Tests prior to the operational implementation of the Physics-Dynamics Coupling

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Introduction

- This note describes a partial second-order accurate approximation of the physical parametrizations in the two-time-level semi-Lagrangianand semi-implicit (2TLSLSI) version of the HIRLAM model.
- The approximation is achieved by averaging all or part of the parameterization tendencies along the semi-Lagrangian trajectory, following the ECMWF approach (Wedi,1999).
- The coupling of the physics to the dynamics in the HIRLAM model is described and compared with the current operational configuration.
- A "first-guess" predictor of the model variables is employed to achieve the coupling of the different parametrization schemes to each other.This predictor value tries to reduce the time-step dependency.

Coupling of parameterizations with the dynamics

The generic one-dimensional advection equation can be written as:

$$\frac{\partial\psi(x,t)}{\partial t}+u(x,t)\frac{\partial\psi(x,t)}{\partial x}=L\{\psi(x,t)\}+N\{\psi(x,t)\} \tag{1}$$

where ψ is a scalar field, u is the advecting velocity and L and N represent the linear and nonlinear terms, respectively.

Following McDonald(1998), the 2TLSLSI method of discretization can be expressed as:

$$\psi_I^{n+1} - \psi_*^n = \frac{\Delta t_+}{2}[L^{n+1} + N^{n+\frac{1}{2}}]_I + \frac{\Delta t_-}{2}[L^n + N^{n+\frac{1}{2}}]_* \tag{2}$$

where $N^{n+\frac{1}{2}} = \frac{(3N^n - N^{n-1})}{2}$

and $\Delta t_\pm = (1 \pm \epsilon_g)\Delta t$; ϵ_g is called the "decentering" parameter (to reduce high-frecuency oscillations). For any field ϕ , $\phi_I^n = \phi(I\Delta x, n\Delta t)$, and $\phi_*^n = \phi(x_*, n\Delta t)$. The subscripts I and $*$ denote, respectively, an evaluation at the arrival point and the departure point of the trajectory. The superscript n denotes the number of time-step.

If physical parameterizations are also included and following the ECMWF approach, the resulting equation is:

$$\psi_I^{n+1} - \psi_*^n = \frac{\Delta t_+}{2}[L^{n+1} + N^{n+\frac{1}{2}} + P^{n+1}]_I + \frac{\Delta t_-}{2}[L^n + N^{n+\frac{1}{2}} + P^n]_* \tag{3}$$

- where one half of the tendency is computed at the arrival point and the other half at the departure point of the trajectory. This approximation is second-order accurate.
- The current reference HIRLAM model makes use only of the parameterization tendencies at the arrival point, being thus the time discretization only first-order accurate for physical processes.

Physics-Dynamics Coupling strategies

Four coupling strategies against the reference version are shown:

- **DPW** Experiment: the contributions of the radiation and convection schemes are averaged along the semi-Lagrangian trajectory and those of the vertical diffusion are taken at the arrival point only.

  The final equation, once the tendencies of the parameterizations are computed, is:

  $$\psi_I^{n+1} - \psi_D^{n+1} = \frac{\Delta t_+}{2}[P_{rad+conv}^{n+1}]_I + \frac{\Delta t_-}{2}[P_{rad+conv}^n]_* + \Delta t P_{vdif,I}^{n+1} \tag{4}$$

- **DPI** Experiment: the radiation and convection tendencies of the previous time-step and interpolated at the departure point are introduced in the semi-implicit adjustment. This alternative implies that around half of the physical tendencies are taken into account by the dynamical tendencies.

  The discretized resulting equation is:

  $$\tilde{\psi}_I^{n+1} - \psi_*^n = \frac{\Delta t_+}{2}[L^{n+1} + N^{n+\frac{1}{2}}]_I + \frac{\Delta t_-}{2}[L^n + N^{n+\frac{1}{2}} + P_{rad+conv}^n]_* \tag{5}$$

And the final equation is:

$$\psi_I^{n+1} - \tilde{\psi}_I^{n+1} = \frac{\Delta t_+}{2}[P^{n+1}_{rad+conv}]_I + \Delta t P^{n+1}_{vdif,I} \tag{6}$$

- **WAL** Experiment: the contributions of the radiation, convection and vertical diffusion schemes are averaged along the semi-Lagrangian trajectory in all equations.

  The final equation, once the tendencies of the parameterizations are computed, is:

$$\psi_I^{n+1} - \psi_D^{n+1} = \frac{\Delta t_+}{2}[P^{n+1}_{rad+conv+vdif}]_I + \frac{\Delta t_-}{2}[P^{n}_{rad+conv+vdif}]_* \tag{7}$$

- **IAL** Experiment: the radiation, convection and vertical diffusion tendencies of the previous time-step and interpolated at the departure point are introduced in the semi-implicit adjustment, except for the extrascalar variable that is not averaged.

  The discretized resulting equation is:

$$\begin{aligned}\tilde{\psi}_I^{n+1} - \psi_*^n &= \frac{\Delta t_+}{2}[L^{n+1} + N^{n+\frac{1}{2}}]_I \\ &+ \frac{\Delta t_-}{2}[L^n + N^{n+\frac{1}{2}} + P^n_{rad+conv+vdif}]_* \end{aligned} \tag{8}$$

  And the final equation is:

$$\psi_I^{n+1} - \tilde{\psi}_I^{n+1} = \frac{\Delta t_+}{2}[P^{n+1}_{rad+conv+vdif}]_I \tag{9}$$

- In the current reference HIRLAM model (**REF** experiment), the contributions of the radiation, convection and vertical diffusion schemes are taken at the arrival point only.

  The final equation is:

$$\psi_I^{n+1} - \psi_D^{n+1} = \Delta t[P^{n+1}_{rad+conv+vdif}]_I \tag{10}$$

Coupling of the parameterization schemes

- The HIRLAM model makes use of the "fractional stepping" approach (Beljaars, 1991). The results depend consequently on the calling sequence.
- In the HIRLAM model this sequence is: first, radiation; second, soil processes; third, vertical diffusion and, lastly, convection. The convection scheme, therefore, uses the tendencies of the vertical diffusion and radiation schemes.
- To keep the idea of "fractional stepping", a "first guess" predictor of the model variables is used.

- In the **DPW** and **DPI** experiments, a "first guess" predictor is employed by using the tendency from the dynamics, the tendency of the radiation and convection at the previous time-step and the tendency of the vertical diffusion at the current time-step (Wedi, 1999):

$$\psi_{predict}^{n+1} = \psi_D^{n+1} + \alpha P_{*,rad+conv}^{n} \Delta t + P_{I,vdif}^{n+1} \Delta t \tag{11}$$

  where ψ_D^{n+1} stands for the dynamical fields at the arrival point. The parameter $\alpha = 0.5$ has been introduced in order to achieve a better balance between the physical parameterizations.

- In the **WAL** and **IAL** experiments, a "first guess" predictor is employed by using the tendency from the dynamics, the tendency of the radiation, vertical diffusion and convection at the previous time-step:

$$\psi_{predict}^{n+1} = \psi_D^{n+1} + \alpha P_{*,rad+conv+vdif}^{n} \Delta t \tag{12}$$

In the proposed schemes the parameterizations at the current time-step are computed in the following calling sequence:

$$P_I^{n+1} = P_{I,rad}^{n+1}(\psi^n) + P_{I,vdif}^{n+1}(\psi_D^{n+1}) + P_{I,conv}^{n+1}(\psi_{predict}^{n+1}) \tag{13}$$

The current reference HIRLAM model (**REF** experiment) uses "fractional stepping" with the following calling sequence:

$$\psi_{predict}^{n+1} = \psi_D^{n+1} + P_{I,rad}^{n+1} \Delta t + P_{I,vdif}^{n+1} \Delta t \tag{14}$$

$$P_I^{n+1} = P_{I,rad}^{n+1}(\psi^n) + P_{I,vdif}^{n+1}(\psi_D^{n+1}) + P_{I,conv}^{n+1}(\psi_{predict}^{n+1}) \tag{15}$$

- Radiation and vertical diffusion schemes are left unchanged.
- The main change is in the convection scheme. The contributions of the radiation and vertical difussion schemes at the current time-step are replaced by those of the radiation, vertical difussion and convection schemes at the previous time-step evaluated at the departure point of the semi-Lagrangian trajectory.

Comparison of numerical accuracy

- The **DPW**, **DPI**, **WAL** and **IAL** experiments are compared to **REF** one:

  - HIRLAM version 6.2,
  - 0.2^ox0.2^o resolution in the horizontal,
  - 40 hybrid levels in the vertical and
  - 326x125 points.

- Mixed (Cubic/Linear) interpolation is used to interpolate the diabatic tendencies P to the departure point of the semi-Lagrangian trajectory.

- In the first time step, the configuration is similar to the reference HIRLAM model.

- To examine the sensitivity of the solutions to changes in the length of the time-step, we assume that the method which has the long time-step solution closer to the short time-step solution is the better method (Wedi,1999).

- Four different 24-hour forecasts have been run with t=60s and t=450s. As a measure for the deviation of the 450s-solution from the assumed correct 60s-solution, the root mean square error has been computed for the three experiments:

$$rmse = \sqrt{\overline{(F_{t=450s} - F_{t=60s})^2}} \qquad (16)$$

  The overbar denotes an average over area. The variables F are the diabatic tendencies integrated vertically and accumulated every time-step over a period of 24 hours.

- By comparing all experiments, I have found that:

  - Summarizing, in any coupling strategies the rmse is smaller than in the reference version, except for the tendency of the cloud water content due to vertical diffusion (figure 1). In the IAL experiment, this tendency increases too much and instability appears. As a consequence, I have chosen WAL and DPW experiments to carry out the parallel runs.

Verification scores

Three parallel runs have been carried out with **DPW**, **WAL** and **REF** experiments.

The general characteristics are:

- HIRLAM version 6.2,
- domain of the RCR model,
- 406x324 points with a 0.2^ox0.2^o resolution in the horizontal,
- 40 hybrid levels in the vertical,
- time step t=300s and

- from 16.11.2003 1200 UTC to 15.12.2003 1200 UTC up to H+48.

Verification scores against observations over the EWGLAM area have been carried out to compare the different schemes.

The DPW experiment shows slightly better scores than REF one in the dew point temperature at 24-hour and 48-hour forecasts and similar scores in the other vertical profiles (figure 2). In the figure 3, the DPW experiment seems slightly better than REF one for large amount of precipitation and slightly worse for small amount; perhaps, related to the smoothness of the fields by averaging along the semi-Lagrangian trajectory.

The WAL experiment shows slightly worse scores than REF one at 500 hPA temperature and wind at 48-hour forecast and quite similar scores in the other vertical profiles (figure 4). In the figure 5, it is noticed that the behaviour of both experiments is quite close or slightly worse for small amount of precipitation.

Strong Convective Case

Since the most important improvement is in the convection scheme, I have studied a case of strong convection.

Strong Convection over the Mediterranean area

The general characteristics of the experiment are:

- HIRLAM version 6.2,
- domain of the RCR model,
- 406x324 points with a 0.2^ox0.2^o resolution in the horizontal,
- 40 hybrid levels in the vertical,
- time step t=300s and
- they were started at 0000 UTC 02.12.2003 up to H+48 with own assimilation cycle each experiment since 16.11.2003 1200 UTC.

The results are compared to 12-hour forecast, the image of satellite and the lightning chart (figure 7).

The pattern of precipitation and the position and depth of the center of the low pressure near Lion's Gulf have been chosen to compare the different experiments. The position is located in both coupling experiments better than reference one, but only the DPW experiment is able to reproduce the depth. The pattern of precipitation of WAL experiment is quite close to the 12-hour forecast one (figures 6 and 7).

Summary

Summarizing, the Physics-Dynamics Coupling strategies in HIRLAM 6.2 lead to:

- more stable results,
- similar accurate results for short time-step and more accurate ones for long time-step,
- a smoothing of the fields, especially precipitation and
- the forecast skill improvement of the new methods is small in the short range, but becomes more appreciable in the medium range.

However, it must be stressed that:

- The effectiveness of the coupling decreases according to the resolution increases.
- The fields of the version 6.2, without coupling, are smoother than previous versions (see Martínez, 2002). As a consequence, the effect of the coupling is smaller.
- The first-guess predictor plays a second role against the physics- dynamics coupling strategies.
- The coupling depends on the parametrization schemes implemented in the model. It could be improved by increasing the implicitness of the formulation with respect to fast processes.

6.- References

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McDonald, A.,1998: The Origin of Noise in Semi-Lagrangian Integrations. Proceedings of the ECMWF Seminar on Recent Developments in Numerical Methods for Atmospheric Modelling, Reading, pp. 308-334.

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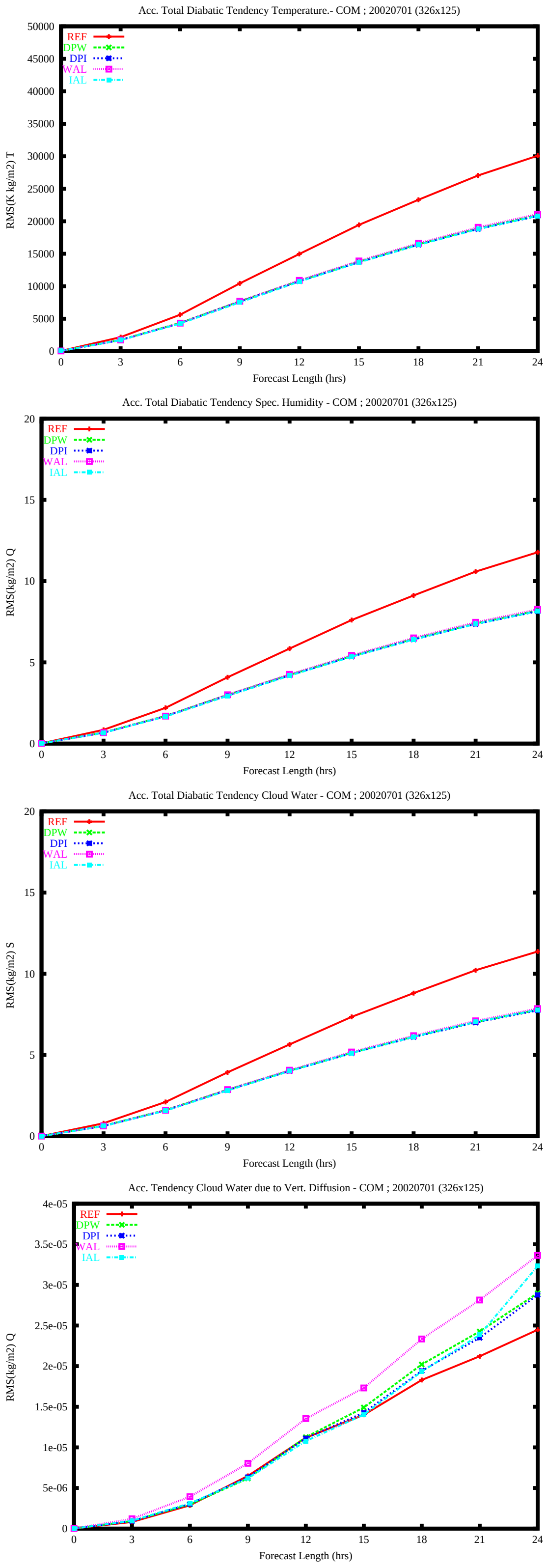

Figure 1: RMSE of the accumulated total diabatic tendency of Temperature (*top*), Specific Humidity (*centre*) and Cloud Water Content (*centre*) and RMSE of the diabatic tendency of cloud water content due to vertical diffusion (*bottom*).

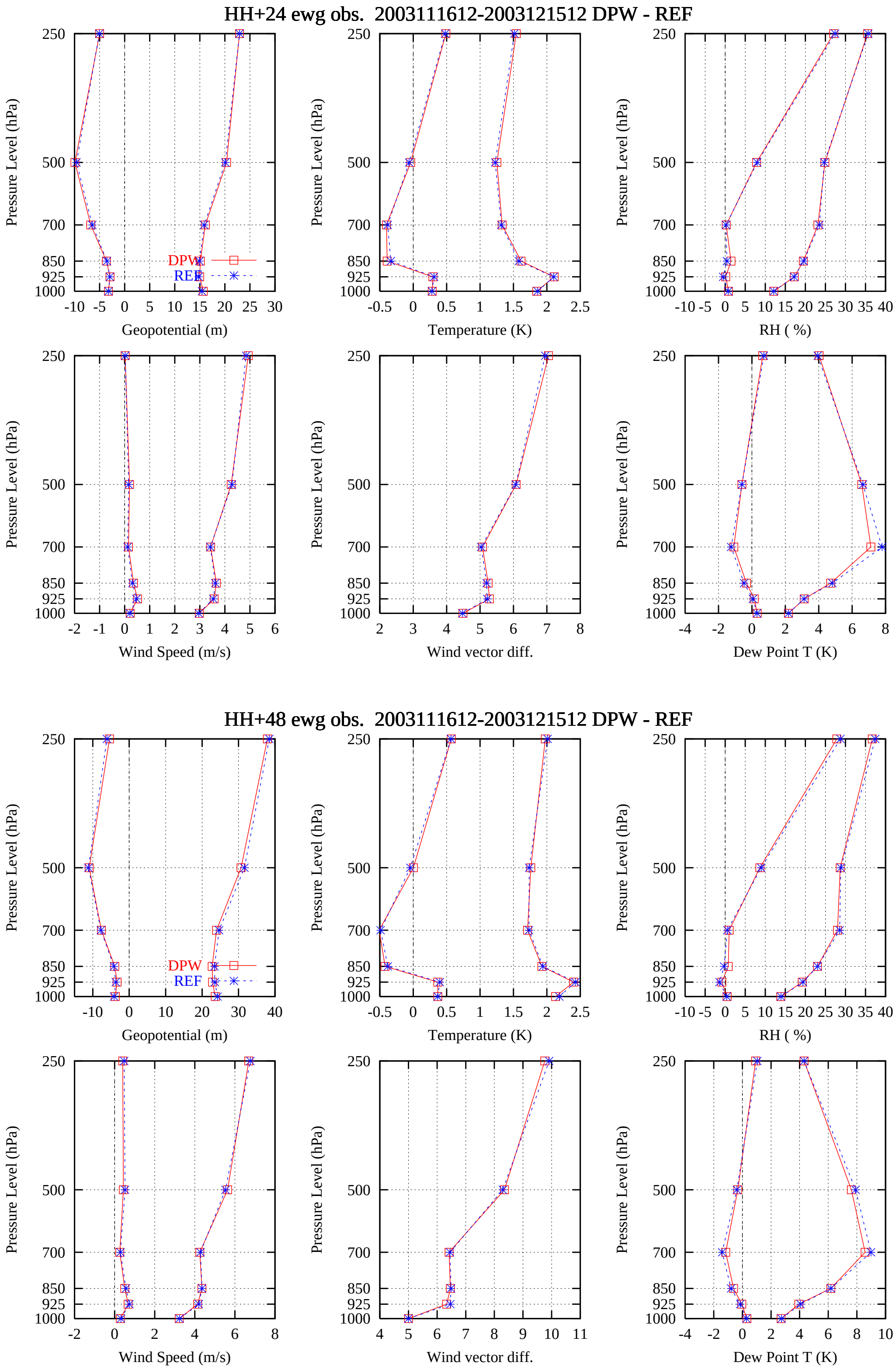

Figure 2: Vertical profiles of the verification scores at 24-hour forecast (*top*) and at 48-hour one (*bottom*) of the DPW and REF experiments.

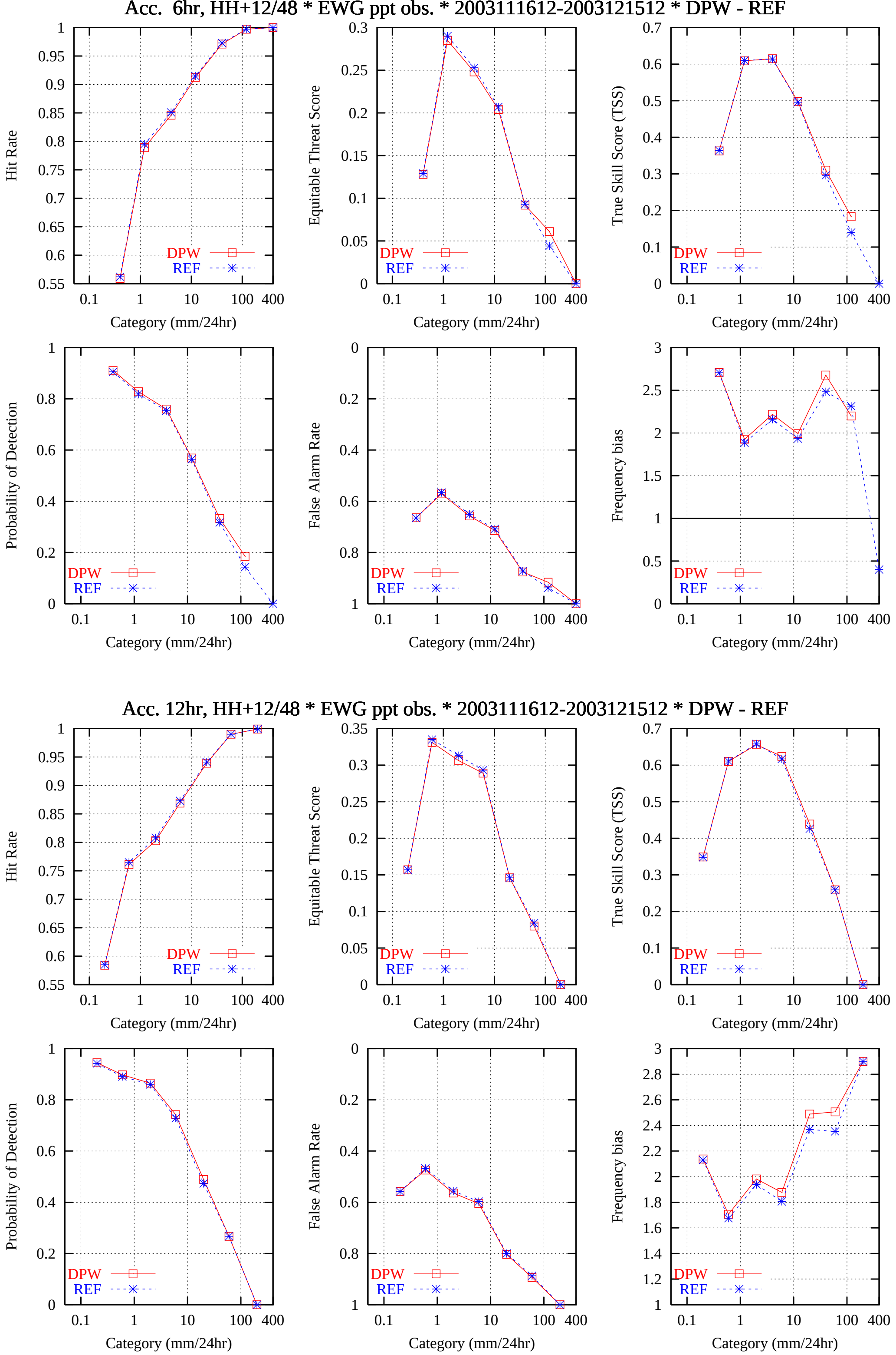

Figure 3: Scores of the 6-hour accumulated precipitation averaged from 12-hour forecast to 48-hour one (*top*) and the same to 12-hour accumulated precipitation (*bottom*) of the DPW and REF experiments.

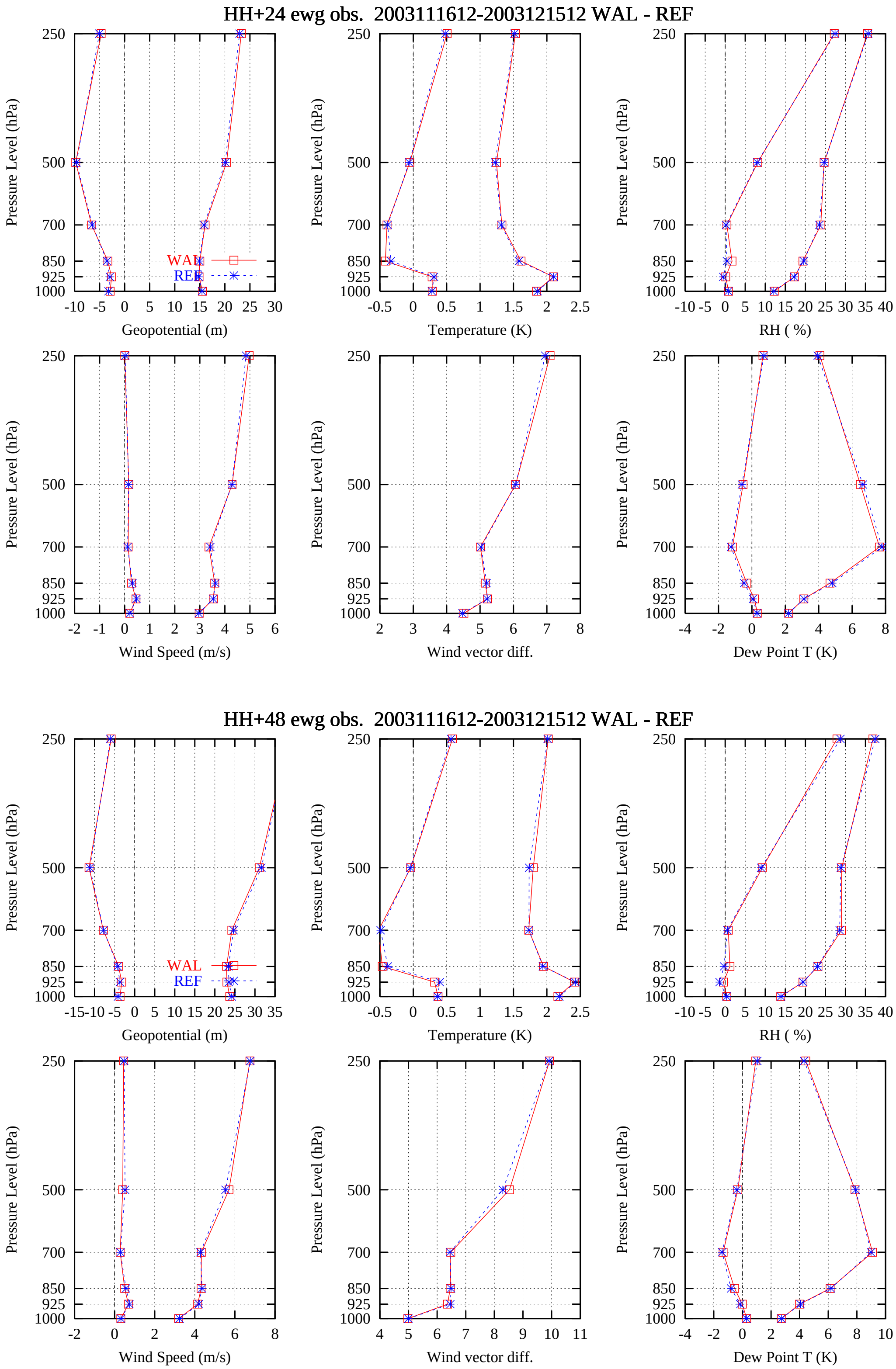

Figure 4: Vertical profiles of the verification scores at 24-hour forecast (*top*) and at 48-hour one (*bottom*) of the WAL and REF experiments.

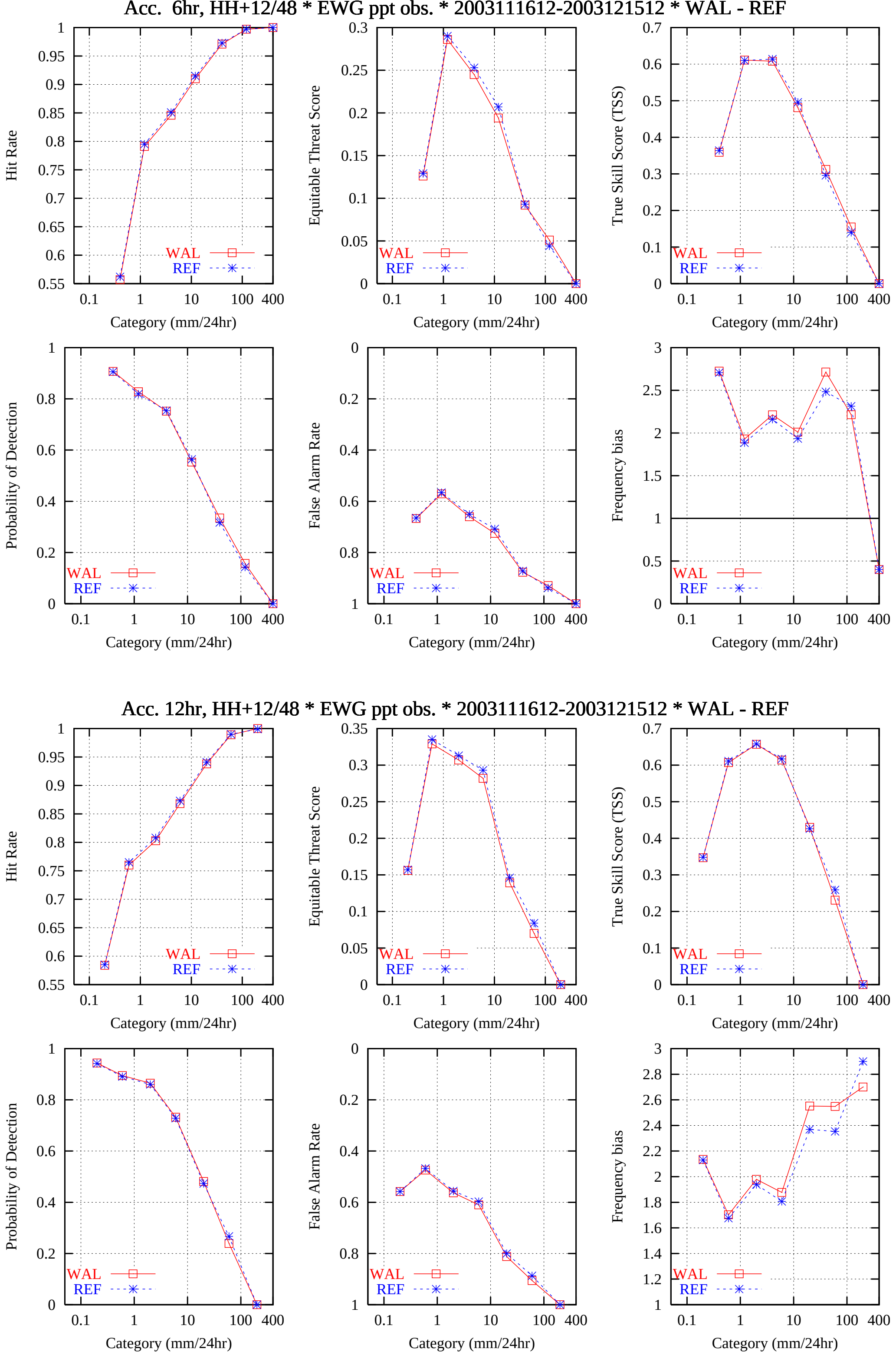

Figure 5: Scores of the 6-hour accumulated precipitation averaged from 12-hour forecast to 48-hour one (*top*) and the same to 12-hour accumulated precipitation (*bottom*) of the WAL and REF experiments.

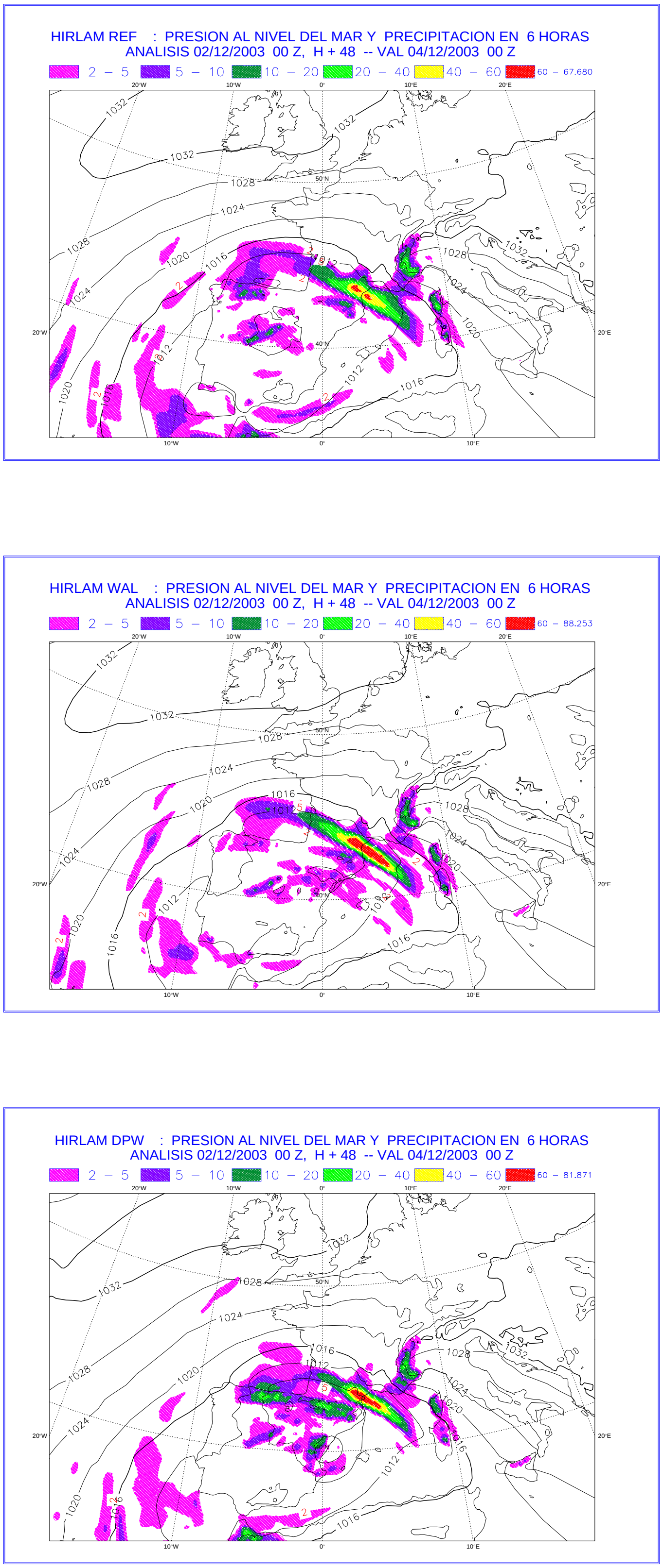

Figure 6: MSLP and 6-hour accumulated precipitation at 48-hour forecast of the REF (*top*), WAL (*centre*) and DPW (*bottom*) experiments.

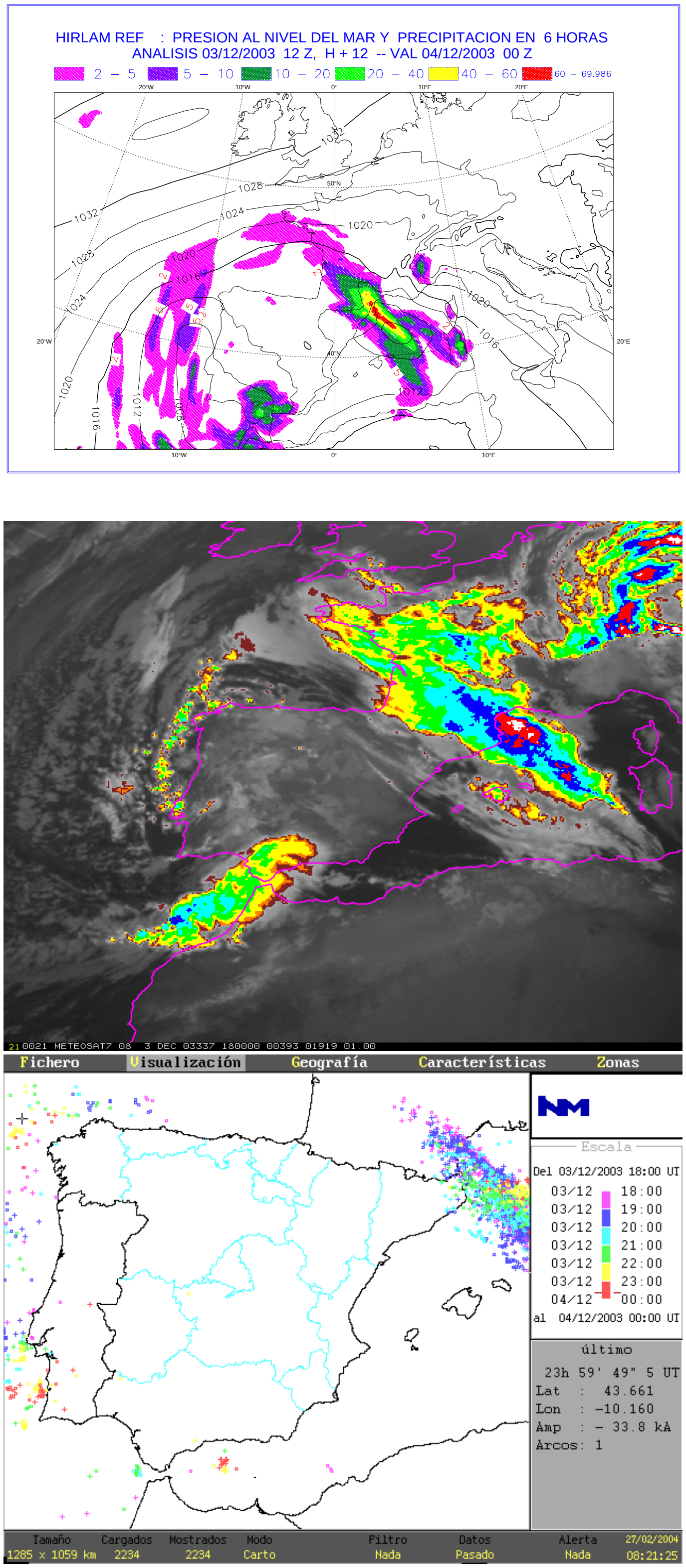

Figure 7: MSLP and 6-hour accumulated precipitation at 12-hour forecast of the REF experiment (*top*), the image of satellite (*centre*) and the lightning chart (*bottom*).