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Modelling atmospheric flows over isolated orography: stable stratification and separation effects

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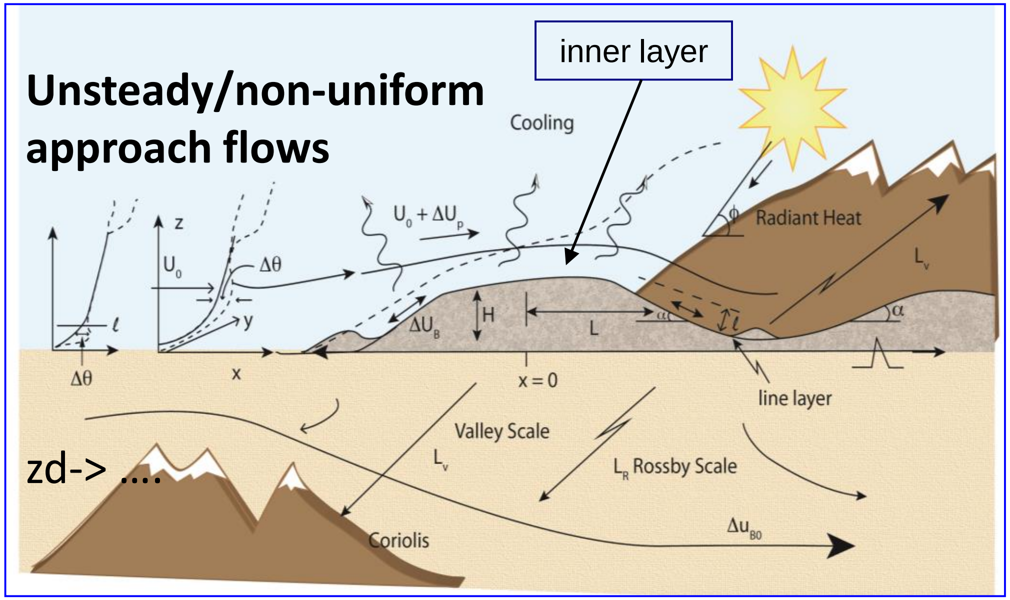
Flow over mountains: interactions of multiple length/time scales & quasi-linear perturbations



<u>Applications</u>

- Development of **fast perturbation** models (quasi-linear);
- **now-casting** for aviation, wind power;
- Improve **air pollution models** (Aermod, ADMS);
- Improvement of **mesoscale models** - especially for <u>internal layers</u> e.g. <u>separation/ inversion layers</u>

<u>Validation of theory for larger mountains</u>:

MATERHORN Field Experiments (I: Sep-Oct 2012; II: May 2013)

Surface layer to mountain to valley scale l_s → L ->Lv

Under conditions: FH<1, FL <<1

negligible / significant buoyancy driven slope flows

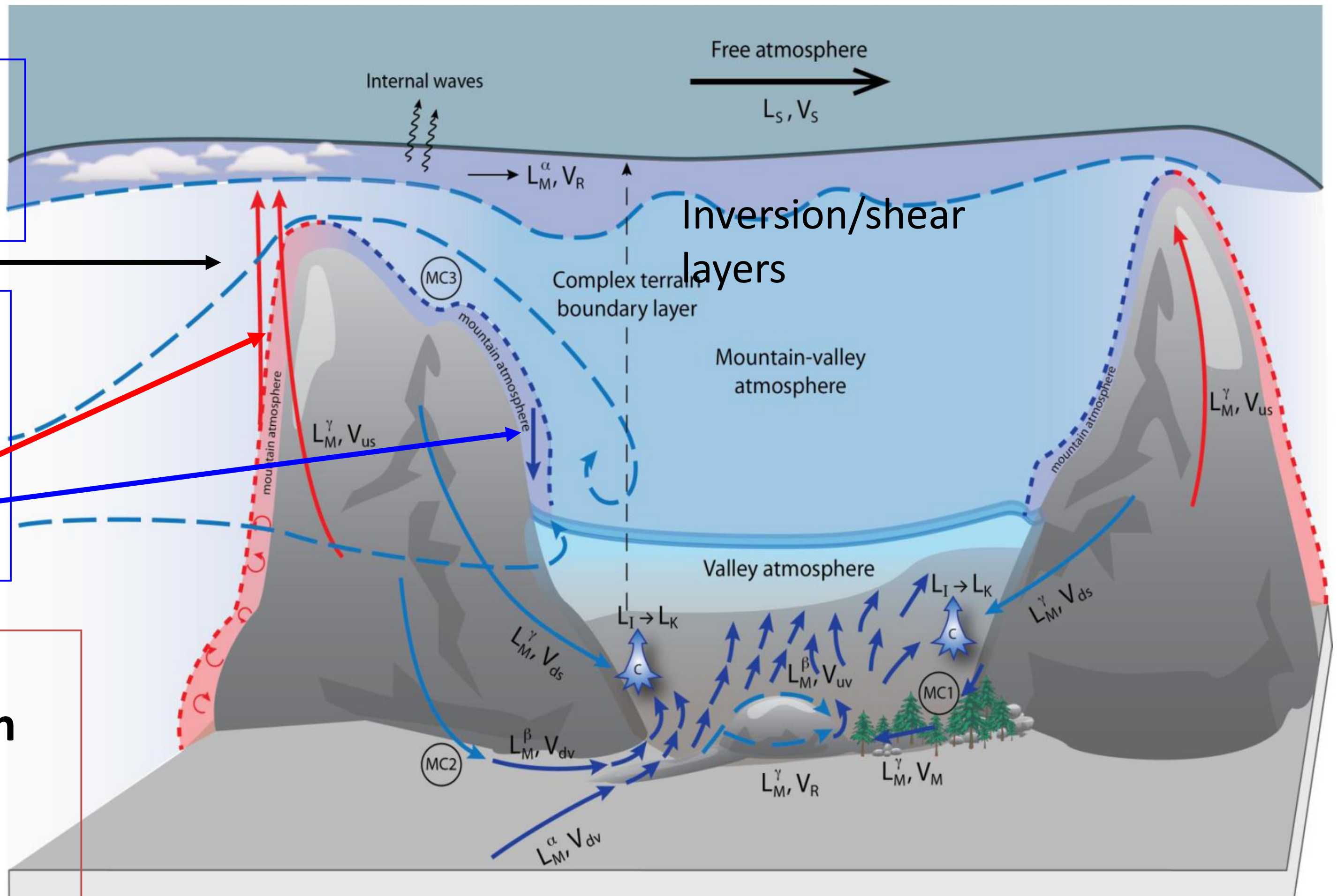
FB >>1, FB <1, L~ h --> Surface --> bl dynamics

High mountains; H~ h = bl thickness; significant buoyancy; $\Delta u_b \sim \Delta u_p$

Dividing streamline at z_d

Entrainment into upslope and downslope flows

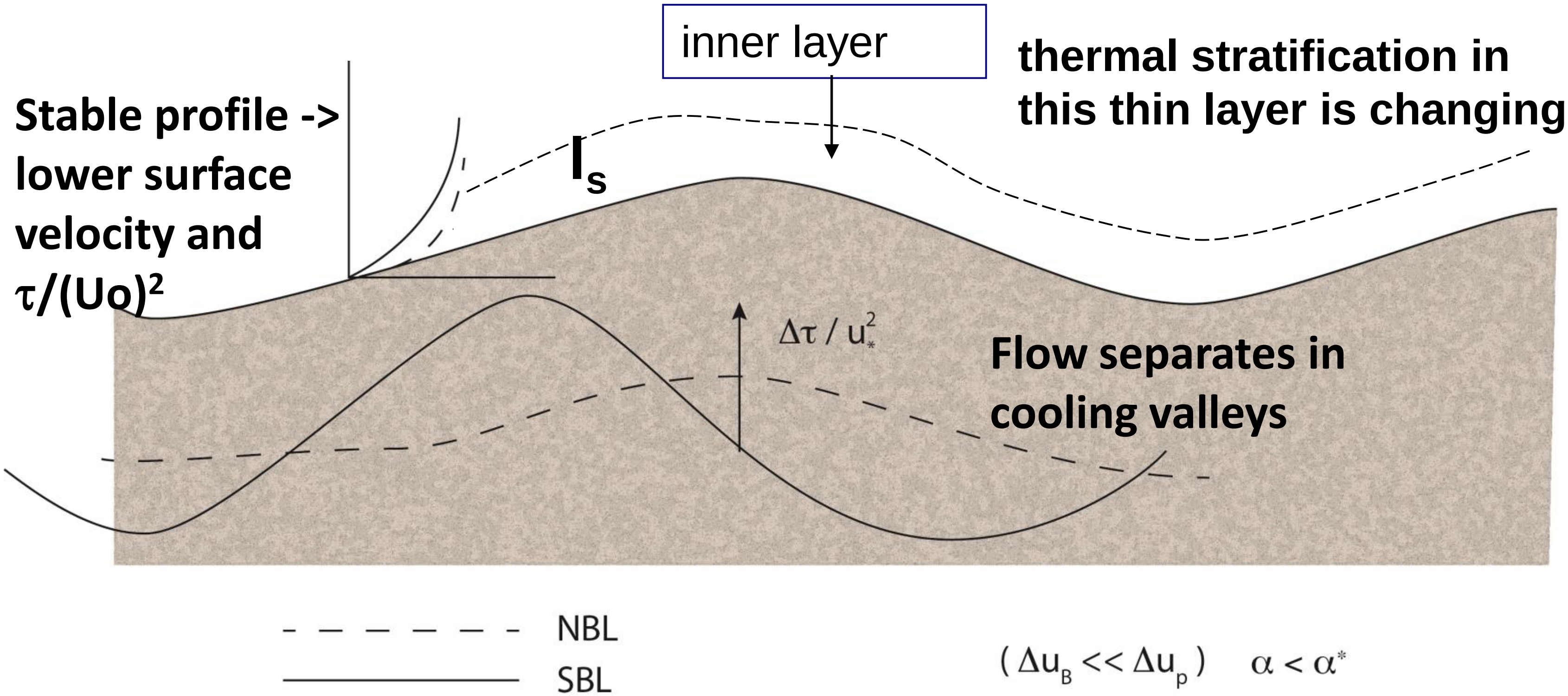
E.g. Borneo **'land beneath the wind'** – stagnant conditions in valleys below mountains.



$$L^{\alpha}_{Macro} \;--> L^{\beta}_{Macro} \;--> L^{\gamma}_{Macro} \;--> L^{\alpha}_{Meso} \;\ldots\ldots\; ----> L_{Kolmogorov}$$

Flow with/over low slopes

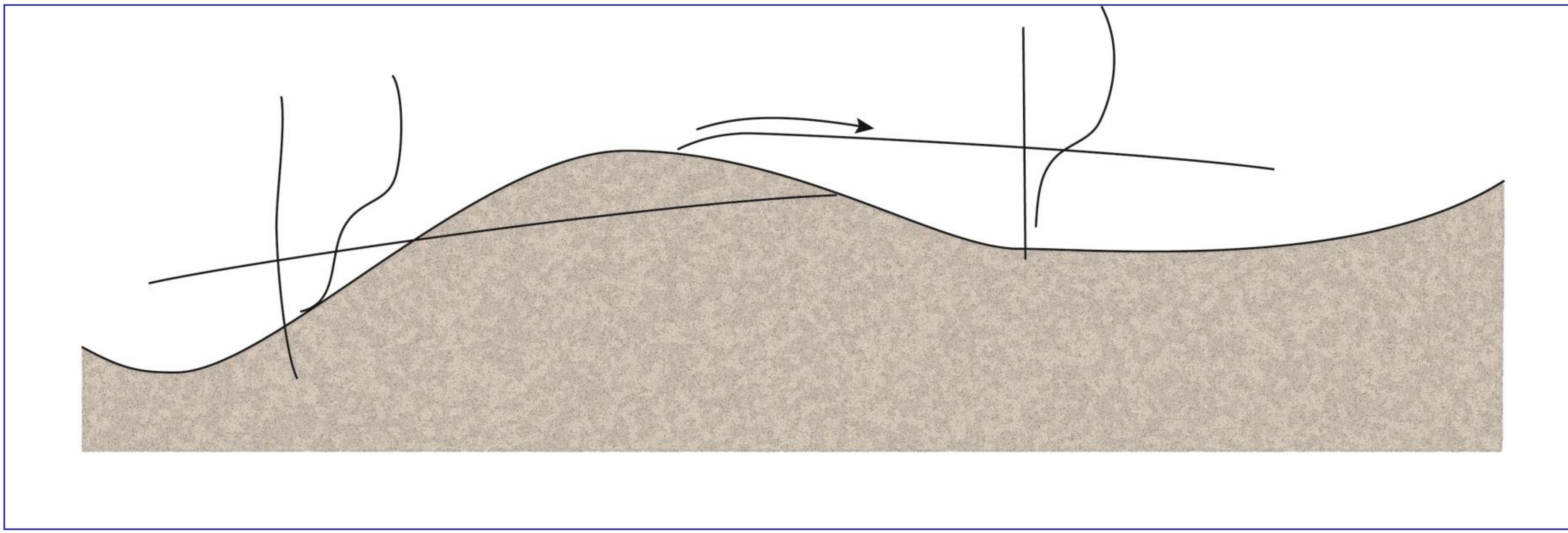
strong cooling-> low, laminar-like turbulence



Stress variation over cooling surface on hill - **like laminar flow** -> ref. Hunt Richards 1984 (via perturbation eddy viscosity modelling-> air pollution effects)- cf **large effect of surface roughness change on flow over hills** (Britter et al 1981)

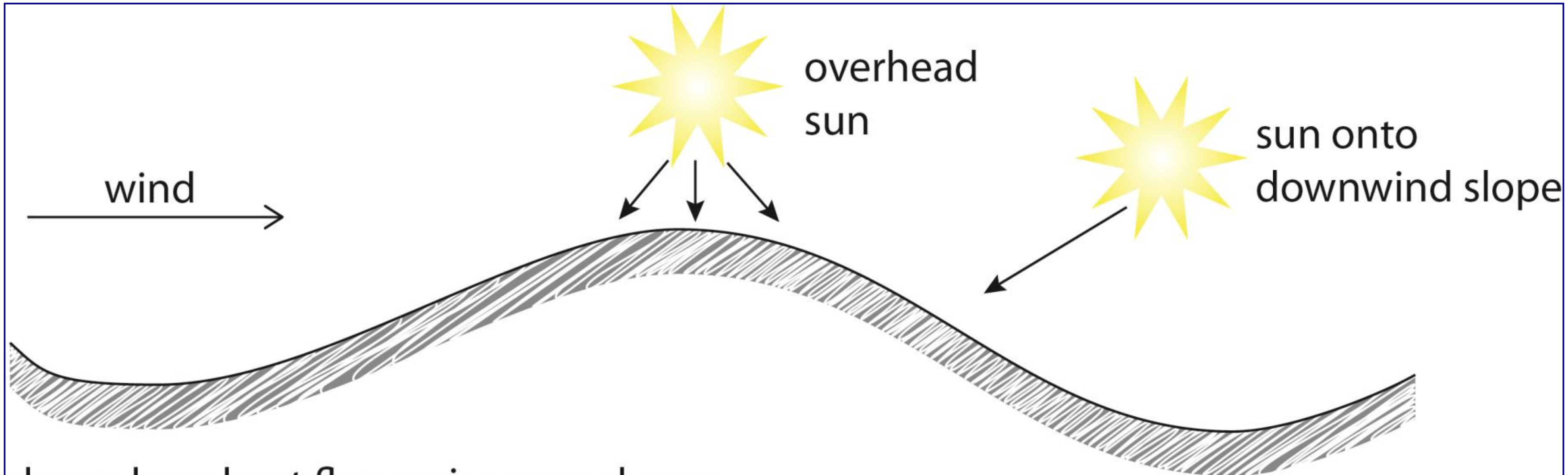
Typical profile resulting from separated flow caused by surface cooling

Slow flow on **cooling slopes** leads to lower temperature ---> **lower turbulence** and **static flow** in valleys



Cf Richardson 1923 – static flow in valley depth ~100m, 10 km long

Effects of significant surface layer buoyancy forces ~ inertia



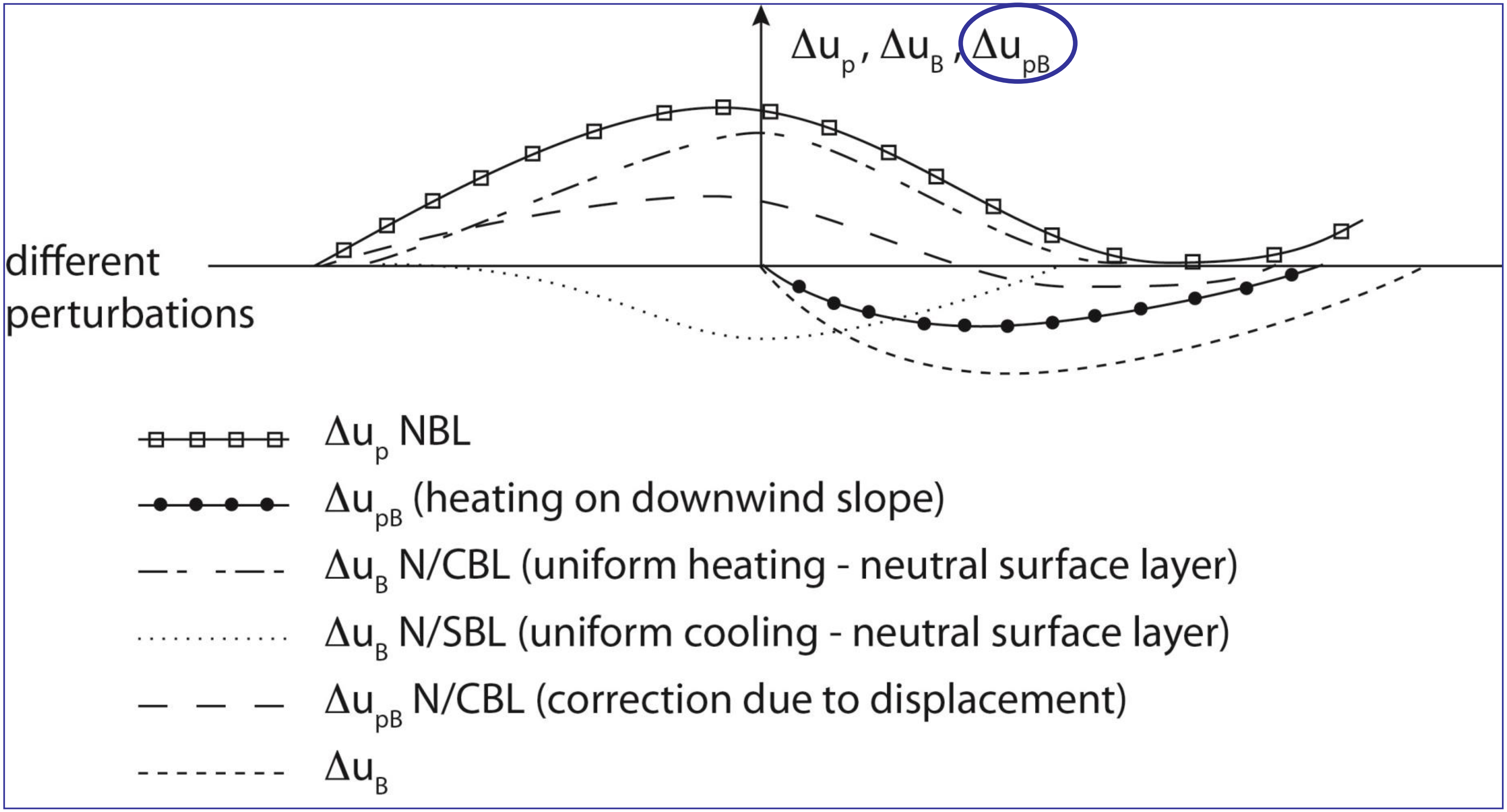
shows how heat flux varies over slopes

- **Simple modelling** shows how the **surface buoyancy perturbation $\Delta u_b \sim \Delta u_p$**, but it varies differently with **x** over the hill – it depends on sun location and slope!

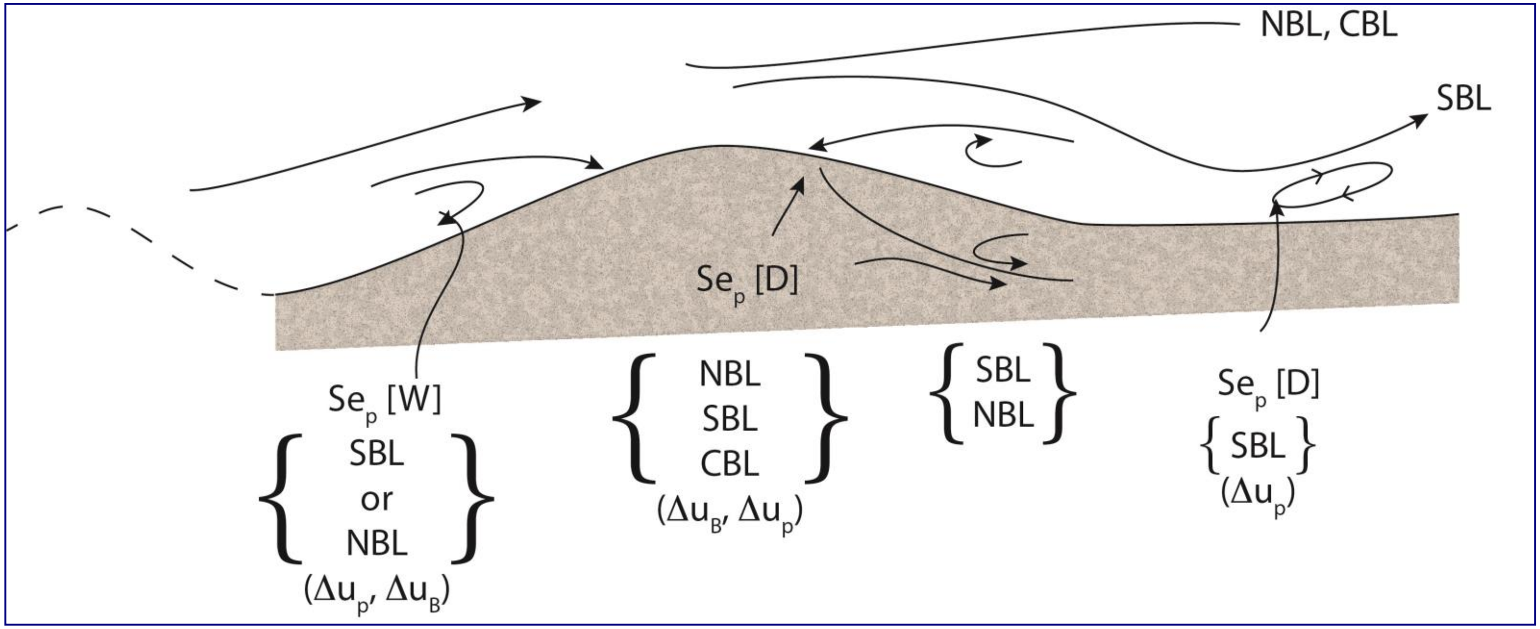
(buoyancy) $\Delta \mathbf{u_b} \sim \int [g'\Delta\theta dx]/U_0$.

- In general **Δu_b varies with x differently to the inertial perturbation Δu_p**. This alters the vertical velocity $\Delta \mathbf{w_b}$ and streamlines over the mountain, i.e. the effective shape of the mountain and thence the external flow $\Delta \mathbf{u}$ changes (by Δu_{pb}), which affects **speed up and separation**.

Perturbation modelling to combine inertia/pressure and slope flows + their effect on external flow Δu_{pb}



Separation driven by inertial/outer buoyancy pressure and surface shear stress on low slopes; also effect of slope flow



NBL - surface shear stress

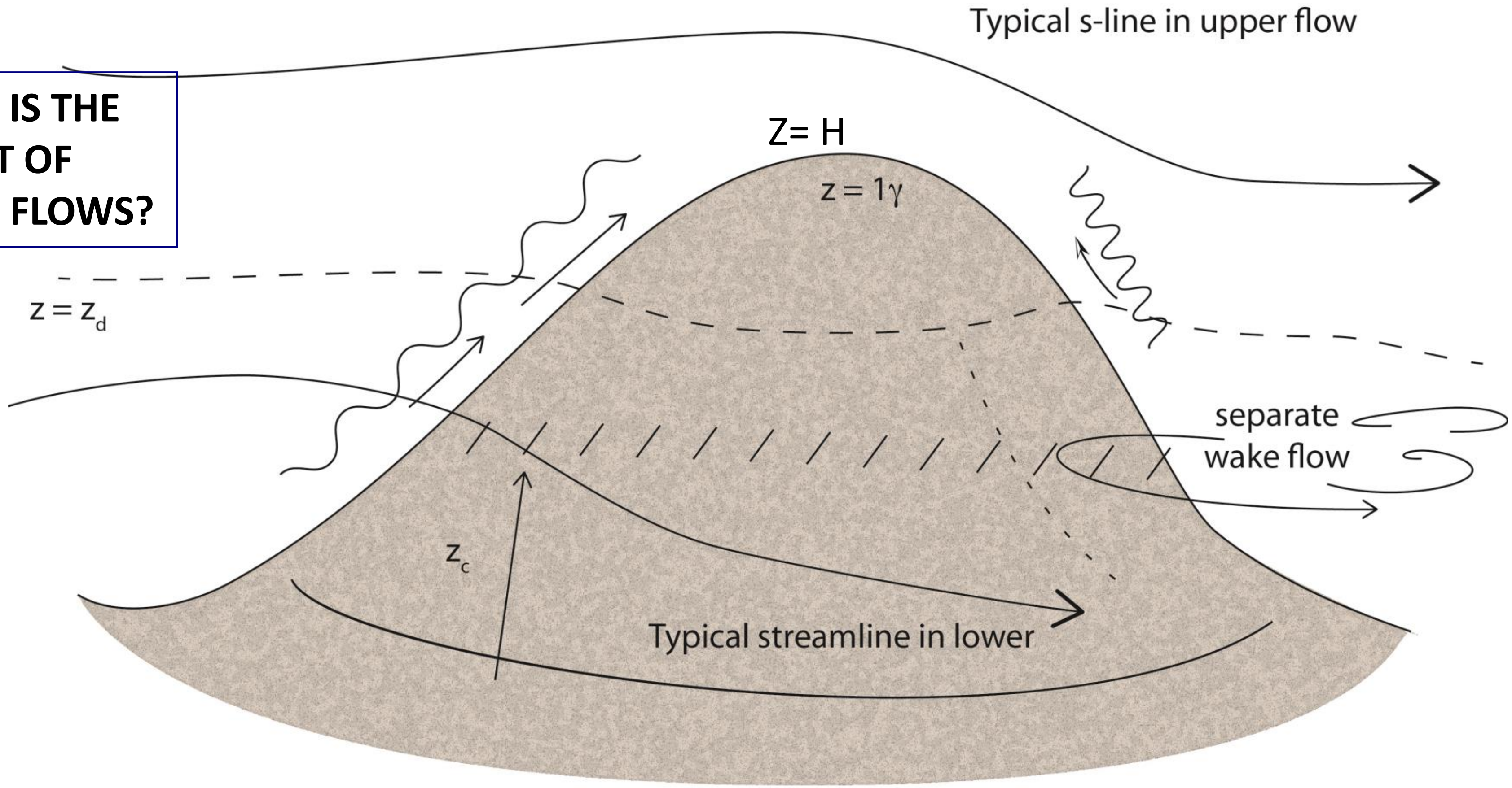
SBL-internal wave effect

- **Here Δu_p effect of inertia and pressure --> separation on upwind (SBL >NBL) and downwind (SBL >NBL) if $l_s \sim L_{MO}$) (eddy viscosity changed)**

- **But if Δu_b is significant → buoyancy driven flow in surface layer --> SBL --> greater upwind but less on downwind**

Low Froude number FH<1 –dividing streamline and separated wake flow

WHAT IS THE EFFECT OF SLOPE FLOWS?

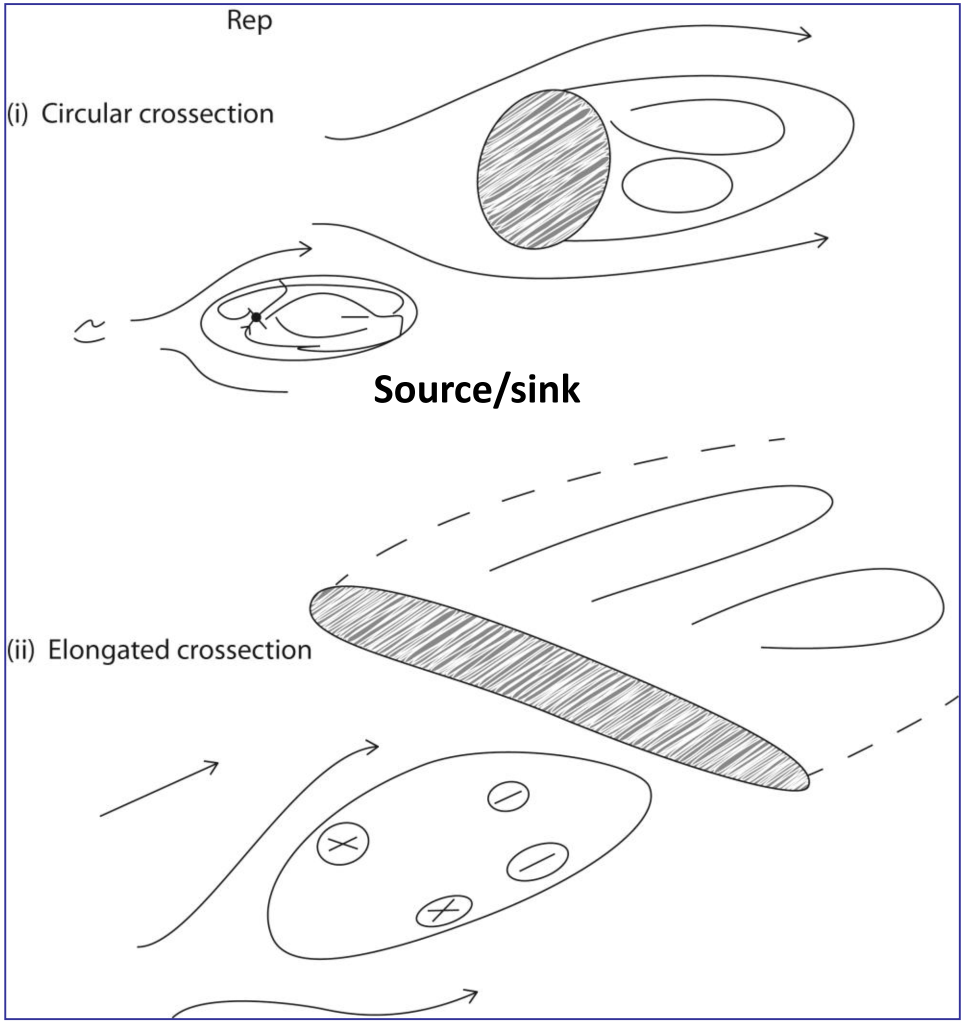


Hunt, Vilenski, Johnson (2006); matching separation to upper waves

Note $\mathbf{z_d = H(1\text{-}FH)}$.

Patterns and potential flow models of separated flow for low FH<1 -

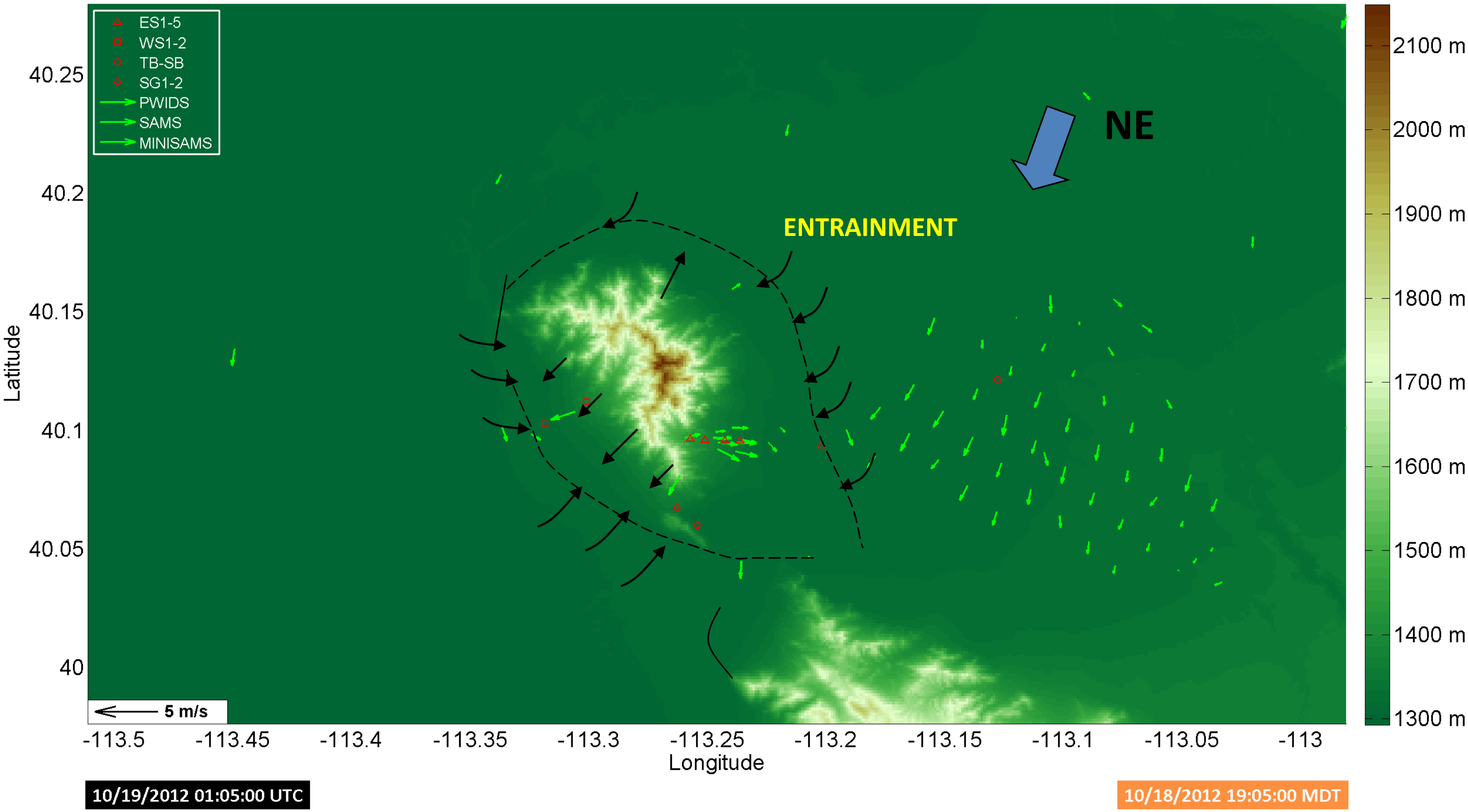
WITHOUT SLOPE FLOWS!



Method used in ADMS/Flowstar model of Carruthers et al.
www.cerc.co.uk

Double source-sink for elongated cross-sections (Parkinson-Jandali 1970

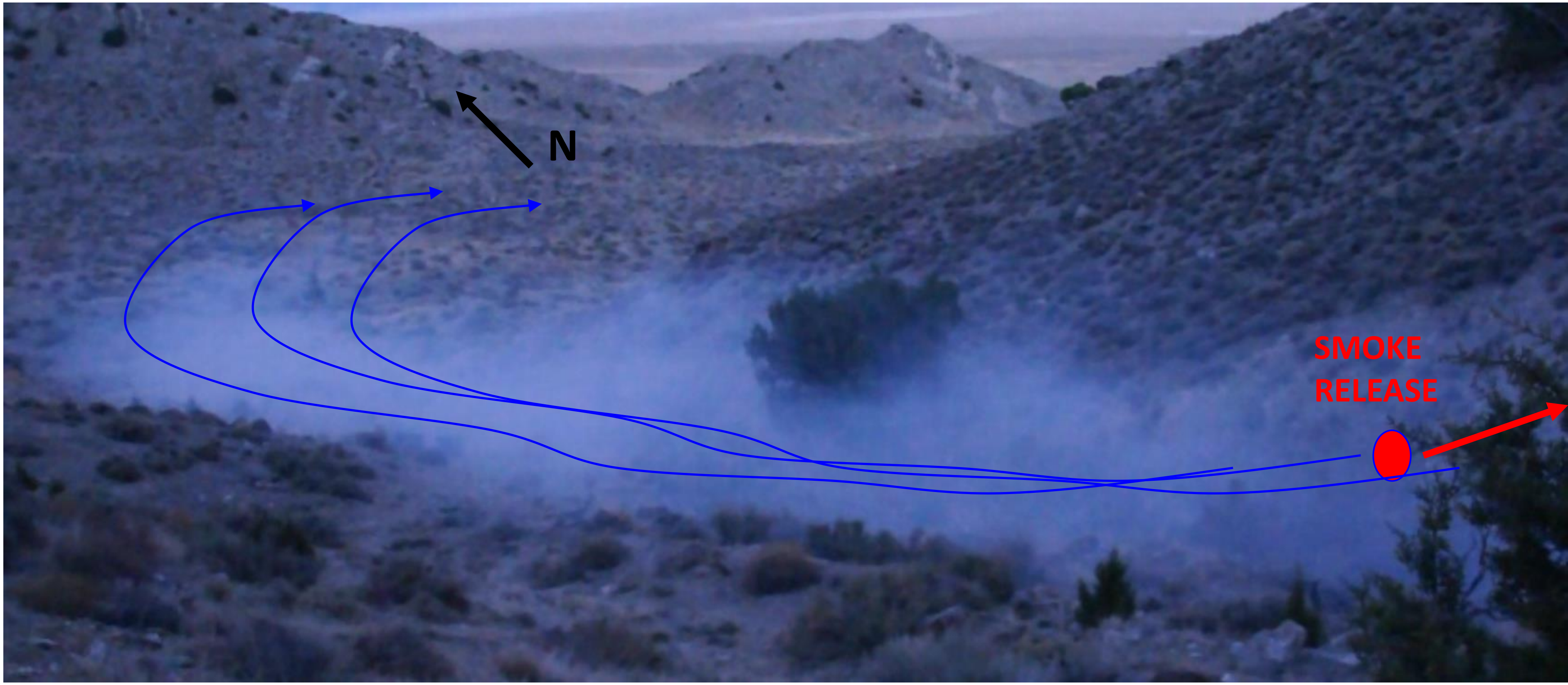
$H=860$ m; $L=12{,}000$ m; $U_0 \sim 2$m/s FH likely < 1
$U_b=0.5\ U_0$



FALL EXPERIMENT (18 Oct 2012)

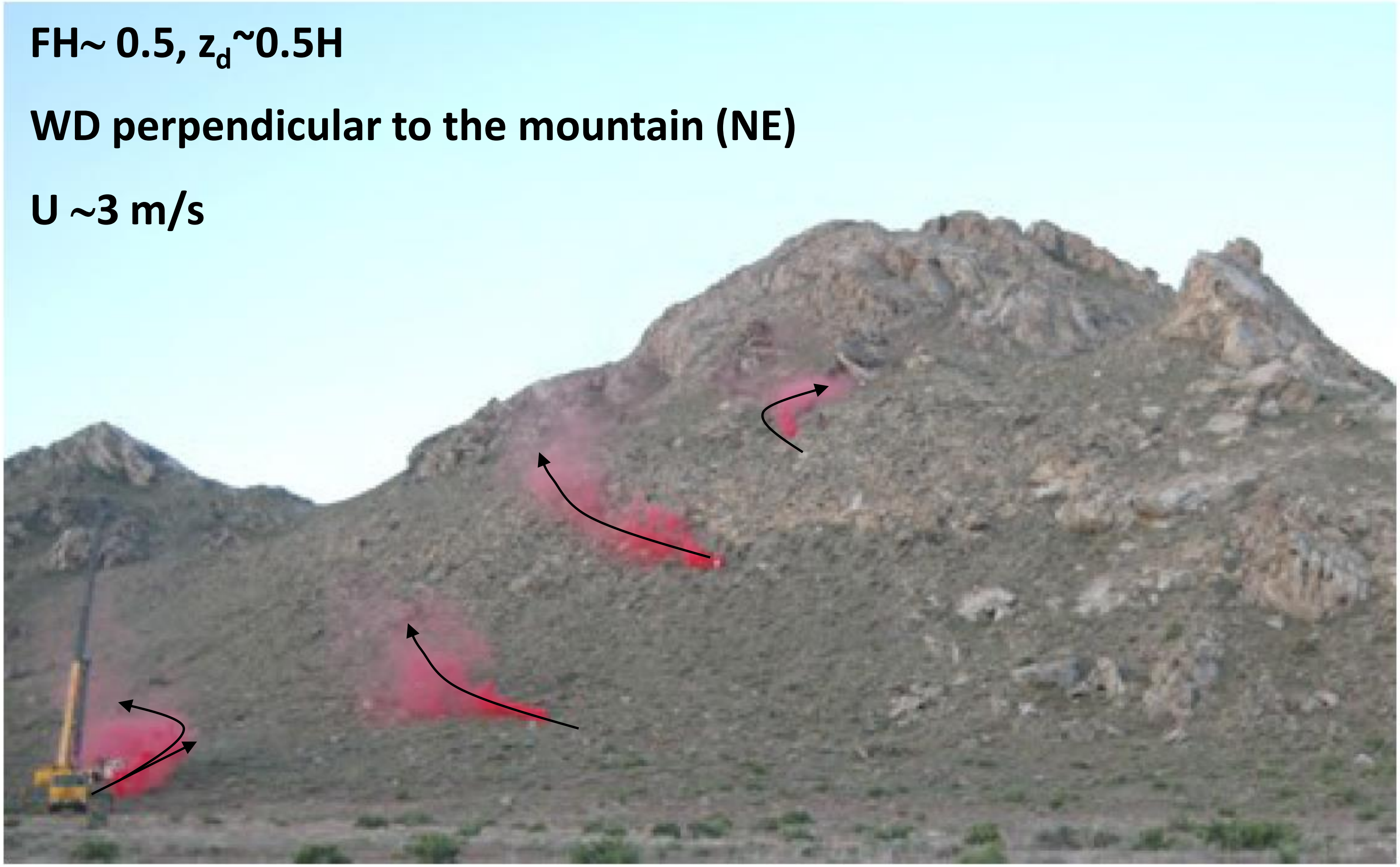
LOCAL TIME

I Experiment: Smoke release at East Slope – initiation of katabatic flow



SMOKE RELEASE CONSISTENT WITH SURFACE FLOW AROUND MOUNTAIN (SEPARATED SL)

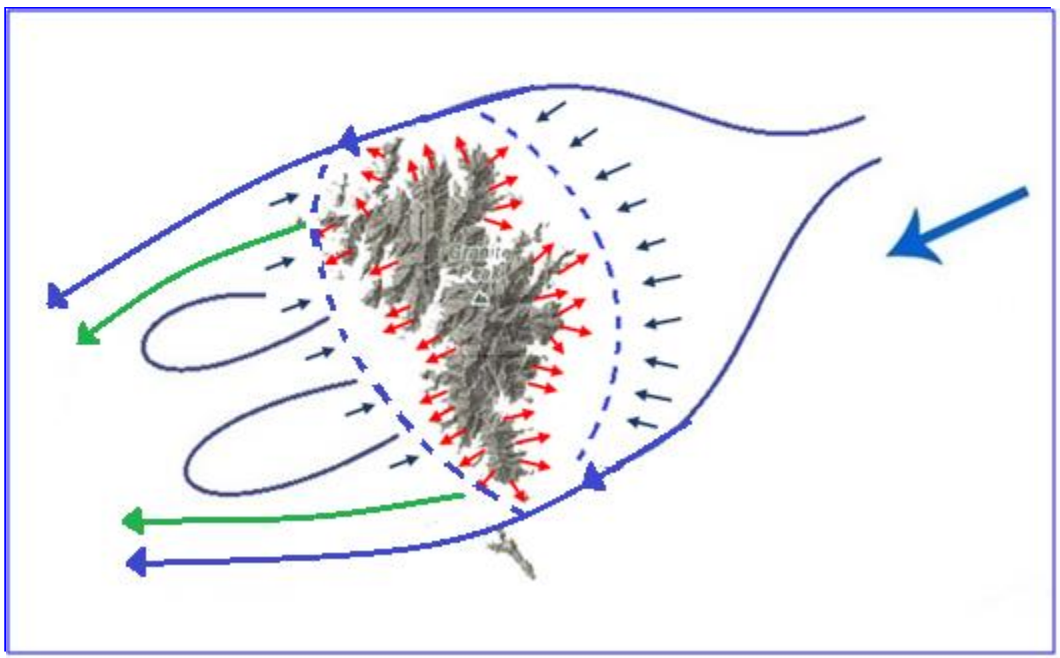
Smoke release NW of Granite - streamlines separation (early morning 6 am)



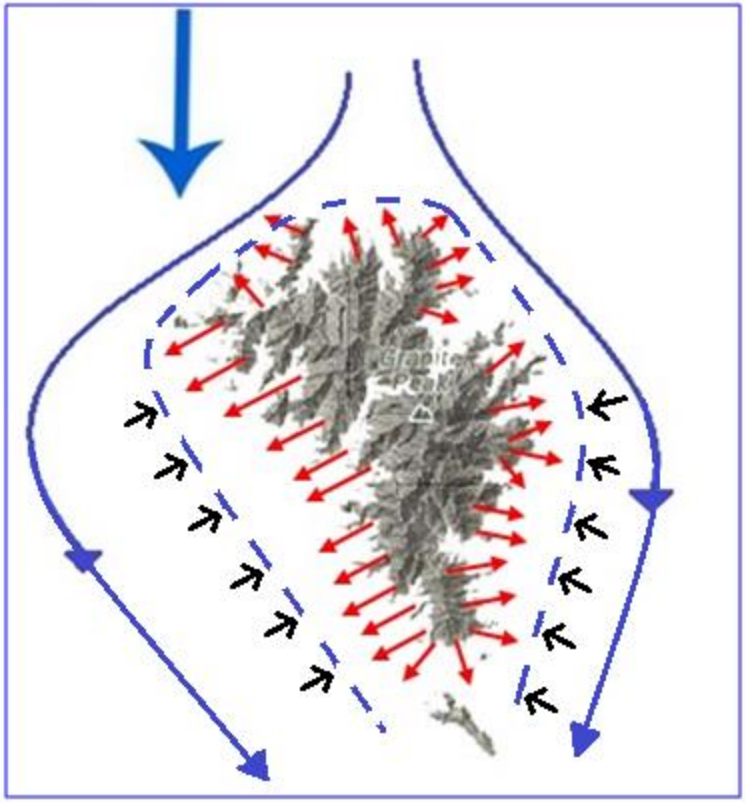
II Experiment: 30 May 2013

Patterns and potential flow models of separated flow for low FH<1 –with up/downslope [source model of separated/entrainment flow]

WD ~ NE

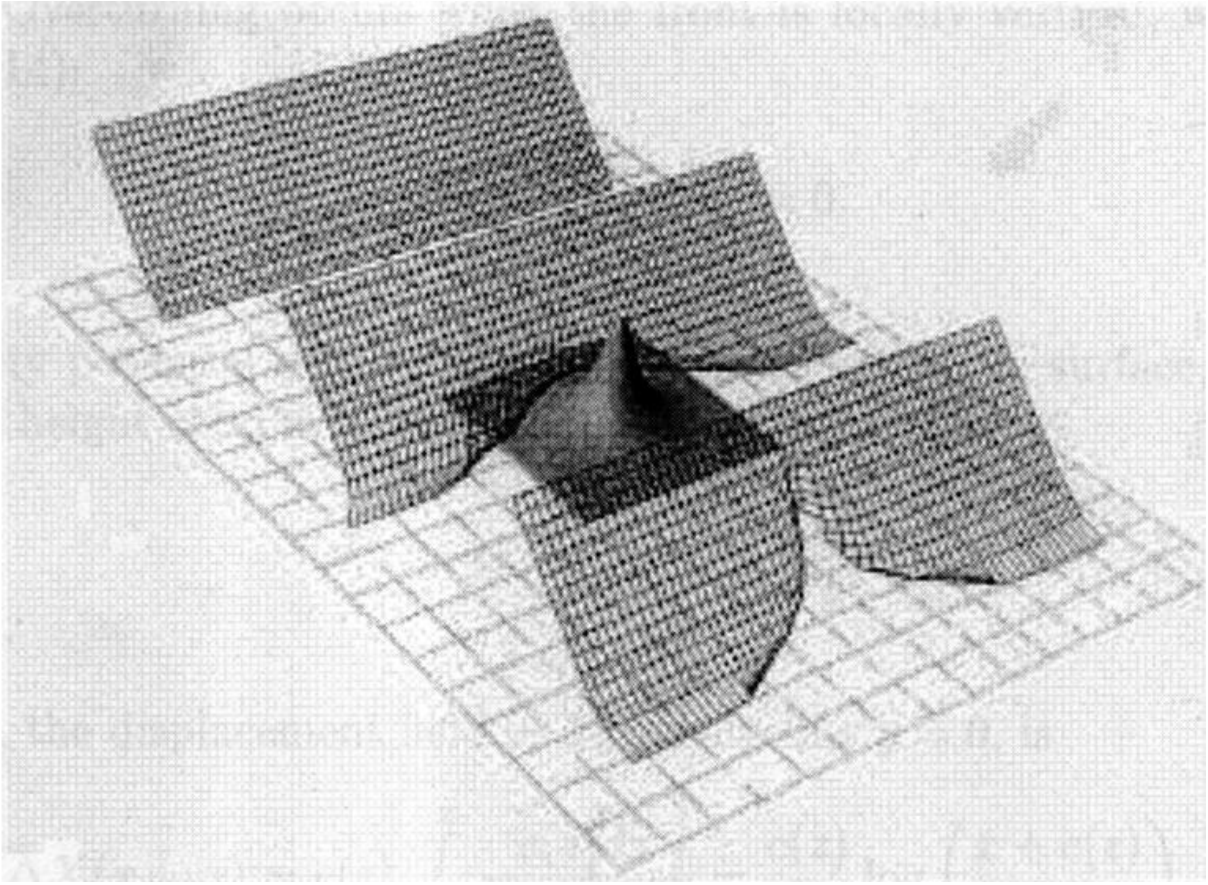


WD ~ N



Weak sloping front distorted while passing around/over isolated hill

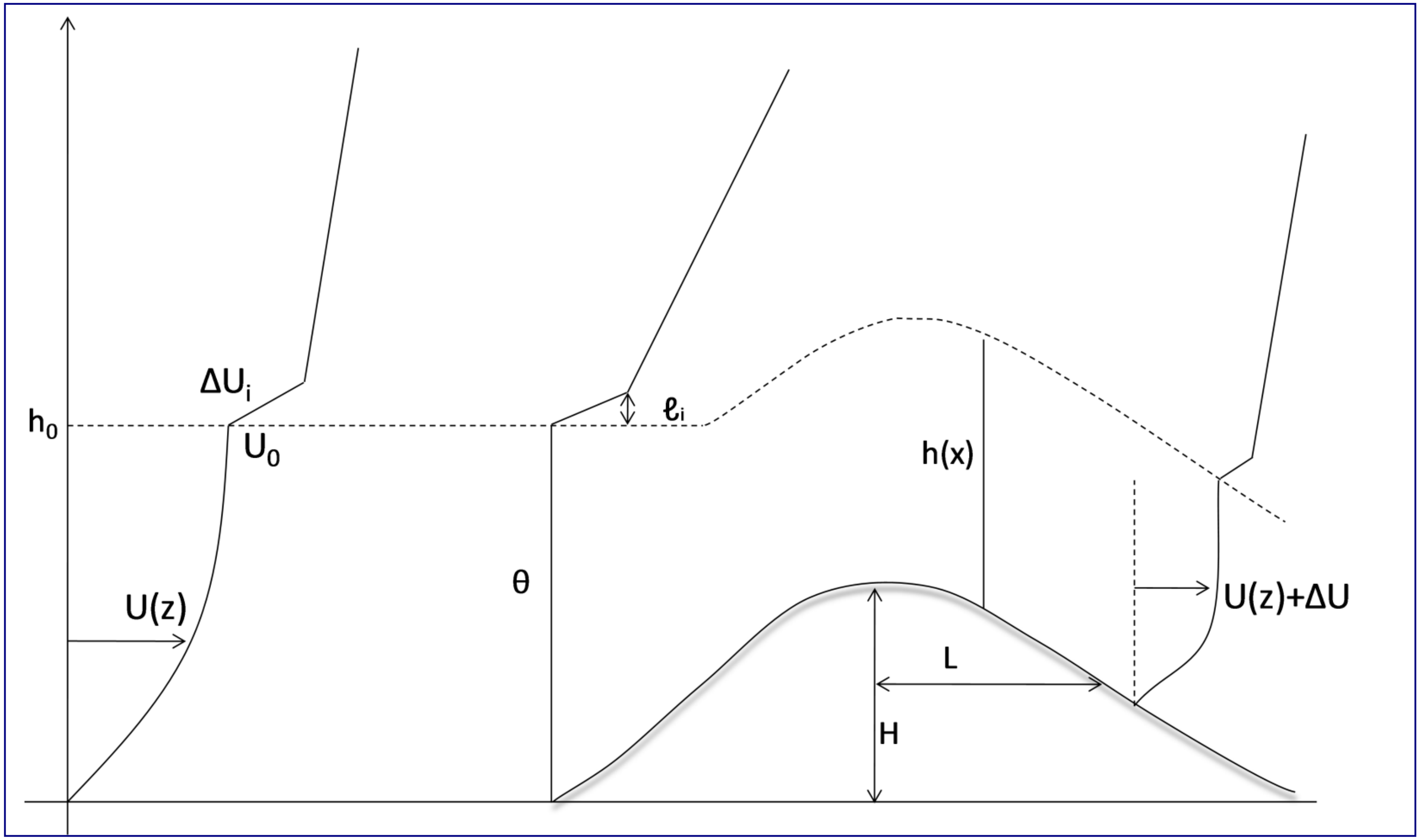
Greenslade, Hunt, Eames, et al. 2006



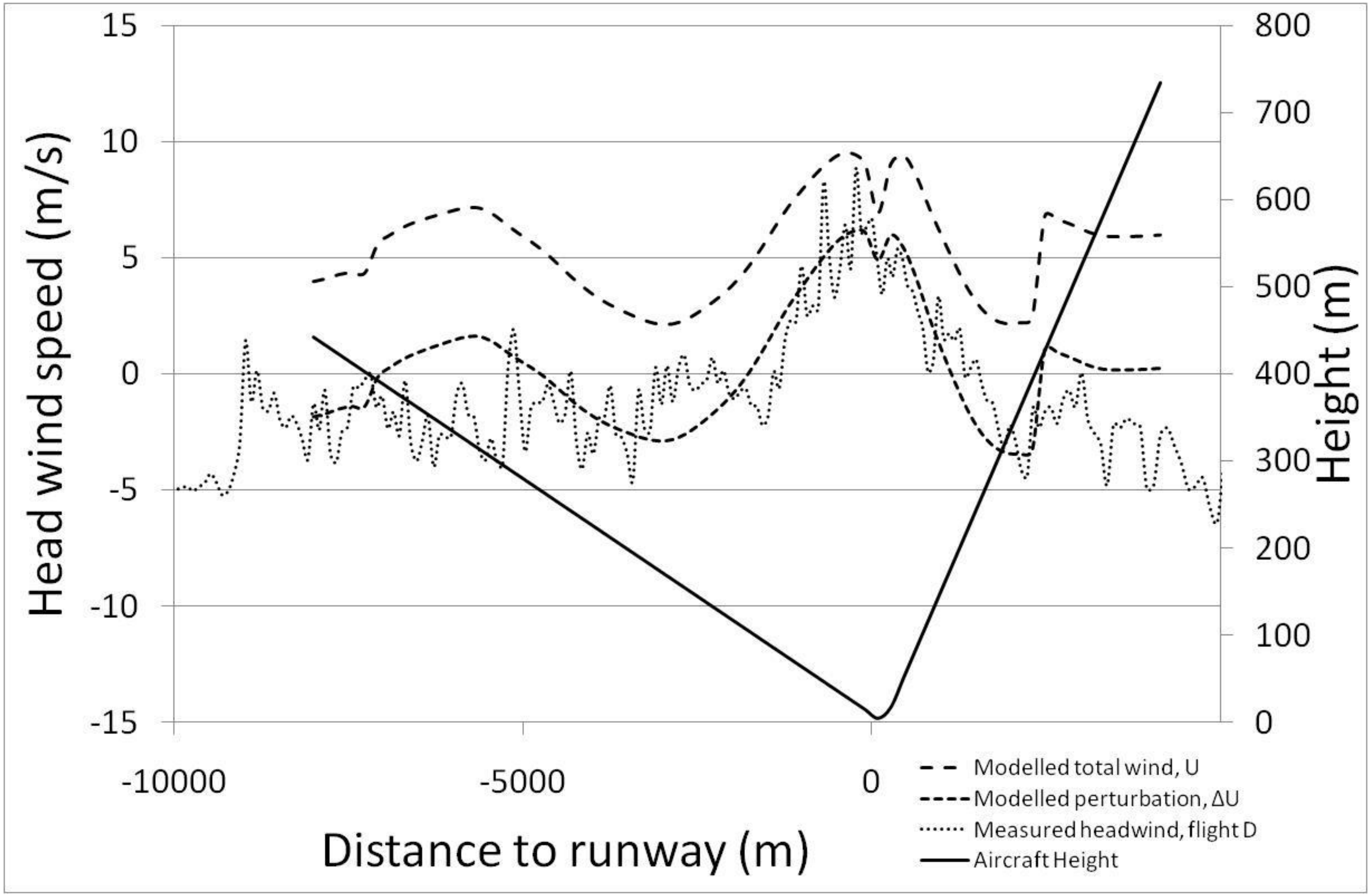
Less stability in mountain wake
--> mixing
&
precipitation

FH<<1 – quasi-horizontal flow. Upstream blocking shows how front is delayed around hill, becomes less stable – similar to synoptic fronts around mountain

Schematic of Inversion /shear layer flow over mountains: application of idealised (thin layer) perturbation modelling for 800 m terrain near Hong Kong International airport Carruthers et al 2013



Perturbation to head wind speed and total head wind compared to aircraft Measurement ϕ =140°, h_0=400m, ΔT=7.19°C



CONCLUSIONS

1. **Field experiments and mesoscale models show how overall flow pattern for isolated and groups of mountains are first of all affected by perturbation blocking, slope flows and dividing streamline structure.**

NEW FEATURES TO BE CONSIDERED

(i) changed near-surface stratification and bl profile; large perturbations even with low slopes (not in current models);

(ii) up/down buoyancy driven slope winds combine with inertial pressure perturbations and produce entrainment from external flow -> effective change of shape of mountains and regions of separated flows.

2. **But small effect of surface stratification and boundary layer when external flow is dominated by internal wave motion.**

3. **Conceptual/analytical modelling requires to:**

(i) include surface detailed modelling of change in surface stability as well as buoyancy driven flow;

(ii) correct for effective change in shape by displacement of bl and change of separated regions;

(iii) to represent source/sink of separated flows.

Acknowledgments

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