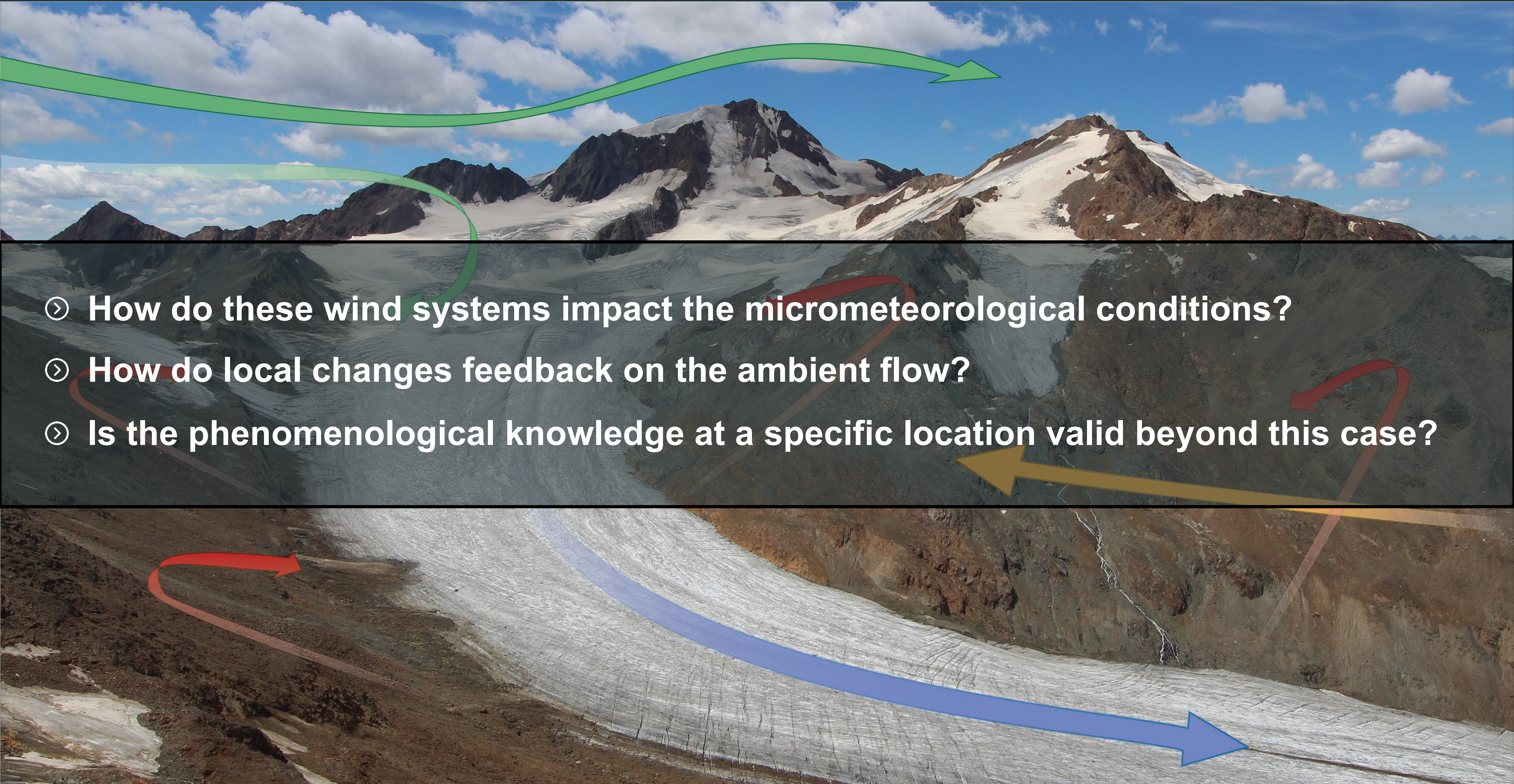
Learning objectives

- Anabatic wind systems
- Katabatic wind systems
- Gap flows
- Föhn winds

Exchange processes over mountains



Micrometeorological condition in complex terrain

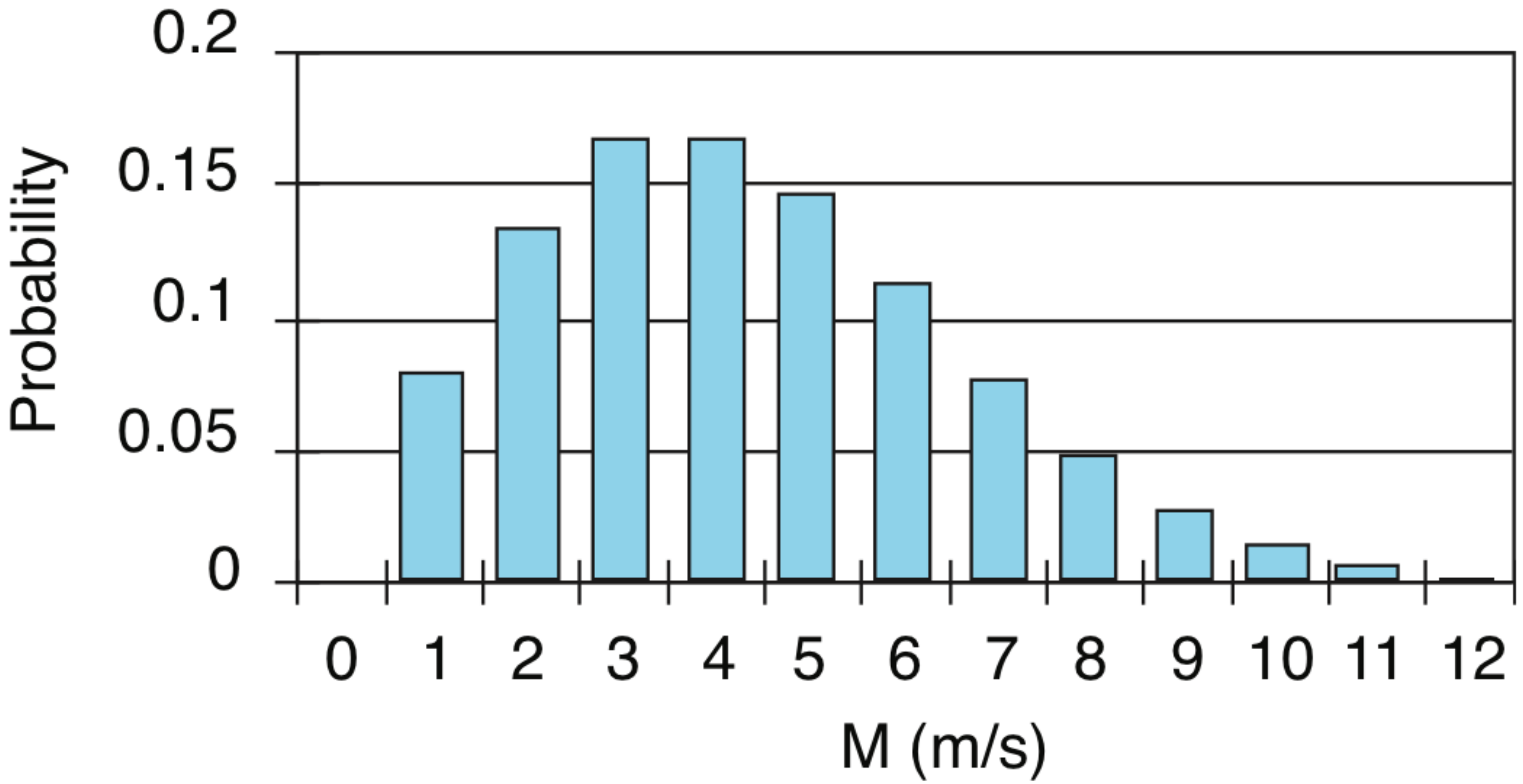


- **How do these wind systems impact the micrometeorological conditions?**
- **How do local changes feedback on the ambient flow?**
- **Is the phenomenological knowledge at a specific location valid beyond this case?**

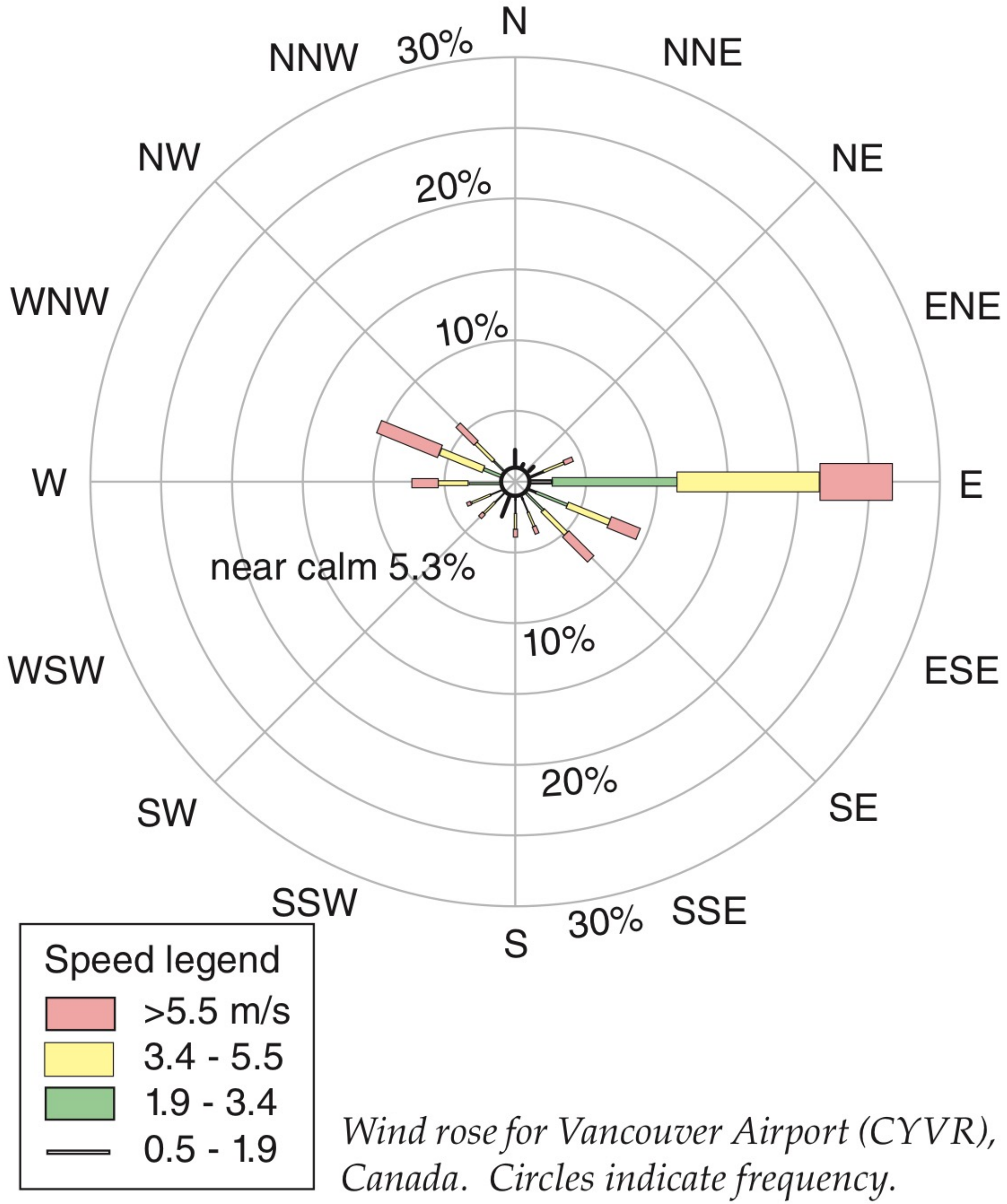
Wind-speed frequency

$$Pr = \frac{\alpha \cdot \Delta M \cdot M^{\alpha-1}}{M_0^{\alpha}} \cdot exp^{-\left(\frac{M}{M_0}\right)^{\alpha}}$$

P	Probability
M_0	proportional to the mean wind speed [m/s]
α	spread parameter
ΔM	bin size or resolution [m/s]

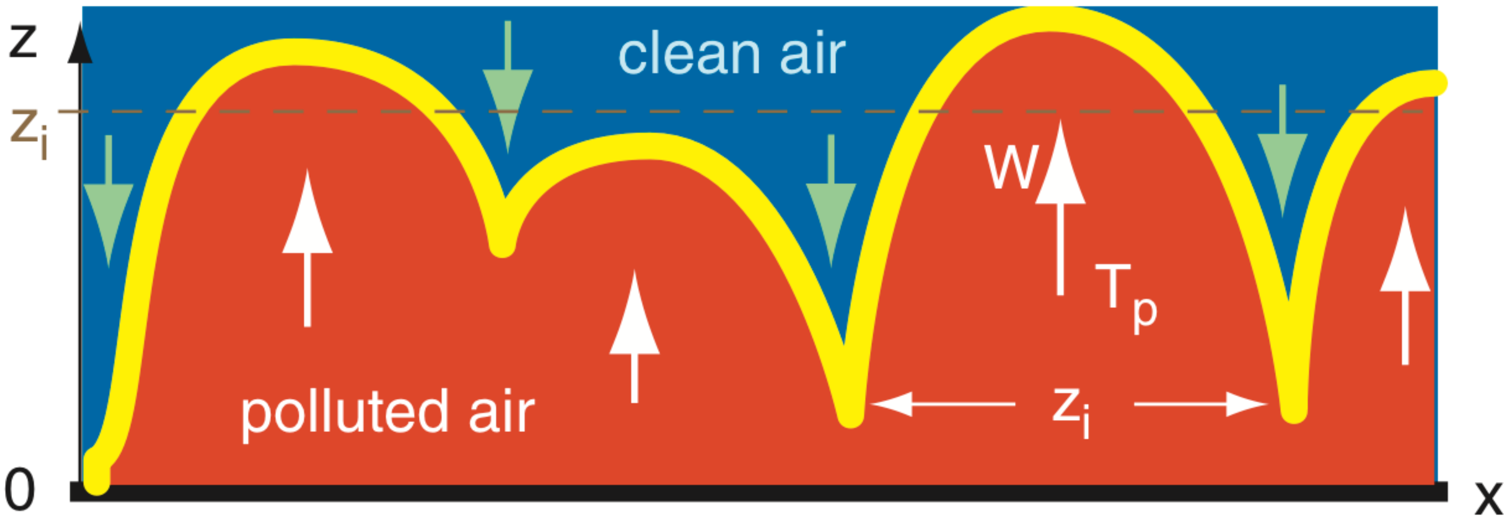


Wind-direction frequency



Wind rose for Vancouver Airport (CYVR), Canada. Circles indicate frequency.

Thermals



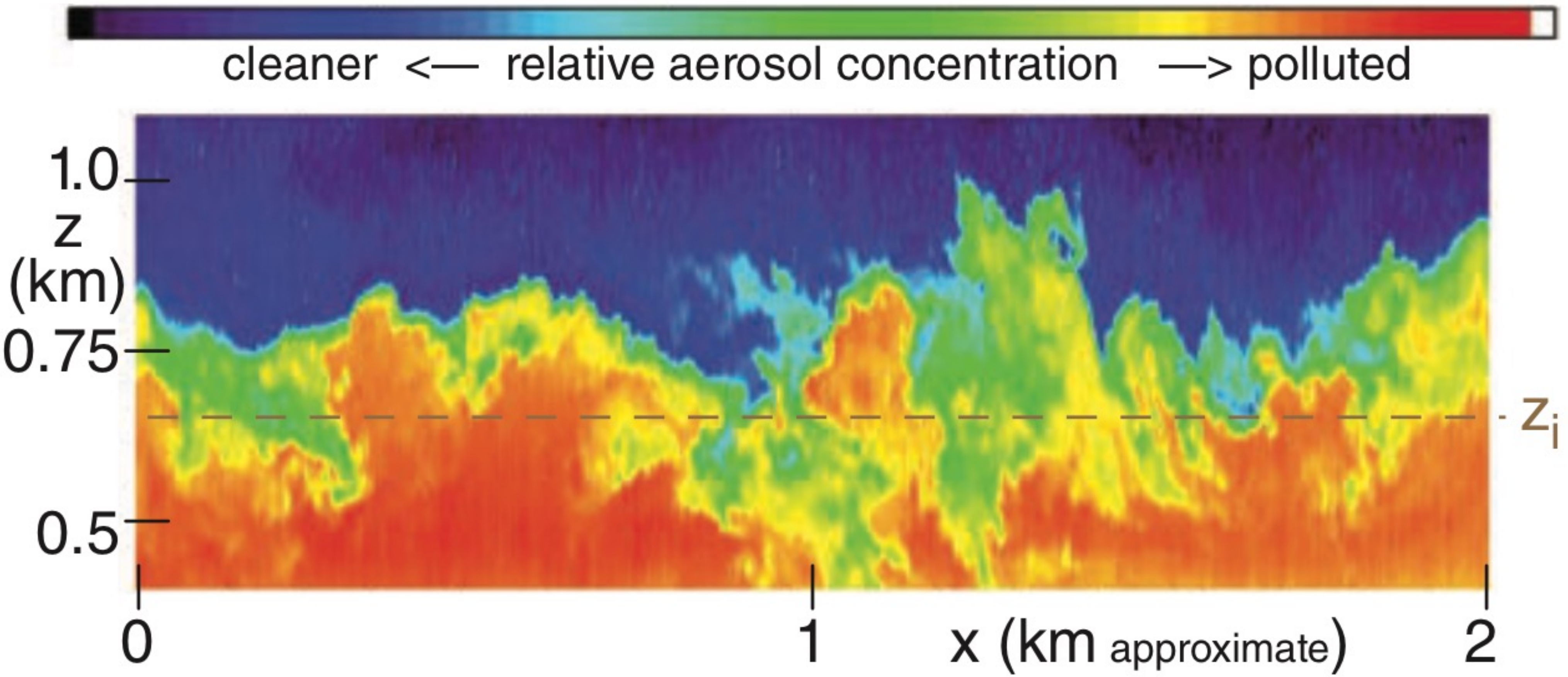
$$\frac{\Delta W}{\Delta t} = \frac{\theta_p - \theta_e}{\bar{T}_e} \cdot |g| - C_w \frac{W^2}{z_i}$$

W: vertical velocity [m/s]
θ_e: potential temperature of the environment [K]
θ_p: potential temperature of the air parcel [K]
T_e: average environmental temperature [K]
g: gravitational acceleration [m/s^2]
z_i: mixed layer depth [m]
$C_w \sim 5$: vertical drag coefficient

Steady-state solution for updraft speed of buoyant thermals

$$\boxed{W = \sqrt{\frac{|g| \cdot z_i}{C_w} \frac{(\theta_p - \theta_e)}{\bar{T}_e}}}$$

Actual thermals are visible to lidar



Newtons Lex secunda (Lagrange'sche perspective)

$$\vec{F} = m \cdot \vec{a} = m \cdot \frac{\Delta \vec{V}}{\Delta t}$$

$$\Rightarrow$$

$$\boxed{\frac{\Delta \vec{V}}{\Delta t} = \frac{\overrightarrow{F_{net}}}{m}}$$

This equations allows to make predictions of wind parcels

$$\frac{\Delta U}{\Delta t} = \frac{\overrightarrow{F_{x\_net}}}{m} \qquad \frac{\Delta V}{\Delta t} = \frac{\overrightarrow{F_{y\_net}}}{m} \qquad \frac{\Delta W}{\Delta t} = \frac{\overrightarrow{F_{z\_net}}}{m}$$

Newtons Lex secunda (Lagrange'sche perspective)

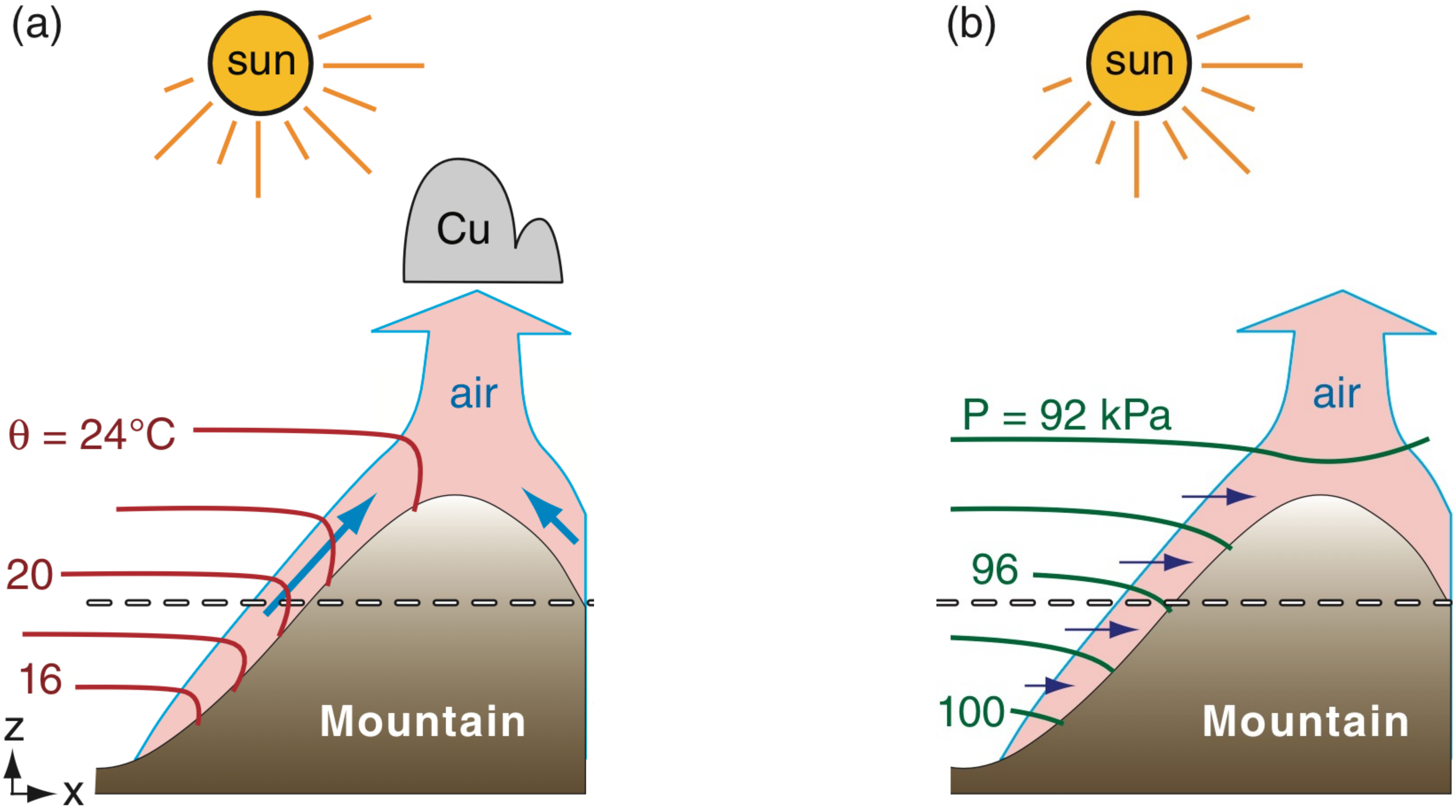
$$\vec{F} = m \cdot \vec{a} = m \cdot \frac{\Delta \vec{V}}{\Delta t} \Longrightarrow \boxed{\frac{\Delta \vec{V}}{\Delta t} = \frac{\overrightarrow{F_{net}}}{m}}$$

This equations allows to make predictions of wind parcels

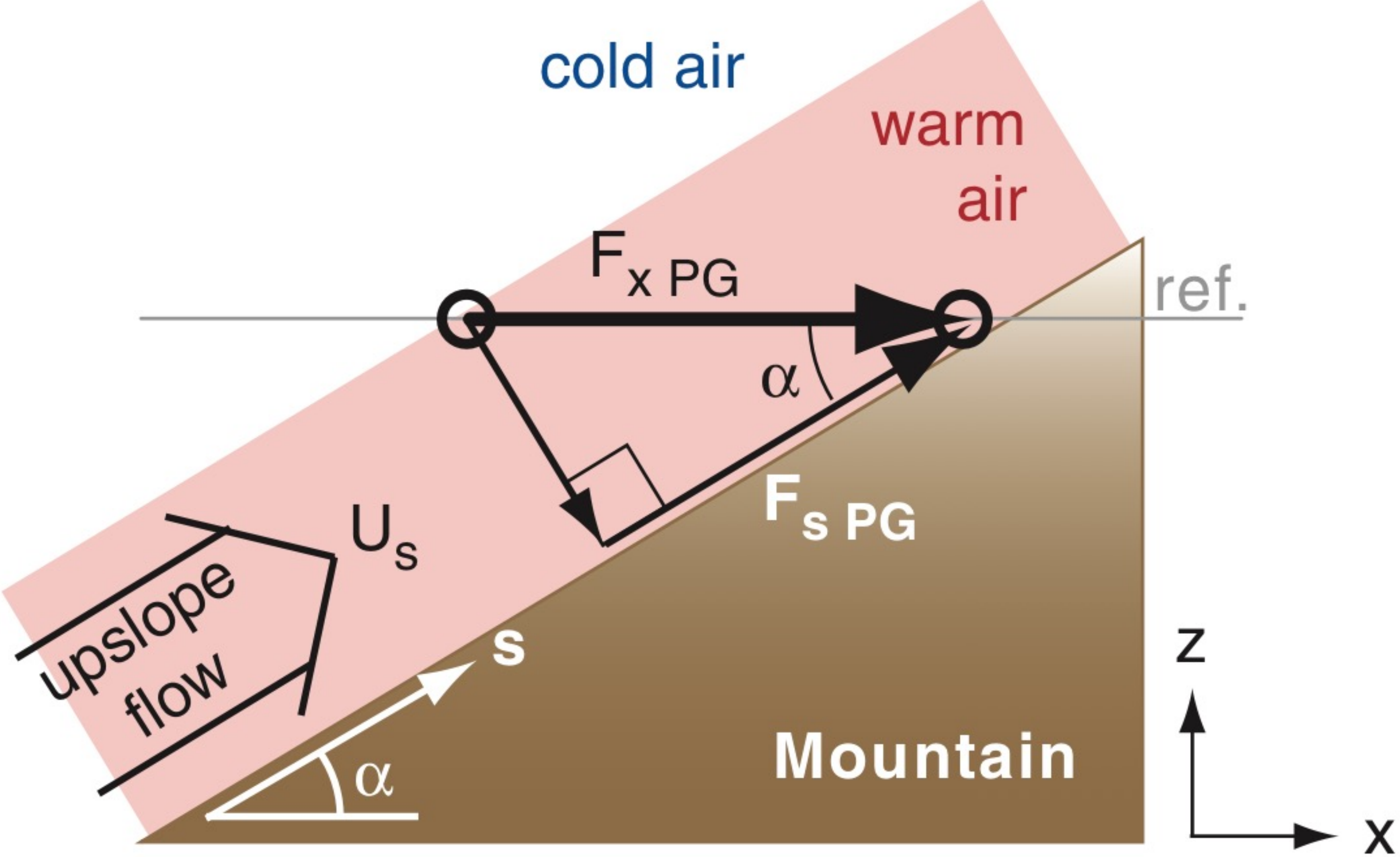
$$\frac{\Delta U}{\Delta t} = \frac{\overrightarrow{F_{x\_net}}}{m} \Longrightarrow U(t + \Delta t) = U(t) + \frac{\overrightarrow{F_{x\_net}}}{m} \cdot \Delta t$$

momentum equation

Cross-valley circulations – Anabatic wind



Cross-valley circulations – Anabatic wind



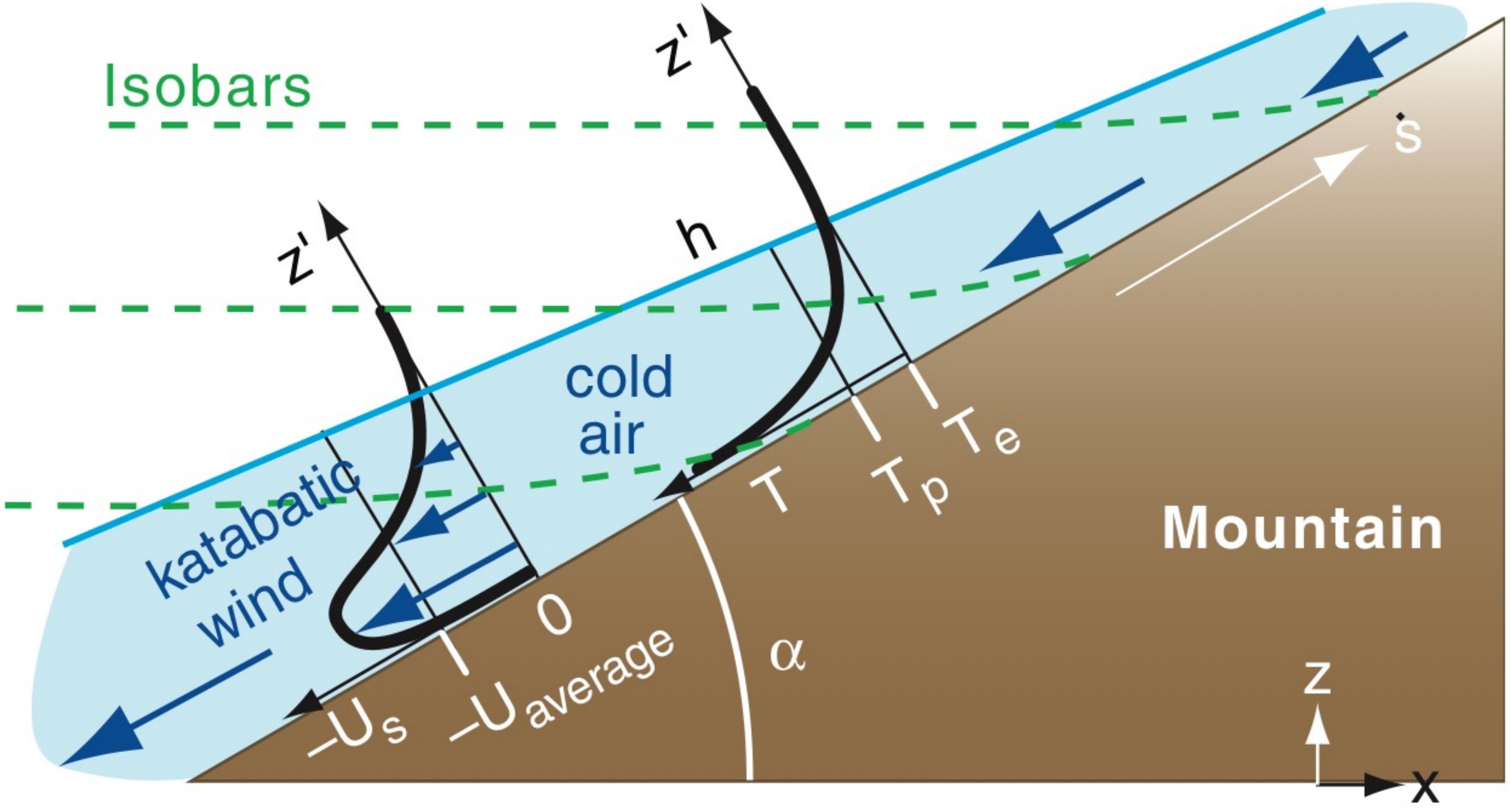
$$\frac{F_{s\ PG}}{m} = |g|\frac{\Delta T}{T_e} \cdot \sin(\alpha)$$

$$\frac{F_{x\ PG}}{m} = |g|\frac{\Delta T}{T_e} \cdot tan(\alpha)$$

$$\boxed{U_S = \sqrt{\frac{\Delta z}{C_D} \cdot |g|\frac{\Delta T}{T_e} \cdot \sin(\alpha)}}$$

U_S: upslow flow speed [m/s]
T_e: potential temperature of the environment [K]
ΔT: temperature differences of air near and far from the slope [K]
T_e: average environmental temperature [K]
g: gravitational acceleration [m/s^2]
α: mountain slow angle [º]
C_D: drag coefficient [-]
z: vertical depth of the slope flow [m]

Cross-valley circulations – Katabatic wind



Average windspeed at distance s downslope

$$\boxed{|U_{av}| = \sqrt{|g| \frac{\Delta T}{T_e} \cdot s * \sin(\alpha)}}$$

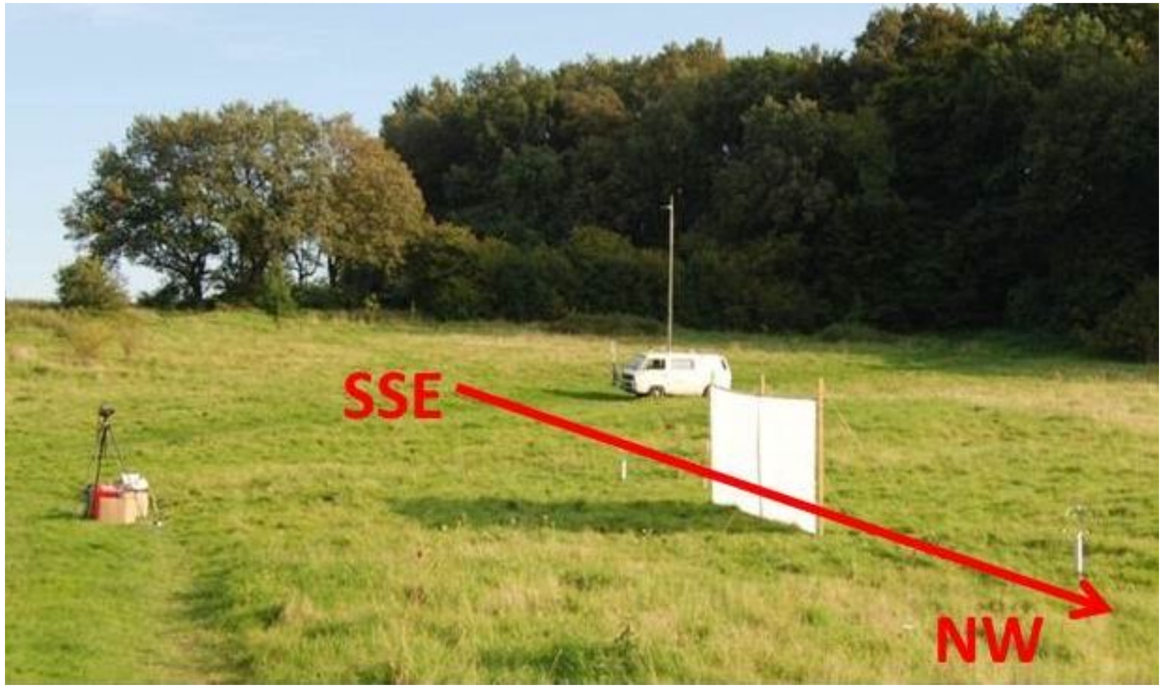
Equilibirum wind speed where drag balances buoyancy

$$\boxed{|U_{eq}| = \sqrt{\frac{h}{C_D} \cdot |g| \frac{\Delta T}{T_e} \cdot \sin(\alpha)}}$$

U_s	upslow flow speed [m/s]
T_e	potential temperature of the environment [K]
ΔT	temperature differences of air near and far from the slope [K]
g	gravitational acceleration [m/s²]

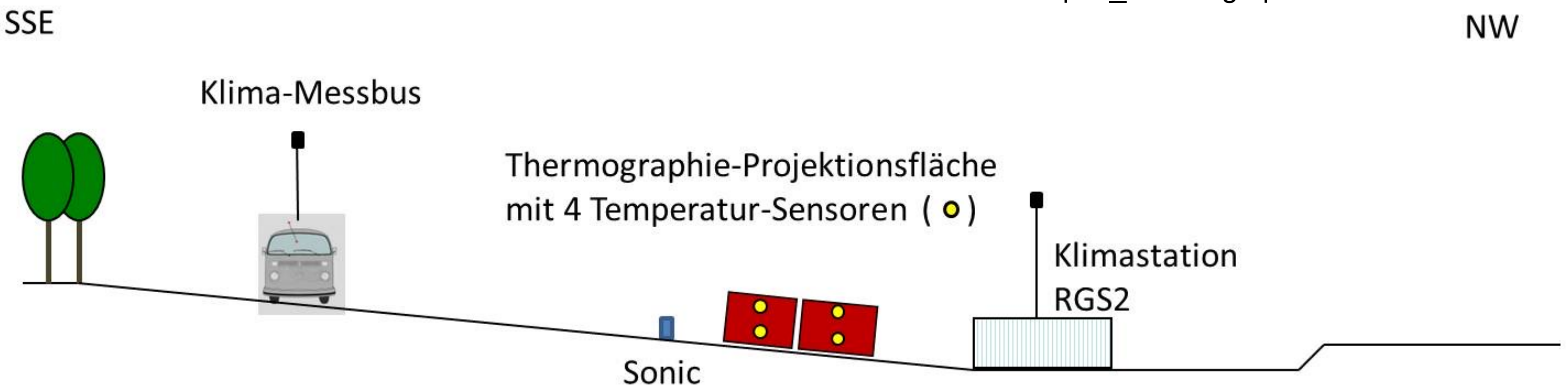
α	mountain slow angle [º]
C_D	drag coefficient [-]
h	vertical depth of the slope flow [m]
s	distance s downslope [m]

Thermography of cold air at a slope



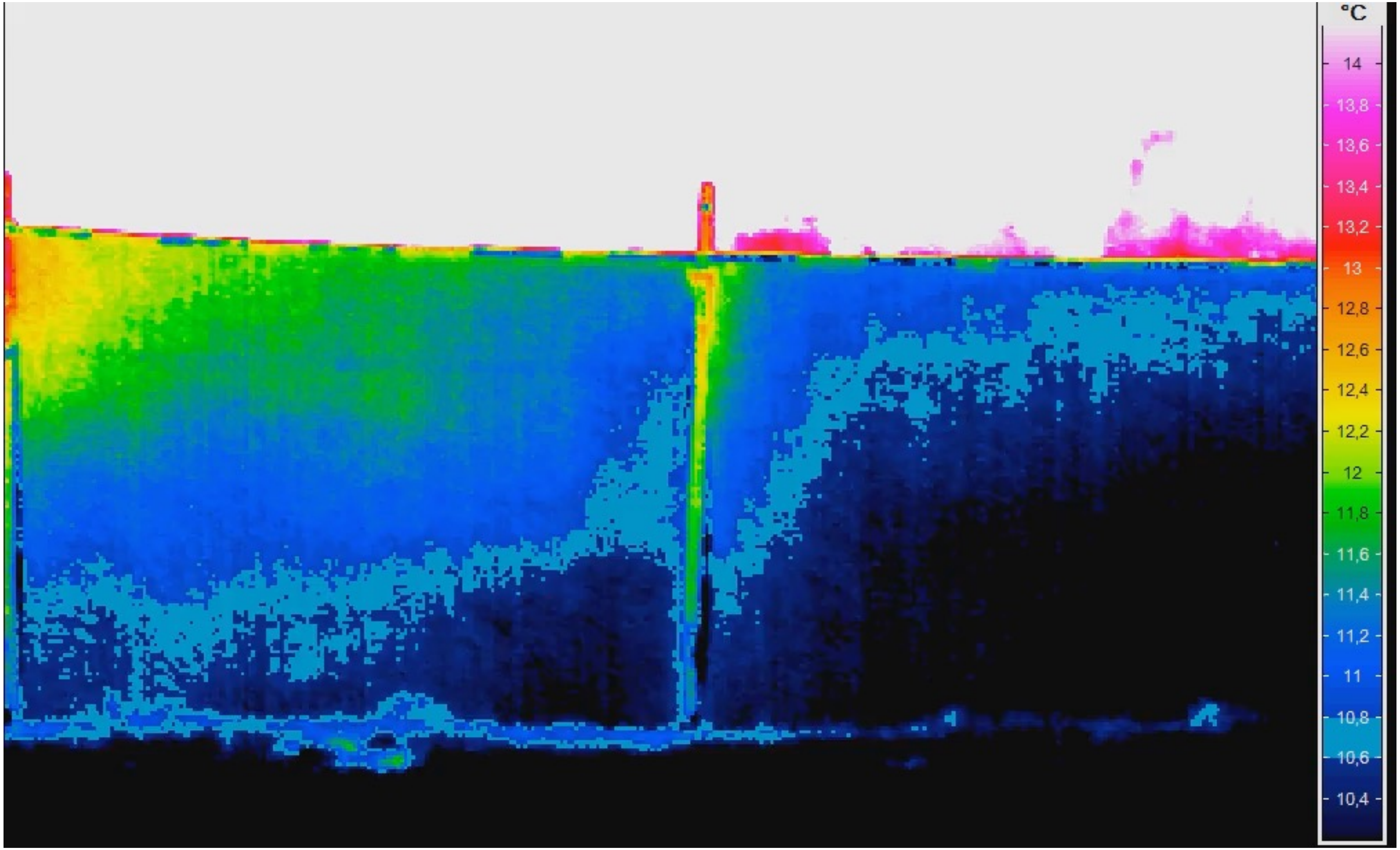
von: Martina Grudzielanek, Geographisches Institut, RUB

Film: 6-Kap06_Thermographie Kaltluft

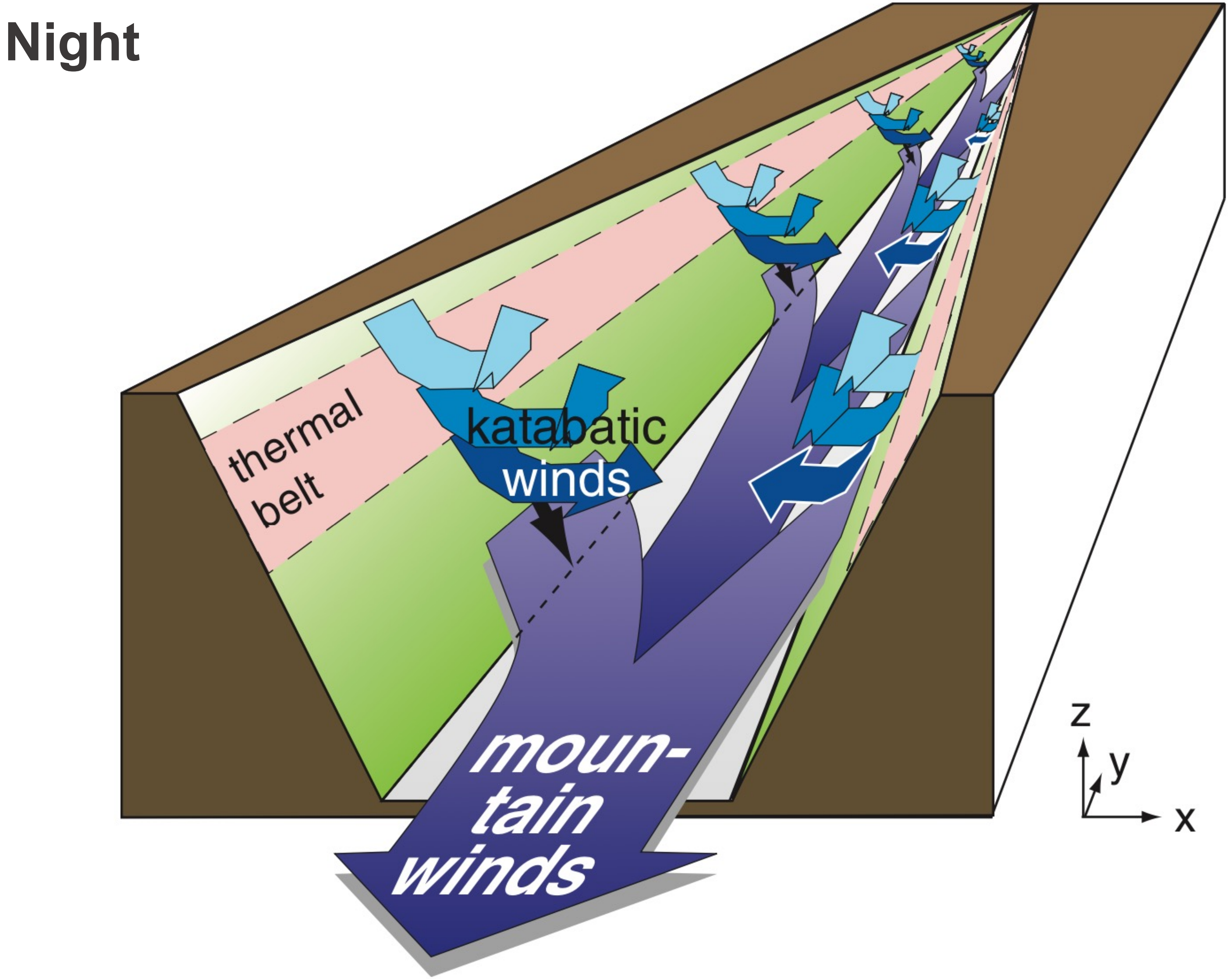


Martina Grudzielanek, Geographisches Institut, RUB

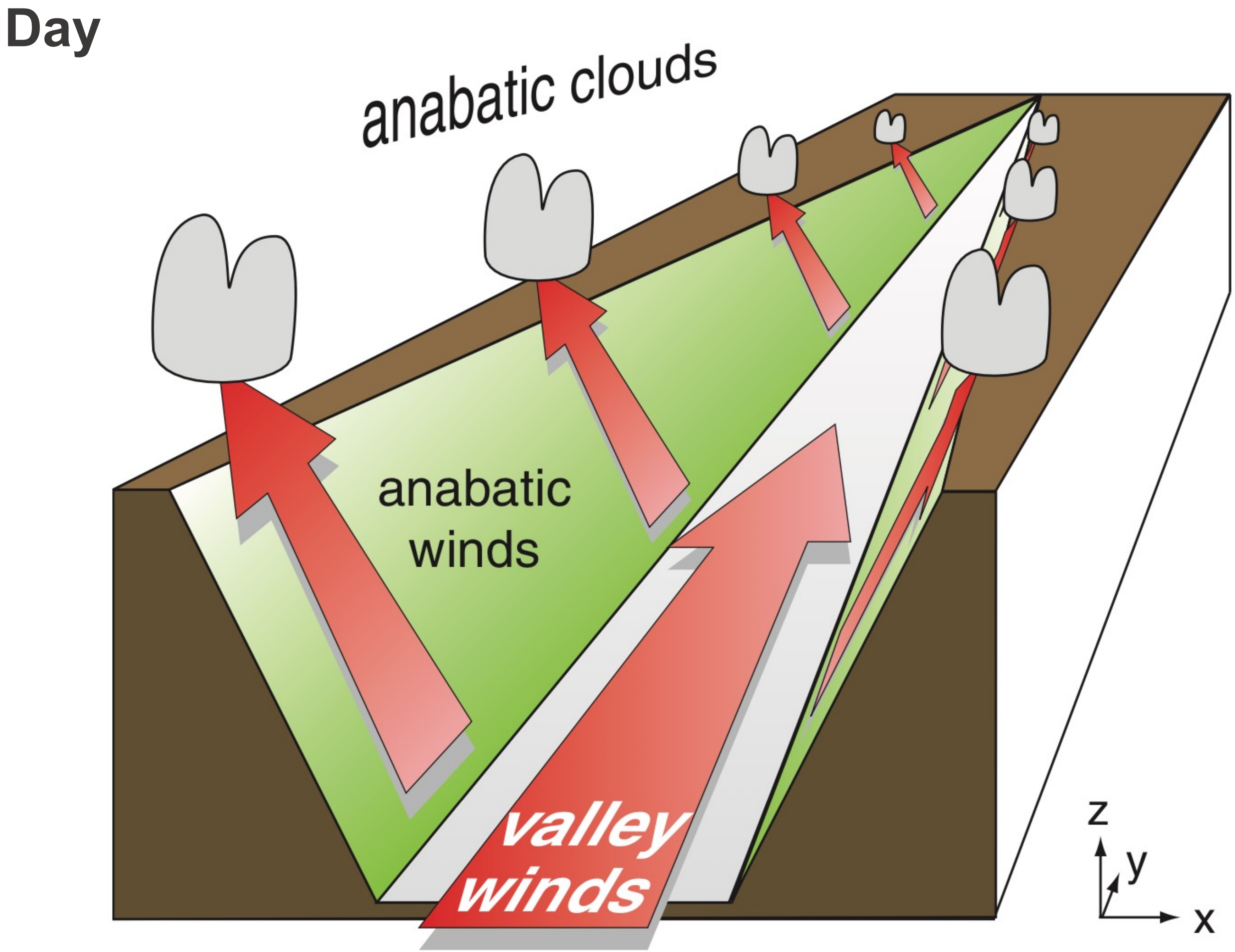
Thermography of cold air at a slope



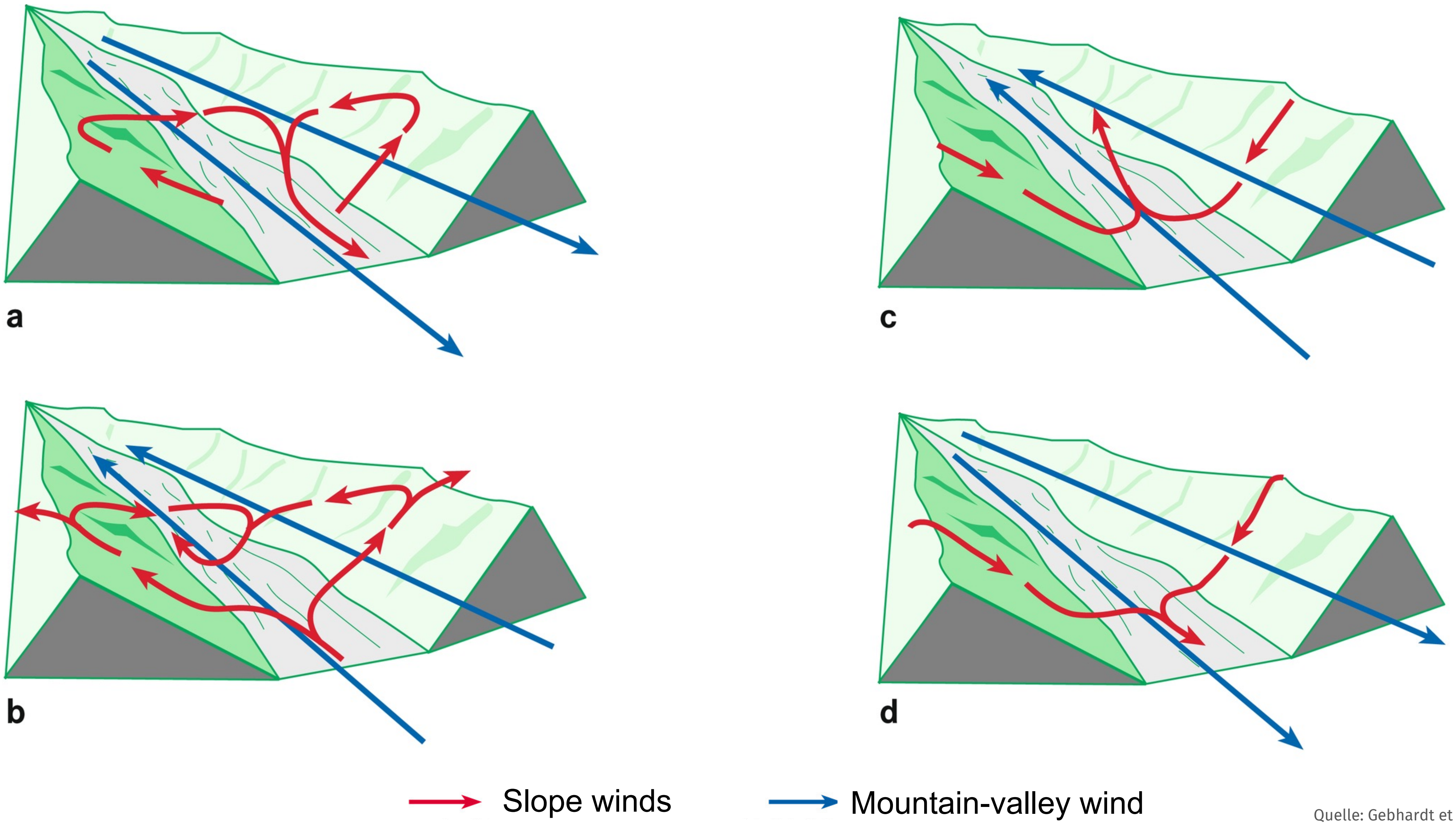
Martina Grudzielanek, Geographisches Institut, Along valley winds



Along valley winds

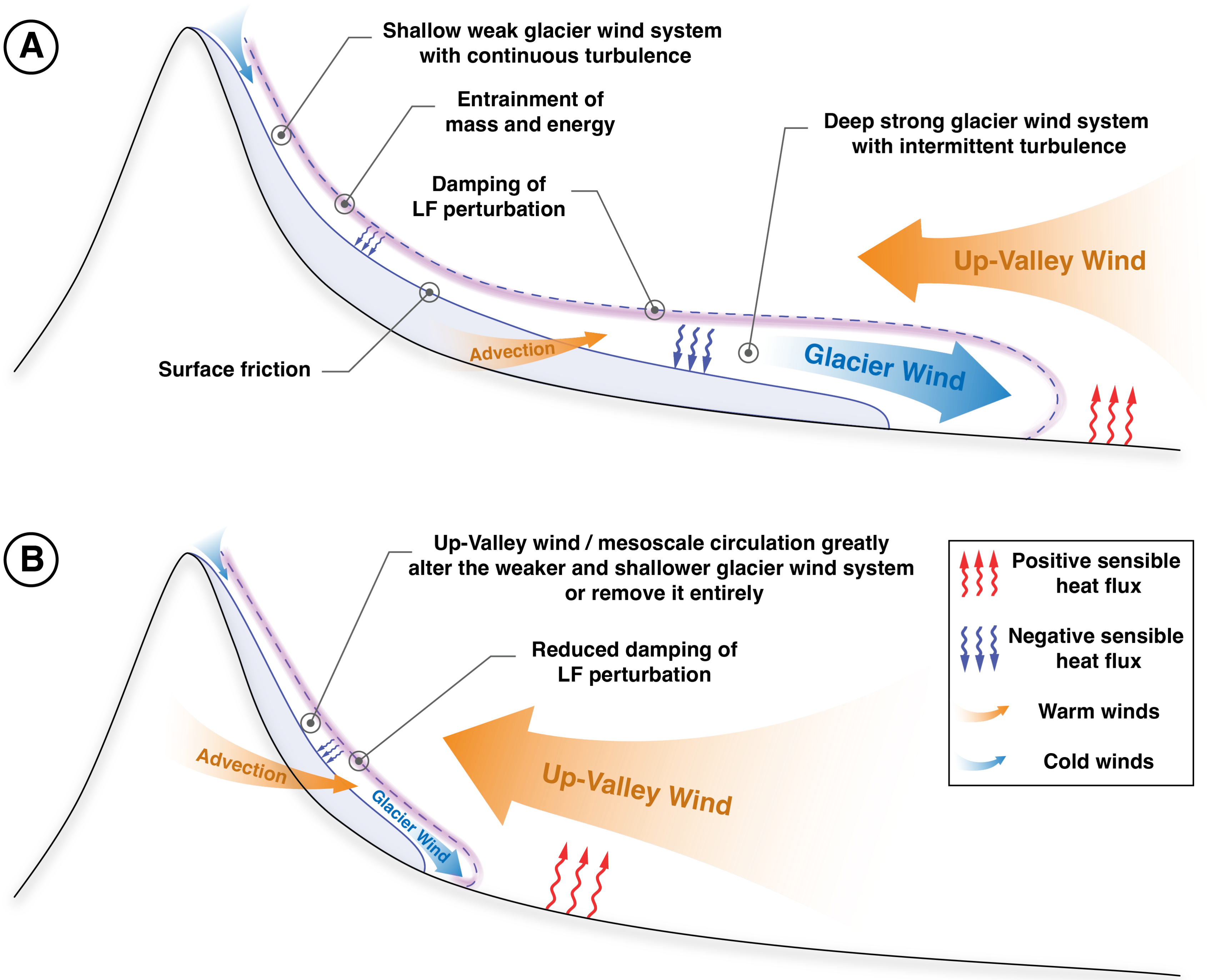


Slope and mountain-valley wind system

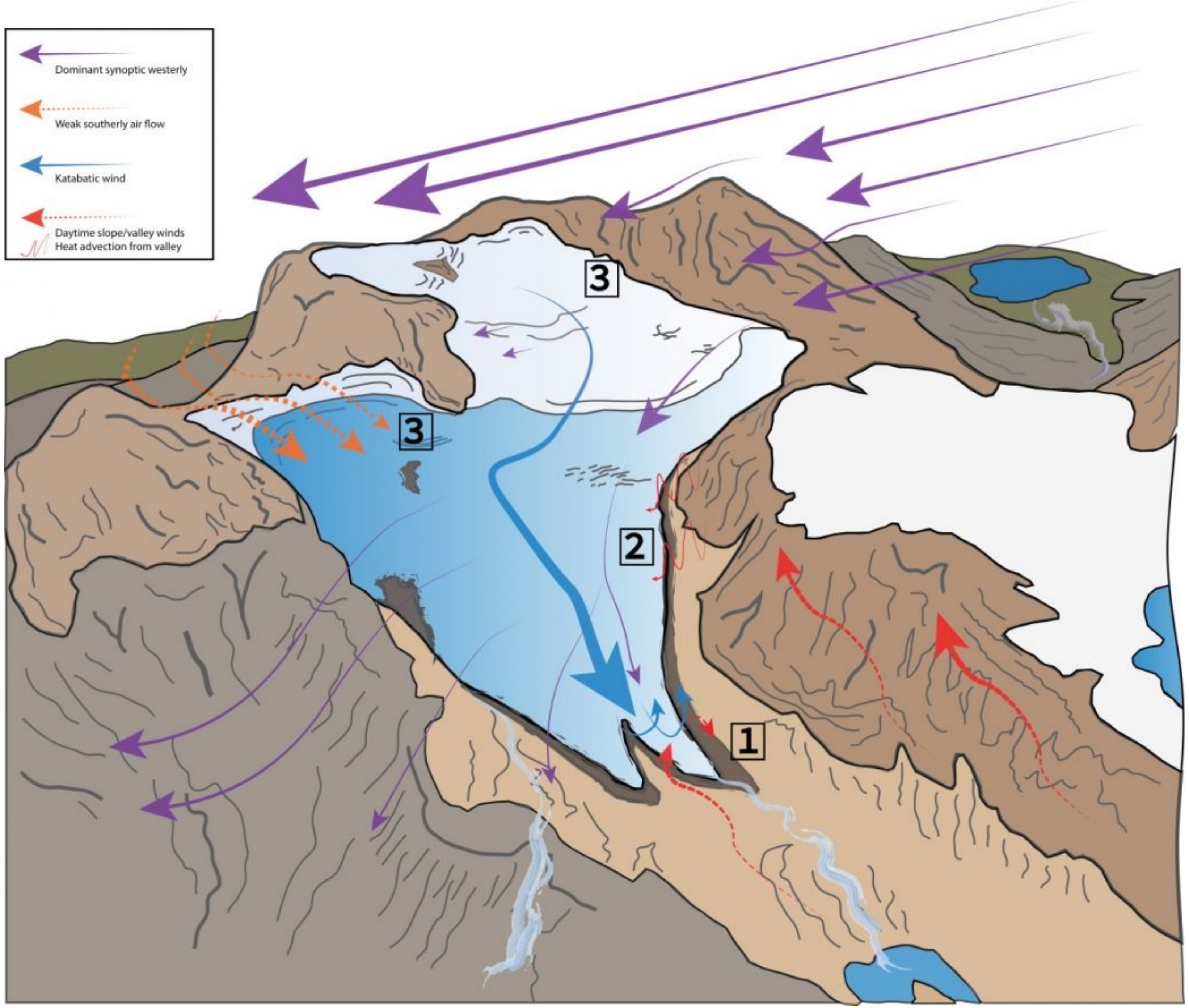


Quelle: Gebhardt et al. 2011: 277

Glacier wind system

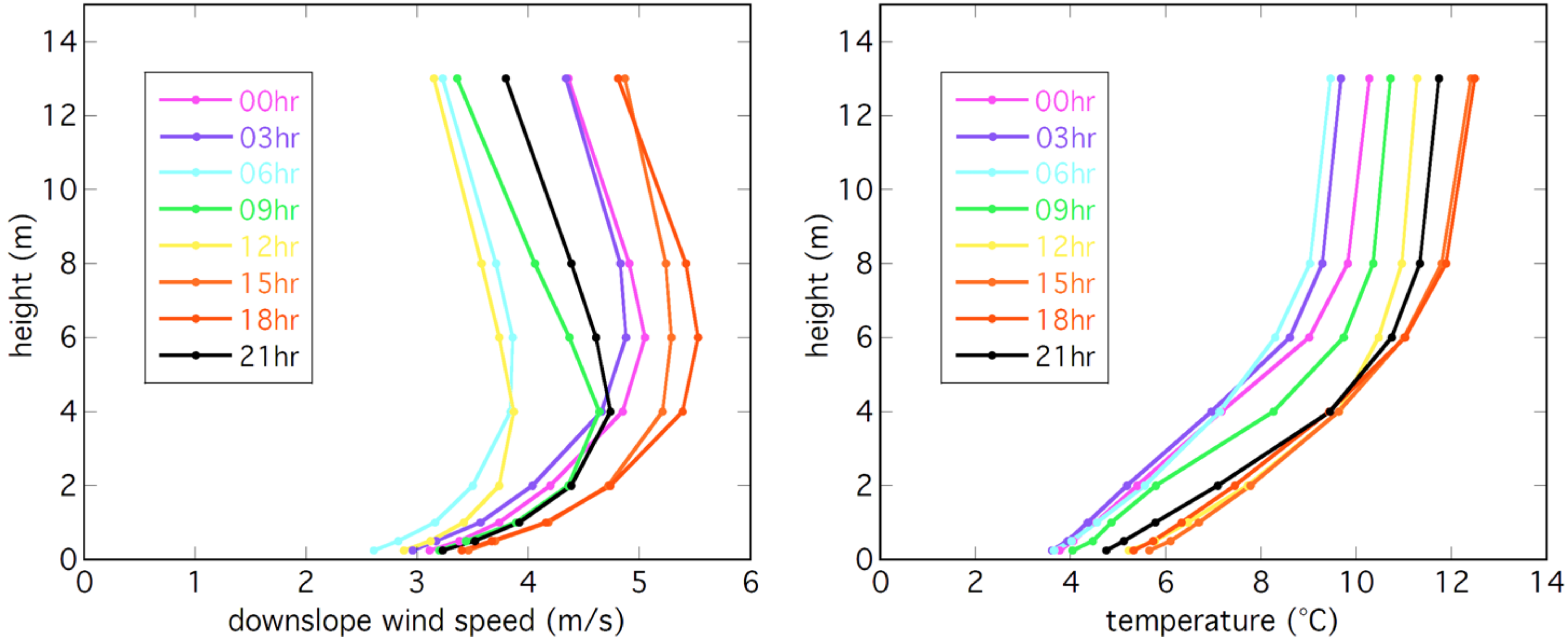


Wind flow in complex terrain



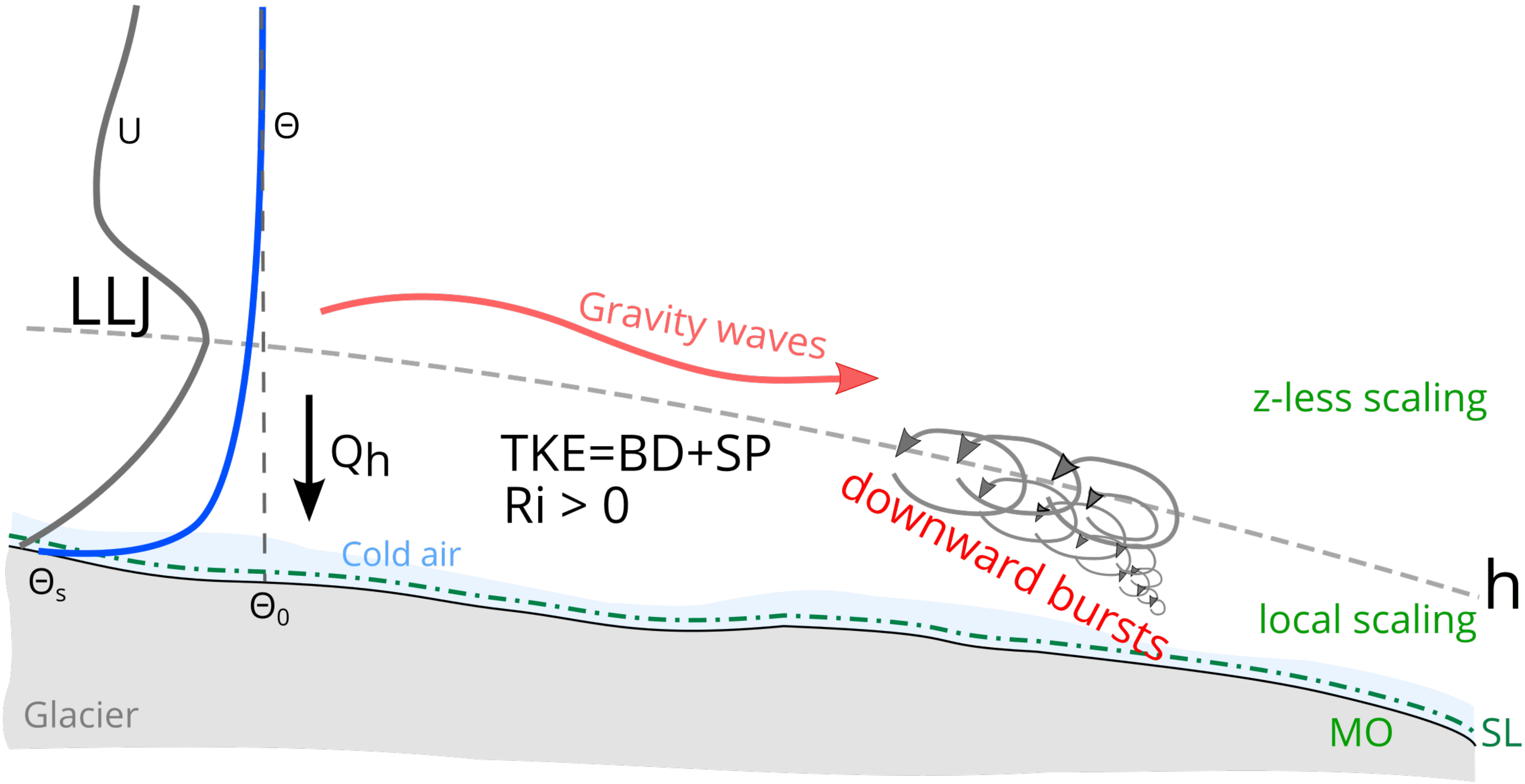
Credit: T Shaw

Observed wind and temperature profiles over alpine glaciers

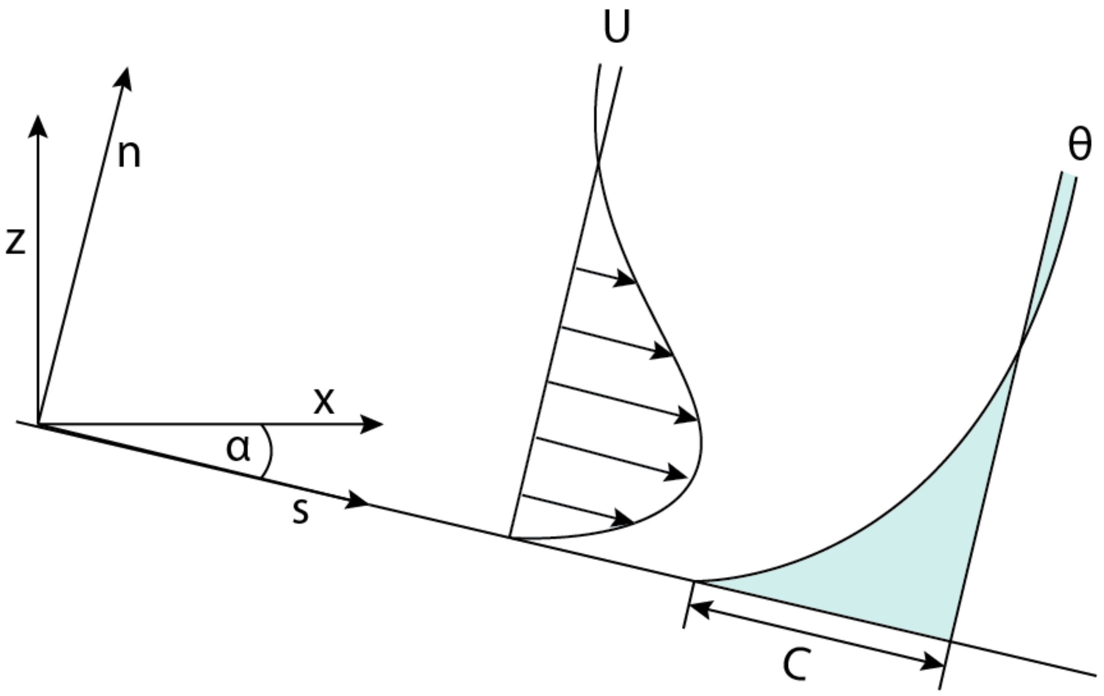


(Source: Oerlemans, 2010)

Boundary layer processes over mountain glaciers



Prandtl model for katabatic winds



$$\theta(z) = C \cdot exp^{-\frac{z}{\lambda}} \cdot \cos\left(\frac{z}{\lambda}\right)$$

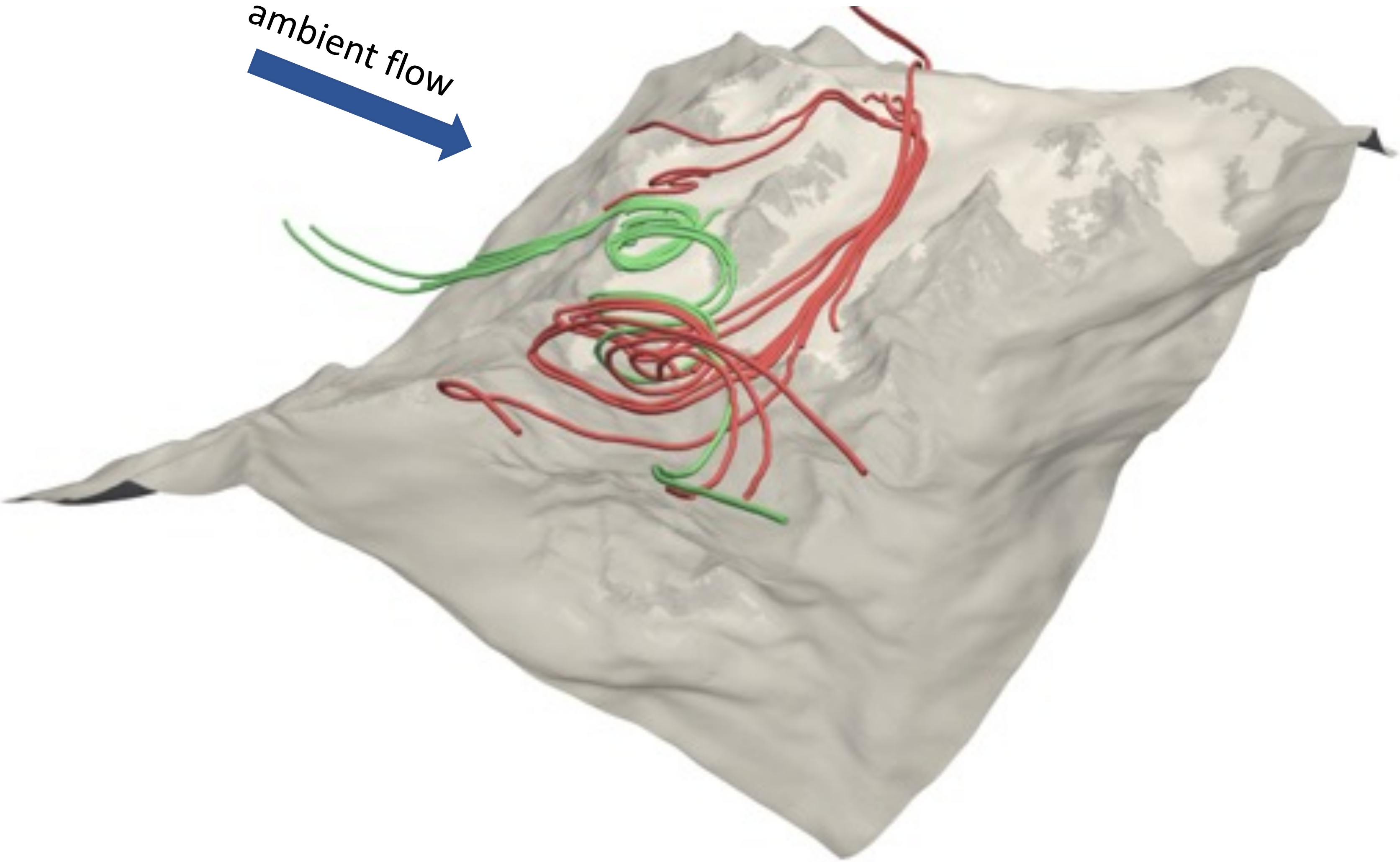
$$u(z) = C \cdot \mu \cdot exp^{-\frac{z}{\lambda}} \cdot \sin\left(\frac{z}{\lambda}\right)$$

$$\lambda = \left(\frac{4 \cdot T_0 \cdot K_m \cdot K_h}{g \cdot s^2 \cdot \gamma_\theta}\right)^{1/4}$$

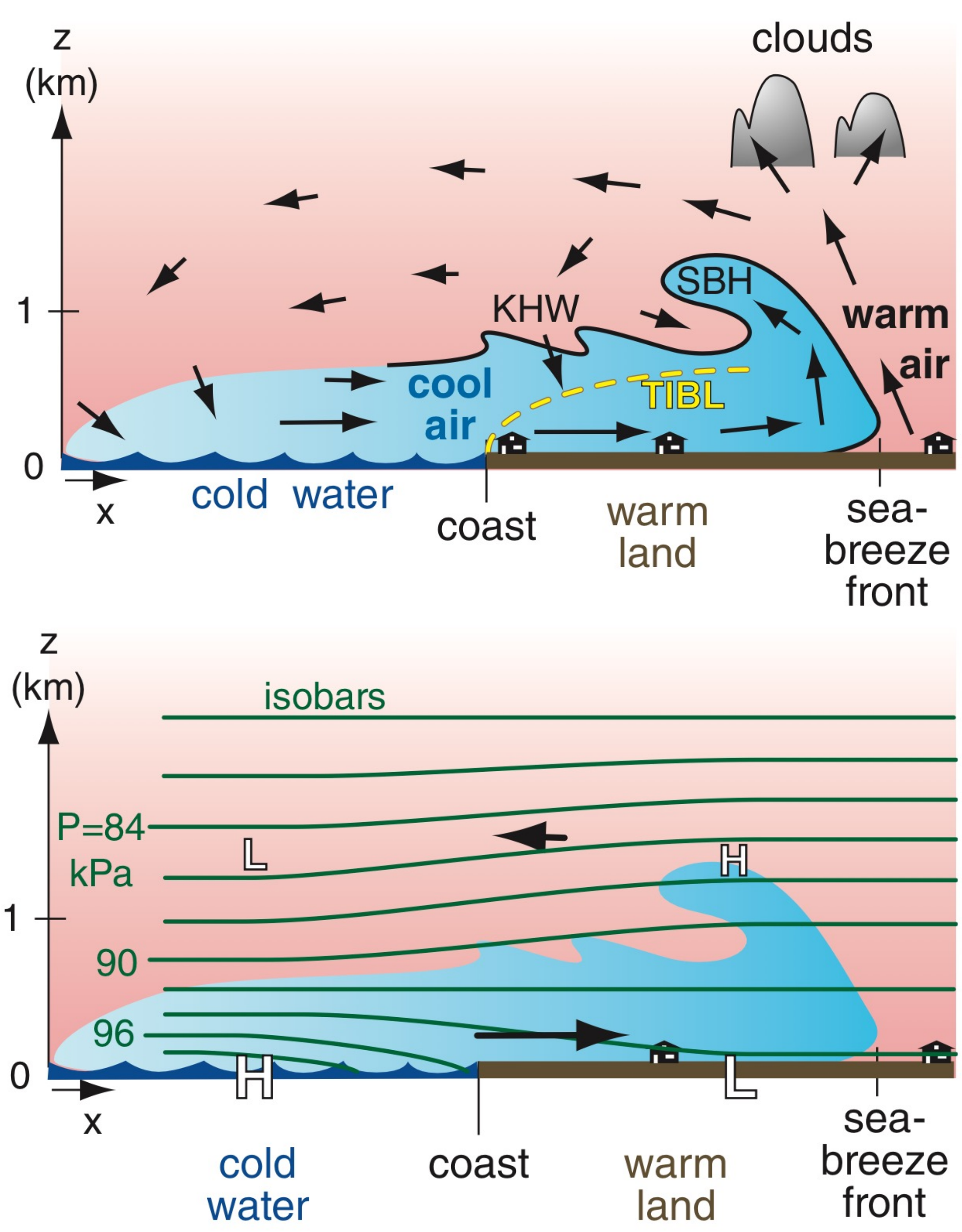
$$\mu = \left(\frac{g \cdot K_h}{T_0 \cdot K_m \cdot \gamma_\theta}\right)^{1/2}$$

Θ	potential temperature [K]
u	wind speed [m s^{-1}]
C	temperature deficit [K]
s	$s = -\sin(slope)$
γ_θ	constant vertical lapse rate [K m^{-1}]
K_m, K_h	turbulent diffusion coefficients $[m^2 s^{-1}]$
T_0	environmental temperature [K]
g	gravitational acceleration [m/s^2]

Flow trajectory

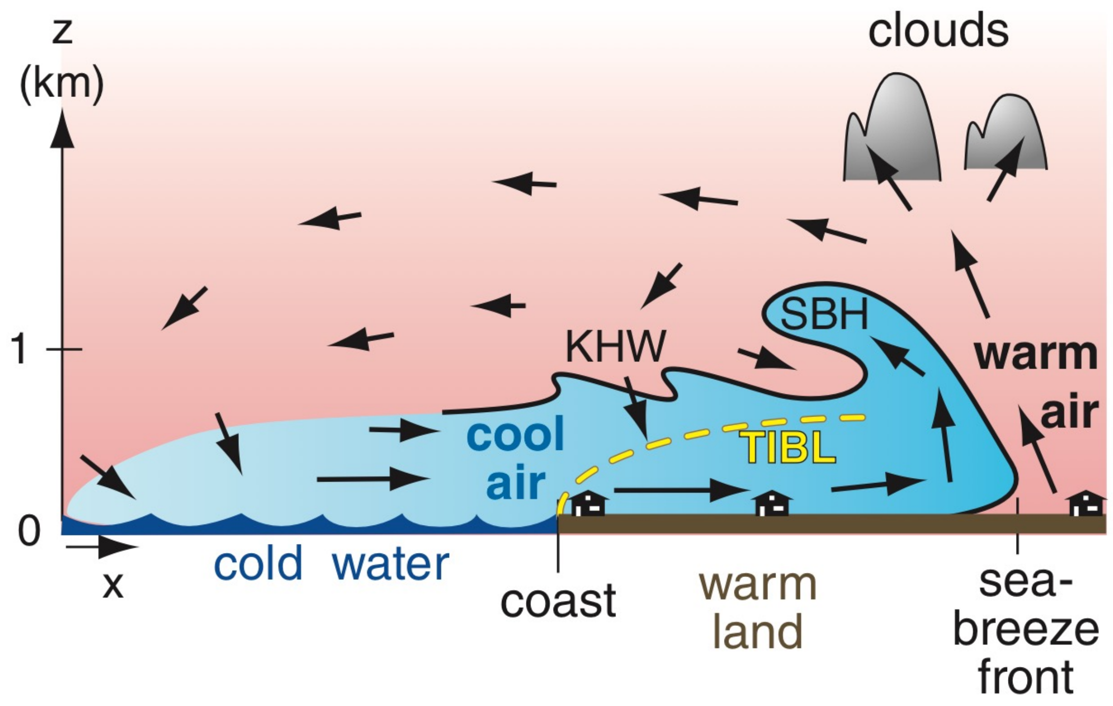


Land-sea breeze



KHW = Kelvin-Helmholz waves
SBH = sea-breeze head
TIBL = thermal internal boundary layer

Land-sea breeze



M_{SBF}	speed of SBF [m/s]
$\Delta\theta_v$	virtual potential temperature difference between cool marine air and the warmer air over land[K]
T_v	absolute average virtual temperature [K]
g	gravitational acceleration [m/s^2]
d	depth of the density current [m]
$k \sim 0.62$	constant
$\omega = 2\pi$ day^{-1} $= 7.27 \cdot 10^{-5}$ s^{-1}	frequency of daily heating/cooling cycle
f_c	Coriolis parameter

Sea breeze wind speed at the coast

$$\boxed{M = 1.15 \cdot M_{SBF}}$$

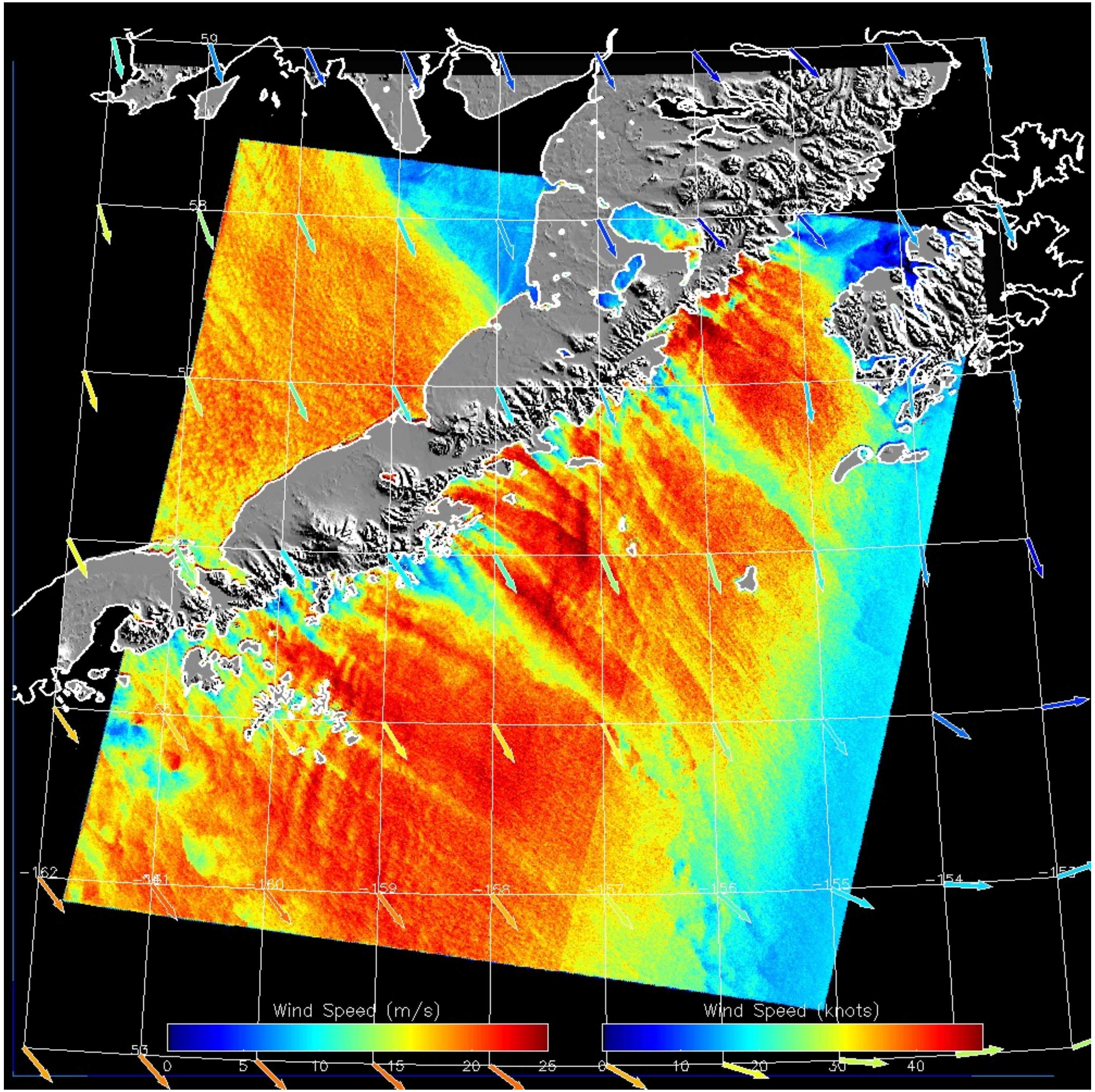
Speed of advance of the sea-breeze front

$$\boxed{M_{SBF} = k \cdot \sqrt{|g| \cdot \frac{\Delta\theta_v}{T_v} \cdot d}}$$

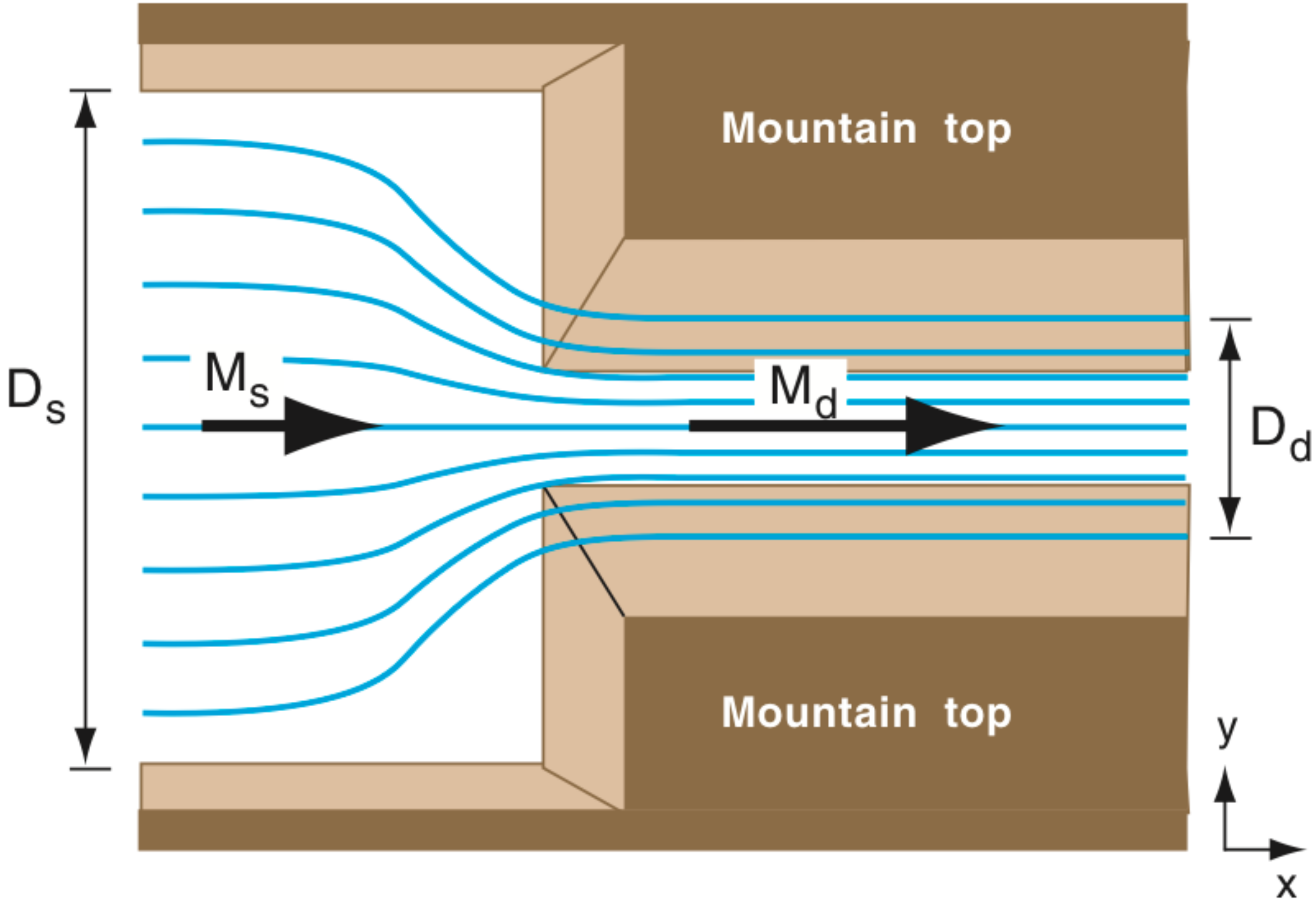
Distance of the sea-breeze advance

$$\boxed{L = \frac{M_{SBF}}{\sqrt{|\omega^2 - f_c^2|}}}$$

Gap winds



Conservation of mass



mass flowing out = mass flowing in

$$\rho \cdot volume\ flow\ out = \rho \cdot volume\ flowing\ in$$

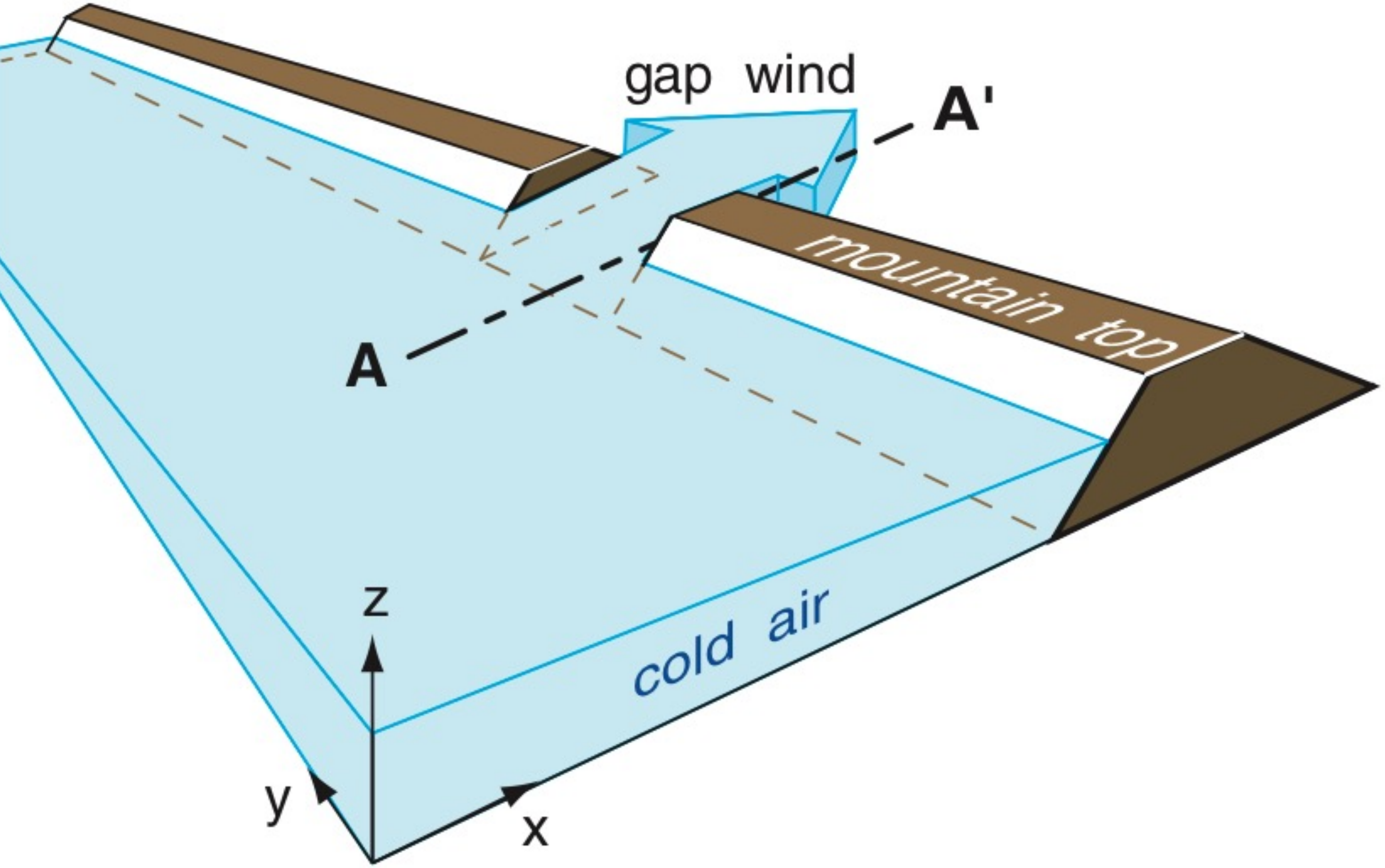
$$\rho \cdot M_d \cdot h \cdot D_d = \rho \cdot M_s \cdot h \cdot D_s$$

if $h = const.$, then:

$$\boxed{M_d = \frac{D_s}{D_d} \cdot M_s}$$

ρ	air density [kg m^{-3}]
h	depth of the flow [m]
M_d	wind speed [m/s]

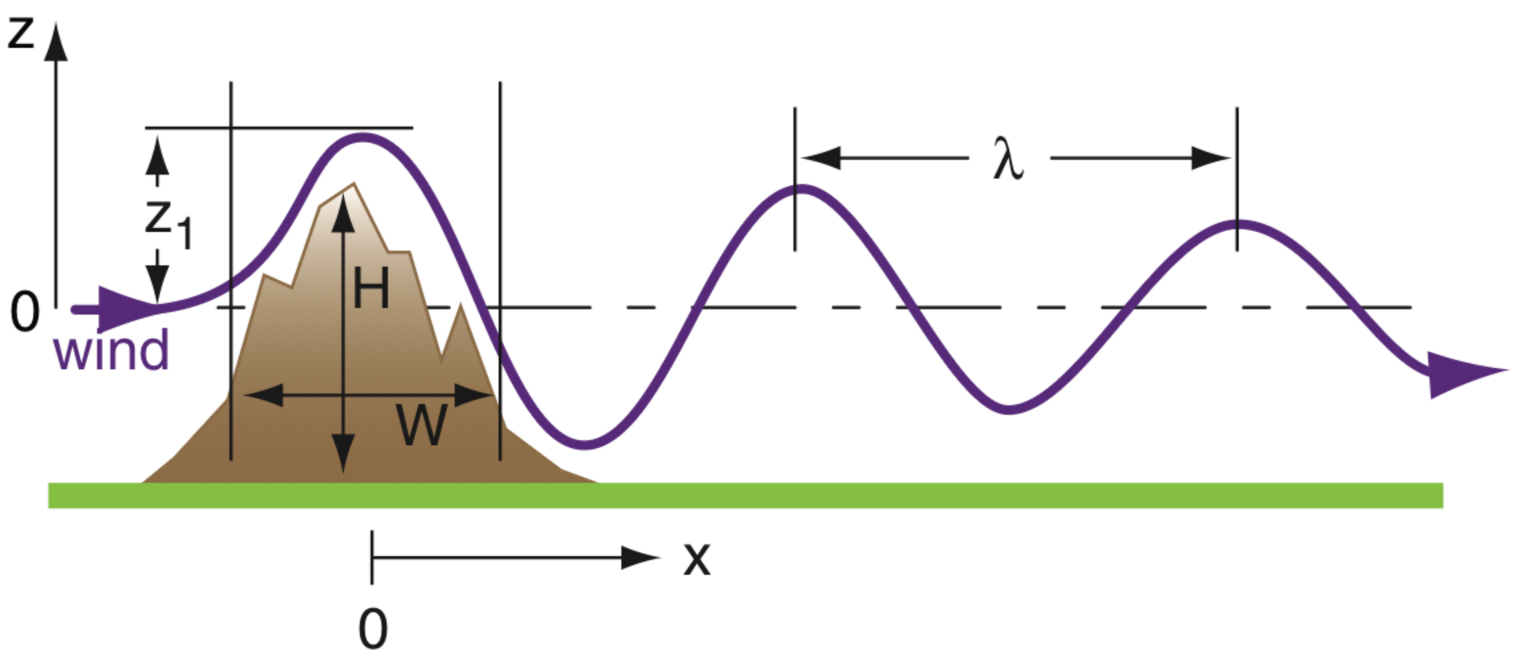
Short-gap winds



Maximum gap wind speed

$$\boxed{M_{gap} = \sqrt{\left[|g| \cdot \frac{\Delta\theta_v}{T_v} \cdot h\right]}}$$

Mountain waves



N_{BV}	Brunt-Väisälä frequency [s^{-1}]
$\Delta\theta_v/\Delta z$	vertical gradient of virtual potential temperature [K/m]
T_v	absolute average virtual temperature [K]
b	damping factor
z_1	initial amplitude of the wave [m]

Natural wavelength

$$\boxed{\lambda = \frac{2\pi \cdot M}{N_{BV}}}$$

Brunt Väisälä frequency

$$\boxed{N_{BV} = \sqrt{\frac{|g|}{T_v} \cdot \frac{\Delta\theta_v}{\Delta z}}}$$

Perturbation of air parcel (damping)

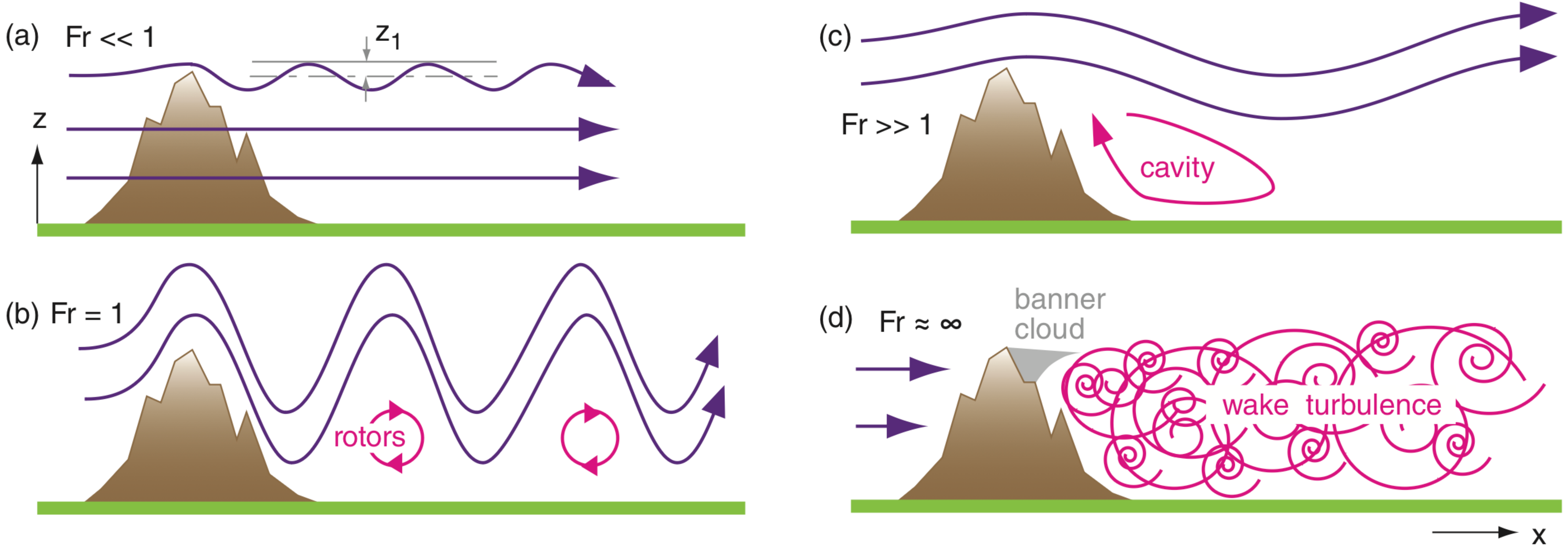
$$\boxed{z = z_1 \cdot \exp\left(\frac{-x}{b \cdot \lambda}\right) \cdot cos\left(\frac{2\pi \cdot x}{\lambda}\right)}$$


Lenticular Clouds

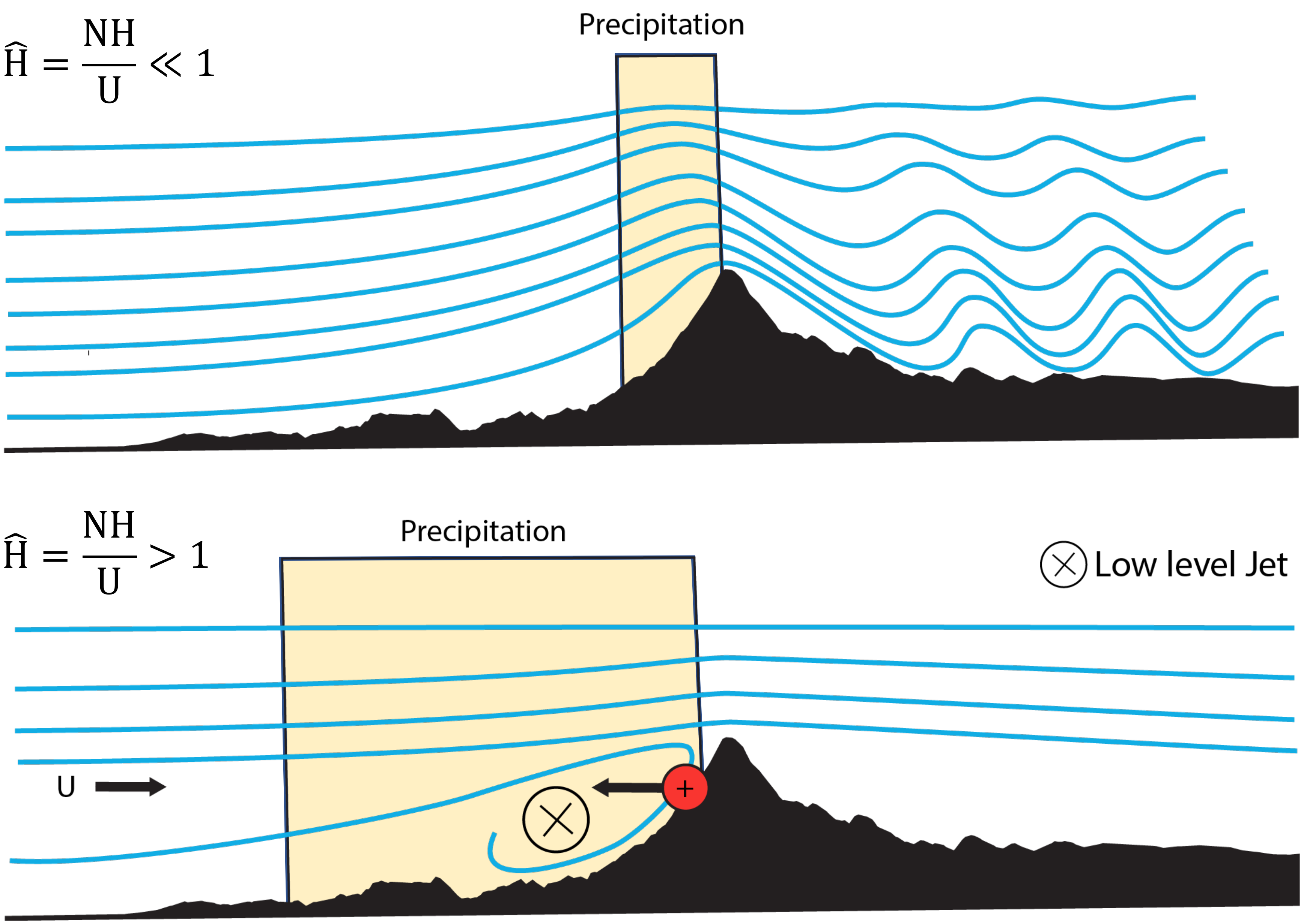
Froude number

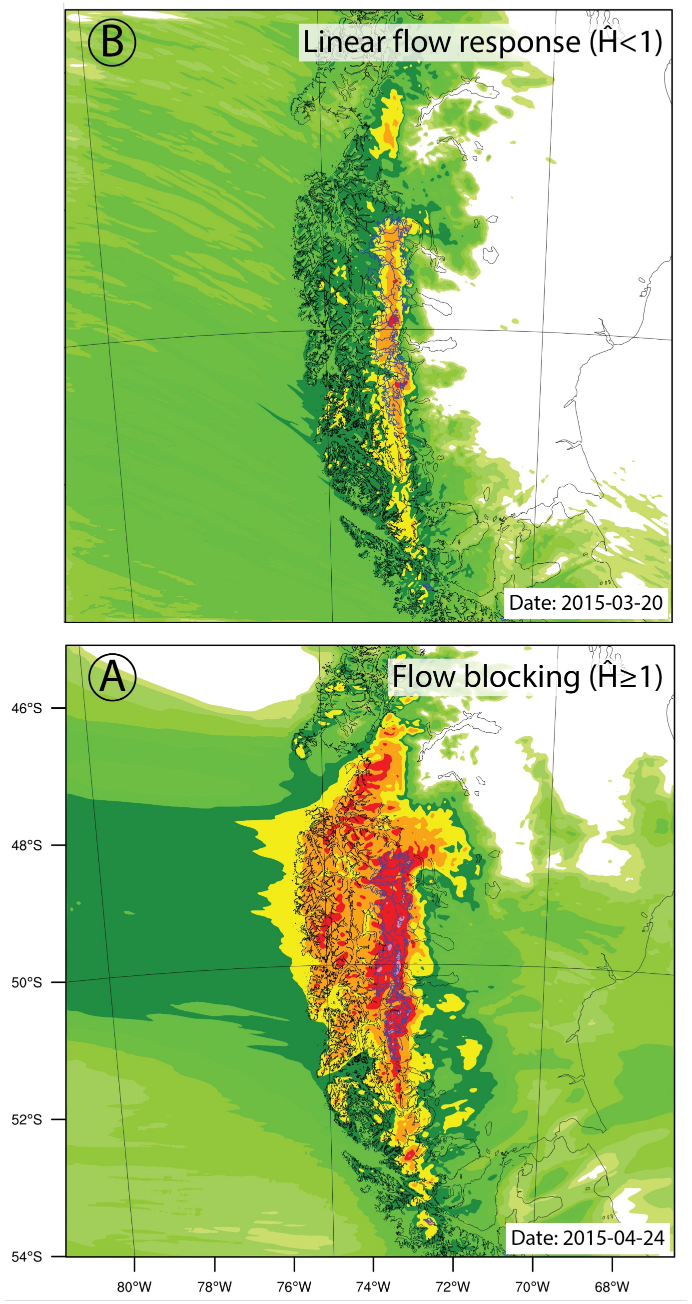
$$\boxed{Fr = \frac{\lambda}{2 \cdot W}}$$

W	hill width [m]



Flow blocking

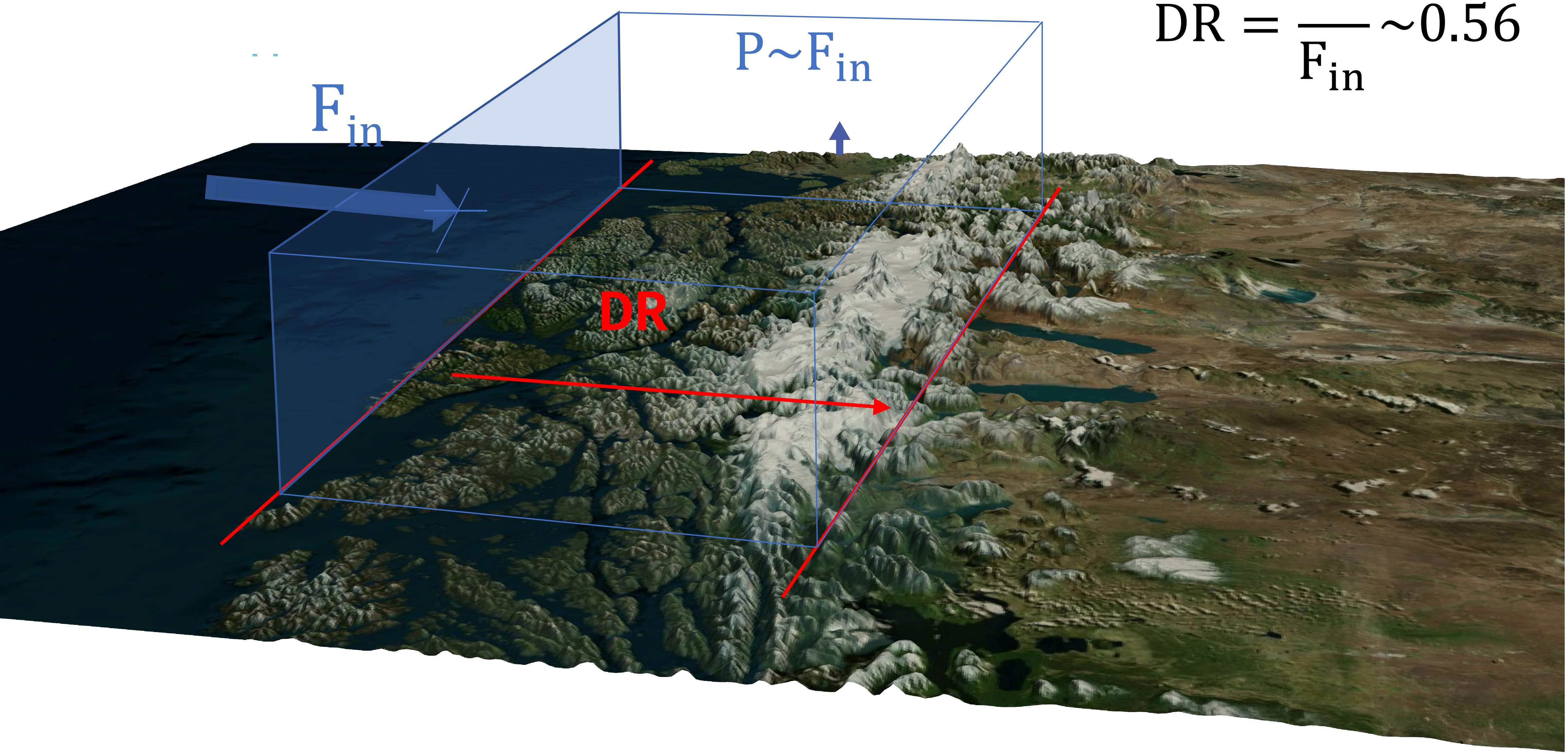




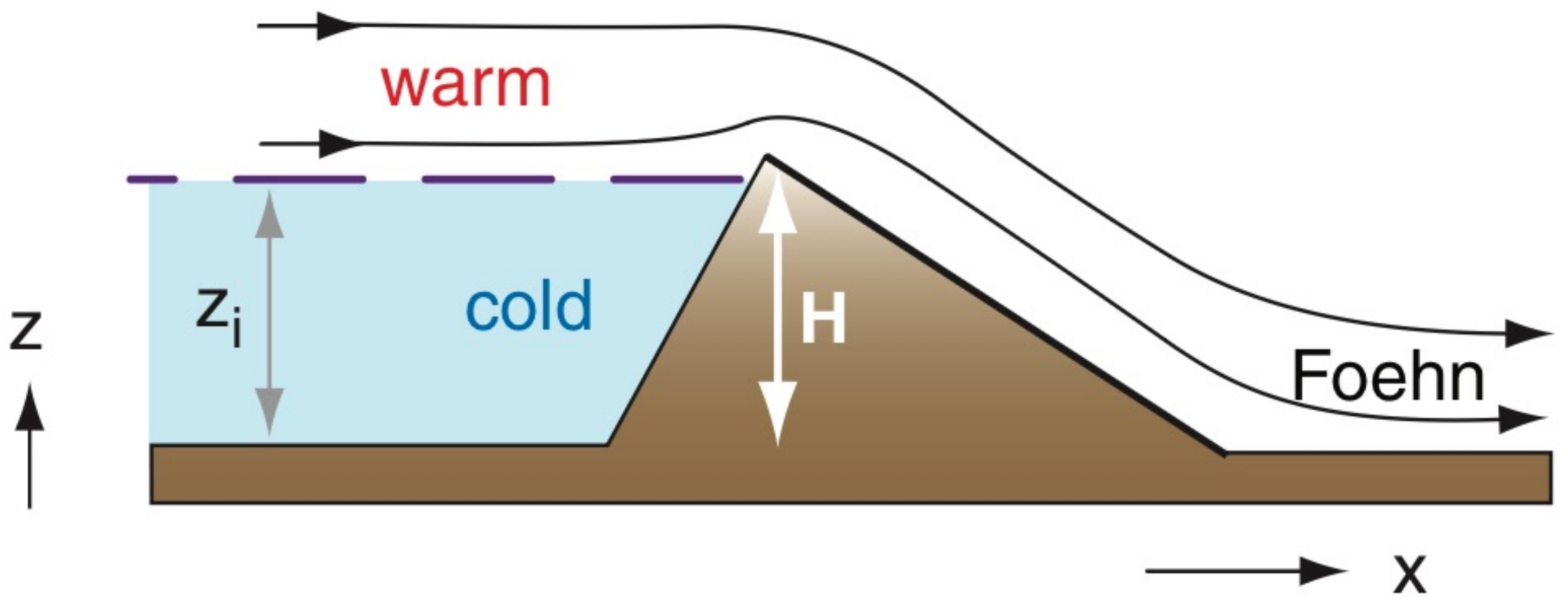
Source: Sauter (2020)

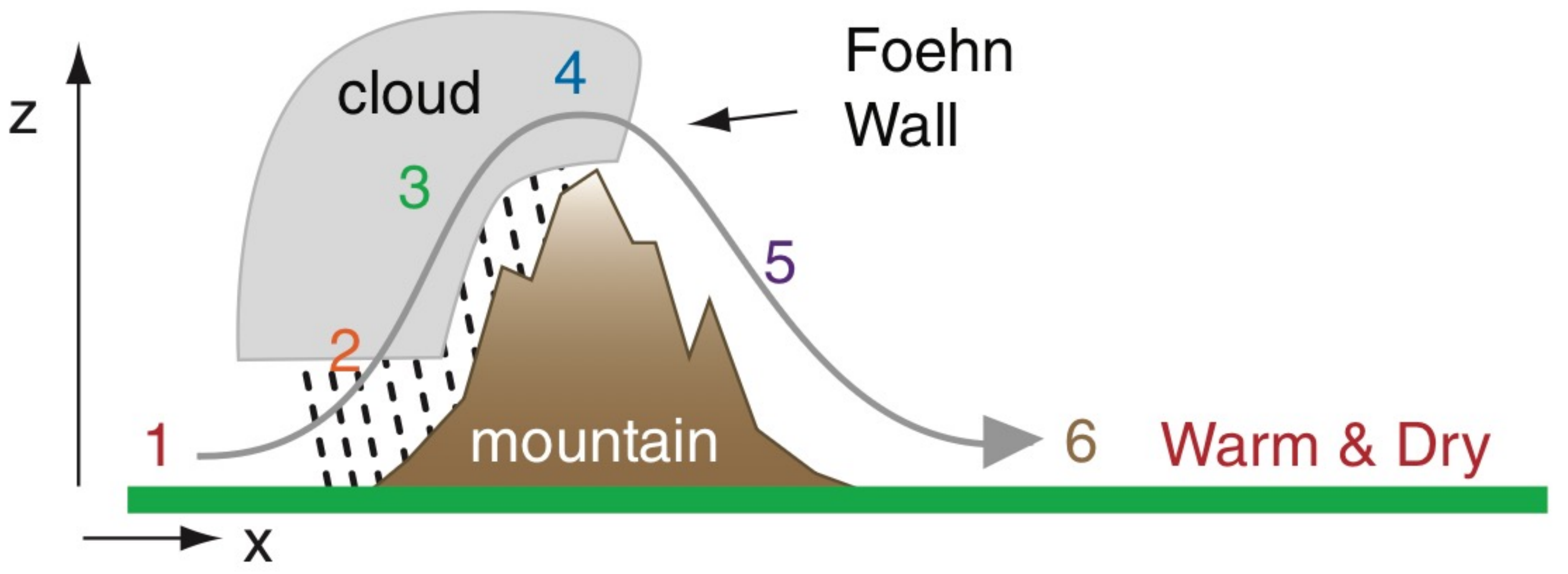
Orographic precipitation

$$\mathrm{DR} = \frac{\mathrm{P}}{\mathrm{F_{in}}} \sim 0.56$$



Föhn winds



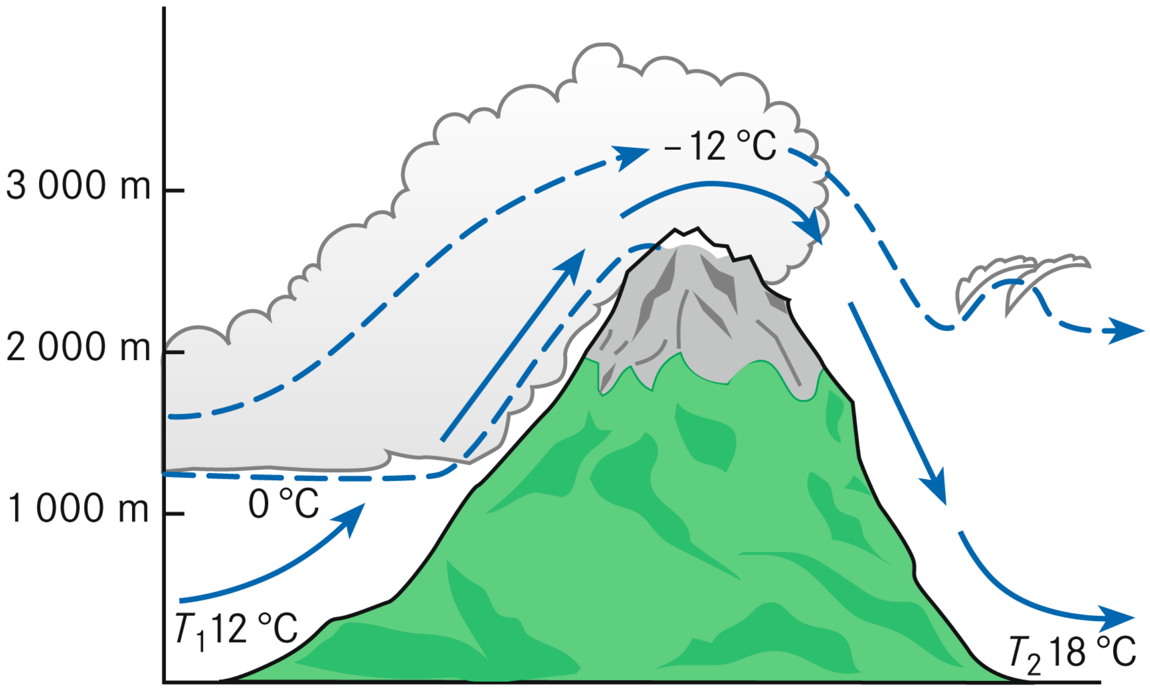


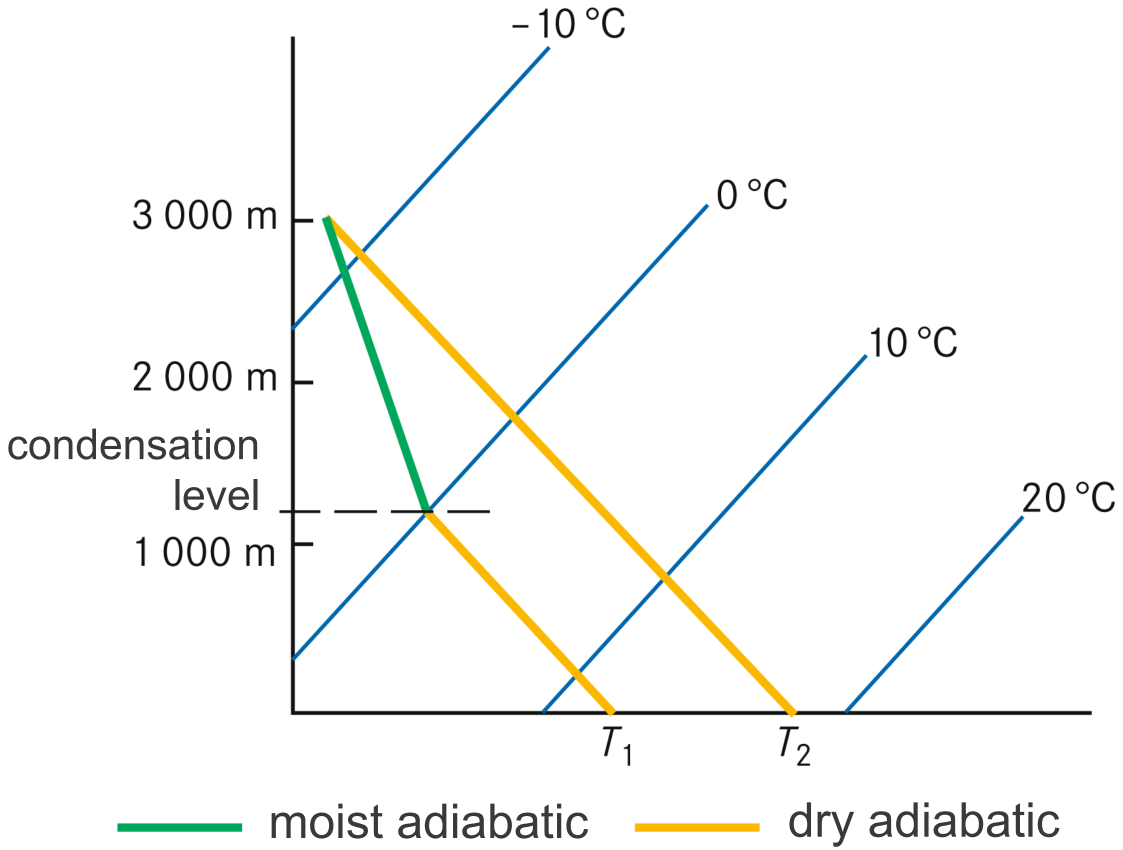
Quelle: Stull, 2020.

Development of Föhn events

Air is forced to ascend at the windward side of the mountains

- Dry adiabatic cooling of air, approx. 1 K per 100 m
- Saturation water vapor decreases, specific moisture is constant
- Consequence: relative humidity increases
  - water condenses when dew point temperature is reached
  - development of clouds at the condesation level



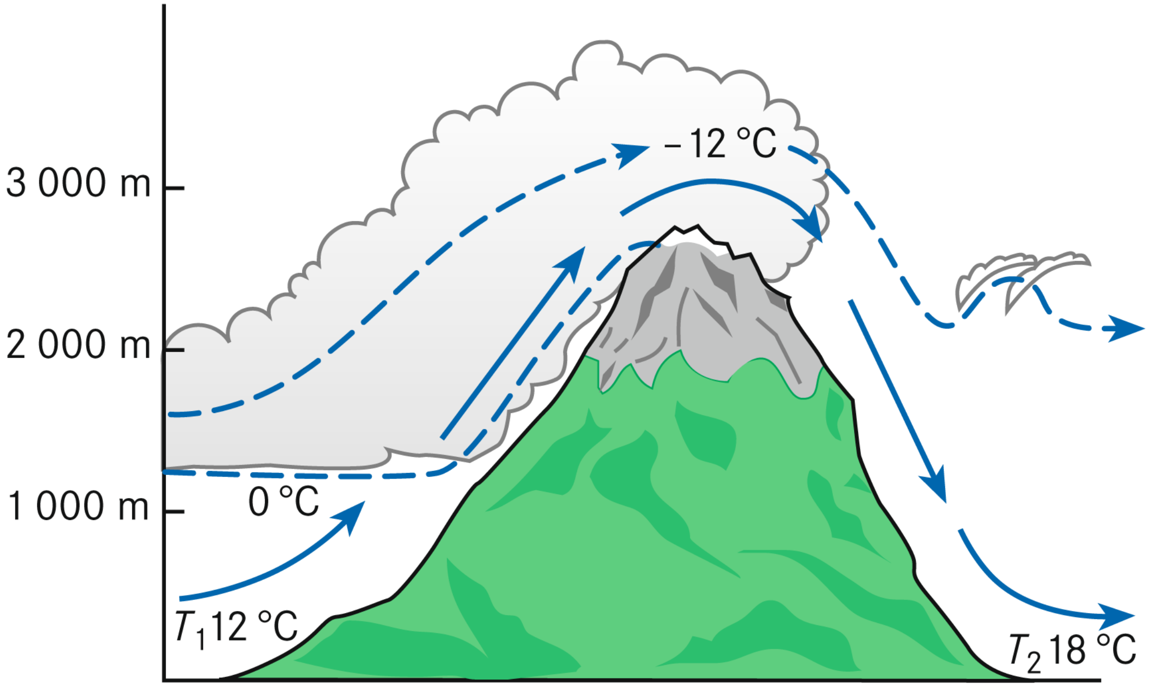


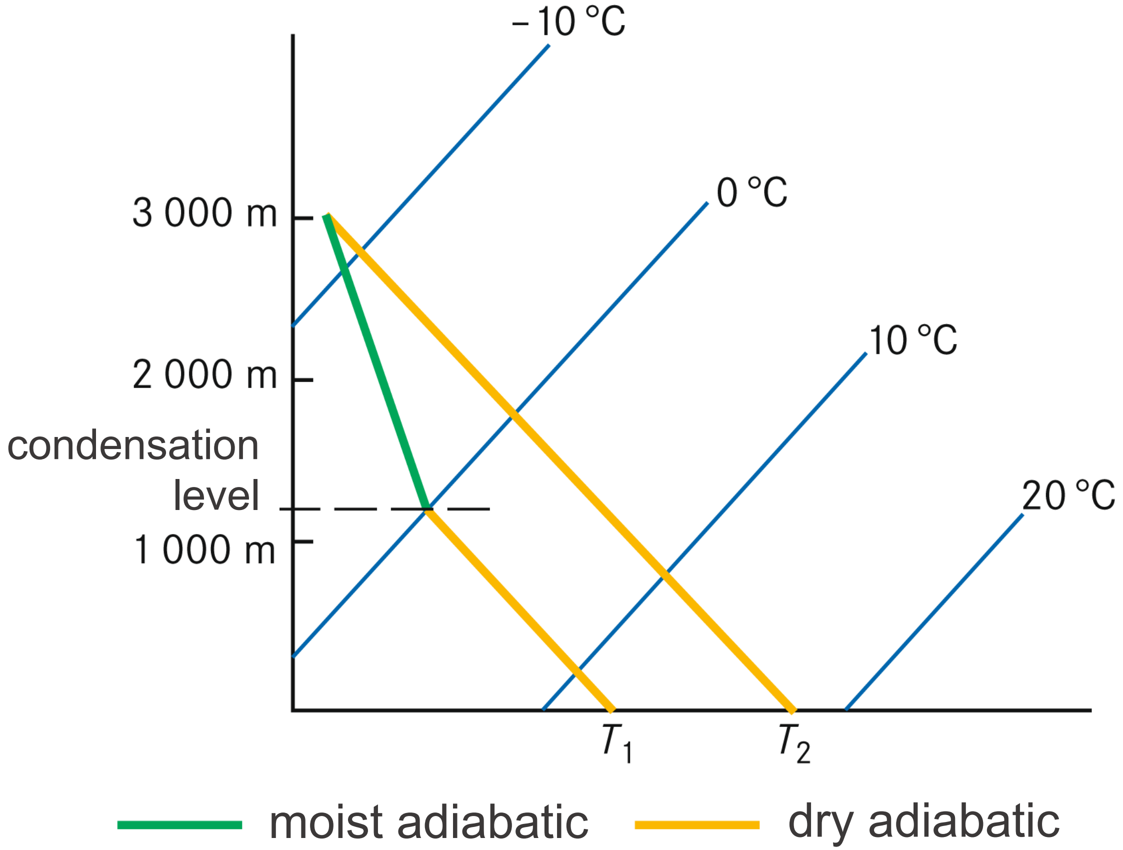
Quelle: Gebhardt et al. 2011: 278

Development of Föhn events

Further ascend: moist adiabatic cooling (0.5 K per 100 m)

- fallout of hydrometeors
- air descends behind the ridge, first moist adiabatic warming then dry adiabatic warming





Quelle: Gebhardt et al. 2011: 278


• Textmasterformate durch Klicken bearbeiten
– Zweite Ebene
• Dritte Ebene
– Vierte Ebene
» Fünfte Ebene

Reminder

- Logarithmic wind profile
- Displacement height and roughness length
- Boundary condition
- Internal boundary layer