An alternative method for handling the interactions between turbulence and phase changes

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The problem of how to treat moist turbulence and the associated diffusive vertical transport of enthalpy and moisture under its three phases (or, equivalently, the 'shallow convection' issue) received a lot of attention over the past 40 years. Ideally one would like to extend without too much distortion the rather well calibrated methods of dry 1D vertical turbulent computation. Many algorithms have been proposed for that purpose, but most if not all of them, to our knowledge, rely on the Sommeria and Deardorff (1977) proposal and on the use of the so-called moist-conservative variables of Betts (1973). The procedure is then roughly as follows:

- Depending on the level of turbulent energy present in the grid-box, some assumptions are made about the PDFs of total water $\boldsymbol{q_t}$ and of liquid water potential temperature $\boldsymbol{\theta_l}$, both variables being assumed as 'conservative' in turbulent displacements with associated phase changes but without generation of precipitation.
- This statistical information allows: (i) to perform computations of the 'resolved' thermodynamic adjustment for the air parcel, with some cloud content $\boldsymbol{C}$ and some adjusted condensed water content $\boldsymbol{q_c}$ as by-products; (ii) with at least one additional hypothesis concerning the flux of $\boldsymbol{q_c}$, to compute the grid-average turbulent buoyancy flux that will contribute to the time evolution of the Turbulent Kinetic Energy (TKE) and maybe of the Turbulent Potential Energy (TPE); (iii) to link, in fine via an equivalent cloud fraction $\boldsymbol{N_{eb}}$, the turbulent fluxes of $\boldsymbol{q_c}$ and of potential temperature $\boldsymbol{\theta}$ to those of $\boldsymbol{q_t}$ and of $\boldsymbol{\theta_l}$ (in the most simple version of such schemes one somehow identifies $\boldsymbol{N_{eb}}$ to $\boldsymbol{C}$).
- Once '(i)' is performed and '(ii)' has produced all the information (vertical exchange coefficients for momentum, heat and moisture, at least) needed to start the vertical diffusion calculations, the primary information given by water vapour $\boldsymbol{q_v}$, plus $\boldsymbol{q_c}$ and $\boldsymbol{\theta}$ is converted to the moist conservative variables, those are transported by diffusion and '(iii)' allows to return to the evolution of the above-mentioned primary variables.
- It should be noted that this procedure amounts to do as if full evaporation takes place before an equivalent dry turbulent transport (but with condensation-modulated coefficients), followed by re-condensation at a rate determined by the analytical shape of the PDFs and by the link between $\boldsymbol{N_{eb}}$ and $\boldsymbol{C}$.
- All the above remains true when considerations about third order correlations are added, allowing some part of the transport of enthalpy and/or moisture to become up-gradient.

In the course of this study we became aware of two limitations of the method just presented:

- The direct link between the 'resolved' thermodynamic adjustment and the treatment of the turbulent flux of $\boldsymbol{q_c}$ allows neither to use another method than the statistical one to determine $\boldsymbol{C}$ nor to distinguish between 'stratiform' and 'convective' origins for the average $\boldsymbol{q_c}$ present in the grid-box prior to the said adjustment. Precisely, within the framework of the so-called 3MT scheme for treating half resolved - half parameterised deep convection (Gerard et al., 2009), we would need such additional degrees of freedom.

- There is an intrinsic problem of vertical staggering: C is obtained by definition in the middle of the model layers while N_{eb} (monotonously depending on C) is required at their edges, i.e. where the fluxes of the prognostic variables are computed and combined. As long as the situation is relatively homogeneous in the vertical things are OK. But at cloud upper and lower edges, it is clear that mixing arbitrarily two radically differing non-linear behaviours will create numerical problems (and even probably physical ones).

To by-pass such obstacles, we propose a new procedure, based on the following three hypotheses:
- The 'resolved' thermodynamic adjustment procedure remains part of the 'moist physics' but its role is disconnected from that of vertical turbulent diffusive transport.
- This adjustment is best performed after the said transport has taken place in order to mix the advective and diffusive inputs to non-deep-convective condensation/evaporation processes.
- It is possible, from the sole 'static' knowledge of the state of the atmosphere at the beginning of the physics time-step, to compute a 'shallow convective cloud cover' C_{scv} at the interfaces between model layers. The latter quantity is such that a $(1- C_{scv})$ vs. C_{scv} weighting of respectively 'dry' and 'fully condensed' buoyancy terms will deliver the input needed for the evolution of TKE (and maybe of TPE).

Of course the last of the three hypotheses is the most daring one of our proposal, but it is at the same time its anchor point. Since the 'true' value of C is yet unknown at the time when turbulent and diffusive computations are performed, a direct link between N_{eb} and C_{scv} (identity in the simplest case) can indeed exist without any vertical staggering problem. Moist buoyancy considerations for the conversion between TKE and TPE are thus directly related to the implicit hypotheses about where condensation/evaporation really takes place during the turbulent vertical transport of q_t, and this seems a sound basis for a physically true and numerically stable algorithm. Some additional remarks are however needed:
- For radiative computations, a preliminary estimate of C should be computed and combined with C_{scv} (as well as with some deep convective cloudiness). It is hoped that something like $C'=1-(1-C^*)(1- C_{scv})$ will rather closely anticipate the future value of C (with C^* the estimate based only on advection). This would be a point of verification of the integrity of the proposed scheme. Obviously the above-mentioned staggering problem has been displaced here (C^* vs. C_{scv}), but probably with less detrimental consequences.
- We left here fully open the actual 'static' analytical derivation of C_{scv} (or equivalently of the total buoyancy flux). What can be said at the present (early) stage of the study is that mimicking, via an analytical inversion, the situation of a heuristic enhancement of exchange coefficients (Geleyn, 1987) gives quite reasonable results. But we would obviously like to make a more 'physical' use of the independency granted in our proposal to the determination of C_{scv}.

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