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

Applications
- 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 internal layers e.g. separation/inversion layers

Validation of theory for larger mountains:
MATERHORN Field Experiments (I: Sep-Oct 2012; II: May 2013)
Surface layer to mountain to valley scale $l_s \rightarrow L \rightarrow Lv$
Under conditions: $FH<1, FL << 1$
  - negligible / significant buoyancy driven slope flows
FB $>>1, FB <1, L \sim h$ --> Surface --> bl dynamics
High mountains; $H \sim h = bl$ thickness; significant buoyancy; $\Delta u_b \sim \Delta u_p$

E.g. Borneo ‘land beneath the wind’ – stagnant conditions in valleys below mountains.
Flow with/over low slopes

**strong cooling-> low, laminar-like turbulence**

Flow separates in cooling valleys

Stable profile -> lower surface velocity and \( \tau/(U_0)^2 \)

**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

- 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!

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

shows how heat flux varies over slopes

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$\Delta u_b \sim \int [g' \Delta \theta dx] / U_0$.

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Perturbation modelling to combine inertia/pressure and slope flows + their effect on external flow $\Delta u_{pb}$.
Separation driven by inertial/outer buoyancy pressure and surface shear stress on low slopes; also effect of slope flow

- Here $\Delta u_p$ 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 $\Delta u_b$ is significant \rightarrow buoyancy driven flow in surface layer --> SBL --> greater upwind but less on downwind
Low Froude number $FH < 1$ – dividing streamline and separated wake flow

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

Note $z_d = H(1-FH)$. 

WHAT IS THE EFFECT OF SLOPE FLOWS?
Patterns and potential flow models of separated flow for low FH<1 -

(i) Circular crosssection

(ii) Elongated crosssection

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

Double source-sink for elongated crosssections (Parkinson-Jandali 1970)

WITHOUT SLOPE FLOWS!
H=860 m; L=12,000 m; $U_0 \sim 2\text{ m/s}$ 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)

FH~ 0.5, zd~0.5H
WD perpendicular to the mountain (NE)
U ~3 m/s

Il 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

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

Less stability in mountain wake --> mixing & precipitation
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 \( \phi = 140°, h_0 = 400 \text{m}, \Delta T = 7.19°C \)
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.
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