On new bulk formulas based on moist-air entropy.

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1 Motivations

In atmospheric modelling, turbulent air-sea fluxes for the momentum, "heat" and moisture are computed from meteorological variables (wind components u and v, dry-air potential temperature θ and water vapour specific content q_v) using bulk formulas.

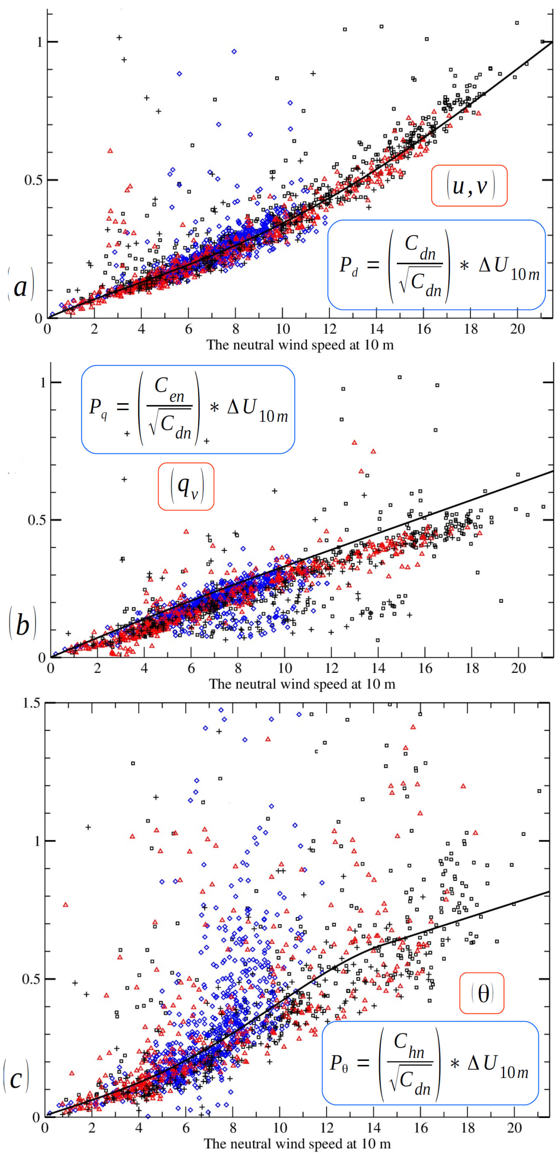

Figure 1: *Scatter-plots of the speed scales equivalent parameters: (a) P_d, (b) P_q and (c) P_θ derived from the neutral exchange coefficients C_{dn}, C_{en} and C_{hn} for the CATCH (black square), EQUALANT (blue diamond), FETCH (red triangle up) and POMME (black plus) experiments.*

In the surface modelling platform SURFEX (Masson et al. 2013, Le Moigne 2013) used by both the AROME NWP model and ARPEGE GCM, these bulk formulas rely on the ECUME parameterization derived from several campaigns, namely CATCH, EQUALANT, FETCH, SEMAPHORE, POMME and EGEE (Belamari and Pirani 2007, Belamari et al. 2016).

While previous versions of the ECUME parameterization provided analytical formulations (as a function of the neutral wind speed at 10 m hereafter referred to as $U_{10\text{m}}$) for the neutral exchange coefficients (drag coefficient C_{dn} for the momentum, Stanton number C_{hn} for the "heat" or θ, and Dalton number C_{en} for the moisture), the current version provides formulations for "speed scales equivalent parameters" P_d, P_θ and P_q derived from these neutral exchange coefficients.

As shown in Figures 1 (a,b,c), the scattering of the points appears as much more important for the dry-air potential temperature speed scale equivalent parameter P_θ when compared to those of both the wind (P_d) and water-vapour specific content (P_q). Moreover, it is observed that the fitted curves for $P_\theta(U_{10\text{m}})$ and $P_q(U_{10\text{m}})$ are different: this means that the Lewis turbulent number, which is the ratio of C_{hn} over C_{en}, and therefore of P_θ over P_q, is greater than unity.

The aim of this note is triple: 1) to trust the recommendations of Richardson (1919) who suggested to use the moist-air entropy as a variable on which the turbulence is acting; 2) to introduce the moist-air entropy potential temperature θ_s derived in Marquet (2011, 2015) instead of the current dry-air potential temperature θ; and 3) to give insights on the dispersion noticed in the scatter-plot obtained for P_θ (Figure 1 c).

2 The moist-air entropy fluxes

The specific value (i.e. per unit mass of *moist-air*) of the moist-air entropy is defined in Marquet (2011, 2015) by $s = s_{ref} + c_{pd} \, \ln(\theta_s)$, where θ_s denotes the moist-air entropy potential temperature, and s_{ref} and c_{pd} are two constants.

If liquid water or ice does not exist, a first-order approximation of the moist-air entropy potential temperature is given by $\theta_s \approx \theta \, \exp(\Lambda \, q_v)$, where $\Lambda \approx 6$ is a constant which depends on the third-law reference values of entropy of dry air and water vapour. The flux of moist-air entropy potential temperature defined as:

$$\overline{w'\theta'_s} \; = \; \rho \;\, C_{sn} \;\, U_{10m} \;\, (\Delta\theta_s)_{\,10m} \qquad (1)$$

can thus be written as:

$$\overline{w'\theta'_s} \; \approx \; \exp(\Lambda \, \overline{q_v}) \;\, \overline{w'\theta'} \; + \; \Lambda \, \overline{\theta_s} \;\, \overline{w'q'_v} \, , \qquad (2)$$

i.e. as the weighted sum of the fluxes of θ and q_v:

$$\overline{w'\theta'} \; = \; \rho \;\, C_{hn} \;\, U_{10m} \;\, (\Delta\theta)_{\,10m} \, , \qquad (3)$$

and $\quad \overline{w'q'_v} \; = \; \rho \; C_{en} \; U_{10m} \; (\Delta q_v)_{\,10m} \; , \qquad (4)$
respectively.

If the turbulence is represented by the fluxes of θ_s and q_v (Eqs.(1) and (4), respectively), one can then derive from Eq.(2) the corresponding flux of θ:

$$\begin{aligned} \overline{w'\theta'} \; \approx \; & (\,\mathrm{Le}_{ts}\,) \; [\; \rho \; C_{en} \; U_{10m} \; (\Delta\theta)_{\,10m} \;] \\ & + \; (\,\mathrm{Le}_{ts} - 1\,) \; \Lambda \; \; \overline{\theta} \; \; \overline{w'q'_v} \, , \end{aligned} \tag{5}$$

where $\mathrm{Le}_{ts} = C_{sn}/C_{en}$ denotes the moist-entropy Lewis turbulent number. If $\mathrm{Le}_{ts} \neq 1$, the second line of (5) exists and the flux of θ is not proportional to the vertical gradient $(\Delta\theta)_{\,10m}/\Delta z$. This prevents defining a Stanton number C_{hn}, and this may explain why the scatter-plot obtained for P_θ is so noisy in Figure 1 (c).

3 Results

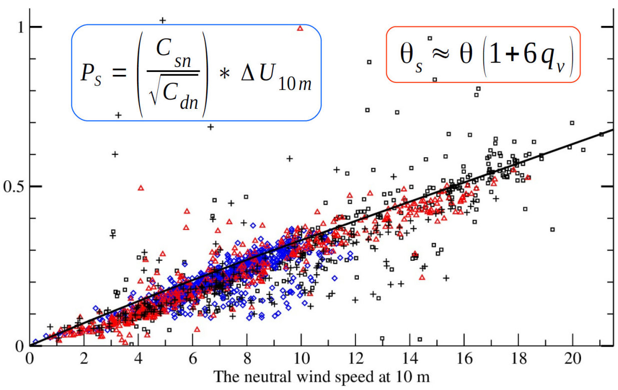

Figure 2: *Same as Fig. 1 (c) but for P_s and C_{sn}.*

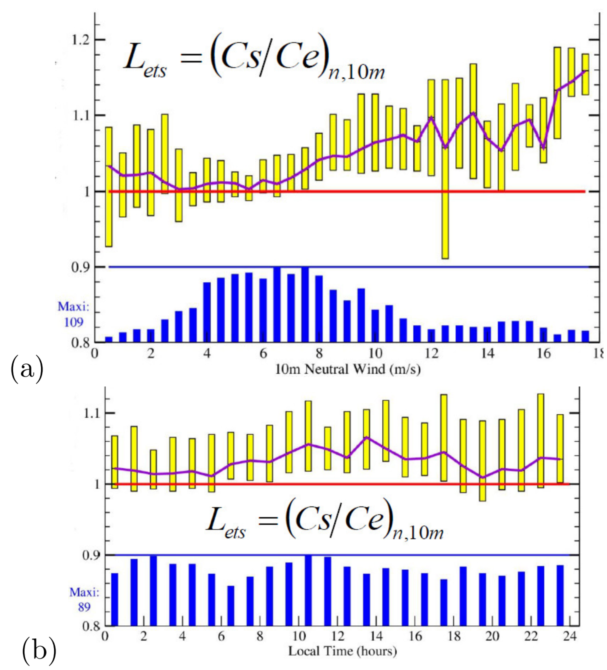

Figure 3: *Boxplots for the moist-entropy Lewis turbulent number $Le_{ts} = C_{sn}/C_{en}$ in terms of (a) $U_{10\mathrm{m}}$ and (b) the UTC local time. The number of observations for each class of wind speed or hours is indicated in blue.*

Figure 2 shows that the scattering of the $P_s(U_{10\mathrm{m}})$ points is much smaller than that of the $P_\theta(U_{10\mathrm{m}})$ points, and is similar to those obtained for the $P_d(U_{10\mathrm{m}})$ and $P_q(U_{10\mathrm{m}})$ points.

Figures 3 (a,b) indicate that the moist-entropy Lewis turbulent number Le_{ts} is often significantly different from unity, especially for small (< 2 m/s) and large (> 8 m/s) wind speeds (Fig. 3 a), as well as for day-time hours (from 8 to 18 h, Fig 3 b).

4 Conclusion

The results shown in Figures 2 and 3 sustain that the observations of CATCH, EQUALANT, FETCH and POMME experiments confirm that the moist-air entropy potential temperature θ_s is a better candidate than the dry-air value θ for applying turbulent processes over oceans.

The mean values of the moist-air entropy turbulent Lewis number Le_{ts} plotted in Figures 3 against the wind speed $U_{10\mathrm{m}}$, and/or the local UTC hours, might serve to build a new parameterization for the moist-air entropy potential temperature flux, from which the typical air-sea "sensible heat" flux may be thereafter derived from Eq.(5).

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