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Physical processes in present and future large-scale models

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Summary

The challenges of linearized physics - Philippe Lopez

Physical parameterizations have become essential components of data assimilation systems, and in particular of the four-dimensional variational method (4D-Var). The 4D-Var approach aims at finding the optimal 3D representation of the atmospheric state (the analysis) at a selected time by blending information coming from a set of observations that are available over a certain time window (6 or 12 hours at ECMWF) with *a priori* information coming from a short-range model forecast (the "background").

This goal is achieved by defining a "cost function" that provides a global measure of the distance between the unknown model state and the model background, on the one hand, and the distance between the unknown state and the observations, on the other hand. The forecast model with physics must be included in the cost function to propagate the model state from the beginning of the 4D-Var assimilation window to the time of each observation, so that model-observation departures can be calculated. The determination of the optimal model state that best fits both the model background and the observations given their assumed respective errors, involves the iterative minimization of the 4D-Var cost function. Therefore, during the minimization, the gradient of the cost function needs to be evaluated, which requires the use of the adjoint of the forecast model. In practice, the adjoint model can be simply seen as the transpose of the tangent-linear model, which itself corresponds to the local derivative of the nonlinear forecast model. However, because the 4D-Var minimization needs to remain computationally affordable and because it relies on the linear hypothesis, the forecast model which is used in the assimilation process must contain a set of physical parameterizations that are simplified compared to those employed in the standard forecast model.

The development of new simplified physical parameterizations for the purpose of data assimilation implies finding the best compromise between realism, computational affordability and linearity. The testing and debugging of the tangent-linear and adjoint codes can be very demanding. In practice, the testing should be performed every time a new model version is released and should verify:

- the correctness of the tangent-linear code (i.e. the first-order Taylor approximation).
- the level of agreement between the tangent-linear simplified parameterizations and the reference nonlinear forecast model, for perturbations with a size typical of 4D-Var increments.
- the exactness of the adjoint code (to the level of machine precision).
- the good behaviour of the linearized physics in 4D-Var data assimilation experiments, but also in singular vector computations (used in the Ensemble Prediction System).

In addition, the linearity assumption inherent in 4D-Var requires the application of some "regularizations" of the tangent-linear and adjoint codes. These regularizations involve either the smoothing of functions that are identified as being too nonlinear or the reduction of perturbations that are found to be prone to spurious amplification in tangent-linear integrations. Such regularization procedures are particularly crucial in the parameterizations of convection, large-scale condensation as well as vertical diffusion (esp. for the perturbations of near-surface exchange coefficients).

The ECMWF 4D-Var minimization uses the most detailed set of physical parameterizations currently available in global systems. It comprises schemes describing vertical diffusion, some surface processes, orographic and non-orographic gravity wave drag, radiation, convection and large-scale condensation. Janisková and Lopez (2013) have demonstrated that the inclusion of linearized physics in the ECMWF 4D-Var minimizations leads to a significant improvement in forecast scores, not only close to analysis time, but also for forecast ranges up to seven days.

However, it has become clear that with the constant increase in both the complexity of the reference nonlinear model and the resolution of the 4D-Var system, it will probably become more and more challenging to ensure that the underlying linearity assumption of 4D-Var remains valid. It might even become impractical or even impossible to make the linearized model (physics but also dynamics) work in an efficient way when resolutions of a few kilometres are used in the minimizations. Fortunately, however, the minimizations involved in current operational global 4D-Var systems are still performed at horizontal resolutions much coarser than 30 km. Alternative data assimilation methods that do not require the actual development of linearized codes do exist (e.g. the Ensemble Kalman Filter), but so far none of those has been able to outperform 4D-Var, especially in global systems.

Reference

Janisková, M. and P. Lopez, 2013: Linearized physics for data assimilation at ECMWF. In S.K. Park and L. Xu (eds.), Data assimilation for Atmospheric, Oceanic and Hydrological Applications (Vol. II), DOI 10.1007/978-3-642-35088-7, ©Springer-Verlag Berlin Heidelberg, 251-286.