Documentation of the LOPEZ scheme in the CLIMATE version 5.0 of ARPEGE (based on the cycle 32t0_op1v2_13 + CNRM/GMGEC modset)

Author : Pascal Marquet, CNRM/GMGEC/EAC (8th of August, 2008)

1 Part A : Motivations

1.1 A1 : Objectives

The aim of the scheme of Lopez (2002) was to describe both the large-scale cloud water content and the large-scale precipitations (liquid and solid), by using some prognostic equations and by describing several physical processes acting between the different species.

The main objective of the prognostic scheme of Lopez was for the purpose of variational assimilation of cloud and precipitation observations. Available since 2001, this scheme was also suitable for the purpose of Climate and short-range NWP simulations, made with the ARPEGE model.

It has been decided in 2001 to test the original scheme of Lopez in the Climate version 4 of ARPEGE, by using the version used in the studies of FASTEX events (cycle 22t1), where two prognostic quantities exist : one cloud water content (liquid water *plus* ice) and one precipitation content (rain *plus* snow).

Since then, the scheme of Lopez has been tested, modified and improved, for both Climate and NWP mode (see Bouyssel, 2005), also in the ALADIN-ALARO team (see Gerard, 2005). Most of the improvements recently made by the NWP team are now available in the Climate version-5 of ARPEGE, via some back-phasing of the code, except the new statistical sedimentation scheme (Geleyn et al., 2008) which is only available in the more recent cycles.

1.2 A2 : The Physical Proceses

The physical processes described by the scheme of Lopez (2002) are based on a "bulk" assumption. They are close to the one described in Fowler et al. (1996).

- The cloud water content and the precipitations are supposed to be pronostic variables, available as input of the scheme.

- The cloud water content (liquid and ice) and the precipitations (rain and snow) form two separate distributions of dropplets. The smaller ones are the suspended cloud condensate, whereas the larger ones are precipitating species.
- The condensation process acts as a source for the condensed cloud water (liquid and ice).
- The evaporation process acts as sinks for the precipitation content (rain and snow)
- The condensed cloud water (liquid and ice) can transform into the precipitation content species (rain and snow) via the processes of auto-conversion and collections (accretion + aggregation + riming).
- The precipitation content species (rain and snow) fall with different fall speeds. The sedimentation processes are computed by a semi-lagrangian internal scheme, allowing the use of the NWP and GCM large time-steps, contrary to the time-stepping method used in Fowler et al. (1996).
- The Freezing-Melting-Bergeron processes between cloud liquid water and cloud ice are not explicitly described. Only the snow melting is computed (between snow and rain). The detrainment from the convection schemes (neither shallow nor deep) are not taken into account.

1.3 A3 : The theory : equations and hypotheses

1.3.1 A3-a : The main "bulk" equations

The grid-cells averages of the condensed water species are denoted by

$\overline{q_l}$	liquid cloud water content
$\overline{q_i}$	ice cloud water content
$\overline{q_r}$	rain precipitation content
$\overline{q_s}$	snow precipitation content

The system of four prognostic equations corresponding to the physical proceses described in the section (1.2) can be written as

$$\left\{ \begin{array}{lcl} \partial(\overline{q_l})/\partial t & = & +C_l - A_l - COL_{(l/r)} - COL_{(l/s)} \\ \partial(\overline{q_i})/\partial t & = & +C_i - A_i - COL_{(i/s)} \\ \partial(\overline{q_r})/\partial t & = & -E_r + A_l + COL_{(l/r)} - F_r \\ \partial(\overline{q_s})/\partial t & = & -E_s + A_i + COL_{(i/s)} + COL_{(l/s)} - F_s \end{array} \right. \qquad (1)$$

The condensation processes C_l and C_i act as source terms of the cloud water contents (liquid and solid). The evaporation and the falling processes, i.e. E_r, E_s, F_r and F_s, act as sink terms for the precipitation contents (rain and snow). The auto-conversion terms A_l

and A_i and the collection terms $COL_{(l/r)}$, $COL_{(i/s)}$ and $COL_{(l/r)}$ act as conversion terms, transforming one species into another.

The three collection processes parameterized in the scheme of Lopez are caused by the differential (constant) fall speed between the cloud species and the precipitating ones. They represent the capture of the cloud species by the precipitations.

$COL_{(l/r)}$	accretion	collection of cloud liquid water by rain
$COL_{(i/s)}$	aggregation	collection of cloud ice by snow
$COL_{(l/s)}$	riming	collection of cloud liquid water by snow

The fourth collection (of cloud ice by rain) is not paramaterized. Indeed, the cloud ice regions are usually located above the rain regions.

1.3.2 A3-b : The condensation/evaporation processes

When the scheme of Lopez (2002) have been implemented first in ARPEGE, in the years 1999-2001, it was associated with the NWP diagnostic turbulent scheme of Louis and no information was available as input on the existing amount of subgrid condensed water.

At that time, a special subroutine (ACNEBSM) has been written by Ph. Lopez in order to compute the cloud-cover and the condensed cloud water (liquid or ice) with the use of the Smith (1990) triangular PDF statistical scheme.

In the present Climate version-5 ARPEGE code, it is possible to compute the cloud-cover and the condensed cloud water in the prognostic (CBR00) TKE scheme, like for instance by using the Bougeault functions, i.e. if LNEBECT=TRUE.

If the statistical cloud water content is denoted by $(\overline{q_c})_{stat}$, the partitioning of the liquid part $(\overline{q_l})_{stat}$ and the solid part $(\overline{q_i})_{stat}$ is obtained with

$$\delta_{ice} \; = \; \begin{cases} 1 - \exp\left[\, (T-T_f)^2/(2\,\Delta T)^2 \,\right] & \text{for } \; T < T_f \;, \\ \\ 0 & \text{otherwise} \;. \end{cases} \tag{2}$$

The value of δ_{ice} is given by the function FONICE(T), contained in the header fctdoi.h, with ΔT = RDT$*$RDTFAC, RDT= 11.82 K and RDTFAC= 0.5, leading to ΔT = 5.91 K. It is thus half of the value RDT used elsewhere in the ARPEGE physics. It is almost twice the value of 3 K chosen in Lopez (2002).

The fluxes of condensation/evaporation are denoted by PFCSQL for the liquid cloud water and by PFCSQN for the solid cloud water. They are computed in ACPLUIZ, with $(\overline{q_c})_{stat}$ as input, following

$$g \, \frac{\Delta\,(\mathrm{PFCSQL})}{\Delta p} \;=\; \frac{(1-\delta_{ice}) \; * \; (\overline{q_c})_{stat} - \overline{q_l}}{\Delta t} \;, \tag{3}$$

$$g \, \frac{\Delta\,(\mathrm{PFCSQN})}{\Delta p} \;=\; \frac{\delta_{ice} \; * \; (\overline{q_c})_{stat} - \overline{q_i}}{\Delta t} \;. \tag{4}$$

1.3.3 A3-c : The auto-conversion processes

The auto-conversion processes start to occur when the values of the suspended condensed water content are larger than some threshold value q_{crit}. It is important to think in terms of the in-cloud values (close to the saturating state), and not with the grid-cell averages (often far from the saturating state).

Let us denote by $\overline{q_c}$ the grid-cell average of the condensed water content, and by $\overline{q_c^*}$ the corresponding in-cloud value, obtained from the large-scale cloud cover $N_s = \text{Max}[\ \varepsilon_N\ ;\ N_s\ ]$ as

$$\overline{q_c^*} \ \equiv \ \text{Max}\left[\ 0\ ;\ \frac{\overline{q_c}}{N_s}\ \right] . \qquad (5)$$

The auto-conversion process can be represented as the in-cloud conversion rate A_c^* from one of the (liquid or solid) condensed water in-cloud value $\overline{q_c^*}$ to the corresponding (liquid or solid) precipitating in-cloud value $\overline{q_p^*}$, with the Kessler (1969) assumption, leading to

$$\left(\frac{\partial \overline{q_c^*}}{\partial t}\right)_{auto} \ \equiv \ -\ A_c^*\ , \qquad (6)$$

$$\left(\frac{\partial \overline{q_c^*}}{\partial t}\right)_{auto} \ \equiv \ -\ \frac{\overline{q_c^*}\ -\ q_{crit}}{\tau_c}\ . \qquad (7)$$

The threshold value q_{crit} and the time scale τ_c are supposed to be two constant terms. They correspond to the physical assumption that the dropplets smaller than a given radius remain suspended cloud condensate, whereas the dropplets larger than a given radius are becoming precipitating species, with a time scale τ_c. The threshold used in this "bulk" scheme is not a critical radius, but a critical specific content q_{crit} for the suspended cloud condensate.

The threshold values for q_{crit} are set from the NAMELIST of ARPEGE. They are not the same for the liquid and the solid species.

$$(q_l)_0 \ = \ \text{RQLCR}\ , \qquad (8)$$

$$(q_i)_0(T) \ \in \ [\ \text{RQICRMIN}\ ;\ \text{RQICRAX}\ ]\ . \qquad (9)$$

From (8) it is as a true constant for the liquid water content. From (9), there is a more complex formulation for the solid water (ice), with a variation between the two extremum values $(q_i)_0^{min} = \text{RQICRMIN}$ and $(q_i)_0^{max} = \text{RQICRAX}$ available in the NAMELIST.

Indeed, in order to allow the autoconversion of ice even at very low temperature, $(q_i)_0(T)$ is assumed to decrease with temperature, according to the formulae (A.1) of Lopez (2002) :

$$(q_i)_0(T) \ = \ (q_i)_0^{max} \ - \ 0.5\left[\ (q_i)_0^{max} - (q_i)_0^{min}\right]\ \{\ 1\ +\ \tanh\left[\ \alpha\,(T - T_f) + \beta\ \right]\ \}\ . \qquad (10)$$

$T_f = 273.16$ K is the triple point temperature.

Over the ice-shell sea regions or over the snow-covered land areas, there is fewer Cloud Condensation Nuclei (CNC) than over the open-sea or free land areas, where more aerosol are available. A first attempt to take into account these differential icy/warm properties is made in the ACMICRO subroutine, by computing the term ZFACICE and by multipying $(q_i)_0(T)$ by 1−ZFACICE∗(1−RQICRSN).

The term ZFACICE is equal to 0 over the open-sea and free land areas, equal to 1 over the icy regions. For RQICRSN = 0.5 (available in the NAMELIST), $(q_i)_0(T)$ is not modified over the open-sea and free land areas, whereas it is divided by a factor 2 over the icy regions. For RQICRSN = 1, $(q_i)_0(T)$ is not modified over the icy regions.

The coefficients α and β are two constant terms in Lopez (2002), see his Appendix-D where $\alpha = -0.1572\ \mathrm{K}^{-1}$ and $\beta = -4.9632$. In the ARPEGE code, due to additional tunings made in the NWP team, α and β depend the two temperature T_1 =RQICRT1 and T_2 =RQICRT2, both available in the NAMELIST.

$$\gamma_1 = -1 + 2\, \frac{(q_i)_0^{max}\,(1-0.999)}{(q_i)_0^{max} - (q_i)_0^{min}}\,, \tag{11}$$

$$\gamma_2 = -1 + 2\, \frac{(q_i)_0^{max} - 1.5\,(q_i)_0^{min}}{(q_i)_0^{max} - (q_i)_0^{min}}\,, \tag{12}$$

$$\gamma_3 = 0.5\ \log\left[\mathrm{abs}\left(\frac{1+\gamma_1}{1-\gamma_1}\right)\right]\,, \tag{13}$$

$$\gamma_4 = 0.5\ \log\left[\mathrm{abs}\left(\frac{1+\gamma_2}{1-\gamma_2}\right)\right]\,. \tag{14}$$

From (11) to (14), α and β are defined by

$$\alpha = \frac{\gamma_3 - \gamma_4}{T_2 - T_1}\,, \tag{15}$$

$$\beta = \gamma_3 - T_2\,\alpha\,. \tag{16}$$

The in-cloud auto-conversion rate A_c^* is computed with both the finite difference (17) plus the analytic method (18). These schemes are obtained by integrating (6) and (7) from the time t with the value $\overline{q_c}^{\,*(-)}$ to the time $t+\Delta t$ with the value $\overline{q_c}^{\,*(+)}$, considering q_{crit} and τ_c as two constant terms.

It results the two following formulations

$$A_c^* \approx -\,\frac{\overline{q_c}^{\,*(+)} - \overline{q_c}^{\,*(-)}}{\Delta t}\,, \tag{17}$$

$$\frac{\overline{q_c}^{\,*(+)} - q_{crit}}{\overline{q_c}^{\,*(-)} - q_{crit}} \approx \exp\left(-\,\frac{\Delta t}{\tau_c}\right)\,. \tag{18}$$

They correspond to discrete solutions of (6) and (7), respectivelly.

From (17) and (18), the auto-conversion rates for the liquid and the solid (ice) water content write

$$A_l^* \approx \left[1 - \exp\left(-\,\frac{\Delta t}{\tau_l}\right)\right]\left[\frac{\overline{q_c}^{\,*(-)} - (q_l)_0}{\Delta t}\right]\,, \tag{19}$$

$$A_i^* \approx \left[1 - \exp\left(-\,\frac{\Delta t}{\tau_i}\right)\right]\left[\frac{\overline{q_c}^{\,*(-)} - (q_i)_0(T)}{\Delta t}\right]\,. \tag{20}$$

The terms A_l^* and A_i^* are denoted by ZDUM in ACMICRO.

The threshold values $(q_l)_0$ and $(q_i)_0(T)$ are given by (8) and (10). The two time constant terms τ_l and τ_i are denoted by ZCAUT in ACMICRO, they write

$$1/\tau_l = \text{RAUTEFR}\,, \tag{21}$$
$$1/\tau_i = \text{RAUTEFS} * \exp[-(\beta)_{ice}\,(T - T_f)\,]\,, \tag{22}$$

with RAUTEFR and RAUTEFS available in the NAMELIST.

The exponential term in (22) is the temperature dependant ice conversion efficiency of Pruppacher and Klett (1998), with the coefficient $(\beta)_{ice} = \text{RAUTSBET} = 0.025$ available in the NAMELIST.

The final grid-cell average auto-convertion rate for the liquid and solid species are computed from (19) and (20) by inverting (5) and by multiplying by the large-scale cloud cover N_s.

$$A_l = \text{Max}\{\,0\,;\ A_l^* * N_s\,\}\,, \tag{23}$$
$$A_i = \text{Max}\{\,0\,;\ A_i^* * N_s\,\}\,. \tag{24}$$

The terms $A_l = \text{PAUTOL}$ and $A_i = \text{PAUTOI}$ are available as output of ACMICRO.

1.3.4 A3-d : The distribution of particle - Fall-velocities.

The classical equations for the collection of suspended cloud species by the precipitating ones are derived in Fowler et al. (1996) by using the Marshall and Palmer (1948) distribution for the rain and the Gunn and Marhall (1958) distribution for the snow.

In the paper of Lopez (2002), the same distribution of Marshall and Palmer (1948) is used for the rain, with the fall speed given by Sachidananda and Zrnić (1986) and Foote and Du Toit (1969). For the ice particles, the ideas of Houze et al. (1979) and Cox (1998) have been taken into account.

For the rain, the spectra of the particle number $N_r(D)$, the mass $M_r(D)$ and the fall velocity $V_r(D)$ express in terms of the particle diameter D as follows

$$N_r(D) = N_{0r}\ \exp(-\,\lambda_r\,D)\,, \tag{25}$$
$$M_r(D) = \rho_w\,\frac{\pi\,D^3}{6}\,, \tag{26}$$
$$V_r(D) = \nu_1\left(\frac{\rho_0}{\rho}\right)^{0.4} D^{\nu_2}\,. \tag{27}$$

The slope λ_r of the Marshall and Palmer distribution is related to the grid-cell average rain content $\overline{q_r}$ by

$$\lambda_r = \left(\frac{\pi\,\rho_w\,N_{0r}}{\rho\,\overline{q_r}}\right)^{1/4}. \tag{28}$$

For the snow, the equivalent spectra of the particle number $N_s(D)$, the mass $M_s(D)$ and the fall velocity $V_s(D)$ express as follows

$$N_s(D) = N_{0s}(T)\ \exp(-\lambda_s D)\,, \tag{29}$$

$$M_s(D) = \sigma_1\, D^{\sigma_2}\,, \tag{30}$$

$$V_s(D) = \tau_1 \left(\frac{\rho_0}{\rho}\right)^{0.4} D^{\tau_2}\,. \tag{31}$$

From Houze et al. (1979), the exponential distribution $N_{0s}(T)$ is temperature dependent. The formulation for $M_s(D)$ is given by Cox (1998).

The slope λ_s of the distribution is related to the snow content $\overline{q_s}$ by

$$\lambda_s = \left(\frac{\Gamma(1+\sigma_2)\, N_{0s}(T)\, \sigma_1}{\rho\, \overline{q_s}}\right)^{1/(1+\sigma_2)}\,. \tag{32}$$

The Gamma function $\Gamma(z)$ is defined for any real z by

$$\Gamma(z) = \int_0^{+\infty} t^{z-1} \exp(-t)\, dt, \tag{33}$$

with $\Gamma(1) = 1$ and the usual properties $\Gamma(z+1) = z\,\Gamma(z)$, leading to $\Gamma(n+1) = n\,!$ valid for any positif integer n.

The computations of $\Gamma(z)$ for any real z are made with the use of approximated FORTRAN functions (either in the module main/arp/module/yomgamma.F90 for the ARPEGE code, or in mpa/micro/internals/gamma.mnh for the meso-NH subroutines).

The associated mass-weighted average fall speed of particles $\overline{V_r}$ for the rain and $\overline{V_s}$ for the snow should be given by

$$\overline{V_r} = 17.116 * \left(\frac{\rho_0}{\rho}\right)^{0.4} (\rho\, \overline{q_r})^{1/6}\,, \tag{34}$$

$$\overline{V_s} = 4.323 * \exp\left[\,0.0204\,(T - T_f)\,\right] \left(\frac{\rho_0}{\rho}\right)^{0.4} (\rho\, \overline{q_s})^{1/6}\,. \tag{35}$$

However, for sake of simplicity, also for important numerical reasons of applying a semi-lagrangian vertical advection method, $\overline{V_r} = \mathrm{TFVR}$ and $\overline{V_s} = \mathrm{TFVS}$ are set equal to some "bulk" constant values in ARPEGE, with both TFVR ≈ 5 m s^{-1} and TFVS ≈ 0.6 m s^{-1} available in the NAMELIST.

1.3.5 A3-e : The collection processes

The distributions (25) to (27) for the rain spectra and (29) to (31) for the snow spectra lead the three collection rates (36) to (38) for $COL_{(l/r)}$, $COL_{(i/s)}$ and $COL_{(l/s)}$.

$$COL_{(l/r)} \equiv \text{accretion} = K_{\text{acc}}^{(l/r)}\ E_{\text{acc}}^{(l/r)}\ \overline{q_l}\ \overline{q_r}\,, \tag{36}$$

$$COL_{(i/s)} \equiv \text{aggregation} = K_{\text{agg}}^{(i/s)}\ E_{\text{agg}}^{(i/s)}(T)\ \overline{q_i}\ \overline{q_s}\,, \tag{37}$$

$$COL_{(l/s)} \equiv \text{riming} = K_{\text{rim}}^{(l/s)}\ E_{\text{rim}}^{(l/s)}\ \overline{q_l}\ \overline{q_s}\,. \tag{38}$$

They express in terms of the product of the 3 collection coefficients (K), the 3 collection efficiencies (E) and appropriate couples of grid-cell mean water species content, i.e. $\overline{q_l}\ \overline{q_r}$ or $\overline{q_i}\ \overline{q_s}$ or $\overline{q_l}\ \overline{q_s}$.

The collection efficiencies write

$$
\begin{aligned}
E^{(l/r)}_{\text{acc}} &= \text{RACCEF}\,, &(39)\\
E^{(i/s)}_{\text{agg}}(T) &= \text{RAGGEF} \;\ast\; \exp\left[\,-\,0.025\,(T-T_f)\,\right]\,, &(40)\\
E^{(l/s)}_{\text{rim}} &= \text{RRIMEF}\,, &(41)
\end{aligned}
$$

with RACCEF, RAGGEF and RRIMEF three constants, all available in the NAMELIST.

The collection coefficients write

$$
K^{(l/r)}_{\text{acc}} = \frac{12.695\;\;\nu_1\;\;\Gamma(3+\nu_2)}{4\;\rho_w}\;\left(\frac{\rho_{ref}}{\rho}\right)^{0.4} \approx\; 4.8108\;\left(\frac{\rho_{ref}}{\rho}\right)^{0.4}, \qquad (42)
$$

$$
K^{(i/s)}_{\text{agg}} = K^{(l/s)}_{\text{rim}} = \frac{0.0485\;\;\tau_1\;\;\pi\;\;\Gamma(3+\tau_2)}{4\;\;\sigma_1\;\;[\,\Gamma(1+\sigma_2)\,]^{\frac{3+\tau_2}{1+\sigma_2}}}\left(\frac{\rho_{ref}}{\rho}\right)^{0.4} \approx\; 17.1623\;\left(\frac{\rho_{ref}}{\rho}\right)^{0.4}. \quad (43)
$$

The numerical values 4.8108 and 17.1623 are the same as the values given in Lopez (2002, Appendix-D), providing that $\nu_1 = 377.8\ \text{m}^{1/3}\ \text{s}^{-1}$, $\nu_2 = 2/3$, $\tau_1 = 21\ \text{m}^{1/2}\ \text{s}^{-1}$, $\tau_2 = 0.5$, $\sigma_1 = 0.069\ \text{kg m}^{-2}$, $\sigma_2 = 2$, $\rho_w = 1000\ \text{kg m}^{-3}$ and $\rho_{ref} = 1.2\ \text{kg m}^{-3}$.

In the subroutine ADVPRC of the ARPEGE code, the coefficients ZCOEFF1, ZCOEFF2 and ZCOEFF2b are equal to

$$
\begin{aligned}
\text{ZCOEFF1} &= 12.695 \;\ast\; \text{RACCEF}\,, &(44)\\
\text{ZCOEFF2} &= 17.1623 \ast \text{RRIMEF}\,, &(45)\\
\text{ZCOEFF2b} &= 17.1623 \ast \text{RAGGEF}\,. &(46)
\end{aligned}
$$

The three collection tendencies are computed with an analytic scheme applied to the terms $\overline{q_l}$ and $\overline{q_i}$. As an exemple, let us derive the result for the accretion term. The equivalent of the auto-conversion results (6), (7), (18) and (19) write

$$
\begin{aligned}
\left(\frac{\partial\overline{q_l}}{\partial t}\right)_{\text{acc}} &\approx \frac{\overline{q_l}^{\,(+)} \;-\; \overline{q_l}^{\,(-)}}{\Delta t} \;=\; -\;\frac{[\,\Delta\overline{q_r}\,]_{\text{acc}}}{\Delta t}\,, &(47)\\
\left(\frac{\partial\overline{q_l}}{\partial t}\right)_{\text{acc}} &\equiv -\;K^{(l/r)}_{\text{acc}}\;\;E^{(l/r)}_{\text{acc}}\;\;\overline{q_l}\;\;\overline{q_r}\,, &(48)\\
\Rightarrow\;\left(\frac{\partial\ln(\,\overline{q_l}\,)}{\partial t}\right)_{\text{acc}} &= -\;K^{(l/r)}_{\text{acc}}\;\;E^{(l/r)}_{\text{acc}}\;\;\overline{q_r}\,, &(49)\\
\text{and so :}\quad \frac{\overline{q_l}^{\,(+)}}{\overline{q_l}^{\,(-)}} &\approx \exp\left[\,-\;K^{(l/r)}_{\text{acc}}\;\;E^{(l/r)}_{\text{acc}}\;\;\overline{q_r}^{\,(-)}\;\;\Delta t\,\right]. &(50)
\end{aligned}
$$

Since the collection processes correspond to conversion terms from the suspended cloud condensate $\overline{q_l}$ or $\overline{q_i}$ into the precipitating species $\overline{q_r}$ or $\overline{q_s}$, the following properties holds

$$
[\,\Delta\overline{q_r}\,]_{\text{acc}} \;=\; \left[\,\overline{q_r}^{\,(+)} - \overline{q_r}^{\,(-)}\,\right]_{\text{acc}} \;=\; -\;[\,\Delta\overline{q_l}\,]_{\text{acc}} \;=\; -\;\left[\,\overline{q_l}^{\,(+)} - \overline{q_l}^{\,(-)}\,\right]_{\text{acc}}, \qquad (51)
$$

$$[\,\Delta\overline{q_s}\,]_{\text{agg}} \;=\; \Big[\,\overline{q_s}^{\,(+)} - \overline{q_s}^{\,(-)}\,\Big]_{\text{agg}} \;=\; -\,[\,\Delta\overline{q_i}\,]_{\text{agg}} \;=\; -\,\Big[\,\overline{q_i}^{\,(+)} - \overline{q_i}^{\,(-)}\,\Big]_{\text{agg}}, \quad (52)$$

$$[\,\Delta\overline{q_s}\,]_{\text{rim}} \;=\; \Big[\,\overline{q_s}^{\,(+)} - \overline{q_s}^{\,(-)}\,\Big]_{\text{rim}} \;=\; -\,[\,\Delta\overline{q_l}\,]_{\text{rim}} \;=\; -\,\Big[\,\overline{q_l}^{\,(+)} - \overline{q_l}^{\,(-)}\,\Big]_{\text{rim}}. \quad (53)$$

From (47) and (50), the final formulae for the decrease in $\overline{q_l}$ due to the accretion process, i.e. $-[\,\Delta\overline{q_l}\,]_{\text{acc}}$, is exacty equal to the corresponding opposite increase in $\overline{q_r}$, i.e. $[\,\Delta\overline{q_r}\,]_{\text{acc}}$. The impact of the accretion process is finally computed as a change in $\overline{q_r}$, given by (54)

$$[\,\Delta\overline{q_r}\,]_{\text{acc}} \;\equiv\; \Big[\,\overline{q_r}^{\,(+)} - \overline{q_r}^{\,(-)}\,\Big]_{\text{acc}} \;=\; \overline{q_l}^{\,(-)}\,\Big\{1 \;-\; \exp\Big[\,-\,K^{(l/r)}_{\text{acc}}\;E^{(l/r)}_{\text{acc}}\;\;\overline{q_r}^{\,(-)}\;\Delta t\,\Big]\Big\}, \quad (54)$$

$$[\,\Delta\overline{q_s}\,]_{\text{agg}} \;\equiv\; \Big[\,\overline{q_s}^{\,(+)} - \overline{q_s}^{\,(-)}\,\Big]_{\text{agg}} \;=\; \overline{q_i}^{\,(-)}\,\Big\{1 \;-\; \exp\Big[\,-\,K^{(i/s)}_{\text{agg}}\;E^{(i/s)}_{\text{agg}}\;\;\overline{q_s}^{\,(-)}\;\Delta t\,\Big]\Big\}, \quad (55)$$

$$[\,\Delta\overline{q_s}\,]_{\text{rim}} \;\equiv\; \Big[\,\overline{q_s}^{\,(+)} - \overline{q_s}^{\,(-)}\,\Big]_{\text{rim}} \;=\; \overline{q_l}^{\,(-)}\,\Big\{1 \;-\; \exp\Big[\,-\,K^{(l/s)}_{\text{rim}}\;E^{(l/s)}_{\text{rim}}\;\;\overline{q_s}^{\,(-)}\;\Delta t\,\Big]\Big\}. \quad (56)$$

The equivalent formulas for the aggregation and the riming processes are given in (55) and (56), with conversion of $\overline{q_l}$ or $\overline{q_i}$ into $\overline{q_s}$, generating positive values of $[\,\Delta\overline{q_s}\,]$.

From the general set of equations (1), and from (51) to (53), the accretion and riming processes cannot transform into the time step Δt more cloud liquid water than the available existing amount at time t, i.e. $\overline{q_l}$. Similarly, the aggregation process cannot transform more cloud ice water than $\overline{q_i}$.

It results the two following important limitations

$$[\,\Delta\overline{q_l}\,]_{\text{acc}} + [\,\Delta\overline{q_l}\,]_{\text{rim}} \;<\; \overline{q_l}\,, \quad (57)$$

$$[\,\Delta\overline{q_i}\,]_{\text{agg}} \;<\; \overline{q_i}\,. \quad (58)$$

1.3.6 A3-f : The evaporation processes

The tendencies due to the evaporation of rain E_r and the sublimation of snow E_s are given by Eq.(9) in Lopez (2002). The distributions (25) and (27) for the rain spectra and (29) and (31) for the snow spectra are used, together with some linearized versions of (C.7) and (C.8) made in Lopez (2002).

Let us define the four constant terms c_3 to c_6 by

$$c_3 \;=\; 2\,*\,0.78\,*\,\sqrt{\pi}\;\approx\;2.765\,, \quad (59)$$

$$c_4 \;=\; 2\,*\,(\pi)^{(3-\nu_2)/8}\;*\;0.31\,*\,\sqrt{\nu_1}\,*\,(\rho_{ref})^{0.2}\;*\;\Gamma\Big(\frac{5+\nu_2}{2}\Big)\;\approx\;30.1\,, \quad (60)$$

$$c_5 \;=\; \frac{4\,*\,0.65}{(2\,*\,\sigma_1)^{2/3}}\;\approx\;9.736\,, \quad (61)$$

$$c_6 \;=\; \frac{5.784\,*\,4\,*\,0.44}{(2\,*\,\sigma_1)^{(5+\tau_2)/6}}\;*\;\sqrt{\tau_1}\,*\,(\rho_{ref})^{0.2}\;*\;\Gamma\Big(\frac{5+\tau_2}{2}\Big)\;\approx\;478.1\,. \quad (62)$$

The coefficients c_3 to c_6 are computed in the subroutine ADVPRC in the local variables ZCOEFF3 to ZCOEFF6.

Let us define the terms $f_3(p)$ and $f_4(T,p)$, two functions of the temperature and the pressure, by

$$f_3(p) \;=\; \left[\;\sqrt{1.669\,10^{-5}}\;*\;2\,10^{-5}\;*\;(\,p_{ref}/p)\;\right]^{1/3} \approx\; 4.34\,10^{-3}\;*\;\left[\frac{p_{ref}}{p}\right]^{1/3}, \quad (63)$$

$$f_4(T,p) \;=\; \frac{R_v\;T}{2\,10^{-5}\;*\;(\,p_{ref}/p)} \;\approx\; 230.8\,10^5\;*\;T\;*\;\left[\frac{p_{ref}}{p}\right]^{-1}. \quad (64)$$

The coefficients f_3 and f_4 are computed in the subroutine ADVPRC in the local variables ZFACT3 and ZFACT4.

Let us define the evaporation and sublimation terms c_{evap} and c_{subl} by

$$c_{evap}(T,p) \;=\; \frac{[\,1-\overline{q_l}/(q_{sat})_l(T)\,]\,[\,1-N_s\,]}{\rho\;\;f_5(T,p)}\;*\;\text{RNINTR}\,, \quad (65)$$

$$c_{subl}(T,p) \;=\; \frac{[\,1-\overline{q_i}/(q_{sat})_i(T)\,]\,[\,1-N_s\,]}{\rho\;\;f_6(T,p)}\;*\;\text{RNINTS}\;*\;\exp\,[\,-\,0.122\,(T-T_f)\,]\,, \quad (66)$$

where RNINTR and RNINTS are both available in the NAMELIST, with f_5 and f_6 defined by

$$f_5(T,p) \;=\; \frac{1}{2.31\,10^{-2}\;*\;R_v}\;*\;\left(\frac{L_v(T)}{T}\right)^2 \;+\; \frac{f_4(T,p)}{(e_{sat})_l(T)}\,, \quad (67)$$

$$f_6(T,p) \;=\; \frac{1}{2.31\,10^{-2}\;*\;R_v}\;*\;\left(\frac{L_f(T)}{T}\right)^2 \;+\; \frac{f_4(T,p)}{(e_{sat})_i(T)}\,. \quad (68)$$

The coefficients f_5 and f_6 are computed in the subroutine ADVPRC in the local variable ZCONDT+ZDIFFV, just before the computations of ZCEV= c_{evap} and ZCSU= c_{subl}.

Let us define

$$c_{E1}(T,p) \;=\; c_{evap}(T,p)\;*\;c_3\,, \quad (69)$$

$$c_{E2}(T,p) \;=\; c_{evap}(T,p)\;*\;c_4\;/\;f_3(p)\,, \quad (70)$$

$$c_{S1}(T,p) \;=\; c_{subl}(T,p)\;*\;c_5\,, \quad (71)$$

$$c_{S2}(T,p) \;=\; c_{subl}(T,p)\;*\;c_6\;/\;f_3(p)\,. \quad (72)$$

The coefficients c_{E1}, c_{E1}, c_{S1} and c_{S2} are computed in the subroutine ADVPRC in the local variables ZCEV1, ZCEV2, ZCSU1 and ZCSU2, respectively.

For given amount of precipitations, either for rain $\overline{q_r}$ or for snow $\overline{q_s}$, the parts of them to be evaporated express in terms of the variables

$$<\overline{q_r}> \;=\; \overline{q_r}\;/\;\{\,\text{RNINTR}\;*\;\rho_w\,\}\,, \quad (73)$$

$$<\overline{q_s}> \;=\; \overline{q_s}\;/\;\{\,\text{RNINTS}\;*\;\exp\,[\,-\,0.122\,(T-T_f)\,]\,\}\,. \quad (74)$$

In the subroutine ADVPRC, $<\overline{q_r}>$ and $<\overline{q_s}>$ are denoted by ZQRNR and ZQRNS, respectively.

The final formulas (75) and (76), analogous of Eqs. (9), (C.7) and (C.8) in Lopez (2002), writes

$$\begin{aligned} \text{EVA} &= c_{E1} * <\overline{q_r}>^{1/2} + c_{E2} * <\overline{q_r}>^{17/24} , && (75) \\ \text{SUB} &= c_{S1} * <\overline{q_s}>^{2/3} + c_{S2} * <\overline{q_s}> . && (76) \end{aligned}$$

The flux terms EVA and SUB are denoted in ADVPRC by ZEVAPPL and ZEVAPPN, respectively. The corresponding decrease in liquid or solid precipitations are denoted by $\Delta <\overline{q_r}>=$ZTQEVAPPL and $\Delta <\overline{q_s}>=$ZTQEVAPPN, respectively. They are computed by choosing the minimum values among three terms, leading to

$$\Delta <\overline{q_r}> = \text{Min}\left\{ <\overline{q_r}> \; ; \; \Delta t \; \frac{\Delta p}{g} \; \text{EVA} \; ; \; \frac{\Delta p}{g} \frac{\text{EVA}}{\text{EVA}+\text{SUB}} \left[(q_{sat})_l(T) - \overline{q_v} \right] \right\}, \quad (77)$$

$$\Delta <\overline{q_s}> = \text{Min}\left\{ <\overline{q_s}> \; ; \; \Delta t \; \frac{\Delta p}{g} \; \text{SUB} \; ; \; \frac{\Delta p}{g} \frac{\text{SUB}}{\text{EVA}+\text{SUB}} \left[(q_{sat})_i(T) - \overline{q_v} \right] \right\}. \quad (78)$$

These limitations for the evaporations and sublimation processes are equivalent to the limitations (57) and (58), valid for the collection processes.

1.3.7 A3-g : The melting

The snow melting is computed in ADVPRC in the term ZQMLTX,

$$\text{ZQMLTX} = \text{Max}\left\{ 0 \; ; \; \frac{\Delta p}{g} \frac{c_p \, (T - T_f)}{L_f - L_v} \right\}, \quad (79)$$

where $L_f - L_v$ is the latent heat of fusion of snow into rain.

1.3.8 A3-h : The sedimentation processes

Differently to the time-stepping method applied in Fowler et al. (1996), the more innovative part of Lopez (2002) concerns the scheme of sedimentation of the precipitating species. In order to use the usual NWP or GCM longest time-step (up to 450 s or so in NWP, and 1800 s in GCM), a kind of semi-lagrangian method is applied in the subroutine ADVPRC, jointly with all the processes of collection, evaporation, sublimation or melting of the precipitations.

A new statistical scheme for the sedimentation of precipitations is presently tested in the NWP version of ARPEGE, in collaboration with the ALARO team, as described in Bouteloup et al. (2005), Bouyssel et al. (2005) and Geleyn et al. (2008). This new statistical scheme is available in the subroutine ADVPRCS and if LSSD=TRUE. It could allow the use of the true formulas (34) and (35) for the fall speed of the liquid or solid particles, instead of the "bulk" constant values TFVR and TFVS, as presently done in ADVPRC.

Up to now, only the original method of Lopez (2002), largely modified by Bouteloup et al. (2005) and Bouyssel et al. (2005), has been tested in the Climate version-5 of ARPEGE.

As a consequence, only the "semi-lagrangian" method used in the subroutine ADVPRC will be described in the present documentation. This subroutine ADVPRC is switched-on if LSSD=FALSE, with the use of constant values for TFVR and TFVS.

Sedimentation / part 1 :

The first step of the sedimentation scheme is to compute, for a given vertical level, the top height (ZZTOP) and bottom height (ZZBOT) of the layer located above it and from which the (liquid or solid) precipitations may reach this level (even if it could evaporate, for instance). The hypothesis of constant fall speed values TFVR and TFVS makes this part of the subroutine shorter in FORTRAN code, and cheaper in CPU time.

Sedimentation / part 2 :

Once ZZTOP and ZZBOT are known, the precipitation content are then computed at the origin point, also the mean precipitation flux (ZQPRTOT and ZQPSTOT), averaged from the top level down to the target layer, including the part generated by the auto-conversion. The average precipitation contents ZQR = ZQPRTOT/ZDZ and ZQS = ZQPSTOT/ZDZ are computed, to be used in the collection and evaporation computations. The layer depth ZDZ is equal to the distance between the top height level ZZTOP and the curent level.

Sedimentation / part 3 :

If LEVAPP=TRUE (available in the NAMELIST), the evaporation and sublimation processes are computed from (77) and (78). The input values (73) and (74) are denoted by ZQR = ZQPRTOT/ZDZ = $\overline{q_r}$ and ZQS = ZQPSTOT/ZDZ = $\overline{q_s}$. The terms EVA and SUB in (75) and (76) are denoted by ZEVAPPL and ZEVAPPN.

Sedimentation / part 4 :

A possible limitation could be switch on if REVASX $\neq 0$ (available in the NAMELIST), leading to LLEVAPX=TRUE. Presently REVASX $= 0$ in the GCM tests, but values such as REVASX $= 2\ 10^{-7}$ have been tested in NWP.

Sedimentation / part 5 :

The collection processes are computed if LCOLLEC=TRUE (available in the NAMELIST), from (54) to (56), plus (57) and (58), with some updated values for ZQR = $\overline{q_r}^{(-)}$ and ZQS = $\overline{q_s}^{(-)}$ in (54) to (56).

These updated values used as input of the collection processes are equal to the one before the evaporation and sublimation processes (i.e. ZQPRTOT and ZQPSTOT), from which the evaporation (ZTQEVAPPL) and sublimation (ZTQEVAPPN) fluxes are removed, leading to ZQPRTOT1=ZQPRTOT-ZTQEVAPPL and ZQPSTOT1=ZQPSTOT-ZTQEVAPPN, with the corresponding updated average values ZQR =ZQPRTOT1/ZDZ and ZQS =ZQPSTOT1/ZDZ.

The updated values after the collection processes are obtained from ZQPRTOT1 and ZQPSTOT1, from which the collections fluxes are removed or added, leading to ZQPR-

TOT2A, ZQPRTOT2B and ZQPSTOT2.

Sedimentation / part 6 :

The snow melting processes are computed if LLMELTS=TRUE (not available in the NAMELIST, set to TRUE at the begining of ADVPRC). The updated values after the melting processes is ZQPSTOT3.

Sedimentation / part 7 :

The final values of PFPEVPL and PFPEVPN (fluxes due to the evaporation of the precipitations), PFPFPL and PFPFPN (fluxes of generation of precipitations) and PFPLSL and PFPLSN (precipitation fluxes) are computed and made available as output of the subroutine ADVPRC.

1.4 A4 : Results and limitations

1.4.1 A4-a : Validations with SCM cases

1.5 A5 : Next modifications and possible improvements

2 Partie B : Interactions

2.1 B1 : Interactions with other parameterizations

2.2 B2 : Interactions with the data flow

2.3 B3 : Interactions with the dynamics

3 Partie C : Algoritmics - Informatic

3.1 C1 : Algorithmic choices - Strong Constraints

3.2 C2 : Algorithmic choices - Weak Constraints

3.3 C3 : Discretisations - spatial or temporal

3.4 C4 : The architecture - list of subroutines

The monitor of the ARPEGE physics is APLPAR. The Lopez (2002) scheme is called if LPROCLD.AND.LCONDWT=.TRUE., with the following sequence of subroutines.

APLPAR : monitor of the ARPEGE physics
> **ACPLUIZ** : general call to the Lopez subroutine (except QNGCOR)
> (ACNEBSM : compute the statistical cloud-cover and cloud-water ; only if LADJCLD=TRUE, and with use of the Smith (1990) triangular PDF) ;
> **in ACPLUIZ** : compute the condensation/evaporation of cloud water, with the statistical cloud water coming as input from the prognostic TKE-CBR00 scheme (if LNEBECT=TRUE) ;
> **ACMICRO** : compute the auto-conversion fluxes with PAUTOL and PAUTOI as output ;
> **ADVPRC** : compute the vertical sedimentation of the precipitation, plus the collection, the evaporation of precipitation and the melting (snow<->rain) processes ;
> (ADVPRCS : will replace ADVPRC, if LSSD=.TRUE.)
> **QNGCOR** : correction for possible negative specific humidity.

3.5 C5 : The architecture - list of NAMELIST options

The four prognostic variables (liquid and solid cloud water, rain and snow) must be defined as prognostic and advective GFL arrays. To do so, a set of new lines must be added in NAMGFL and NAMFA.

For the Liquid water (YL_NL), there are 8 lines to be added in NAMGFL.
&NAMGFL
YL_NL%LGP=.TRUE., ; Grid-Point (or spectral) type ?
YL_NL%LGPINGP=.TRUE., ; Grid-Point field input as Grid-Point ?
YL_NL%LT1=.TRUE., ; Field in t+dt GFL ?
YL_NL%LPHY=.FALSE., ; Field in physics GFL ?
YL_NL%LREQOUT=.TRUE., ; Field required in output (or not) ?
YL_NL%LADV=.TRUE., ; Advections required (or not) ?
YL_NL%LQM=.TRUE., ; Quasi-Monotone interpolations required (or not) ?
YL_NL%NREQIN=1, ; 1 if required in input ; 0 if not ; -1 if set to REFVALI

The same set of 8 lines must be added in NAMGFL for the other prognostic fields, with YL_NL replaced by YI_NL for the solid cloud water (Ice), the name YR_NL for the Rain and the name YS_NL for the Snow.

&NAMFA
YFAL%NBITS=12, ; GRIB packing : nb of bits to code in FA (liquid cloud water)

The same lines must be added in NAMFA, with YFAL%NBITS replaced by the name YFAI%NBITS for the solid cloud water (Ice), the name YFAR%NBITS for the Rain and the name YFAS%NBITS for the Snow.

&NAMPHY

LCONDWT=.TRUE., ; use of prog. condensed water in the Physics
LPROCLD=.TRUE., ; to switch-on the Lopez scheme
LEVAPP=.TRUE., ; to switch-on the evaporation of precipitations
LCOLLEC=.TRUE., ; to switch-on the collection processes
LNEBECT=.TRUE., ; use of Bougeault-Bechtold PDFs (<-> TKE-CBR)
LSSD=.FALSE., ; to switch-on the (next) statistical sedim. scheme

The usual tunable papareters are in the Namelist NAMPHY0.

&NAMPHY0

RQLCR=200. E-6, ; auto-conversion : threshold (liquid) (kg/kg)
RAUTEFR=0.001, ; auto-conversion : value for $1/\tau_l$ (unit in s^{-1})
RQICRMAX=30. E-6, ; maxi auto-conv. threshold (solid) (kg/kg)
RQICRMIN=0.2 E-6, ; mini auto-conv. threshold (solid) (kg/kg)
RAUTEFS=0.001, ; auto-conversion : value for $1/\tau_i$ (unit in s^{-1})
RAUTSBET=0.025, ; auto-conversion : the coefficient $(\beta)_{ice}$
RQICRT1=-80., ; auto-conversion : first temperature for $(q_i)_0$ (T_1, in K)
RQICRT2=30., ; auto-conversion : second temperature for $(q_i)_0$ (T_2, in K)
RQICRSN=0.5, ; auto-conv. : tunes the impact of CNC concentration on $(q_i)_0$
RDTFAC=0.5, ; auto-conv. : tunes the width of δ_{ice}in term of RDT= 11.82 K
RACCEF=1.0, ; collection efficiencies (accretion)
RAGGEF=0.2, ; collection efficiencies (aggregation)
RRIMEF=1.0, ; collection efficiencies (riming)
RNINTR=0.8 E+7, ; collection : a global tuning for c_{evap}
RNINTS=0.2 E+7, ; collection : a global tuning for c_{subl}
TFVR=5.0, ; Fall speed for rain (m/s)
TFVS=0.6, ; Fall speed for snow (m/s)
REVASX=0., ; to limit (if > 0) the evaporation of precipitations

4 Partie D : Références

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