The dynamics of heat lows over flat terrain

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Previous Investigations

Modelling studies of heat lows ...
Definition and Main Findings
(Rácz and Smith, 1999, henceforth RS99)

**Heat Low (HL)**

- HL has a minimum surface pressure in the late afternoon or early evening, while relative vorticity is strongest in early morning. So, HL is not approximately in quasi-geostrophic balance.
- The low-level convergence is associated with the sea breeze and nocturnal low-level jet.
- HL is characterized by an anticyclonic PV anomaly relative to its environment on account of greatly reduced static stability in the convectively well-mixed boundary layer.
- The horizontal components of relative vorticity and horizontal potential temperature gradient make a non-negligible contribution to the PV in certain flow regions.

**Heat Trough**
Conclusions

1. Implementation of corrected and extended version of radiation scheme leads to a more realistic depth of the daytime mixed layer.

2. The upper-level anticyclone extends through much of the troposphere, but has a maximum strength in the lower troposphere.

3. The anticyclone develops steadily over a period of a few days and is associated with the return branch of sea-breeze circulation in lower troposphere and slow diurnal-mean outflow in the middle and upper troposphere.

4. The upper anticyclone is largely in gradient wind balance.

5. The gravity wave has a significant effect on the radial and vertical components of motion field at any one time.

6. In a mean sense we can distinguish between distinct patterns of the tangential flow component
   • between midnight and noon, when the low-level cyclone is strongest, and
   • between noon and midnight when it is much weaker.
The Basic Model Features for the Heat Low

Modified version of hydrostatic primitive-equation model described by Rácz and Smith, 1999.
Main changes:

- implementation of radiation scheme;
- relaxation scheme for the horizontal BC;
- 10 additional upper model levels with increased horizontal diffusion.

The Basic Model Features for the Heat Low

Northern hemisphere

199 points
Radiation Scheme (Raymond (1994))

Equivalent potential temperature tendency

\[
\frac{d\theta_e}{dt} = L + \dot{R}
\]  \hspace{1cm} (1)

\(\theta_e\) – equivalent potential temperature,
\(L\) – relaxation to a background state of the atmosphere,
\(\dot{R}\) – radiative heating rate.

\[
\dot{R} = \frac{\theta_e}{Qc_pT} (Q_{\text{sol}} + Q_{\text{therm}})
\]  \hspace{1cm} (2)

\(Q_{\text{sol}}, Q_{\text{therm}}\) – contributions due to the absorption of solar and long-wave radiation, respectively.

\[
Q_{\text{sol}} = \epsilon \cos \alpha Q_{\text{max}} \exp \left\{ -\left( \frac{z - z_{\text{max}}}{z_w} \right)^2 \right\}
\]  \hspace{1cm} (3)

\(\epsilon\) – measure of fraction of clear sky, \((\epsilon = 1)\)
\(\cos(\alpha)\) – cosine of the zenith angle of the sun,
\(Q_{\text{max}}\) – maximum heating rate,
\(z_{\text{max}}\) – height (fixed) of maximum heating,
\(z_w\) – fixed height.

\[
\frac{d\theta}{dt} = \dot{R} = \frac{\theta}{Qc_pT} Q_{\text{therm}} + \frac{\theta}{T} Q_{\text{sol}}
\]  \hspace{1cm} (4)

\[
Q_{\text{sol}} = \epsilon \cos \alpha \left[ Q_{\text{max}}^t \exp \left\{ -\left( \frac{z - z_{\text{max}}^t}{z_{w}^t} \right)^2 \right\} + Q_{\text{max}}^s \exp \left\{ -\left( \frac{z - z_{\text{max}}^s}{z_{w}^s} \right)^2 \right\} \right]
\]  \hspace{1cm} (5)

t and \(s\) indicate the values corresponding to the troposphere or stratosphere, respectively.

Parameters used in equation (5)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_{\text{max}}^t)</td>
<td>(3.5 \times 10^{-5}) K s(^{-1}) \approx 3 K day(^{-1})</td>
</tr>
<tr>
<td>(z_{\text{max}}^t)</td>
<td>(3 \times 10^3) m</td>
</tr>
<tr>
<td>(z_{w}^t)</td>
<td>(4 \times 10^3) m</td>
</tr>
<tr>
<td>(Q_{\text{max}}^s)</td>
<td>(5 \times 10^{-4}) K s(^{-1}) \approx 43 K day(^{-1})</td>
</tr>
<tr>
<td>(z_{\text{max}}^s)</td>
<td>(5 \times 10^4) m</td>
</tr>
<tr>
<td>(z_{w}^s)</td>
<td>(1.8 \times 10^4) m</td>
</tr>
</tbody>
</table>
Radiation Scheme

In a gray-atmosphere model for the thermal radiation

\[ Q_{\text{therm}} = -\frac{d}{dz} \left( I^+ - I^- \right) \tag{6} \]

\( I^+, I^- \) – upward and downward radiances.

With the Schwarzschild-Schuster approximation

\[ \frac{dI^+}{dz} = \rho \mu (\sigma_{sb} T^4 - I^+) \tag{7} \]

\[ \frac{dI^-}{dz} = -\rho \mu (\sigma_{sb} T^4 - I^-) \tag{8} \]

\( \mu \) – effective absorptivity of the atmosphere in the infrared,
\( \sigma_{sb} \) - the Stefan-Boltzmann constant.

\[ \mu(z) = \mu_0 + \mu_1 \exp(-z/H) \tag{9} \]

\( H = 7000 \text{ m}, \)
\( \mu_0 = 4.0 \times 10^{-4} \text{ m}^2/\text{kg}, \)
\( \mu_1 = 3.0 \times 10^{-4} \text{ m}^2/\text{kg}. \)

\[ Q_{\text{therm}} = -\rho \mu \left( 2\sigma_{sb} T^4 - I^+ - I^- \right) \tag{10} \]

At the top of domain:

a) assumed radiative equilibrium
\( I^+ = 0 \) replaced by \( dI^+/dt = 0, \)
b) \( T = 230 \text{ K} \) at \( P = 0.7 \text{ hPa}. \)
Impact of Radiation Scheme

Without radiation scheme

With new radiation scheme

\( \theta \), Potential Temperature (2 K)

\( \mathbf{V} \), Tangential Wind Component (2 m/s)

17.00 h

05.00 h

Solid lines – Zn, dashed lines – Az circulations.
Conclusions

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Impact of Radiation Scheme

17.00 h

Radial wind speed, contour 1 m/s

Vertical velocity, contour 2 cm/s

05.00 h

Solid lines – outward, dashed lines – inward flow.

Solid lines – upward, dashed lines – downward flow.
Impact of Radiation Scheme

Evolution in time

Radial wind speed, contour 1 m/s

Difference of potential temperature, contour 1.5 K

Solid lines – offshore,
dashed lines – onshore flow.

$(\theta_{\text{inland}} - \theta_{\text{offshore}})$
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Balanced Diagnostics

Vertical cross-sections of unbalanced pressure gradient force per unit mass, contour $5 \times 10^{-5}$ m/s$^2$

Solid lines – outward-, dashed lines – inward- pressure gradient force.
Spin-up

First 6 days
Spin-up

Vertical cross-sections of the radial (upper panels) and tangential (lower panels) wind components during first 3 days, contour interval 2 m/s

Inward
Outward

Az
Zn

18 h
24 h
42 h
48 h
66 h
72 h

U
V
Absolute Angular Momentum Budget

\[ M = rv + \frac{1}{2}fr^2 \]  \hspace{1cm} (11)

\[ \frac{\partial M}{\partial t} + u \frac{\partial M}{\partial r} + w \frac{\partial M}{\partial z} = F \]  \hspace{1cm} (12)

\[ M - \text{absolute angular momentum}, \]
\[ r - \text{radius}, \]
\[ v - \text{tangential wind speed}, \]
\[ f - \text{Coriolis parameter}. \]

\[ F - \text{frictional torque}. \]

Solid lines – gain, dashed lines – loss of absolute angular momentum.
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Figure 13: Hovmöller diagrams of (a) radial velocity, and (b) vertical velocity at a height of 8 km during the first six days of integration. The contour interval in (a) is 0.5 m s$^{-1}$, with solid lines indicating outward and dashed lines inward flow; the contour interval in (b) is 1 m s$^{-1}$, with solid lines indicating upward and dashed lines downward flow. The thick vertical line shows the position of the coast, with land to the left and sea to the right. This figure is available in colour online at www.interscience.wiley.com/journal/qj
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Impact of Radiation Scheme

6-hourly mean of tangential wind component, contour 2 m/s

Solid lines – Zn, dashed lines – Az circulation.
The diurnal variation (mature stage – day 11) of
the strength of the heat low ($v_{max}, p_{min}$),
the strength of the upper-level anticyclone ($v_{min}$),
the strength of the maximum inflow ($u_{min}$),
the strength of the maximum outflow ($u_{max}$),
surface pressure on the domain boundary ($p_R$).

$4 \Rightarrow R = 400 \text{ km} // 8 \Rightarrow R = 800 \text{ km} // 12 \Rightarrow R = 1200 \text{ km}$
Thanks for your patience and attention!