Sub-grid condensation

CNRM/GMME/Méso-NH

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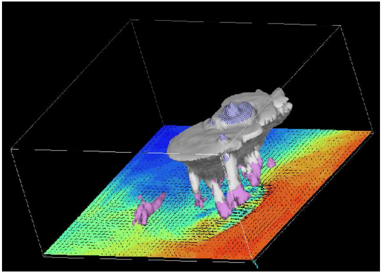
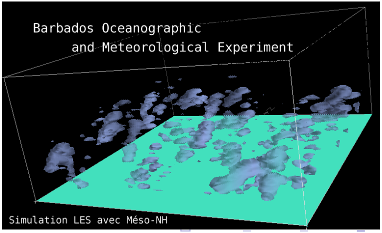


Small clouds compared to the model resolution : parametrised cloud effects on the mean grid scale variables (turbulence, convection), they should also play a role in the buoyancy terms and for the radiation.



Cloud water/ice content

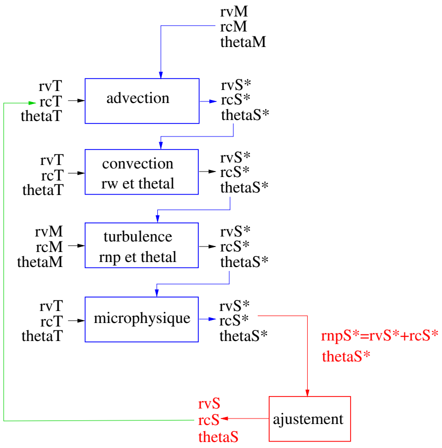
Diagnostic cloud water/ice content

If the cloud water content is not an historical variable of the model : the cloud water is transported from one time step to the next one by r_v (+ the effects of latent heat release on T). Cloud water content and cloud fraction are diagnosed for the radiation scheme.

Pronostic cloud water/ice content

If the cloud water content is an historical variable : it gives the mean r_c in a grid box (sub-grid cloud included). The cloud fraction may still be a diagnostic variable (Méso-NH) or a pronostic one (ECMWF).

Pronostic cloud water/ice cycle in Méso-NH



In Méso-NH, tendencies of r_c, r_i and θ computed by the processes before the adjustment are overwritten by the adjustment.

Nevertheless, these processes have an impact on conservative variables (r_w and θ_l).

The two types of adjustment in Méso-NH

« All or nothing » adjustment

Cloud water (and ice) can exist only if the mean historical variables are supersaturated when we reach the ajustment ($\overline{r_v} \geq r_{v\,sat}(\overline{\theta})$). In this case, cloud is formed until a saturated equilibrium between $\overline{T}$, $\overline{r_c}$ and $\overline{r_i}$ is reached. If the processes before saturation created cloud water and the mean variables are undersaturated, the cloud is evaporated. The cloud fraction is 1 if the grid is saturated or zero if it is not.

The two types of adjustment in Méso-NH

Condensation : a threshold problem

The pronostic variables $\overline{r_v}$ and $\overline{r_c}$ are mean grid scale variables (smoothed or diluted variables). So,

- Localy, inside the grid box, the threshold of saturation may be reached even if it is not the case for the mean variables : subgrid (fractionnal) clouds.
- On the opposite, the mean variables may be just saturated such that in the « all or nothing » scheme we get a cloud cover of 1. But in the reality, the grid box may be locally very much supersaturated and not sarurated in some others places. Then we should get a fractionnal cloud cover ($N < 1$) instead of a complete one ($N = 1$).

The two types of adjustment in Méso-NH

Sub-grid adjustment

The formation of cloud water (and ice) is allowed even if the saturation is not reached by the mean historical variables. Formulation based on stastistical cloud distribution and/or empirical results are used to compute N, $\overline{r_c}$ (and $\overline{r_i}$). These new values overwrite the one obtained when we reach the adjustment and the value of $\overline{\theta}$ is updated.

Note that the adjustement processes do not change the value of the conservative variables. They only operate a projection of the conservative variables on the non-conservative ones.

Local r_c

Local saturation

Whenever cloud is present locally inside the grid box, the mixing ratio is equal to the saturation mixing ratio $r_{vs}(\theta, p)$. This can be expressed using the conservative variable θ_l, a first-order Taylor expansion and neglecting the variations of r_{vs} with pressure as :

$$r_v = r_{vs}(\theta, p) \approx r_{vs}(\theta_l) + (\frac{\partial r_{vs}}{\partial \theta})_{\theta_l}(\theta - \theta_l)$$

Rate of change of r_{vs}

Using the Clausius-Clapeyron relation, we have

$$J = \left(\frac{\partial r_{vs}}{\partial \theta}\right)_{\theta_l} = \frac{r_{vs}(T_l)L_v}{R_v T_l \theta_l}$$

Local r_c

r_c in a saturated zone

The cloud water mixing ratio is then given by :

$$r_c = r_{np} - r_v = r_{np} - r_{vs}(\theta_l) - J(\theta - \theta_l).$$

Since by definition, $\theta - \theta_l = \frac{L_v}{C_{ph}} \Pi_{ref}^{-1} r_c$, this gives :

$$\begin{aligned} r_c &= r_{np} - r_{vs}(\theta_l) - J \frac{L_v}{C_{ph}} \Pi_{ref}^{-1} r_c \\ \longrightarrow r_c &= \frac{r_{np} - r_{vs}(\theta_l)}{1 + M} \end{aligned}$$

where $M = J \frac{L_v}{C_{ph}} \Pi_{ref}^{-1}$

Local r_c

General expression of r_c

$$r_c = \text{Max}\left(0, \frac{r_{np} - r_{vs}(\theta_l)}{1 + M}\right).$$

Distance to local saturation within the grid

$$s = \frac{r_{np} - r_{vs}(\theta_l)}{2(1+M)}.$$

may be seen as a quantity that diagnoses the distance to local saturation within the grid

- $s \geq 0$, there is saturation locally (in that case, $r_c = 2s$)
- $s < 0$, there is no saturation (in that case, $r_c = 0$)

Stastistics of distance to saturation

Fluctuation of distance to saturation

$$s = \overline{s} + s'$$

- $s' \geq -\overline{s}$, there is saturation locally
- $s' < -\overline{s}$, there is no saturation locally

To first order approximation :

$$s' = \frac{r_{np}' - J\theta_l'}{2(1+M)}$$

$s' = r_c'/2$ in a fully saturated grid ; this gives the formulation of the fluctuation of cloud mixing ratio in a first order «all or nothing» adjustment process

Stastistics of distance to saturation

Standard deviation

$$\left(\overline{s'^2}\right)^{1/2} = \sigma_s = \frac{\left(\overline{r'^2_{np}} + J^2\overline{\theta'^2_l} - 2J\overline{r'_{np}\theta'_l}\right)^{\frac{1}{2}}}{2(1+M)}$$

Useful and usual notations

Normalized fluctuation

$$t = s'/\sigma_s$$

is a centered, normalized variable

Mean normalised distance to saturation

$$Q_1 = \frac{\overline{s}}{\sigma_s} = \frac{\overline{r_{np}} - r_{vs}(\overline{\theta_l})}{2(1+M)\sigma_s}$$

Saturation with new variables

In terms of t, saturation is present whenever

$$t \geq -Q_1$$

Statistical expression of cloud characteristics

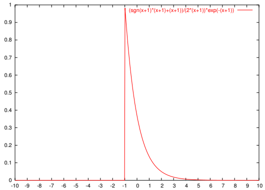
Empirical probability distribution

We suppose that we know $G(t)dt$, the probability distribution of t

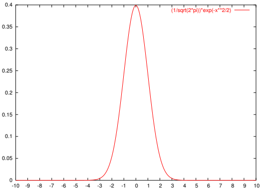
The probability distribution function $G(t)$ was originaly a gaussian distribution function (Sommeria and Deardorff, 1977). However, Bougeault (1981, 1982) showed that this would underestimate the cloud fraction in most cases, because actual distributions are skewed. He proposed several solutions, the most general being the Gamma probability density. The importance of using skewed distributions has been confirmed by later work (Cuijpers and Bechtold, 1994).

Statistical expression of cloud characteristics

In the Méso-NH scheme, the skewness of $G(t)$ depends on the value of Q_1 (the bigger the distance to full saturation, the larger the skewness)



$Q_1 < -2$



$Q_1 \geq 0$

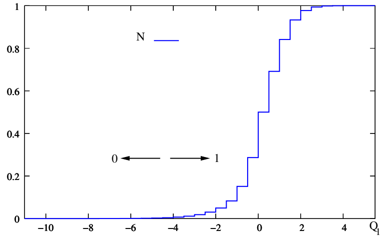
The case $-2 \leq Q_1 < 0$ is a linear interpolation of the case above.

Statistical expression of cloud characteristics

Cloud cover

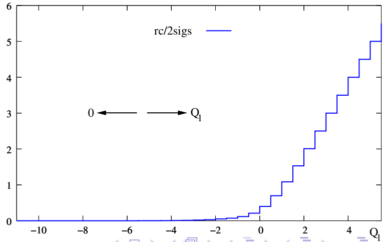
The fraction of the grid cell occupied by clouds is then

$$N = \int_{-Q_1}^{+\infty} G(t)dt$$



Mean cloud water content

$$\frac{\overline{r_c}}{2\sigma_s} = \int_{-Q_1}^{+\infty} (Q_1 + t)G(t)dt$$



Eddy flux of cloud water with sub-grid condensation

As the turbulence scheme is written for conservative variables, the non-conservative (historical) variable fluxes $\overline{w'r'_v}$, $\overline{w'r'_c}$, $\overline{w'r'_i}$ and $\overline{w'\theta'}$ have to be retrieved from $\overline{w'r'_w}$ and $\overline{w'\theta'_l}$ (ϕ_3, ψ_3, buoyancy production and tendencies of historical variables).

$$\begin{aligned}\overline{w'\theta'} &= \overline{w'\theta'_l} + \frac{L_v}{C_{p_h}}{\Pi_{ref}}^{-1}\overline{w'r'_c} + \frac{L_s}{C_{p_h}}{\Pi_{ref}}^{-1}\overline{w'r'_i} \\ \overline{w'r'_v} &= \overline{w'r'_{np}} - \overline{w'r'_c} - \overline{w'r'_i}\end{aligned}$$

The resolution of this system is possible only with a parametrisation of the turbulent cloud water fluxes $\overline{w'r'_c}$ and $\overline{w'r'_i}$.

In a «all or nothing» scheme

$$\frac{1}{2}\overline{w'r'_c} = \overline{w's'} = \frac{\overline{w'r'_{np}} - J\overline{w'\theta'_l}}{2(1+M)}$$

In a sub-grid condensation scheme

$$\frac{\overline{w'r'_c}}{\overline{w's'}} = \lambda_3 \frac{\overline{s'r'_c}}{\sigma_s^2}.$$

According to Bougeault (1981, 1982)

$$\frac{\overline{s'r'_c}}{2{\sigma_s}^2} = \int_{-Q_1}^{+\infty} t(Q_1+t)G(t)dt\,.$$

λ_3 is an empirical coefficient (Bechtold et al., 1993)

In Méso-NH,

$$\begin{aligned} Q_1 \geq 0 &\quad : \quad \lambda_3 = 1 \\ Q_1 < -2 &\quad : \quad \lambda_3 = 3 \\ -2 \leq Q_1 < 0 &\quad : \quad \lambda_3 = 1 - Q_1 \end{aligned}$$

Final flux expression

$$\overline{w' r'_c} = A_{moist} \overline{w' r'_{np}} + A_\theta \overline{w' \theta'_l},$$

$$A_{moist} = \frac{\lambda_3 \frac{\overline{s' r'_c}}{2{\sigma_s}^2}}{1 + M},$$

$$A_\theta = -J \frac{\lambda_3 \frac{\overline{s' r'_c}}{2{\sigma_s}^2}}{1 + M}.$$

Practical implementation in Méso-NH physics

Activation of the scheme

The « strict » Bougeault adjustment scheme is coded with the warm microphysics (CCLOUD='KESS', LSUBG_COND=TRUE). Then, it is not (yet ?) ported inside Arome.

Data flow in Méso-NH

- σ_s is computed by the turbulent scheme (TURB) and transmitted to the ajustment routine (FAST_TERM and CONDENS) at the end of the time step ;
- FAST_TERM gives the final value of the mean thermodynamic variables (θ_S, $r_v S$, $r_c S$,$r_i S$), the cloud cover for the radiation scheme and $\overline{s' r_c'}/(2{\sigma_s}^2)$ for the turbulence at the next time step.

Simplified formulation of $\sigma_{s\,turb}$ (Bechtold and Chaboureau, 2002)

First order closure expression, computable in any numerical model

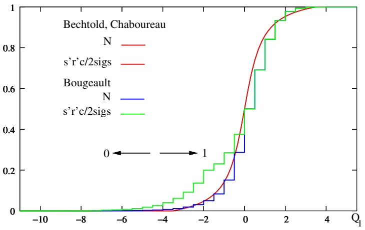
$$\sigma_{s\,turb} = c_\sigma L \left[\overline{a}^2 \left(\frac{\partial \overline{r_w}}{\partial z} \right)^2 - 2 \frac{\overline{a}\overline{b}}{c_{p\,h}} \frac{\partial \overline{h_l}}{\partial z} \frac{\partial \overline{r_w}}{\partial z} + \frac{\overline{b}^2}{c_{p\,h}} \left(\frac{\partial \overline{h_l}}{\partial z} \right)^2 \right]$$

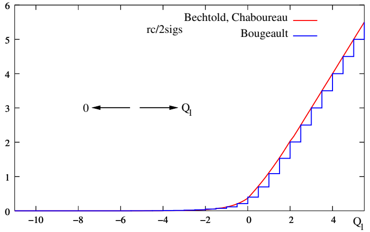
Contribution from convection

Contribution of the convective updraft to the variance of s directly computed from the convective mass flux M, output of Kain-Fritsch-Bechtold convection scheme

$$\sigma_{s\,conv} = \alpha M f \left(\frac{z}{z^*} \right)$$

Analytical formulation of N and $\overline{r}_c$





Bechtold et Chaboureau, 2002

$$N = max\{0, min[1, 0.5 + 0.36 \arctan(1.55 Q_1)]\}$$

Bechtold et Chaboureau, 2002

$$\overline{r_c}/(2\sigma_s) =$$

$$\begin{array}{rl} \exp(1.2Q_1 - 1) & Q_1 < 0 \\ e^{-1} + 0.66Q_1 + 0.086Q_1^2 & 0 \leq Q_1 \leq 2 \\ Q_1 & Q_1 > 2 \end{array}$$

Activation of the scheme

The Bechtold and Chaboureau analytical formulations for N, $\overline{r_c}$and $\overline{r_i}$ are coded with the cold microphysics (CCLOUD='ICE3', LSUBG_COND=TRUE) which is ported inside Arome (subroutines ICE_ADJUST and CONDENSATION). But the formulations are very close from the statistic formulations tabulated in CONDENS.

In ICE_ADJUST (with LSUBG_COND=TRUE), σ_s may be the value computed in the turbulence scheme (LSIGMAS=TRUE). In a warm case, this configuration is very close from KESS + LSUBG_COND=TRUE.

But σ_s may also be $\sigma_{s\,turb}$ from Bechtold and Chaboureau, 2002 (LSUBG_COND=TRUE, LSIGMAS=FALSE and LSIG_CONV=FALSE) or $\sigma_{s\,turb} + \sigma_{s\,conv}$ (LSUBG_COND=TRUE, LSIGMAS=FALSE and LSIG_CONV=TRUE).

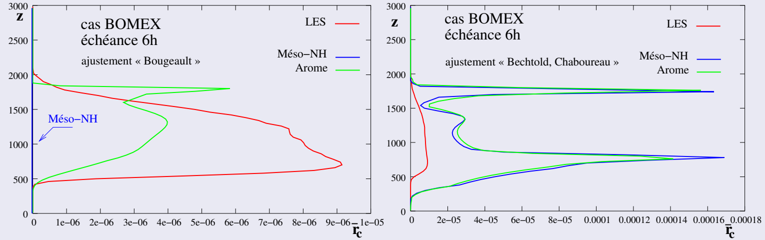
Data flow in Méso-NH

- σ_s is computed by the turbulent scheme (TURB) and a convective mass flux is computed in the convection scheme (CONVECTION). They are transmitted to the ajustment routines (ICE_ADJUST and CONDENSATION) at the end of the time step ;
- ICE_ADJUST gives the final value of the mean thermodynamic variables (θ_S, $r_v S$, $r_c S$,$r_i S$), the cloud cover for the radiation scheme and $\overline{s' r_c'}/(2{\sigma_s}^2)$ for the turbulence at the next time step.

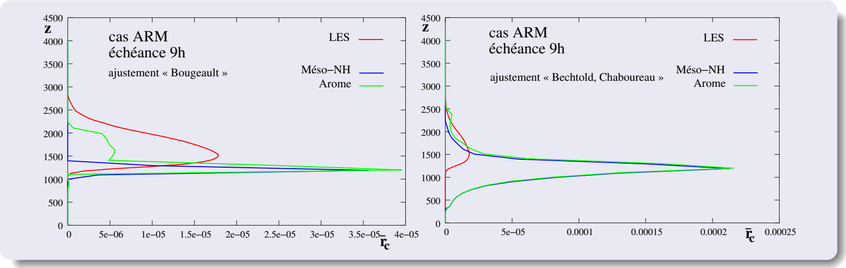
Data flow in AROME

- ICE_ADJUST gives the pseudo-final value of the mean thermodynamic variables of the physics (θ_S, $r_v S$, $r_c S$,$r_i S$), the cloud cover for the radiation scheme and $\overline{s' r'_c}/(2{\sigma_s}^2)$ for the turbulence of the pseudo-next time step (which are in the same call of APL_AROME).
- σ_s is computed by the turbulent scheme (TURB) and a convective mass flux is computed in the convection scheme (CONVECTION). They are transmitted to the ajustment routines (ICE_ADJUST and CONDENSATION) at the begining of the next call of APL_AROME ;

Bomex 1D case



Eurocs 1D case



Pronostic $\overline{r_c}_{conv}$

Idea

Try to use more directly the $\overline{r_c}$ diagnosed by the convection scheme (instead of the intermediate variable σ_s).

IN TEST

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Contribution of a convective mass flux to σ_s

Mass flux contribution in the variances $\overline{{r'_{np}}^2}$ and $\overline{{\theta'_l}^2}$

Following Bechtold et al, 1995 and Lenderink and Siebesma, 2000

$$\overline{\phi'^2} = \underbrace{2\tau_\phi K \left(\frac{\partial\overline{\phi}}{\partial z}\right)^2}_{\text{vertical diffusion}} \underbrace{-2\tau_\phi M(\phi_{up} - \overline{\phi})\frac{\partial\phi}{\partial z}}_{\text{mass flux}}$$