Using short-term physical tendencies to study the dynamical balance of atmospheric models. AT-14

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I. Introduction

Dynamical imbalances between the physical processes included in an atmospheric model can have an impact on the realism of the climate of a model and its variability. It is often observed that the climate of a model may differ from that of observations and detailed diagnostics are necessary to assess whether adjustments in the physical parameterizations used for convection, radiative and dynamical processes lead to a state that is close to observations. Rodwell and Palmer (2007) have proposed to use diagnostics based on short-term physical tendencies of the model when analyses are used as initial conditions. Such diagnostics provide useful information about the consistency of the physics as it relaxes to the model's own climatology in the first moments of the integration. On the other hand, it is well known that analyses can themselves create spin-up problems that need to be addressed by using normal mode initialization or digital filtering to remove spurious gravity waves. Gauthier and Thépaut (2001) showed that 4D-Var analyses provide initial conditions that are better balanced and do not require as much the application of other constraints to maintain this equilibrium.

Regional climate models are initialized by reanalyses and driven by reanalyses or output from global climate run, often obtained by another model. Diagnostics proposed by Rodwell and Palmer (2007) could provide helpful information about whether the driving global model and the regional one are concordant.

II. Objective and methodology

In this study, the Rodwell and Palmer diagnostics are used to:

- assess the GEM (Global Environmental Multiscale) model's balance when initialized by 3D-Var or 4D-Var analyses (produced by the Meteorological Service of Canada).
- evaluate this equilibrium when the GEM model is initialized by "external" analyses (e.g., ECMWF ERA-Interim reanalyses)
- apply the diagnostics to a regional model, the Canadian Regional Climate Model (CRCM) and assess its equilibrium when driven by different data (4D-Var analyses and ERA-Interim reanalyses).

The diagnostic parameter used in our study is applied to temperature and defined as :

$$\frac{1}{m}\sum_{i=1}^{m}\dot{T}_i^{total} = \frac{1}{m}\sum_{i=1}^{m}\sum_{p=1}^{k}\dot{T}_i^{(p)}$$

where m is the total number of simulations and $\dot{T}_i^{total}$ is the total temperature tendency, that is, the sum of individual temperature tendencies $\dot{T}_i^{(p)}$ associated with each physical process considered in the model.

The physical processes considered here are: radiation, convection, advection, vertical diffusion and large scale condensation.

Spatial mean of this diagnostic parameter are computed on specified regions to assess the model's equilibrium averaged horizontally and/or vertically.

II. Global model

In this experiment, the objective is to evaluate the global model dynamical equilibrium when different initial conditions are used based on 3D-Var and 4D-Var analyses from MSC (Laroche and Sarrazin, 2010) and ECMWF ERA-interim (Dee *et al.*, 2011).

The model used in this study is the GEM model (Côté *et al.*, 1998 ; Bélair *et al.*, 2009) in a global uniform configuration and a resolution around 50 km at the equator. The model has 80 vertical levels with a top at 0.1 hPa. The time step is 15 minutes.

In each experiment, a set of simulations starting every six hours from 00 UTC on 01 January 2009 to 18 UTC on 31 January 2009. The model's integrations are up to 5 days.

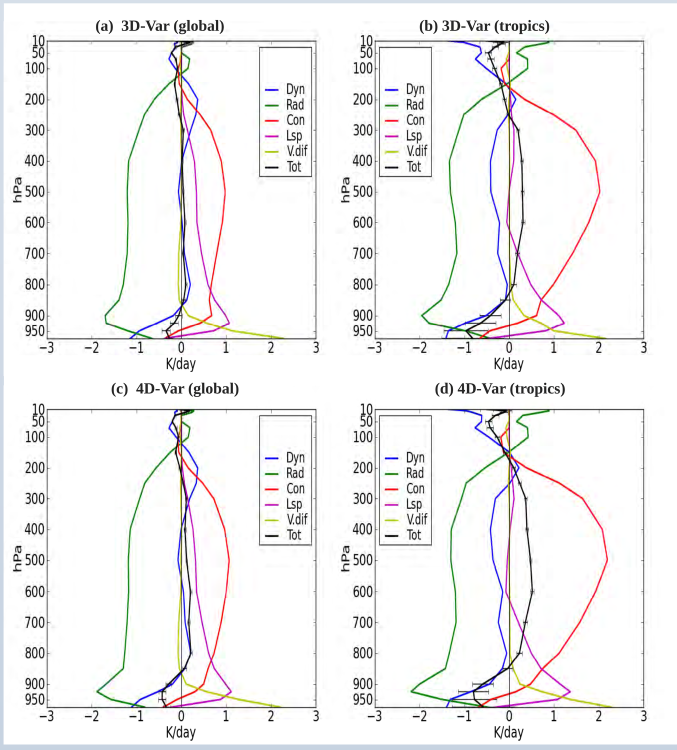

Fig. 1. Temperature tendency profiles averaged over the first six hours excluding the first time step associated with advection (Dyn), radiation (Rad), convection (Con), large scale condensation (Lsp), vertical diffusion (V.dif) and the total tendency (Tot). Horizontal bars are 99% confidence intervals. Results are for integrations from 3D-Var analyses averaged a) globally, and b) over the Tropics, and similarly from 4D-Var analyses (c, and d).

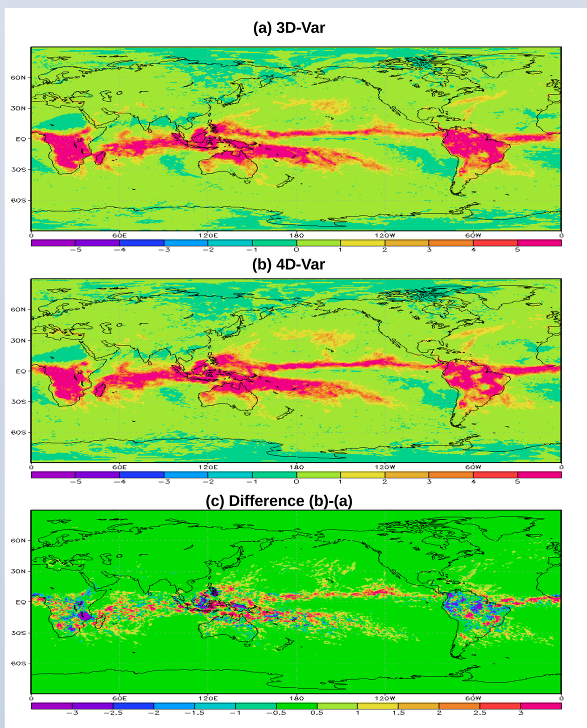

Fig. 2. Initial temperature tendency due to convection (in K/day) at 500 hPa level.

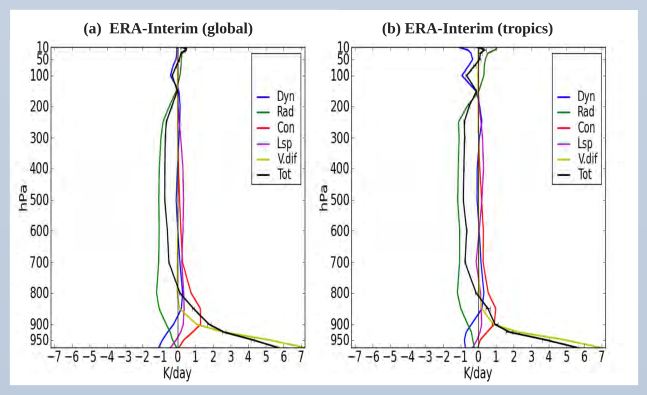

Fig. 3. Same as fig.1 but with ERA-Interim reanalyses as initial conditions.

Comparing the results for 3D-Var and 4D-Var, the convection activity is stronger in the ITCZ when GEM model is initialized by 4D-Var analyses suggesting that a recalibration of the convection parameterization scheme may be needed.

Important imbalances are found when using ERA-Interim reanalyses due to strong vertical diffusion in lower atmospheric layers and an absence of convection as well. These imbalances may be attributed to differences between the model used in assimilation and that used to make the forecasts.

III. Canadian Regional Climate Model (CRCM)

Regional climate models are usually initialized by global model analyses or reanalyses and driven at lateral boundaries by reanalyses or global climate output. In this experiment, we use a regional climate model to assess its dynamical equilibrium when initialized and driven by different data sources.

The regional climate model is the Canadian Regional Climate Model (CRCM), version 5, (Zadra *et al.*, 2008) covering North America (Fig. 4) at a horizontal resolution around 20 km and 80 vertical levels up to 0.1 hPa. The CRCM is a limited-area version of the GEM global model and the physical parameterization schemes are the same. The time step is 10 minutes.

Two sets of 12-h integrations have been performed starting every six hours from 00 UTC on 01 January 2009 to 18 UTC on 30 January. In the first set, the model is initialized and driven at its boundaries every 6-h by 4D-Var MSC analyses while in the second set, ERA-Interim reanalyses are used.

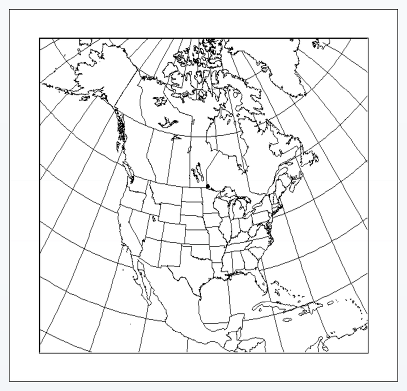

Fig. 4. CRCM model domain

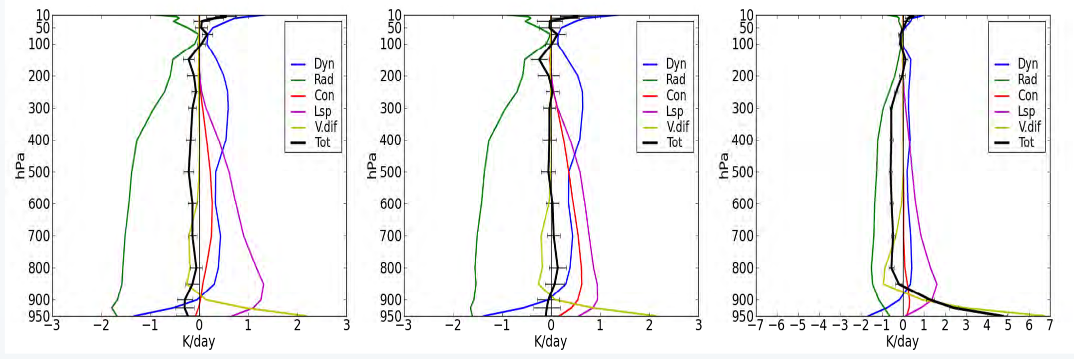

Fig. 5. Initial temperature tendency (in K/day) obtained from : (a) CRCM initialized and driven by 4D-Var, (b) GEM global initialized by 4D-Var, and (c) CRCM initialized and driven by ERA-Interim reanalyses. All results have been averaged over the CRCM domain.

Results show imbalances for the CRCM when initialized and driven by ERA-Interim reanalyses with strong vertical diffusion in lower levels (stronger than that observed in the GEM global model). Convection is also missing inducing a net cooling in the middle troposphere.

GEM global tendencies obtained by averaging on the CRCM domain show better dynamical equilibrium. This indicates that the global configuration model reaches its own climatology faster than the limited area model (LAM) with the same settings.

Results indicate the advantage of producing regional analyses based on CRCM. This would allow better validation and assessment of equilibrium between physical processes represented by CRCM.

IV. Tendency diagnostic for longer periods

In this experiment, tendency diagnostic has been computed when the model is run for a longer period. The aim is to examine the time needed for the model to restore its equilibrium state, its own climatology.

Integrations of 5-days were performed every 6-h from 00 UTC on 01 January 2009 for a period of 30 days. As before, the GEM global model and the CRCM limited-area model are used with different initial and boundary conditions (for CRCM).

In the case of CRCM, the tendency diagnostic is first computed by including the pilot region and secondly, excluding it, considering only the model's free zone.

GEM global model

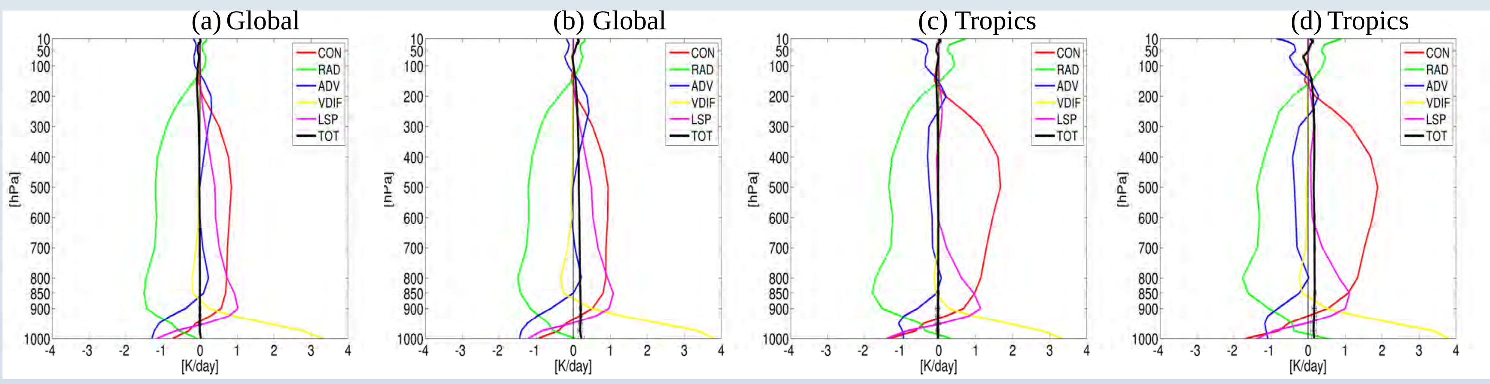

Fig. 6. Temperature tendency profiles computed at the end of a 30 days global model run. In (a) and (c) the model is initialized by 4D-Var analyses and by ERA-Interim reanalyses in (b) and (d).

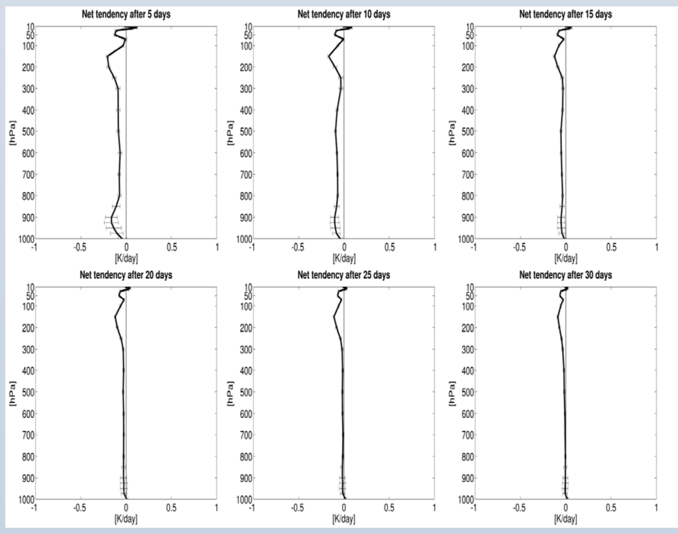

Fig. 7. Temperature's net tendency profiles computed at 5-days interval. Simulations are initialized by 4D-Var analyses

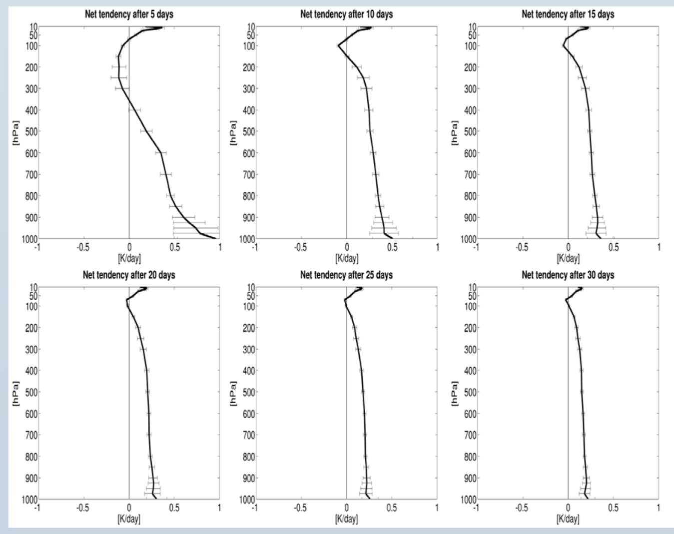

Fig. 8. As Fig. 7 but with simulations initialized by ERA-Interim reanalyses.

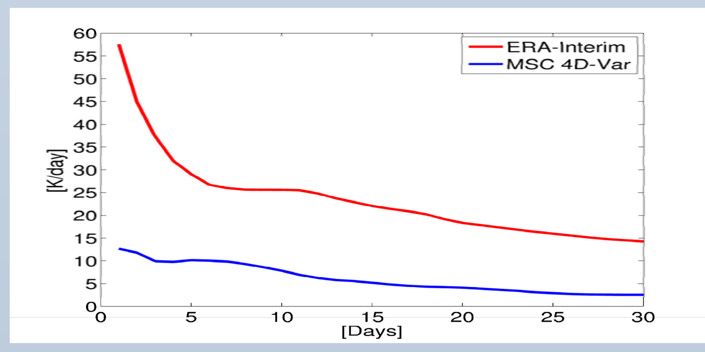

Fig. 9. Vertically integrated absolute temperature net tendency.

Results show that the global GEM model is almost balanced after 30 days run when 4D-Var MSC analyses are used as initial conditions. The net tendency is very close to zero except in levels above 300 hPa where small imbalances still exist.

When initialized by ERA-Interim, the model still exhibit imbalances with heating at all levels.

These results indicate that initial conditions impact still exist after 30-days integration and the model needs a longer integration time to achieve its balance.

CRCM regional model

In this experiment, two CRCM runs were performed each for 30 days starting on 00 UTC on 01 January 2009. In the first simulation, MSC 4D-Var analyses are used as initial and boundary conditions. In the second, ERA-Interim reanalyses are employed to initialize and drive the model. Boundary data are supplied every six hours. The tendency diagnostic is averaged over the integration domain including the blending zone and the model's free zone.

Diagnostics including the blending zone

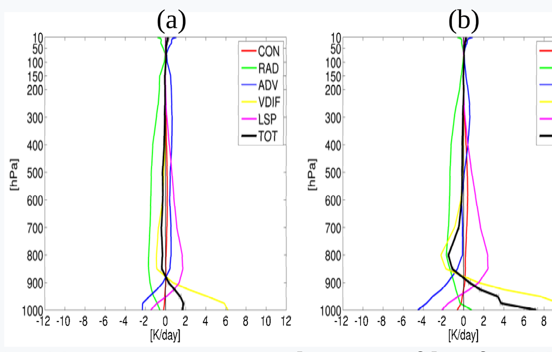

Fig. 10. Temperature tendency profile after 30 days.
(a) run with Initial and boundary data from 4D-Var analyses.
(b) run with ERA-Interim as initial and driving data.

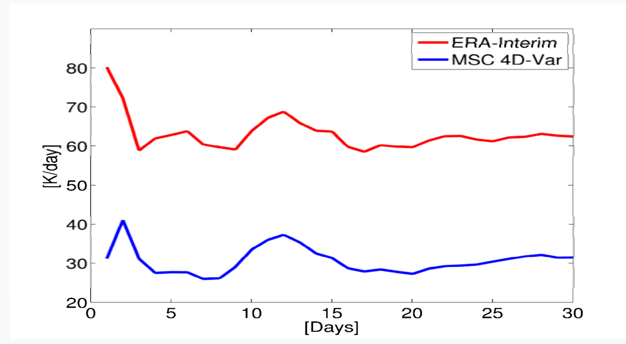

Fig. 11. Vertically integrated absolute net temperature tendency.

In the two simulations, profiles and integrals show that the model is still imbalanced after 30 days. However, the 4D-Var run shows better equilibrium. The larger imbalances are found in the model low levels.

Diagnostics over the model free zone only

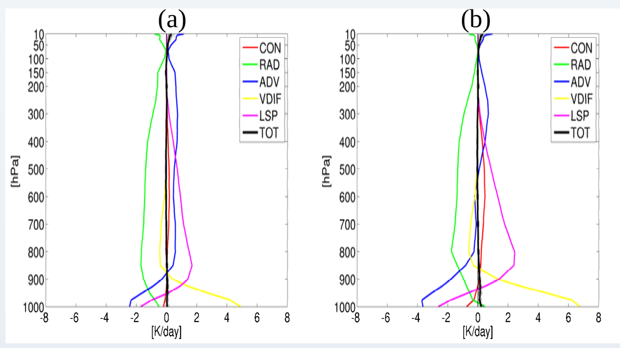

Fig. 12. Temperature tendency profile after 30 days.
(a) run with initial and boundary data from 4D-Var analyses.
(b) run with ERA-Interim as initial and driving data.

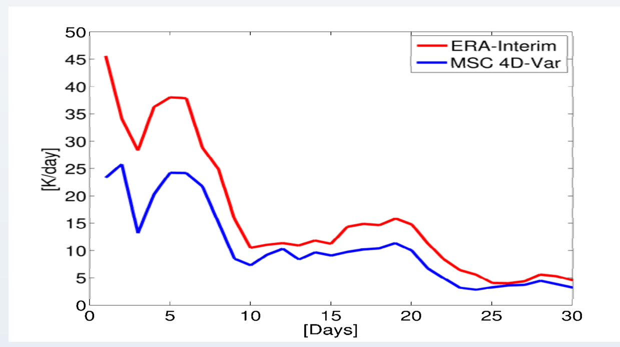

Fig. 13. Vertically integrated absolute net temperature tendency.

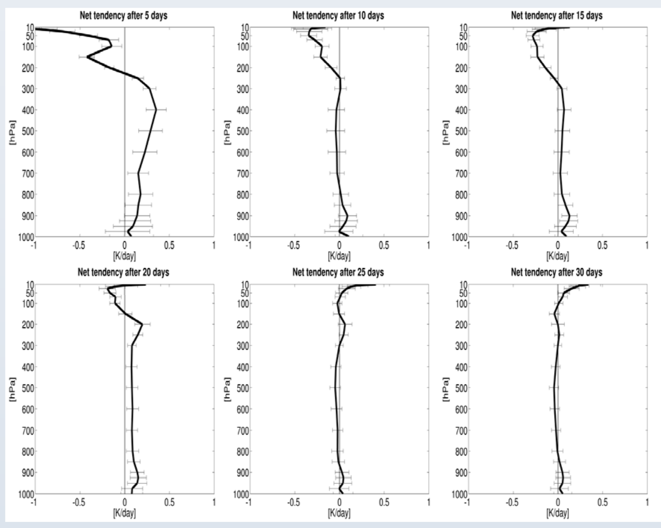

Fig. 14. Temperature net tendency profiles computed after different integration length. Simulations are initialized and driven by 4D-Var analyses

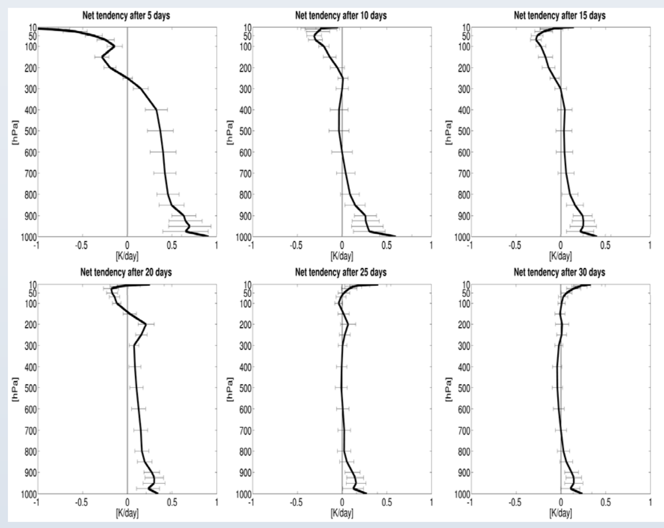

Fig. 15. As Fig. 14 but with simulations initialized and driven by ERA-Interim reanalyses.

When considered only in its free zone, the model's equilibrium is better in the two runs. The net tendency computed after 30 days is similar for the two simulations. However, in the lowest levels, the model is better balanced in the 4D-Var integration.

V. Summary and conclusions

- This study has shown that the dynamical equilibrium of a model is sensitive to initial conditions and to boundary forcing.
- Significant differences are observed when the global GEM model is initialized from 3D-Var and 4D-Var analyses. For the latter, convection in the ITCZ is stronger and a recalibration of the physics may be needed to take into account the impact of having a 4D-Var analysis.
- Results show that an external analysis not produced by the model, such as those from ERA-Interim in our case, can induce serious initial imbalances reflecting differences with respect to the model used in the assimilation.
- The CRCM is therefore in better equilibrium when initialized and driven by MSC 4D-Var analyses.
- Results from 30-days integrations indicate that a model is converging more rapidly towards its own climatology when initialized and driven by its own analyses than when external analyses are used. Even after 30 days, imbalances persist and longer simulations are needed to restore the dynamical balance.

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