IMPROVING GENERAL CIRCULATION MODELS
BY USING TENDENCY RESIDUALS AS ADDITIONAL FORCING

Eigil Kaas(1), Annette Guldberg(1), Shuting Yang(1) and Michel Déqué(2)

(1) Danish Meteorological Institute, Lyngbyvej 100, Copenhagen 2100, Denmark, ek@dmi.dk
(2) Météo-France CNRM/GMGEC/EAC, 42 Avenue Coriolis, 31057 Toulouse Cedex 01, France

The long term mean flow simulated in General Circulation Models (GCMs) of the atmosphere exhibits certain systematic errors compared to climatology. These errors are due to errors in the tendencies of the prognostic variables computed from the model equations; i.e. forcing errors. Generally, patterns of systematic errors and forcing errors are quite different due to atmospheric energy dispersion and feedback.

In this study the long term mean forcing residuals (i.e. minus the errors) are calculated for the winter season for all the dynamical prognostic variables in the ARPEGE/IFS model. This is done via assimilating ERA data into the model using a very simple data assimilation (nudging). The identified forcing residuals have then been used as additional forcing in a series of climate simulations where the ARPEGE/IFS model is run with observed SSTs as lower boundary conditions. The modified model has considerably smaller systematic errors than the corresponding control simulation and it shows improved capability for seasonal predictions.

1. FORCING RESIDUALS

Forcing residuals have been obtained from re-assimilation of the ECMWF ERA data into the ARPEGE/IFS model (climate version 2) which is a T42, three time level, Eulerian, spectral model, with semi-implicit treatment of the gravity wave terms (Déqué et al., 1994). The version used here is modified to have the same 31 vertical levels as in the ERA data. The assimilation consists of a simple relaxation or nudging:

$$\Psi_{n,m}(t+\Delta t) = \Psi^{*}_{n,m}(t+\Delta t) + 2\Delta t \frac{(\Psi^{ERA}_{n,m}(t+\Delta t) - \Psi_{n,m}(t+\Delta t))}{\tau} \quad , \qquad (1)$$

where $\Psi_{n,m}$ indicates a prognostic variable for total and zonal wave number n and m, Δt is the length of the time step, the upper index * denotes the preliminary one-step forecast just before the nudging, upper index *ERA* indicates the reanalysis variable the model is being relaxed towards, and τ is the relaxation time. The field Ψ^{ERA} is interpolated in space to match the T42 mountains of ARPEGE and in time between the 6 hourly ERA data using a cubic spline. Only the dynamical variables temperature, vorticity, divergence and logarithm of surface pressure are assimilated to minimise a possible continuous moisture spin-up problem. For the same reason the divergent part of the wind field has been only "weakly assimilated", i.e. with large τ.

When τ is reasonably short Ψ stays close to Ψ^{ERA}, and therefore the last fraction on the right hand side - the relaxation term - is an approximation to (minus) the forcing error. It is the climatology ($\overline{R_{n,m}}$) - varying with the season - of this term which is used as residual forcing in our otherwise free climate simulations:

$$\Psi_{n,m}(t+\Delta t) = \Psi^{*}_{n,m}(t+\Delta t) + 2\Delta t\overline{R_{n,m}} \quad , \qquad (2)$$

where upper index * as before indicates a standard model time step valid at time $t + \Delta t$. In practice ($\overline{R_{n,m}}$) was calculated in two steps or iterations: In a first re-assimilation the τ values were 24 hours for temperature and log surface pressure, 6 hours for vorticity and 48 hours for divergence. In the stratosphere the relaxation was considerably weaker due to less confidence in the re-analyses there. The climatology over all ERA years of the relaxation term from this assimilation was used as residual forcing in an intermediate model. This model was then used in a second re-assimilation where only temperature was assimilated with a τ value of 48 hours. The relaxation term during this assimilation was very weak except in the polar night upper troposphere and stratosphere, where it was comparable to that in the first assimilation. The total residual used in all the simulations below is the sum of the relaxation terms in the first and the second assimilation. Note that this residual is the same for all the simulations and that it only varies with the season. Figure 1 shows an example of the temperature residual forcing in January. One can see that in the tropics additional heating is needed in the upper troposphere in regions of strong convection. Due to the long relaxation times one should, however, be careful considering these residuals as true representatives of errors in the model parameterisation. This is because there is a mutual adjustment between wind and mass fields, i.e. a real error in the wind field could be detected as an error in the mass field and visa versa.

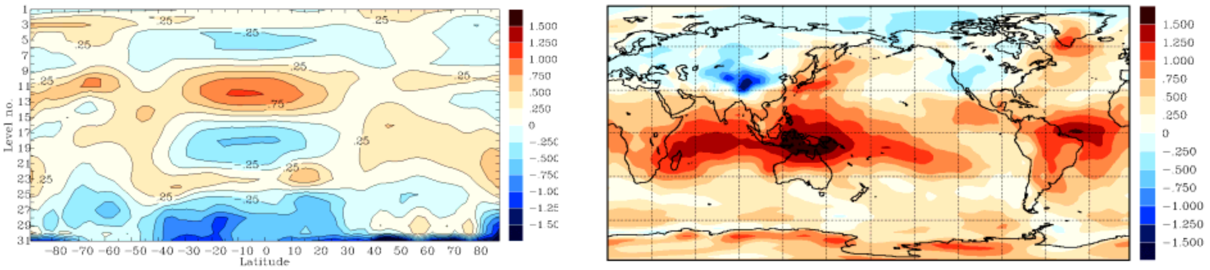

Figure 1: Climatology of the total residual temperature forcing in January. Left panel shows zonal mean forcing for model levels 1 (top) to 31 (bottom). Right panel shows horizontal distribution at model level 12 (approximately 250 hPa). Units: °C/day.

2. SIMULATED CLIMATE

The climate simulations cover 14 winters and are performed with inter-annually varying SSTs taken from the ERA data base. Two ensembles initiated from ERA data on the 22 and 23 Nov. have been performed for each of the winters 1979/80, …, 1992/93 with the uncorrected (control) version of the model and with the empirically modified model (2), using the same residual forcing for all the winters. Figures 2 and 3 show a few examples of the reduction in systematic errors seen with the flux corrected model version as compared to the standard model. For the zonal mean temperature the cold bias in the control simulation upper tropical troposphere is eliminated in the modified model. This is maybe not surprising since an artificial heating was added in these regions, but at other locations there is no such direct relationship between model long term systematic error and residual forcing. For the wind field (not shown), there are error reductions corresponding to those seen in the mass field.

Concerning precipitation (not shown) there are only moderate differences between the control and modified model, except that the ITCZ is somewhat more confined in the modified version and the precipitation in the Indonesian area is enhanced. The global mean value in the control simulations is 3.5 mm/day while it is slightly less, 3.3 mm/day, in the simulations with the modified model.

Not only the long term mean fields are improved, so is the dynamic variability as can be seen from figure 4 which as an example shows the standard deviation of the 2.5-6 day band-pass filtered 500 hPa height field. Obviously much of the so called zonalisation problem with two strong storm tracks at 40 to 50°N is eliminated.

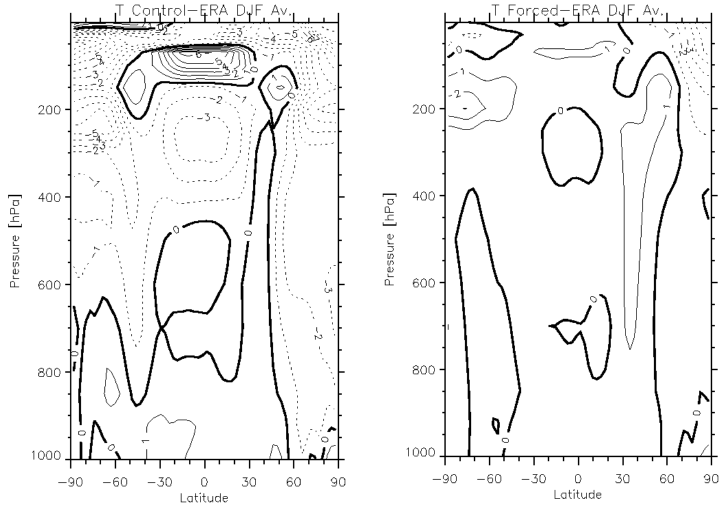

Figure 2: Long term zonal mean systematic errors of temperature in control simulations (left) and in empirically forced simulations (right) as compared to ERA data. The figure is based on data from Dec, Jan and Feb in winters 1979/80, …, 1992/93. Cont. int: 1°C with negative contours dashed.

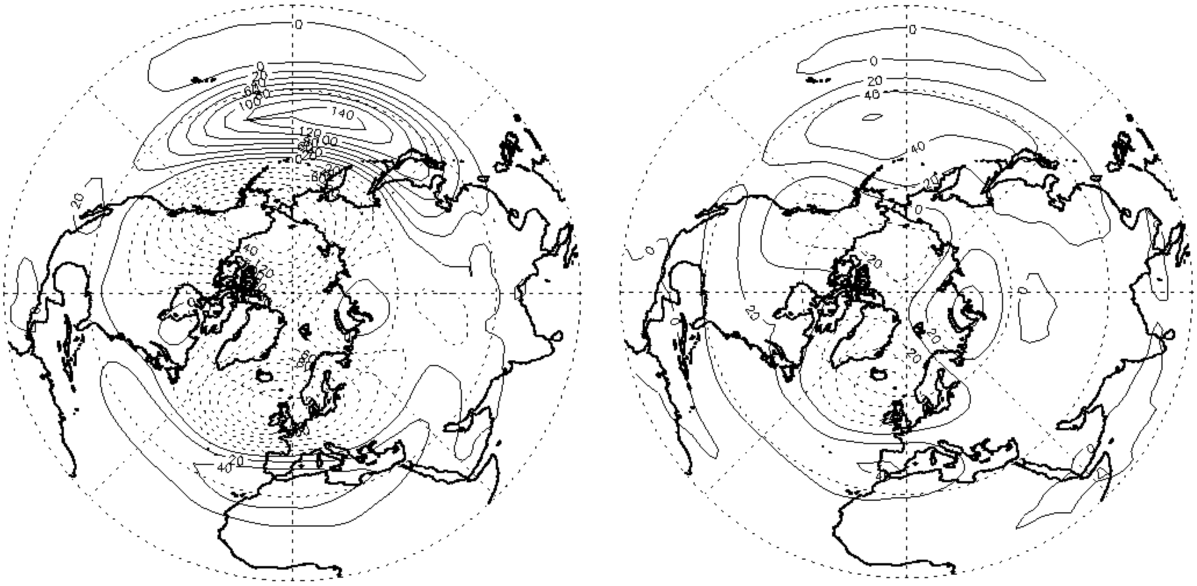

Figure 3: Long term zonal mean systematic errors of 500 hPa height in control simulations (left) and in empirically forced simulations (right) as compared to ERA data. The figure is based on data from Dec, Jan and Feb in winters 1979/80, …, 1992/93. Contour interval: 20 m with negative contours dashed.

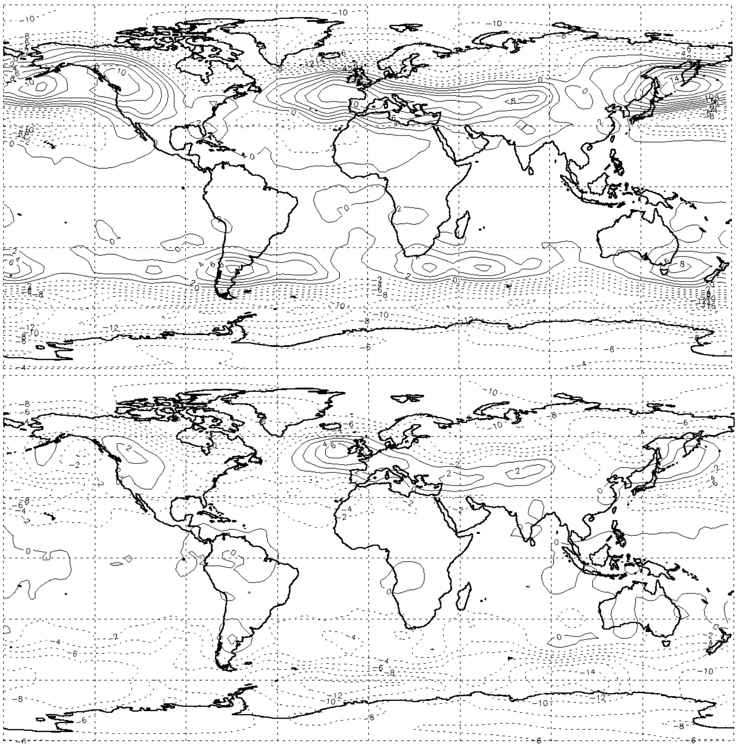

Figure 4: As figure 3, but for standard deviation of the 2.5-6 day band-pass filtered 500 hPa height fields. Contour interval: 2 m with negative values dashed.

3. SKILL OF SEASONAL PREDICTIONS

The local response to a remote forcing anomaly related to e.g. sea surface anomalies is critically dependent on the shape of the background flow which defines the energy dispersion characteristics. Also the anomalous local air-sea interaction is dependent on the mean flow. Therefore a model with reduced systematic errors should show improved capabilities for seasonal prediction. To investigate if this is the case we have calculated the temporal correlation between the 14 simulated (ensemble mean) and observed winter (DJF) averages of mean sea level pressure. Figure 5 shows the spatial distribution of these correlations. For both the control and the modified simulations there is - as expected - generally most potential predictive skill in the tropics, particularly in the Pacific region. In the control simulations there are large regions of negative correlations which locally reach .75 indicating that the standard model is responding to the SST anomalies, but with the wrong sign. Note, however, that only 14 numbers are used to calculate the correlations which casts certain doubts on the local significance.

The overall predictive capability of the modified model is much improved relative to the standard model and the areas of negative correlations are almost gone. Most dramatic improvement is seen in the Pacific area and in the polar regions, particularly in the southern hemisphere. There is, however, one formal flaw in these statements, since the climatological residual forcing includes all years, whereby the forcing is not totally free of information from the individual years to be predicted.

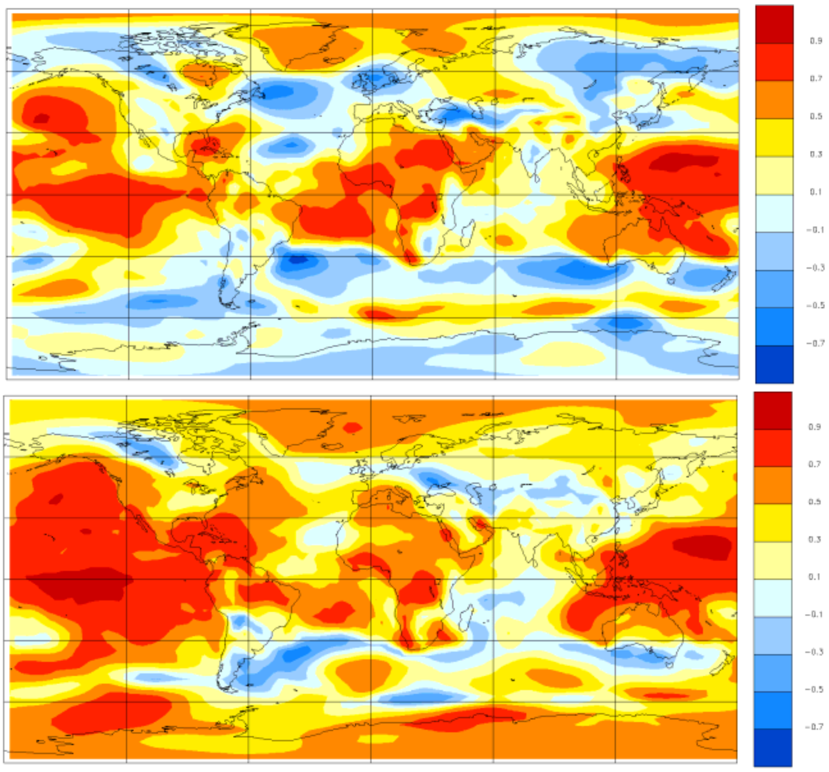

Figure 6: Temporal correlation between 14 simulated (ensemble mean) and observed (ERA) winter (DJF) averages of mean sea level pressure. Control simulations in upper panel, and empirically modified model simulations in lower panel. Cont. int.: .2

4. OUTLOOK

Future work will include seasonal prediction tests in cross-validation mode, i.e. with independently generated forcings. It will also be possible to build a model of residuals, since there are systematic relationships between the residuals and SST anomalies and actual flow (not shown).

5. AKNOWLEDGEMENTS

The work is part of the POTENTIALS project which is financially supported by the European Commissions 4th FRAMEWORK PROGRAMME "Environment and Climate Research Programme" under contract number ENV4-CT97-0497. Home page: http://www.dmi.dk/pub/POTENTIALS/

6. REFERENCES

Déqué, M., C. Dreveton, A. Braun, D. Cariolle, 1994. The ARPEGE/IFS atmosphere model: a contribution to the French community climate modelling. *Clim. Dyn.*, **10**, 249-266.