Semi-Implicit Spectral Computations and Predictor-Corrector Schemes in the Cycle 44 of ARPEGE/IFS.

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Abstract:

This documentation describes two types of schemes allowing to stabilize the numerical discretizations of the models: the semi-implicit scheme and the iterative centred-implicit scheme (sometimes called predictor-corrector scheme). An algorithmic description to different types of equations, and some technical information (organigramme) are provided.

Résumé:

Cette documentation décrit deux types de schémas permettant de stabiliser les discrétisations numériques des modèles: le schéma semi-implicite et le schéma ICI (centré implicite itératif) encore appelé prédicteur-correcteur. On fournit une application de ces algorithmes à différents jeux d’équations, ainsi que des informations techniques (organigramme).
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1 Introduction.

1.1 Interest of semi-implicit and iterative centred-implicit schemes.

For both hydrostatic and non-hydrostatic models it is necessary to treat implicitly the linear terms source of (fast moving) gravity waves to ensure a good stability. Hence the resolution of equations involve the inversion of a linear system leading to a Helmholtz equation: inversion of such a system is more convenient to do in spectral space.

For non-hydrostatic models the semi-implicit scheme is generally not sufficient (especially for a two-time level semi-Lagrangian scheme) and some non-linear terms have also to be treated implicitly; for that one uses an iterative centred-implicit (abbreviated into “ICI”) scheme. The iterative centred-implicit schemes are often called “predictor-corrector” schemes, but in a theoretical point of view one has normally to reserve this appellation for a subset of iterative centred-implicit schemes with only one iteration. The iterative centred-implicit scheme can have an incremental formulation or a non-incremental formulation. The one which is coded in ARPEGE/IFS and its LAM version (for both hydrostatic and non-hydrostatic models) and which will be retained and described is a non-incremental one. All the additional calculations generated by an iterative centred-implicit scheme are mainly done in the grid-point calculations and in the spectral transforms.

1.2 The different models described.

- 2D shallow-water model.
- 3D primitive equations model (denoted as HYD).
- 3D fully elastic NH model with \( \hat{Q} \) and \( d \) or \( d_4 \) NH prognostic variables (denoted as NHEE or NH-PDVD).

1.3 Other restrictions of this documentation.

- In the non-hydrostatic model with \( \hat{Q} \) and \( d \) or \( d_4 \) NH prognostic variables, only the option with \( \hat{Q} \) and \( d \) as prognostic variables (options \texttt{NPDVAR=2, NVDVAR=3}) is currently described. The choice of \( d_4 \) as prognostic variable \texttt{NVDVAR=4} does not change the expression of linear terms.
- Linear systems are written for thin layer equations: in practical, they don’t change for deep layer equations because the radius \( r \) is linearised around a reference value equal to \( a \).

For the (Wood and Staniforth, 2003) NH deep-layer system, hydrostatic pressures (\( \Pi, \Pi_s \)) must be replaced by mass-integrated coordinates (\( \bar{\Pi}, \bar{\Pi}_s \)) in the linear system.
2 Denotations.

- $M$ is the mapping factor. $\bar{M}$ is a reference mapping factor for semi-implicit computations. $\bar{M} = c$ (stretching factor) if semi-implicit scheme with reduced divergence (LSIDG=F in YOMDYN). $M = M$ (mapping factor) if semi-implicit scheme with unreduced divergence (LSIDG=T in YOMDYN).
- $a$ is the Earth mean radius.
- $r$ is the radius. The reference value of $r$ for the linearisation is the mean radius $a$. In the thin layer equations, $r = a$ everywhere. In the LVERCOR=T (White and Bromley, 1995) deep-layer equations, $r$ is replaced by a pseudo-radius $\tilde{r}$, depending only on the hydrostatic pressure. All the equations involving the radius will be written with the denotation $\tilde{r}$.
- $V$ is the horizontal geographical wind. Its zonal component is $U$. Its meridian component is $V$.
- $D$ is the unreduced divergence of horizontal wind, $D'$ is the reduced divergence. $D$ and $D'$ are linked by the relationship $D = (a/r) * M^2 * D'$.
- $\zeta$ is the unreduced vorticity of horizontal wind, $\zeta'$ is the reduced vorticity. $\zeta$ and $\zeta'$ are linked by the relationship $\zeta = (a/r) * M^2 * \zeta'$.
- $w$ is the $z$-coordinate vertical velocity: $w = \frac{dz}{dt}$.
- $T$ is the temperature. $T^*$ is a vertically-constant reference temperature which is used in the semi-implicit scheme and in some non-hydrostatic equations. Default value is 300 K or 350 K according to configuration. If LSIDG=T (use of virtual temperature in spectral transforms instead of real temperature), $T^*$ is used as a reference virtual temperature (same default value).
- $T^*_a$ is a cold vertically-constant reference temperature which is used in the semi-implicit scheme in the NH vertical divergence equation; it is recommended to have $T^*_a$ lower than the current temperature.
- $q$ is the humidity.
- $\Pi$ is the hydrostatic pressure, $\Pi_s$ is the hydrostatic surface pressure. $\Pi^*$ is a reference hydrostatic pressure and $\Pi^*_s$ is a reference hydrostatic surface pressure, which are used in the semi-implicit scheme and in some non-hydrostatic equations. These reference quantities are vertically dependent and “horizontally” (i.e. on $\eta$ surfaces) constant. Default value of $\Pi^*_s$ is generally between 800 hPa and 1000 hPa. $\Delta \Pi^*$ are layer depths corresponding to a surface hydrostatic pressure equal to $\Pi^*_s$.
- $\Pi_{sst}$ is a reference hydrostatic pressure equal to the surface pressure of the standard atmosphere (variable VP00). Default value is 101325 Pa.
- $\omega = \frac{d\Pi}{dt}$ is the total temporal derivative of the hydrostatic pressure (vertical velocity in hydrostatic pressure coordinate).
- $gz$ is the geopotential height.
- $\Phi$ is the total geopotential (equivalent height in the shallow-water model), $\Phi_s$ is the surface geopotential (i.e. the orography). In the thin layer equations, $\Phi = gz$. $\Phi_s$ is assumed to be always equal to $gz_s$. $\Phi^*$ is a reference equivalent height which is only used in the shallow-water model (semi-implicit scheme). Default value of $\Phi^*$ is 100000 J/kg. $\Delta \Phi^*$ is a reference geopotential depth computed on model levels.
- $\Omega$ is the Earth rotation angular velocity.
- $r$ is the vector directed upwards, the length of which is the Earth radius $a$.
- $g$ is the gravity acceleration constant, assumed to be vertically constant in the current documentation. For the (Wood and Staniforth, 2003) deep-layer NH equations, the reference value of $g$ (vertically constant) is taken into account in the semi-implicit scheme.
- $R$ is the gas constant for air and $R_d$ is the gas constant for dry air.
- $c_p$ is the specific heat at constant pressure for air and $c_{pd}$ is the specific heat at constant pressure for dry air.
- $c_v$ is the specific heat at constant volume for air and $c_{vd}$ is the specific heat at constant volume for dry air.
- $\nabla$ is the unreduced first order horizontal gradient on $\eta$-surfaces. $\nabla'$ is the reduced first order horizontal gradient. These two operators are linked by the relationship $\nabla = (a/r) * M * \nabla'$.
- $p$ is the pressure, $p_s$ is the surface pressure.
- $Q$ is the pressure departure variable. Expression of $\dot{Q}$ is:

$$\dot{Q} = \log \frac{P}{\Pi}$$

(1)
• $D_3$ is the true 3D divergence. In the thin layer equations, expression of $D_3$ is:

$$
D_3 = \nabla V + \frac{p}{\frac{d}{RT}} \nabla \Phi \left( \frac{\partial V}{\partial \eta} \right) - \frac{gp}{\frac{d}{RT}} \left( \frac{\partial w}{\partial \eta} \right).
$$

(2)

• $d$ is the vertical divergence. In the thin layer equations, the relationship between $d$ and the height-coordinate vertical velocity $w$ is:

$$
d = - \frac{gp}{RT} \left( \frac{\partial w}{\partial \eta} \right).
$$

(3)

• Variable $d_4 = d + \frac{p}{\frac{d}{RT}} \nabla \Phi \left( \frac{\partial V}{\partial \eta} \right)$ can be also used as prognostic variable.

• $L$: number of layers of the model.

• $A, B$ define hydrostatic pressure on the $\eta$ levels ($\Pi = A + B \Pi_s$, where $\Pi_s$ is the hydrostatic surface pressure).

• $\beta$ coefficient for the semi-implicit scheme (between 0 and 1).

• $\gamma, \tau, \nu, \mu, G^*, S^*, N^*$ are generic denotations for linear operators (see subsection 4.2).

• $L^*, Q^*$ and $T^*$ are generic denotations for linear operators used in non-hydrostatic models (see subsection 4.2).

• $H, C, N$ are intermediate constants used in the semi-implicit scheme of the non-hydrostatic model. Definitions are respectively:

$$
H = \frac{R_d T^*}{g}
$$

(4)

$$
C = \sqrt{\frac{R_d T^* c_p d}{\nu c_d}}
$$

(5)

$$
N = \frac{g}{\sqrt{c_p d T^*}}
$$

(6)

• For a variable $X$ defined at full levels, $\langle X \rangle$ is the vector of coordinates ($X_1; \ldots; X_i; \ldots; X_L$).

• $R_{inte}$ is the vertical integration operator used in the case $\text{LVERTFE}=.T.$:

  - $\int_{\eta=0}^{\eta=1} X \, d\eta$ is discretised by $[R_{inte}]_{(top, surf)} \langle X \rangle$.
  - $\int_{\eta=0}^{\eta=1} X \, d\eta$ is discretised by $[R_{inte}]_{(top,t)} \langle X \rangle$.
  - $\int_{\eta=\eta_l}^{\eta=1} X \, d\eta$ is discretised by $[R_{inte}]_{(l, surf)} \langle X \rangle$.

• $R_{deri}$ is the vertical first-order derivative operator used in the case where VFE are also applied to derivatives.
3 General considerations.

3.1 Advection schemes.

* Explicit Eulerian equations: In Eulerian form of equations, the time dependency equation of a variable \( X \) writes as:

\[
\frac{\partial X}{\partial t} = -U \nabla \times X + A + F
\]  

where \( U \) is the 3D wind, \( \nabla \times \) is the 3D gradient operator, \( A \) is the dynamical contribution, and \( F \) is the physical contribution. \( X(t + \Delta t) \) is computed knowing \( X(t - \Delta t) \) at the same grid point.

* Explicit semi-Lagrangian equations: In semi-Lagrangian form of equations, the time dependency equation of a variable \( X \) writes as:

\[
\frac{dX}{dt} = A + F
\]  

In a three-time level semi-Lagrangian scheme (abbreviated into SL3TL scheme) \( X(t + \Delta t) \) is computed at a grid point \( F \) knowing \( X(t - \Delta t) \) at the point \( O \) (not necessary a grid point) where the same particle is at \( t - \Delta t \). In a two-time level semi-Lagrangian scheme (abbreviated into SL2TL scheme) \( X(t + \Delta t) \) is computed at a grid point \( F \) knowing \( X(t) \) at the point \( O \) (not necessary a grid point) where the same particle is at \( t \).

3.2 Semi-implicit treatment of linear terms.

* Adding of a semi-implicit correction: In all cases the linear terms source of gravity waves must be treated implicitly, in order to allow time-steps compatible with an operational use of the model. Expression of the linear terms is obtained assuming a definition of a reference state. The reference state is defined by a dry resting isotherm atmosphere in hydrostatic balance, reference orography is zero. Equations (7) and (8) become respectively (9) and (10):

- Eulerian scheme:
  \[
  \frac{\partial X}{\partial t} = -U \nabla \times X + A + F + [SI_{correction}]
  \]  

- Semi-Lagrangian scheme:
  \[
  \frac{dX}{dt} = A + F + [SI_{correction}]
  \]

* Discretisation of equations (9) and (10): Equations (9) and (10) give the following discretized equations, where \( \Delta t \) is the time step, \( L \) is the linear term source of gravity waves, \( \beta \) is a tunable parameter (\( \beta = 0 \) corresponds to an explicit formulation, \( \beta = 1 \) to an implicit formulation):

  - Eulerian scheme (all computations are done at the same grid point):
    \[
    [SI_{correction}] = -\beta L^t + 0.5\beta L^{t - \Delta t} + 0.5\beta L^{t + \Delta t}
    \]  

  - Three-time level semi-Lagrangian (SL3TL) scheme (without uncentering factor):
    \[
    [SI_{correction}] = -\beta L^t + 0.5\beta L^{t - \Delta t} + 0.5\beta L^{t + \Delta t}
    \]  

where \( X^{t+\Delta t} - \beta \Delta t L^{t+\Delta t} \) is computed at the final grid point of the semi-Lagrangian trajectory, \( X^{t-\Delta t} \) and \( \beta \Delta t L^{t-\Delta t} \) are computed at the origin point of the semi-Lagrangian trajectory, \( -2\beta \Delta t L^t \) is computed as an average between the origin and final points of the trajectory, \( A \) is computed either at the medium point or as an average between the origin and final points of the trajectory. If there is a uncentering factor \( \epsilon \) replace \( \Delta t \) by \( (1 - \epsilon) \Delta t \) for terms at the origin point, \( \Delta t \) by \( (1 + \epsilon) \Delta t \) for terms at the final point. For more details see documentation (IDSL) about the semi-Lagrangian scheme.

  - Two-time level semi-Lagrangian (SL2TL) scheme (without uncentering factor):
    \[
    [SI_{correction}] = -\beta L^{t+0.5\Delta t} + 0.5\beta L^t + 0.5\beta L^{t+\Delta t}
    \]  

where \( X^{t+\Delta t} - 0.5\beta \Delta t L^{t+\Delta t} \) is computed at the final grid point of the semi-Lagrangian trajectory, \( X^t \) and \( 0.5\beta \Delta t L^t \) are computed at the origin point of the semi-Lagrangian trajectory, \( -\beta \Delta t L^{t+0.5\Delta t} \) and \( A \)
are computed either at the medium point or as an average between the origin and final points of the trajectory. If there is a first-order uncentering factor \( \epsilon \) replace \( \Delta t \) by \((1 - \epsilon)\Delta t\) for terms at the origin point, \( \Delta t \) by \((1 + \epsilon)\Delta t\) for terms at the final point. For more details see documentation (IDSL) about the semi-Lagrangian scheme.

\( \mathcal{L}^{t+0.5 \Delta t} \), \( \mathcal{L}' \) and \( \mathcal{L}'^{t-\Delta t} \) are computed in grid point space. The right-hand side members of equations (12), (14) and (16) are computed in grid point space, then transformed into spectral space. Entering spectral space a system of equations of the following type must be solved:

\[
X^{i+\Delta t} - \beta \Delta t \mathcal{L}^{t+\Delta t} = X^* \tag{17}
\]

for a leap-frog scheme, and:

\[
X^{i+\Delta t} - 0.5\beta \Delta t \mathcal{L}^{t+\Delta t} = X^* \tag{18}
\]

for a two-time level semi-Lagrangian scheme, where \( X^* \) is known and \( X^{i+\Delta t} \) is unknown.

### 3.3 Iterative centred-implicit schemes and combination with semi-implicit schemes.

In some cases (especially in the non-hydrostatic models), the model with a semi-implicit treatment of linear terms may remain unstable, hence a treatment by an iterative centred-implicit scheme may be necessary. In the following description one sticks to non-incremental formulations.

**Algorithm:** The total number of iterations is denoted by \( N_{\text{iter}} \).

- The iteration number \((i = 0)\) computes an estimation \( X^{i+\Delta t}_{(i=0)} \) of \( X^{i+\Delta t} \) with a normal semi-implicit scheme.
- Iterations \((i > 0)\): the \( i \)-th iteration \((i > 0)\) computes \( X^{i+\Delta t}_{(i)} \) (after inversion of Helmholtz equation) knowing \( X^{i+\Delta t}_{(i-1)} \). The final value of \( X^{i+\Delta t} \) is equal to \( X^{i+\Delta t}_{(i=N_{\text{iter}})} \).
- Horizontal diffusion is always done at the last iteration, it can be done optionally at the other iterations.
- This scheme is controlled by the key \( \text{LPC}_\text{FULL}=\text{T} \).
- For unlagged physics, the physics has to be computed for the iteration \((i = 0)\) only. For lagged physics, iterations 0 to \( N_{\text{iter}} - 1 \) are adiabatic ones, iteration \( N_{\text{iter}} \) is diabatic one.

**Discretisation of algorithm:**

- First iteration \((i = 0)\): One has to start from the discretisations of equations for a model with no iterative centred-implicit formulation (see documentsations (IDEUL) and (IDSL)). For a leap-frog scheme the calculations are the same ones. For a SL2TL scheme, \((A - \beta \Delta t \mathcal{L})^{t+0.5 \Delta t}_{(i=0)}\) is assumed to be equal to \((A - \beta \Delta t \mathcal{L})^{t+0.5 \Delta t}\) if no extrapolation is done (case \( \text{LNECS}=\text{T} \)), and to \(1.5(A - \beta \Delta t \mathcal{L})^{t} - 0.5(A - \beta \Delta t \mathcal{L})^{t-\Delta t}\) if extrapolation is done (case \( \text{LNECS}=\text{F} \)). For a SL2TL case with no uncentering factor that yields the following discretisations (physics is assumed to be unlagged):
  
  - no extrapolation:
    \[
    (X^{i+\Delta t}_{(i=0)}-0.5\Delta t\beta \mathcal{L}^{t+\Delta t}_{(i=0)}F) = [0.5\Delta t A' - 0.5\Delta t \beta \mathcal{L}']F + [X^t + 0.5\Delta t A' - 0.5\Delta t \beta \mathcal{L}^t + 0.5\Delta t \beta \mathcal{L}^t + \Delta t F^t]_{O(i=0)}
    \]
  
  - extrapolation: discretisation is identical to the case with no iterative centred-implicit scheme and conventional extrapolation (type \( \text{LSETTLS}=\text{F} \)); the RHS terms other than \( X^t \) and \( F^t \) can be replaced by a “spatio-temporal” average; see documentation (IDSL).

- Following iterations \((i > 0)\): The general iteration writes (no uncentering, unlagged physics):
  
  - Eulerian scheme (\( ADV \) stands for advection terms):
    \[
    X^{i+\Delta t} = \Delta t (X^t + t \mathcal{L}^{t+\Delta t}_{(i)}) + \Delta t (X^{i+\Delta t} - X^{i+\Delta t}_{(i-1)}) + \Delta t (X^t A' - \beta \mathcal{L}^t + \Delta t F^t)_{O(i=0)}
    \]

  - which can be rewritten:
    \[
    X^{i+\Delta t} = \Delta t (X^t A' - \beta \mathcal{L}^t + \Delta t F^t)_{O(i=0)}
    \]

7
– SL3TL (without uncentering factor):

\[ X_{O(i)}^{t+\Delta t} - \Delta t \beta L_{(i)}^{t+\Delta t} \]

\[ = X_{O(i)}^t + \left[ \Delta t A_{(i-1)}^{t+\Delta t} - \Delta t \beta L_{(i-1)}^{t+\Delta t} \right]_F + \left[ \Delta t A_{(i)}^{t-\Delta t} - \Delta t \beta L_{(i)}^{t-\Delta t} \right]_{O(i)} + \left[ \Delta t \beta L_{(i)}^{t-\Delta t} + 2 \Delta t F_{(i)}^{t-\Delta t} \right]_{O(i)} \]

which can be rewritten:

\[ X_{O(i)}^{t+\Delta t} - \Delta t \beta L_{(i)}^{t+\Delta t} \] \[ = X_{O(i)}^t + \left[ \Delta t A_{(i-1)}^{t+\Delta t} - \Delta t \beta L_{(i-1)}^{t+\Delta t} \right]_F + \left[ \Delta t A_{(i)}^{t-\Delta t} - \Delta t \beta L_{(i)}^{t-\Delta t} \right]_{O(i)} + \left[ \Delta t \beta L_{(i)}^{t-\Delta t} + 2 \Delta t F_{(i)}^{t-\Delta t} \right]_{O(i)} \]

The iterative centred-implicit algorithm also applies to re-compute the semi-Lagrangian trajectory (see documentation (IDSL) for more details), the position of the origin point at the \( i \)-th (resp \( i-1 \)-th) iteration is \( O(i) \) (resp. \( O(i-1) \)).

– SL2TL (without uncentering factor):

\[ X_{O(i)}^{t+\Delta t} - 0.5 \Delta t \beta L_{(i)}^{t+\Delta t} \] \[ = X_{O(i)}^t + \left[ 0.5 \Delta t A_{(i-1)}^{t+\Delta t} - 0.5 \Delta t \beta L_{(i-1)}^{t+\Delta t} \right]_F + \left[ 0.5 \Delta t A_{(i)}^{t-\Delta t} - 0.5 \Delta t \beta L_{(i)}^{t-\Delta t} \right]_{O(i)} + \left[ 0.5 \Delta t \beta L_{(i)}^{t-\Delta t} + \Delta t F_{(i)}^t \right]_{O(i)} \]

which can be rewritten:

\[ X_{O(i)}^{t+\Delta t} - 0.5 \Delta t \beta L_{(i)}^{t+\Delta t} \] \[ = X_{O(i)}^t + \left[ 0.5 \Delta t A_{(i-1)}^{t+\Delta t} - 0.5 \Delta t \beta L_{(i-1)}^{t+\Delta t} \right]_F + \left[ 0.5 \Delta t A_{(i)}^{t-\Delta t} - 0.5 \Delta t \beta L_{(i)}^{t-\Delta t} \right]_{O(i)} + \left[ 0.5 \Delta t \beta L_{(i)}^{t-\Delta t} + \Delta t F_{(i)}^t \right]_{O(i)} \]

The iterative centred-implicit algorithm also applies to re-compute the semi-Lagrangian trajectory (see documentation (IDSL) for more details), the position of the origin point at the \( i \)-th (resp \( i-1 \)-th) iteration is \( O(i) \) (resp. \( O(i-1) \)). Remark: when the iterative centred-implicit scheme is used, the stable extrapolation \( \text{LSETTL}=\text{T} \) is never involved.

* Cheap version of this algorithm: In a semi-Lagrangian scheme, it is possible not to iterate the position of the origin point \( O \) (i.e \( O(i) = O(i-1) \)): this cheap version is activated if \( \text{LPC}_\text{CHEAP}=\text{T} \).

It is coded only for a non-extrapolating SL2TL scheme. In this case the quantity to be interpolated (i.e. \( [0.5 \Delta t A_{(i-1)}^t + \Delta t F_{(i)}^t]_{O(i)} \)) needs to be interpolated at the predictor step only. It is then stored in a buffer and reused at the corrector steps without any interpolation.

3.4 Introduction of uncentering for semi-Lagrangian schemes.

Averages along the semi-Lagrangian trajectory will be weighted by \((1-\epsilon)\) at the origin point and \((1+\epsilon)\) at the final point. If the uncentering coefficient \( \epsilon \) is horizontally constant the algorithms remain valid, replacing \( \beta \) by \((1+\epsilon)\beta\).

3.5 Limited area models (ALADIN, AROME).

Particular features for LAM models are not described in detail, only brief comments are mentioned. Most parts of this documentation remain valid, the main differences with ARPEGE/IFS are:

- The LAM model shallow-water model is not coded.
- Option \( \text{LIMPFF}=\text{T} \) is not coded.
- Option \( \text{LESIDG}=\text{T} \) replaces \( \text{LSIDG}=\text{T} \), and is available only with the tilted-rotated Mercator projection. See (IDESIDG) about its implementation.
- Some spectral calculations are done in routines named \( \text{ESP}_\text{SI} \) which are LAM counterparts of \( \text{SP}_\text{SI} \) routines. The algorithm is the same as in global model but the truncation of the spectral representation is elliptic and not triangular.

3.6 Finite elements on the vertical.

The option with finite element vertical discretisations is coded for the hydrostatic model and partly for the NH models. For VFE, the main modifications in the semi-implicit scheme are the following ones:

- The discretisation of \( \Pi, \alpha \) and \( \delta \) at full levels is different.
- The model avoids as possible to compute quantities at half levels; all vertical integrals directly provide quantities at full levels.
- The vertical integrals contained in some linear operators \((\gamma, \tau \) and \( \nu \)) are discretised differently, as a matricial multiplication with special coefficients (contained in the matrix \( \mathcal{R}_{\text{vert}} \)) computed in the setup code under \( \text{SUVERTFE} \); the vertical integration is done by routine \( \text{VERINT} \).
- In NH models there are also vertical derivatives with a specific treatment.
4 Prognostic variables and quantities involved in the semi-implicit scheme.

4.1 Prognostic variables.

Prognostic variables can be split into different classes:

- **3D variables**, the equation RHS of which has a non-zero adiabatic contribution and a non-zero semi-implicit correction contribution. They are called “GMV” in the code (“GMV” means “grid-point model variables”). This class of variables includes the components of the horizontal wind $V$, temperature $T$, and the two additional non-hydrostatic variables in a non-hydrostatic model. Details about equations of the NH variables in the NH-PDVD model (choice of the two additional prognostic variables, discretisations, linearisation for semi-implicit scheme) can be found for example in (IDNHPB).

- **3D “conservative” variables**. The equation RHS of these variables has a zero adiabatic contribution, only the diabatic contribution (and the horizontal diffusion contribution) can be non-zero. They are called “GFL” in the code (“GFL” means “grid-point fields”). This class of variables includes for example humidity $q$, liquid water, ice, cloud fraction, ozone, and some extra fields.

- **2D variables**, the equation RHS of which mixes 3D and 2D terms, has a non-zero adiabatic contribution and a non-zero semi-implicit correction contribution. They are called “GMVS” in the code (“GMVS” means “grid-point model variables for surface”). This class of variables includes the logarithm of surface pressure (continuity equation).

Only the GMV and GMVS variables appear in the semi-implicit scheme. In the shallow-water 2D model, only GMV variables exist, this class of variables includes the components of the horizontal wind $V$, and the equivalent height $\Phi - \Phi_s$ (continuity equation).

4.2 Quantities used for vertical discretisations and linear operators.

The following quantities and operators may have different discretisations according to the fact that finite differences (FD) or finite elements (VFE) are used for vertical discretisations in the model. The following abbreviations will be used:

- **FD0**: finite differences ($\text{LVERTFE}=.F.$) using $\text{NDLNPR}=0$.
- **FD1**: finite differences ($\text{LVERTFE}=.F.$) using $\text{NDLNPR}=1$.
- **FD**: finite differences ($\text{LVERTFE}=.F.$), any value for $\text{NDLNPR}$.
- **VFE**: vertical finite elements ($\text{LVERTFE}=.T.$).

4.2.1 Operators “alpha” and “delta”.

These operators are used for discretisations of some vertical integrals. They have a different expression according to the value of variables $\text{NDLNPR}$, $\text{LVERTFE}$.

- **FD0**:
  - For a layer $l$ between 2 and $L$ (and also $l = 1$ if the pressure at the top of the model is not zero), $\alpha^*$ and $\delta^*$ are discretised as follows at full levels:
    
    $$
    \alpha_l^* = 1 - \frac{\Pi_l^* - 1}{\Delta \Pi_l^*} \log \left( \frac{\Pi_l^*}{\Pi_{l-1}^*} \right)
    \tag{19}
    $$

    $$
    \delta_l^* = \log \left( \frac{\Pi_l^*}{\Pi_{l-1}^*} \right)
    \tag{20}
    $$

  - For the layer $l = 1$ if the pressure at the top of the model is zero:
    
    * $\alpha_l^* = 1$ at METEO-FRANCE.
    * $\alpha_l^* = \log(2)$ at ECMWF.
    * $\delta_l^*$ has in theory an infinite value, but in the code it is computed with a top pressure equal to 0.1 Pa to provide a finite value.

- **FD1**:
  - For a layer $l$ between 2 and $L$ (and also $l = 1$ if the pressure at the top of the model is not zero), $\alpha^*$ and $\delta^*$ are discretised as follows at full levels:
    
    $$
    \alpha_l^* = 1 - \sqrt{\frac{\Pi_l^*}{\Pi_{l-1}^*}} = 1 - \frac{\Pi_l^*}{\Pi_{l-1}^*}
    \tag{21}
    $$
\[ \delta_i^* = \frac{\Delta \Pi_i^*}{\Pi_i^*} = \frac{\Delta \Pi_i^*}{\sqrt{\Pi_{i-1}^* \Pi_{i+1}^*}} \]  
\[ \Pi^* \text{ is discretised as follows at full levels:} \]
\[ \Pi_i^* = \sqrt{\Pi_{i-1}^* \Pi_{i+1}^*} \]  
\[ \text{Denotation } \alpha_{i-1}^* \text{ is used for quantity } 1 - \frac{\Pi_{i-1}^*}{\Pi_i^*} \text{ instead of denotation } \beta_i^* \text{ of (Bubnová et al., 1995).} \]

- For the layer \( l = 1 \) if the pressure at the top of the model is zero:
  * \( \alpha_{l-1}^* = 1 \) and \( \alpha_{l=0}^* = 1 \).
  * \( \delta_{l=1}^* = 1 + c_{\text{up}}/R_d \).
  * \( \Pi_{l=1}^* = \Delta \Pi_{l=1}/\delta_{l=1}^*. \)

- VFE: for a layer \( l \) between 1 and \( L \), \( \alpha^* \) and \( \delta^* \) are discretised as follows at full levels:
  \[ \alpha_l^* = \frac{\Pi_l^* - \Pi_{l-1}^*}{\Pi_{l-1}^*} \]  
  \[ \delta_l^* = \frac{\Delta \Pi_l^*}{\Pi_{l+1}^*} \]
  \[ \text{where } \Pi_i^* = A_i + B_i \Pi_i^*. \text{ See documentation (IDEUL) for computation of } A_i \text{ and } B_i \text{ in this case. Formulae } (24) \text{ and } (25) \text{ provide finite values of } \alpha_l^* \text{ and } \delta_l^* \text{ even if the pressure at the top of the model is zero. } \alpha_l^* \text{ is not used in the SI scheme in this case because vertical integrals are directly provided at full levels without the intermediate state of interlayer data.} \]

### 4.2.2 Vertical integrals and linear products.

These operators are used in both hydrostatic and non-hydrostatic models.

* **Linear operator “*G*”, and its dimensionless counterpart \( \mathbf{G}^* \):** this operator is applied to temperature and pressure departure variable to compute linear term in momentum equation.

  - For a variable \( Z \), \( (\mathbf{G}^* Z) \) is a discretisation of vertical integral: \( \int_0^Z \frac{\partial \Pi^*}{\partial \eta} Z d\eta \)
  - \( \gamma Z = R_s(\mathbf{G}^* Z) \)
  - VFE expression of this discretisation is:
    \[ (\mathbf{G}^* Z)_l = \left[ R_{\text{inte}}(t, \text{surf}) \right] \frac{Z \delta^*}{\Delta \eta} \]  
  - FD expression of this discretisation is:
    \[ (\mathbf{G}^* Z)_l = \alpha_l^* Z_l + \sum_{k=l+1}^L Z_k \delta_k^* \]  
  
  Remark: if \( \text{LSPRT= T.} \), \( \mathbf{G}^* \) is applied to virtual temperature instead of real temperature.

* **Linear operator “*r*”, and its dimensionless counterpart \( \mathbf{S}^* \):** this operator is applied to divergence to compute linear term in temperature equation.

  - For a variable \( Z \), \( (\mathbf{S}^* Z) \) is a discretisation of vertical integral: \( \int_0^Z \frac{\partial \Pi^*}{\partial \eta} Z d\eta \)
  - \( \tau Z = [R_s T^*]R_{\text{cp,d}}(\mathbf{S}^* Z) \) if \( \text{LSPRT=} \text{F}. \)
  - \( \tau Z = [(R_s T^*)/(R_{\text{cp,d}})](\mathbf{S}^* Z) \) if \( \text{LSPRT=} \text{T.} \) (equivalent to apply a linear operator in a system of equations using virtual temperature).

  - VFE expression of this discretisation is:
    \[ (\mathbf{S}^* Z)_l = \frac{\delta^*}{\Delta \Pi_l^*} \left[ R_{\text{inte}}(t, \text{top}) \right] \frac{\Delta \Pi^* Z}{\Delta \eta} \]  
  - FD expression of this discretisation is:
    \[ (\mathbf{S}^* Z)_l = \frac{1}{\Pi_l^*} \left[ R_{\text{inte}}(t, \text{top}) \right] \frac{\Delta \Pi^* Z}{\Delta \eta} \]
    \[ (\mathbf{S}^* Z)_l = \alpha_l^* Z_l + \frac{\delta_l^*}{\Delta \Pi_l^*} \sum_{k=l+1}^{l-1} \Delta \Pi_k^* Z_k \]  

Remark: according to the expression of \( \delta_l^* \) in this case, this equation can be rewritten:
**Linear operator “ν”, and its dimensionless counterpart N**: this operator is applied to divergence to compute linear term in continuity equation.

- For a variable \( Z \), \((N^*Z)\) is a discretisation of vertical integral: \( \frac{1}{\Pi^*} \int_0^{\Pi^*} \frac{\partial \Pi^*}{\partial \eta} Z \, d\eta \)
- \( \nu Z = N^*Z \) (because use of \( \log \Pi_s \)).
- VFE expression of this discretisation is:
  \[
  (N^*Z) = \frac{1}{\Pi^*} \left[ \Pi \right]^{top,surf} \left( \Delta \Pi^* \frac{\partial Z}{\partial \eta} \right)
  \]
  \( (\text{30}) \)
- FD expression of this discretisation is:
  \[
  (N^*Z) = \frac{1}{\Pi^*} \sum_{i=1}^{L} \Delta \Pi^*_i Z_i
  \]
  \( (\text{31}) \)

**Linear operator “µ”, and its dimensionless counterpart I**: this operator is applied to \( \log(\Pi_s) \) to compute linear term in momentum equation.

- I is the identity matrix: \( IZ = Z \).
- \((\mu Z) = R_d T^* Z \) if \( \text{LSPRT} = \text{F} \).
- \((\mu Z) = (R_d^2/R) T^* Z \) if \( \text{LSPRT} = \text{T} \). (equivalent to apply a linear operator in a system of equations using virtual temperature).

**Relationship between these vertical operators and definition of constraint C1:**

Continuous equations ensure the following identity:

\[
G^*S^* - S^* - G^* + N^* = 0
\]
(32)

According to the vertical discretisation used, this identity may or may not be matched by the discretised operators. Definition of “constraint C1” is: the discretised operators matches equation (32).

- FD0 and VFE: constraint C1 is not ensured.
- FD1: constraint C1 is ensured.

In the NH-PDVD model, constraint C1 SHOULDN’T be ensured if one wants the complete elimination of variables in order to provide a “one variable” Helmholtz equation computing the vertical divergence. This is why the FD1 is preferred to FD0 when using FD discretisation. For VFE, Helmholtz equation treatment requires adaptations to take account of the fact that constraint C1 is not ensured.

When constraint C1 is not ensured, we introduce the dimensionless quantity \( \text{COR} \):

\[
\text{COR} = \frac{c_v d}{R_d^2 T^*} \ddot{\gamma} \tau - \frac{c_v d}{R_d c_p d} \gamma - \frac{c_v d}{c_p d} \ddot{\gamma} \tau + \frac{c_v d}{c_p d} \nu = \frac{c_v d}{c_p d} (G^*S^* - S^* - G^* + N^*)
\]
(33)

### 4.2.3 Vertical derivatives and mixed operators (NH models only).

These operators are used in non-hydrostatic models only.

**Linear operator “L^*”:** this operator, called Laplacian operator, is applied to the pressure departure variable to compute linear term in the vertical divergence equation (NH-PDVD model).

- For a variable \( Z \), \((L^*Z)\) is the vertical double derivative \( \left[ \Pi^* \frac{\partial}{\partial \Pi^*} \left( \frac{\partial \Pi^* Z}{\partial \Pi^*} \right) \right] \).
- FD expression of this discretisation is:
  
  - Layers 2 to \( L - 1 \):
    \[
    (L^*Z)_t = A_t^* Z_{t-1} + B_t^* Z_t + C_t^* Z_{t+1}
    \]
    (34)

  Expressions of \( A_t^* \), \( B_t^* \) and \( C_t^* \) are:

  \[
  A_t^* = \frac{\Pi_{t-1}}{\delta_{l}^* (\Pi_t^* - \Pi_{t-1}^*)}
  \]
  (35)

  \[
  B_t^* = -\frac{1}{\delta_{l}^*} \left( \frac{\Pi_t^*}{\Pi_t^* - \Pi_{t-1}^*} + \frac{\Pi_{t+1}^*}{\Pi_{t+1}^* - \Pi_{t}^*} \right)
  \]
  (36)
\[ C_l^* = \frac{\Pi_{l+1}^*}{\delta_l^*(\Pi_{l+1}^* - \Pi_l^*)} \]  

(37)

Note that equation (34) can be rewritten:

\[ (L^*Z)_l = A_l^*(Z_{l-1} - Z_l) + C_l^*(Z_{l+1} - Z_l) \]  

(38)

- Layer 1: The quantity \( Z \) to which is applied \( L^* \) is assumed to be zero at the top of the model, that means that the term \( A_1^*(Z_0 - Z_1) \) has to be replaced by \(-A_1^*Z_1\). In practical, \( A_1^* \) has to be set to zero if the top hydrostatic pressure is zero, and the general formula valid for any non-zero top pressure is:

\[ A_1^* = \frac{\Pi_{\text{top}}^*}{\delta_1^*(\Pi_1^* - \Pi_{\text{top}}^*)} \]  

(39)

\[ C_1^* = \frac{\Pi_2^*}{\delta_1^*(\Pi_2^* - \Pi_1^*)} \]  

(40)

and, if the top hydrostatic pressure is zero:

\[ B_1^* = -C_1^* \]  

(41)

This upper condition is stable at least when the top hydrostatic pressure is zero.

That leads to the following formula for \( (L^*Z)_1 \):

\[ (L^*Z)_1 = -A_1^*Z_1 + C_1^*(Z_2 - Z_1) \]  

(42)

- Layer \( L \): The quantity \( Z \) to which is applied \( L^* \) is assumed to be constant below the full level \( l = L \), that means that the term \( C_L^*(Z_{L+1} - Z_L) \) has to be replaced by 0. In practical, \( C_L^* \) is set to zero. \( A_L^* \) matches the general expression:

\[ A_L^* = \frac{\Pi_{L-1}^*}{\delta_L^*(\Pi_L^* - \Pi_{L-1}^*)} \]  

(43)

Application of formula (38) would lead to \( B_L^* = -A_L^* \) but we actually use the formula (34) with a slightly different expression for \( B_L^* \):

\[ B_L^* = -\frac{\Pi_L^*}{\delta_L^*(\Pi_L^* - \Pi_{L-1}^*)} \]  

(44)

That leads to the following formula for \( (L^*Z)_L \):

\[ (L^*Z)_L = A_L^*(Z_{L-1} - Z_L) - A_L^* \left( \frac{\Pi_L^*}{\Pi_{L-1}^*} - 1 \right) Z_L \]  

(45)

- VFE expression of this discretisation in the NH-PDVD model: this topic is still in progress, at least two solutions have been implemented:
  - one option uses a second-order derivative operator \([R_{\text{deri}}]\) (case \( \text{LVFE}_{\text{LAPL}_{\text{HALF}}} = \text{F}\)).
  - one option mixes a first-order VFE derivative operator \([R_{\text{deri}}]\) and a first-order FD derivative operator (case \( \text{LVFE}_{\text{LAPL}_{\text{HALF}}} = \text{T}\)).

- Remarks for NH-PDVD model:
  - stability is ensured only if the top hydrostatic pressure is zero.
  - FD1 expressions have been chosen in order to match “constraint C2” (definition of “constraint C2” will be given below, in paragraph explaining linear operator \( T^* \)).

* Linear operator “\( T^* \)” for NH-PDVD model, and definition of “constraint C2”:

General definition of \( T^* \) uses a combination of linear operators \( L^* \), \( \tau \) and \( \gamma \).

Definition of \( T^* \) writes:

\[ T^* = \frac{g^2 L^* \left( \frac{\epsilon_{\text{vd}} g \delta^2 \tau \gamma - \epsilon_{\text{vd}} c_p g \delta^2 \tau - \epsilon_{\text{vd}} \gamma \right)}{R_d N^2 C^2} \]  

(46)

Using definitions for \( C \) and \( H \) (see equations (5) and (4)) this equation can be rewritten:

\[ T^* = \frac{L^* \left( T^* c_p g \tau \gamma - c_p g C^2 \tau - C^2 T^* \gamma \right)}{H^2 N^2 C^2} \]  

(47)
Using $G^*$ and $S^*$ this equation can be rewritten:

$$T^* = \frac{g^2 L^* (S^* G^* - (c_{pd}/c_{vd}) S^* - (c_{pd}/c_{vd}) G^*)}{N^2 C^2}$$ (48)

We can now introduce definition of “constraint C2”:

- **Strong constraint C2**: $T^*$ is the identity matrix.
- **Weak constraint C2**: $T^*$ matches (49):

$$T^* = (I + L^* Q^*)$$

and does not depart too much from identity matrix. $Q^*$ is a diagonal matrix equal to $\delta^* - 2\alpha^*$.

Continuous equations ensure “strong” constraint C2. In some cases this is possible to match “weak” constraint C2 in discretised equations, and from now “constraint C2” will mean “weak constraint C2”.

According to the vertical discretisation used, “constraint C2” may or may not be matched by the discretised operators.

- FD0 and VFE: constraint C2 is not ensured.
- FD1: constraint C2 is ensured.
- We can notice that either C1 and C2 are both ensured, or none of C1 and C2 are ensures.
- Elimination between equations to obtain Helmholtz equation does not assume that constraint C2 is ensured (use of formula (46)).
- Discretisations of $T^*$ matching constraint C2 or close to constraint C2 are preferred, in order to ensure numerical stability.

**Discretisation:**

- FD1: constraint C2 is ensured, and formula (49) is used. In this case, $T^*$ is a tri-diagonal operator, like $L^*$. Expression of the elements of the associated matrix is:

$$T^*_{(l,t)} = 1 - \frac{1}{\delta^*_l} \left( \frac{\Pi^*_l}{\Pi^*_l - \Pi^*_l_{t-1}} + \frac{\Pi^*_t}{\Pi^*_l_{t+1} - \Pi^*_l} \right) (\delta^*_l - 2\alpha^*_l)$$ (50)

$$T^*_{(1,1)} = 1$$ (51)

$$T^*_{(l,t-1)} = \frac{1}{\delta^*_l} \left( \frac{\Pi^*_{l-1}}{\Pi^*_l - \Pi^*_l_{t-1}} \right) (\delta^*_l_{t-1} - 2\alpha^*_l_{t-1})$$ (52)

$$T^*_{(l,t+1)} = \frac{1}{\delta^*_l} \left( \frac{\Pi^*_{l+1}}{\Pi^*_l_{t+1} - \Pi^*_l} \right) (\delta^*_l_{t+1} - 2\alpha^*_l_{t+1})$$ (53)

with some particular expressions at the top and the bottom.

Discretisation of diagonal matrix $Q^*$ is: $Q^*_{(l,t)} = (\delta^*_l - 2\alpha^*_l)$, and if the top hydrostatic pressure is zero, $Q^*_{(1,1)} = 0$.

- FD0 and VFE: constraint C2 is not ensured. Formula (46) is used (use VFE or FD0 discretisations of $\gamma$, $\tau$, $L^*$).
5 Semi-implicit scheme, no Coriolis term in the semi-implicit scheme.

Equations are written for a leap-frog scheme (Eulerian scheme or SL3TL scheme). For a SL2TL scheme replace \( \Delta t \) by \( 0.5 \Delta t \).

5.1 3D hydrostatic primitive equations model.

* Expression of the linear term \( \mathcal{L} \) for GMV and GMVS variables:
  
  • Continuity equation \( (X = \log(\Pi_\nu)) \):
    \[
    \mathcal{L} = -\nu(M^2 D') \tag{54}
    \]
  
  • Divergence equation \( (X = D') \):
    \[
    \mathcal{L} = -\nabla^2 (\gamma T + \mu \log \Pi_\nu) \tag{55}
    \]
  
  • Vorticity equation \( (X = \zeta') \):
    \[
    \mathcal{L} = 0 \tag{56}
    \]
  
  • Temperature equation \( (X = T) \):
    \[
    \mathcal{L} = -\tau(M^2 D') \tag{57}
    \]

* System to be solved: Equations are written for \( \log(\Pi_\nu) \) as a prognostic variable for continuity equation.

\[
\log(\Pi_\nu)_{t+\Delta t} + \beta \Delta t M^2 \nu D'_{t+\Delta t} = P^* \tag{58}
\]

\[
D'_{t+\Delta t} + \beta \Delta t \nabla^2 (\gamma T_{t+\Delta t} + \mu \log(\Pi_\nu)_{t+\Delta t}) = D'^* \tag{59}
\]

\[
T_{t+\Delta t} + \beta \Delta t M^2 \tau D'_{t+\Delta t} = T^* \tag{60}
\]

\( P^*, D'^*, T^* \) correspond to \( X^* \) defined in equation (17) and are available in spectral arrays (YDSP%SP, YDSP%DIV, YDSP%T) at the beginning of the spectral computations. Equations (58) to (60) yield (61) (Helmholtz equation):
\[
(\mathbb{I} - \beta^2 \Delta t^2 B \nabla^2 M^2) D'_{t+\Delta t} = D'^* - \beta \Delta t \nabla^2 (\gamma T^* + \mu P^*) \tag{61}
\]

where \( B = \gamma \tau + \mu \nu \) is a matricial operator \( L * L \) (precomputed in routines SUDYN, SUBMAT and stored in the array SIB).

When \( M = M_b \) it is more convenient to rewrite equation (61) as:
\[
(\nabla^2 - \beta^2 \Delta t^2 B M^2) D'_{t+\Delta t} = \nabla^2 D'^* - \beta \Delta t (\gamma T^* + \mu P^*) \tag{62}
\]

which shows a symmetric matricial operator in the left hand side.

* Spectral computations to solve system of equations (58) to (60). Algorithm works zonal wave number by zonal wave number \( m \) \( 0 \) \( m \) varies between 0 and the truncation \( N_x \) and performed in the routine SPCSI before all horizontal diffusion schemes. For a given zonal wave number \( m \):
  
  • After a preliminary memory transfer the right-hand side member of equation (61) is computed for all total wave numbers \( n \) between \( m \) and \( N_x \).
  
  • The diagonalisation of \( B \) is used: \( B = Q^{-1} A Q \), where \( A \) is a diagonal \( L * L \) matrix, the diagonal coefficients \( a_i \) of which are stored in the array SIVP, \( Q \) is a \( L * L \) matrix stored in the array SIMI, \( Q^{-1} \) is stored in the array SIMO. Note that the vertical operators \( \nu, \mu, \gamma, B, Q \) commute with the horizontal operators \( \nabla^2 \) and \( M^2 \).
  
  • Inversion of Helmholtz equation if \( M = c \): algorithm is done according to the following steps:
    
    - Do a multiplication by \( Q \).
    - Helmholtz equation (61) becomes, for each eigenmode \( l \):
      \[
      (I - \beta^2 \Delta t^2 a_l \nabla^2 M^2) Q D'_{t+\Delta t} = Q(Q^{-1} \gamma T^* + \mu P^*) \tag{63}
      \]
      
      - For each eigenmode \( l \) and each zonal wave number \( m \): \( (I - \beta^2 \Delta t^2 a_l \nabla^2 M^2) \) is a diagonal matricial operator \((N_x + 1 - m) (N_x + 1 - m)\), spectral coefficients of the right-hand side member of (63) are simply divided by the diagonal coefficients of this matrix. That yields \( Q D'_{t+\Delta t} \).
      
      - Multiplying by \( Q^{-1} \) one obtains \( D'_{t+\Delta t} \).
• Inversion of Helmholtz equation if \( \mathbf{\nabla}^2 = M \): inversion of Helmholtz equation is more complicated because the left-hand side member of Helmholtz equation contains values of the divergence for all levels and five total wave numbers \((n - 2 \text{ to } n + 2)\). Of course \( M^2 \) is a symmetric pentadiagonal matrix, for a given zonal wave number \( m \). Pay attention to the fact that \( M^2 \) does not commute with the diagonal operator \( \nabla^2 \).
  
  Do a multiplication by \( Q \).
  
  Helmholtz equation (61) (resp. (62)) becomes, for each eigenmode \( l \):
  
  \[
  (I - \beta^2 \Delta t^2 a_l \nabla^2 M^2) Q D_{l+\Delta t}' = Q(D^* - \beta \Delta t \nabla^2 (\gamma T^* + \mu P^*))
  \]
  
  (resp.):
  
  \[
  (\nabla'^{-2} - \beta^2 \Delta t^2 a_l M^2) Q D_{l+\Delta t}' = Q(\nabla'^{-2}D^* - \beta \Delta t (\gamma T^* + \mu P^*))
  \]
  
  Equation (65) is used for \( m > 0 \). For each eigenmode \( l \) and each zonal wave number \( m \):
  
  \( (\nabla'^{-2} - \beta^2 \Delta t^2 a_l M^2) \) is a symmetric pentadiagonal matricial operator \((N_s + 1 - | m |) \times (N_s + 1 - | m |)\).
  
  The factorisation \( LU \) of this matrix is computed, where \( L \) is a lower triangular tridiagonal matrix, \( U \) is an upper triangular tridiagonal matrix with coefficients equal to 1 on the main diagonal. All useful coefficients of \( L, U \) are computed in the set-up routine \texttt{SUHEG} and stored in the array \texttt{SIHEG}.
  
  The right-hand side member of (65) is computed, then multiplied by the inverse of the symmetric pentadiagonal operator \( (\nabla'^{-2} - \beta^2 \Delta t^2 M^2 a_l) \) (resolution of two tridiagonal triangular systems by routine \texttt{MXTURS}). That yields \( QD_{l+\Delta t}' \).
  
  - For the zonal wave number \( m = 0 \) equation (64) is used rather than (65) to avoid a division by 0 for \((m, n) = (0, 0)\). The only difference is that the pentadiagonal but non-symmetric operator \( (I - \beta^2 \Delta t^2 a_l \nabla^2 M^2) \) is factorised and inverted. All useful coefficients of \( L, U \) are computed in the set-up routine \texttt{SUHEG} and stored in the arrays \texttt{SIHEG} and \texttt{SIHEG2}.
  
  - Multiplying by \( Q^{-1} \) one obtains \( D_{l+\Delta t}' \).

• Once known \( D_{l+\Delta t}' \) equation (58) provides \( \log(\Pi_l)_{t+\Delta t} \) and equation (60) provides \( T_{l+\Delta t} \). If \( \mathbf{\nabla}^2 = M \), spectral multiplications by \( M^2 \) are performed by the product of a symmetric pentadiagonal matrix of dimensions \((N_s + 1 - | m |) \times (N_s + 1 - | m |)\) (useful coefficients computed in routine \texttt{SUESMAP} (resp. \texttt{SCGMAP} in LAM models)) and stored in the array \texttt{ESCGMAP} (resp. \texttt{SCGMAP} in LAM models)) by a vector containing spectral coefficients \((m, n)\) for \( n \) varying from \(| m | \) to \( N_s \).

• Semi-implicit scheme ends by a final memory transfer.

5.2 3D NH-PDVAR model.

The code described is valid for options \texttt{NPDVAR=2} and \texttt{NVDVAR=3}. For \texttt{NVDVAR=4} the linear terms are the same as for \texttt{NVDVAR=3}.

* Expression of the linear term \( \mathcal{L} \) for GMV and GMVS variables:

• Continuity equation \((X = \log(\Pi_l))\):

  \[
  \mathcal{L} = -\nu(M^2 D')
  \]

• Divergence equation \((X = D')\):

  \[
  \mathcal{L} = -\nabla^2[\gamma T - T^*(\gamma Q) + \mu \log(\Pi_s) + R_d T^* \mathbf{\nabla}^* Q]
  \]

• Vorticity equation \((X = \zeta')\):

  \[
  \mathcal{L} = 0
  \]

• Temperature equation \((X = T)\):

  \[
  \mathcal{L} = -\frac{R_d T^*}{c_{vd}} [M^2 D' + d]
  \]

• Pressure departure variable equation \((X = \hat{Q})\):

  \[
  \mathcal{L} = -\left[\frac{C_{pd}}{c_{vd}} (M^2 D' + d) - \frac{c_{pd}}{R_d T^*} \tau (M^2 D') \right]
  \]

• Vertical divergence equation \((X = d)\):

  \[
  \mathcal{L} = -\frac{\beta^2}{R_d T^*} (L^* \mathbf{\nabla}^2 Q)
  \]
**System to be solved:** Equations are written for \( \log(\Pi_t) \) as a prognostic variable for continuity equation.

\[
\log(\Pi_{t+\Delta t}) + \beta \Delta t \nu (\bar{M} D'_{t+\Delta t}) = \mathcal{P}'
\]  
(72)

\[
D'_{t+\Delta t} + \beta \Delta t V'^2 \gamma T_{t+\Delta t} - T^* (\gamma Q_{t+\Delta t}) + \mu \log(\Pi_{t+\Delta t}) + R_d T^* \dot{Q}_{t+\Delta t} = \mathcal{D}'
\]  
(73)

\[
\dot{Q}_{t+\Delta t} + \beta \Delta t \left[ \frac{c_{pq}}{c_{vu}} (\bar{M} D'_{t+\Delta t} + d_{t+\Delta t}) - \frac{c_{pq}}{c_{vu}} \tau (\bar{M} D'_{t+\Delta t}) \right] = \dot{\mathcal{Q}}^*
\]  
(74)

\[
d_{t+\Delta t} + \frac{c_{pq}^2}{R_d T^*} (\bar{M} D'_{t+\Delta t} + d_{t+\Delta t}) = \mathcal{D}^*
\]  
(75)

\[
T_{t+\Delta t} + \beta \Delta t \frac{c_{pq}^2}{c_{vu}} (\bar{M} D'_{t+\Delta t} + d_{t+\Delta t}) = \mathcal{P}^*
\]  
(76)

\( \mathcal{P}'^*, \mathcal{D}'^*, \dot{\mathcal{Q}}^*, \dot{\mathcal{D}}^*, T^* \) correspond to \( \lambda^* \) defined in equation (17) and are available in spectral arrays (\( \text{YDSP}\%\text{SP}, \text{YDSP}\%\text{DIV}, \text{YDSP}\%\text{SPD}, \text{YDSP}\%\text{SVD}, \text{YDSP}\%\text{T} \)) at the beginning of spectral computations.

**Elimination of variables:** The following calculations are valid for both \( \bar{M} \) horizontally constant and \( \bar{M} \) horizontally variable. All the constants and the vertical operators commute with \( V'^2 \) and \( \bar{M} \).

- Elimination of \( T, \dot{Q} \) and \( \log(\Pi_t) \) between equations (72), (73), (74) and (76) leads to equation (77):

\[
\begin{align*}
D'_{t+\Delta t} - (\beta \Delta t)^2 V'^2 [R_d T^* \left( \frac{\gamma}{R_d} - 1 \right) - \frac{c_{pq}}{c_{vu}} \tau - \frac{c_{pq}}{c_{vu}} \gamma \bar{M} D'_{t+\Delta t} + \left( -R_d T^* \frac{c_{pq}}{c_{vu}} \gamma \right) d_{t+\Delta t}] \\
+ [1 - (\beta \Delta t)^2 V'^2 (C^2 (1 + COR)) \bar{M} D'_{t+\Delta t}] D_{t+\Delta t} = \mathcal{D}'^*
\end{align*}
\]  
(77)

\( \mathcal{D}''^* \) is defined by equation (78):

\[
\mathcal{D}''^* = \mathcal{D}'^* + \beta \Delta t V'^2 [R_d T^* \left( \frac{\gamma}{R_d} - 1 \right) \dot{Q}^* - \gamma T^* - R_d T^* \mathcal{P}^*]
\]  
(78)

We use the relationship \( c_{vu} - c_{vd} = R_d \), the definition of \( C \) and we isolate the term \( \text{COR} \) (see equation (33)): this equation can be rewritten:

\[
[-(\beta \Delta t)^2 V'^2 (C^2 - T^* \gamma)] d_{t+\Delta t} + [1 - (\beta \Delta t)^2 V'^2 (C^2 (1 + COR)) \bar{M} D'_{t+\Delta t}] D_{t+\Delta t} = \mathcal{D}''^*
\]  
(79)

Quantity \( \text{COR} \) is zero when the constraint “C1” is fulfilled. This is the case for the finite-difference vertical discretisation with \( \text{NDLNPR} = 1 \). In the other cases, \( \text{COR} \) is generally non-zero but weak (\( \text{COR} < < 1 \)).

- Elimination of \( \dot{Q} \) between equations (74) and (75) leads to equation (80):

\[
d_{t+\Delta t} - (\beta \Delta t)^2 
\frac{T^*}{T_a} \left[ \frac{L^*}{H^*} (-c_{pd} \tau + C^2) \bar{M} D'_{t+\Delta t} + \frac{c_{pd}^2}{H^2} L^* d_{t+\Delta t} \right] = \mathcal{D}''^*
\]  
(80)

where \( \mathcal{D}''^* \) is defined by:

\[
\mathcal{D}''^* = \mathcal{D}'^* + \beta \Delta t \frac{T^*}{T_a} \left[ \frac{L^*}{H^*} \dot{Q}^* \right]
\]  
(81)

- When \( \text{COR} = 0 \), elimination of \( \dot{D}' \) between equations (79) and (80) leads to Helmholtz equation (84):

\[
\begin{align*}
&\left[ I - \beta^2 \Delta t^2 C^2 (\bar{M}^2 \nabla^2 T^*) + \frac{\tau}{T_a} \frac{T^*}{T_a} \right] d_{t+\Delta t} \\
&= (I - \beta^2 \Delta t^2 C^2 (\bar{M}^2 \nabla^2 T^*)) \mathcal{D}''^* + \beta^2 \Delta t^2 \frac{L^*}{H^2} \left( -c_{pd} \tau + C^2 \right) \bar{M}^2 \mathcal{D}''^*
\end{align*}
\]  
(82)

which can be rewritten:

\[
\begin{align*}
&\left[ I - \beta^2 \Delta t^2 C^2 \frac{T_f}{T_a} \frac{L^*}{H^2} \right] \left( \beta^2 \Delta t^2 C^2 + \beta^4 \Delta t^4 N^2 C^2 \frac{T_f}{T_a} T^* \right) \bar{M}^2 \nabla^2 T^* d_{t+\Delta t} \\
&= (I - \beta^2 \Delta t^2 C^2 (\bar{M}^2 \nabla^2 T^*)) \mathcal{D}''^* + \beta^2 \Delta t^2 \frac{L^*}{H^2} \left( -c_{pd} \tau + C^2 \right) \bar{M}^2 \mathcal{D}''^*
\end{align*}
\]  
(83)

or:

\[
\begin{align*}
&\left[ I - \beta^2 \Delta t^2 C^2 \left( I - \beta^2 \Delta t^2 C^2 \frac{L^*}{H^2} \right)^{-1} \left( I + \beta^2 \Delta t^2 N^2 \frac{T_f}{T_a} T^* \right) \bar{M}^2 \nabla^2 T^* \right] d_{t+\Delta t} \\
&= \left( I - \beta^2 \Delta t^2 C^2 \frac{T_f}{T_a} \frac{L^*}{H^2} \right)^{-1} \left( I - \beta^2 \Delta t^2 C^2 \bar{M}^2 \nabla^2 T^* \right) \mathcal{D}''^* + \beta^2 \Delta t^2 \frac{L^*}{H^2} \left( -c_{pd} \tau + C^2 \right) \bar{M}^2 \mathcal{D}''^*
\end{align*}
\]  
(84)
**In the LHS of equation (84), we denote by **B** the following matrix, by analogy with the hydrostatic model:**

$$B = C^2 \left( I - \beta^2 \Delta t^2 C^2 \frac{T^*}{\nabla^2} \right)^{-1} \left( I + \beta^2 \Delta t^2 N^2 \frac{T^*}{\nabla^2} \right)$$  \hspace{1cm} (85)

The LHS of equation (84) can be rewritten:

$$\left[ I - \beta^2 \Delta t^2 B \; \overline{M}^2 \nabla^2 \right]$$

If we compare with the LHS of the Helmholtz equation in the hydrostatic case we can notice three things:

- The order of \(\overline{M}^2\) and \(\nabla^2\) is inverted (these two operator do not commute if \(\overline{M}\) is not constant).
- B now depends on \(\Delta t\), it must be recomputed each time the timestep is changed.
- B is now a tridiagonal matrix (at least in the LVERTF...-F. discretisation).

**When \(\overline{M} = M\) it is more convenient to rewrite equation (84) as:**

$$\left[ \nabla^2 - \beta^2 \Delta t^2 C^2 \left( I - \beta^2 \Delta t^2 C^2 \frac{T^*}{\nabla^2} \right)^{-1} \left( I + \beta^2 \Delta t^2 N^2 \frac{T^*}{\nabla^2} \right) \overline{M} \right] \nabla^2 \hat{d}_{i+\Delta t}$$

$$= \left( I - \beta^2 \Delta t^2 C^2 \frac{T^*}{\nabla^2} \right)^{-1} \left[ \left( I - \beta^2 \Delta t^2 C^2 \overline{M} \nabla^2 \right) \hat{D}^{**} + \beta^2 \Delta t^2 \frac{T^*}{\nabla^2} (-c_{\mu t}^2 C^2) \overline{M} \hat{D}^{**} \right]$$  \hspace{1cm} (86)

which shows a symmetric matricial operator in the left hand side.

**Spectral computations to solve system of equations (72) to (76).** The algorithm has some similarities with what is done in the hydrostatic model. Algorithm works zonal wave number by zonal wave number.

- Algorithm works zonal wave number by zonal wave number (some similarities with what is done in the hydrostatic model).
- Algorithm works zonal wave number by zonal wave number (some similarities with what is done in the hydrostatic model).
- The algorithm has inversion of Helmholtz equation if \(\overline{M} = M\) then dependencies on \(\Delta t\) and \(\overline{M}\).

**Spectral computations to solve system of equations (72) to (76).** The algorithm has some similarities with what is done in the hydrostatic model. Algorithm works zonal wave number by zonal wave number (some similarities with what is done in the hydrostatic model). Algorithm works zonal wave number by zonal wave number (some similarities with what is done in the hydrostatic model).

- Inversion of Helmholtz equation if \(\overline{M} = M\): inversion of Helmholtz equation is more complicated because the left-hand side member of Helmholtz equation contains values of \(d\) for all levels and five total wave numbers \((n-2)\) to \((n+2)\). Of course \(M^2\) is a symmetric pentadiagonal matrix, for a given zonal wave number \(m\). Pay attention to the fact that \(M^2\) does not commute with the diagonal operator \(\nabla^2\).
− Do a multiplication by $Q$.
− Helmholtz equation (84) (resp. (86)) becomes, for each eigenmode $l$:
\[
(1 - \beta^2 \Delta t^2 a_l M^2 \nabla^2) Q d_{i+\Delta t} = Q \left(1 - \beta^2 \Delta t^2 C^2 \frac{T}{T^2 + \gamma^2} \right)^{-1} \left[ (1 - \beta^2 \Delta t^2 C^2 M^2 \nabla^2) \hat{D}^{**} + \beta^2 \Delta t^2 \frac{T}{T^2 + \gamma^2} (-c_{p,i} T + C^2 M^2) \hat{D}^{**} \right]
\]
resp.:
\[
(1 - \beta^2 \Delta t^2 a_l M^2) \nabla^2 d_{i+\Delta t} = Q \left(1 - \beta^2 \Delta t^2 C^2 \frac{T}{T^2 + \gamma^2} \right)^{-1} \left[ (1 - \beta^2 \Delta t^2 C^2 M^2 \nabla^2) \hat{D}^{**} + \beta^2 \Delta t^2 \frac{T}{T^2 + \gamma^2} (-c_{p,i} T + C^2 M^2) \hat{D}^{**} \right]
\]
− Equation (89) is used for $m > 0$. For each eigenmode $l$ and each zonal wave number $m:\nabla^2 (1 - \beta^2 \Delta t^2 a_l M^2) = 0$ is a symmetric pentadiagonal matrix operator $(N_l + 1 - |m|)*(N_l + 1 - |m|)$. For the case where the constraint $C_1$ is not matched (non zero COR) to be used.
− For the zonal wave number $m = 0$ equation (88) is used rather than (89) to avoid a division by 0 for $(m, n) = (0, 0)$. The only difference is that the pentadiagonal but non-symmetric operator $(1 - \beta^2 \Delta t^2 a_l M^2 \nabla^2)$ is factorised and inverted. All useful coefficients of $L, U$ are computed in the set-up routine SUNHHEG and stored in the array SIHEG.
− For the case where the constraint $C_1$ is not matched (non zero COR) the matrix $L$ is a pure diagonal operator, but when $M = M [I - (\beta \Delta t)^2 \nabla^2 C^2 M^2]$ is a purely diagonal operator, the LHS yields $\hat{D}_i^{**}$. Note that when $M^2$ is constant, $[I - (\beta \Delta t)^2 \nabla^2 C^2 M^2]$ is a purely diagonal operator, but when $M = M [I - (\beta \Delta t)^2 \nabla^2 C^2 M^2]$ is a pentadiagonal operator which has to be inverted by a LU method (all useful coefficients of $L, U$ are computed in the set-up routine SUNHHEG and stored in the arrays SIHEG and SIHEGB). This introduces additional calls to routines MXPTM if $M = M$, or $M = M [I - (\beta \Delta t)^2 \nabla^2 C^2 M^2]$ for the case $LSIDG = T$ (resp. $LESIDG = T$ in LAM models), spectral multiplications by $M^2$ are performed by the product of a symmetric pentadiagonal matrix of dimensions $(N_l + 1 - |m|)*(N_l + 1 - |m|)$ useful coefficients computed in routine SUMSAP (resp. USESAP in LAM models) and stored in the array SCGMAP (resp. ESCGMAP in LAM models) by a vector containing spectral coefficients $(m, n)$ for $n$ varying from $|m|$ to $N_l$.
− Semi-implicit scheme ends by a final memory transfer.

* **Case where the constraint C1 is not matched (non zero COR):** An iterative algorithm has been implemented, which can briefly described as follows:
- The total number of iterations is NITERHELM.
- For the predictor step, we replace COR by 0 and we do the eliminations and the inversion of the Helmholtz equation like previously described.
- For the corrector step, the term containing COR is put in the RHS, it is multiplied by $D_{i+\Delta t}$ at the previous iteration. The LHS is unchanged, so the elimination and the Helmholtz solving can be done like in the predictor step. We rather take as unknowns the increments between the current iteration and the predictor step, that allows to simplify the calculation of the RHS for the corrector step (some terms become 0).
5.3 2D shallow-water model.

* Expression of the linear term $\mathcal{L}$:
  - Continuity equation ($X = \Phi$):
    \[ \mathcal{L} = -\Phi^* M^2 D' \]  \hspace{1cm} (91)
  - Divergence equation ($X = D'$):
    \[ \mathcal{L} = -\nabla^2(\Phi) \]  \hspace{1cm} (92)
  - Vorticity equation ($X = \zeta'$):
    \[ \mathcal{L} = 0 \]  \hspace{1cm} (93)

* System to be solved:
  \[ \Phi_{t+\Delta t} + \beta \Delta t M^2 \Phi^* D'_{t+\Delta t} = \mathcal{H}^* \]  \hspace{1cm} (94)
  \[ D'_{t+\Delta t} + \beta \Delta t \nabla^2(\Phi_{t+\Delta t}) = d' \]  \hspace{1cm} (95)

$\mathcal{H}^*$, $d'^*$ correspond to $X^*$ defined in equations (17) and are available in spectral arrays (YDSP%SP, YDSP%DIV) at the beginning of the spectral computations. Equations (94) and (95) yield (96) (Helmholtz equation):

\[ (1 - \beta^2 \Delta^2 \Phi^* \nabla^2 M^2) D'_{t+\Delta t} = \nabla^2 - \beta \Delta t \nabla^2(\mathcal{H}^*) \]  \hspace{1cm} (96)

When $M = M$ it is more convenient to rewrite equation (96) as:

\[ (\nabla^{-2} - \beta^2 \Delta^2 \Phi^* M^2) D'_{t+\Delta t} = \nabla^2 - \beta \Delta t (\mathcal{H}^*) \]  \hspace{1cm} (97)

which shows a symmetric matricial operator in the left hand side.

* Spectral computations to solve system of equations (94) and (95). Algorithm works zonal wave number by zonal wave number $m$ ($|m|$ varies between 0 and the truncation $N_s$) and performed in the routine SPC2 before all horizontal diffusion schemes. For a given zonal wave number $m$:
  - After a preliminary memory transfer the right-hand side member of equation (96) is computed for all total wave numbers $n$ between $m$ and $N_s$.
  - Inversion of Helmholtz equation if $M = c$: for each zonal wave number $m$: $(1 - \beta^2 \Delta^2 \Phi^* \nabla^2 M^2)$ is a diagonal matricial operator $(N_s + 1 - |m|) \ast (N_s + 1 - |m|)$. Spectral coefficients of the right-hand side member of (96) are simply divided by the diagonal coefficients of this matrix.
  - Inversion of Helmholtz equation if $M = M$: inversion of Helmholtz equation is more complicated because the left-hand side member of Helmholtz equation contains values of the divergence for all levels and five total wave numbers ($n = 2$ to $n + 2$).

  - For $m > 0$ equation (97) is used. For each zonal wave number $m$: $(\nabla^{-2} - \beta^2 \Delta^2 M^2 \Phi^*)$ is a symmetric pentadiagonal matricial operator $(N_s + 1 - |m|) \ast (N_s + 1 - |m|)$. The factorisation LU of this matrix is computed, where $L$ is a lower triangular tridiagonal matrix, $U$ is an upper triangular tridiagonal matrix with coefficients equal to 1 on the main diagonal. All useful coefficients of $L, U$ are computed in the set-up routine SUHREG and stored in the array SIHREG. The right-hand side member of (97) is multiplied by the inverse of the symmetric pentadiagonal operator $(\nabla^{-2} - \beta^2 \Delta^2 \Phi^* M^2)$ (resolution of two tridiagonal triangular systems by routine MXTURS). That yields $D'_{t+\Delta t}$.

  - For the zonal wave number $m = 0$ equation (96) is used preferably than (97) to avoid a division by 0 for $(m, n) = (0, 0)$. The only difference is that the pentadiagonal but non-symmetric operator $(1 - \beta^2 \Delta^2 \Phi^* \nabla^2 M^2)$ is factorised and inverted. All useful coefficients of $L, U$ are computed in the set-up routine SUHREG and stored in the arrays SIHREG and SIHREG2.

  - Once known $D'_{t+\Delta t}$ equation (94) provides $\Phi_{t+\Delta t}$. When $M = M$, spectral multiplications by $M^2$ are performed by the product of a symmetric pentadiagonal matrix of dimensions $(N_s + 1 - |m|) \ast (N_s + 1 - |m|)$ (useful coefficients computed in routine SUSMAP and stored in the array SCGMAP) by a vector containing spectral coefficients $(m, n)$ for $n$ varying from $|m|$ to $N_s$.

  - Semi-implicit scheme ends by a final memory transfer.

5.4 Plane geometry (LAM models).

For 3D models, semi-implicit calculations are done in ESPCSI, ESPNHSI, instead of SPCSI, SPNHSI. Option LSIDG=.T. has an equivalent LESIDG=.T. designed for LAM models, coded only for a tilted-rotated Mercator projection.
6 Inclusion of Coriolis term in the semi-implicit scheme.

Although this term is non linear, it may be added to linear terms in the semi-implicit scheme. Equations are written for a leap-frog scheme (Eulerian scheme or SL3TL scheme). For a SL2TL scheme replace $\Delta t$ by $0.5\Delta t$. In ARPEGE/IFS this option is coded for both Eulerian and semi-Lagrangian schemes (3D model and shallow-water model). This option is available only in unstretched untilted spherical geometry, in setting LIMPF=.T. in namelist NAMdyn. The reason to use such option is accuracy for long range forecasts (but not stability issues: LIMPF=.F. is as stable as LIMPF=.T. but may lead to worse scores for long-range forecasts).

This option is limited to global model with unstretched and untilted geometry. In unstretched and untilted global model Coriolis parameter $f = 2\Omega \sin \theta$ writes as a first degree polynomial of the sinus of computational sphere latitude. This simple property is lost in stretched or tilted geometry and in LAM models.

6.1 Semi-implicit scheme including Coriolis term in the 3D hydrostatic model.

6.1.1 Thin layer equations.

* Expression of the linear term $\mathcal{L}$: Equations (55) and (56) become respectively:

- Divergence equation ($X = D'$):
  \[
  \mathcal{L} = -\nabla'^2(\gamma T + \mu \log \Pi_s) - 2\nabla' (\Omega \wedge \mathbf{V})
  \] (98)

- Vorticity equation ($X = \zeta'$):
  \[
  \mathcal{L} = -2k(\nabla' \wedge (\Omega \wedge \mathbf{V}))
  \] (99)

* System to be solved: Equations (58) and (60) are unchanged. Equation (59) is replaced by the two following equations, for divergence and vorticity. Restriction to unstretched untilted global model allows to replace $D'$ by $D$, $\zeta'$ by $\zeta$, $\nabla'$ by $\nabla$.$$

\begin{align*}
D_{t+\Delta t} + \beta \Delta t \nabla'^2 (\gamma T_{t+\Delta t} + \mu \log (\Pi_{s,t+\Delta t})) + \beta \Delta t (2\nabla (\Omega \wedge \mathbf{V})) &= D^* \\
\zeta_{t+\Delta t} + \beta \Delta t (2k(\nabla (\Omega \wedge \mathbf{V}))) &= \zeta^*
\end{align*}
\] (100)

$D^*$, $\zeta^*$ correspond to $X^*$ defined in equation (17) and are available in spectral arrays (YDSP%DIV, YDSP%VOR) at the beginning of the spectral computations.

* Divergence and vorticity in spherical geometry: For a vector $\mathbf{Y}$ of horizontal components $Y_x$ and $Y_y$, the divergence and vertical component of vorticity write as:

\[
\begin{align*}
\nabla \mathbf{Y} &= \frac{1}{a \cos \theta} \left[ \frac{\partial Y_x}{\partial \lambda} + \frac{\partial}{\partial \theta} (Y_y \cos \theta) \right] \\
\kappa (\nabla \wedge \mathbf{Y}) &= \frac{1}{a \cos \theta} \left[ \frac{\partial Y_y}{\partial \lambda} - \frac{\partial}{\partial \theta} (Y_x \cos \theta) \right]
\end{align*}
\] (102)

(103)

* Helmholtz equation: Using relations (102) and (103) in equations (100) and (101) lead to the following equations:

\[
\begin{align*}
D_{t+\Delta t} + \beta \Delta t \nabla'^2 (\gamma T_{t+\Delta t} + \mu \log (\Pi_{s,t+\Delta t})) + \beta \Delta t (-2\Omega \sin \theta) \zeta_{t+\Delta t} + \beta \Delta t \left( \frac{2\Omega \cos \theta}{a} \right) U_{t+\Delta t} &= D^* \\
\zeta_{t+\Delta t} + \beta \Delta t (2\Omega \sin \theta) D_{t+\Delta t} + \beta \Delta t \left( \frac{2\Omega \cos \theta}{a} \right) V_{t+\Delta t} &= \zeta^*
\end{align*}
\] (104)

(105)

The four following expressions are used, for each complex spectral coefficient:

- Relationship between divergence and velocity potential $\chi$:
  \[
  D = \nabla^2 \chi
  \] (106)

- Relationship between vorticity and stream function $\psi$:
  \[
  \zeta = \nabla^2 \psi
  \] (107)
• (106) and (107) can be rewritten, for each complex spectral component:

\[ D_{(m,n)} = \frac{n(n+1)}{a^2} \chi^{(m,n)} \]  

(108)

\[ \zeta_{(m,n)} = \frac{n(n+1)}{a^2} \psi^{(m,n)} \]  

(109)

• Relationship between \( U, \psi \) and \( \chi \):

\[ (Ua \cos \theta)_{(m,n)} = \text{im} \chi^{(m,n)} + (n-1)\epsilon^{(m,n)} \psi^{(m,n-1)} - (n+2)\epsilon^{(m,n+1)} \psi^{(m,n+1)} \]  

(110)

• Relationship between \( V, \psi \) and \( \chi \):

\[ (Va \cos \theta)_{(m,n)} = \text{im} \psi^{(m,n)} - (n-1)\epsilon^{(m,n)} \chi^{(m,n-1)} + (n+2)\epsilon^{(m,n+1)} \chi^{(m,n+1)} \]  

(111)

where \( \epsilon^{(0,0)} = 0 \) and:

\[ \epsilon^{(m,n)} = \sqrt{\frac{n^2 - m^2}{4n^2 - 1}} \]  

(112)

Equations (108) to (111) allow to eliminate \( U_{t+\Delta t} \) and \( V_{t+\Delta t} \) in equations (104) and (105).

\[ \begin{aligned}
1 - i \frac{2\beta \Delta t}{n(n+1)} D_{(m,n),t+\Delta t} + \beta \Delta t \nabla^2 (\gamma T_{(m,n),t+\Delta t} + \mu \log(\Pi_{\alpha})_{(m,n),t+\Delta t}) - \beta \Delta t (2\Omega(\sin \theta)\zeta)_{(m,n),t+\Delta t} \\
- \beta \Delta t \frac{2\epsilon^{(m,n)}}{n+1} \zeta_{(m,n-1),t+\Delta t} + \beta \Delta t \frac{2\epsilon^{(m+1,n)}}{n+1} \zeta_{(m,n+1),t+\Delta t} = \mathcal{D}_{\leftarrow}^{(m,n)}
\end{aligned} \]  

(113)

\[ \begin{aligned}
1 - i \frac{2\beta \Delta t}{n(n+1)} \zeta_{(m,n),t+\Delta t} + \beta \Delta t (2\Omega(\sin \theta)D)_{(m,n),t+\Delta t} + \beta \Delta t \frac{2\epsilon^{(m,n)}}{n+1} D_{(m,n+1),t+\Delta t} \\
- \beta \Delta t \frac{2\epsilon^{(m+1,n)}}{n+1} D_{(m,n-1),t+\Delta t} = \zeta_{\rightarrow}^{(m,n)}
\end{aligned} \]  

(114)

Multiplication by \( \sin \theta \) is eliminated by using the following relationship valid for any variable \( X \), in not stretched and not tilted geometry:

\[ ([\sin \theta]X)_{(m,n)} = \epsilon^{(m,n)} X_{(m,n-1)} + \epsilon^{(m,n+1)} X_{(m,n+1)} \]  

(115)

Equations (113) and (114) become:

\[ \begin{aligned}
1 - i \frac{2\beta \Delta t}{n(n+1)} D_{(m,n),t+\Delta t} + \beta \Delta t \nabla^2 (\gamma T_{(m,n),t+\Delta t} + \mu \log(\Pi_{\alpha})_{(m,n),t+\Delta t}) - \beta \Delta t \frac{2\epsilon^{(m,n)}}{n+1} \zeta_{(m,n-1),t+\Delta t} \\
- \beta \Delta t \frac{2\epsilon^{(m+1,n)}}{n+1} \zeta_{(m,n+1),t+\Delta t} = \mathcal{D}_{\leftarrow}^{(m,n)}
\end{aligned} \]  

(116)

\[ \zeta \text{ is eliminated in equation (116) by using (117) in replacing } \eta \text{ by } n - 1 \text{ then by } n + 1. \text{ Equation (116) becomes:} \]

\[ \begin{aligned}
\left[ 1 - i \frac{2\beta \Delta t}{n(n+1)} + \frac{(2\beta \Delta t)^2}{1 - 1/t^2} \frac{\epsilon^{(m,n)}}{n+1} \right] D_{(m,n),t+\Delta t} + \frac{(2\beta \Delta t)^2}{1 - 1/t^2} \frac{\epsilon^{(m,n)}(n+1)}{n+1} D_{(m,n+2),t+\Delta t} \\
+ \frac{(2\beta \Delta t)^2}{1 - 1/t^2} \epsilon^{(m,n)}(n+1) D_{(m,n-2),t+\Delta t} + \frac{(2\beta \Delta t)^2}{1 - 1/t^2} \epsilon^{(m,n)}(n+1) D_{(m,n+2),t+\Delta t}
\end{aligned} \]  

(117)

\( T_{t+\Delta t} \) and \( \log(\Pi_{\alpha})_{t+\Delta t} \) are eliminated by using equations (58) and (60). That leads to Helmholtz equation (119):

\[ \begin{aligned}
\left[ 1 - i \frac{2\beta \Delta t}{n(n+1)} + \frac{(2\beta \Delta t)^2}{1 - 1/t^2} \frac{\epsilon^{(m,n)}}{n+1} \right] D_{(m,n),t+\Delta t} + \frac{(2\beta \Delta t)^2}{1 - 1/t^2} \frac{\epsilon^{(m,n)}(n+1)}{n+1} D_{(m,n+2),t+\Delta t} \\
+ \frac{(2\beta \Delta t)^2}{1 - 1/t^2} \epsilon^{(m,n)}(n+1) D_{(m,n-2),t+\Delta t} + \frac{(2\beta \Delta t)^2}{1 - 1/t^2} \epsilon^{(m,n)}(n+1) D_{(m,n+2),t+\Delta t}
\end{aligned} \]  

(118)

Equation (119) is solved in eigenmodes space. The right-hand side member needs a multiplication by a tridiagonal complex matrix, for each zonal wave number \( m \). Inversion of Helmholtz equation is equivalent to invert a pentadiagonal complex matrix (done in routine SIMPLICO), for each zonal wave number \( m \). All computations are currently (in cycle 44) done in SPCSI. For \( m = 0 \) complex operators become real operators.
* Determination of other quantities at $t + \Delta t$: Equation (118) is used to compute $\zeta_{t+\Delta t}$ (for each zonal wave number $m$), multiplication by a complex tridiagonal matrix). Then equation (58) is used to compute $\log(\Pi_{t+\Delta t})$ and equation (60) is used to compute $T_{t+\Delta t}$.

6.1.2 Deep layer equations (according to White and Bromley, 1995).

Equations (98) to (101) remain valid. Only the horizontal part of the Coriolis term ($-2\Omega \wedge V$) can be included in the semi-implicit scheme. The term ($-2\Omega \wedge Wk$) remains explicit. Equations (100) to (119) remain valid, replacing $D$ by $(rs/a)D$, $\zeta$ by $(rs/a)\zeta$, $\nabla$ by $(rs/a)\nabla$. The code of spectral computations is unchanged.

6.2 Semi-implicit scheme including Coriolis term in the 3D NH-PDVD model.

Extending such an algorithm to the 3D NH-PDVD model in not stretched and not tilted geometry is possible but not straightforward. Most difficulties come from the fact that the unknown in the Helmholtz equation is $d$ and not $D'$.

6.2.1 Thin layer equations.

* Expression of the linear term $\mathcal{L}$: Equations (67) and (68) become respectively:
  
  - Divergence equation ($X = D'$):
    \[ \mathcal{L} = -\nabla'^2[\gamma T - T'(\gamma \hat{Q})] + \mu \log(\Pi) + R_d T' \hat{Q} - 2\nabla' (\Omega \wedge V) \]  
  
  - Vorticity equation ($X = \zeta'$):
    \[ \mathcal{L} = -2\kappa [\nabla' \wedge (\Omega \wedge V)] \]  

* Helmholtz equation: Elimination of $T$, $\hat{Q}$ and $\log(\Pi)$ between equations (72), (74), (76), and the modified (73) is done like for the case $\text{LIMPF}=\text{F}$. We have now a 3-equations system with the unknowns $d$ or $d_4$, $D'$ and $\zeta'$ (equation of $\zeta'$ is identical to the hydrostatic one). Since $\text{LIMPF}$ can work only with a not stretched not tilted spherical geometry, we omit the mapping factor and we replace $D'$ and $\zeta'$ by $D$ and $\zeta$ everywhere.

The relationships (106), (107), (106), (109), (108), (110), (111), (112), (115) are still used, in the same manner as in the hydrostatic model. Using these relationships allows to replace the occurrences of $U$ and $V$ exactly as it is done in the hydrostatic model (calculations are not detailed) and to have only the spectral components of $d$ (or $d_4$), $D'$ and $\zeta'$.

To simplify, we adopt the following denotations:

  - $B_1 = -C^2$
  - $BC_1 = -C^2 \ast \text{COR}$
  - $B_2 = -C^2 + T'^* \gamma$
  - $B_3 = -\frac{T'^*}{\tau^*} \frac{\nabla'}{\tau^*} \mathcal{L}'(-c_{p,q}T + C^2)$
  - $B_4 = \frac{T'^*}{\tau^*} \frac{C^2}{\tau^*} \mathcal{L}'$

Equations for $d$ (or $d_4$), $D$ and $\zeta$ become:

\[
\begin{align*}
\left[ I - i \frac{2\beta \Delta t}{n(n+1)} \right] \zeta_{(m,n),t+\Delta t} + \beta \Delta t \left[ \frac{2\Delta \zeta_{(m,n),t+\Delta t}}{n} \right] D_{(m,n),t+\Delta t} + \left[ (\beta \Delta t)^2 B_2 \right] d_{(m,n),t+\Delta t} = D_{(m,n),t+\Delta t} \\
\left[ (\beta \Delta t)^2 B_2 \right] D_{(m,n),t+\Delta t} + \left[ (\beta \Delta t)^2 B_3 \right] d_{(m,n),t+\Delta t} = D_{(m,n),t+\Delta t} \\
\left[ I - i \frac{2\beta \Delta t}{n(n+1)} \right] \zeta_{(m,n),t+\Delta t} + \beta \Delta t \left[ \frac{2\Delta \zeta_{(m,n),t+\Delta t}}{n} \right] D_{(m,n),t+\Delta t} = \zeta_{(m,n),t+\Delta t} \\
\end{align*}
\]
\( \zeta \) is eliminated in equation (122) by using (124) in replacing \( n \) by \( n-1 \) then by \( n+1 \) (exactly like we do in the hydrostatic model). Equation (122) becomes:

\[
\begin{align*}
&\left[ I - \frac{2\beta \Delta t}{n(n+1)} + (2\beta \Delta t)^2 \frac{e^{2}}{(n-1)(n+1)} \frac{(n-1)}{n^2} + \frac{(2\beta \Delta t)^2}{(n+1)(n+2)} e^{2} + \frac{(\beta \Delta t)^2}{(n+1)} (n+2) \frac{2\nabla^2(B_1 + BC)}{\nabla} \right] D_{(m,n),t+\Delta t} \\
&+ \frac{(2\beta \Delta t)^2}{1-\frac{2\beta \Delta t}{n(n+1)}} e^{(m,n-1)} e^{(m,n-1)} D_{(m,n-2),t+\Delta t} + \frac{(2\beta \Delta t)^2}{1-\frac{2\beta \Delta t}{n(n+2)}} e^{(m,n+1)} e^{(m,n+2)} D_{(m,n+2),t+\Delta t} \\
&= D_{(m,n)}^{**} + \frac{(2\beta \Delta t)^2}{1-\frac{2\beta \Delta t}{n(n+1)}} e^{(m,n-1)} e^{(m,n-1)} D_{(m,n-2),t+\Delta t} + \frac{(2\beta \Delta t)^2}{1-\frac{2\beta \Delta t}{n(n+1)}} e^{(m,n+1)} e^{(m,n+1)} D_{(m,n+2),t+\Delta t}
\end{align*}
\]

(125)

The similarities with the hydrostatic model are the following ones:

- The \( \zeta^{*} \) terms added to \( D_{(m,n)}^{**} \) are the same ones than those added to \( D_{(m,n)} \) in the hydrostatic Helmholtz equation. We introduce the following quantity:

\[
D_{(m,n)}^{**} = D_{(m,n)} \frac{\Delta t}{\Delta t} (n+1) e^{(m,n)} n \zeta^{*} + \frac{(2\beta \Delta t)}{(n+1)} \frac{n}{(n+1)} \zeta^{*} + \frac{(2\beta \Delta t)}{n(n+1)} \frac{n}{(n+1)} \zeta^{*} \quad (126)
\]

- In the LHS, the additional terms containing \( \Omega \) (in factor of \( D_{(m,n-2),t+\Delta t}, D_{(m,n+2),t+\Delta t} \) and \( D_{(m,n+2),t+\Delta t} \)) are the same as in the hydrostatic model.

That means that some pieces of code present in the hydrostatic code (the call to SIMPLICO and most of the input dummy arguments of SIMPLICO) can be re-used with no significant change in the NH model.

The main difference with the hydrostatic model, which will provide an additional difficulty, is the elimination between the \( D \) equation and the \( d \) equation. We first assume that \( COR = 0 \) (constraint C1) and, like in the case LIMPF=F, we do the elimination in order to have an Helmholtz equation with \( d \) unknown.

Equation (123) is used three times, for the total wave numbers \( n-2, n \) and \( n+2 \) to do the elimination of \( D_{(m,n-2),t+\Delta t}, D_{(m,n+2),t+\Delta t} \) and \( D_{(m,n+2),t+\Delta t} \). After this elimination, a left multiplication of the LHS and of the RHS by \( 1 + (\Delta t)^2 B_1 \) (which commutes with all the coefficients containing \( \Omega \)) is performed. We obtain an Helmholtz equation containing \( d_{(m,n-2),t+\Delta t}, d_{(m,n+2),t+\Delta t} \) and \( d_{(m,n+2),t+\Delta t} \) in the LHS:

\[
\begin{align*}
\left[ I - (\beta \Delta t)^2 B \nabla^2 - \frac{2\beta \Delta t}{n(n+1)} + (2\beta \Delta t)^2 \frac{e^{2}}{(n-1)(n+1)} \frac{(n-1)}{n^2} + \frac{(2\beta \Delta t)^2}{(n+1)(n+2)} e^{2} + \frac{(\beta \Delta t)^2}{(n+1)} (n+2) \frac{2\nabla^2(B_1 + BC)}{\nabla} \right] d_{(m,n),t+\Delta t} \\
+ \frac{(2\beta \Delta t)^2}{1-\frac{2\beta \Delta t}{n(n+1)}} e^{(m,n-1)} e^{(m,n-1)} d_{(m,n-2),t+\Delta t} + \frac{(2\beta \Delta t)^2}{1-\frac{2\beta \Delta t}{n(n+2)}} e^{(m,n+1)} e^{(m,n+2)} d_{(m,n+2),t+\Delta t} \\
= I + (\beta \Delta t)^2 B_1 d_{(m,n)}^{**} + D_{(m,n)}^{**} \quad (127)
\end{align*}
\]

where

\[
D_{(m,n)}^{**} = \left[ I + (\beta \Delta t)^2 B_1 \nabla^2 - \frac{2\beta \Delta t}{n(n+1)} + (2\beta \Delta t)^2 \frac{e^{2}}{(n-1)(n+1)} \frac{(n-1)}{n^2} + \frac{(2\beta \Delta t)^2}{(n+1)(n+2)} e^{2} + \frac{(\beta \Delta t)^2}{(n+1)} (n+2) \frac{2\nabla^2(B_1 + BC)}{\nabla} \right] D_{(m,n)}^{**} \\
+ \frac{(2\beta \Delta t)^2}{1-\frac{2\beta \Delta t}{n(n+1)}} e^{(m,n-1)} e^{(m,n-1)} D_{(m,n-2),t+\Delta t} + \frac{(2\beta \Delta t)^2}{1-\frac{2\beta \Delta t}{n(n+1)}} e^{(m,n+1)} e^{(m,n+1)} D_{(m,n+2),t+\Delta t}
\]

(128)

We can first remark that the RHS of the Helmholtz equation requires an additional multiplication by a complex pentadiagonal matrix which is not present in the hydrostatic model. Such a multiplication is done in the routine SI_MXPTCO which re-uses some input dummy arguments of SIMPLICO. This multiplication computes a quantity which must be added to the \( D_{(m,n)}^{**} \) term, before applying the inverse of \( I + (\beta \Delta t)^2 B_1 \).

Once computed its RHS, equation (127) is solved in eigenmodes space. Inversion of Helmholtz equation is equivalent to invert a pentadiagonal complex matrix (done in routine SIMPLICO), for each zonal wave number \( m \); the coefficients are the same ones as in the hydrostatic model, the only difference being the content of \( B \) (filled in the set-up), so this is transparent in routine SPNHSI. All computations are currently (in cycle 44) done in SPNHSI, by calling routine SIMPLICO. For \( m = 0 \) complex operators become real operators.

Once computed \( d_{(m,n),t+\Delta t} \), equation (125) is used to retrieve \( D_{(m,n),t+\Delta t} \). Equation (125) contains \( D_{(m,n-2),t+\Delta t}, D_{(m,n+2),t+\Delta t} \) and \( D_{(m,n+2),t+\Delta t} \), that means that we need a second complex matrix inversion (there was only one in the hydrostatic model). But we can notice that the coefficients in the LHS look like those present in the LHS of the Helmholtz equation:

\[
23
\]
• All the coefficients containing $\Omega$ are exactly the same ones of the Helmholtz equation.
• The coefficient $(\beta \Delta t)^2 B \nabla^2$ of the Helmholtz equation is replaced by $-(\beta \Delta t)^2 B_1 \nabla^2$, where $B_1$ is already a (constant coefficients) diagonal matrix.

That means that, for this complex matrix inversion, routine SIMPLICO can be re-used without any change (the only input coefficient which changes is the one containing the eigenvalues).

Once computed $D_{t+\Delta t}$, equation (124) allows to retrieve $\zeta_{t+\Delta t}$, and this piece of calculations is identical to what is done in the hydrostatic model.

* **Determination of other quantities at** $t+\Delta t$: Retrieval of $T$, $\hat{Q}$ and $\log(\Pi_s)$ at $t+\Delta t$ is done exactly like in the LIMPF=F case.

* **Combination with the NITERHELM algorithm when the constraint C1 is not matched:** This is possible and now implemented.

### 6.2.2 Deep layer equations (according to Wood and Staniforth, 2003).

Equations (120) to (124) remain valid. Only the horizontal part of the Coriolis term ($-2\Omega \wedge V$) can be included in the semi-implicit scheme. The term ($-2\Omega \wedge w_k$) remains explicit. Equations (125) to (127) remain valid, replacing $D$ by $(r/a)D$, $\zeta$ by $(r/a)\zeta$, $\nabla$ by $(r/a)\nabla$. The code of spectral computations is unchanged.

### 6.3 Semi-implicit scheme including Coriolis term in the 2D shallow-water model.

Such an algorithm is also coded in the 2D shallow-water model in not stretched and not tilted geometry.

• Replace $(\gamma T + \mu \log(\Pi_s))$ by $\Phi$ in equation (98).
• Replace $(\gamma T_{t+\Delta t} + \mu \log(\Pi_s))_{t+\Delta t}$ by $\Phi_{t+\Delta t}$ in equations (100) and (104).
• Replace $(\gamma T_{(m,n),t+\Delta t} + \mu \log(\Pi_s)_{(m,n),t+\Delta t})$ by $\Phi_{(m,n),t+\Delta t}$ in equations (113), (116) and (118).
• Replace $(\gamma T^*_I_{(m,n)} + \mu P^*_{(m,n)})$ by $H^*_{(m,n)}$ in equation (119).
• Once computed $D'_{t+\Delta t}$ equation (94) provides $\Phi_{t+\Delta t}$.
7 Spectral multiplications by polynomial expressions of the mapping factor.

* Expression of mapping factor \( M \) in spectral space in ARPEGE. Let us denote by:
  - \( a_c = 0.5(c + \frac{1}{2}) \)
  - \( b_c = 0.5(c - \frac{1}{2}) \)
  - \( \epsilon_{(0,0)} = 0 \)
  - \( \epsilon_{(m,n)} = \sqrt{\frac{n^2 - m^2}{n^2 - 1}} \)

Expression of \( M \) is:

\[
M = a_c + b_c \xi
\]

where \( \xi \) is the sinus of computational sphere latitude. Expression of \([MX]_{(m,n)}\) is:

\[
[MX]_{(m,n)} = b_c \epsilon_{(m,n)} X_{(m,n-1)} + a_c X_{(m,n)} + b_c \epsilon_{(m,n+1)} X_{(m,n+1)}
\]  

(129)

It is easy from (130) to retrieve the coefficients of spectral multiplication by any first degree polynomial of \( M \). This is equivalent to a multiplication by a tridiagonal symmetric matrix in spectral space.

* Expression of \( M^2 \) in spectral space in ARPEGE.

\[
[M^2X]_{(m,n)} = b_c^2 \epsilon_{(m,n)} \epsilon_{(m,n-1)} X_{(m,n-2)} + 2a_c b_c \epsilon_{(m,n)} X_{(m,n-1)} + (a_c^2 + b_c^2 (\epsilon_{(m,n)}^2 + \epsilon_{(m,n+1)}^2)) X_{(m,n)}
\]

\[+ 2a_c b_c \epsilon_{(m,n+1)} X_{(m,n+1)} + b_c^2 \epsilon_{(m,n+2)} \epsilon_{(m,n+2)} X_{(m,n+2)}
\]  

(131)

This is equivalent to a multiplication by a pentadiagonal symmetric matrix in spectral space.

* Expression of \( M \) and \( M^2 \) in spectral space in LAM models. This formula is only valid on a tilted-rotated Mercator projection, and it assumes that the reference latitude of the projection is at the middle of sub-domain C+I.

If we assume that the plane coordinates will be not slanted relatively to the longitudes and latitudes of the Mercator projection, the mapping factor \( M \) always depends only on the \( y \) coordinate and never vary along the \( x \) coordinate.

\[
M = \frac{1}{\cos \theta} = \frac{1}{\sqrt{1 - \mu^2}} = \cosh(y/a)
\]

where \( \mu = \sin \theta \), the \( y \) coordinate (this is an distance measured on the plane projection) assumes that \( y = 0 \) at the apparent equator, and \( a \) is the mean Earth radius. \( M \) is not a low order polynomial function of \( y \) so even in this case it needs to be approximated. The approximation used is, for a Fourier decomposition of \( M^2 \), to have only two harmonics.
8 Organigramme of the spectral part of the semi-implicit computations.

8.1 Set-up and control routines until STEPO.

CNT0 ->
  * SUOYOMA ->
    - SUCT0
    - SUOYNA
    - SUGEDYMETRY -> SUSMAP, SUESMAP, and so on
  * SUOYOMB ->
    - SUDYN ->
      * SUALDYNB (global model) or SUELDYNB (LAM model).
      * SUGHIST (hydrostatic model) ->
        - GPHPRE
        - SUBMAT -> SITNU and SIGAM
        - EIGSOL
        - SCORDO
        - MINV
      - SUSI (NH models) ->
        - GPHPRE
        - SUBMATMAT -> SISEVE and MINV (NH-PDVD model)
        - EIGSOL
        - SCORDO
        - MINV
      - SUHHEG -> SUH and SUHES (LSIDG=T only)
      - SUENHHEG -> SUH and SUHES (LESIDG=T only, NH-PDVD model)
  * SUNHSHI (NH models) ->
    - GPHPRE
    - SUDYNMAT -> SISEVE and MINV (NH-PDVD model)
    - EIGSOL
    - SCORDO
    - MINV
    - SUNHHEG -> SUH and SUHES (LSIDG=T only, NH-PDVD model)
    - SUENHHEG -> SUH and SUHES (LESIDG=T only, NH-PDVD model)
  * SUNHSHI_TESTCONV (NH models)

CNT1 -> CNT2 -> CNT3 -> CNT4 ->
  - SUHHEG -> SUH and SUHES (LSIDG=T only)
  - SUENHHEG -> SUH and SUHES (LESIDG=T only)
  - SUNHSHI (NH model) -> (see above)
  - STEPO -> (see below)

* Adjoint code: For adjoint code STEPO is replaced by STEPOAD, organigramme is slightly different between CNT0 and STEPOAD. For example CNT3 is replaced by CNT3AD, CNT4 is replaced by CNT4AD.

* Tangent linear code: For tangent linear code STEPO is replaced by STEPOTL, organigramme is slightly different between CNT0 and STEPOTL. For example CNT3 is replaced by CNT3TL, CNT4 is replaced by CNT4TL.

8.2 Direct code under STEPO or tangent linear code under STEPOTL.

STEPO or STEPOTL ->
  * SPCM ->
    - SPCTMPFINIT (LIMPET=T only)
    - TRMTOS (transposition routine for distributed memory)
    - SPCEI (hydrostatic model) ->
      - SITNU -> VERINT
      - SIGAM -> VERINT
    - SPCEIPGSOLVE (LIMPET=T only) -> TRSTOM, SIMPLICO, TRMTOS
    - MXMAOP
    - MXMURS and MXTURE (LSIDG=T or LESIDG=T only)
    - MXPTMA (LSIDG=T or LESIDG=T only)
    - SPHSHI (NH-PDVD model) ->
      - SIDD -> SIGAM and SISEVE
      - SI_CCOR
    - MXPTMA (LSIDG=T or LESIDG=T only)
    - SIESEV -> VERINT
    - SITNU -> VERINT
    - SIMPLICO and SI_MXPTCO (LIMPET=T only)
    - MXMAOP
    - MXMURS and MXTURE (LSIDG=T or LESIDG=T only)
    - SIGAM -> VERINT
    - TRSTOM (transposition routine for distributed memory)
    - SPCHPFPPOST (LIMPET=T only)
    - SPCHDOR (horizontal diffusion)
  * SPZM -> SPZC ->
- SIMPLICO (LIMPF=T only)
- MIXTURS (LSIDG=T or LESIDG=T only)
- MXTURE (LSIDG=T or LESIDG=T only)
- MXPTMA (LSIDG=T or LESIDG=T only)
- BALADSM

In LAM models:
- ESPCM, ESPCSI, ESPNHSI, ESPCHOR are called instead of SPCM, SPCSI, SPNHSI, SPCHOR.

8.3 Adjoint code under STEPOAD.

STEPOAD ->
* SPCMAD ->
  - BRPTOB -> PE2SET
  - SPCIMPFSOLVEAD (LIMPF=T only) -> TRMTOS, SIMPLICOAD, TRMTOS
  - MMAGP
  - MIXTURS and MIXTURE (LSIDG=T or LESIDG=T only)
  - MXPTMA (LSIDG=T or LESIDG=T only)
  - [ SPNHSIAD (NH-PDVD model, not yet coded) ] ->
    - SITADH -> VERINTAD
    - SPCIMPFSOLVEAD (LIMPF=T only) -> TRSTOM, SIMPLICOAD, TRMTOS

In LAM models:
- ESPCMAD, ESPCSIAD and ESPCHORAD are called instead of SPCMAD, SPCSIAD, SPNHSIAD and SPCHORAD.

8.4 Action done by these routines.

* Set-up routines:
  - SUCTO: computes 0-level control variables, and also some variables linked to dynamics.
  - SUDYNA: set-up for dynamics, part A.
  - SUDYN: set-up for dynamics, part B.
  - SUSI: set-up for hydrostatic SI scheme.
  - SUNH: set-up for non-hydrostatic SI schemes.
  - SUNHTESTConv: test convergence necessary condition of the NITERHELM algorithm (NH-PDVD SI scheme).
  - GPHPRE: some reference vertical-dependent hydrostatic pressure quantities.
  - SCORDO: reorders eigenvalues and eigenvectors in order to have ascending values of eigenvectors.
  - SUEH: computes array SIB containing operator B respectively for 3D hydrostatic model, 3D NH-PDVD model.
  - SUGEO: geometry set-up.
  - SUSM: computes array SCGMAP containing coefficients for spectral multiplication by $M^2$.
  - SUES: computes array ESCGMAP containing coefficients for spectral multiplication by $M^2$ (LAM models, tilted-rotated Mercator projection).
  - SUHEH (SUEHEH in LAM models): computes the LU factorisation of Helmholtz operator in case of semi-implicit scheme with unreduced divergence. Routine SUHEH (resp. SUEHEH) is called only if LSIDG=.T. (resp. LESIDG=.T.), for 3D hydrostatic model and 2D shallow-water model (and more generally when the elimination gives an Helmholtz equation with $D$ as unknown).
  - SUNHH (resp. SUEHH in LAM models): the same as SUHEH (resp. SUEHEH in LAM models) but for the NH-PDVD model.
  - SUALDYNB (ARPEGE) or SUELDYNB (LAM models): allocation of some arrays used in the semi-implicit scheme.
* Control routines: CNT0, CNT1, CNT2, CNT3, CNT4, CNT3AD, CNT4AD, CNT3TL, CNT4TL, STEPO, STEPOAD, STEPOTL are control routines. STEPO (resp. STEPOAD, STEPOTL) manages one direct (resp. adjoint, tangent linear) integration timestep.

* Routines under STEPO, STEPOAD or STEPOTL:
  - SPCSI: semi-implicit scheme spectral computations in the hydrostatic model.
  - SPNHSI: semi-implicit scheme spectral computations in the NH-PDVD model.
  - SPC2: spectral space computations, including the semi-implicit scheme and all horizontal diffusion schemes in the 2D model.
  - SPCM: distributed memory interface for SPCSI and SPNHSI.
  - SPC2M: distributed memory interface for SPC2.
  - Their LAM models counterparts have names ESPC.. instead of SPC...
  - These routines have adjoints (same names + “AD”).
  - SPCIMPFINIT, SPCIMPFPOST, SPCIMPFSSOLVE: contain code for LIMPF=T case.
  - SITNU: computes a linear application by operator \( \nu \) (see equations (31) and (30)).
  - SIGAM: computes a linear application by operator \( \gamma \) (see equations (27) and (26)).
  - VERINT: does vertical integrations (vertical finite element scheme).
  - VERDER: does vertical derivations (vertical finite element scheme).
  - SI CCCOR: computes \( \text{COR} \) (NH-PDVD model).
  - SISEVE: computes a linear application by operator \( \mathbf{L}^* \) in the NH-PDVD model (see equation (34)).
  - SIDD: performs the elimination of \( T, \log \Pi_s \) and \( \hat{Q} \) in the linear system of NH-PDVD equations (in order to compute the RHS of the Helmholtz equation).
  - BALADSM: solve linear balance equation in spectral space to convert vorticity into geopotential (used for vorticity 2D equation only).

* Linear algebra routines (project XLA/ALGOR):
  - EIGSOL: finds eigenvalues and eigenvectors of a matrix.
  - MINV: inverts a matrix.
  - MXTURE: inverts a set of tridiagonal (lower or upper) triangular matrices.
  - MXTURS: combines two calls to MXTURE to invert a set of symmetric pentadiagonal matrices, the decomposition \( \mathbf{LU} \) of which is known.
  - MXPTMA: products of a set of pentadiagonal matrices by a set of matrices or vectors.
  - MXMAOP: matrix by matrix product.
  - SIMPLICO: solves a set of set of complex pentadiagonal systems (in practical called when LIMPF=T).
  - SI_MXPTCO: complex multiplications by a penta-diagonal matrix (in practical called when LIMPF=T).
  - SUHER: performs the \( \mathbf{LU} \) factorisations of a set of non symmetric pentadiagonal matrices.
  - SUHES: performs the \( \mathbf{LU} \) factorisations of a set of symmetric pentadiagonal matrices.

* Distributed memory routines (for ex. transposition routines) doing communications between processors: the list of transposition and communication routines used in horizontal diffusion scheme is the following: TRSTOM, TRMTOS, BRPTOB and PE2SET; see documentation (IDDM) about distributed memory features for the action of these routines.
9 Other remarks.

9.1 Adjoint and tangent linear codes.

These codes have been updated for semi-implicit computations in cycle 44, for 3D hydrostatic model and 2D model. Use of both options \texttt{LSIDG=.F.} and \texttt{LSIDG=.T.} is possible for adjoint and tangent linear codes of semi-implicit scheme in cycle 44 (except for non-hydrostatic model). Notice that tangent linear of \texttt{SPCSI} is \texttt{SPCSI} itself.

9.2 Place of calculation of linear terms in grid-point space.

In the 3D model, we find such calculations in \texttt{CPEULDYN} for the Eulerian advection and in \texttt{LACDYN} (calleees \texttt{LASSIE, LANHSI}) for the semi-Lagrangian advection. Grid-point coupling also needs to compute these terms to add them to couplers (routine \texttt{ESEIMPLS} called by \texttt{ECOUPL1}).

In the 2D model, we find such calculations in \texttt{CPG2} for the Eulerian advection and in \texttt{LACDYN} for the semi-Lagrangian advection.

Linear term calculations are done according to the following pattern:

- **3D hydrostatic model:**
  - one call to \texttt{SITNU}.
  - two calls to \texttt{SIGAM}.
  - if \texttt{LSPRT}=T, a conversion for the \textit{T}-equation linear term.
  - if \texttt{LIMPF}=T, add Coriolis term to wind-equation linear term.

- **3D NH-PDVD model:**
  - one call to \texttt{SIPTP}.
  - two calls to \texttt{SIDD}.
  - one call to \texttt{SISEVE}.
  - if \texttt{LSPRT}=T, a conversion for the \textit{T}-equation linear term.
  - if \texttt{LIMPF}=T, add Coriolis term to wind-equation linear term.

- **timestep of calculation (given for predictor step):**
  - Eulerian advection: linear terms for \(X(t - \Delta t) - 2X(t)\).
  - SL3TL advection: linear terms for \(X(t)\) and \(X(t - \Delta t)\).
  - SL2TL advection: linear terms for \(X(t)\).
  - coupler: linear terms for coupler instant.

9.3 Place of inversion of semi-implicit scheme in spectral space.

- The semi-implicit calculations are done after mass corrector computations.
- The semi-implicit calculations are done before spectral nudging (LAM models).
- The semi-implicit calculations are done before horizontal diffusion.
- The semi-implicit calculations are done before nudging (climate models).
- If an ICI scheme is activated (\texttt{LPC\_FULL=T}), spectral semi-implicit calculations should be done at all iterations.

9.4 Some distributed memory features in spectral calculations.

- The total number of processors involved in the A-level parallelisation is \texttt{NPRTRW}.
- The total number of processors involved in the B-level parallelisation is \texttt{NPRTRN}.
- The total number of processors is \texttt{NPROC=NPRTRW*NPRTRN}.
- One processor treats only a subset of zonal wave numbers.
- If \texttt{LSIDG=.T.} or \texttt{LIMPF=.T.} spectral part of the semi-implicit scheme is done zonal wave number by zonal wave number. A call to \texttt{SPCSI} currently treats only one zonal wave number (case \texttt{LLONEM=.T.}).
- In the other cases a call to \texttt{SPCSI} can treat several wave numbers: currently all the zonal wave numbers treated by the current processor (case \texttt{LLONEM=.F.}).
- All the \texttt{NFLEVG} layers are treated together, there is no subdivision into packets of \texttt{NFLEVL} layers when the second level of parallelisation is activated contrary to the horizontal diffusion. That means that additional transpositions (\texttt{TRSTOM} in the direct code) are necessary between the semi-implicit calculations of \texttt{SPCSI} and the horizontal diffusion calculations of \texttt{SPCHOR} to convert the fields from the \texttt{NFLEVG} structure required in the semi-implicit calculations to the \texttt{NFLEVL} structure required in the horizontal diffusion calculations.
- In LAM models the way of distributing \texttt{ESPCSI} and \texttt{ESPNSIS} is the same one as in \texttt{SPCSI} and \texttt{SPNSIS}.
10 Precomputed module and namelist quantities.

These modules are auto-documented so description of each variable is provided in the code source. We can recall here the most important variables to know for each module:

- **Modules for geometry:**
  - **SPGEOM** (spectral geometry).
  - **YOMVERT** (all variables).
- **YOMARG** (0-level control, former command line) and **YOMCT0** (0-level control):
  - NCONF, LELAM (in **NAMARG**).
  - LR3D, LR2D, LRSHW, LRVEQ.
  - LNHDYN (in **NAMCT0**).
  - LRPLANE (in **NAMCT0**).
- **YOMCVER** (vertical finite element discretisation keys): most of variables. Some of these variables are in namelist **NAMCVER**.
- **YOMDIM**, **YOMDIMV** and **YOMDIMF** (dimensioning): most of variables. Some of these variables are in namelist **NAMDIM**.
- **YOMDYNA** (adiabatic dynamics: first part):
  - LPCFULL, LPCCHEAP (predictor-corrector scheme).
  - LNESC, LNESCST, LNSCSTL, LSETTLS, LSETTLST, LSETTLLSV (extrapolation).
  - LAPRXPXK, NDLNPR, RHYDR0 (vertical discretisation).
  - LSLLC2, LSLL.
  - NPDVAR, NVDVAR, ND4SYS, LNHDYN, LNHDYN, RC_PD1 (NH model).
  - LGWADV, NGWADVST, LRDBBC (treatment of vertical divergence equation in NH model).
  - LVERCOR, LRWSDLW, LRWSDLR, LRWSDLR2, LRWSDLG, LCRWVW (deep-layer equations).
  - Some of these variables are in namelist **NAMDYNA**.
- **YOMDYN** (adiabatic dynamics: second part). The following variables are attributes of YRDYN:
  - LSIDG, BETADT ($\beta$), RBT, RBTS2, NITERHELM, LIMPF (semi-implicit scheme).
  - REFGEO, SIPR ($\Pi$, $\Pi$), SITR ($T^*$), SITRA ($T^*$), SITUB, SIPUB, SITIME, SIRPRG ($R_T^*$), SIRPRN (equal to 1): reference values used in the semi-implicit scheme.
  - VESL, XIDT.
  - NSITER, NCURRENT, NRHDI_LASTITERPC (predictor-corrector scheme).
  - SIDELP ($\Delta \Pi^*$), SIRDEL ($\delta$), SIALPH ($\alpha^*$).
  - SITLAF and SITLAH (full-level and half-level reference hydrostatic pressure).
  - SIDPHI ($\Delta \Phi^*$).
  - SIB (matrix $B$ in Helmholtz equation).
  - SIVP (eigenvalues $a_i$ of $B$), SIMI ($Q = \text{eigenvectors of } B$), SIMO ($Q^{-1}$).
  - SIFAC (matricial operator for NH model only, i.e. $I - \beta^2 \Delta t^2 C^2 (T^*/T^*) (1/H^2)L^*$)
  - SIFACI: inverse of SIFAC.
  - SIHEG:
    - Hydrostatic model or 2D shallow-water model: for $m > 0$ contains the non-zero diagonals of $LU$ decomposition of $(\nabla'^2 - \beta^2 \Delta t^2 a_i M^2)$; for $m = 0$, contains the non-zero diagonals of $L$ of the $LU$ decomposition of $(I - \beta^2 \Delta t^2 a_i \nabla'^2 M^2)$.
    - NH-PDVD 3D model: for $m > 0$ contains the non-zero diagonals of $LU$ decomposition of $(\nabla'^2 - \beta^2 \Delta t^2 a_i M^2)$; for $m = 0$, contains the non-zero diagonals of $L$ of the $LU$ decomposition of $(I - \beta^2 \Delta t^2 a_i M^2 \nabla'^2)$.
  - SIHEG2:
    - Hydrostatic model or 2D shallow-water model: for $m = 0$ contains the non-zero diagonals of $U$ of the $LU$ decomposition of $(I - \beta^2 \Delta t^2 a_i \nabla'^2 M^2)$.
    - NH-PDVD 3D model: for $m = 0$ contains the non-zero diagonals of $U$ of the $LU$ decomposition of $(I - \beta^2 \Delta t^2 a_i M^2 \nabla'^2)$.  

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- SIHEGB for NH-PDVD 3D model: for $m > 0$ contains the non-zero diagonals of $LU$ decomposition of $(\nabla' - \beta^2 \Delta t^2 CM^2)$; for $m = 0$ contains the non-zero diagonals of $L$ of the $LU$ decomposition of $(I - \beta^2 \Delta t^2 \nabla'^2 CM^2)$.

- SIHEGB2 for NH-PDVD 3D model: for $m = 0$ contains the non-zero diagonals of $U$ of the $LU$ decomposition of $(I - \beta^2 \Delta t^2 \nabla'^2 CM^2)$.

Some of these variables are in namelist $\text{NAMdyn}$.

- $\text{YOMRIP}$ (date and timestep related variables). The following variables are attributes of $\text{YRRIP}$. Some of these variables are in namelist $\text{NAMRIP}$.
  - TSTEP, TDT (timestep).

- $\text{YEMdyn}$ (LAM model dynamics): LESIDG, RTHRESIDG. RTHRESIDG is in namelist $\text{NEMdyn}$.

- $\text{YOMMPP0}$ and $\text{YOMMP}$ (distributed memory environment, see documentation (IDDM) for more details).

- $\text{YOMSP}$ and $\text{YOMSP5}$ (spectral arrays).
11 References.

11.1 Publications.


For non-hydrostatic and deep-layer models aspects:


11.2 Internal notes and documentation.

• (TDECDYN) 2016: IFS technical documentation (CY41R2). Part III: dynamics and numerical procedures. Available at “https://software.ecmwf.int/wiki/display/IFS/Official+IFS+Documentation”.
• (TDECTEC) 2016: IFS technical documentation (CY41R2). Part VI: technical and computational procedures. Available at “https://software.ecmwf.int/wiki/display/IFS/Official+IFS+Documentation”.
• (IDPC) Bénard, P., 2002: Incremental versus non-incremental predictor-corrector schemes. Appendix A of the previous internal note.
• (IDBAS) Yessad, K., 2017: Basics about ARPEGE/IFS, ALADIN and AROME in the cycle 44 of ARPEGE/IFS (internal note, available on the intranet server “http://www.umr-cnrm.fr/gmapdoc/”).
• (IDDH) Yessad, K., 2017: Horizontal diffusion in the cycle 44 of ARPEGE/IFS (internal note, available on the intranet server “http://www.umr-cnrm.fr/gmapdoc/”).
• (IDRD) Yessad, K., 2017: Sphere to sphere transforms in spectral space in the cycle 44 of ARPEGE/IFS: configuration 911 (internal note, available on the intranet server “http://www.umr-cnrm.fr/gmapdoc/”).
• (IDDM) Yessad, K., 2017: Distributed memory features in the cycle 44 of ARPEGE/IFS (internal note, available on the intranet server “http://www.umr-cnrm.fr/gmapdoc/”).
• (IDEUL) Yessad, K., 2017: Integration of the model equations, and Eulerian dynamics, in the cycle 44 of ARPEGE/IFS (internal note, available on the intranet server “http://www.umr-cnrm.fr/gmapdoc/”).
• (IDESIDG) Yessad, K., 2006: Implementation of option LESIDG in ALADIN (internal note, 13pp).

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