A new way to compute the energy budget in GCMs and NWP models with the use of the enthalpy flux: the EBEX-2000 campaign.

by Pascal Marquet

Météo-France. CNRM/GMAP. Toulouse. France. *E-mail: pascal.marquet@meteo.fr*

1) Motivations - Introduction.

The surface energy budget is computed in GCM and NWP models by making the sum of net radiation (R_n), ground (G), sensible (H) and latent heat ($L\,.\,E$) fluxes, where E is the flux of evaporation ($\rho\,\overline{w'q'_v}$) and $L = L_v$ or L_s are the latent heat of vaporization or sublimation, depending on $T < T_0$ or $T > T_0 = 273.15$ K.

However, it is shown in Montgomery (1948), Businger (1982) and Marquet (2015b) that the flux of energy is equal to the flux of enthalpy $\rho\,\overline{w'h'}$, which is the sum of $c_p\,\overline{w'T'}$ and $L_h\,\overline{w'q'_v}$ (plus other terms if liquid water or ice exist, which are not studied here). If the first term represents the sensible flux, with c_p equal to the moist-air specific heat (at constant pressure), the difference in enthalpy of dry air and water vapour $L_h = h_v - h_d$ is different from both L_v and L_s. This result prevents $L_h\,\overline{w'q'_v}$ to represent the usual latent heat flux considered in GCM and NWP models.

The third-law definitions of the specific enthalpy h and L_h (Marquet 2015a,b) were used in Marquet *et al.* (2018) to study the energy balance closure problem (Foken, 2008) for the Météopole-Flux (MF) dataset. However, the lack of evaluation of G prevented this MF closure to be accurate with either L_v or L_h.

In the present study, the EBEX-2000 dataset (Oncley *et al.*, 2007) is used to study more realistic and relevant energy balance closure.

2) The present EBEX-2000 budget.

All terms of the energy budget are plotted in Fig.1 for the EBEX-2000 dataset. They are computed for an average over the 41 days and the 9 stations of the campaign. The fluxes are measures at 4.7 m above the ground, which is far above the height of about 1 m for the canopy of the cotton field, which is uniform over the 300 × 1200 m^2 area where the 9 measurements sites were placed. This leads to very good conditions for studying the energy balance closure problem.

The residual $Res = R_n - G - H - L_v.E$ is larger than 60 W/m^2 to 70 W/m^2 for daytime conditions, with a daily mean value of +21.3 W/m^2. These large values are typical of observed imbalance of energy closure, although all the "major" correction terms are taken into account (water on sonic anenometer ; Webb and Oxygen correction on hygrometer ; spatial separation of hygrometer and anenometer ; storage of energy by soil, vegetation and air added in G).

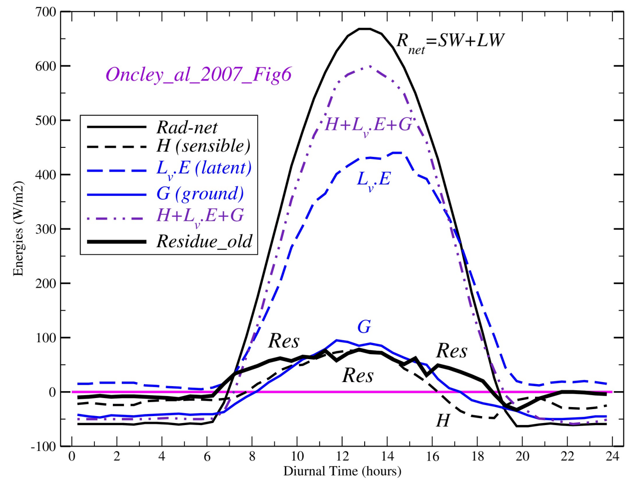

Figure 1: *The EBEX-2000 budget with the latent heat $L_v.E$.*

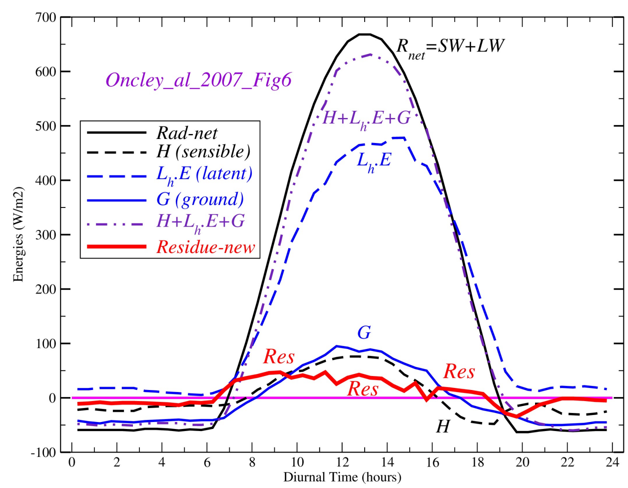

Figure 2: *The EBEX-2000 budget with the latent heat $L_h.E$.*

There is a clear diurnal cycle for all terms. This means that a possible source of imbalance (Res) could be due to any of the energy fluxes R_n, $L_v.E$, H or G. Crude evaluations (Marquet 2015b, *et al.* 2018) show that $L_h(T)$ is about +8 % larger than $L_v(T)$ for $T \approx 300$ K, where the latent heats are computed as

$$L_v(T) \approx 2501 + (c_{pv} - c_l)\,(T - T_0)\,, \quad \text{(in kJ/kg)}$$
$$L_h(T) \approx 2603 + (c_{pv} - c_{pd})\,(T - T_0)\,, \quad \text{(in kJ/kg)}$$

where $c_{pv} - c_l \approx -2.37$ kJ/kg, $c_{pv} - c_{pd} \approx +0.84$ kJ/kg, and $L_h(T_0) = 2603$ kJ/kg is given by applying a third-law hypothesis at 0 K for solid states of all species of the moist atmosphere (N_2, O_2, Ar, CO_2, H_2O).

If $L_v.E \approx 400$ W/m^2 is replaced by $L_h.E$, an increase of the turbulent fluxes by +8 % corresponds to

+32 W/m^2 at midday). This is about half of Res and it is thus relevant to test if the use of the flux $L_h.E$ may lead to more relevant energy closure.

3) The new EBEX-2000 budget.

The new budget of energy computed with $L_h(T) = h_v(T) - h_d(T)$ is plotted in Fig.2. Comparisons of the residues are facilitated in the zoomed Fig.3. The new residue (in red) is much smaller than with $L_v(T) = h_v(T) - h_l(T)$. The diurnal cycle is removed, with a decrease from 9 h to 18 h from +40 to +10 W/m^2.

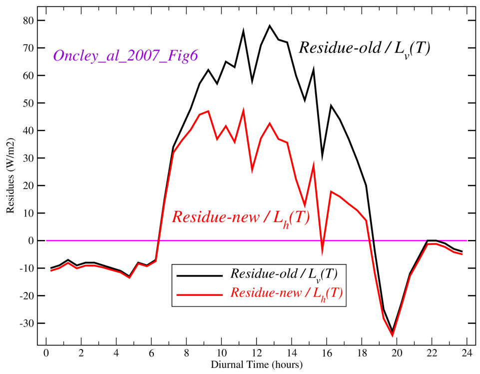

Figure 3: *The residuals with major correction terms computed with the latent heat fluxes $L_v.E$ or $L_h.E$.*

The impact of $L_h(T)$ on Res reaches −39 W/m^2 at 15 h. The new (41 days and 9 sites) daily average of the residue is close to +8.7 W/m^2 and is reduced by 12.6 W/m^2, or 59 %. The imbalance in budget energy is thus largely reduced if the flux of enthalpy is computed with the sum $\rho \, c_p \, \overline{w'T'} + \rho \, L_h \, \overline{w'q'_v}$.

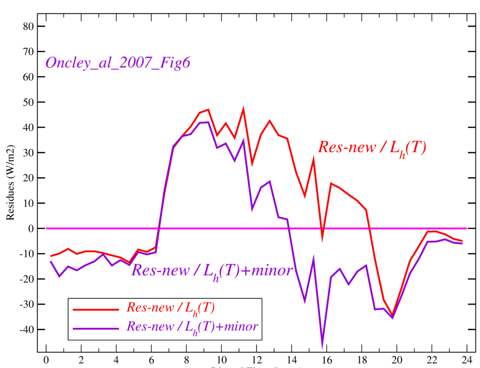

Figure 4: *The new residuals computed with L_h and with both the major and the minor correction terms.*

The residues shown in Fig.4 are computed by adding the "minor" corrections due to vertical divergence (departure from "constant fluxes" hypothesis), horizontal divergence (advection) and photosynthesis (by plants).

The daily averages for the 41 days and 9 sites mean values (with "major+minor" corrections) are +9.1 W/m^2 with $L_v(T)$ and −3.5 W/m^2 with $L_h(T)$. The imbalance in budget energy computed with $L_h(T)$ and the new flux of enthalpy is thus close to equilibrium and becomes negative. Moreover, the residue becomes smaller than ±40 W/m^2, with positive value in the morning and negative values in the evening. These new patterns look like true residual errors.

4) Conclusions.

It is shown that the budget of energy of EBEX-2000 can be nearly balanced in (time and sites) average if the sum of "sensible" and "latent" heats are replaced by the flux of enthalpy $\rho \, \overline{w'h'} = \rho \, c_p \, \overline{w'T'} + \rho \, L_h \, \overline{w'q'_v}$.

Differently, the equations for temperature dT/dt at the surface and in the atmosphere must still involve the usual definition of "sensible" and "latent" heat fluxes $\rho \, c_p \, \overline{w'T'} + \rho \, L_v \, \overline{w'q'_v}$ (or $\rho \, L_s \, \overline{w'q'_v}$ over icy surface).

This complex situation can be understood because we use both of the two equivalent equations:

$$\frac{dh}{dt} = A = (\ldots) - \frac{1}{\rho} \, \vec{\nabla}. \left(h_k \, \vec{J}_k \right) \quad \text{and}$$

$$\frac{d(c_p T + L_v^0 \, q_v)}{dt} = B = (\ldots) - \frac{1}{\rho} \, \vec{\nabla}. \left(L_v^0 \, \vec{J}_v + c_{pk} \, T \, \vec{J}_k \right),$$

where $L_v^0 = L_v(0\,\mathrm{K})$, $\vec{J}_k$ are the diffusion fluxes and the implicit sums $h_k \, \vec{J}_k$ and $c_{pk} \, \vec{J}_k$ are for dry air and water vapour (this note is for clear air with $q_l = q_i = 0$).

These equations are fully equivalent, but $A \neq B$ because the left and right hand sides are not the same due to $h \neq c_p T + L_v^0 \, q_v$. Therefore, it is not possible to close at the same time the budget for the energy ($A = 0$ with the use of L_h) and for the Moist Static Energy $c_p T + L_v^0 \, q_v$ ($B = 0$ with the use of L_v). The way the budget of energy is computed in GCMs and NWP models must be improved by relying on general thermodynamics and by using $L_h = h_v - h_d$ (not L_v).

References

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