Daytime development of the boundary layer over a plain and in a valley under fair weather conditions

A comparison by means of idealized numerical simulations

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*International Conference on Alpine Meteorology - Aviemore, UK, 26th May 2011*
Summary

- The volume-effect theory.
- Large-eddy simulations.
- Characterization of the valley boundary layer (VBL).
- Comparison of the VBL and CBL.
- A test of the volume-effect theory.
The volume-effect theory

- Is it true that thermal energy is distributed to a smaller volume in a valley?
Simulation domains

- **Two valleys** with different bottom width (0 and 5 km respectively) and equal depth (2000 m), with valley walls sloping at 30°.
- Equal heat input from the opposite slopes, variable in time, determined by a surface energy budget model, max. $\approx 400 \, \text{W m}^{-2}$.
- **Large-eddy simulation** (ARPS), $dx = dy = 50 \, \text{m}$, $20 \, \text{m} < dz < 70 \, \text{m}$. Averaging: in the along-valley direction, and in 10-min periods.
Plan view /1: narrow valley

Near-surface v (m s$^{-1}$), t = 18000 s
Plan view /2: wide valley

Near-surface v (m s\(^{-1}\)), t = 18000 s
Cross-section view
Valley boundary layer

- Heating in the valley atmosphere is initially more relevant at an altitude between 2000 and 3000 m (detrainment from the thermal plumes over mountain tops).
- At the same time, but at lower heights, mid-valley subsidence brings potentially warm air towards the valley bottom. Further below, turbulent convection occurs (Whiteman & McKee, 1982).
VBL vs. CBL: thermal structure evolution
VBL vs. CBL: thermal structure evolution /2

(profiles taken after an equal thermal energy input)
Some calculus…

\[
\frac{\partial \bar{\rho} \bar{\theta}}{\partial t} = - \frac{\partial \rho \bar{u}_i}{\partial x_i} - \frac{1}{c_p} \frac{\partial H_i}{\partial x_i} - \frac{1}{c_p} \bar{\theta} \frac{\partial Q_i}{\partial x_i}
\]

\[
\frac{\partial}{\partial t} \int_V \bar{\rho} \bar{\theta} dV = - \int_{\partial V} \bar{\rho} \bar{u}_i n_i d(\partial V) - \frac{1}{c_p} \int_{\partial V} H_i n_i d(\partial V) - \frac{1}{c_p} \int_V T \frac{\partial Q_i}{\partial x_i} dV
\]

Q negligible, \( \rho(t) = \text{const} \), heat flux only from the ground surface

\[
\int_V \bar{\theta}_{t_2} dV - \int_V \bar{\theta}_{t_1} dV = - \frac{1}{\rho c_p} \int_{t_1}^{t_2} \left( \int_{\partial V} H_i n_i d(\partial V) \right) dt
\]

\[
= \frac{1}{\rho c_p} \int_{t_1}^{t_2} \left( \int_{S_0} H_0 i n_i dA_0 \right) dt
\]

\[
= \frac{1}{S \Delta t} \int_{t_1}^{t_2} \left( \int_{S_0} H_0 i n_i dA_0 \right) dt \equiv \bar{H}_0
\]

\[
\frac{1}{V} \int_V \bar{\theta}_{t_2} dV = \Theta_{t_2}
\]

\[
\frac{1}{V} \int_V \bar{\theta}_{t_1} dV = \Theta_{t_1}
\]

\[
(\Theta_{t_2} - \Theta_{t_1}) = \frac{1}{(h - z)} \frac{\bar{H}_0 \Delta t}{\rho c_p}
\]
VBL vs. CBL: $\theta$ profiles

$\approx 2$ K

(profiles taken after an equal thermal energy input)
VBL vs. CBL: $\theta$ profiles /2

$\approx 2$ K
VBL vs. CBL: θ profiles /3

θ profiles

height (km)

θ (K)

≈ 2 K
• The depth of the fully developed BL ($h$) is different in the two valleys.
• The average height a.s.l. of the ground surface ($z$) is also different.
• The average depth ($h - z$) is comparable.
Bulk BL properties /2

<table>
<thead>
<tr>
<th>parameter</th>
<th>units</th>
<th>plain</th>
<th>narrow valley</th>
<th>wide valley</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t$</td>
<td>s</td>
<td>29400</td>
<td>25200</td>
<td>25200</td>
</tr>
<tr>
<td>$\int_0^{\Delta t} H_0 dt$</td>
<td>$10^6$ J m$^{-2}$</td>
<td>6.27</td>
<td>6.30</td>
<td>6.26</td>
</tr>
<tr>
<td>$h$</td>
<td>m</td>
<td>2700</td>
<td>3800</td>
<td>3300</td>
</tr>
<tr>
<td>$\bar{z}$</td>
<td>m</td>
<td>0</td>
<td>1000</td>
<td>580</td>
</tr>
<tr>
<td>$V = S(h - \bar{z})$</td>
<td>m$^3$</td>
<td>2700$S$</td>
<td>2800$S$</td>
<td>2720$S$</td>
</tr>
<tr>
<td>$\Theta_{t_2}$</td>
<td>K</td>
<td>306.0</td>
<td>309.1</td>
<td>307.8</td>
</tr>
<tr>
<td>$\Theta_{t_1}$</td>
<td>K</td>
<td>304.0</td>
<td>307.2</td>
<td>305.8</td>
</tr>
<tr>
<td>$\Theta_{t_2} - \Theta_{t_1}$</td>
<td>K</td>
<td>2.0</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>$\theta_{t_2}^{sfc} - \theta_{t_1}^{sfc}$</td>
<td>K</td>
<td>5.6</td>
<td>8.3</td>
<td>6.9</td>
</tr>
<tr>
<td>$\bar{H}_0$</td>
<td>W m$^{-2}$</td>
<td>214</td>
<td>246</td>
<td>251</td>
</tr>
</tbody>
</table>
The atmospheric volume subject to thermal perturbations is not appreciably different in the valley and plain environments. Furthermore, the mean potential temperature increment is also comparable in the three cases. The surface potential temperature increment is anyway larger in valleys.

No “volume effect” seems to occur. Rather than volume, the key factor seems to be the vertical extent of thermally driven flow: thermal circulations are considerably deeper in valleys than above the plain. Hence, they entrain potentially warmer air from higher levels into the (well mixed) boundary layer.

Upslope flow transports heat beyond the mountain top level. As a consequence, the mean temperature increase within the valley is (much) smaller than what would be expected based on the volume effect argument (see poster by J. Schmidli).
Limitations

• This idealization is most representative of the dynamics of real valleys during the morning phase, when slope winds are the dominant flow pattern.

• Several potentially important factors are neglected, including:
  – Along-valley (cool) advection related to the valley breeze.
  – Synoptic flow aloft: transversal heat advection, excitement of internal gravity waves.
  – Radiative flux convergence into the valley atmosphere.
  – Stratification intensity changing along the vertical (Steinacker, 1984).

• However, the simulation framework reproduces exactly the conceptual framework of the volume-effect theory. Indeed, it shows one of its limits and provides an alternative interpretation.
Conclusions

• Under equal thermal forcing, near-surface air does become warmer within a valley than above a plain.

• This does NOT happen because thermal energy is confined to a smaller volume in the valley! In fact, under equal forcing the atmospheric volume subject to thermal perturbations is roughly the same in the VBL and CBL.

• Rather, the larger temperature increase at the surface happens because the deeper mixing above valleys favours the entrainment of potentially warmer air from higher levels of the free atmosphere into the VBL.
Thank you for your attention


Serafin, S., and D. Zardi, 2011: Daytime development of the boundary layer over a plain and in a valley under fair weather conditions: A comparison by means of idealized numerical simulations. 
*J. Atmos. Sci.*, in press.
Circulation along the cross-valley axis /1
Circulation along the cross-valley axis /2
Circulation along the cross-valley axis /3
Circulation along the cross-valley axis /4

F. Defant, 1951
Lagrangian analysis /1
Lagrangian analysis

Trajectory 2, y (km) vs. z (km)

Trajectory 2, y (km) vs. x (km)

Trajectory 2, y and z (km) vs. t (hr)

Skew T–log P diagram
Lagrangian analysis /3
Lagrangian analysis /4

- Air parcels are subject to heat input only during their along-slope ascent. Potential temperature rise: \( \approx 7 \text{ K in 30 minutes}! \)
- Once the mountain top is reached, parcels ascend vertically and their motion immediately becomes adiabatic.
- After overshooting and mixing with potentially warmer air aloft, air parcels reach their LNB.
- Other phases of the parcel motion are adiabatic.
Valley heating process

- Cross valley flow dominated by upslope flows and compensating air motions (lateral detrainment at mountain top level, mid-valley subsidence below).
- Subsidence in the valley core: *top-down warming* mechanism. Turbulent convection at the valley floor: *bottom-up warming*.

\[
\frac{\partial \bar{\theta}}{\partial t} = -\bar{u}_j \frac{\partial \bar{\theta}}{\partial x_j} - \frac{\partial \bar{w}' \bar{\theta}}{\partial x_j} - \left( \frac{1}{\rho c_p} \frac{T}{\partial Q_j} \right)
\]

- Advective top-down warming (-w∂θ/∂z) and convective bottom-up warming (-∂<w'θ'>/∂z) antagonize each other.
Valley heating process /2

narrow valley

wide valley
The valley boundary layer (VBL) includes:
- a CBL/ML generated by surface heating.
- elevated turbulent layers, where the atmosphere is warmed and becomes weakly turbulent due to advection of heat and TKE.
- a non-turbulent stable region where air subsides towards the valley floor to compensate upward motion along the slopes.

The depth of the VBL appears to be related to the level of neutral buoyancy of air parcels in the thermal plumes developing on mountain tops.
Valley boundary layer /2
Valley boundary layer /3

narrow valley

wide valley
• In a first phase the heating rate (evaluated from the slope of isentropes, $\partial \theta/\partial t$) is approximately equal at all heights below crest height: *subsidence in the valley core (S)*.

• Later, temperature increases at a lower rate, and isentropes ($\partial \theta/\partial t$) are approximately vertical near the surface: *growth of a mixed layer (ML)*.
VBL vs. CBL: ΔT and Δp

- $T_{\text{valley}} - T_{\text{plain}}$ vs. $z$, narrow valley
- $T_{\text{valley}} - T_{\text{plain}}$ vs. $z$, wide valley
- $p_{\text{valley}} - p_{\text{plain}}$ vs. $z$, narrow valley
- $p_{\text{valley}} - p_{\text{plain}}$ vs. $z$, wide valley
A three-dimensional case
Potential temperature profiles (6 h)
Valley-plain temperature differences (6 h)
Valley-plain pressure differences (6 h)
Up-valley wind speed (6 h)