MOUNTAIN METEOROLOGY

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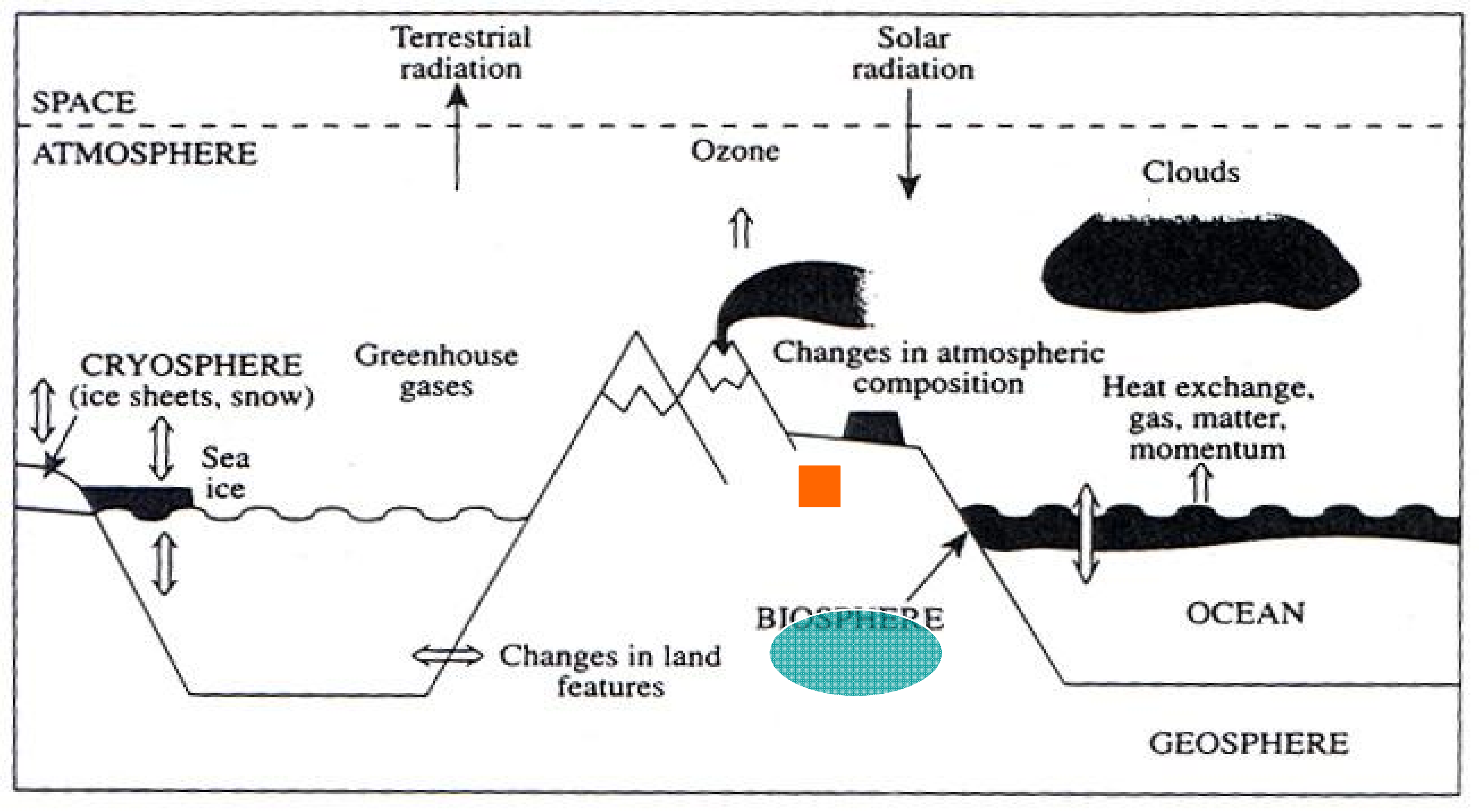
OUTLINE

- **Intro: Background, scales…**
- **Valley flows: Katabatic ↔ Anabatic wind**
- **Mountain waves & downslope windstorms**
- **Forced convection & storms**
- **Discussion & Future Avenues**

~ Climate System ~



$$\frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + f\varepsilon_{ij3}\overline{U}_j + \frac{\partial}{\partial x_j}\underbrace{\left(\nu \frac{\partial \overline{U}_i}{\partial x_j} - \overline{u_i u_j}\right)}_{\tau_{ij}}$$

+Thermodyn., Mass, Moisture conservation, etc.

Overall importance of the pristine (or otherwise?) Mountainous Environment

SCALES & PARAMETERS

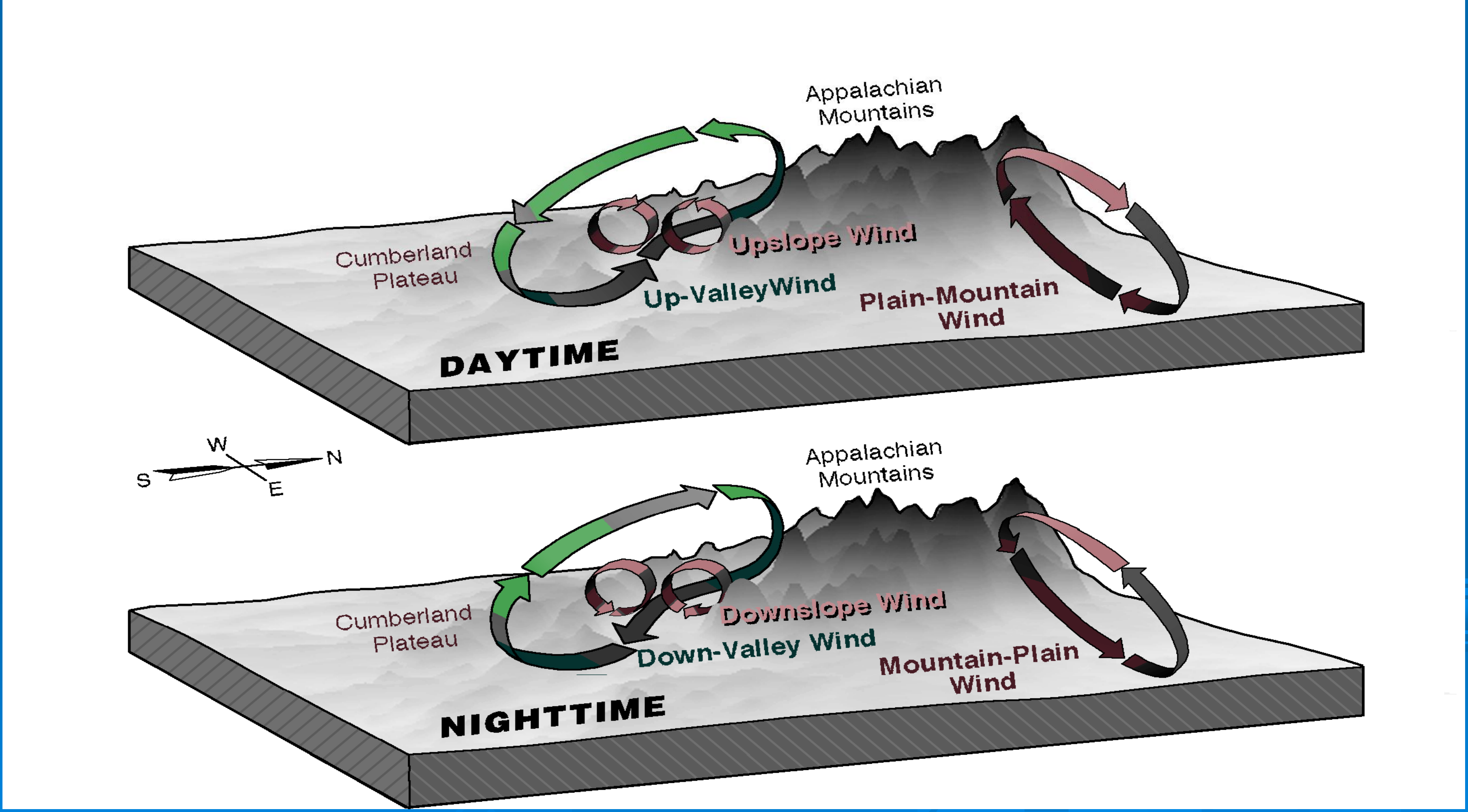
There’re several natural length-scales in the atmosphere with which the mountain width, L, can be compared:

- The Atmospheric Boundary-Layer (ABL) depth
- Downwind Drift Distance (DDD) during a buoyancy oscillation
- DDD during formation & fallout of precipitation
- DDD during 1 rotation of Earth
- Earth radius

Table 1.1 Atmospheric scale definitions. (Adapted after Thunis and Borstein 1996)

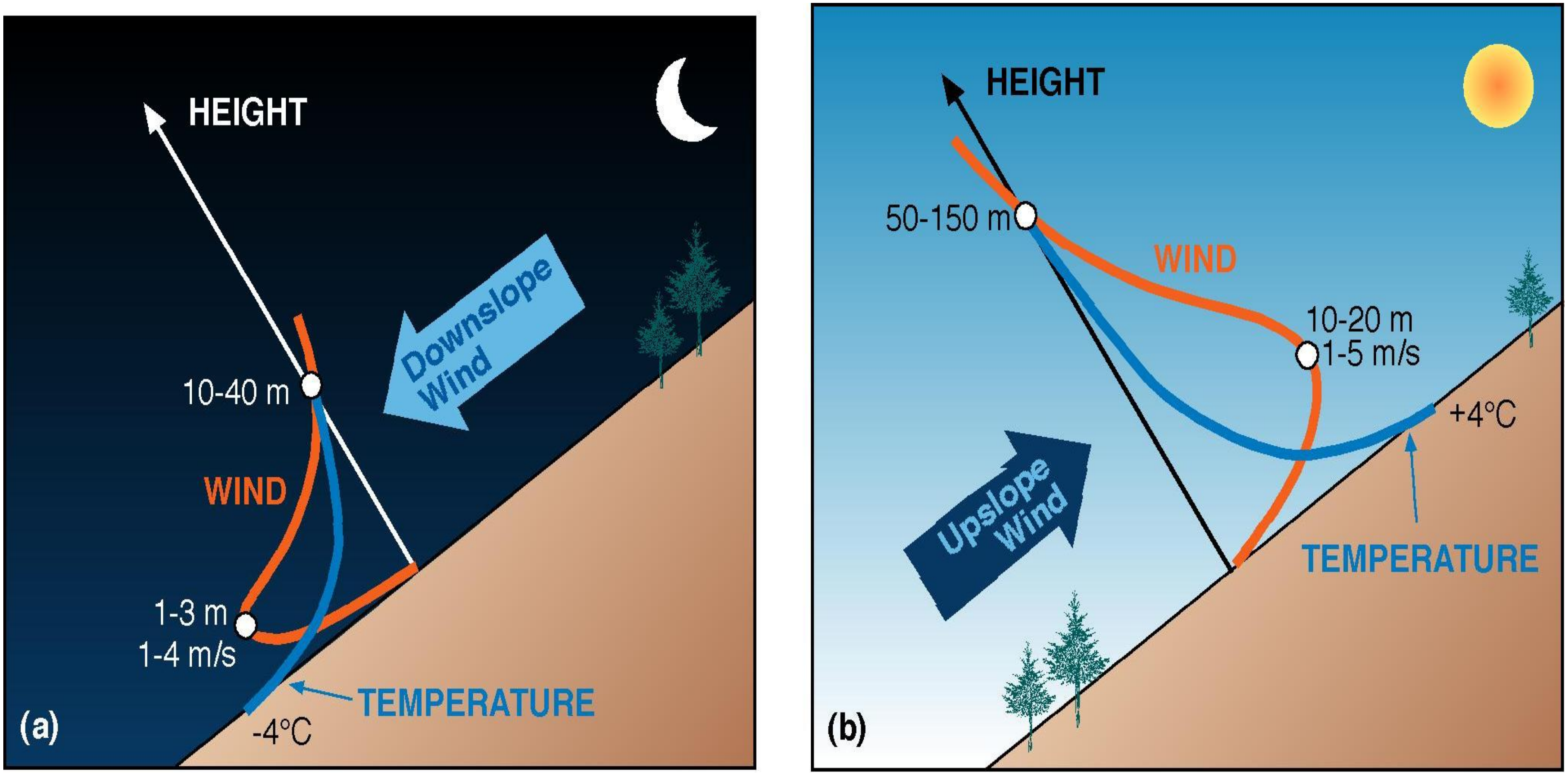
Horizontal Scale	Lifetime	Stull (1988)	Pielke (2002)	Orlanski (1975)	Thunis and Bornstein (1996)	Atmospheric Phenomena
	1 month	Macro	Synoptic Regional	Macro-α	Macro-α	General circulation, long waves
10 000km				Macro-β	Macro-β	Synoptic cyclones
2000 km	1 week			Meso-α	Macro-γ	Fronts, hurricanes, tropical storms, short cyclone waves, mesoscale convective complexes
200 km	1 day	Meso	Meso	Meso-β	Meso-β	Mesocyclones, mesohighs, supercells, squall lines, inertia-gravity waves, cloud clusters, low-level jets thunderstorm groups, mountain waves, sea breezes
20 km	1 h	Micro	Micro	Meso-γ	Meso-γ	Thunderstorms, cumulonimbi, clear-air turbulence, heat island, macrobursts
2 km				Micro-α	Meso-δ	Cumulus, tornadoes, microbursts, hydraulic jumps
200 m	30 min			Micro-β	Micro-β	Plumes, wakes, waterspouts, dust devils
20 m	1 min			Micro-γ	Micro-γ	Turbulence, sound waves
2 m	1 s	Micro δ			Micro-δ	

Valley Flows



After **Whiteman, 2000**

Slope Flow Theory



Whiteman (2000)

Katabatic & Anabatic flows

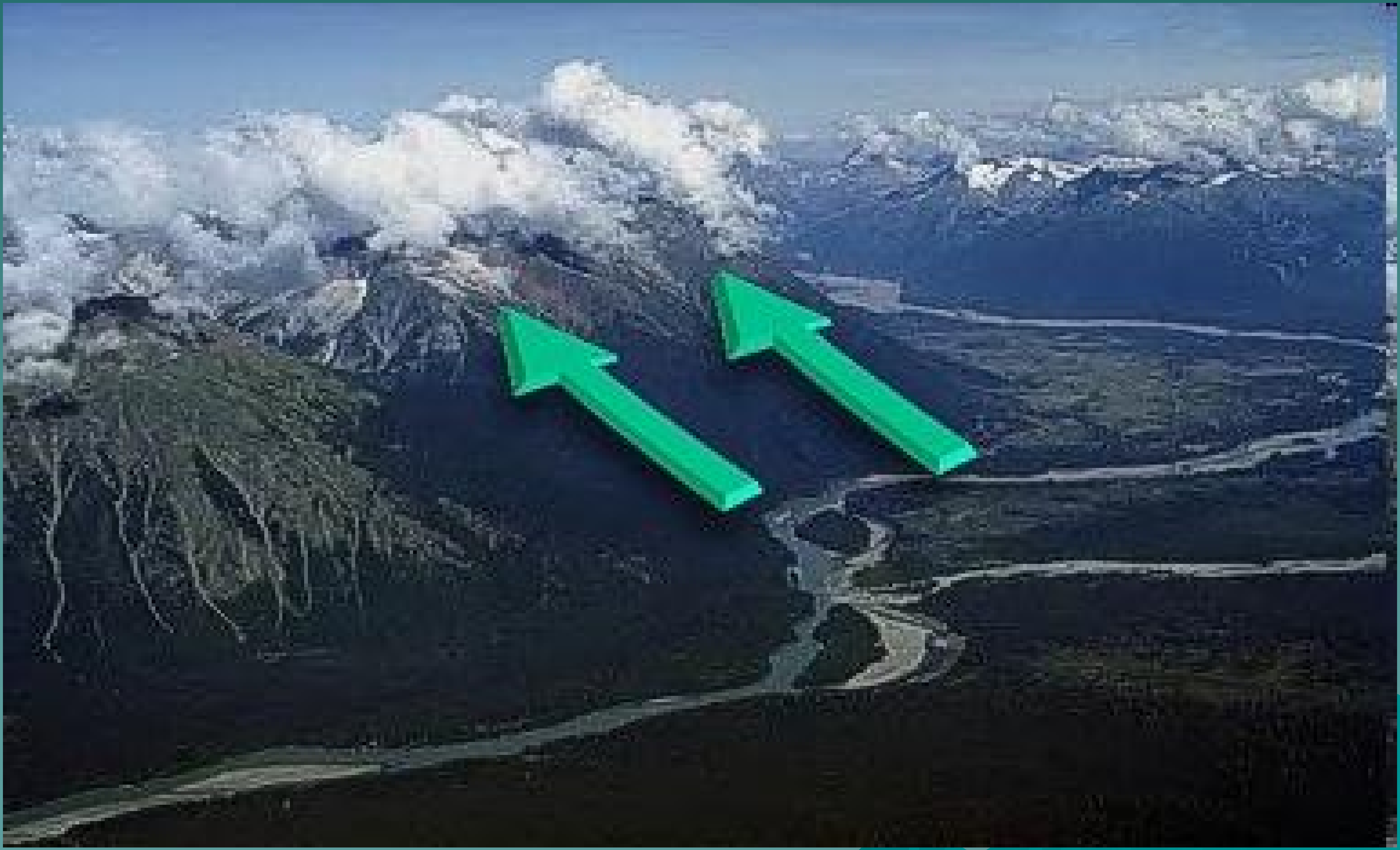
Prandtl model ⇔ 1D analytic solution (*u*, *θ*)

- Exponentially decaying with height z, OK in idealized conditions only, e.g., glacier wind
- **Extensive field obs. & numerical fine-scale modeling necessary – expensive**
- *But much money in tourism, agriculture & climate*

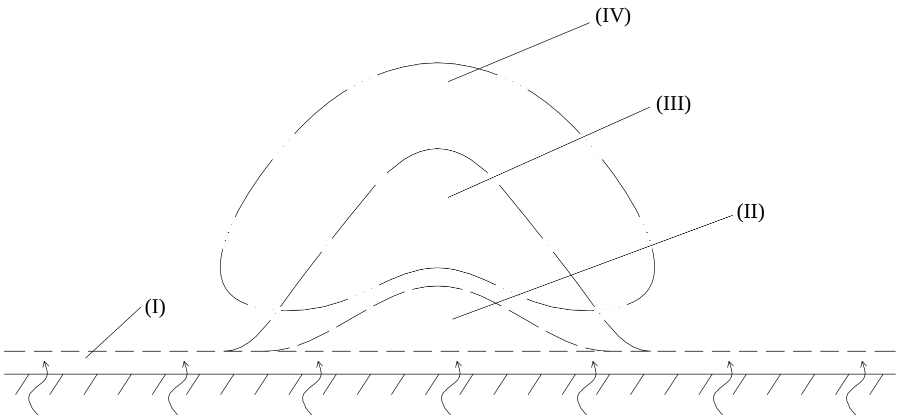
Clouds Make Slope Flow Visible

Bernhard Muehr photos, Karlsruher Wolkenatlas © 2000

Clouds due to Forced Convection & Slope Flows

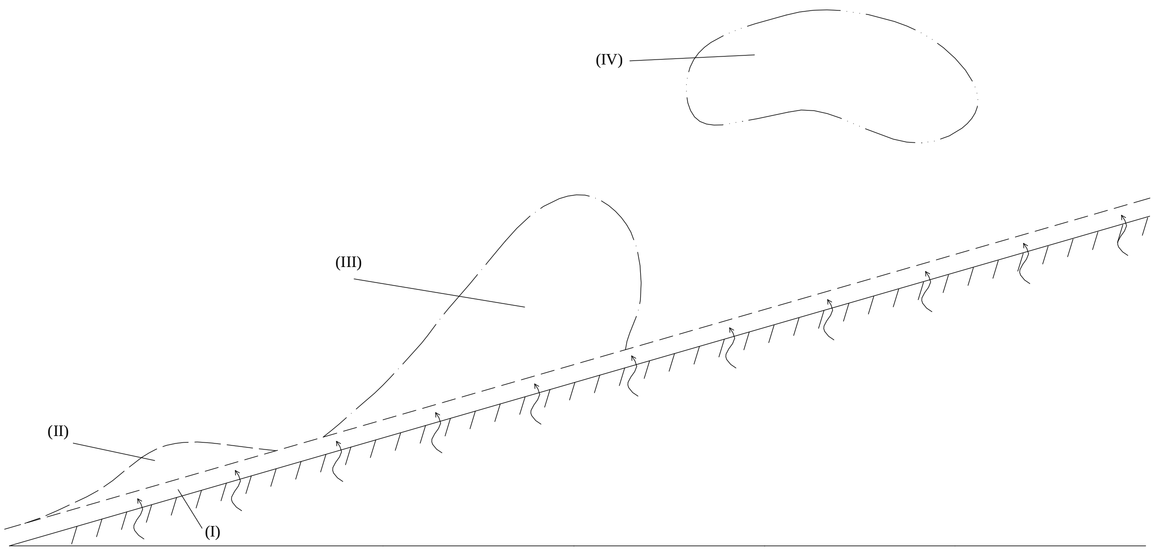


Thermal blob



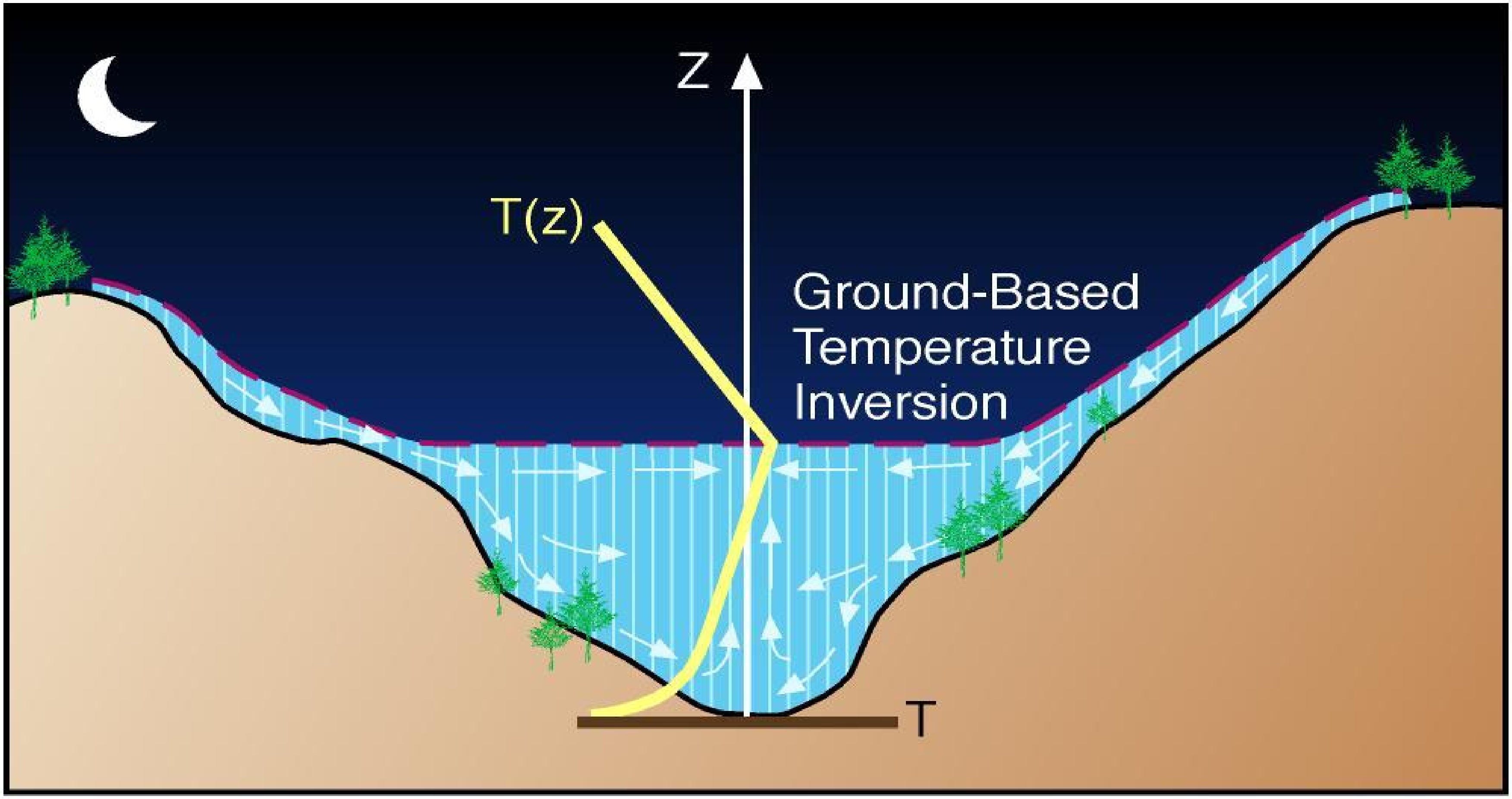
Detachment occurs when

$$Ra = Ra_C = \frac{g\left(\Delta T / T_0\right) D_C^3}{\nu\kappa} \approx 10^3$$



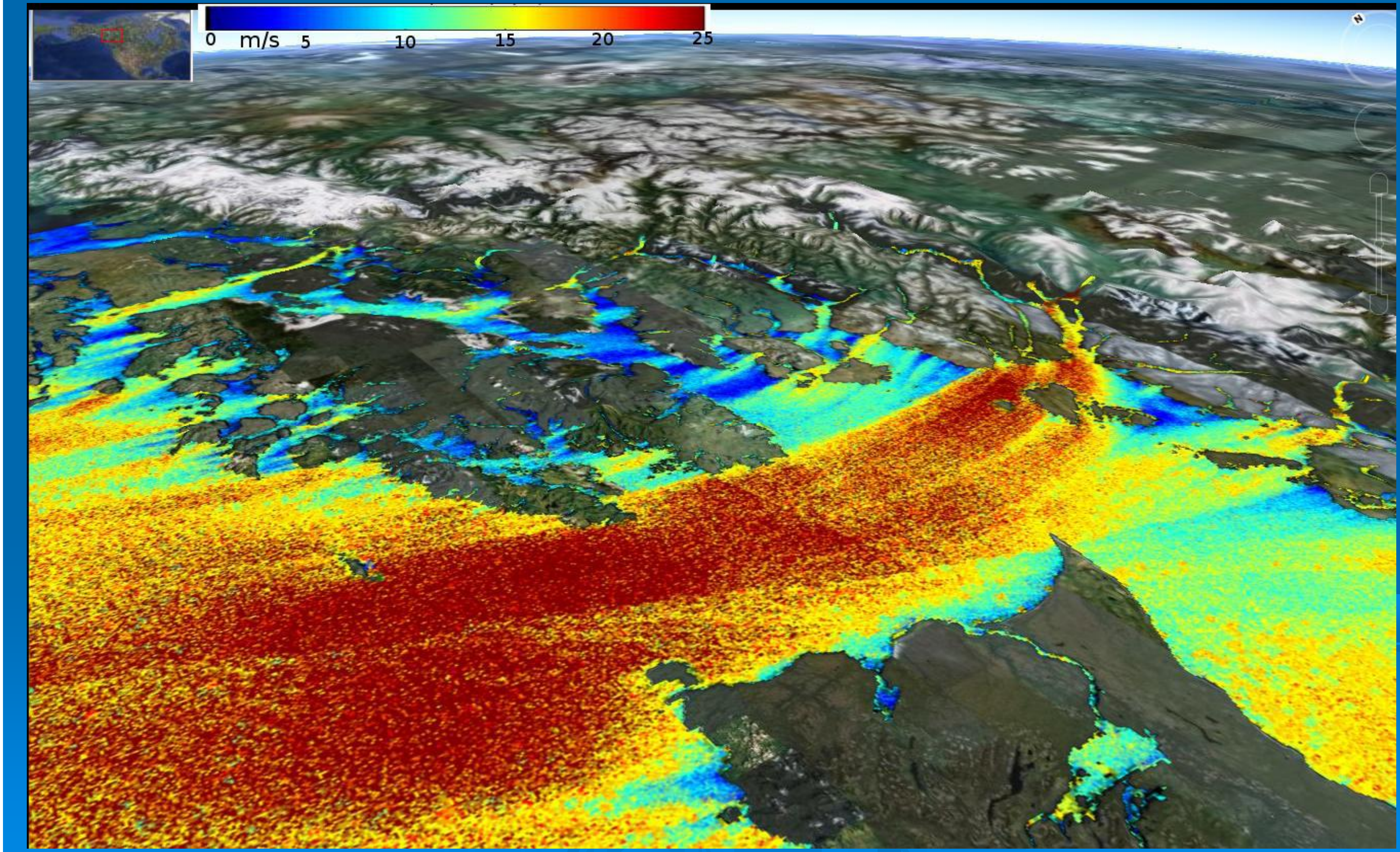
After J.H.Fernando, 2005

Downslope flows leave the slope…



Whiteman (2000)

GAP FLOWS, é   Coast Mnt., NW of USA (SAR data)

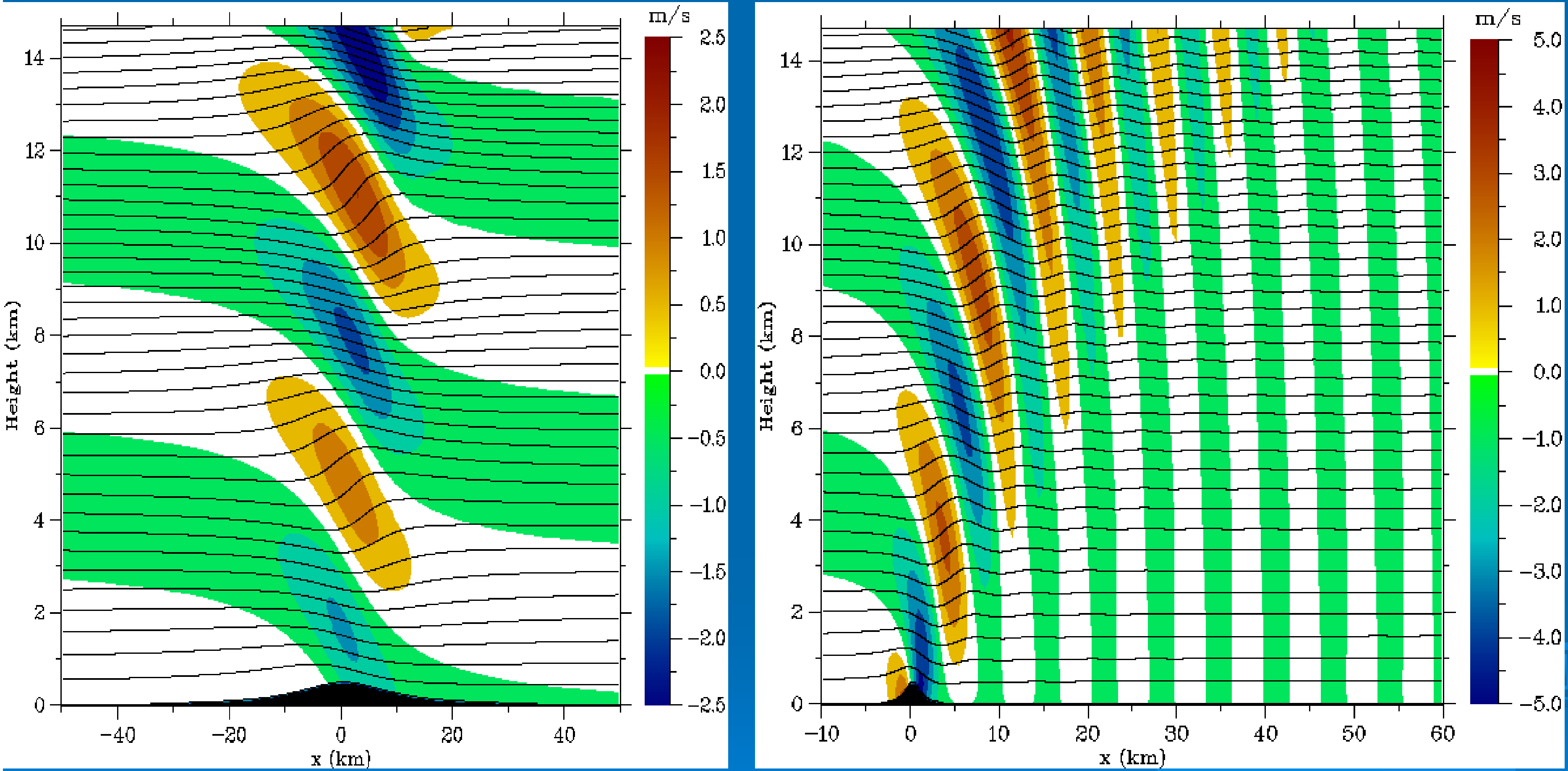


Ron B. Smith, the father of modern **MM** (mid-70’s onward)

- *D. Durran, R. Rotunno, J. Klemp, D. Whiteman, V. Grubišić, Ch. Schär, G. Zängl, H. Olafsson, L. Gutman, J. Fernando, S. Mobbs, M. Teixeira, Y.-L. Lin, H. Volkert, S. Vosper. G. Mayr, Ph. Bougeault, J. Doyle, I. Vergeiner, R. Pielke, J. Egger, S. Grønås,…*

- **Some principal #’s: $Fr_{hor} = U/(NL)$, $R_O = U/(fL)$**
- **$Fr_{vert} = U/(Nh)$, if ≤ 1 ⇔ wave breaking**

Hydrostatic & Non-hydrostatic mountain waves

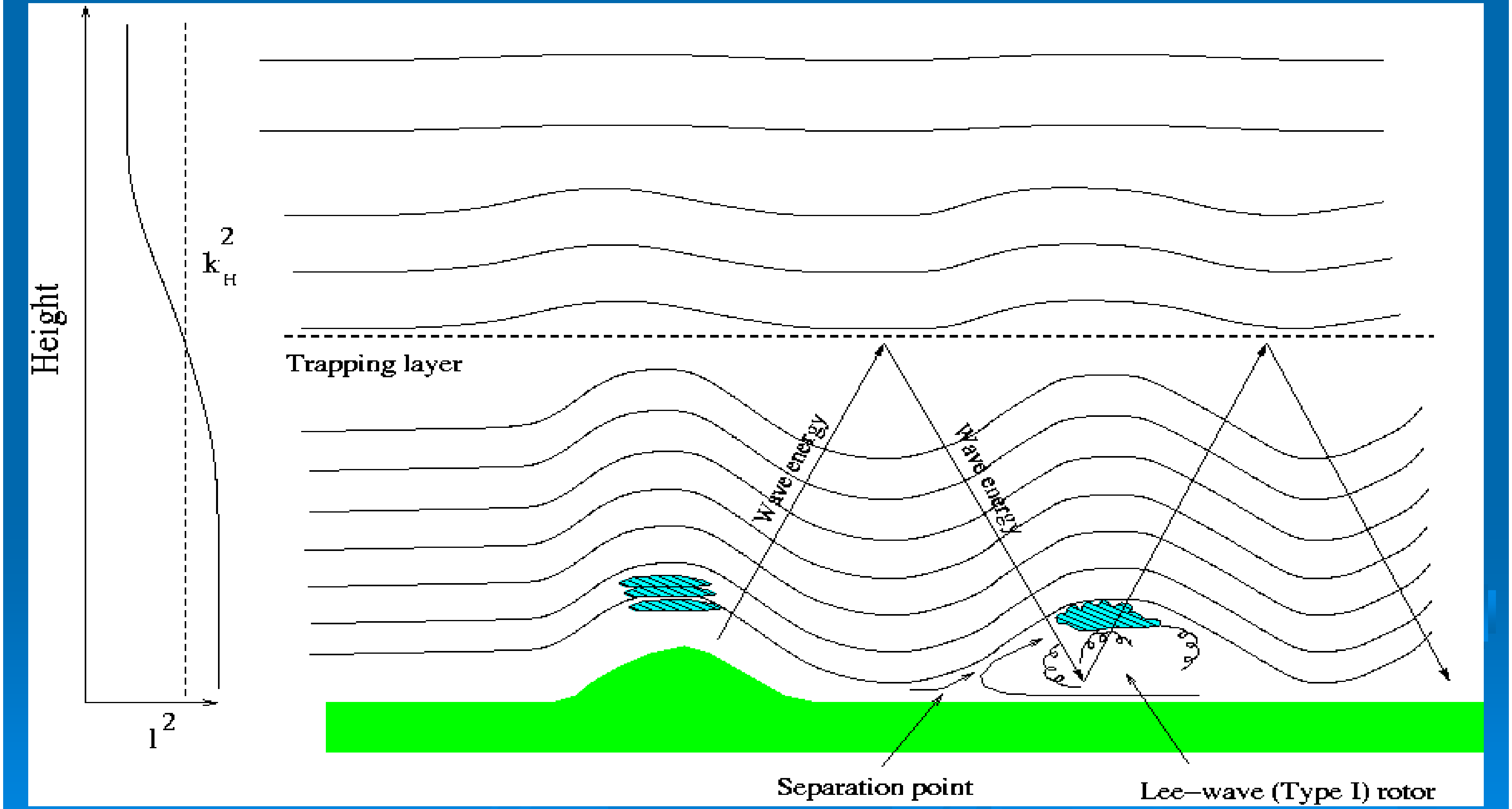


Fr_{hor} = 0.1 ⇔ hydrostatic

Fr_{hor} = 1 ⇔ non-hydrostatic

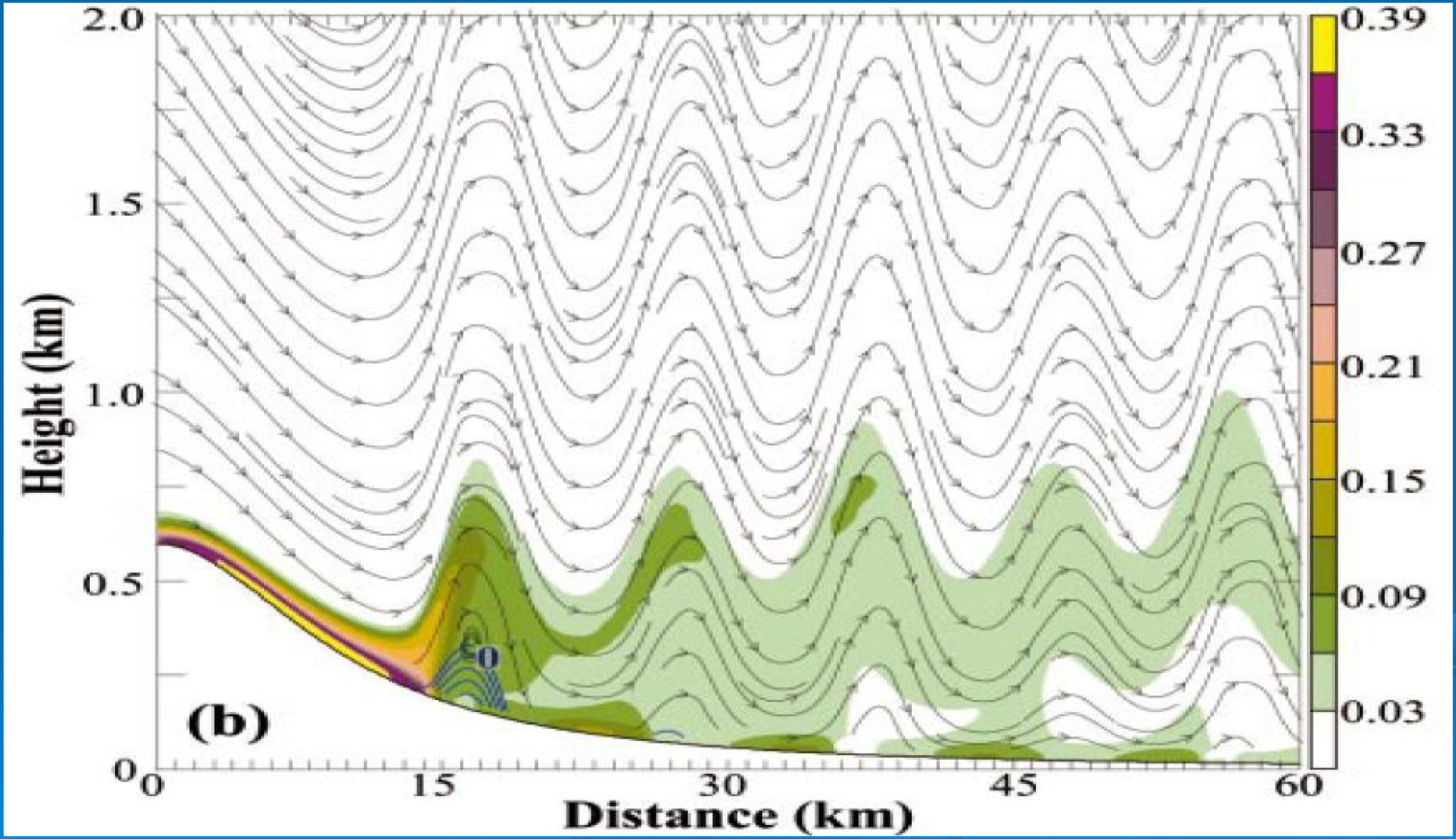
Vertical velocity (color), isentropes (lines); after Jackson, Mayr & Vosper 2011 (JMV11)

Lee waves & rotors



After JMV11

Numerical simulation of “lighter” lee-wave rotors, Doyle & Durran JAS2002

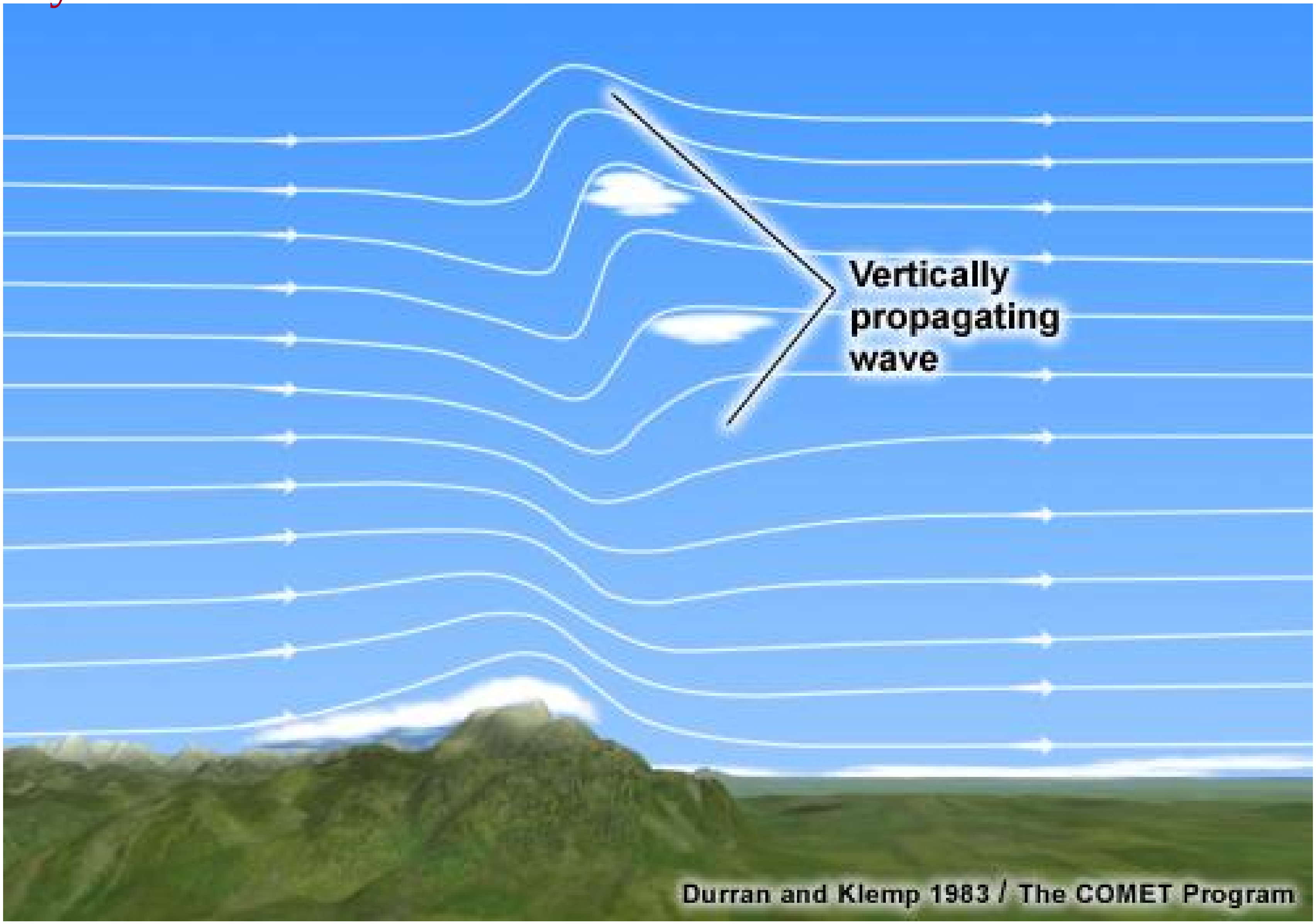


"Heavy lee-side rotors": mountain-wave breaking & possibly hydraulic jump (HJ),the Sierra Nevada, 5 March 1950, photo by Robert Symons

'Terrain induced Rotor Experiment', T-REX, V. Grubišić et al. photo by Barbara Brooks, also near the Owens Valley, the Sierra Nevada, Calif., USA, 25 March 2006

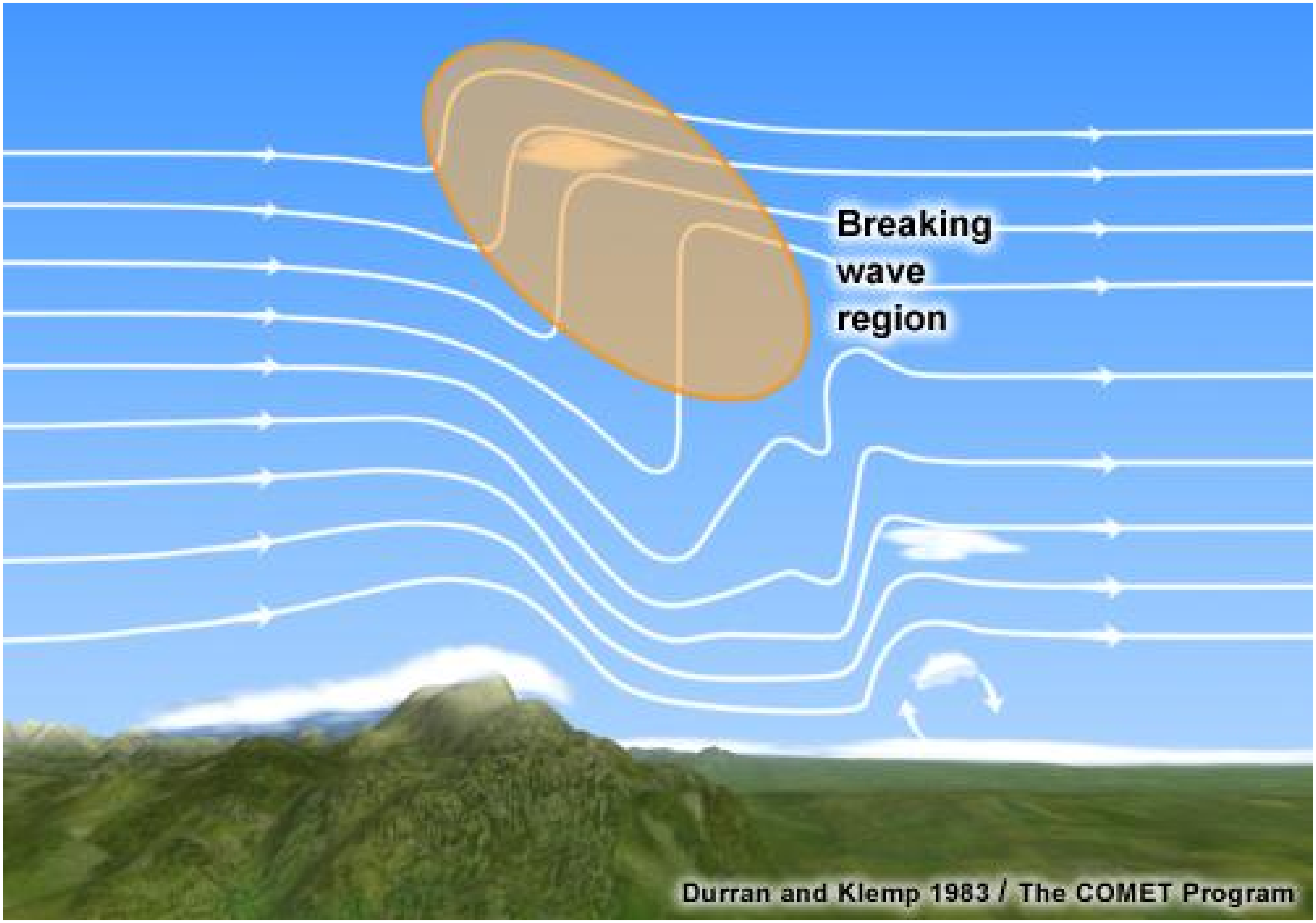
AIRFLOW OVER A MOUNTAIN

weakly nonlinear:



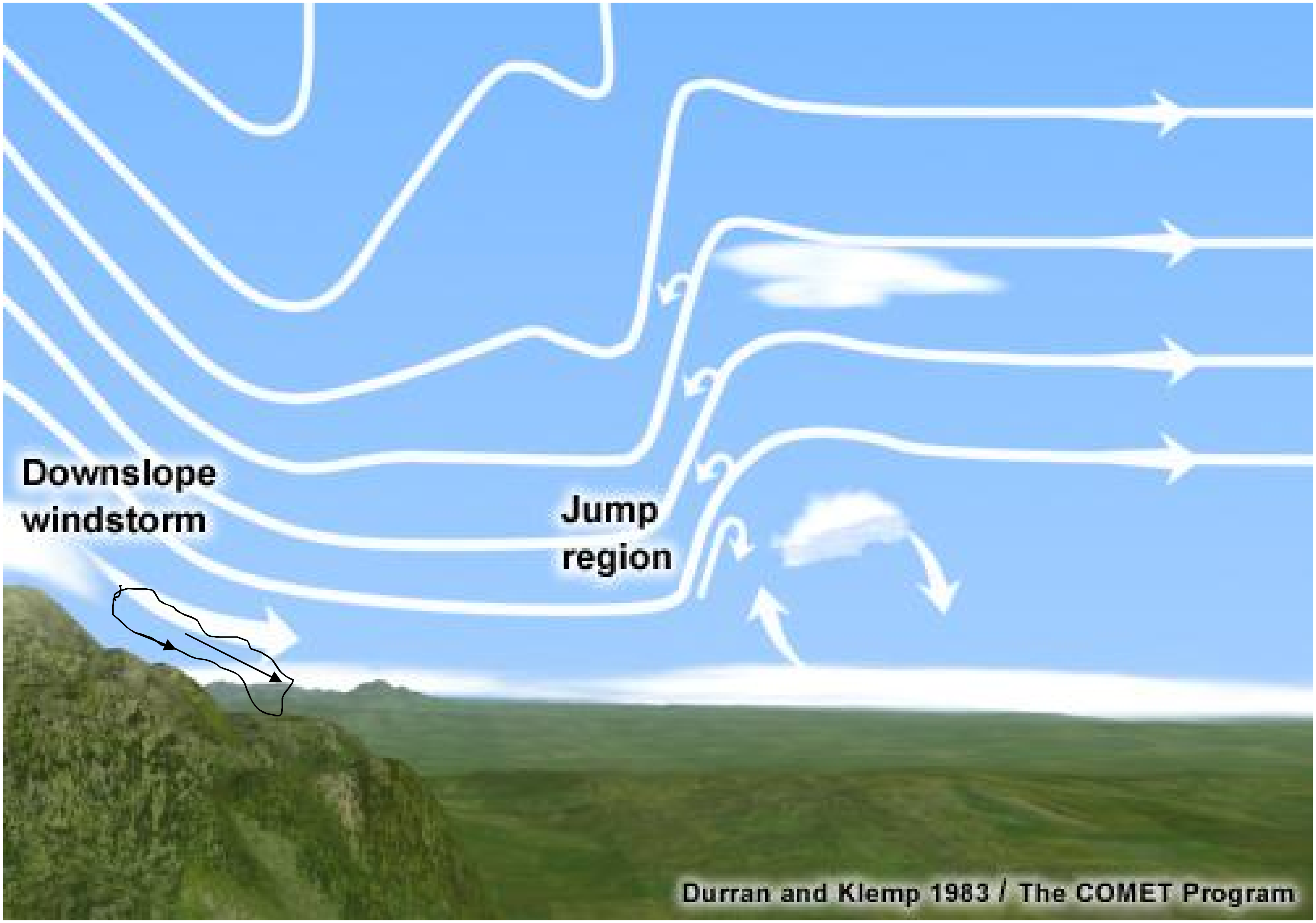
Durran and Klemp 1983 / The COMET Program

Strongly nonlinear flow over mountain



Durran and Klemp 1983 / The COMET Program

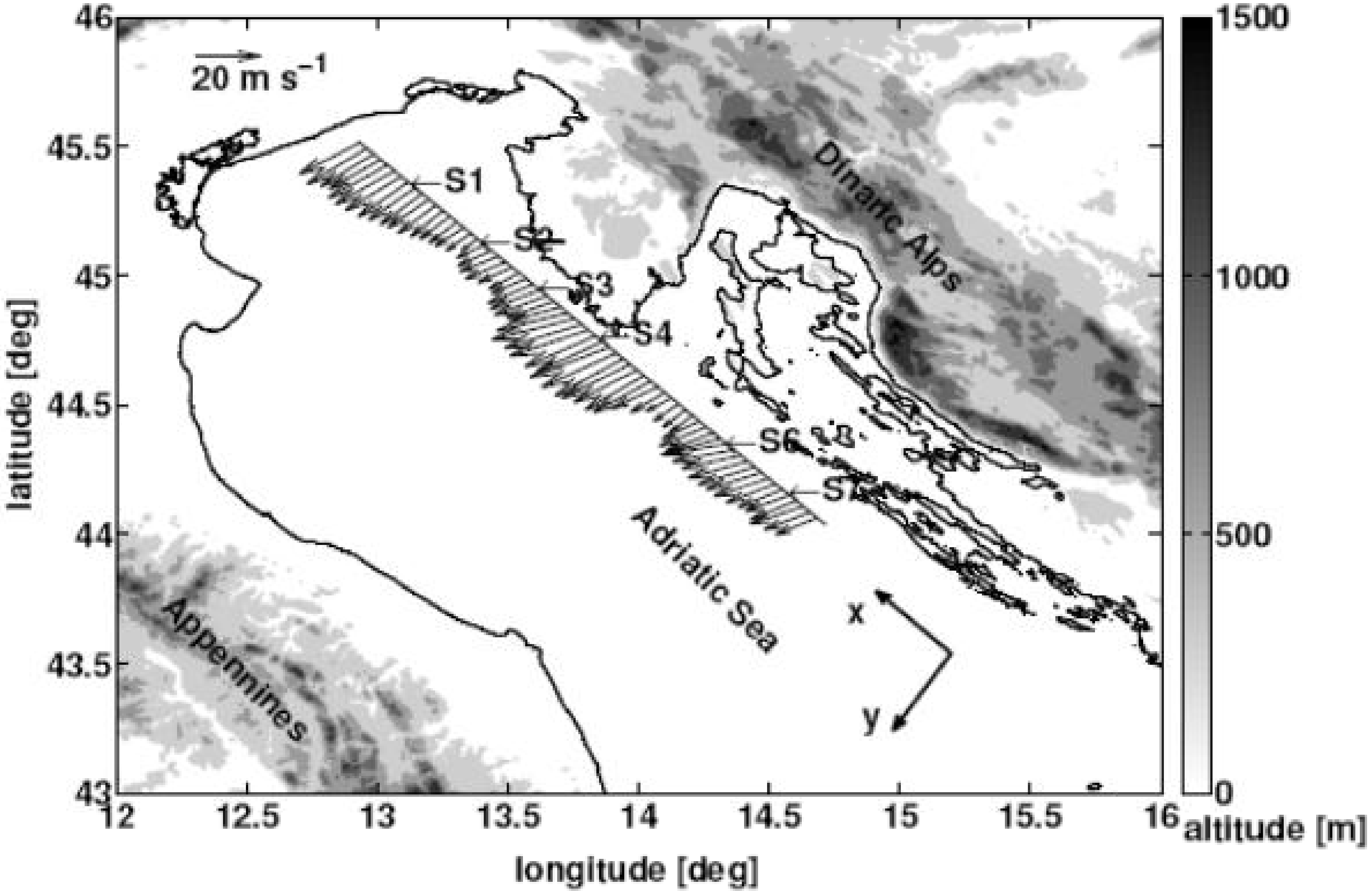
Various types of waves interact with mean flow & turbulence



Durran and Klemp 1983 / The COMET Program

to Austria ŷ

BORA DOWNSLOPE WINDSTORM



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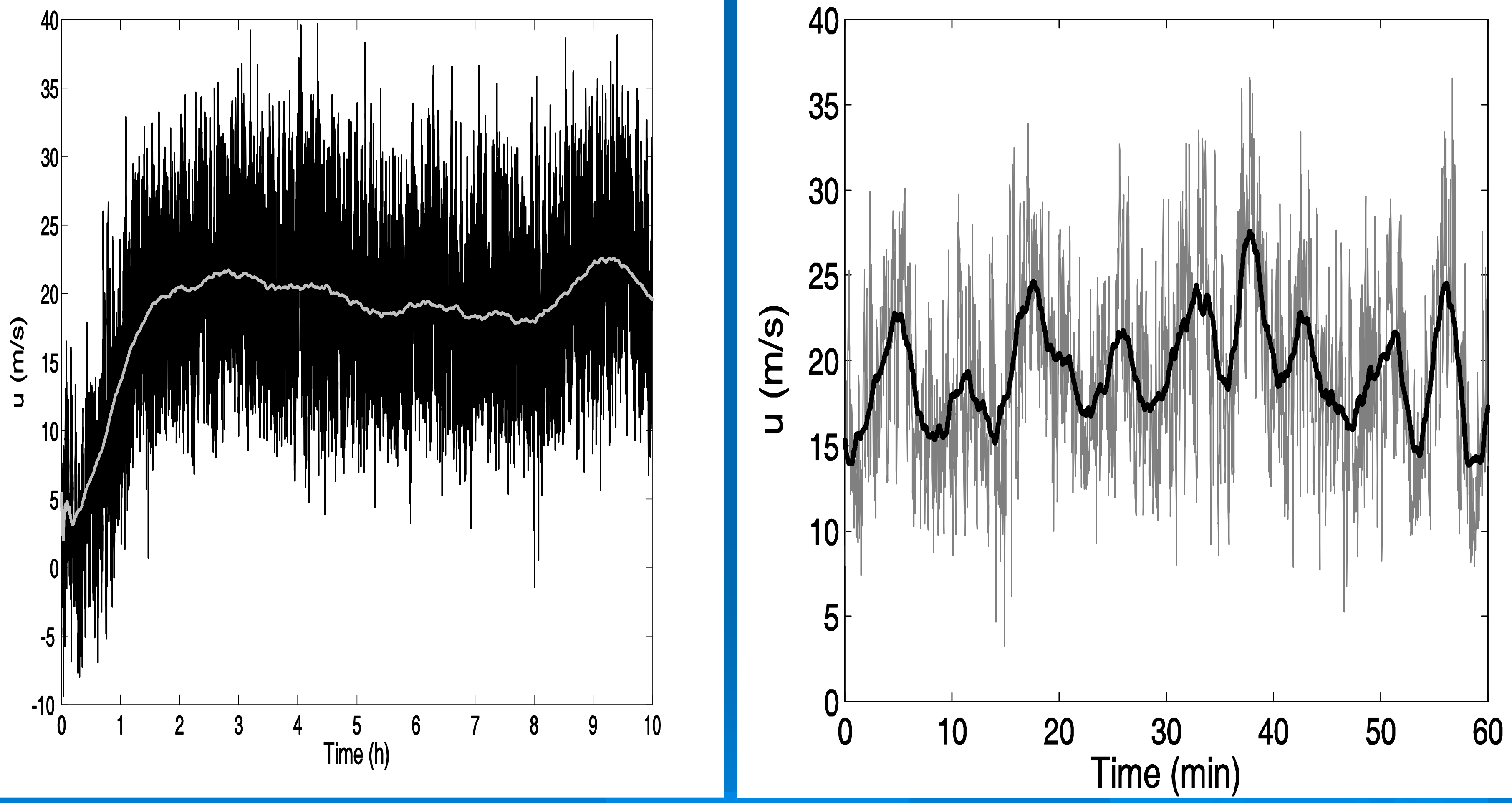
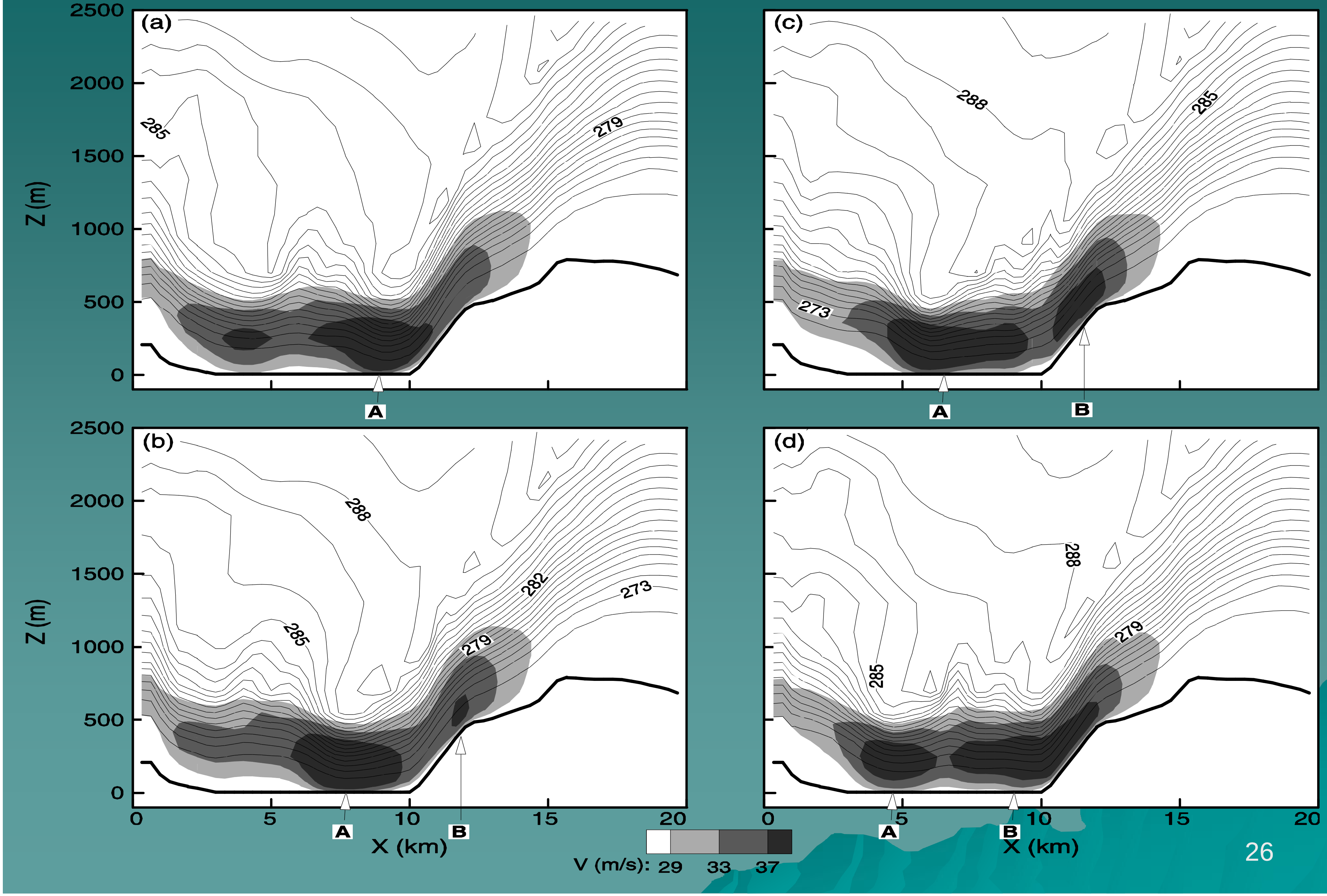
to Greece Ÿ

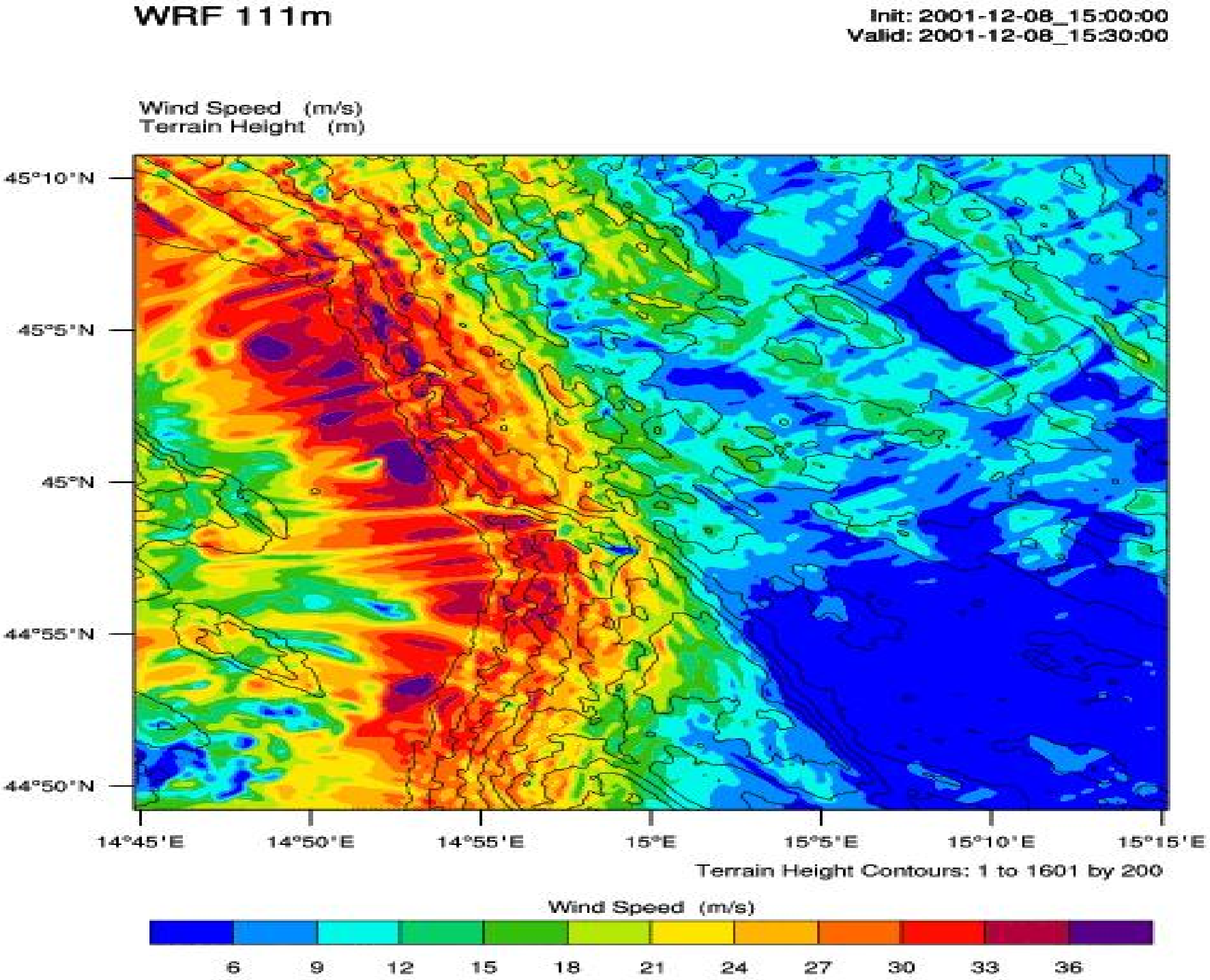
Downslope windstorm gusts may surpass 70 m/s (hurricane speeds)



TYPICAL SEVERE BORA EPISODE, ADRIATIC COAST, EUROPE, 08/12/2001; 6TH HOUR EXPANDED ï **PULSATIONS**! Data sampling 1 sec.

Pulsations: WS > 28m/s shaded, θ by 1K, severe Adriatic Bora 12/2001, a→d) 650, 750, 850, 950 sec. A, B = individual pulsations, Belušić et al. QJRMS2007





Courtesy of Mark Žagar, 'Vestas', Denmark

JAS, 2006: POULOS ET AL.
SUBMITTED

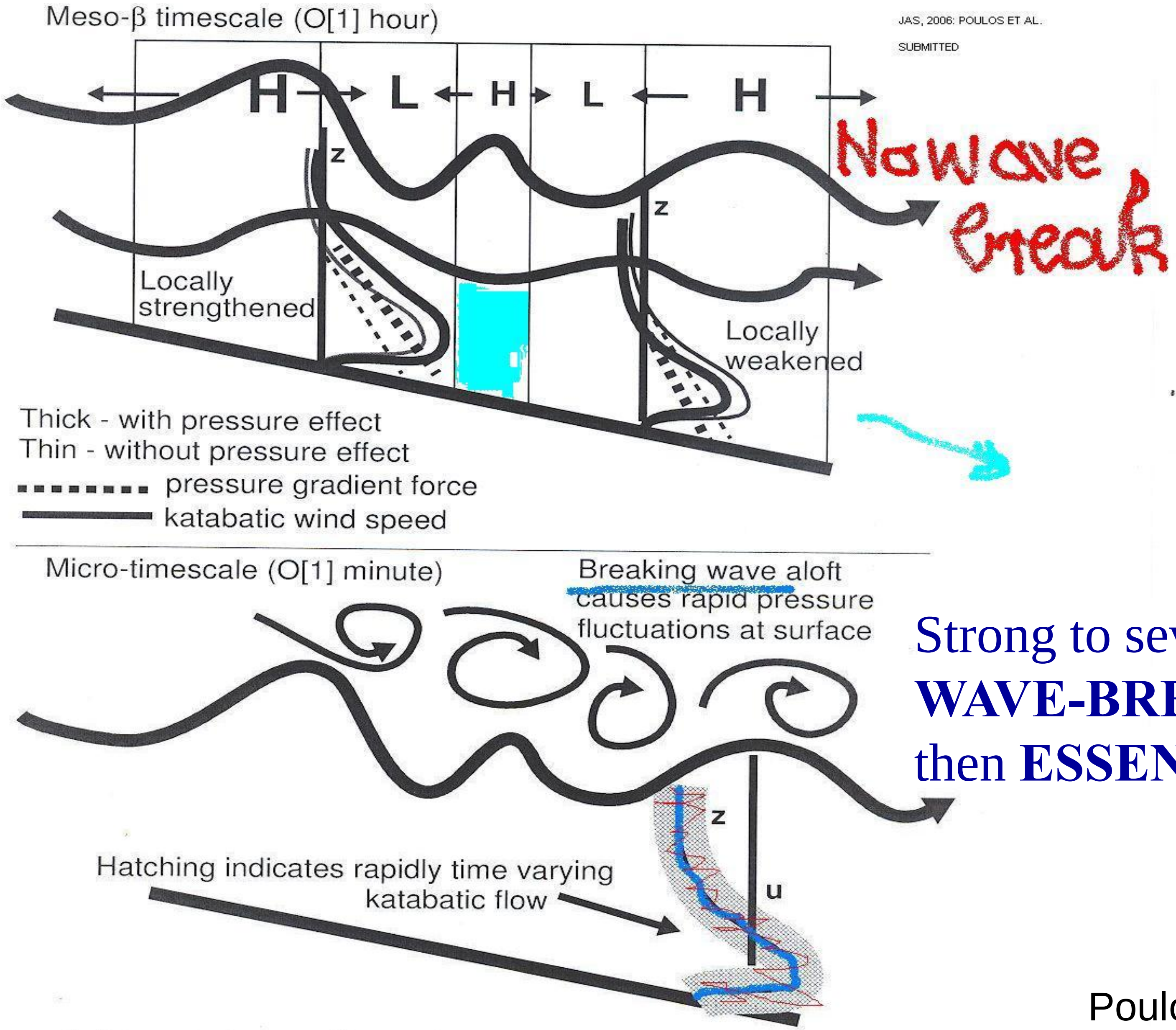
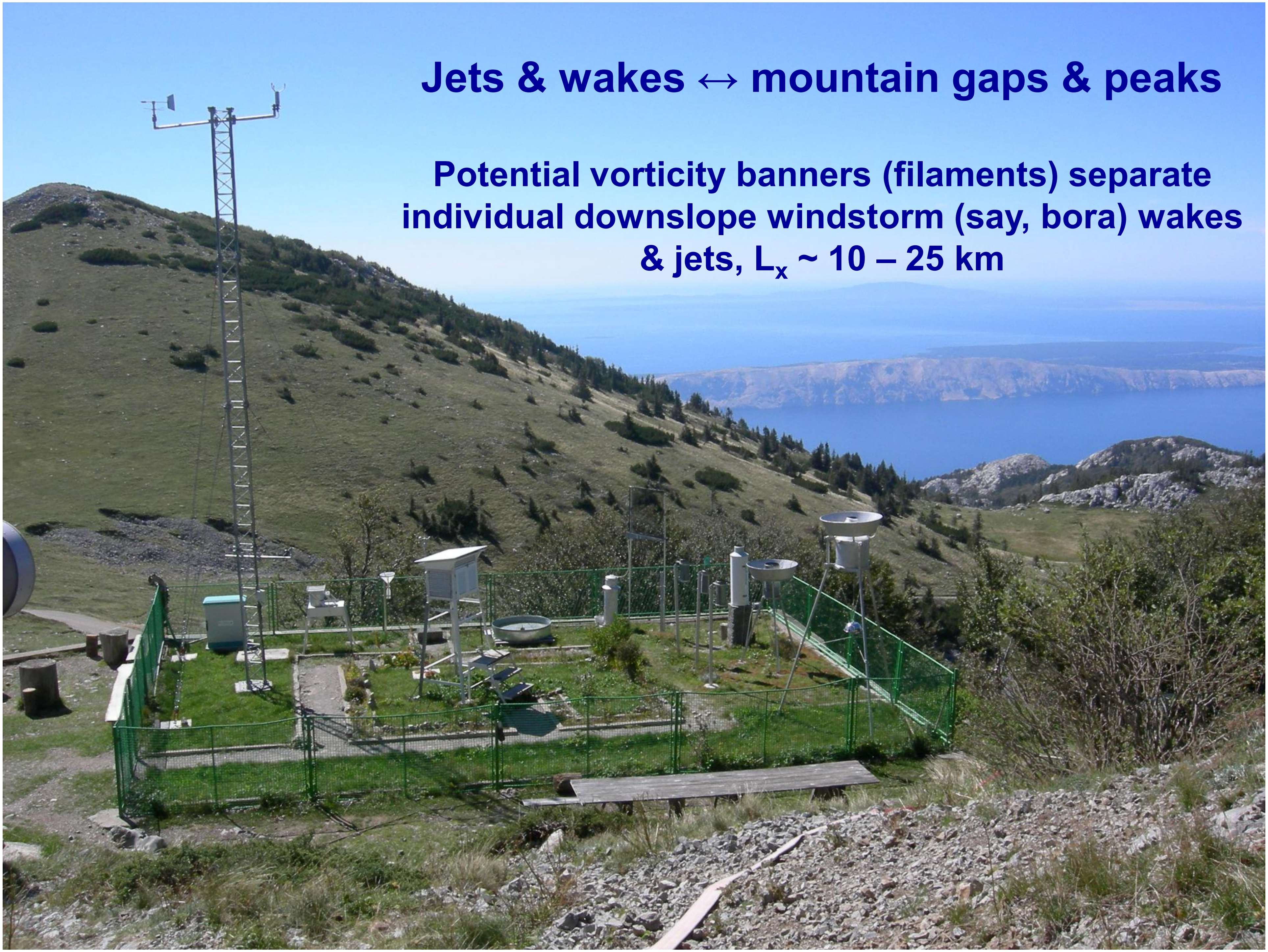


Figure 12. Schematic diagrams of the two dynamic pressure effects of mountain waves on katabatic flow. The upper diagram shows that, depending on location, katabatic flow can be either strengthened (upper slope case) or weakened (lower slope case), due to the integrated column pressure structure of the mountain wave and the locally induced pressure gradient (arrows). The lower diagram shows that a breaking mountain wave aloft causes rapid pressure fluctuations which, in turn, causes rapid katabatic flow fluctuations.

Strong to severe bora cases: **WAVE-BREAKING** is then **ESSENTIAL**

Poulos et al. JAS2000



Jets & wakes ↔ mountain gaps & peaks

Potential vorticity banners (filaments) separate individual downslope windstorm (say, bora) wakes & jets, L_x ~ 10 – 25 km

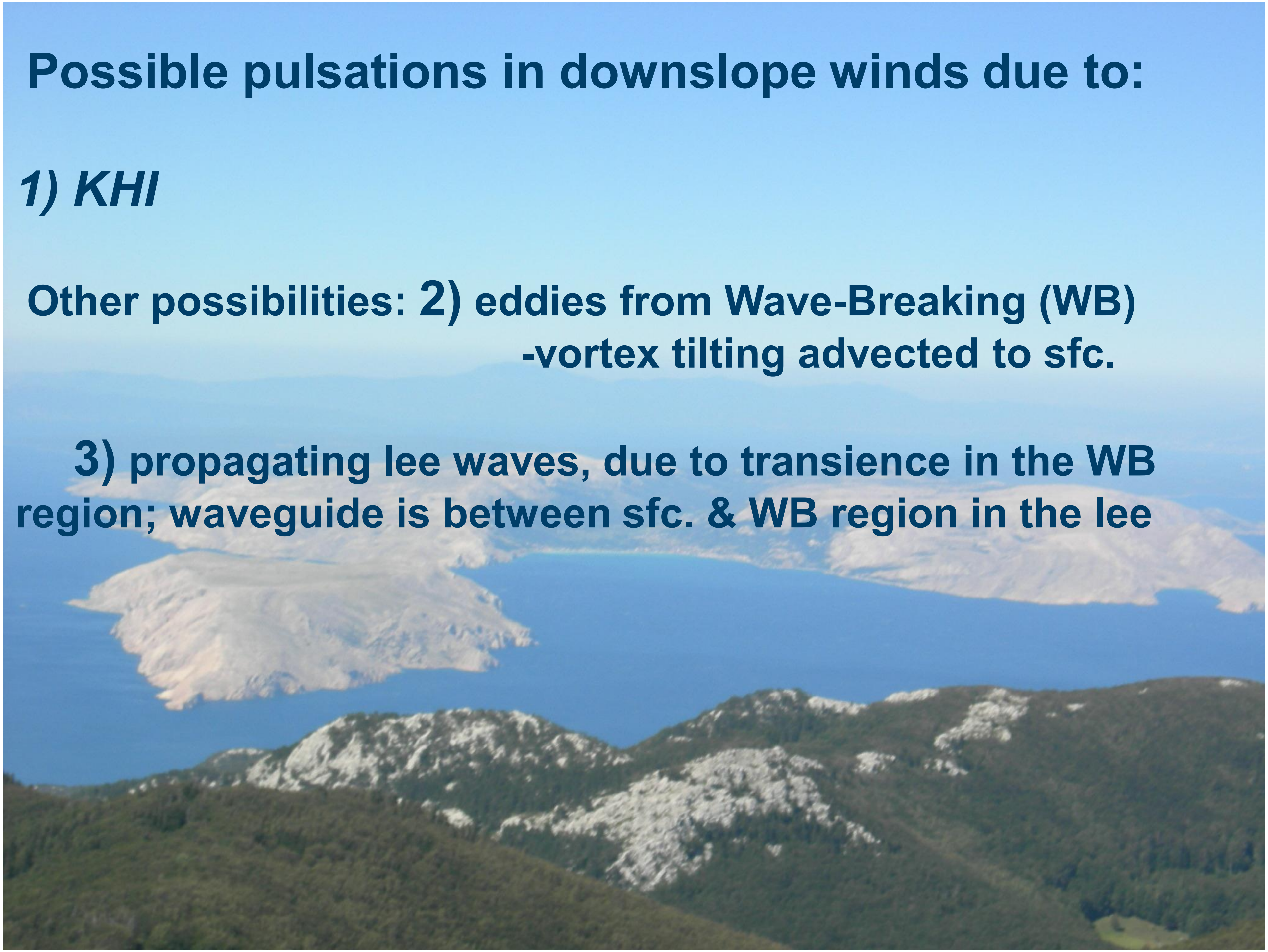
- Difficult to obtain representative data over such terrain
- Even when/where occasionally done so, it is uneasy to reproduce them up to a meaningful level of confidence & exploration via mesoscale models

Possible pulsations in downslope winds due to:

1) KHI

Other possibilities: 2) eddies from Wave-Breaking (WB)
-vortex tilting advected to sfc.

3) propagating lee waves, due to transience in the WB region; waveguide is between sfc. & WB region in the lee



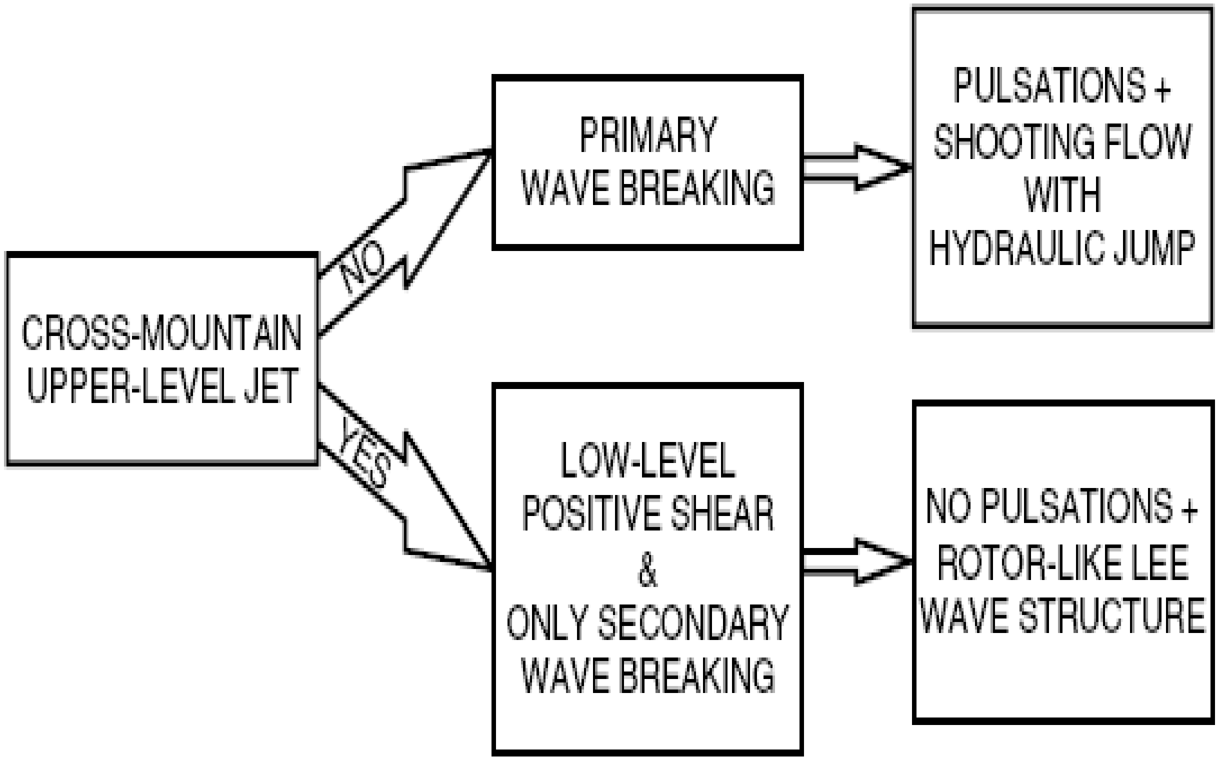


Figure 17. Summary schematic depicting the pulsations dependence upon the upper-tropospheric cross-mountain jet.

Wake in the lee

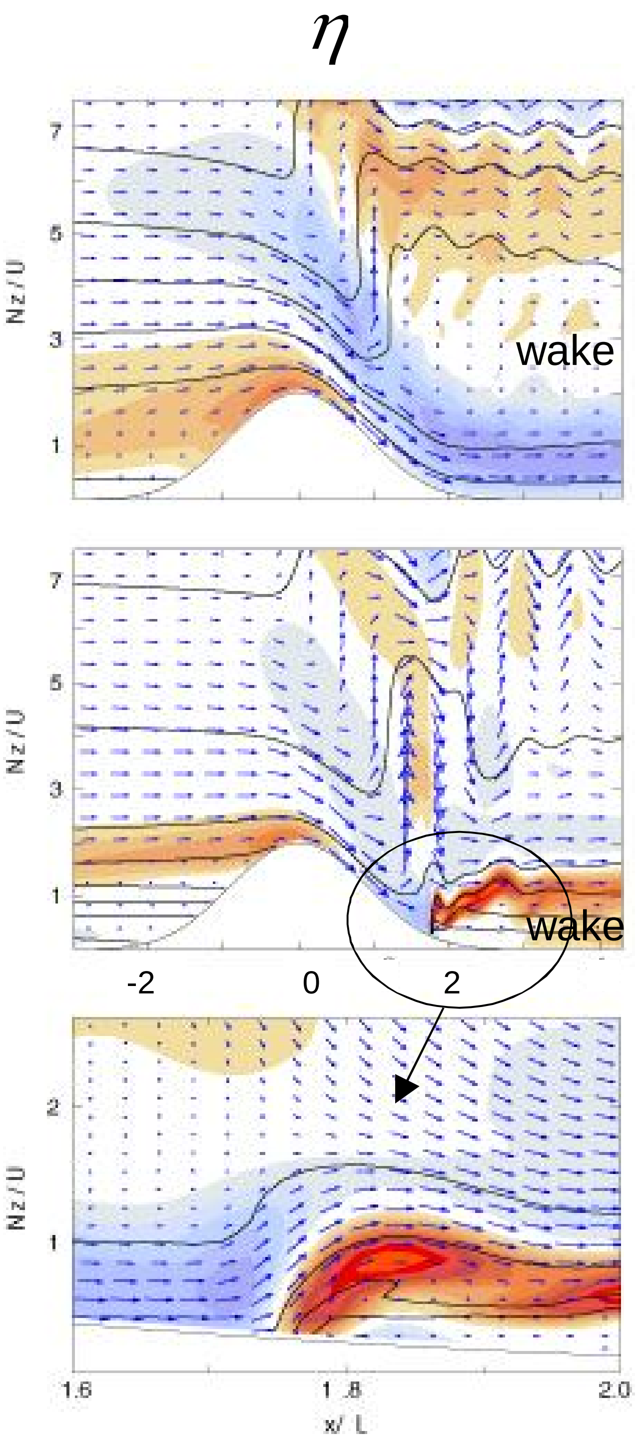
2 main types of formation

Wave Breaking
N,U constant

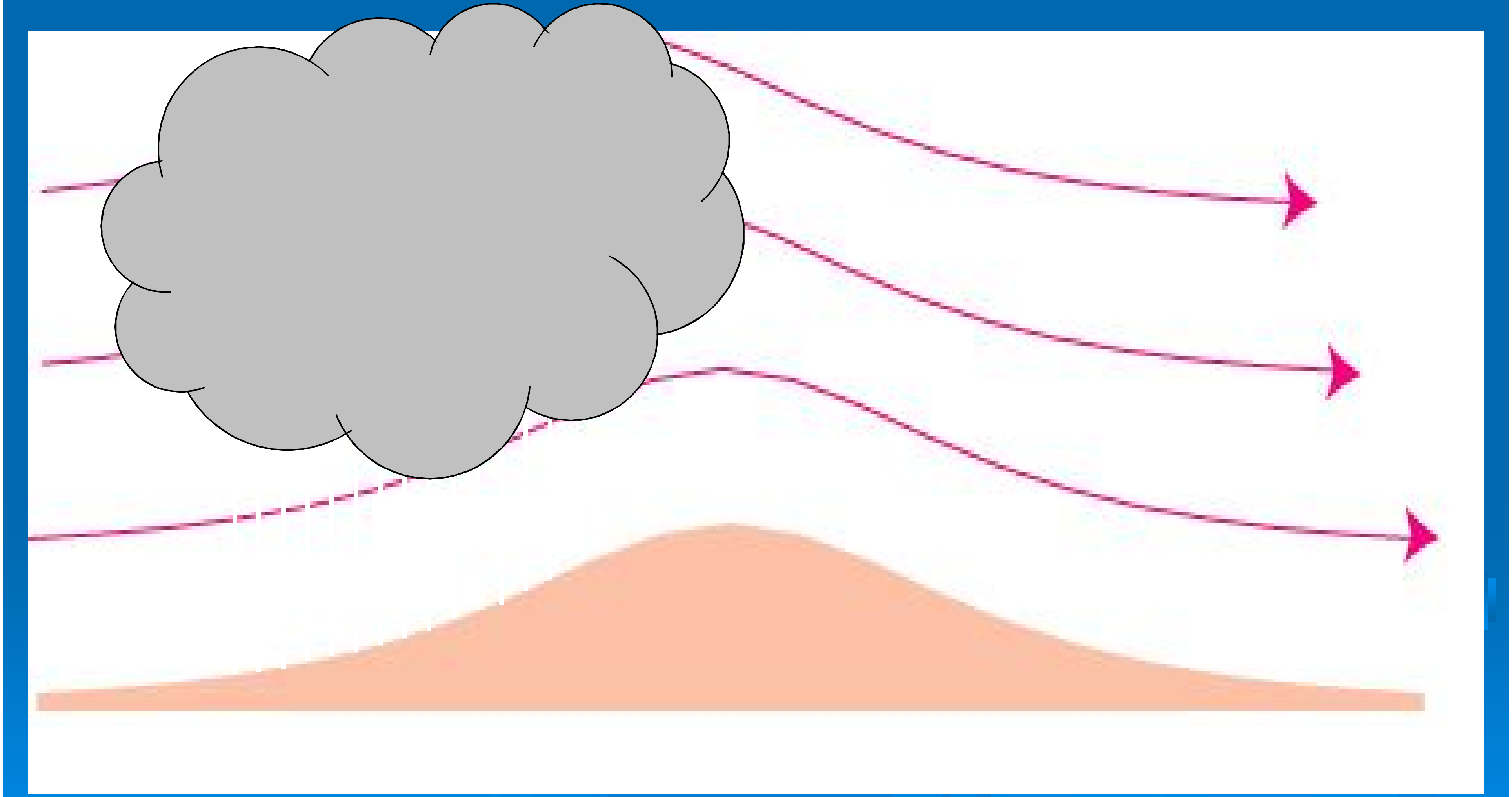
Upstream blocking
2-layer *N* with *U* constant

After: Epifanio & Rotunno, JAS2005

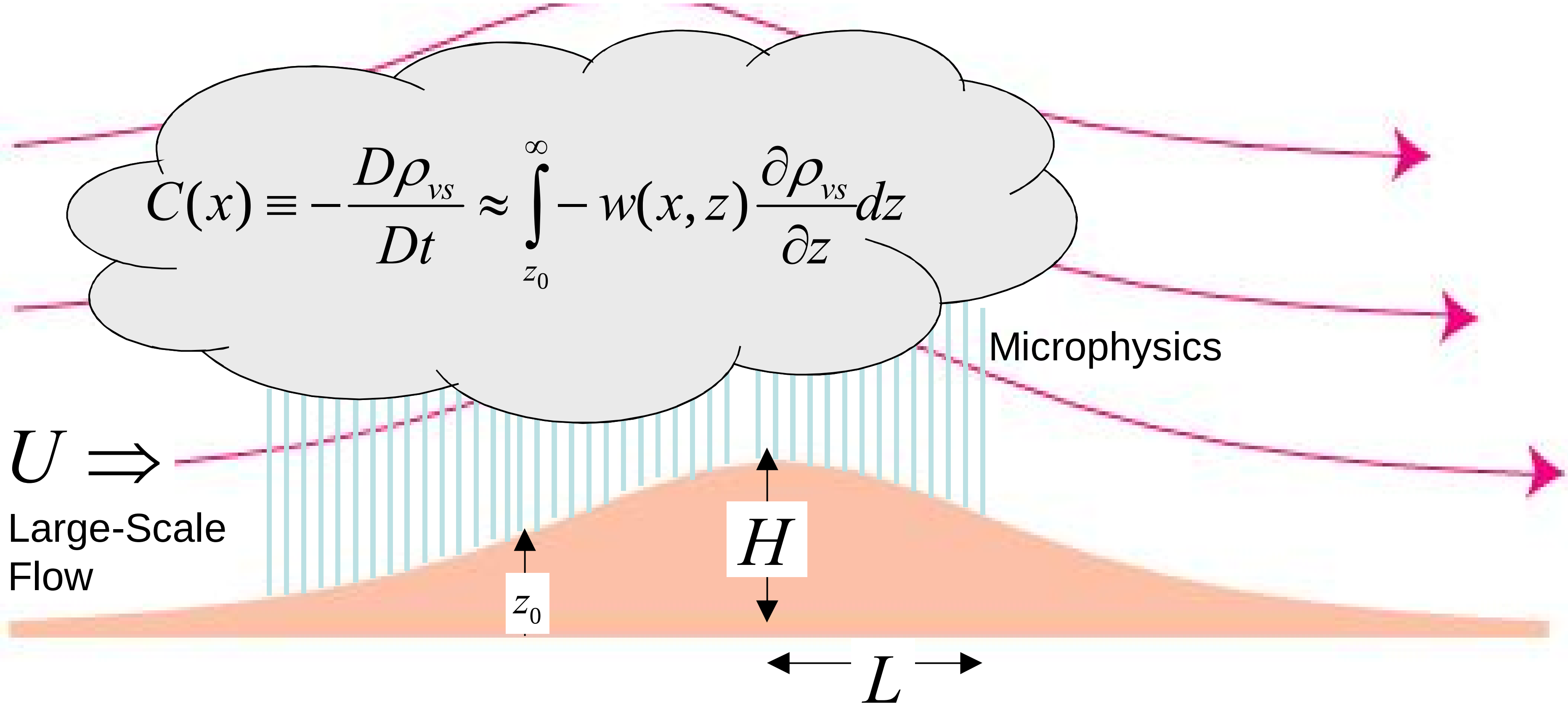
Nonlinear, nonhydrostatic model,
2D Obstacle / 3D y-periodic domain



Orographic Precipitation



After R. Rotunno, 2005



$$C(x) \equiv -\frac{D\rho_{vs}}{Dt} \approx \int_{z_0}^{\infty} -w(x,z)\frac{\partial \rho_{vs}}{\partial z}dz$$

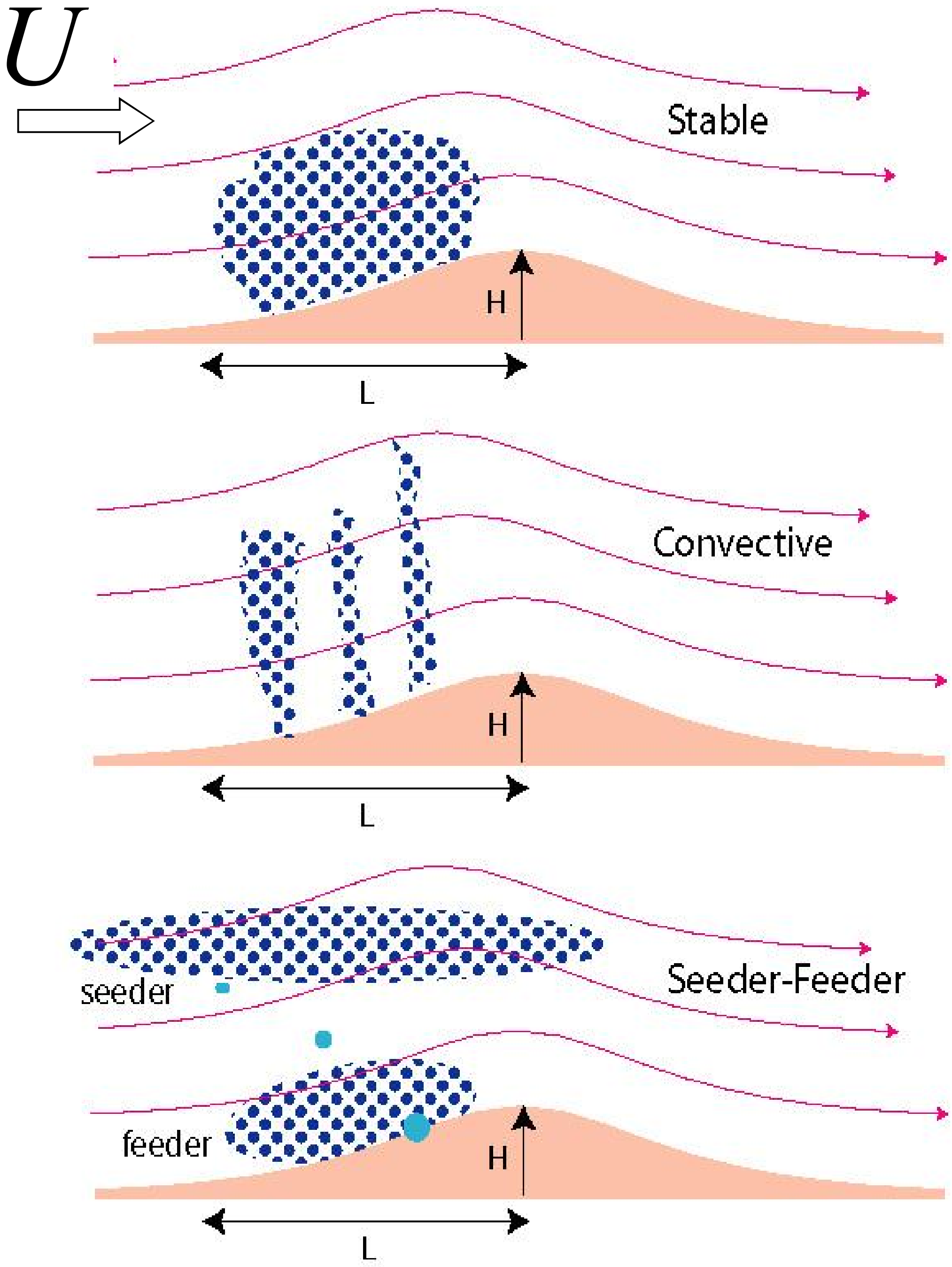
$C(x)$ = Column-Integrated Condensation

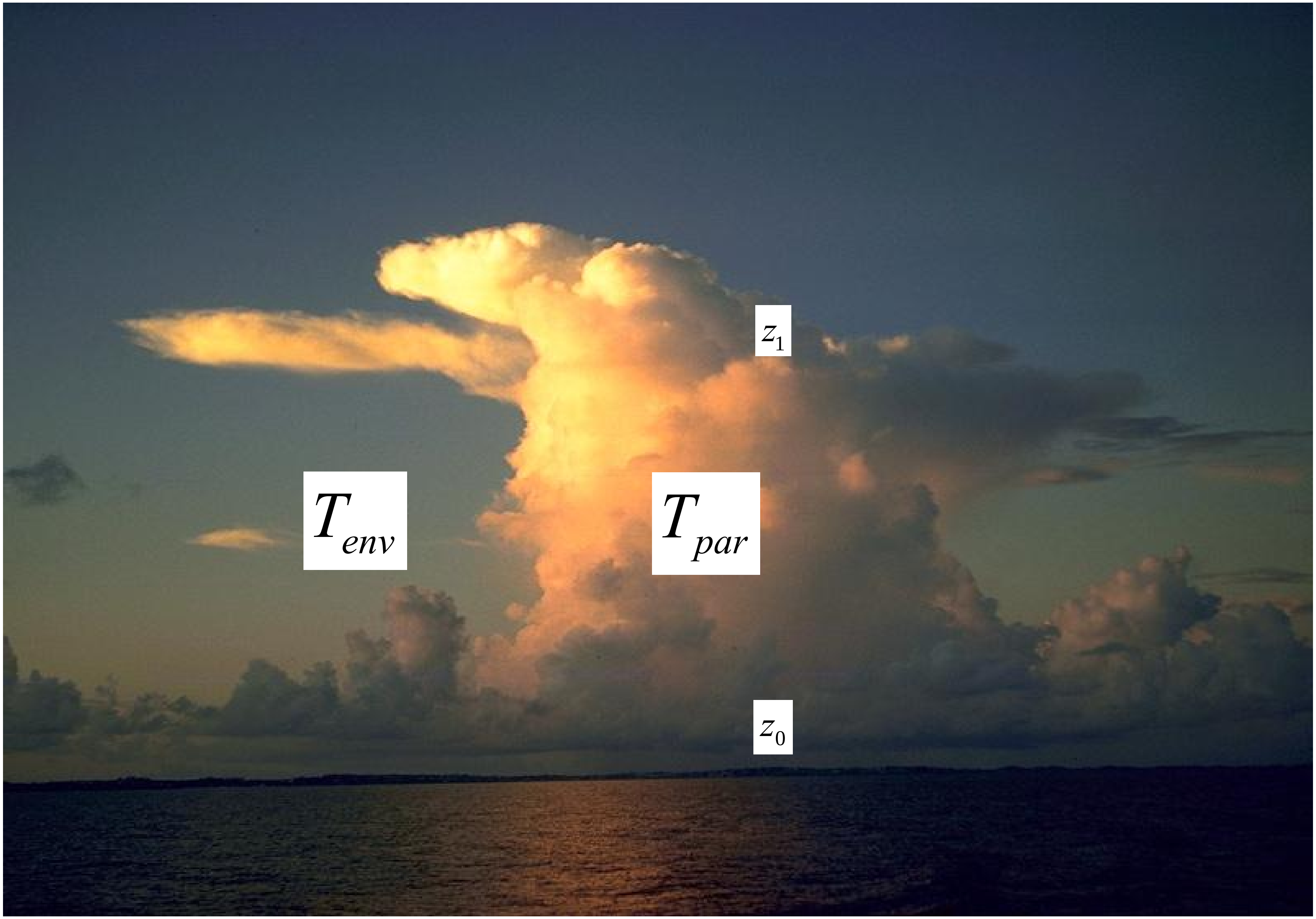
Dynamics→

$$\boxed{w = w(H, L, U, Stability, Coriolis, 3D\ Effects)}$$

ρ_{vs} = saturation vapor density

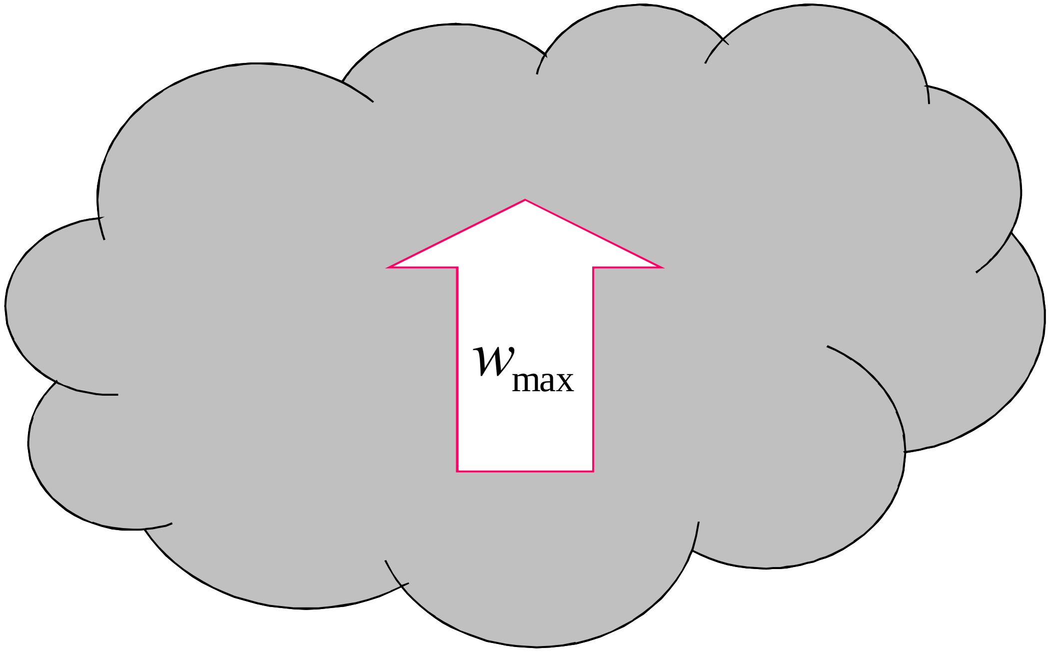
Types of Orographic Effects on Moist Convection





$$T_{par} > T_{env}$$

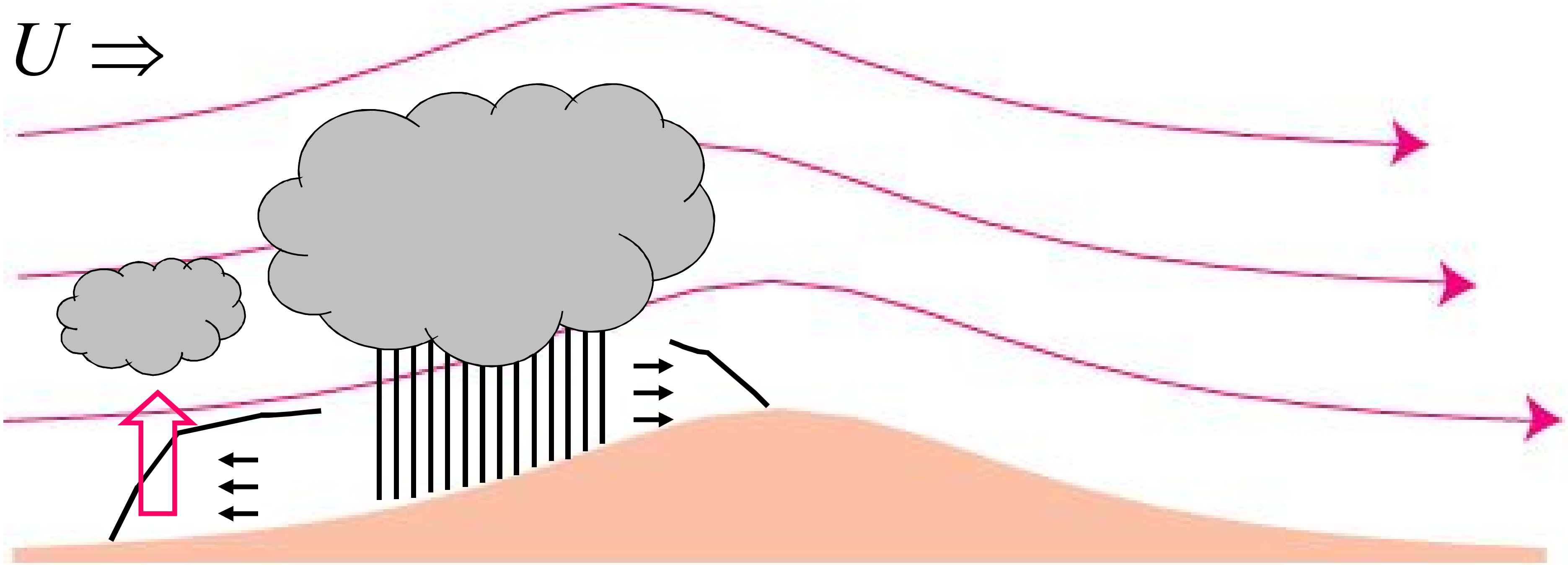
$$w_{\max} = \sqrt{2 \times CAPE} \sim 2-50m/s$$



$$\boxed{C(z_0) = \int_{z_0}^{\infty} -w(x,z)\frac{\partial \rho_{vs}}{\partial z}dz}$$

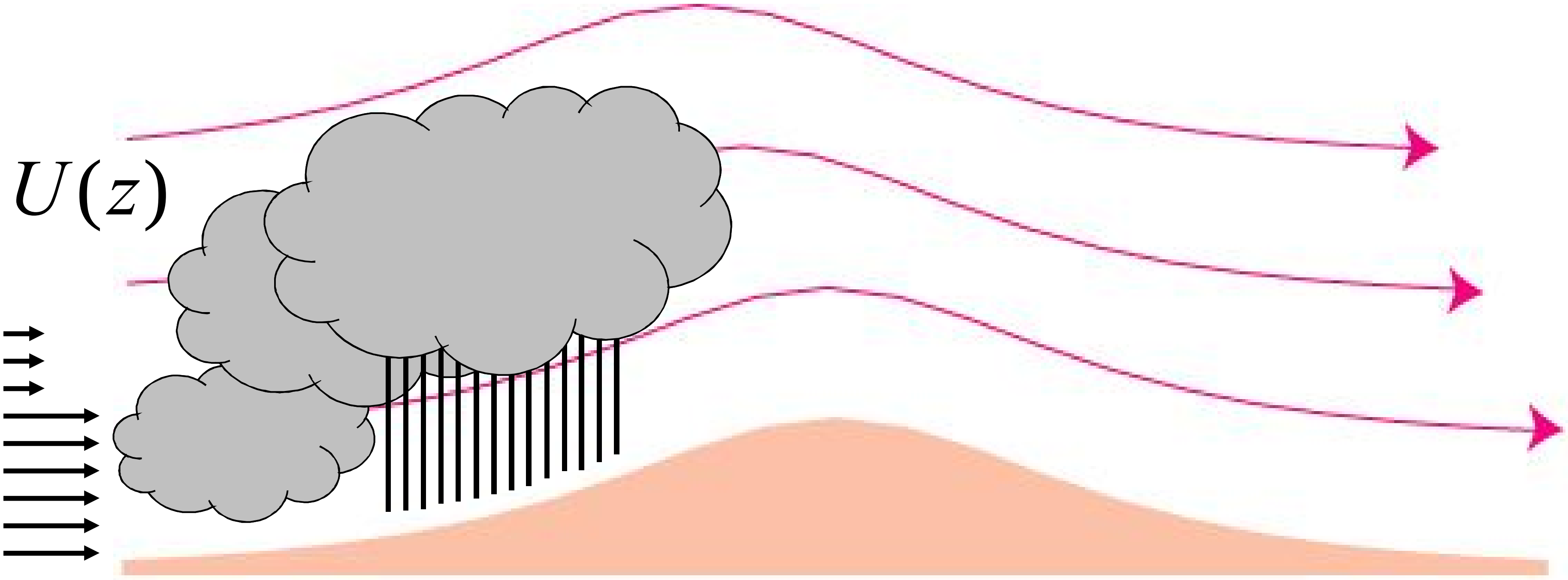
$$\boxed{C(z_0) \approx w_{\max}\rho_{vs}(z_0) = 2m/s \times \quad \times .01Kg/m^3 = 72\ mm/h\ !!!}$$

Cool Air Outflows May Initiate New Cells Upstream →



Chu & Lin, JAS2000

Rain Accumulation Large if Wind Varies with Height such that Cells are Stationary with respect to Mountain →



Cb’s that do not produce enough ice crystals usually fail to produce enough static electricity to cause lightning

FUTURE MM AVENUES

-Better spatio-temporal data coverage & use of remote sensing

-Better data assimilation over complex terrain into NWP

-Parameterization improvements for sfc. properties, momentum-heat-moisture-matter exchange, ever better (Δx_j, Δt)

-The role of the upwind waves, convection & ABL is largely unknown

*-Mountain Meteorology (**MM**) relies on top quality data, best models & theoretical advancements*

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