DANISH METEOROLOGICAL INSTITUTE

TECHNICAL REPORT

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POTENTIALS
Project On Tendency Evaluations using New Techniques Atmospheric Long-term Simulations

Progress report for the second project year (1/1 1999 - 31/12 1999)

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Project On Tendency Evaluations using New Techniques to Improve Atmospheric Long-term Simulations

(Contract no. ENV4-CT97-0497)

Coordinator, Eigil Kaas, DMI

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Content:

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This second status report of POTENTIALS consists of three main sections describing

1) Organisational and logistic matters. This is a short section listing the project organisation, the official meetings and so on.
2) A summary of the entire project and its progress. The figures presented in this part are extracts from the more elaborate individual partner contributions.
3) Individual partner contributions. The authors of these contributions are identical to the scientific investigators at the individual institutions.

Organisational

The 5 partners (all contractors) in the project are listed in table 1 together with the principal investigators. There has been two official project meetings in 1999 held 1-4 June in Bologna, Italy and 9-10 December in Toulouse, France.

INSTITUTION	PRINCIPAL (RESPONSIBLE) INVESTIGATOR
Danish Meteorological Institute (DMI)	Eigil Kaas (co-ordinator)
Météo-France (CNRM/GMGEC/EAC)	Michel Déqué
Max Planck Institut für Meteorologie (MPI)	Bennert Machenhauer
Laboratoire de Météorologie Dynamique du CNRS (LMD)	Robert Vautard
Consorzio interuniversitario per la gestione del centro di calcolo elettronico dell’Italia Nord-Orientale (CINECA)	Franco Molteni

Table 1. List of partners and investigators

The project is to a high degree administrated and co-ordinated via an Internet home page. The reader is referred to that for more organisational details. It is located at:

http://www.dmi.dk/pub/POTENTIALS/

The home-page includes 8 sub pages:

1. Summary. This page includes a summary of the project and its actual progress.
2. Participants. Provides information about partners and includes addresses, phone numbers, e-mail addresses etc.
3. Work-programme. An http and pdf version of the official work-programme approved by the EU-Commission.
4. Progress reports. Includes http or pdf versions of the annual reports (of which this is an example).
5. Data. Information about data availability (these pages are left blank)
6. Partner information. Needed ongoing information to the partners.
7. Publications. Includes a list of publications produced within the project (some of these are electronically accessible) and a general reference list including publications which are relevant to POTENTIALS.
8. Other projects. Short description of other projects which are interrelated to POTENTIALS.

Summary of the project and its progress

Overview

The overall objectives of POTENTIALS are to identify and minimise the tendency - or forcing - errors in four different atmospheric general circulation models (GCMs). In this way new model versions are obtained which are improved relative to the basic versions, in the sense that the total forcing errors are reduced without introducing compensations between multiple errors. The improved models are developed and tested with special attention to simulation of regional climate over Europe and to seasonal prediction. The four models are two state of the art atmospheric climate models (ARPEGE/L31 and ECHAM/L19) and two simpler GCMs (a 5 level primitive equation (PE) model and a 3 level quasi geostrophic (QG) model). The large models are mainly run at T42 and T63 spectral truncation, while the two simpler models are run at T21 resolution.

Three different techniques have been used to estimate tendency errors and these all involve assimilation of re-analyses and other data into the atmospheric models as the fundamental element. These are nudging, a variational method and slow normal model insertion. It is mainly the 15 year ERA15 re-analyses from the European Centre for Medium Range Weather Forecasts (ECMWF) which have been assimilated after a proper interpolation to the resolution of the four GCMs. The estimation of tendency errors by assimilation is a difficult task, particularly in unbalanced models based on e.g. the PE's. This is because imbalances (often seen as gravity wave noise) between wind and mass fields after spatial and temporal interpolation to the grid of the actual model leads to spurious tendencies in e.g. the wind field which obviously should have been in the mass field and visa versa. Also the problem of moisture spin up constitutes a major problem and a source of error when estimating tendency errors. For these reasons an unforeseeable amount of work has been devoted to ensure optimal interpolations and the use of data assimilation techniques which provide us with true tendency errors of the slow manifold in the model relative to the slow manifold in the observations.

The models are improved in two fundamentally different ways: either by a full three dimensional flux correction which empirically compensates the identified tendency errors in the prognostic equations or by using the tendency errors as a guideline for improving the physical parameterisation of the GCMs. During the second project year most work was devoted to the first.

Some important results obtained during the second project year are:

- The coding and testing of slow normal mode insertion (SNMI) was finished. As mentioned above an improved methodology for estimation of tendency errors in the two state of the art climate models was given considerably more attention than originally planned. The SNMI described briefly below (and in more detail under the MPI partner contribution), is a new method developed as part of POTENTIALS which should circumvent some of the problems associated with standard nudging.

- The planned assimilation based on nudging and covering all 15 ERA years has been finished for both the DMI and the CNRM versions of ARPEGE and for the 5 level PE model. This work has resulted in global space/time maps of tendency errors which have and will be used for improving the models.

- The systematic errors of flux corrected models are generally much reduced. The flux corrections have been applied to the 5 level PE model; the DMI and the CNRM versions of ARPEGE (based on the nudging assimilation); and to the QG model (based on variational assimilation)

- The predictability on seasonal time scales is somewhat improved when using flux corrections in the DMI version of ARPEGE, but not in the CNRM version. There are indications that improvements are also present for the 5 level PE model.
- A low order model with empirical parameterisation of tendency errors relative to the reference QG model has been build. The parameterisation is based on the analogue method and the low frequency variability as well as mean climate is quite similar to that of the reference QG model.

PROGRESS OF THE INDIVIDUAL WORKING TASKS

The individual working tasks are described in detail in the work programme (see http://www.dmi.dk/pub/POTENTIALS/Workprog.pdf). In the following the status of each task after the second project year is described.

Task 1 (Identification of tendency errors):

During the project it was realised that too little effort was originally put into this fundamental task. This is because many unreported sensitivity experiments have shown that the results in the remaining tasks (2-5) are critically dependent on the methodology used to obtain the tendency errors of a given model relative to a reference data set (e.g. re-analyses).

Nudging is the basic assimilation method in the project. During the second project year assimilation of all 15 years of ERA data were completed for the DMI and the CNRM versions of ARPEGE and for the 5 level PE model. The resulting estimates of average tendency residuals (i.e. minus the tendency errors) in ARPEGE are very similar to those reported in the first status report. Fig. 1 and 2 shows the 15 year temporal average, zonal mean tendency residuals of the 5 level PE model in January and July, respectively. Even though there are differences the residuals for the two seasons are surprisingly similar and mainly confined to the upper model levels.

Since most conclusions in the project are based on the nudging technique and sensitivity experiments have indicated that resulting forcing is critically dependent on the choice of relaxation parameters it was deemed necessary to investigate this technique and its possible limitations in more detail. Fig. 3 shows an example of this where a twin modelling approach was undertaken. Thus a basic model run with the DMI version of ARPEGE was used to mimic observations and data from this simulation was stored every 6 hours for a given January. This is also the frequency for which ERA data are available. Then nudging was used to assimilate these data into a model version without gravity wave drag (GWD). The relaxation time constants were as for the assimilation of ERA data (i.e. 6 hours for vorticity, 24 hours for temperature and surface pressure and 48 hours for divergence). Fig. 3 shows that the wind forcing due to GWD is estimated very well, albeit slightly too weak by the nudging technique. A second assimilation of data from the relevant month was next performed. This was done with a version of the model without GWD but with a constant flux correction corresponding to that in Fig. 3b. This second iteration resulted in a weak additional residual (not shown). It should be mentioned that even though the true GWD in ARPEGE only acts on the wind field, the nudging assimilation results in a very small estimated contribution also to the temperature field (see DMI partner contribution for more details). To investigate if the identified residuals reflect the true tendency contribution from GWD a series of 1000 day perpetual January simulations were performed. With long term mean sea level pressure as an example Fig. 4 shows that the climate of the flux corrected model without GWD is very similar to that of a model version also without GWD, but with a constant flux correction equal to the exact long term average contribution from the GWD parameterisation scheme. This is particularly true for flux corrections based on the sum of tendency residuals from the first and the second assimilation. It is concluded that nudging constitutes a very good approach for identifying errors in the wind forcing of the model.

It has also been investigated in a similar twin experimental set up if one can identify known errors in the temperature forcing (heating). In this experiment - described under the CNRM partner contribution - the tendency from the radiation code was intentionally set to zero. An attempt to reconstruct the average heating rates via nudging towards a model version including radiation was somewhat disappointing, since fairly long relaxation times as used in the project resulted in somewhat too small heating rates. At the time of writing it was, however, realised that a coding error related to the nudging assimilation might explain at least some of this result. Therefore it is not shown here.

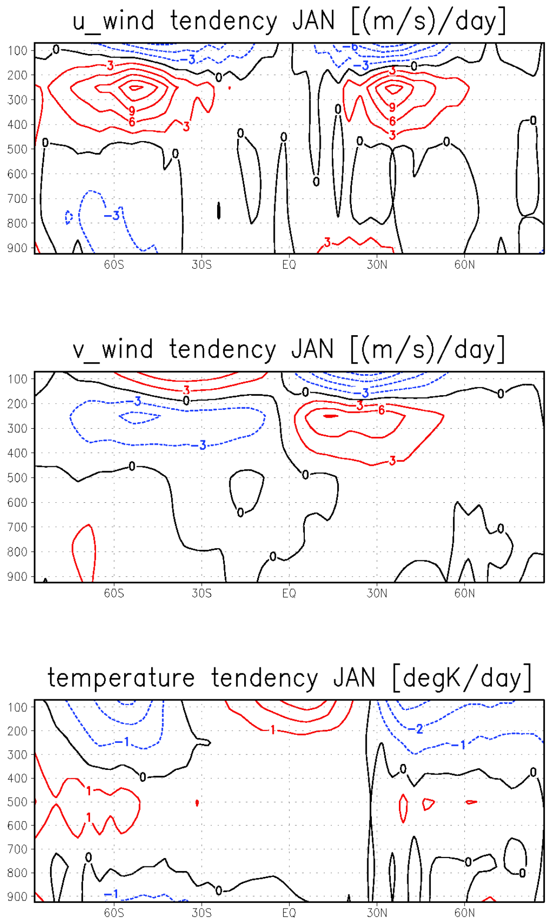

Fig. 1. Latitude-pressure cross section of the average model tendency residuals in January for the 5 level primitive equation model. Panel (a) zonal wind; (b) meridional wind; (c) temperature. Contour interval 3 m/s/day in (a), 0.5 m/s/day in (b) and 1 C/day in (c).

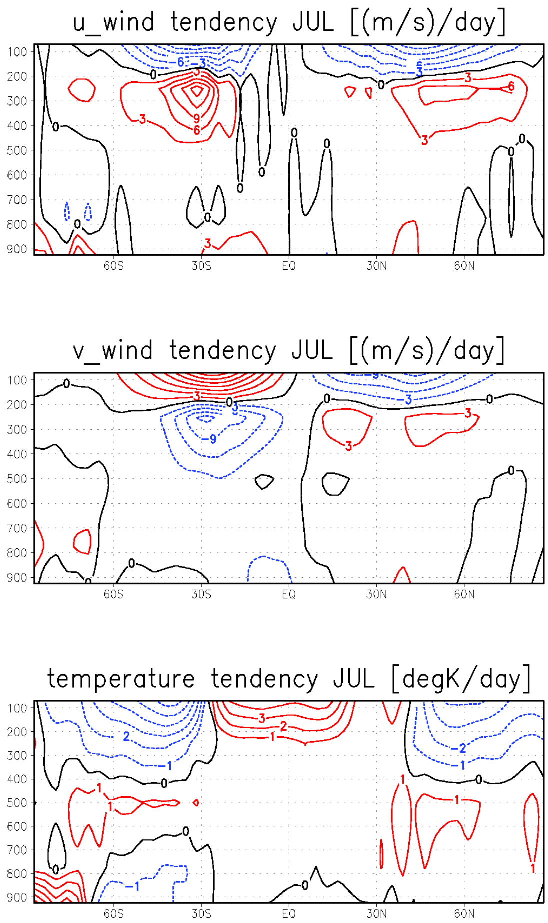

Fig.2. As Fig. 1 but for July.

It was clear already at the beginning of the project that moisture variables should not be assimilated as this would lead to unrealistic tendencies related to a kind of constant moisture spin up. It was also realised at a rather early state that this solution did not solve all problems and that other approaches were needed to further minimise the moisture spin up problem as well as problems related to misinterpretation gravity wave tendencies. The simple solution followed by DMI and CNRM has been to use the nudging assimilation technique but with a weak relaxation of the divergent wind component. At MPI a new technique more firmly based on theory has been developed and tested during the second project year. The technique is called slow normal model insertion (SNMI) and is considered a fundamental achievement of the project. The work has similarities to and replaces *task 1b* in the original work programme. SNMI consists in a substitution of the slow modes of the model by the slow modes of the reanalyses. Consequently, the fast modes of the model are free to change according to the model equations and they should adjust to the "Machenhauer balance" (Machenhauer, 1977). The SNMI technique was developed to overcome the basic disadvantage of standard nudging where the state variables used to compute model tendencies and thereby the forcing errors are not exactly equal to the interpolated analyses. But an obvious side advantage should be an elimination of the moisture spin up problem due to more realistic dynamically balanced divergence fields. Fig. 5c illustrates that there are only very small differences between the total global mean precipitation when using the standard nudging technique and the SNMI in the ECHAM model. It is anticipated that the explanation for the more large scale precipitation (Fig. 5b) in the nudging assimilation is the presence of more gravity wave noise which gives rise to spurious model resolved vertical motions leading to release of more "large scale" precipitation (probably on rather small spatial scale and of small intensity).

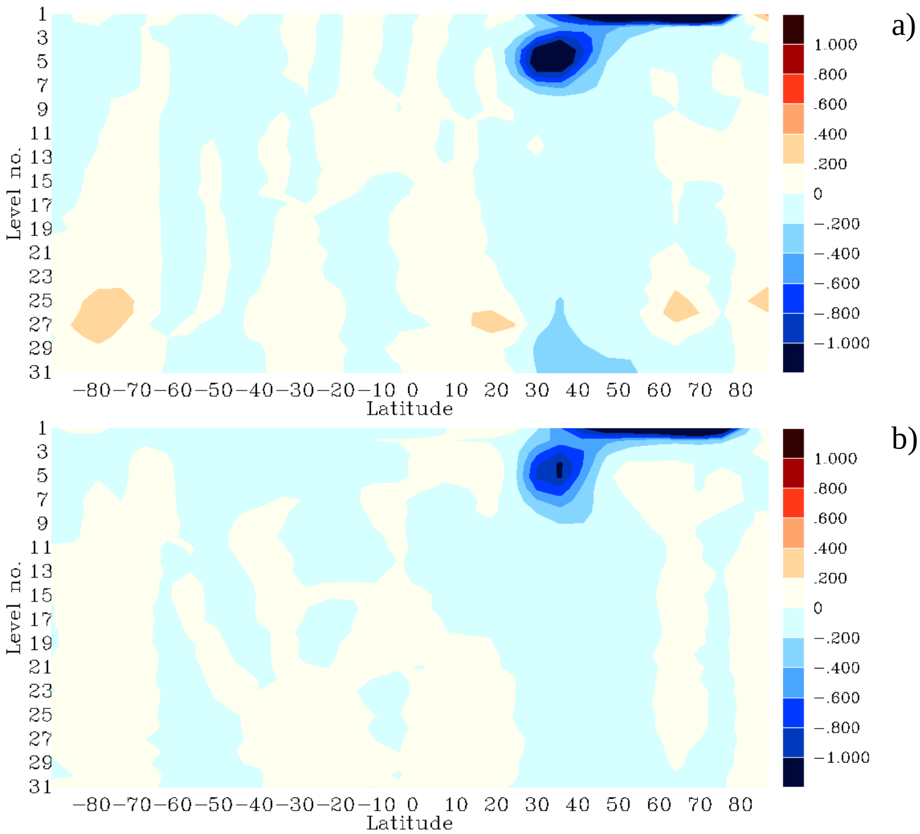

Fig. 3. Upper panel (a) shows the temporal average zonal mean GWD tendency contribution to zonal wind for a randomly selected January simulated with ARPEGE (DMI version). Lower panel (b) shows the tendency contribution estimated via the nudging technique by assimilating data from the relevant month into a model version without GWD. Units: m/sec/day.

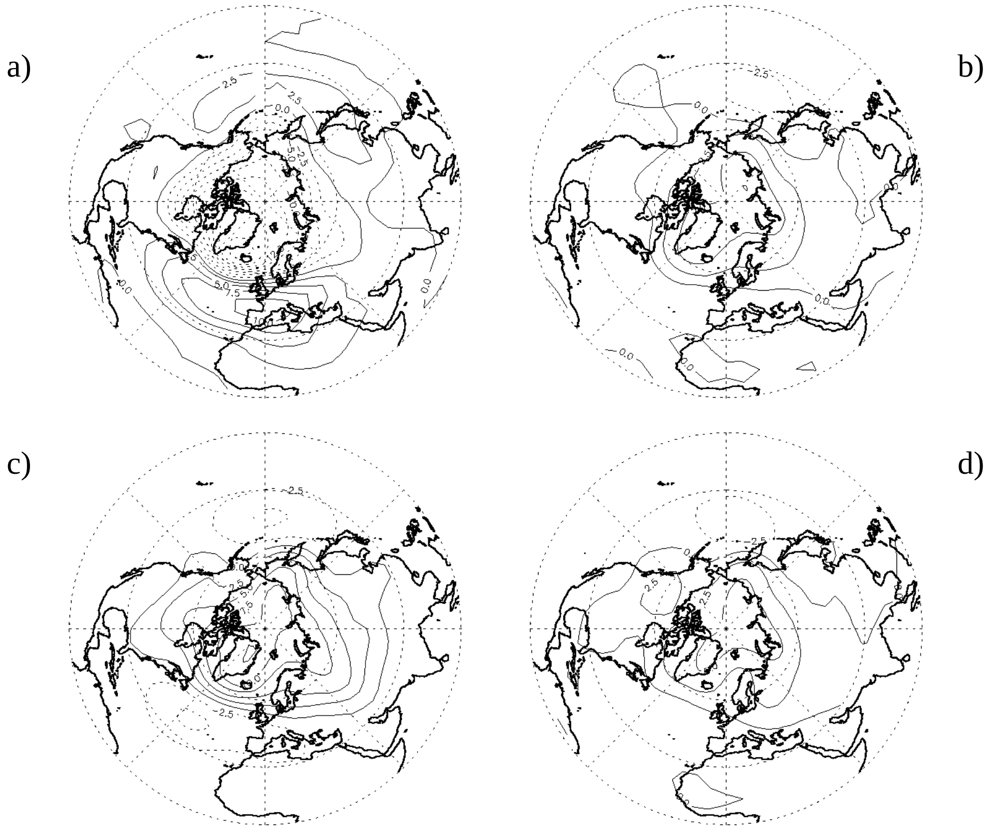

Fig. 4. Difference in mean sea level pressure between four different 1000 day perpetual January simulations without GWD parameterisation and the corresponding control simulation. All simulations are performed with ARPEGE (DMI-version) at T21 horizontal resolution. Panel a) shows difference between a standard simulation without GWD and the control; panel b) the difference for fixed wind and temperature forcing obtained via an iterative nudging procedure; panel c) the difference for fixed wind and temperature forcing obtained via a standard nudging assimilation (corresponding to forcing in Fig. 3b); and panel d) the difference for fixed wind forcing equal to the exact temporal average tendency contribution from GWD (corresponding to Fig. 3a).

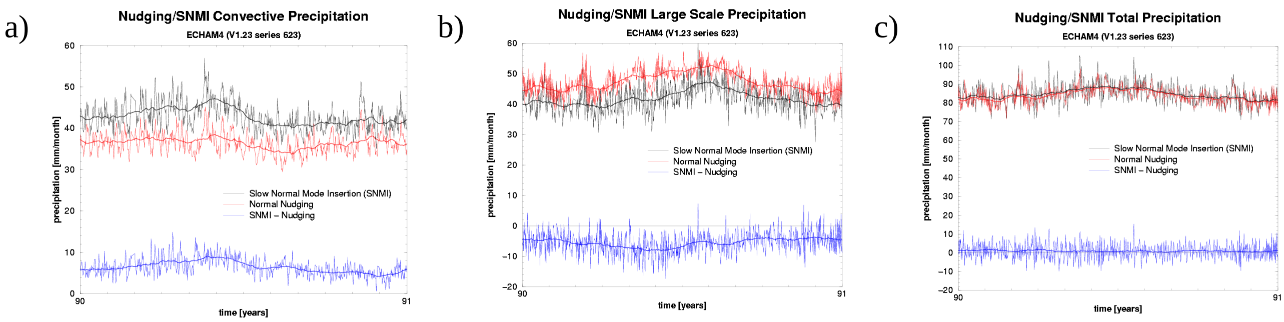

Fig. 5. Time series of global mean convective (a), large scale (b) and total (c) precipitation in ECHAM for assimilation via slow normal mode insertion (black) and via nudging (red). The difference is shown in blue. Units: mm/month.

Task 2 (Objective tuning of physical parameterization):

In this task it is attempted to use information obtained in task 1 to improve the physical parameterisation of the models. Quite some work was done during the first project year, but so far this task is behind schedule for the PE model. It is planned to improve the simple parameterisation in the PE model during the last 6 months of the project.

The most important result so far has been the success in tuning the horizontal diffusion in an Eulerian version of ARPEGE and in ECHAM by a minimisation of tendency errors in a low resolution model version relative to a high resolution version. This work which was partly done within a previous EU-project (MILLENNIA, contract no. ENV4-CT95-0101) and partly in POTENTIALS has resulted in a paper published in Tellus (Kaas et al., 1999). The work was basically finished after the first project year. Since the results were not reported in detail in the status report after the first year we here show the basic result (Fig. 6), namely that a negative diffusive damping is needed for intermediate wave numbers in order to more correctly account for non-linear interactions with unresolved scales.

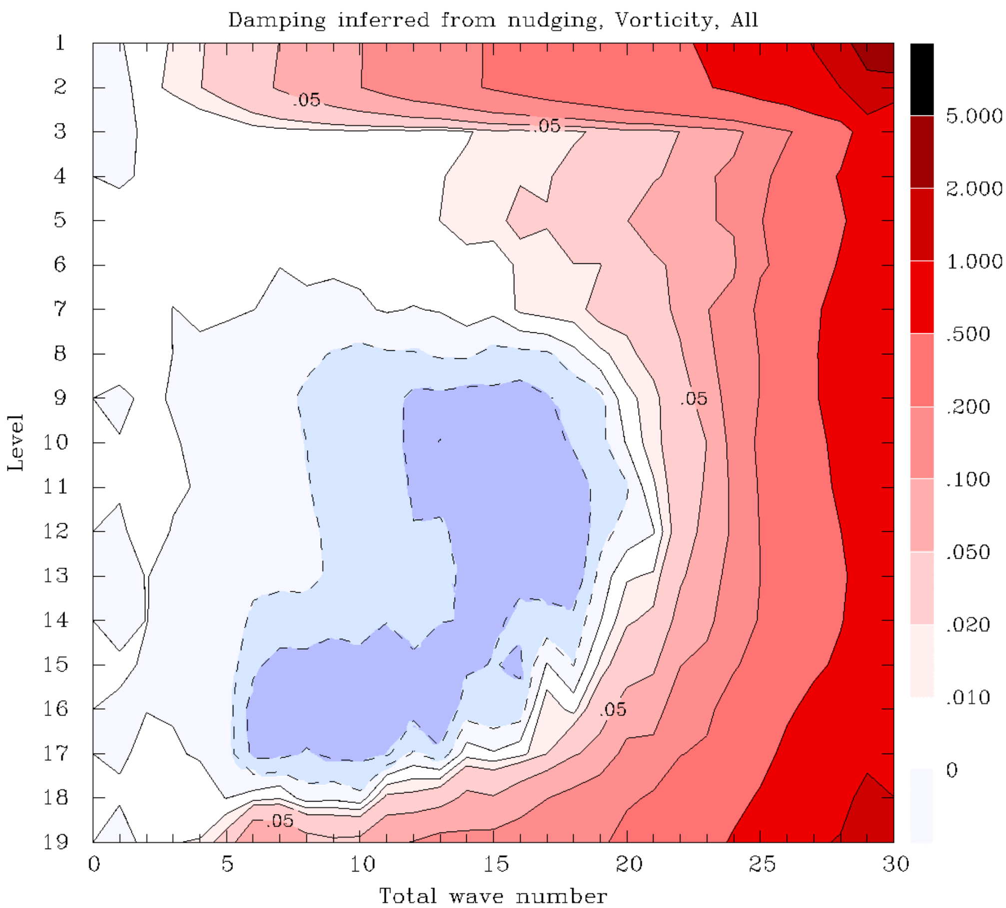

Fig. 6. Empirical damping function (i.e. the relative damping of all spectral components) for vorticity in a T30 version of ECHAM calculated from tendency errors of the T30 model version relative to a T106 version. Vertical axis shows model level with level 1 at top of model. Horizontal axis shows total wave number. Note the negative damping in the middle troposphere at intermediate wave numbers. The positive damping near the model top reflects no more than a re-construction of a strong damping at these wave numbers, even in the T106 training model version. Units are day^{-1} with contours at -.2, -.1, -.05, -.02, -.01, 0., .01, , .02, .05, .1, .2, .5, 1., 2., 5., with positive values shaded and negative stippled.

Task 3 (Long runs with improved physical parameterisation):

The purpose of this task is to investigate if improvements in the physical parameterisation (and in the dynamics) based on guidance from the identified tendency errors (task 1) leads to improved simulations of climate. Part of this work was done during the first project year while the activities during the second year were rather limited. The main results in the second year were obtained with the ECHAM model where it is indicated that part of the rather strong positive surface pressure bias over the polar region in ECHAM could be due to too thick sea ice. This statement is based on indications that a negative temperature tendency errors dominates the lower troposphere along the ice margin in the Atlantic sector of the arctic basin (see the partner contribution from MPI for details)

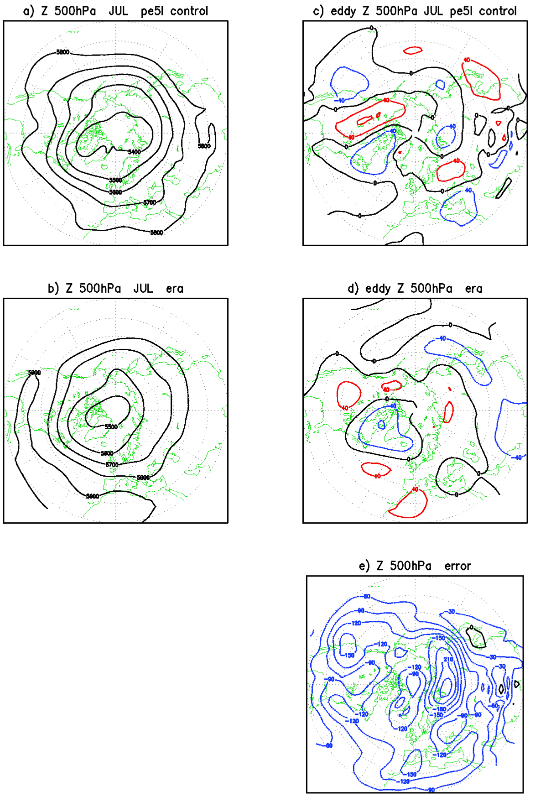

Fig. 7. Climatology of 500-hPa height from a perpetual July run of the 5-level PE model (a) and from ECMWF reanalysis (b); and mean model error (e). Contour interval 100 m in (a) and (b) and 30m in (e) with red/blue corresponding to positive/negative values. c) and d) show the eddy component of the fields in a) and b), respectively, with a 40m contour interval.

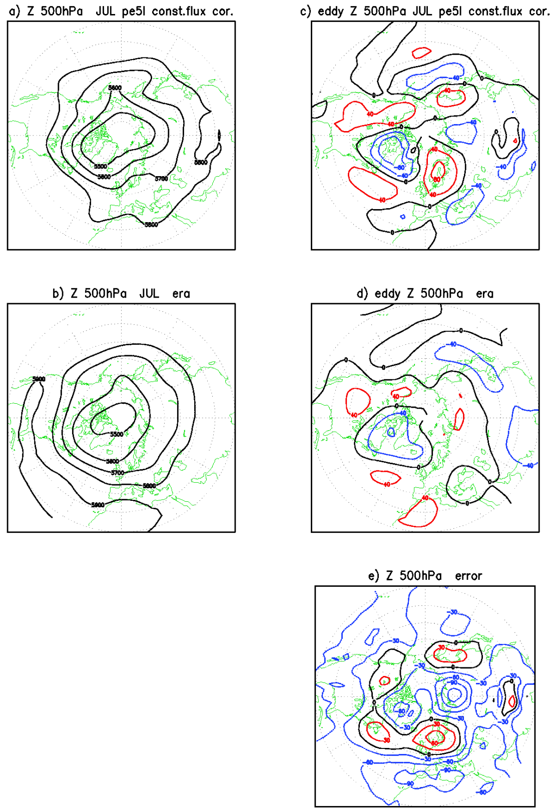

Fig. 8. As Fig. 7 but for the climatological constant flux correction integration. Same contour intervals.

Task 4 (Flux corrected long term simulations):

In this task it is investigated if long term atmospheric simulations running with the empirical forcing identified from tendency residuals (task 1) show improved climatology in terms of mean climate and variability. Several perpetual January simulations of length 1000 days have been performed with the DMI version of ARPEGE (see e.g. Fig. 1), and 120 month perpetual January and July simulations have also been run with the 5 level PE model in flux corrected mode. So far the simulations with ARPEGE and the 5 level PE model have all been with constant flux corrections, i.e. the correction term was independent of the flow and/or the underlying SST. Figure 7 and 8 compares the July performance in terms of long term mean climate of the 5 level PE model in its standard configuration (Fig 7) and in flux corrected mode (Fig. 8), i.e. with the residuals in Fig. 2 as constant additional forcing. It can be seen that the systematic errors are generally smaller in Fig. 8. than in Fig. 7.

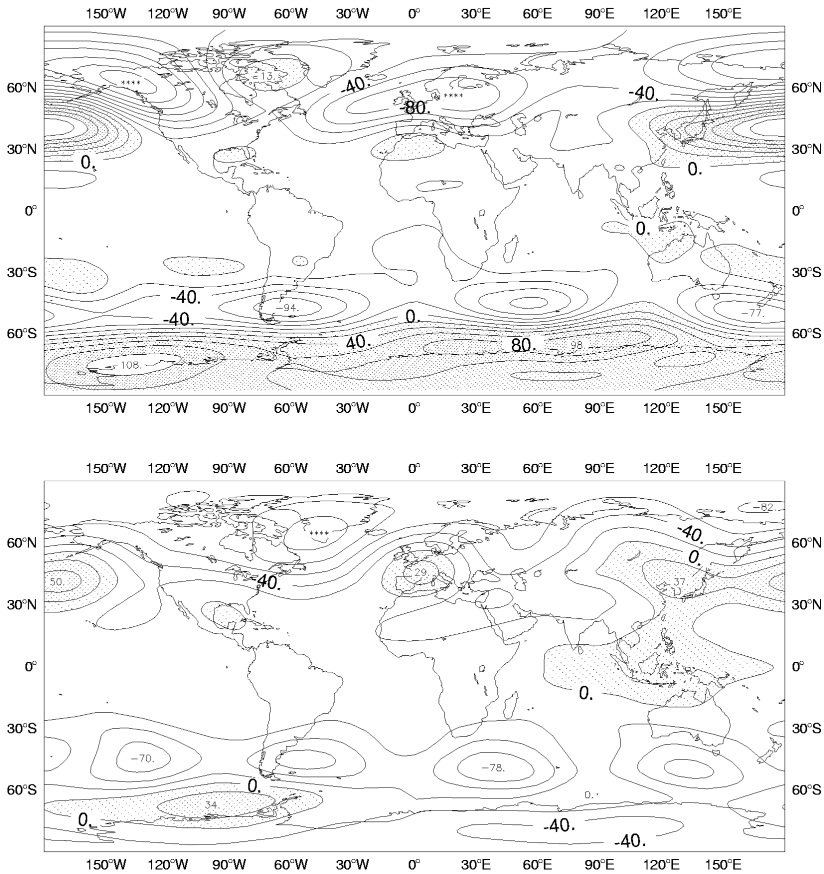

Fig. 9. Mean winter (JFM) 500 hPa height systematic error in the standard model (top), ARPEGE CNRM-version, and in the corrected model (bottom). Contour interval 20 m, negative values are shaded.

Another way to consider reductions in systematic errors in long flux corrected simulations is to look at the long term mean climate of the ensemble seasonal predictions (task 5) with ARPEGE. These predictions show that we have indeed reduced the systematic errors considerable by the introduction of the empirical additional forcing. Fig. 9 shows an example of this for 500 hPa height simulated with the CNRM version of ARPEGE. The figure is based on the ERA climatology in JFM for the period 1980-1993 and on JFM data from 9 member ensemble forecast covering the period DJFM for each of the 14 winters 1979/80 - 1992/93. The systematic forecast errors are clearly smaller in the simulation including the flux corrections (lower panel). An even stronger improvement has been obtained with the DMI version of ARPEGE (see the DMI partner contribution).

Flux corrected simulations employing a correction term which depends on the actual flow have so far only been applied to the 3 level QG model. The work is described in D'Andrea and Vautard (2000) and was reported in the previous progress report. During the second year a theoretical issue more axed on the parameterisation of tendency errors in low order models was addressed since it was natural to try and extend the approach in D'Andrea and Vautard (2000) to the construction of a very low dimensional model of the sole low-frequency variability. This model is based on projection of the QG model onto only 10 Empirical Orthogonal Functions (of the flow in the standard QG model) and on empirical (flow dependent) parameterisation of the tendency errors relative to the standard QG model. The low order model behaves surprisingly similar to the QG model itself, both in terms of mean climate and in terms of low-frequency variability (see LMD partner contribution for more details). This proves that (i) the dynamics of the low frequency variability are low dimensional, and (ii) that trailing scales, neglected by the EOF filtering can be parameterised in terms of the resolved scales. The scale interaction that is parameterised is mainly the feedback of baroclinic transient eddies on the large scale flow. The time dependent parameterisation of the tendency error in terms of the flow (based on an analogue technique) has proven to be essential, with respect to a time mean and a stochastical forcing, to obtain these results.

Task 5 (Seasonal prediction):

The underlying assumption in the last task of the project is that improved mean climate - or background flow - will also lead to a more realistic response of the atmosphere to forcing related to the lower atmospheric boundary conditions like SST. This is because energy dispersion in the atmosphere depends critically on the background environment which defines the dispersion relationships and the critical lines in the atmosphere. The task involves a series of predictability test simulations with the ARPEGE (both the DMI and CNRM versions) and with the PE model.

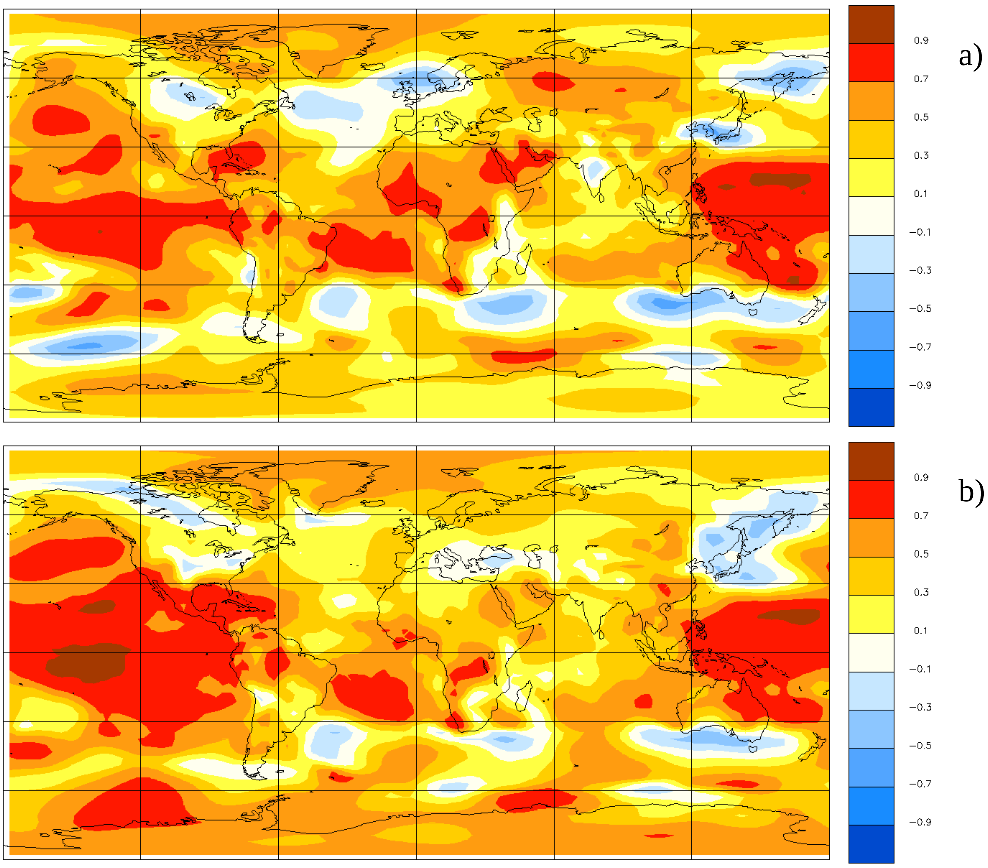

Fig. 10. Temporal correlation between observed (ERA) winter (DJF) average and 9 member ensemble forecast averages (ARPEGE, DMI version) of mean sea level pressure. Upper panel (a) for control simulations and lower panel (b) for empirically forced simulations.

During the second project year and after a considerable amount of experimentation related to task 1 and to task 4, nine member ensemble simulations have now been performed for all the years of the

ERA re-analyses. At DMI these forecasts have only been carried out for the winter months, while all 4 seasons have been predicted with the CNRM version of ARPEGE. The experimental set up has been exactly as for the uncoupled simulations in the PROVOST project. I.e. the models were started from analysed observed initial conditions on nine consecutive days in late November, late February, late May and late August and they were run for a period of 4 months (3 months for the DMI experiments). First a set of control forecasts were made followed by an identical set employing corrections of the identified tendency errors (task 1) in the atmosphere. The corrections were fixed in time, although smoothly varying with the average annual cycle; i.e. the same corrections were used every year. For the DMI version the flux corrected forecasts show a considerable increase of skill relative to the control forecasts in the southern hemisphere, particularly at high latitudes and in the Pacific region. This can e.g. be seen from Fig. 10 showing anomaly correlation maps for mean sea level pressure. In the Northern hemisphere, there are no clear and general signs of improvement. Note, that the tendency errors were identified over the same period as we verify the performance, here in terms temporal correlations. Then the estimates of skill are not made with independent data. It should, however, be noted that since the empirical forcing is fixed in time it cannot "by itself" contribute to a temporal anomaly correlation. For the CNRM version of ARPEGE no improvement has been seen. The reasons for this could be that this model version has considerably smaller systematic errors than the DMI (uncorrected) version. In other words the starting point before applying the flux corrections is much better for the CNRM version.

It has, however, been seen that the identified residual forcing (task 1) for ARPEGE varies somewhat from year to year and, furthermore, that this variation to some extent follows local SST anomalies. Thus, there could be room for a parameterisation of residual forcing as function of SSTs/sea ice resulting in better scores than those presented in Fig. 10b or even as function of the actual atmospheric flow. Such a parameterisation will be investigated during the last 6 months of the project.

There are indications that also the 5 level PE model shows improved sensitivity to SST lower boundary forcing. This can be seen e.g. from Fig. 11 which shows northern hemisphere 500 hPa geopotential height differences between a typical El Niño (January 1983) and a La Niña (January 1989) event. It can be seen that the empirically forced model is more in accordance with the observed differences between the two years than the standard model. One should of course be careful to draw too many conclusions from a single month of observations.

DEVIATIONS FROM THE WORK PROGRAMME

The POTENTIALS project is rather innovative compared to most other projects since new ideas never tried before are being developed and tested with some real risks of failure as consequence. Therefore, it should not be possible to follow the original work programme in all details. In spite of this - and surprisingly enough - the main structure of the 5 tasks listed above is still valid.

The project has been prolonged by a half year compared to the original planning in the work programme, and therefore some tasks are behind schedule. Deviations from the work programme are mainly related to task 1 which for reasons described above, has been given much more weight than planned. The consequence of this is that parts of task 2 (*task 2c* and *task 2d*) and task 3 (*task 3b*) has been (and will be given) reduced attention.

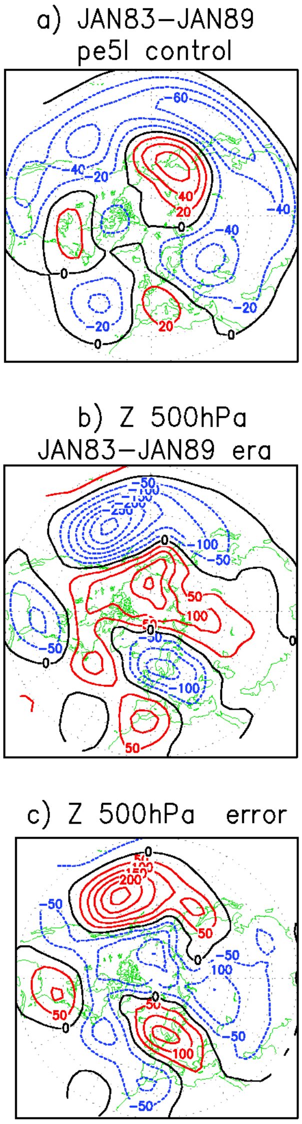

Fig. 11. 500 hPa geopotential height difference between January 1983 and January 1989. (a) Perpetual January control integrations of the 5-level model, difference between 1983 and 1989; (b) ERA 1983-1989; (c) error. Contour interval 20m in (a), 50m in (b) and (c).

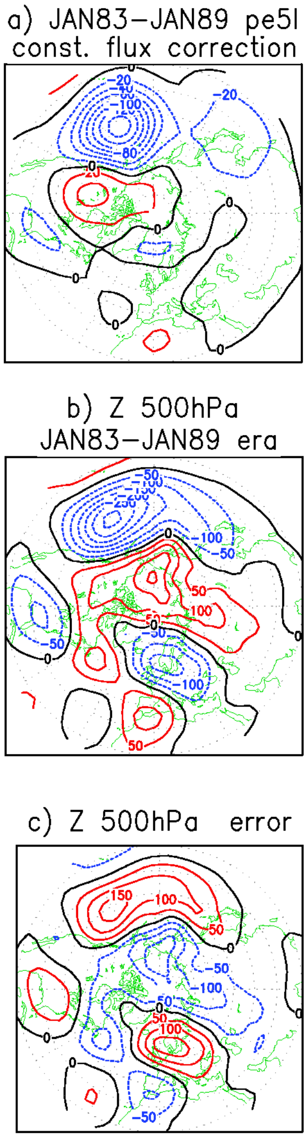

Fig.12 As in Fig.11 but for the 83/89 simulations in constant flux correction.

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POTENTIALS

Contract no. ENV4-CT97-0497

Danish Meteorological Institute (DMI).

Contribution to progress report for the second project year (1/1 1999-31/12 1999)

By Annette Guldberg and Eigil Kaas

Overview

The role of DMI is to:

- Co-ordinate the project
- Use assimilation to obtain estimates of tendency residuals. To study the assimilation technique (nudging) used, a test experiment has been set up for using this technique to reconstruct gravity wave drag. In order to be able to assimilate the ECMWF reanalysis (ERA) data with the ARPEGE model, version 2 it is necessary to have the ERA data in the right resolution (T42 and 31 vertical levels). The transformation of the ERA data to a form that can be used by the ARPEGE model has been completed for the whole period covered by the ERA data (1979-1993). This part of the work was almost completed after the first project year.The ERA data have been assimilated by the ARPEGE model for all the winter months in the ERA period (i.e. November, December, January, February and March 1979-1993) and an estimate of the models forcing errors has been obtained every 6th hour. The analyses of these simulations are ongoing.
- Perform simulations with long term mean tendency residuals as constant forcing. One of DMI's objectives is to test whether the model errors can be parameterised empirically, and a simple way of doing this is to use time averages of the forcing errors as a constant correction term. The mean for the ERA period of the monthly averages of the forcing errors have been used as correction terms in the model equations. 9 member ensemble forecasts have been made for the 14 winters covered by the ERA period both with the standard version of ARPEGE and with the corrected version.
- To use tendency residuals as guideline for improving the physical parameterisation. This part of the work was to a large extent finished by the tuning of the horizontal diffusion. To the extent it is feasible within the remaining part of the project a further test of a new cloud parameterisation will be attempted.
- To empirically parameterise tendency residuals. This part of the work will be carried out during the last 6 months of the project.

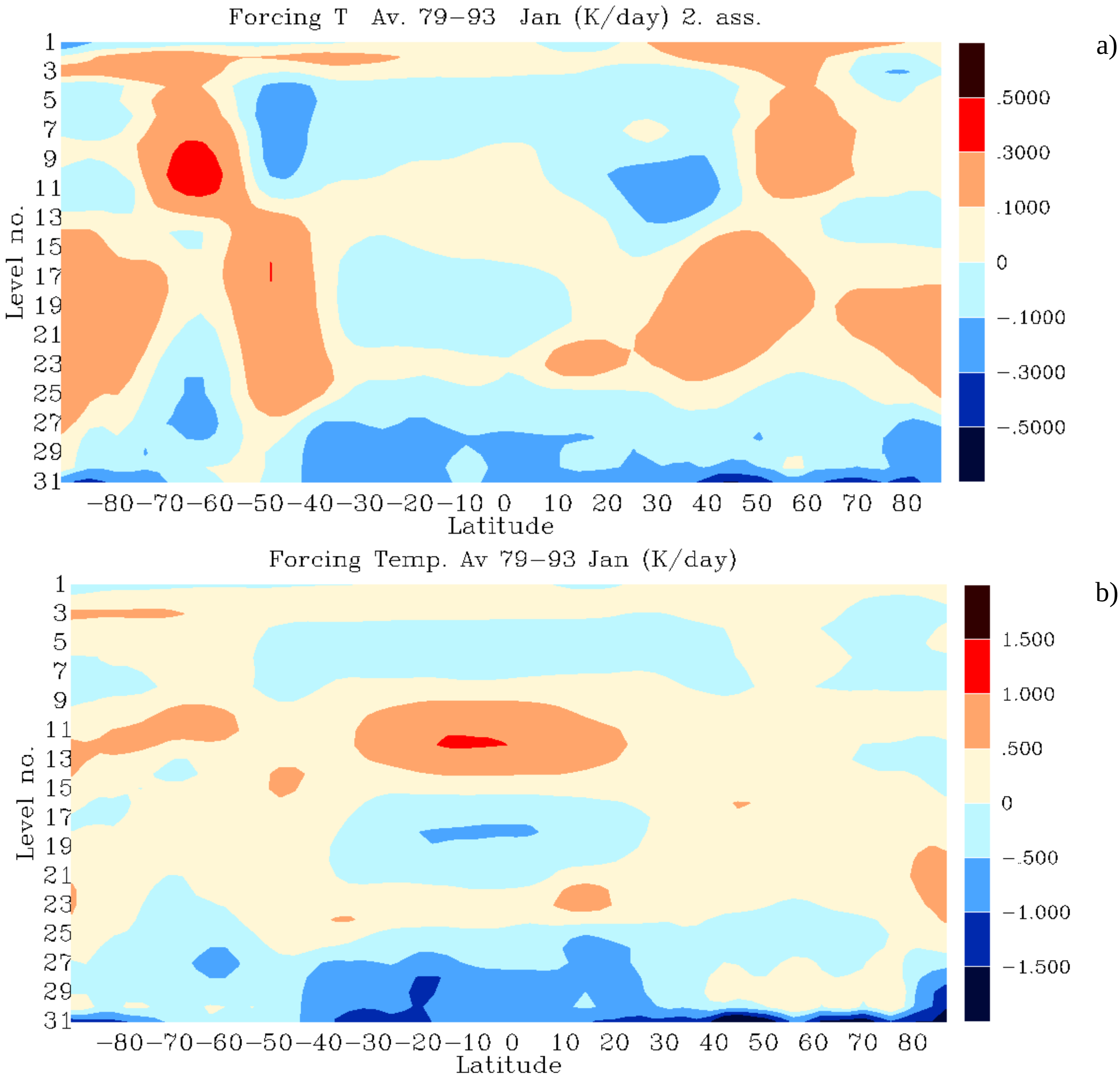


Fig. 1. 15 year average temperature residual (K/day) for January. Upper panel (a) shows the additional residual needed for the second iteration and the lower panel (b) shows the total residual which is used as additional forcing in the corrected seasonal forecasts. Model levels are numbered with 31 as the level closest to the ground. Note the finer contour levels in panel a).

Scientific results

Seasonal prediction

Within the POTENTIALS project an important subject is to investigate the possibility of empirical parameterisation of the model errors as correction terms to the model equations.

In order to determine the forcing errors of the model the ERA data have been assimilated using the nudging technique. The data have been assimilated for all the winter months covered by the ERA data. The time constants for the nudging were 6 hours for vorticity, 48 hours for divergence, 24 hours for temperature and surface pressure. Monthly means of the forcing residuals (i.e. minus the forcing errors) were obtained and the average over the 14 years in the ERA period was made and used as correction to the model equations. When running the model with this correction for the winter season a very cold stratosphere over the North Pole developed. It is anticipated that the excessive cooling is related to the gravity wave drag scheme. To avoid this a second assimilation was done as follows. For each winter the monthly averages of the forcing residuals from the first assimilation for that specific winter was used as correction terms and a the second assimilation done with the corrected model version. Only temperature was nudged with a long time constant of 48 hours, i.e. only a very weak nudging. The average of the sum of the climatologic monthly means of the forcing residuals from the two assimilations was then used as the final correction term. Fig. 1b shows the zonal mean of the final correction term for temperature. In the lower troposphere the correction term generally contributes as a cooling, whereas the upper troposphere is dominated by a warming in the tropics. Fig. 1a illustrates that the additional temperature forcing, i.e. the residual, from the second assimilation is indeed small compared to the total in Fig. 1b. Notice that the scale is not the same in the two panels.

a) b)

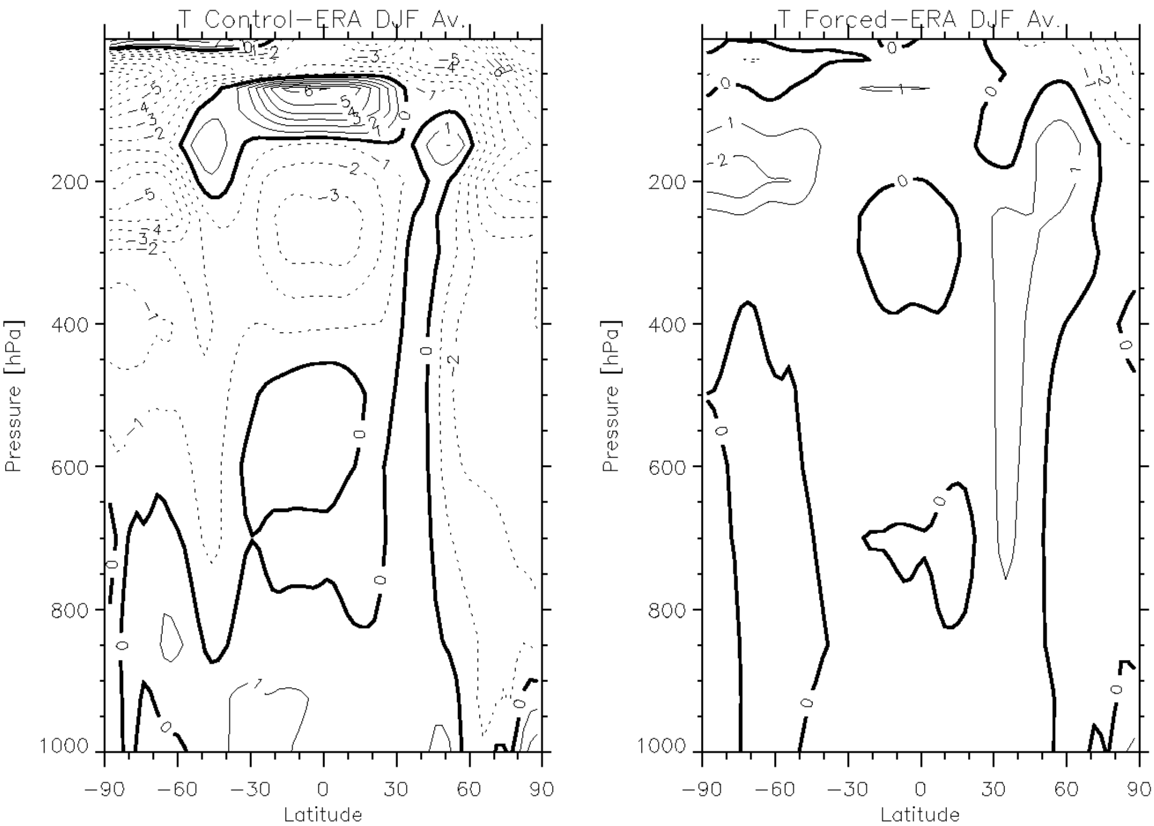


Fig. 2. Difference between 9 member ensemble zonal mean temperature for DJF and corresponding ERA climatology. Left panel (a) shows the systematic forecast errors for the control simulations and right panel (b) for the forced simulations. Contour interval is 1 degree C with negative contours dashed.

Nine-member ensemble forecasts for the 14 winters in the ERA period was next performed both with the standard version of the model (control runs) and with the corrected version of the model (forced runs). Fig. 2 (temperature) and 3 (mean sea level pressure) show the difference between the nine member ensemble winter forecast climatology averaged over the 14 winters in the period 1979-1993 and the ERA climatology - for the control run and the forced run respectively. Fig. 2a shows the difference between the control forecasts and the ERA climatology, and it is seen that in the lower troposphere the differences are small but in the upper troposphere and in the stratosphere there are rather large biases. The model is too warm in the lower stratosphere in the tropics but in the rest of the stratosphere it is too cold. Fig. 2b shows the difference between the forced run and the climatology and it is seen that there is a much better agreement between the winter climatology of the forced run and the ERA data. From Fig 3 it is seen that also for mean sea level pressure the climatology of the forced model is in much better agreement with ERA climatology than the control model. So with respect to climatology the corrected model is much improved compared to the standard version of the model.

a) b)

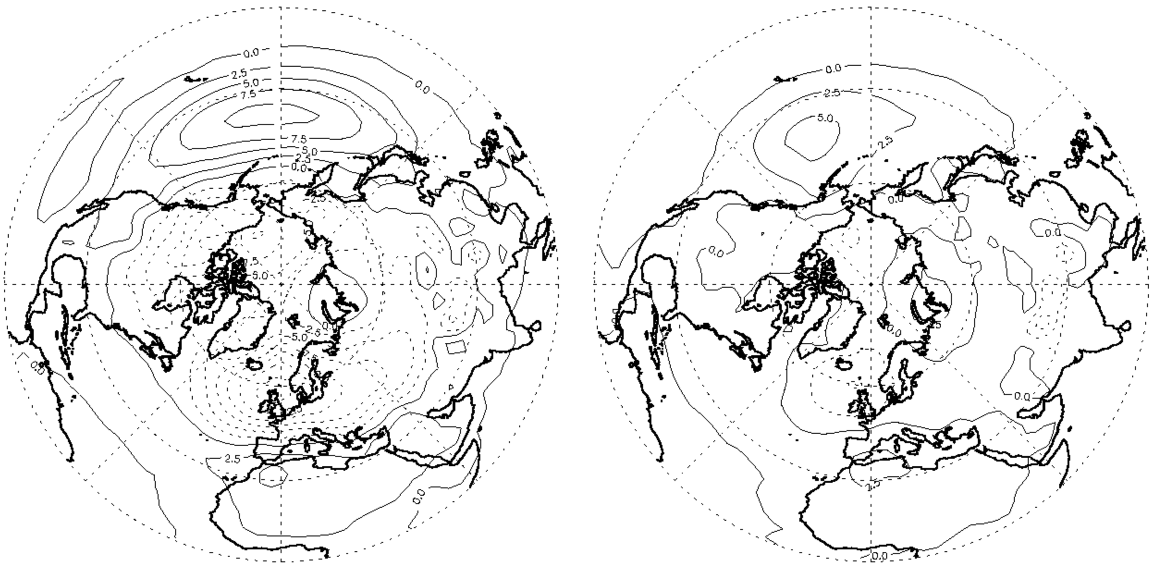
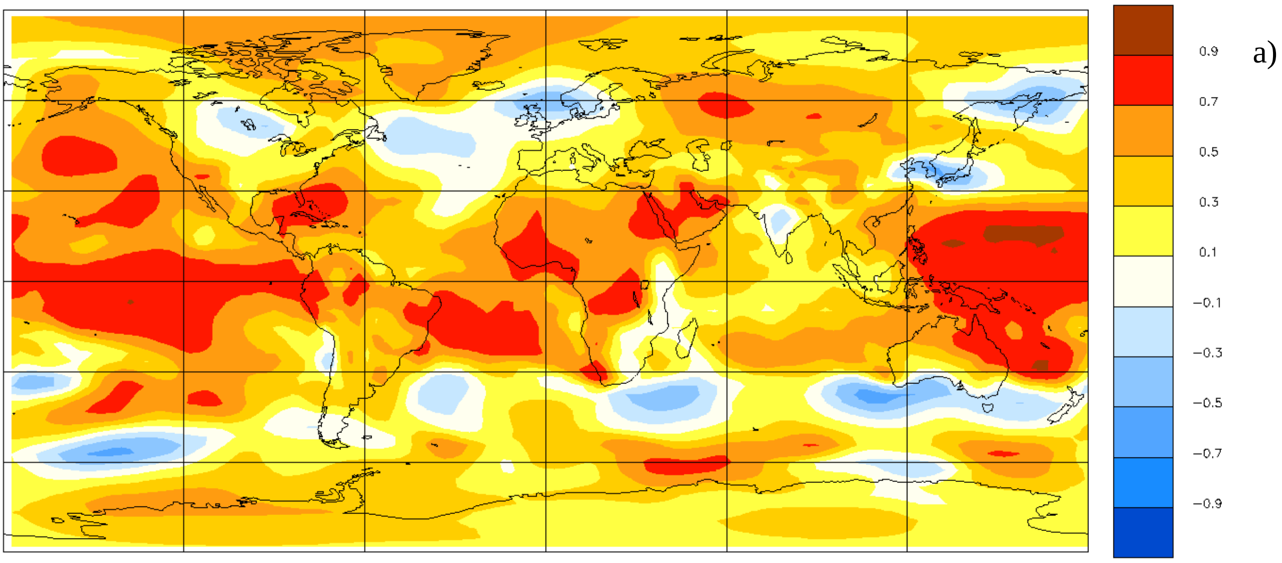


Fig. 3. Difference between 9 member ensemble mean sea level pressure in DJF and corresponding ERA climatology for the northern hemisphere. Left panel (a) shows the systematic forecast errors for the control simulations and right panel (b) for the forced simulations. Contour interval is 2.5 hPa with negative contours dashed.

In order to investigate the ability of the two model versions to make seasonal predictions the anomaly correlation has been used for measuring the skill of the models. Fig. 4a shows the time correlation between the anomalies of the control run and the ERA data for mean sea level pressure. Fig. 4b shows the same as Fig. 4a but for the forced run. In both cases there is a high skill in the tropics especially over the Pacific. In the southern hemisphere the skill is generally higher for the forced model, but in the northern hemisphere there is no general improvement using the corrected model.



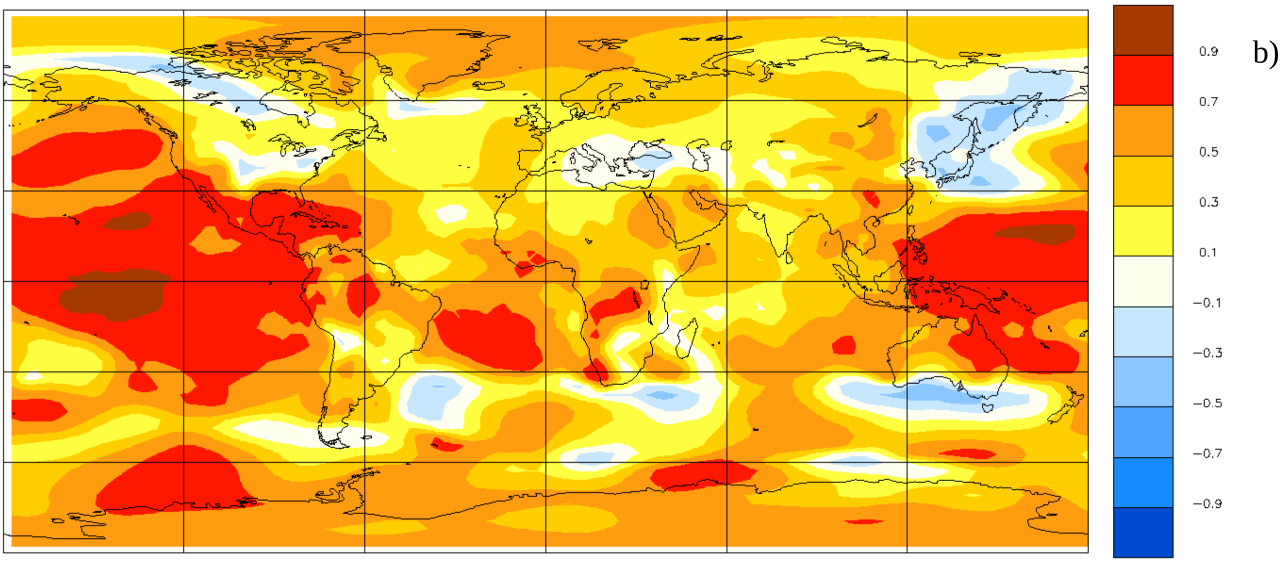


Fig. 4. Temporal correlation between observed (ERA) winter (DJF) average and 9 member ensemble forecast averages of mean sea level pressure. Upper panel (a) for control simulations and lower panel (b) for empirically forced simulations.

Reconstruction of gravity wave drag (GWD).

To study - in retrospect - the reliability of the nudging technique it is tested how well the method can reconstruct a well known forcing error in the wind field. In order to make this test the normal version of the model at T21 horizontal truncation and with 31 vertical levels is first run and output is stored every 6 hours (like the frequency of the ERA data). During this one month simulation the exact long term average tendency contribution from GWD is monitored and stored. In the relevant version of ARPEGE this is a forcing only acting on the momentum equations. Fig. 5a shows the zonal mean zonal wind forcing due to GWD. The model is next run without gravity wave drag but nudged towards the output from the control run with relaxation time constants equal to those used for assimilation of ERA data, i.e. 6 hours for the rotational wind field, 24 hours for the mass field and 48 hours for the divergent wind field. Ideally it should be possible to re-construct the wind forcing in Fig 5a but due the relative weak nudging the reconstructed GWD estimated from the wind forcing residual is somewhat too weak as seen in Fig. 5b. It is, however, extreme well aligned with the true forcing in Fig. 5a, and it is therefore concluded that nudging should constitute a highly adequate method for identifying forcing errors in the wind field which can then be used as a guideline for improving the physical parameterisation. In additional to the wind residual there is also a weak induced temperature residual forcing (Fig. 6). This is because the weak nudging towards the output from the control run leaves room for dynamic adjustments with induced meridional circulations. The missing forcing from the gravity wave drag will therefore show up in both the wind and the mass field. This illustrates a weakness of the method.

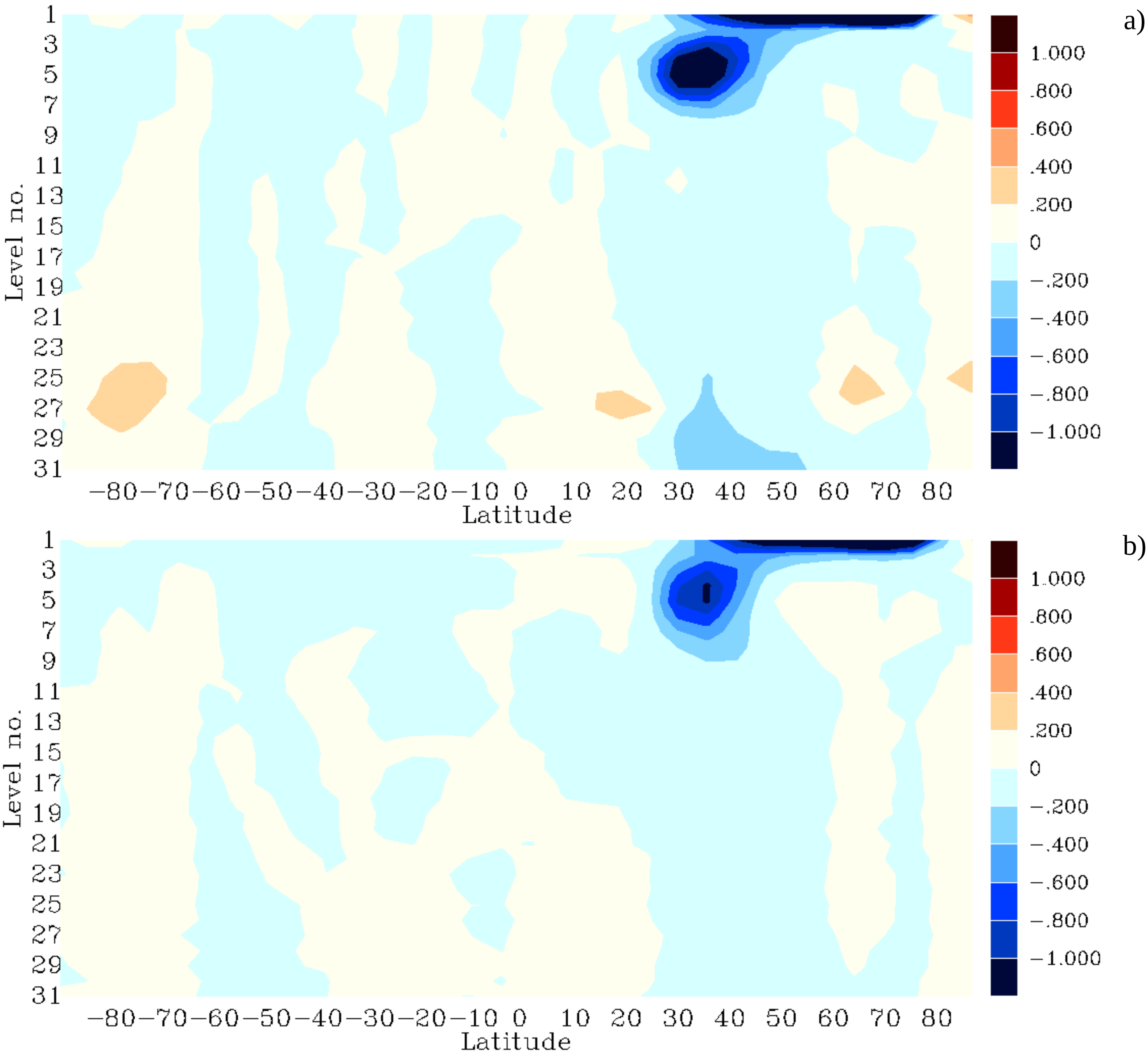


Fig. 5. Upper panel (a) shows the temporal average zonal mean GWD tendency contribution to zonal wind for a given month simulated with ARPEGE. Lower panel (b) shows the tendency contribution estimated via the nudging technique by assimilating data from the relevant month into a model version without gravity wave drag. Units: m/sec/day.

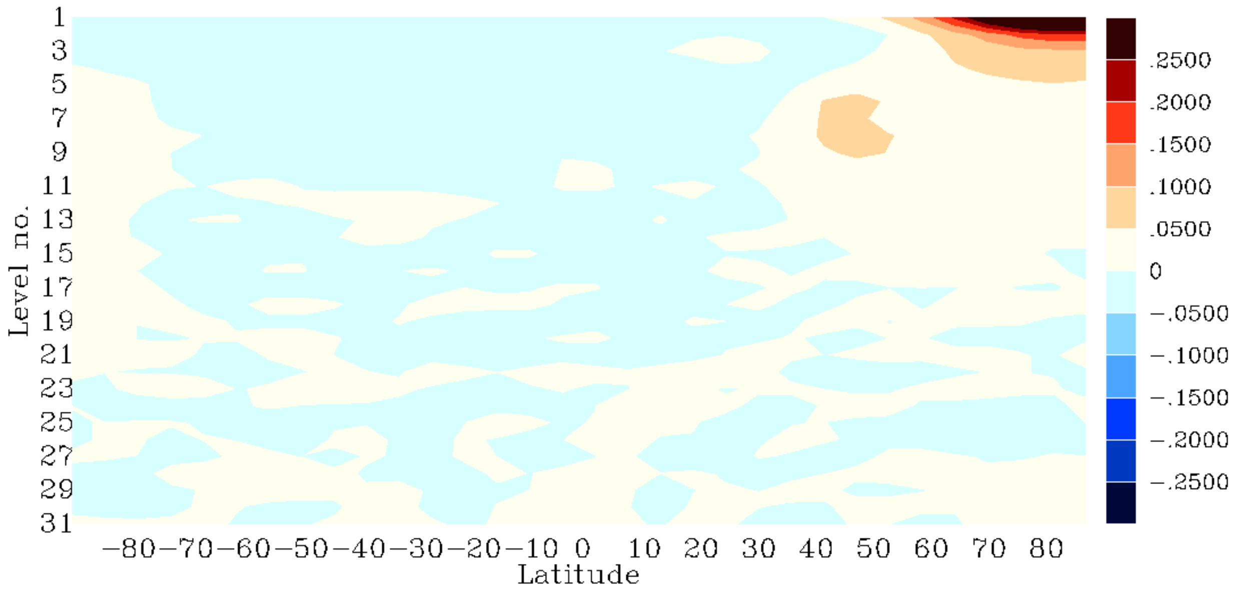


Fig. 6. Temporal average zonal mean temperature residual obtained via the nudging technique by assimilating data from one given month (same as in Fig. 5) into the version of ARPEGE without gravity wave drag. Units: K/day.

To test how well the identified potential vorticity forcing, i.e. combined wind and temperature forcing in Fig. 5b and Fig. 6, corresponds to that reflected in Fig. 5a, five 1000 day perpetual January simulations have been carried out. The first simulation is a control simulation with the standard version of the model, i.e. including GWD. The second is a simulation without GWD at all. The third is a simulation without GWD but with a fixed wind forcing equal to the exact average contribution from GWD during one month (corresponding to Fig. 5a). The fourth is without GWD but with a fixed wind and temperature forcing obtained via nudging (corresponding to Fig 5b and Fig. 6). The fifth is equal to the fourth, but the forcing used has been modified by adding a very small additional tendency contribution which was obtained via a second nudging assimilation, using the same time relaxation constants as in the first assimilation, i.e. 6, 24 and 48 hours. Fig. 7 illustrates the main findings from the 5 simulations for mean sea level pressure. Panel a shows the long term difference between simulation 2 and 1, and the well known "zonalization" of the model without GWD parameterisation is clearly seen with the pressure being almost 20 hPa lower north west of Iceland and more than 10 hPa higher to the north of the Iberian Peninsula. The difference between simulations 3 and 1 in Fig. 7d shows that the fixed forcing equal to one month average contribution from GWD removes almost all systematic differences from the run including GWD It represents the best one can hope to obtain with a fixed forcing obtained via the nudging. Fig. 7c shows the difference between simulations 4 and 1. The magnitude of the systematic errors are much reduced, and are generally of opposite sign than those in Fig. 7a. This indicates that the residual forcing imposed to the model is slightly too strong. This was in fact the motivation for introducing the final nudging assimilation where it is investigated if an iterative procedure leads to improved results. Fig. 7b displaying the difference between simulations 5 and 1 shows that this is the case since this plot is very similar to Fig. 7d. We conclude that the systematic tendency error identified via the nudging technique represents a very realistic potential vorticity forcing since the effect of applying this forcing is very close to the effect of the true systematic GWD forcing. Furthermore, it is seen that an iterative nudging procedure leads to even better results.

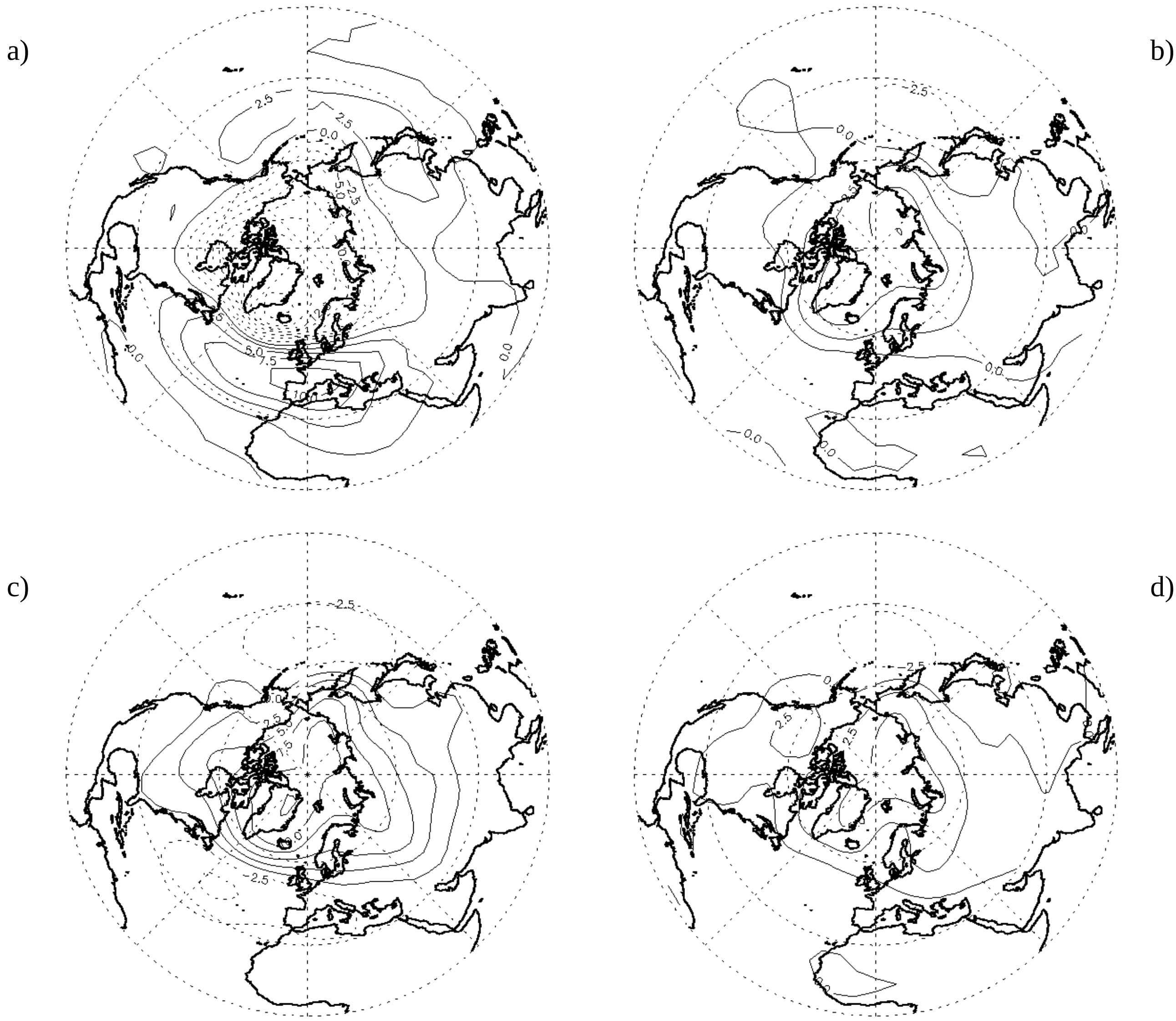


Fig. 7. Difference in mean sea level pressure between four different 1000 day perpetual January simulations without GWD parameterisation and the corresponding control simulation. All simulations are performed with ARPEGE at T21 horizontal resolution. Panel a) shows difference between a standard simulation without GWD and the control, panel b) the difference for fixed wind and temperature forcing obtained via an iterative nudging procedure, panel c) the difference for fixed wind and temperature forcing obtained via a single nudging assimilation (corresponding to Fig. 5b and Fig. 6), and panel d) the difference for fixed wind forcing equal to the exact temporal average tendency contribution from GWD.

Progress and future work

DMI's contribution to the work is slightly delayed, but the half year extension of the project should account for this. The main work left is to set up a simple parameterisation of the residual forcing which can be applied during long simulations and seasonal predictability tests. Furthermore, time will be devoted to writing of scientific articles and the final project report.

Presentations of the project

In 1999 the project was presented by DMI employees at

- the "European Geophysical Society's 24th General Assembly", 19-23 April in the Hague,

- the "Second International Conference on Reanalyses", 23-27 August at ECMWF, UK
- the "4th International Conference on Modelling of Global Climate Change and Variability", 13-17 September in Hamburg,
- IUGG99, 19-30 July in Birmingham, UK

via the following oral presentations:

Kaas, E., A. Guldberg, W. May, M. Déqué: "Using tendency errors to tune the parameterisation of unresolved scale interactions in atmospheric general circulation models". EGS, Haag, 22/4.

Déqué, M. and E. Kaas: A new method for identifying model errors and thus improving GCM., EGS, Haag, 22/4.

Guldberg, A., E. Kaas, W. May and M. Déqué: "Parameterizing unresolved scale interactions", IUGG99, 19-30/7.

and the posters:

Déqué, M., A. Guldberg, E. Kaas: Using the nudging technique to drive a GCM with ERA data. Second International Conference on Reanalyses, 23-27/8.

Yang, S., E. Kaas, A. Guldberg, M. Déqué: On dynamical seasonal prediction employing flux corrections in the atmospheric model component. 4th International Conference on Climate Change and Variability., Hamburg, D, 13-17/8.

Furthermore, the article on improved tuning of horizontal diffusion in ARPEGE and ECHAM has now been published:

Kaas, E., A. Guldberg, W. May and M. Déqué, 1999: Using tendency errors to tune the parameterisation of unresolved dynamical scale interactions in atmospheric general circulation models, *Tellus*, **51A**, 612-629.

POTENTIALS

Contract no. ENV4-CT97-0497

Météo-France (CNRM/GMGEC/EAC)

Contribution to progress report for the second project year (1/1 1999-31/12 1999)

By Michel Déqué

Objectives

The role of Météo-France/CNRM in the project is to introduce, with the DMI, the nudging technique in the ARPEGE/IFS system, to validate the approach, to assimilate the ECMWF reanalyses (ERA) with ARPEGE/IFS cycle 18 in order to get a database of correction terms, and to use these terms to improve seasonal forecasts over the whole ERA period.

Description of the work

The mean tendency error calculated with the 15 year simulation with a relaxation towards ERA, calculated during the first year of the project, has been applied as a constant forcing to 15 winter forecasts with ARPEGE. The poor results have driven us to repeat the nudging simulation with a smaller relaxation constraint. We observe a reduction of the systematic error, but no improvement of the predictability. A third 15-year nudging simulation with a low relaxation on moisture fields has been produced to create model initial conditions including a better assimilation of soil moisture. The seasonal forecast scores are similar to those obtained with initial conditions directly interpolated from ERA data, with a possible (but not significant) improvement in summer mid-latitude temperatures

The second part of the activity was devoted to a more fundamental approach of the nudging technique. As stability arguments require long relaxation times, whereas analytic approaches show that the relaxation times should be as short as possible, we have investigated the impact of the relaxation time in two simple cases: the model relaxed toward itself (twin nudging), and the replacement of the radiation code by the nudging, with increasing values for the relaxation time.

Scientific results

A Predictability studies

As mentioned in the first year report, a 15-year simulation of ARPEGE (cycle 18d) has been performed with a relaxation versus 6-hourly ERA data interpolated at each time step. The relaxation time is 6 hours for vorticity, divergence, temperature, surface pressure logarithm, and surface temperature. The differences between the model prognostic variables and ERA data, multiplied by the relaxation constant have been averaged monthly for the 15 years. It represents the tendency error of the model.

When subtracting this tendency in the model equations at each time step and running the model, it explodes after 20 days of integration. Increasing the horizontal resolution in the stratosphere allows to stabilize it. Another solution consists of suppressing the horizontal diffusion in the nudging simulation, so that the tendency error does not include "counter-diffusion" terms in the stratosphere: then no horizontal diffusion is needed in the forcing simulation to stabilize it.

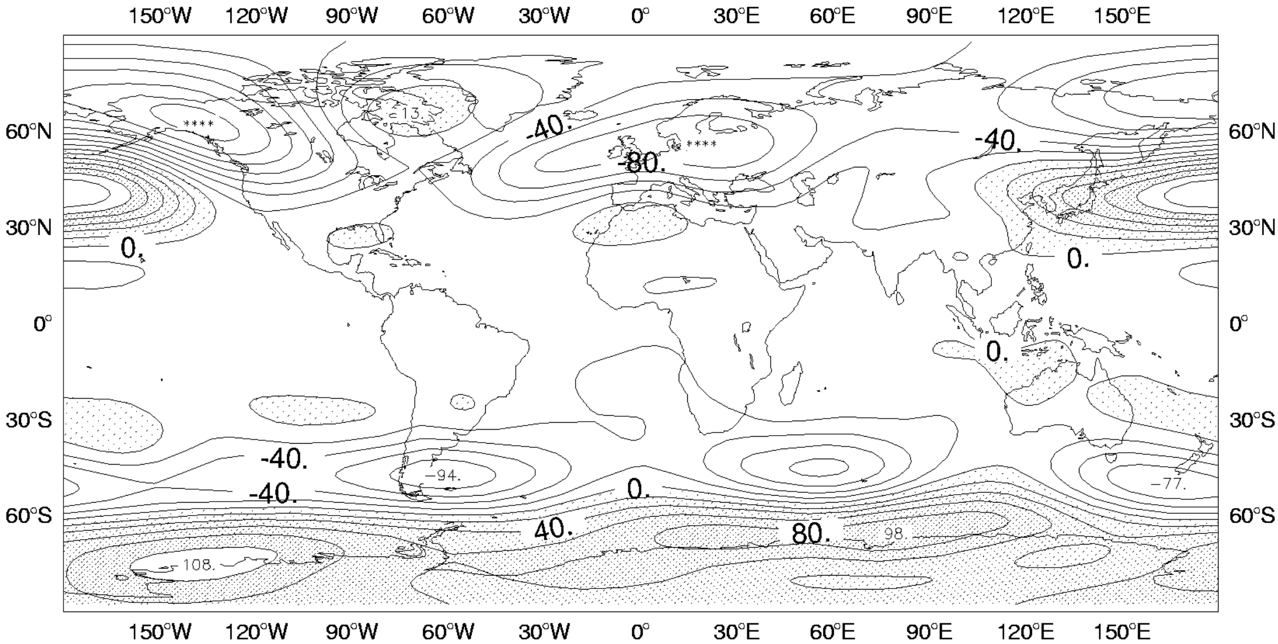
A set of 15 winter (4-month) forecasts, starting at the end of November of each ERA year, has been produced in the same conditions as in the PROVOST experiment, i.e. with prescribed monthly observed sea surface temperature. The difference is that cycle 18d is used and only 3 members are considered. The anomaly correlation over the northern hemisphere for the last 3 month average (JFM) is 0.33 for 500 hPa height, 0.17 for 850 hPa temperature, and 0.21 for precipitation. When we repeat the 15x3 four-month forecasts with the tendency error subtracted, the anomaly correlations become 0.09, 0.06, and 0.22. Except for precipitation, the predictability is strongly degraded. Moreover, the model systematic error is generally increased.

Given the very promising results of our DMI partners, we have decided to partly adopt their technical set-up. The relaxation constant was set to 6 h for vorticity, 24 h for temperature, divergence, and surface pressure, 48 h for surface temperature. But we did not perform a second-step nudging. A second 15-year nudging experiment versus ERA has been performed, and the tendency errors have been computed. They are smaller than in the first nudging, in particular at the surface and in the upper stratosphere. A second set of 12 mean monthly tendency errors has been calculated.

The "revisited PROVOST" experiment has been extended from 3 to 9 members, in order to ensure a better statistical stability of the scores, and to allow to get confidence intervals for the scores based on 3-member forecast. Indeed, when two scores are compared on the same period (e.g. 1979-1993), there is a source of uncertainty due to the choice of the forecast members. By random drawings of 3 members amongst the 9 members available, there are 84 possibilities for each winter, so about 10^{29} possible scores. A set of 100 anomaly correlations can be calculated and ranked, so that a 95% confidence interval about the mean anomaly correlation can be provided. Then, it is possible to compare two experiments and answer to the question of statistical significance for 3-member forecast scores. For 9-member forecasts, the solution is less simple, but a statistical tool is under development.

A second "revisited PROVOST" experiment has been produced with the introduction of a systematic correction based on the second nudging experiment. As shown in Figure 1, the systematic error is reduced. The root mean square systematic error for JFM 500 hPa height over the northern hemisphere is 55 m in the standard forecasts versus 40 m in the corrected forecasts. For 850 hPa temperature, it decreases from 2.3 K to 1.6 K. For precipitation, it decreases from 1.2 mm/day to 0.9 mm/day.

In the case of the forecast scores (time correlation between the 15 forecasts and the 15 observations at each grid point), the improvement is much less obvious (Figure 2). Mean scores over the northern hemisphere have been calculated, by a spatial average of the 3 covariance terms separately: the result is different from the spatial average of correlations, but has a better statistical sense. The results are displayed in Table 1.



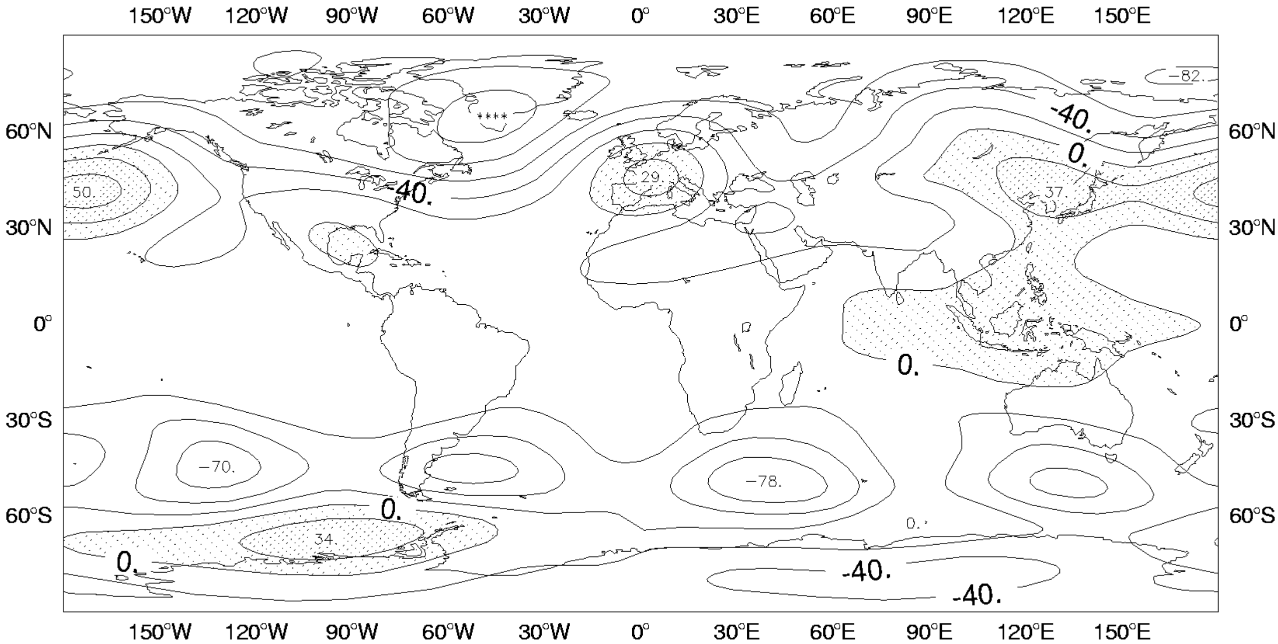


Figure 1: Mean winter (JFM) 500 hPa height systematic error in the standard model (top) and in the corrected model (bottom). Contour interval 20 m, negative values are shaded.

One can see in Table 1 that the corrective term in the model equations produces a degradation of the scores. However the difference does not pass the 95% significance level with 3 members. But as we are at the margins of the interval, we can suspect that the scores with 9 members are significantly affected by the correction.

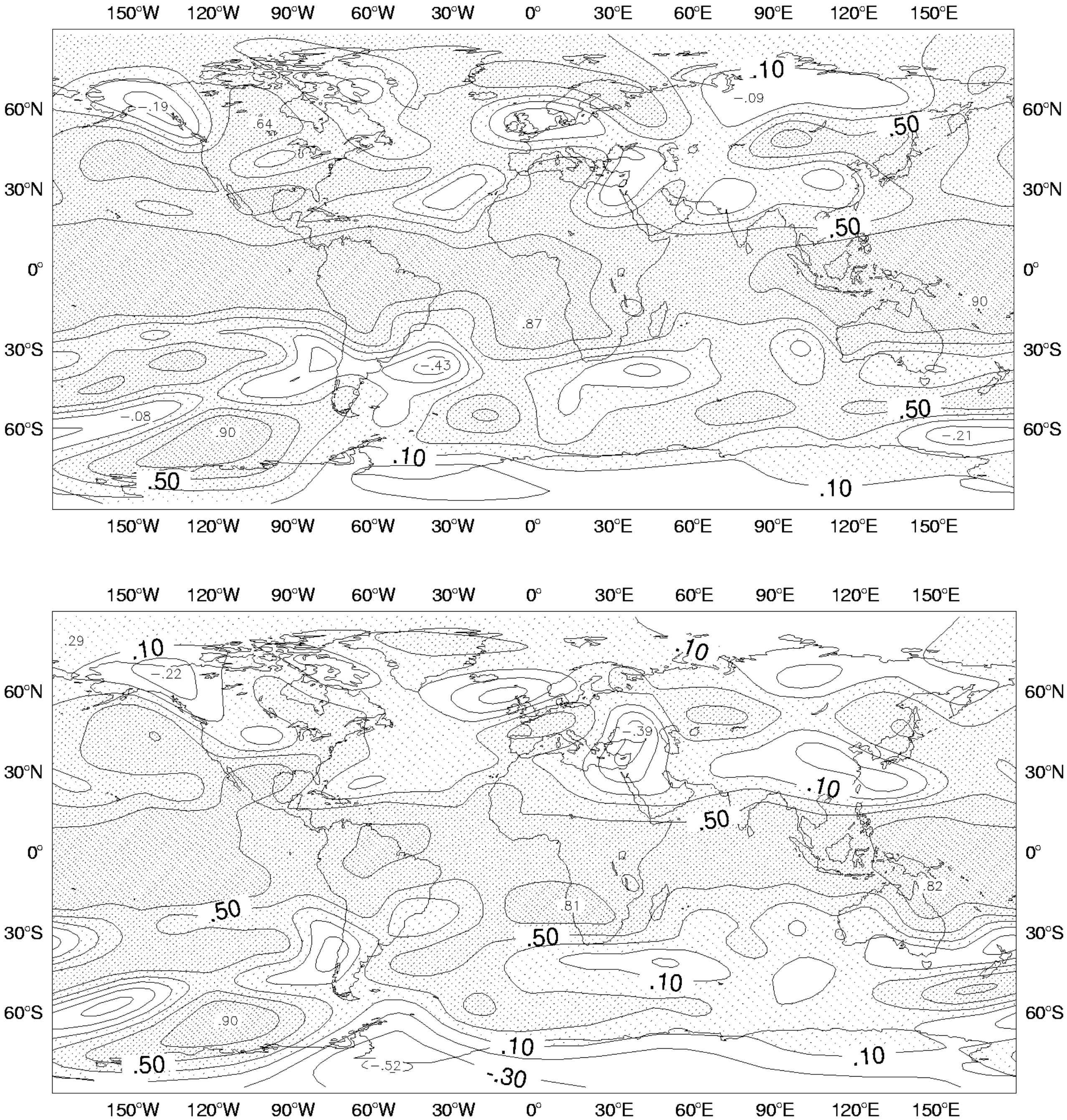


Figure 2: Winter (JFM) 500 hPa height correlation between the forecasts and the observations in the standard model (top) and in the corrected model (bottom). Contour interval .20, values above .10 are shaded.

Table 1 shows also the mean scores (including summer) of a third predictability experiment. Indeed, we have performed a third 15-year nudging simulation towards ERA in which a weak relaxation (10 days) of atmospheric moisture is introduced. The idea is to produce ARPEGE prognostic data which have nearly the same atmospheric values as ERA data (except for moisture) but with surface moisture and deep soil temperature in better agreement with the physics of the model. Indeed, the soil moisture interpolated from ERA has little interannual variability, because of a strong relaxation towards climatology, and, after rescaling to the field capacity and wilting point of ARPEGE soil model, produces too dry conditions in the first month of the forecasts.

		JFM9	JFM 3	JAS9	JAS 3
Z500	standard	.40	.32 [.19,.43]	.03	.03 [-.05,.11]
	corrected	.29	.25 [.14,.33]		
	assimilated I.C.	.34	.28 [.18,.37]	.08	.05 [-.02,.12]
T850	standard	.30	.23 [.14,.32]	.14	.10 [.04,.17]
	corrected	.18	.16 [.08,.25]		
	assimilated I.C.	.23	.19 [.12,.26]	.20	.14 [.06,.20]
Precip	standard	.28	.22 [.18,.26]	.06	.04 [.00,.08]
	corrected	.28	.22 [.18,.27]		
	assimilated I.C.	.26	.21 [.17,.25]	.03	.02 [-.01,.06]

Table 1: Winter (JFM) and summer (JAS) mean correlation for 500 hPa height, 850 hPa temperature, and precipitation over the northern hemisphere. The scores are given for the three experiments, namely the standard "revisited PROVOST", the version including the systematic correction (winter only), and the standard version but with initial conditions coming from the third nudging simulation ("4D-non var" assimilation). The scores are given for 9-member forecasts (mean only), and 3-member forecasts (mean and 95% interval).

The standard model has thus been run using the ARPEGE fields from this third nudging experiment as initial conditions, instead of interpolated ERA data. This is a kind of poor man 4D non-variational assimilation. In winter, the soil is close to saturation in the northern midlatitudes, so we cannot expect any improvement: indeed we get a (non-significant) degradation of the scores which tends to show that the scores of our standard forecast experiment are possibly in the upper part of their statistical distribution. In summer, we get an increase from 0.14 to 0.20 (non-significant as well) for temperature.

B Validation of the nudging technique

The systematic correction we have introduced in the model reduces to some extent (20-30%) but does not cancel out the systematic error. Moreover, it deteriorates (strongly in the first corrected forecast experiment, weakly in the second one) the model predictability. The way we calculate the empirical systematic correction seems to be essential. In a first step, we have to verify that this technique is able to produce the right correction term in two cases for which we know the true value of the estimate.

B.1 twin nudging

In this first experiment, the true correction is zero. The model is nudged toward itself without any modification. In principle, the two trajectories should be identical. This is true if:

- the two starting situations are identical
- the data from the reference run are saved at each time step (no interpolation)
- the relaxation time is one time step and the time discretization is explicit (hard nudging)

In our case, some noise develops in the model due to the time interpolation and discretization, and the evaluation of the tendency error gives an estimate of the background noise plus the methodological error if any.

The reference simulation starts on 1st November from a preliminary long GCM run situation and extends till end of February. All historical variables (temperature, moisture, wind, surface variables) are saved every 3 hours. The nudged simulation starts from the same situation. All historical variables are relaxed each time step, with a time constant of one time step, towards the data from the reference simulation. As the data are interpolated in time between the 3-hourly saved steps, some misfit exists between the second trajectory and the interpolated values of the first trajectory. This is sufficient to maintain the two trajectories at some distance. The average of the forcing term over the last 3 months of the simulation shows that there is a systematic tendency equivalent to a residual warming of 0.04 K/day and a moistening of 0.04 gkg^{-1}/day of the global atmosphere.

Figure 3 shows the zonal mean tendency for zonal velocity and temperature as a function of height. One can see that the warming is concentrated in the lower troposphere and in the summer polar upper stratosphere, whereas the cooling is maximum in the summer polar lower stratosphere. As far as wind is concerned, relatively strong tendencies occur near the surface.

a) b)

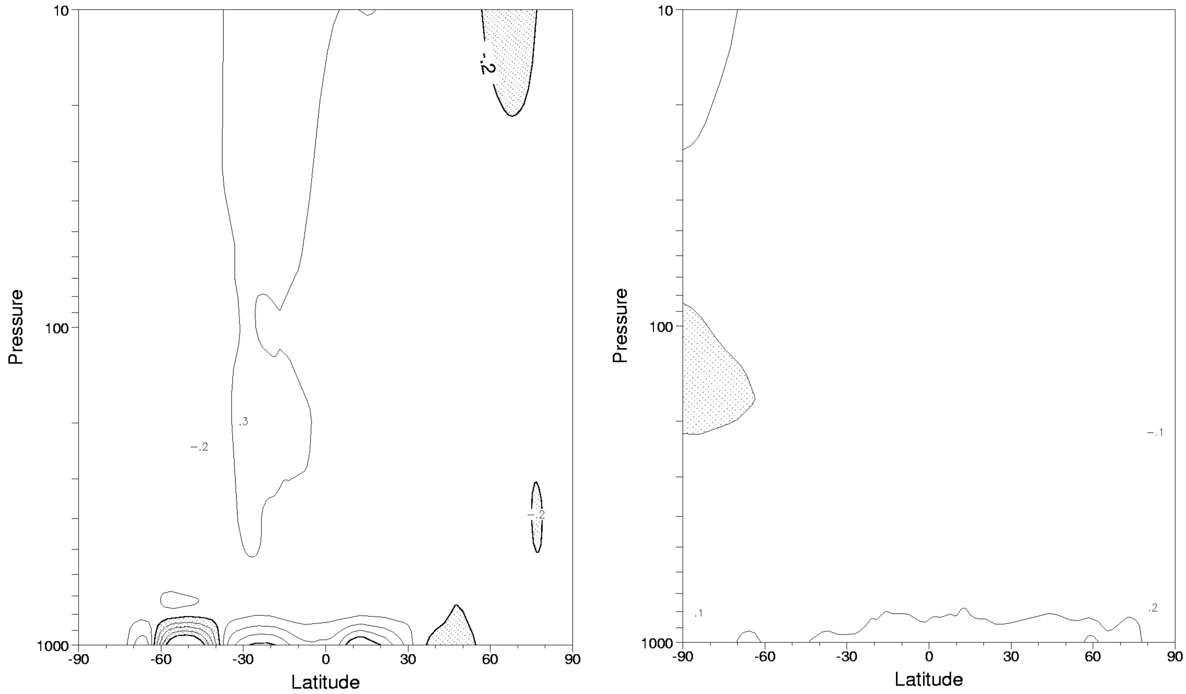


Figure 3: Tendency of the ARPEGE model with respect to itself for zonal velocity (left) and temperature (right) in DJF. Contour interval 0.4 (K/day or ms-1/day), shading below -0.2

B.2 radiation suppression

Now we have evaluated the background noise of the method, we can make a strong modification in the model. The suppression of the radiation code is easy to implement in a GCM, and also easy to analyze, since radiation acts only on temperature. A third simulation has thus been performed, with all radiation fluxes set to zero, and a relaxation towards the first simulation with a time constant of 30 min. The global atmospheric drift is a warming of the troposphere and a cooling of the stratosphere. The average column is warmed up by 0.83 K/day. Figure 4 shows that the tendency for velocity is very similar to Figure 3. In order to validate the tendency, we have calculated the tendency produced by the atmospheric radiative fluxes in the first simulation. The result is displayed in Figure 5. As expected, the pattern is the opposite of Figure 5. The tropospheric cooling corresponds to the infrared emission and the stratospheric warming corresponds to the solar absorption by the ozone layer. In global average, the cooling by the radiative processes is 0.85 K/day. Given the noise level of 0.04 K/day, we can consider that the nudging simulation can capture with a good accuracy the impact of the radiative processes.

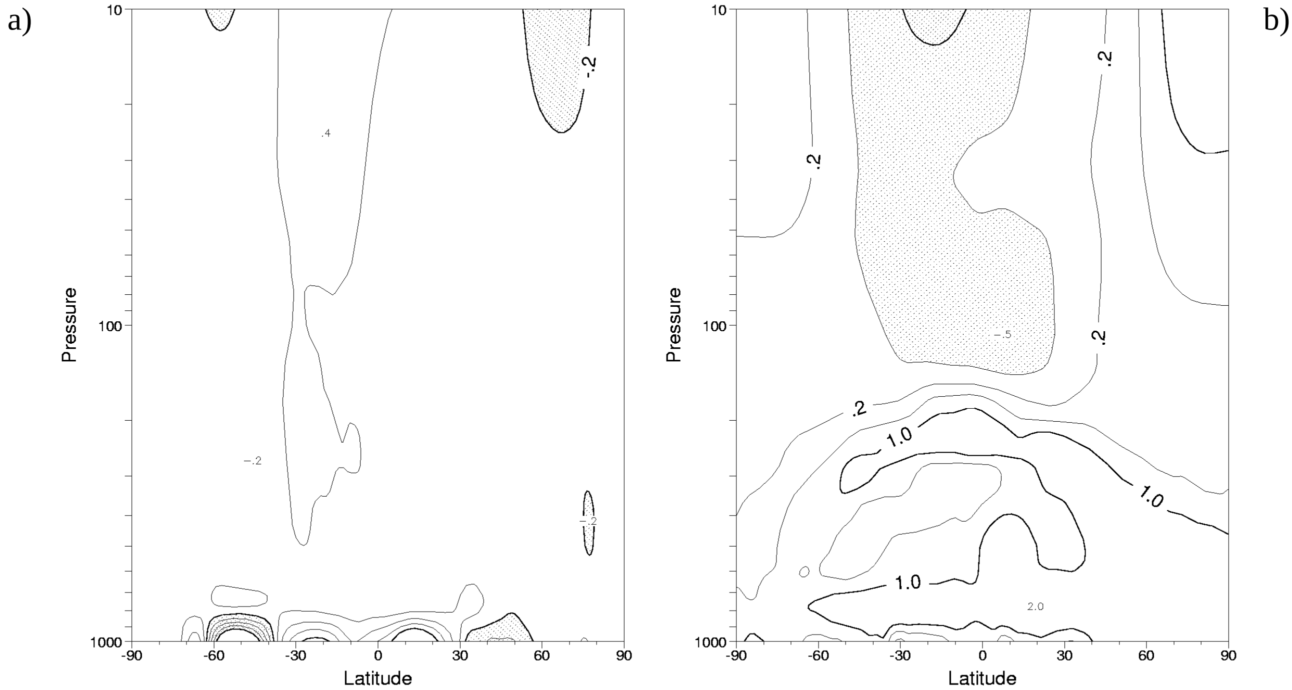


Figure 4: As Figure 3, but with radiation processes deactivated in the relaxed simulation.

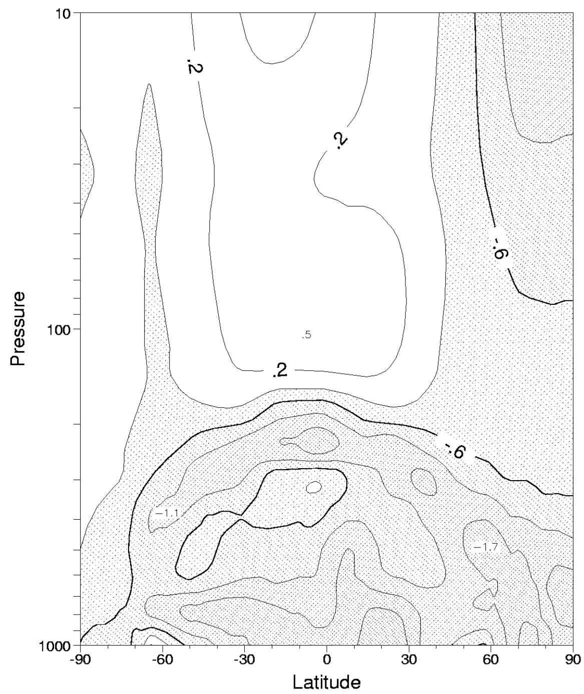


Figure 5: Temperature tendency due to radiation in DJF. Contour interval 0.4 K/day, shading below -0.2 K/day.

a) b)

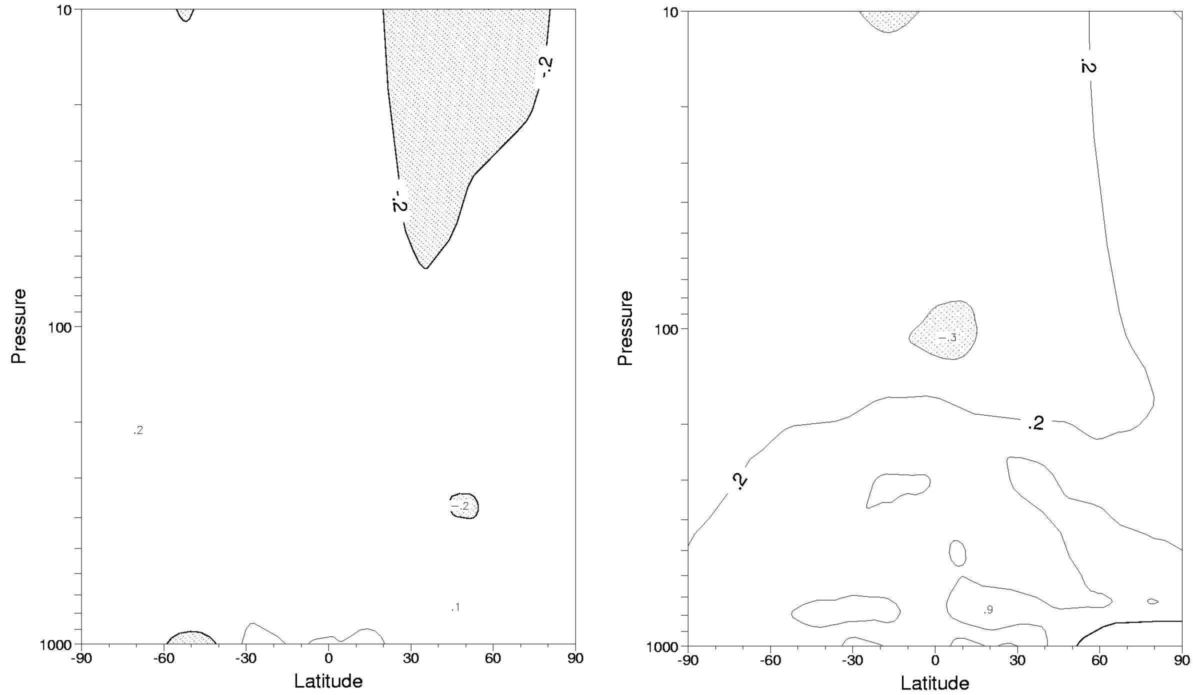


Figure 6: as Figure 4, but with a time constant of 6 h for the relaxation

a) b)

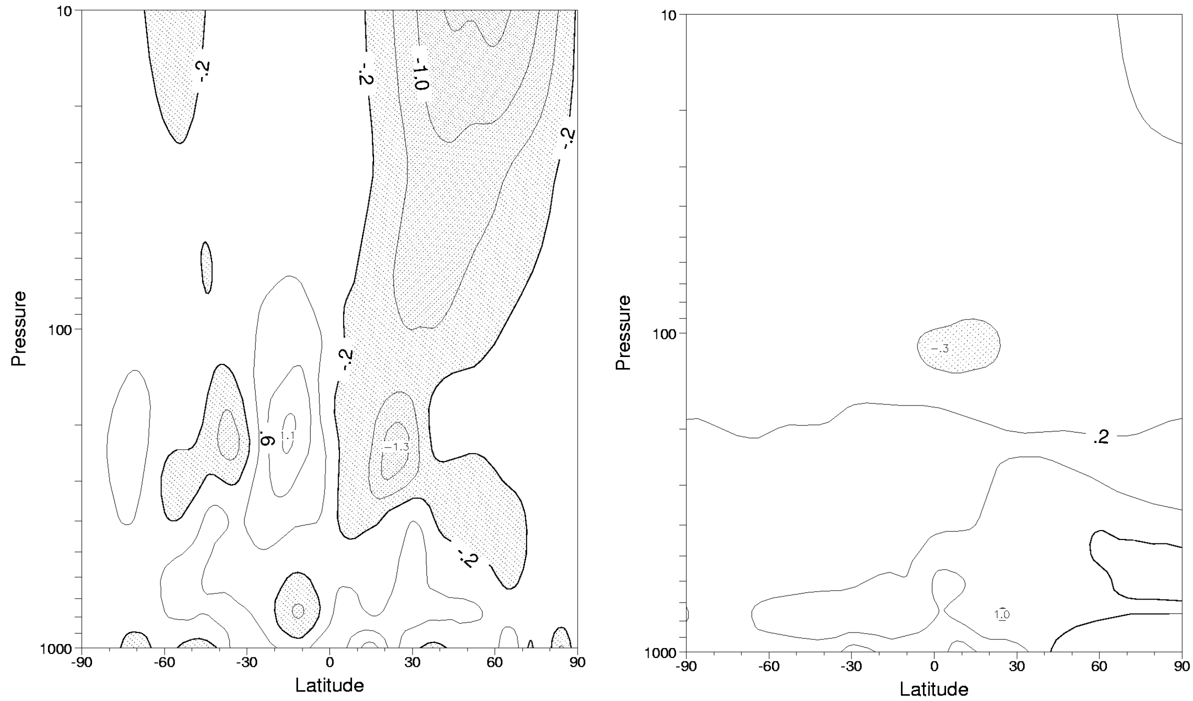


Figure 7: as Figure 4, but with a time constant of one day for the relaxation

The nudging simulation has been repeated twice with a time constant of 6 h (Figure 6), and with a time constant of 24 h (Figure 7). One can see that the tendency of temperature decreases with the strength of the relaxation, but the tendency of wind, and also of the other variables like moisture, increases. One can also see that the strong velocity tendencies at the surface disappear, indicating a better dynamical balance of the model.

This example illustrates the difficulty in the choice of the relaxation time. If the aim is to identify the missing component with accuracy, a short time is necessary. If the aim is to use the estimated tendency to replace the missing phenomenon, a larger value of the time constant provides forcing terms which are in better dynamical balance. Even though it seems odd to parameterize a radiation code by the constant forcing of Figure 7, it is probably more accurate than using the constant forcing of Figure 4 because of the strong wind tendencies at the surface. In the case of radiation, one knows *a priori* that the impact is only on temperature, and one could decide that only the temperature forcing should be taken into account. But in more complex cases, for example when estimating the deficiencies of the dynamical scheme, or the role of unresolved horizontal fluctuations one must take into account all prognostic variables.

A possible solution to this dilemma could be to subtract the pattern from Fig. 3, considered as the error due to the time interpolation, to the pattern from Fig. 4. Another possibility could be to reconstruct the missing component iteratively: a relatively large time relaxation is taken, but a second nudging simulation includes the correction term, then a third nudging simulation includes the sum of the two correction terms, etc... It can be shown with a linear system that this iterative process converges towards the same limit as when the relaxation time tends to zero.

In a further step, it would be interesting to replace the relaxation term in the equations by the time average of this term (i.e. the opposite of the estimate of the tendency). It is not possible to replace the radiation code by a constant forcing in a GCM, since radiation acts as a stabilizer through the infrared emission: such a GCM run would explode after a few weeks. The experiments carried out by our DMI partner with the suppression of the gravity wave drag parameterization show that this correction term acts, in average, similarly to the removed parameterization.

Workplan for the end of the project

During the last six months, we will test the possibility of using a systematic correction which depends on the SST forcing, rather than a constant one. We will consider the best possible prediction by taking for each month of the 15 years, the mean tendency error of the same month in a relaxed simulation. The impact on the seasonal forecast scores will be compared with the reference case without correction.

We will use the nudging technique to test the impact of a new parameterisation of the convection, based on the so-called CAPE closure assumption.

We will continue to investigate the efficiency of the method by producing a 15-year twin nudging exactly with the same conditions as the ERA nudging. The tendency errors will be examined.

POTENTIALS

Contract no. ENV4-CT97-0497

Max Planck Institut für Meteorologie (MPI).

Contribution to progress report for the second project year (1/1 1999-31/12 1999)

By Bennert Machenhauer and Ingo Kirchner

The progress of the work

The work at MPI on the POTENTIALS project was concentrated in the second year on the following sub-tasks, related mainly to the identification of forcing errors (Task 1) and objective tuning of physical parameterisation:

- implementation of the "Slow Normal Mode Insertion (SNMI)" data assimilation technique, a new general tendency diagnostics and error detection method, developed here for the ECHAM model (Task 1b). The technique is being compared with the standard nudging technique (Task 1a) developed in parallel for the same GCM.
- analysis of systematic error structures in different ECHAM4 experiments and, in order to support model improvements (Task 2) and deduction of possible reasons for the errors by use of a combination of dynamical meteorological reasoning and SNMI tendency error estimates.

The achievements and results

<u>Development and testing of forcing error detection methods</u>

At MPI assimilation of the ECMWF re-analyses in the T42 ECHAM4 model was started up in 1998 using the Jeuken et al. (1996) nudging (or relaxation) technique. Preliminary experiments with ECHAM using this technique had already been made at MPI and DMI but the code had to be adapted for the purpose of systematic tendency (or forcing) error detection. We wanted in particular to determine systematic errors in the forcing coursed by defects in the physical parameterisation schemes when the state of the atmosphere and the Earth surface of the model is as realistic as possible. Basic problems are dynamical imbalance causing spurious gravity oscillations and the hydrological spin up problem both of which problems that must be dealt with.

Test of standard nudging technique

It was expected that much of the dynamical imbalance problem could be eliminated by the use of a nudging technique tested by Jeuken et al. (1996) for a T21 version of ECHAM. Here the time mean difference between the model tendencies and the observed (analyzed) tendencies are extracted from a continuous model integration in which the model variables, by a Newtonian relaxation, are nudged toward the analyzed values, interpolated in time and space. Thus, in the continuous integration the interpolated analyzed values are gradually assimilated into the model. Jeuken et al. (1996) found best results when variables dominating in Rossby modes (vorticity and surface pressure) were relaxed strongly to the observed (analyzed) values and variables dominating in gravity modes (divergence and temperature) were relaxed less strongly. In that way less gravity waves are excited and those which are supposed to be damped gradually by dispersion and dissipation mechanisms in the model (geostrophic adjustment like in dynamical initialization). They did not relax the humidity field because of the poor quality of that field in the analyses. Thus, the hydrological cycle was only indirectly forced in the assimilation run. In our implementation and in most experiments we have assimilated the same prognostic variables and used the same nudging coefficients as Jeuken et al. (1996).

It is well known that model forecasts starting from standard analyses have a precipitation spin up problem. This is the case for the ERA data as well. The explanation given for that is that typically, the vertical velocity field (or divergence field) in the analysis are not consistent with the humidity field which is also believed to be too much smoothed out by the analysis of the observations because their density generally are too low to support analysis of sharp gradients. Also it is believed that the divergence field is too weak in the analysis. As a consequence of this theory too little precipitation is released in the beginning of the forecast and it takes some time before the model reaches the model's long term mean state. The so called "spin up" period for global precipitation is typically 2 - 3 days. In their nudging experiments Jeuken et al. (1996) used 6 hour forecasts instead of the analyses themselves in order to get larger and thus more realistic values of divergence. In order to compare with the SNMI method in our experiments we have not followed this practise but are using the actual ERA analyses. Here, however, as Jeuken et al. (1996) we are not using the humidity fields.

Development and tests of the Slow Normal Mode Insertion (SNMI) Method

A disadvantage of the Jeuken et al. (1996) standard nudging technique is that the state variables used to compute model tendencies and thereby the forcing errors are not exactly equal to the interpolated analyzed values which are supposed to be the most realistic ones. In order to try to alleviate this we developed an alternative approach building on a dynamical adjustment toward a nonlinear normal mode balance (or "Machenhauer balance"), Machenhauer (1977).

The following new normal mode approach is being tried out and compared with the standard nudging technique. The ECMWF re-analyses (ERA) are available in a T106, L31 resolution every 6 hours. We use the initialized version which is at first vertically interpolated to the pressure of the 19 levels used in ECHAM and then truncated to the T42 resolution used presently in standard climate simulations. To avoid spurious large tendencies caused by dynamical imbalances of fast gravity modes only the Rossby modes and the slow gravity modes, linearly interpolated in time from their 6-hourly values, are inserted in the model every time step. We do that in practice by projecting at first the model fields minus ERA fields on the fast gravity modes of the T42 model and then subtracting the resulting fields from the total ERA fields.Thus, the fast gravity modes are free to change according to the model equations. They are specified only initially but are forced during the assimilation process by the nonlinear adiabatic and diabatic terms in the model equations. Due to the damping mechanisms of the model, i.e. the Asselin time-filter and the model's diffusion terms, they are supposed to adjust to a Machenhauer balance in which for each mode its tendency is approximately zero, or in other words a state in which the linear term in the tendency equation is balanced by the nonlinear adiabatic and diabatic terms. Since previous model experiments has indicated that gravity modes with a period less than 24 hours are well balanced we have chosen a cut-off period of 24 hours. By this technique we expected to avoid spurious systematic tendency errors caused by high frequency noise. Fig. 1 shows that this is in fact achieved with the SNMI method, whereas it is not with the standard nudging assimilation method.

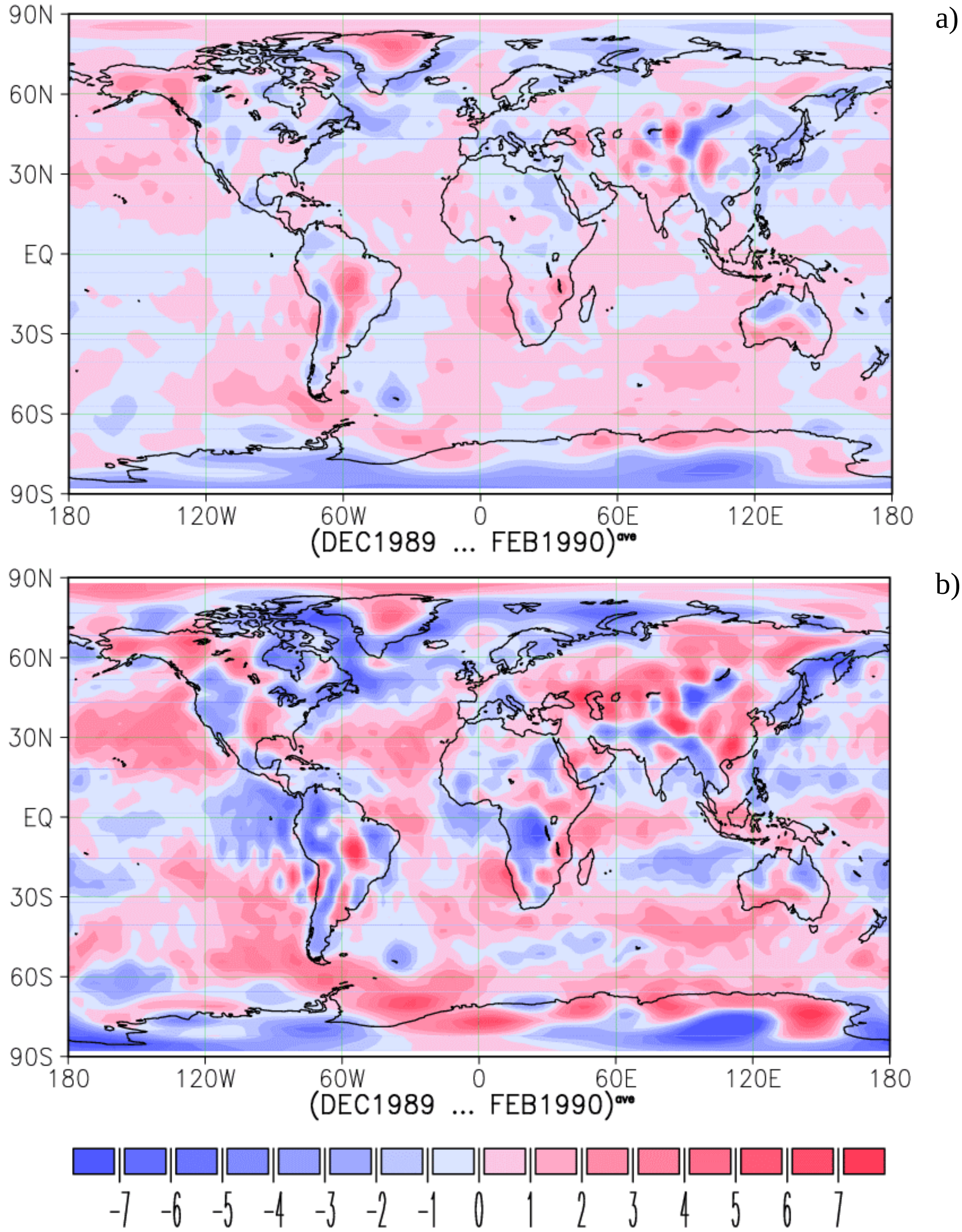


Fig. 1. Mean tendency error for the logarithm of the surface pressure obtained via slow normal mode assimilation (a) and via nudging (b) in the period Dec. 1989 - Feb. 1990. Units: 10^{3} day^{-1}.

We furthermore expected to get realistic divergence fields and thereby realistic vertical velocity fields for the T42 resolution. This is a first prerequisite for an elimination of the spin up problem. A second necessary condition is that the moisture fields are realistic. As the analyzed fields are most likely not realistic, they are not used. Instead, as in the Jeuken nudging technique, we suppose that the model itself can establish realistic moisture fields, as well as consistent fields of the other prognostic variables involved in the hydrological cycle, when those fields are predicted by the model. That the spin-up problem has been reduced slightly in the SNMI analyses compared to that in a Jeuken assimilation is shown in Fig. 2.

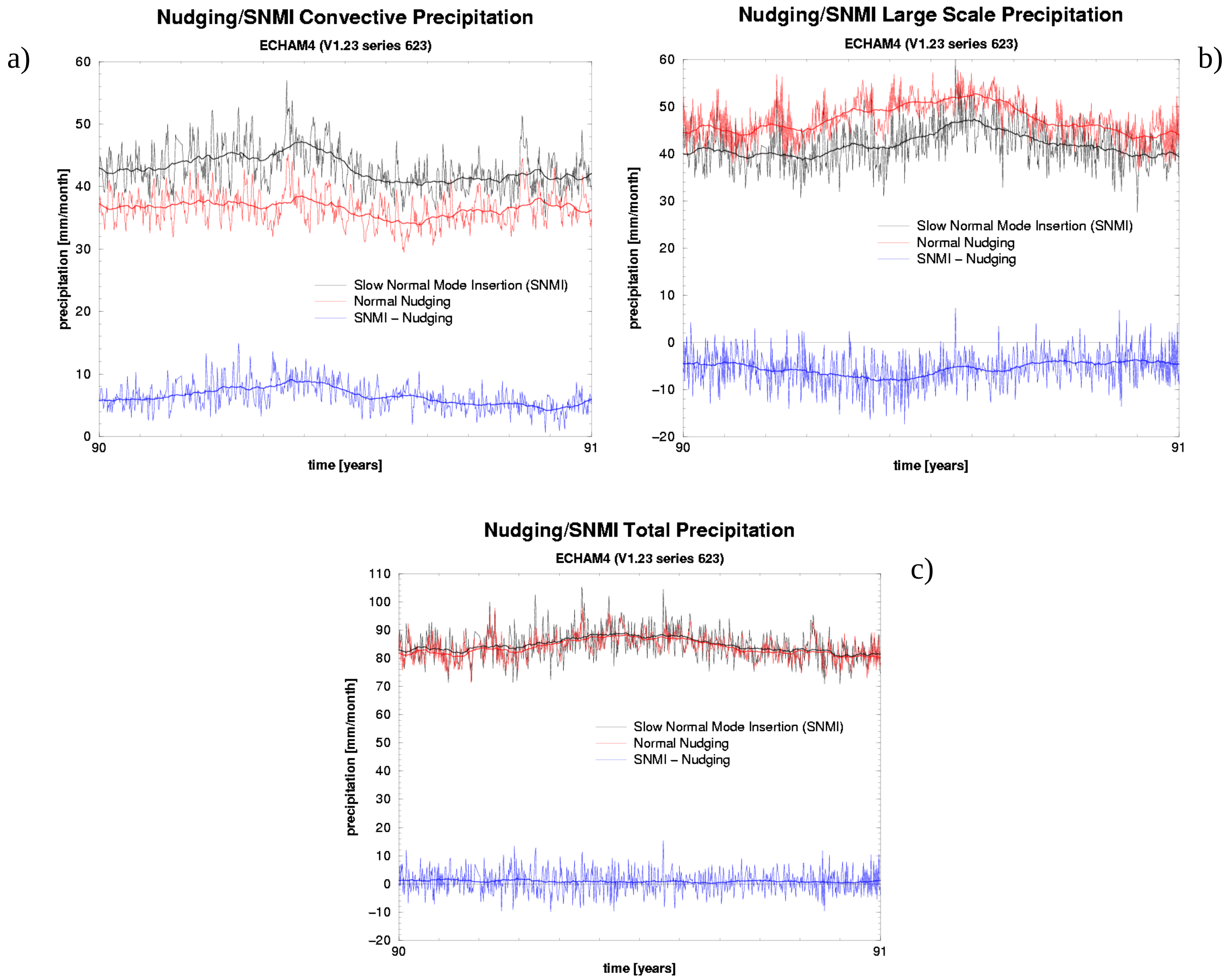


Fig. 2. Time series of global mean convective (a), large scale (b) and total (c) precipitation for assimilation via slow normal mode insertion (black) and via nudging (red). The difference is shown in blue. Units: mm/month.

It is seen that globally the convective precipitation is largest with SNMI assimilation but that the large scale precipitation is largest with the traditional nudging. For the total global precipitation it is seen that SNMI gives slightly more precipitation than nudging. We are presently investigating the reasons for these differences but we think that the explanation for more large scale precipitation in the nudging assimilation is more gravity noise which gives rise to spurious model resolved vertical motions leading to release of more "large scale" precipitation (probably rather small scale and of small intensity).

The planed comparisons with observed precipitation has also been started up. For mid latitudes some case studies with a T106 version of ECHAM (H.-S. Bauer, personal communication) has shown that the instantaneous (6-hourly accumulated) precipitation patterns seem to be the more realistic with SNMI assimilation than when using Jeuken nudging. Also monthly mean fields seem to be more realistic with the T42 SNMI assimilation as illustrated in the Fig. 3.

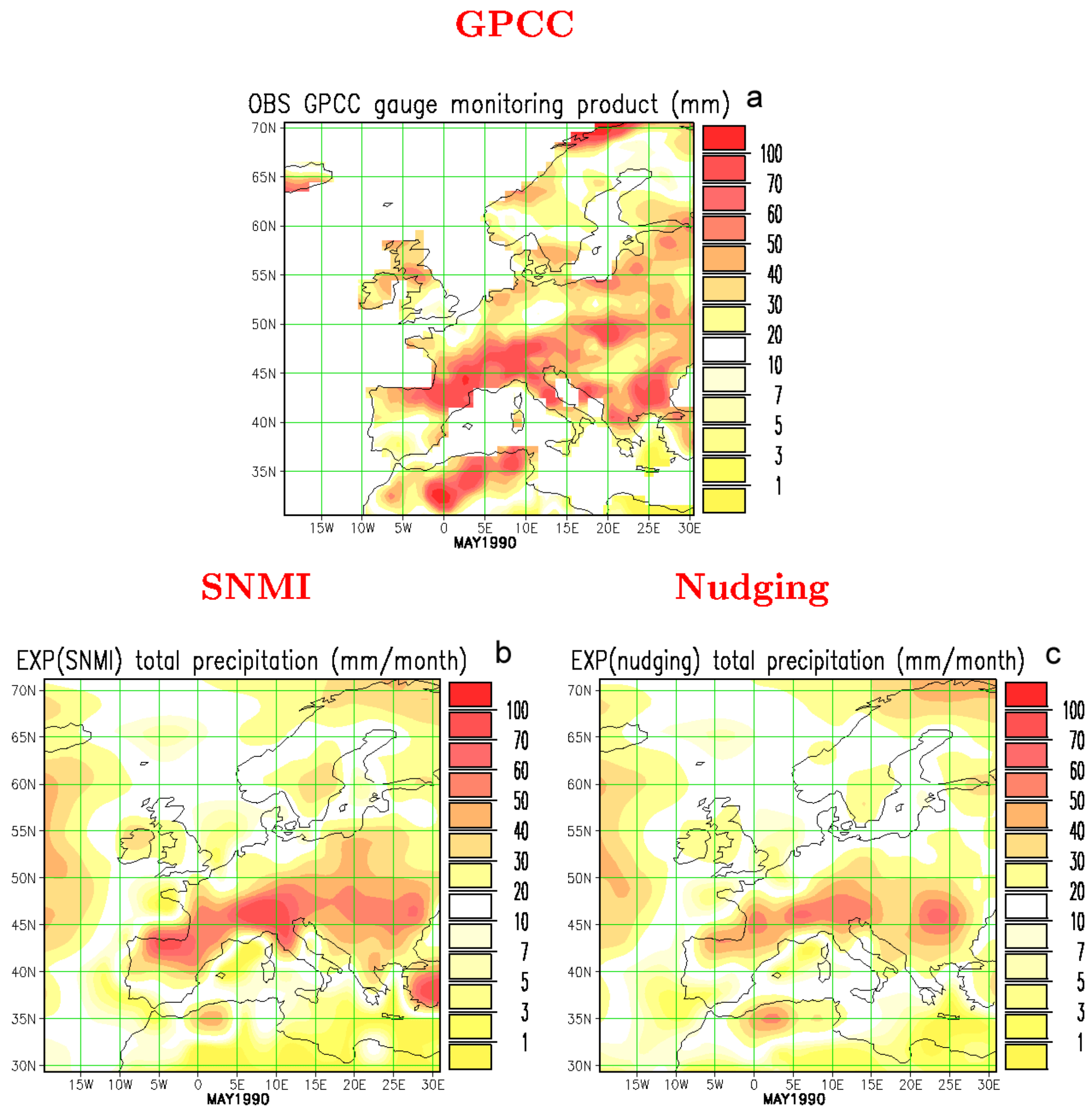


Fig. 3. Monthly averaged precipitation for May 1990 over Europe. Panel a) is is analysed by and made available from the Global Precipitation Climatology Centre (GPCC) in a 1°x1° resolution, panel b) is obtained via slow normal mode assimilation and and panel c) is obtained via nudging assimilation.

Systematic model errors and their possible causes

We continued the work on the analysis of systematic errors in different ECHAM4 experiments which were stated up in 1998. The analysis was concentrated on fields derived from the geopotential height field in the middle troposphere (500 hPa) and near the surface (1000 hPa). The differences between the model seasonal mean state and the observed state based on ERA data were studied and by the uses of a combination of dynamical meteorological reasoning and SNMI tendency error estimates. We have tried to deduce the possible reasons for the errors.

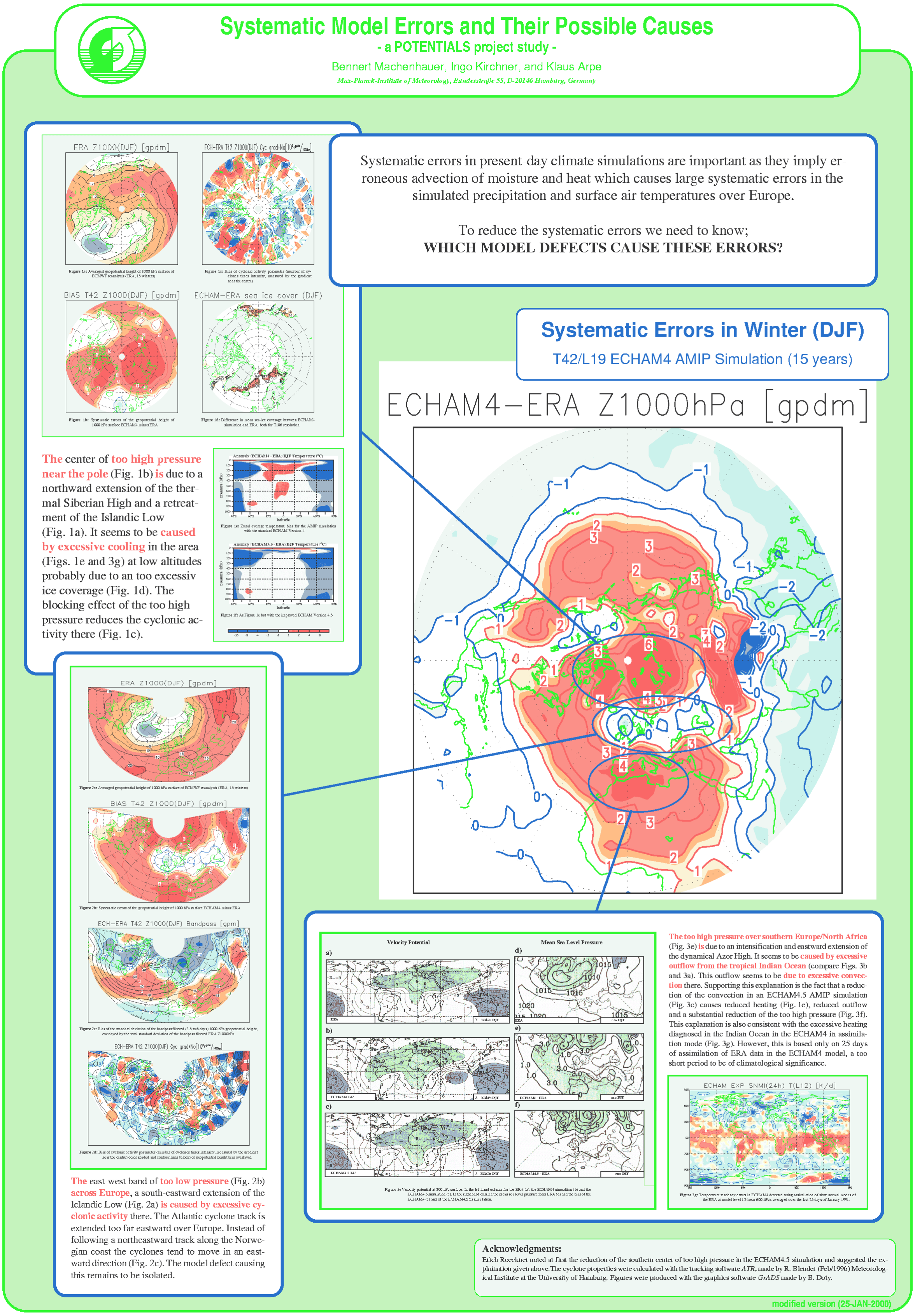


Fig. 4. Poster. Note the reference to the individual figures in the text.

As a typical example we illustrate in Fig. 4 (a poster) common systematic errors in the winter season (DJF) which were found in all simulations analysed: Two positive bias centres (too high pressure) are situated near the pole, one north of Europe-Asia and one over North America. Further south at southern mid-latitudes, between 30N and 50N, we find positive centres (one or two) over the Pacific Ocean and over the Atlantic/Mediterranean. Between these polar and southern mid-latitude positive bias centres we find an approximately east-west orientated band of negative biases, generally from Greenland over northern Europe and northern Asia to Alaska. In some of the simulations additional negative centres are found in connection with the Rocky Mountains and the Himalayas. The systematic errors are pretty similar in all T42 simulations but some dependence on resolution is found: In a T106 simulation analysis we found generally larger amplitudes with the positive biases dominating, whereas in a T30 simulation we found that generally the positive biases are decreased and the negative ones are increased, so that here the negative biases tend to dominate. Inspection of the corresponding 500 hPa bias maps (not presented) show that the biases are approximately equivalent barotropic, increasing somewhat in amplitude with height from the 1000 hPa to the 500 hPa.

In the poster (Fig. 4) we consider the systematic errors over the European sector which are responsible for large systematic errors in simulations of the European climate (Machenhauer et al., 1996, 1998).

The east west band of too low pressure (Fig. 4/2b) across Europe, a south-eastward extension of the Icelandic Low, seems to be caused by excessive cyclonic activity. This is evidenced by the bias maps of the cyclone track parameter (the standard deviation of the bandpass filtered, 2.5 - 6 days, 1000 hPa geopotential) (Fig. 4/2c) and of the frequency of cyclones (Fig. 4/2d) (red colours larger values than in ERA). The Atlantic storm track is in the model simulation extended too far eastward over Europe. Instead of following a northeastward track along the Norwegian coast the cyclones tend to move in an eastward direction. The model defect causing this remains to be isolated although it may be connected with the processes which are responsible for the centres of too high pressure to the north and to the south.

The too high pressure over southern Europe/North Africa (Fig. 4/3e) is due to an intensification and eastward extension of the dynamical Azore High. It seems to be connected to excessive outflow from the Indian Ocean, compare the ECHAM4 modelled velocity potential in 200 hPa shown in Fig. 4/3b with the corresponding ERA field in Fig. 4/3a. This outflow seems to be due to excessive convection there. Supporting this explanation is the fact that a reduction of the convective precipitation in an ECHAM4.5 AMIP simulation causes reduced heating (Fig. 4/1e), reduced outflow (Fig. 4/3c) and a substantially reduction of the too high pressure (Fig. 4/3f). This explanation is further supported by the excessive heating diagnosed by the SNMI method in the tropics, in particular in the Indian Ocean, as shown in Fig. 4/3g and in Fig. 5.

Finally, the centre of too high pressure near the pole (Fig. 4/1b) is due to a northward extension of the thermal Siberian High and a retreatment of the Icelandic Low (Fig. 4/1a). It seems to be caused by excessive cooling in this region (Figures 1e, 3g and Fig. 5), at low altitudes. This is probably due to an too excessive ice coverage as evidenced in Fig. 4/1d which shows that the ice coverage actually used in AMIP simulations are excessive compared to the more realistic coverage used in ERA. The blocking effect of the too high pressure reduces the cyclonic activity there (Fig. 4/1c).

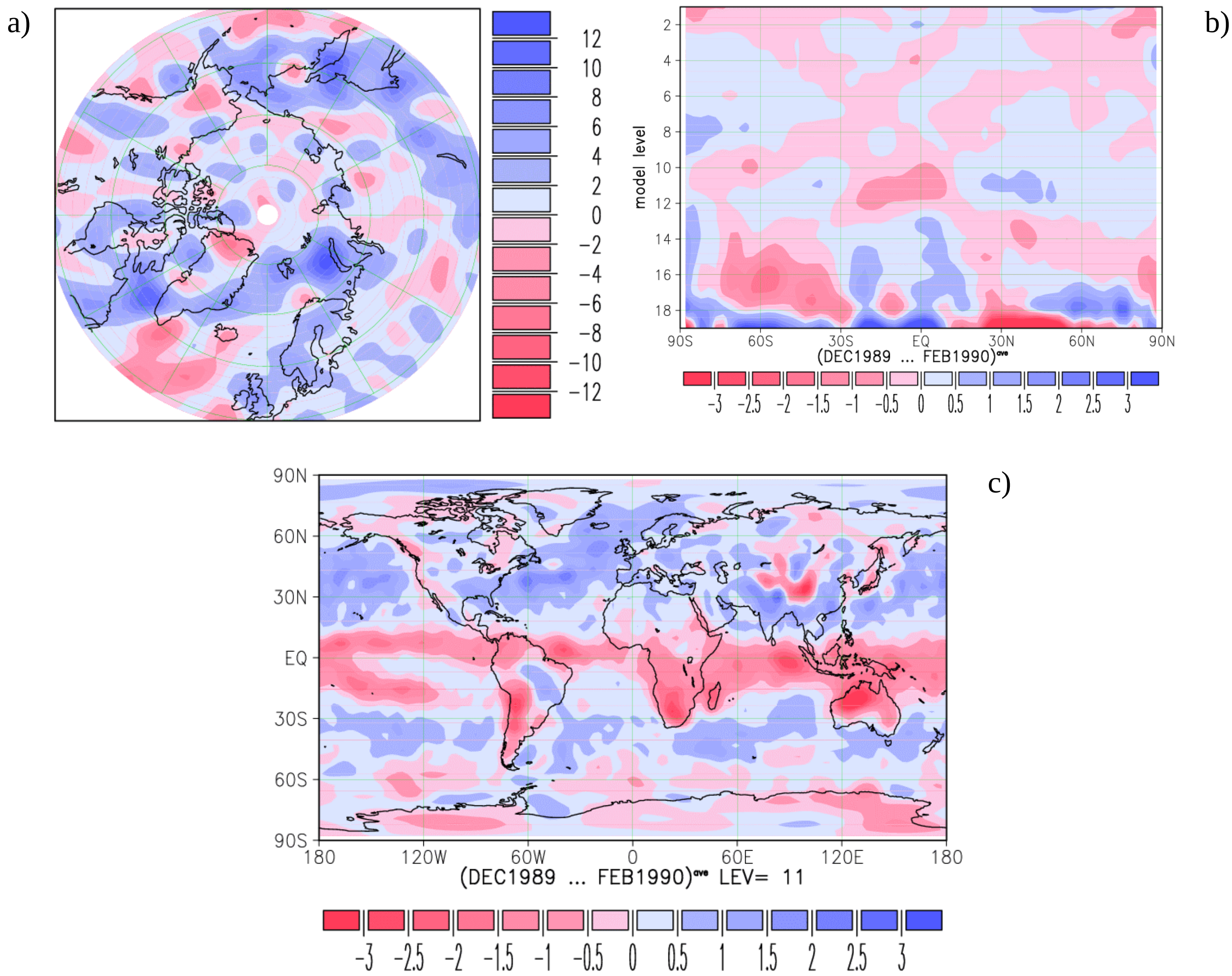


Fig. 5. Average temperature tendency error obtained via nudging for Dec. 1989 - Feb. 1990. Panel a is for the Northern Hemisphere, model level 18, panel b shows the zonal mean for all 19 model levels and panel c is for model level 11. Units K/day.

Deviations from and modifications of the work plan

The project should have been finished after 2 years, but due to the delays during development and testing of the tendency error detection methods and the ECHAM code modifications (see previous yearly report) some tasks have not been finished. We expect however, to do that during the coming six month period of extension.

Task 1, identification of forcing errors, will be finished in the near future with a paper on the SNMI method and with our contributions to a common paper on the nudging method. These papers must be based on long assimilations with both methods using ECHAM4 and ECHAM4.5.

Presently we are planing AMIP simulation with a new version of the ECHAM4.5 model, modified according to the tendency errors deduced by the SNMI method, in particular with ERA ice coverage instead of AMIP ice coverage (Task 2c, improving physical parameterisation in ECHAM). We expect that this run will have substantially reduced systematic errors an thus constitute the long simulation promised in Task 3b of the work plan, which will be handed over to the MERCURE project. The results of that simulation and our studies of systematic errors will be described in a third paper, hopefully with a title like the following: "Systematic Model Errors in the ECHAM Model: their Causes and their Elimination".

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POTENTIALS

Contract no. ENV4-CT97-0497

Laboratoire de Météorologie Dynamique du CNRS (LMD).

Contribution to progress report for the second project year (1/1 1999-31/12 1999)

By Fabio D'Andrea

Progress

In the second year of the project, we addressed a theoretical point, more axed on the parameterisation of tendency errors (task 4 of work programme) than on their estimation (task 1). The study was conducted in a "reference model" framework, i.e. the observed data were substituted by a long run of a GCM. The reference model was the three-levels quasigeostrophic model, with horizontal discretization of spectral T21, that was used by LMD throughout the project .(Marshall and Molteni, 1993)

A reduced model was constructed, projecting the equations of the reference model on its 10 leading EOFs (Empirical Orthogonal Functions). This model is obviously affected by model-error with respect to the reference one: we have tested the possibility of leading the reduced model to have the same climatology of the reference one by tendency error correction.

The reduced model, because of the EOF filtering, is a model of the sole large-scale and low-frequency dynamics of the reference one, and has thus a very interesting dynamical interpretation. In literature, many authors have hypothesized that the low frequency (10 to 90 days of period) atmospheric variability should be modelisable by a low order system of equations. Observational studies based on the measure of the statistical degrees of freedom of the low-frequency variability have found numbers ranging from 10 to 50 depending on the method. This means that a 10 to 50 variables model should e sufficient for modelling this variability (see Fraederich, 1995).

Such a model have remained for about 20 years a theoretical challenge. In the first year of the project, very interesting results were obtained on the modellization of the low-frequency variability of the QG model by tendency error empirical correction. It was therefore natural, although not explicitly included in the work programme, to try and extend this approach to the construction of the low dimensional model of the sole low-frequency variability. We have shown that, at least in the reference case, this model can be constructed with 10 variables only.

In the reference model framework, there is no problem of tendency error estimation. At every time step, the error is easily computed by its definition (see section 2.2.1 of work programme) as difference of the tendencies of the reference and reduced model. A long library of tendency error can be thus computed, starting from a long (10000 days) integration of the reference model.

Once the library constructed, a closure term has been constructed on the reduced model that expresses the tendency error as a function of the reduced model state. In detail, the tendency error contemporary of analogues of the state was chosen, in a procedure similar to that employed in the first year of the project to correct the QG model (see D'Andrea and Vautard 2000).

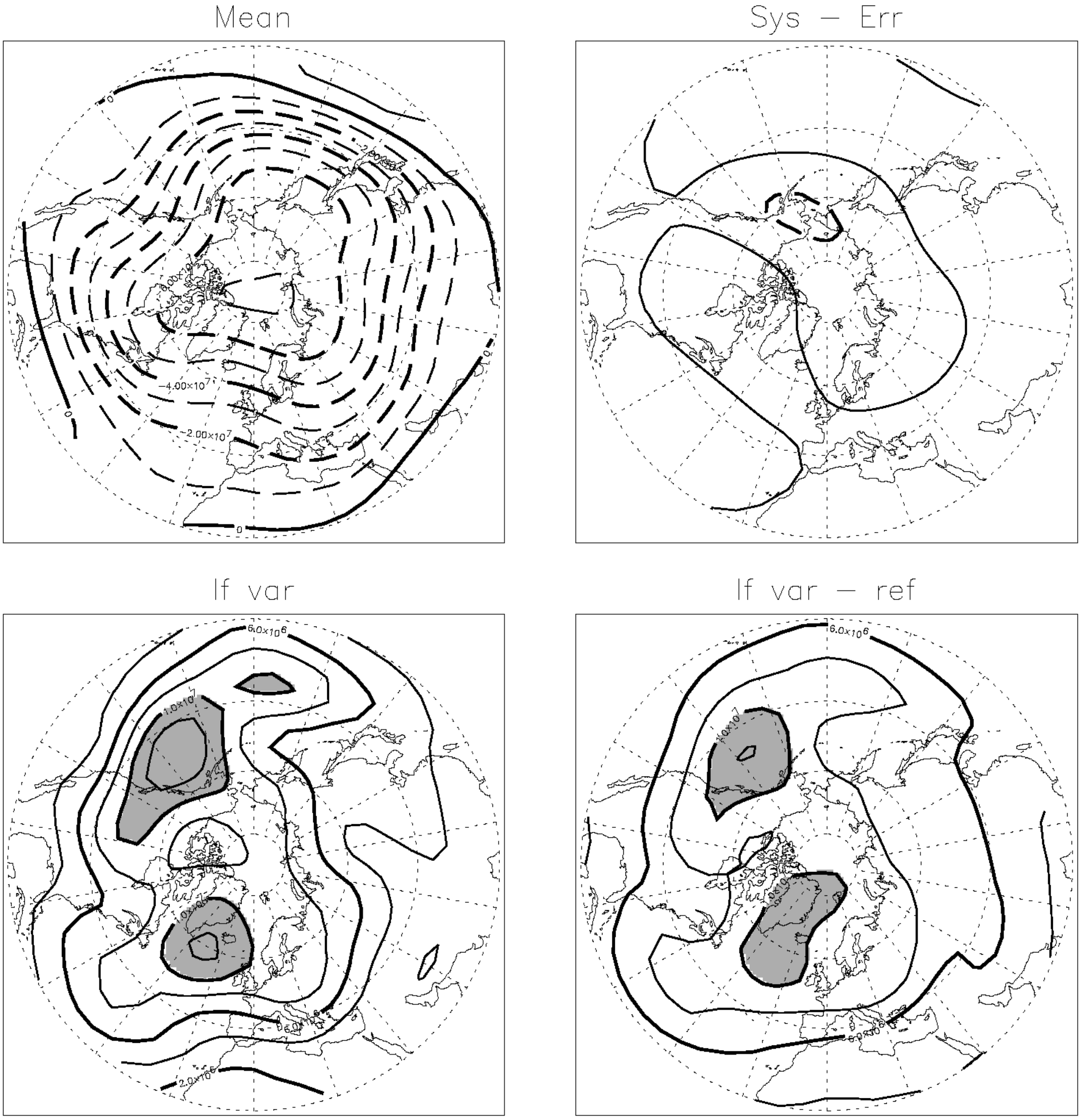

Fig. 1. Top-left: Mean streamfunction field at 500 hPa of the QG model truncated on the first 10 EOFs. Top-right, 500 hPa streamfunction systematic error of the reduced model with respect to the full reference model. Bottom-left low-frequency standard deviation of the EOF-truncated model. Bottom-right the same thing for the reference model. Contours: top-left panel every 10^7 m^2s^{-1}, other panels 2 10^6 m^2s^{-1}.

With such a correction, the reduced model has a mean state and low-frequency variance that is very similar to that of the reference one. This can be seen in Fig. 1, where basic 500 hPa climatology of the reduced model is shown. The maximum systematic error amplitude (top-right panel), transformed into geopotential height, would be of about 25 meters.

The features of low frequency variability such as weather regimes and intra-seasonal oscillation are also extremely well reproduced (not shown). This proves that (i) the dynamics of the low frequency variability is low dimensional, and (ii) that trailing scales, neglected by the EOF filtering can be parameterised in terms of the resolved scales. The scale interaction that is parameterised is mainly the feedback of baroclinic transient eddies on the large scale flow. The time dependent parameterisation of the tendency error in terms of the flow has proven to be essential, with respect to a time mean and a stochastical one, to obtain such results.

Having a reduced model of the low frequency variability of the atmosphere is not only a theoretical achievement. It is also a tool for analysing the dynamical nature of the phenomena of the low-frequency, taking advantage from the fact that all other dynamics is by definition filtered out.

Two main results were obtained; first, the relation between global equilibrium states and weather regimes was analysed. Global equilibrium states, i.e. states were the phase-space speed of the reduced model is minimum, were sought for. Three states were found, and are shown in Fig. 2. One bears the signature of a strong positive arctic oscillation, and two show opposite phases of PNA and NAO. Hemispheric weather regimes, considered as statistically recurrent states, are not trivially explaiable as these large scale equilibria of the circulation. In the reduced model, the quasi-equilibrium states were only in partial correspondence with the weather regimes. There is nevertheless an indication that better correspondence should be found by comparing regional regimes and regional equilibrium states.

Second, a dynamical explanation was found for an intraseasonal Branstator-Kushnir-like oscillation. An large-scale, regressive oscillation with a period of around 40 days was found on the full reference QG model by Plaut and Vautard (1994) in the Euro-Atlantic sector. The reduced model gives an explanation of this oscillation as an oscillatory linear instability (with very similar periodicity and phase pattern) of two global equilibrium states. It can be shown that this instability creates an oscillation between the two phases of the NAO. This discovery (if confirmed in the real atmosphere) could be of great importance, as it shows the existence of a preferential path of transition between equilibrium states, and hence between weather regimes, constiituting a potential long term predictable component of the midlatitude circulation.

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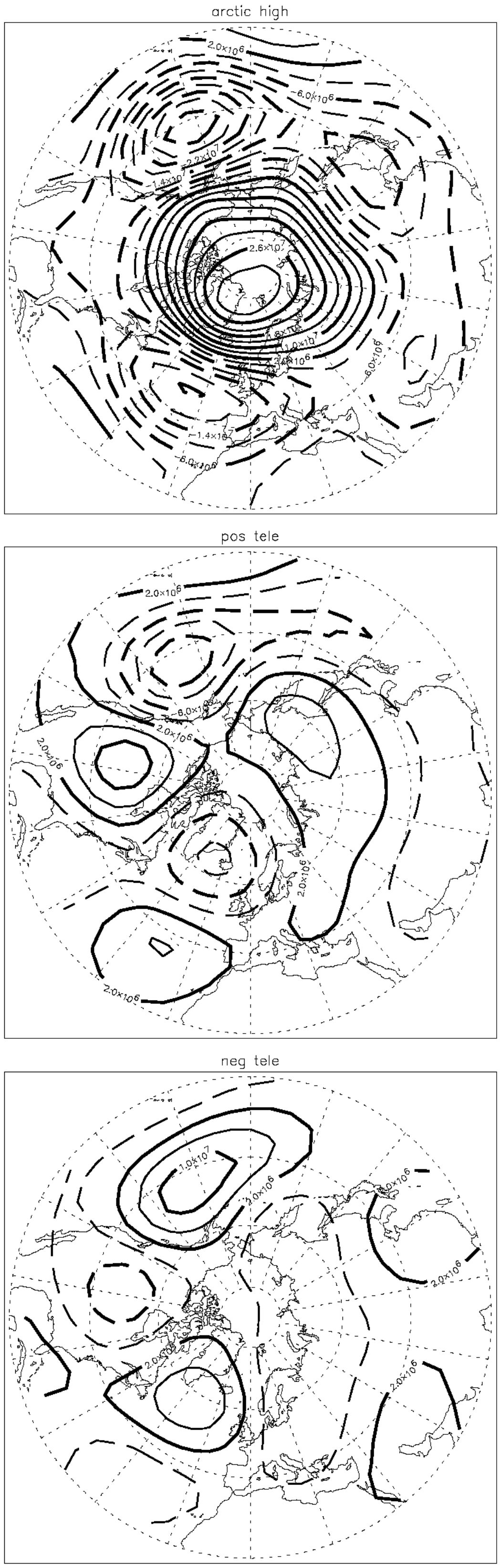

Fig. 2. Anomaly field of the 500 hPa part of the quasi-stationary states of the low-order model. Contours every 4 10^6 m^2s^{-1}, negative contours dashed. From top to bottom row: Arctic High, Positive Teleconnection and Negative Teleconnection state

POTENTIALS

Contract no. ENV4-CT97-0497

Consorzio interuniversitario per la gestione del centro di calcolo elettronico dell’Italia Nord-Orientale (CINECA).

Contribution to progress report for the second project year (1/1 1999-31/12 1999)

By Susanna Corti

1. Summary

During the second project year, CINECA’s contribution to POTENTIALS has been focussed on three main points:

- Applying the nudging technique to compute the residual tendency in a Primitive Equation (PE) model for both cold (January) and warm (July) periods and for selected years characterised by anomalous SSTs. (tasks 1a and 1d).
- Climate simulations (using the PE model) with constant flux correction identified from the nudging technique (task 4a).
- Experiments with constant flux correction during specific winters characterised by large and opposite SST anomalies (task 5c).

The first point is presented in Section 2, while Section 3 is devoted to the climate simulations in constant flux correction. In Section 4 results of the experiments with opposite SST anomalies are shown. Plans for future work are to be found in Section 5.

2. Tendency errors.

The data assimilation based on Newtonian relaxation (otherwise called “nudging”) has been used here to compute model tendencies with respect to the ECMWF reanalysis fields. Tendencies are extracted from a continuous model integration in which the model variables are nudged toward the (re)analysed values. Since observational data are not available for each model time step, to obtain data for every model time step, reanalysis fields have been linearly interpolated.

a. Model

The model is a primitive equation model with 5 vertical levels and a T30 spectral truncation with a dynamical core developed by I. Held at GFDL and simplified parameterisations of sub-grid-scale physical processes developed at CINECA by F. Molteni. Such parameterisations include: surface fluxes of momentum and energy, convection, large scale condensation, cloud cover, short wave radiation, long wave radiation and vertical diffusion (shallow convection). Furthermore during the first POTENTIALS year a radiation multi-band scheme (with two short-wave bands and four long-wave bands), a new refined diagnostic cloud scheme, a dependence of land-surface drag on topographic height, a revised scheme for the vertical diffusion of moisture, and the introduction of a (weak) drag on stratospheric mean-zonal have been introduced.

Two integrations of this model version (control), one in perpetual-January and one in perpetual July mode, have been performed using climatological SST and land-surface conditions computed from the ECMWF reanalysis (ERA).

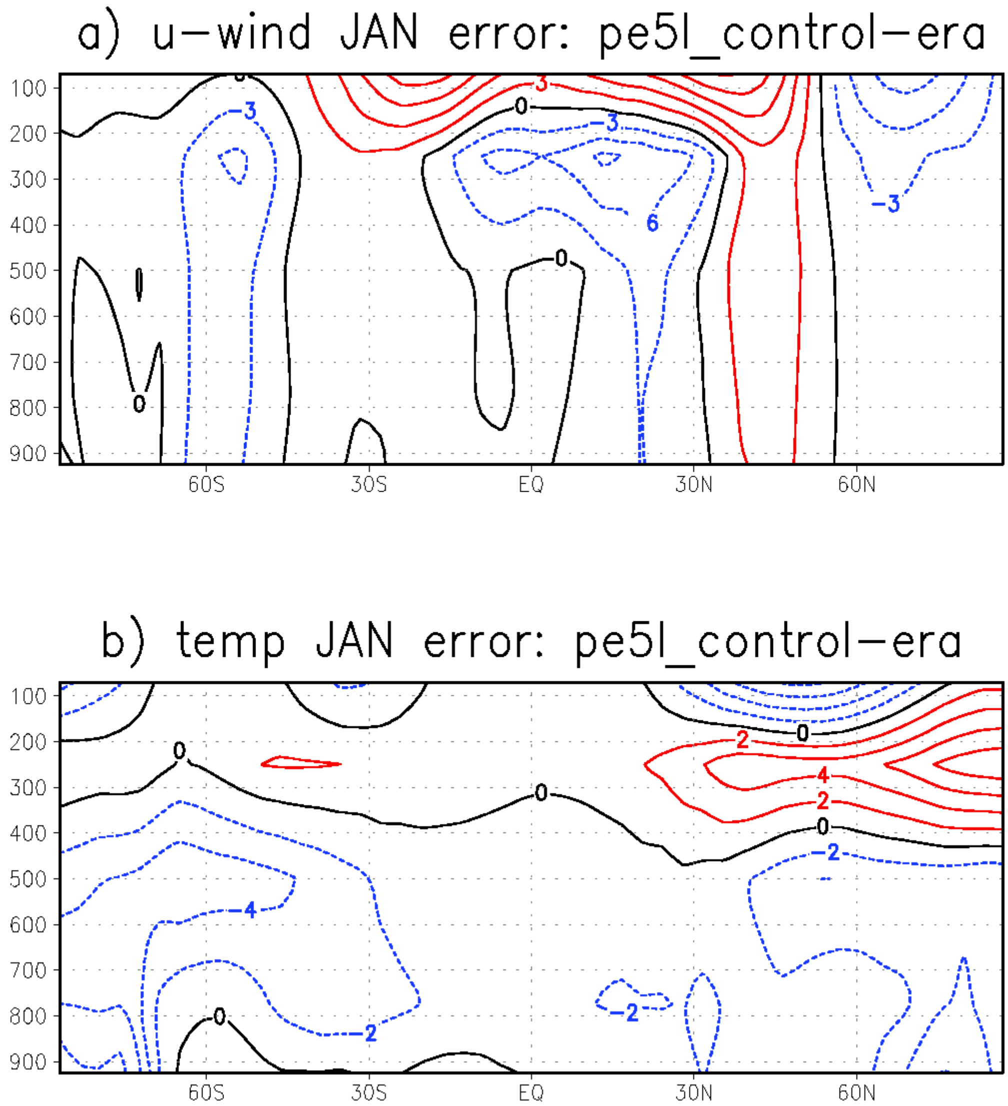

Fig. 1. Comparison between Latitude-pressure cross sections of temperature and zonal-wind for the perpetual January control run and the corresponding data from the ERA January climatology. (a) zonal-wind mean model error; (b) temperature mean model error. Contour interval 3 m/s in (a) and 2 C in (b).

Zonal mean cross sections of zonal-wind and temperature for the perpetual January control run are compared with corresponding data from the ERA January climatology in Figs. 1a and 1b respectively. The zonal-mean temperature error is of the order of 2 C in most of the model atmosphere, with larger errors limited at high latitudes of both hemispheres. For the zonal-mean wind, apart from a clear overestimation of stratospheric westerlies, easterly errors of moderate amplitude occur in the upper tropical troposphere and in the southern mid-latitudes.

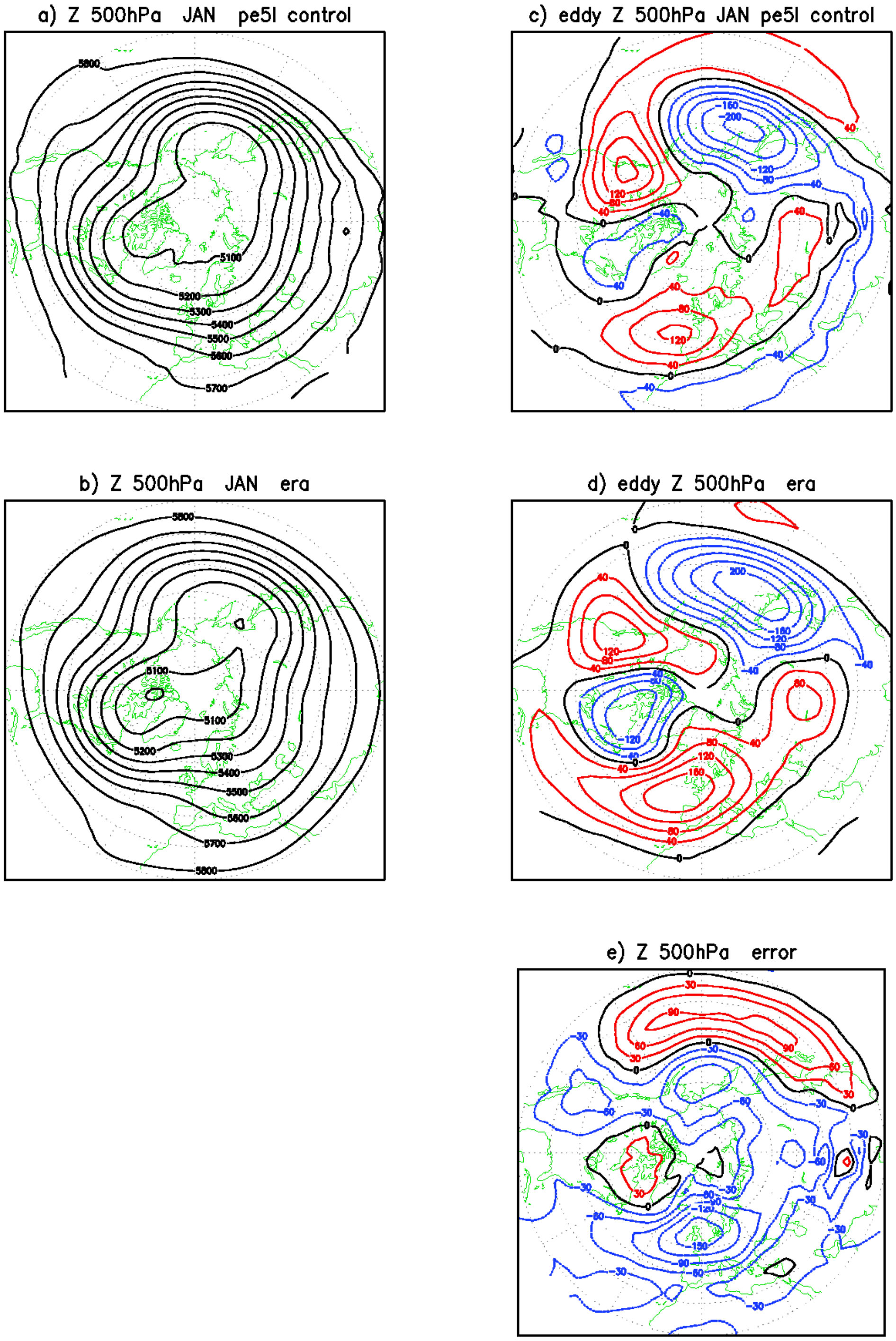

Fig. 2: Climatology of 500-hPa height from a perpetual January run of the 5-level model (a) and from ECMWF reanalysis (b); and mean model error (e). Contour interval 100 m in (a) and (b), 30m in (e) with red/blue corresponding to positive/negative values. c) and d) show the eddy component of the fields in a) and b), respectively, with a 40m contour interval.

The model January climatology of 500-hPa height, again compared with ERA, is displayed in Fig. 2, which shows both full fields and errors, and their eddy components. The 500-hPA northern extratropical mean flow has a level of realism comparable to that of much more sophisticated

GCMs, with systematic errors reaching a maximum amplitude of about 90m in the North Pacific region and 150m in the Euro-Atlantic region. The main feature of the model systematic error is the underestimation of the strength of the Euro-Atlantic quasi-stationary ridge, while the ridge over the West Coast of North America is well simulated.

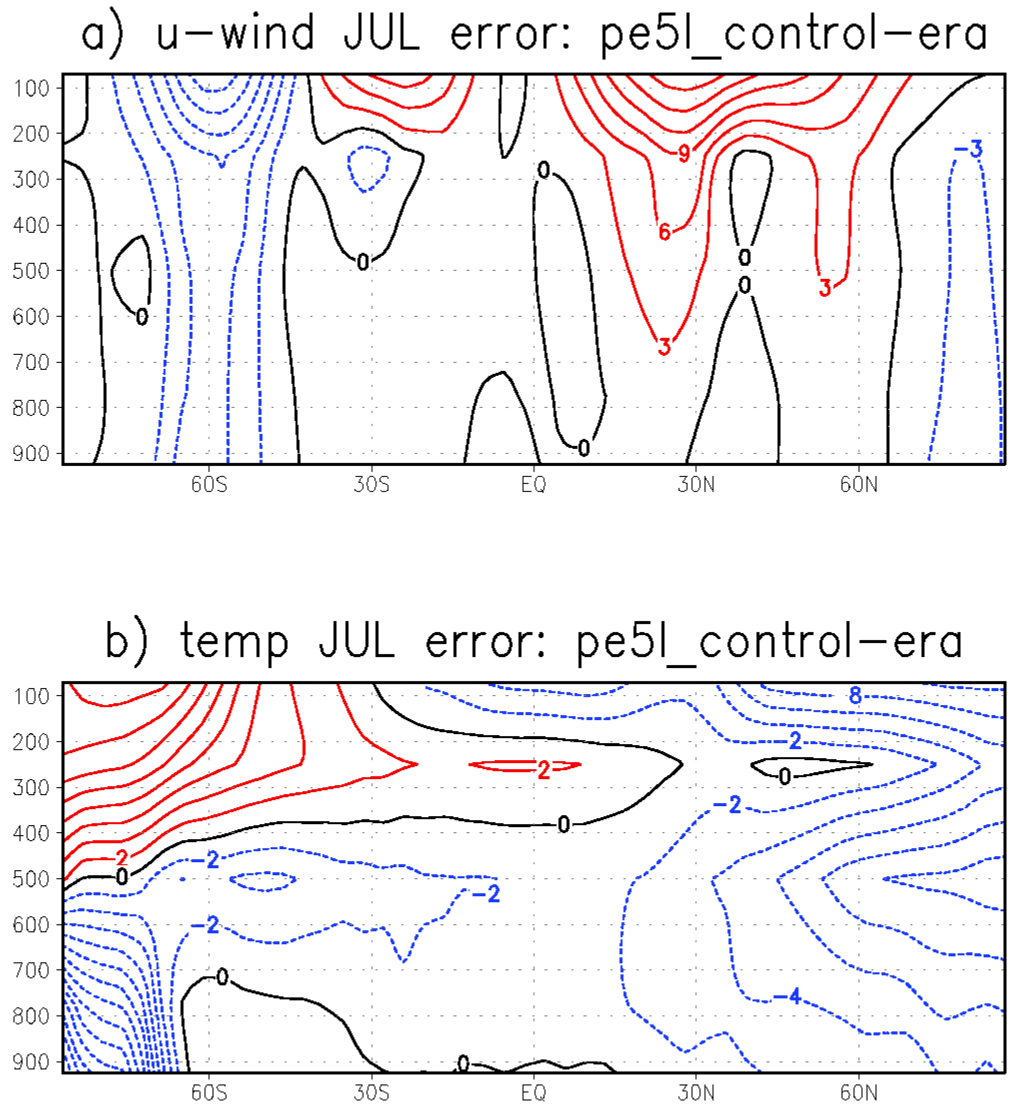

Fig. 3: Comparison between Latitude-pressure cross sections of temperature and zonal-wind for the perpetual July control run and the corresponding data from the ERA July climatology. (a) zonal-wind mean model error; (b) temperature mean model error. Contour interval 3 m/s in (a) and 2 C in (b).

Fig. 3 shows zonal mean cross-sections errors of temperature and zonal-wind for the perpetual July simulations. The temperature errors are larger than in winter, although most of the large differences occur in the stratosphere and over Antarctica. Consistent with this, the wind errors are largely confined to the stratosphere, and the model does a good job at representing the tilted vertical structure of the zonal wind profile in the summer hemisphere. The model simulation of the geopotential height climatology at 500 hPa (see Fig. 4) is much less satisfactory and it needs to be improved.

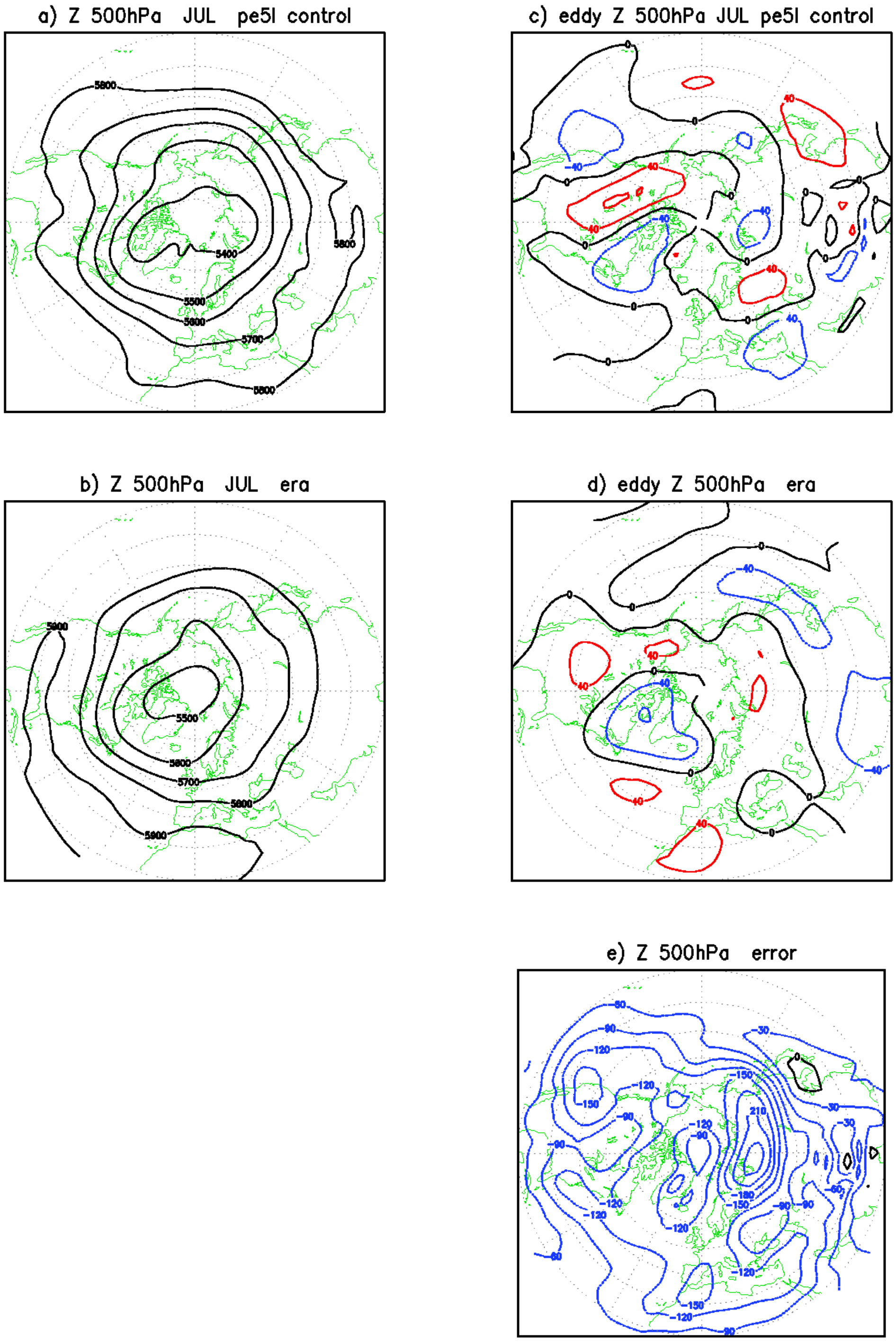

Fig. 4: Climatology of 500-hPa height from a perpetual July run of the 5-level model (a) and from ECMWF reanalysis (b); mean model error (c). Contour interval 100 m in (a) and (b), 30m in (c) with red/blue corresponding to positive/negative values. d), e), f) show the eddy component of the fields in a), b), and c) respectively, with a 40m contour interval.

b. Nudging

In the “nudging” procedure the model is forced towards the reanalysis data through a Newtonian relaxation term (Jeuken et al., 1996; Kaas et al. 1999):

$$X(t+\Delta t) = X^{*}(t+\Delta t) + 2\Delta t \frac{(X^{OBS}(t+\Delta t) - X(t+\Delta t))}{\tau} \qquad (1)$$

Here *X* represents any prognostic model variable, Δt is the length of the time step, the upper index * denotes the preliminary prognostic variable just before nudging, upper index OBS indicates the "observed" value the model is being relaxed towards, and τ is the relaxation time. The choice of τ was made in order to satisfy two requirements. Firstly τ cannot be too long, otherwise the observed fields will have little effect on the solution. On the other hand, τ must not be so short that the relaxation term dominates the model forcing. In this case, possible dynamical imbalances in the observations may be amplified. The appropriate compromise values for τ with respect to the model prognostic variables were found to be the following:

Zonal wind and meridional wind	τ= 6 hr.
Temperature	τ= 24 hr
Surface pressure	τ= ∞
Humidity	τ= ∞

c. Model tendency errors

The observed tendency vector of a prognostic variable *X* (observed state vector) can be formally split in two terms:

$$\left.\frac{\partial X}{\partial t}\right|_{OBS} = \left.\frac{\partial X}{\partial t}\right|_{MOD} + R \qquad (2)$$

where $\partial X/\partial t|_{MOD}$ is a tendency as it is modelled. The residual vector *R* is the difference between the two tendencies. The long term mean of *R* (<*R*>) is a measure of the systematic tendency or forcing error in a model.

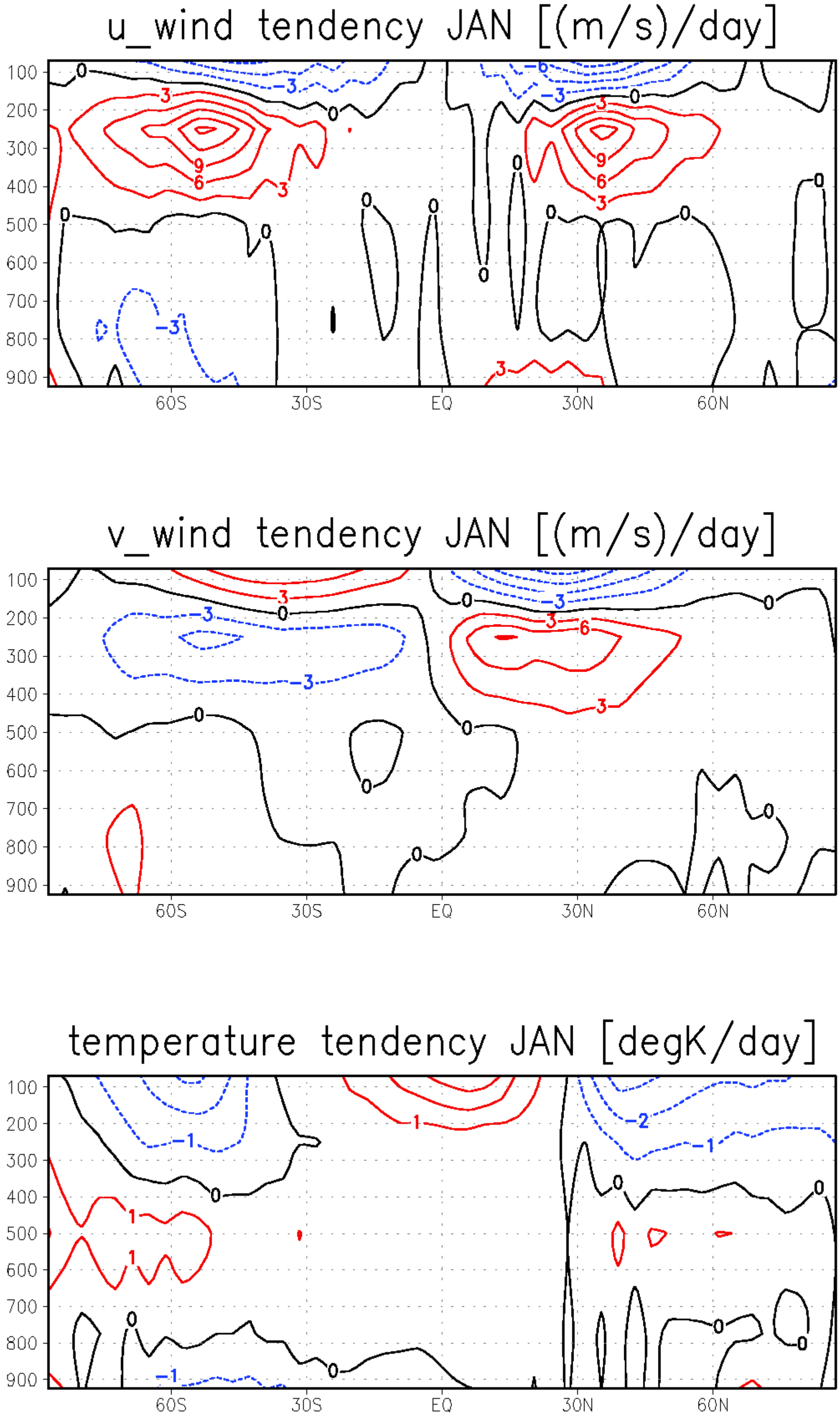

Fig. 5: Latitude-pressure cross section of the average model tendency errors in January for: (a) zonal wind; (b) meridional wind; (c) temperature. Contour interval 3 m/s in (a), 0.5 m/s in (b) and 1 C in (c).

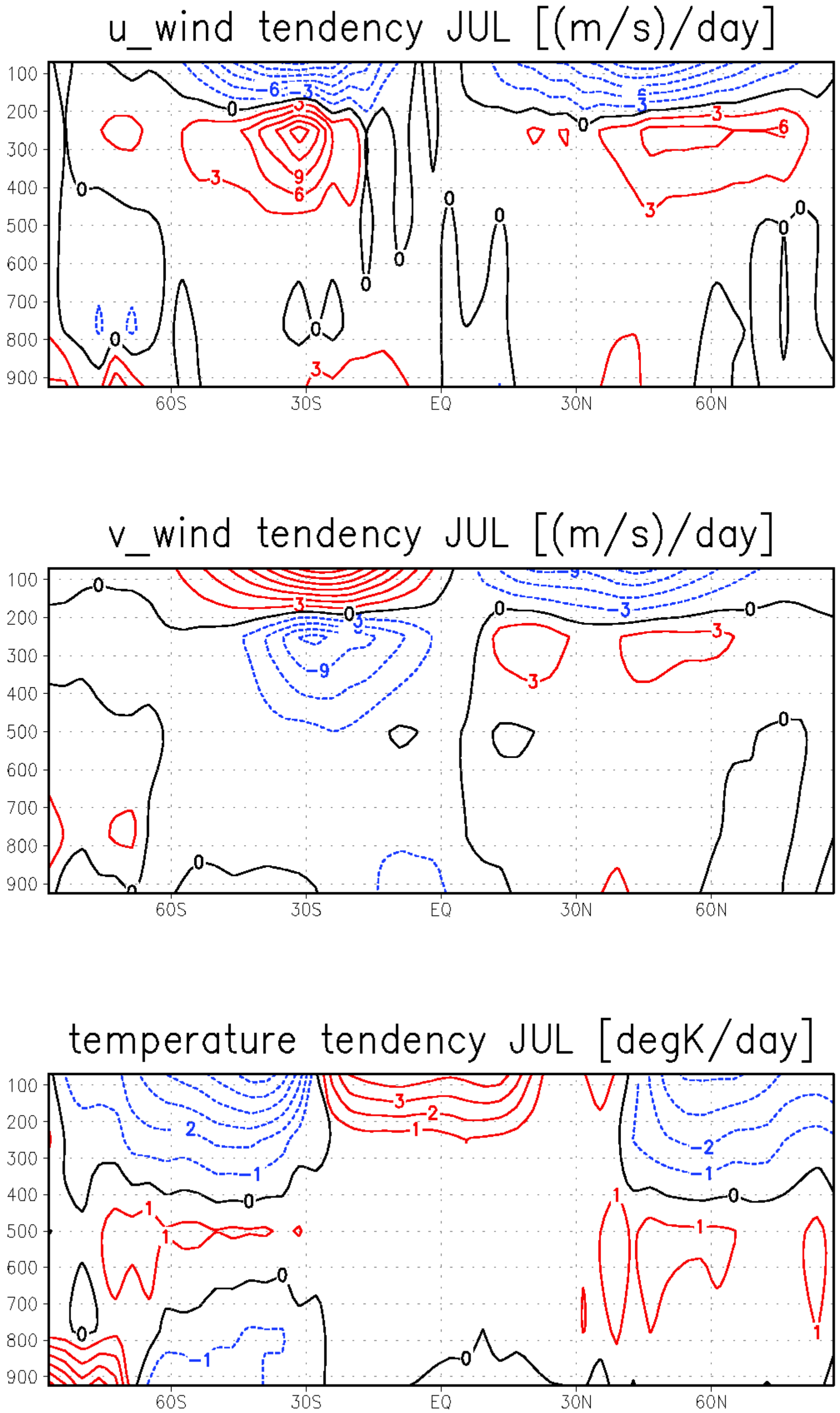

Fig.6: As Fig. 5 for July.

Figure 5 and 6 shows the average tendency (<*R*>) of the model “nudged” variables (e.g. wind and temperature) with respect to the ECMWF reanalysis fields (1979-1993) of January and July respectively. Tendency fields have been displayed as zonal mean cross section in order to allow a quick comparison with the systematic error fields in Figs.1and 3. In principle the forcing error can be quite different from the systematic error. In fact *R* describes where the model is wrong and can be geographically far from the location of the model systematic errors, which can be defined rather as “symptomatic” errors. The lack of correspondence between forcing and systematic errors can be seen for example in the January zonal wind pattern (Figs. 5a and 1a): the easterly systematic error which occur in the upper tropical troposphere doesn’t have a tendency error counterpart. Another example is given by the temperature error fields in July where the systematic cooling over the Northern Hemisphere seems to be caused by an excessive average warm tendency in the extratropics high troposphere and stratosphere.

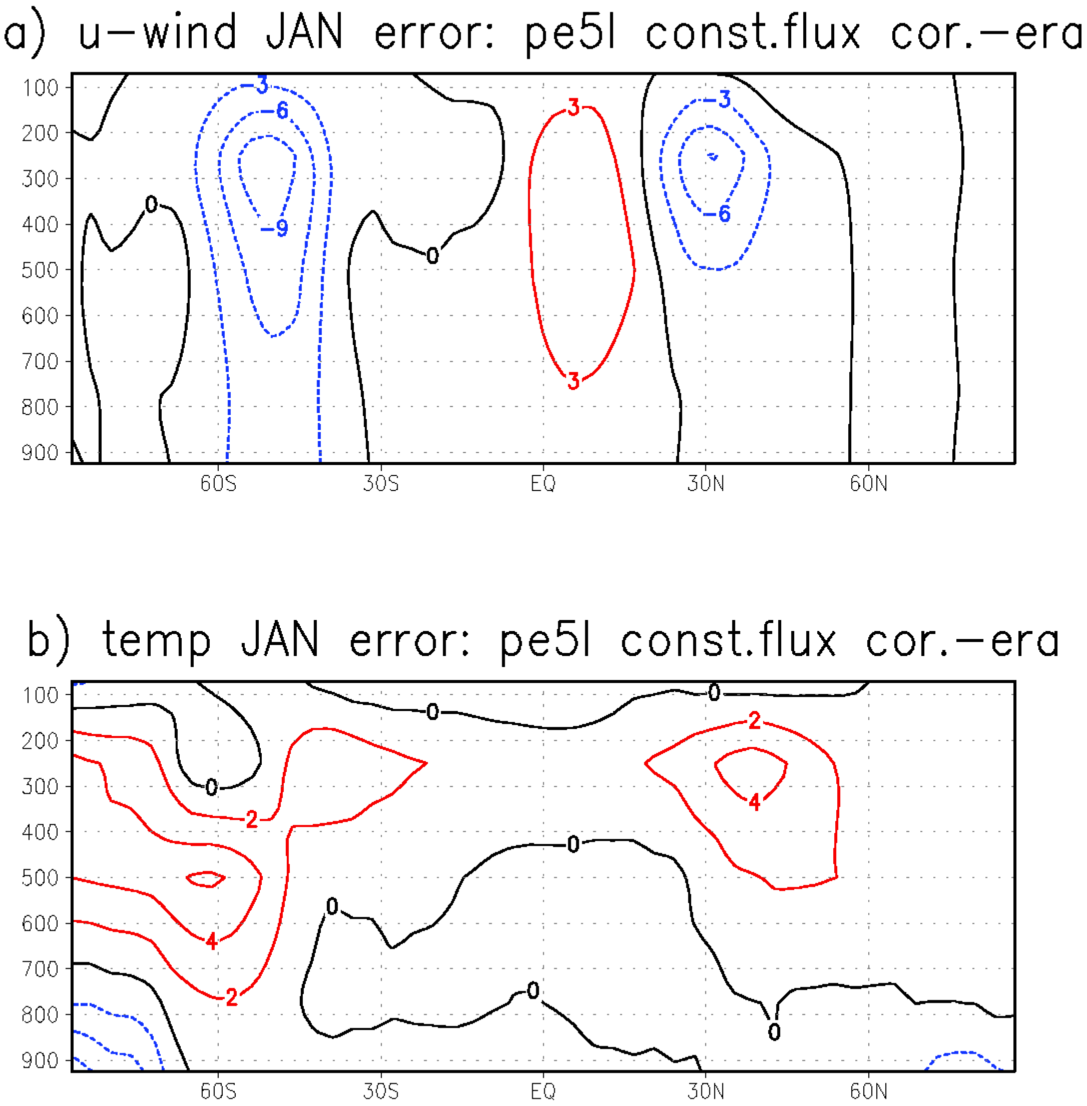

Fig.7 As Fig. 1 but for the climatological constant flux correction integration. Same contour interval.

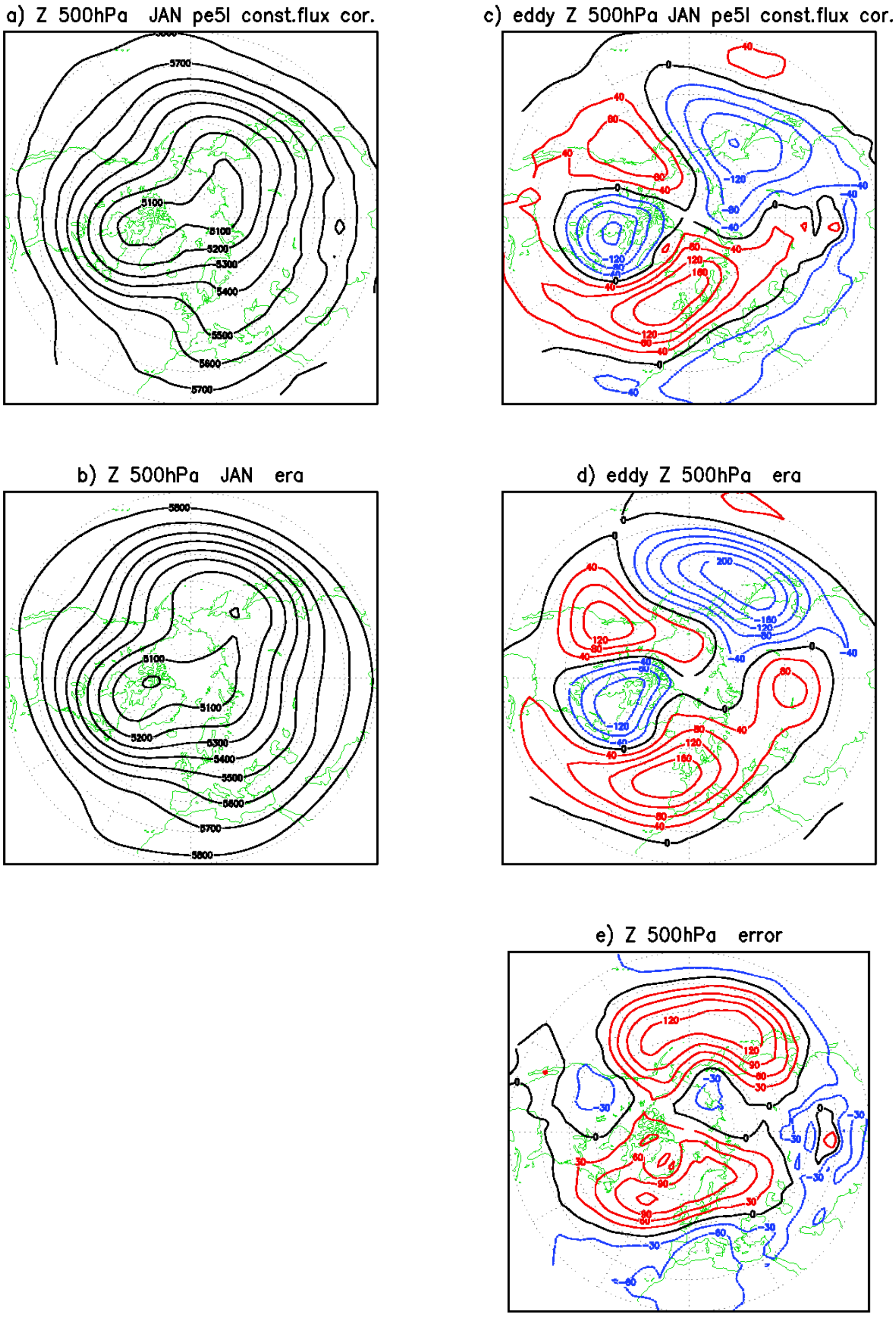

Fig.8 As Fig. 2 but for the climatological constant flux correction integration. Same contour interval.

3 Simulations in constant flux correction.

In this section we present two experiments in which the model errors have been used as correction terms in the model equations. The hope was to construct a mostly dynamical but also somehow statistical model that should have smaller systematic errors than the "original" (i.e. purely dynamical) one. The simplest way of parameterising tendency errors was suggested by Roads (1987). He suggested to use the long-term mean of *R* for a given season as a constant correction forcing. Since this method has been tested by the author in a quasi-geostrophic model with good results (Corti et al. 1997; Corti and Palmer 1997; Molteni and Corti 1998), it was decided to try the same technique to improve the primitive equation model performances.

Figures 7 and 8, which should be compared to the companion figures 1 and 2 corresponding to the control integration, show the model systematic error in January from a 120-month perpetual winter integration in constant flux correction (i.e. adding to the model equations the empirical constant forcing shown in Fig. 5). Results are acceptable, but not so good as one could expect. As far as the zonal wind concerns, the overestimation of stratospheric westerlies has been corrected, but now we have a larger error in the southern midlatitudes. The temperature error field is characterised by a modest warming in most of the model atmosphere, with larger errors limited at the Southern Hemisphere. The simulation of the 500-hPA northern extratropical mean flow (Fig. 8) has been improved over the Euro-Atlantic sector (where the control presents the largest systematic error), but now the strength of the stationary ridge over the West Coast of North America is underestimated.

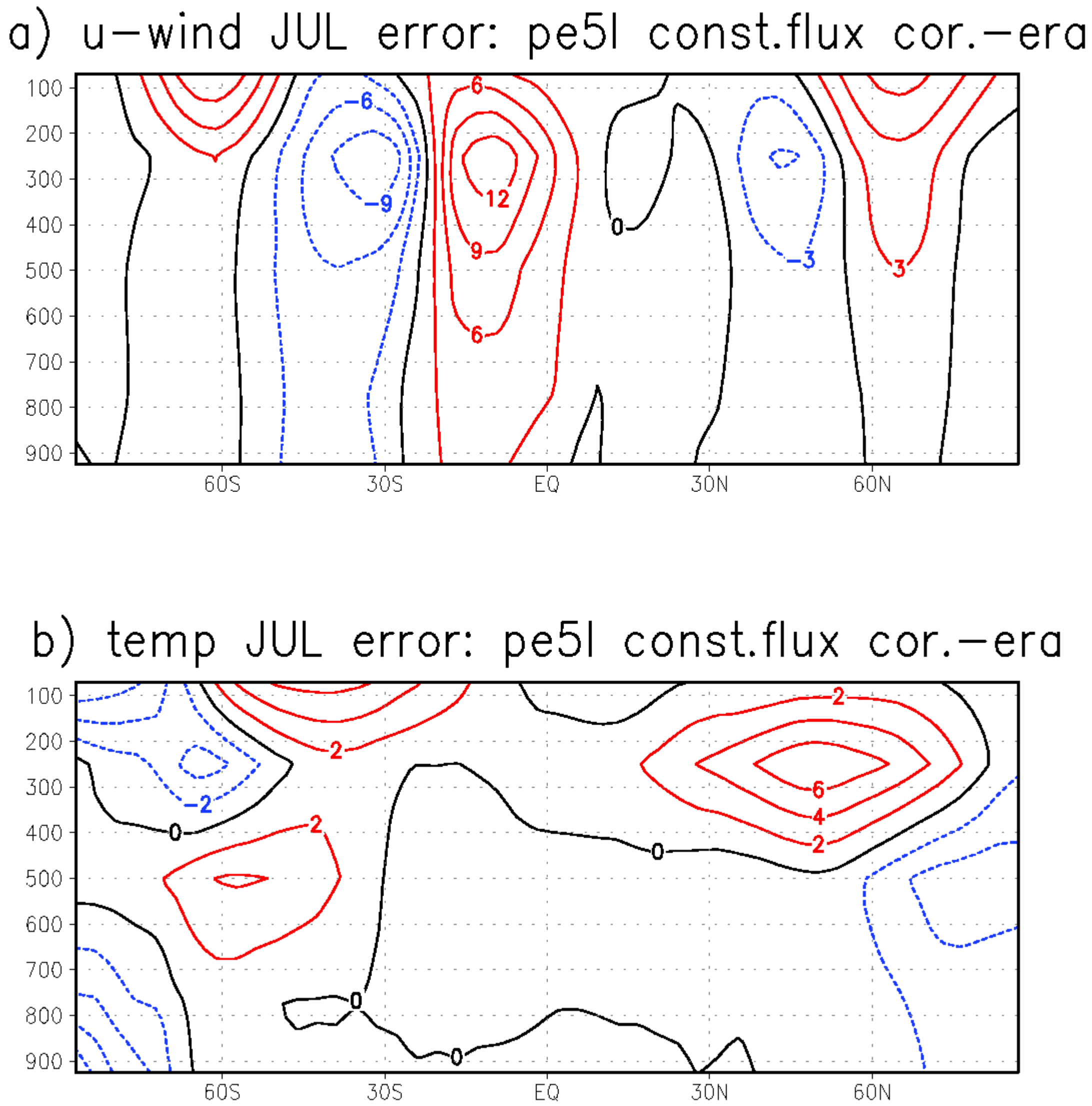

Fig.9 As Fig. 3 but for the climatological constant flux correction integration. Same contour interval.

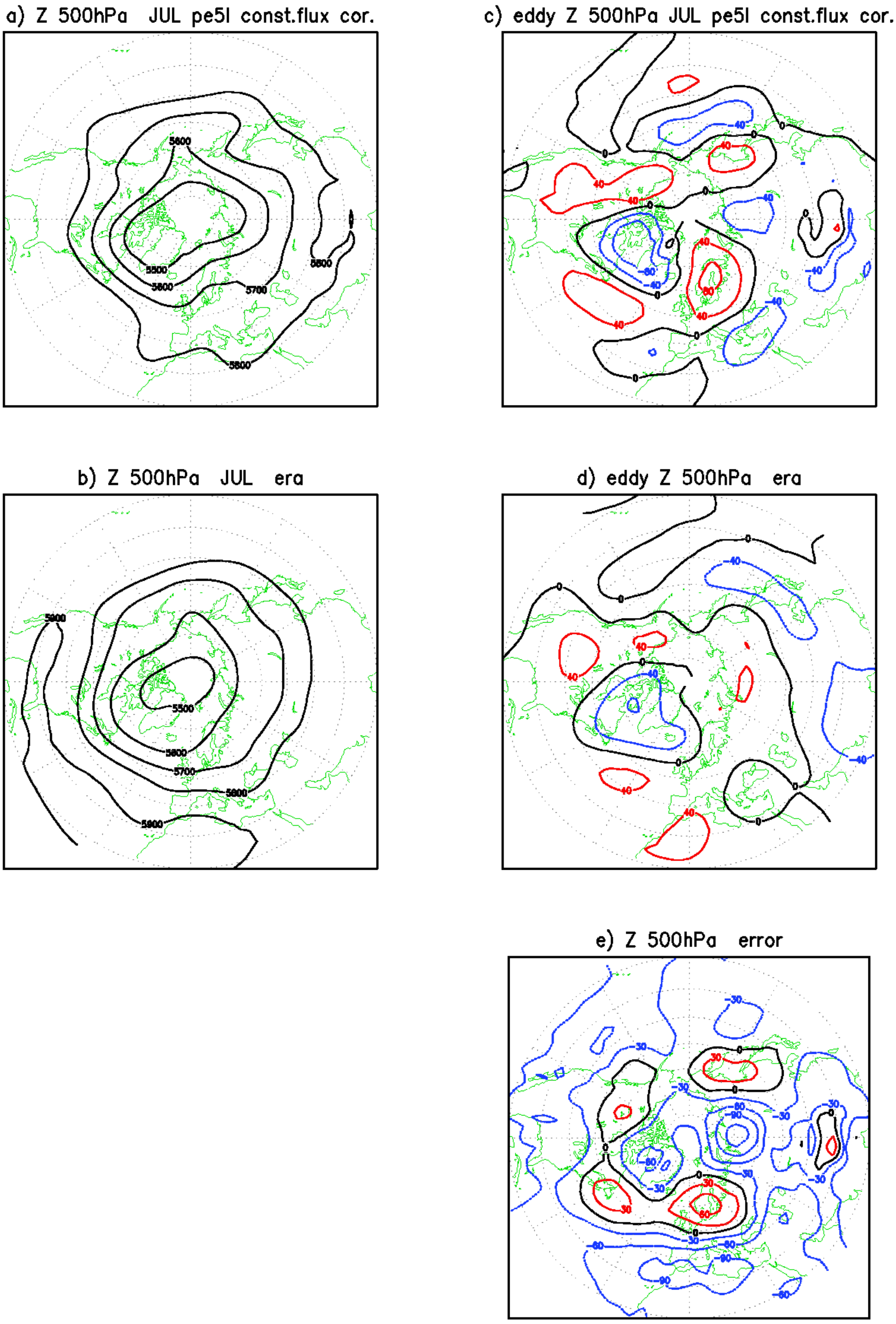

Fig.10 As Fig. 4 but for the climatological constant flux correction integration. Same contour interval.

Results, in terms of systematic errors, of the corresponding July integration (with the empirical forcing shown in Fig.6) are shown in Figs. 9 (zonal wind and temperature) and 10 (geopotential height). The wind errors in the stratosphere, which occurred in the control integration, have been partially corrected, but now the error is enhanced in the Southern Hemisphere upper troposphere. Temperature error is low (compared to the control integration) almost everywhere apart from the warm bubble, which presents a maximum of 6 C, in the northern midlatitudes upper troposphere. The model July climatology at 500 hPa is shown in Fig. 10. Compared to the control, results of the constant flux correction simulation are quite good, with systematic errors reaching a maximum amplitude of about 120m over Siberia (against the 230m of the control integration).

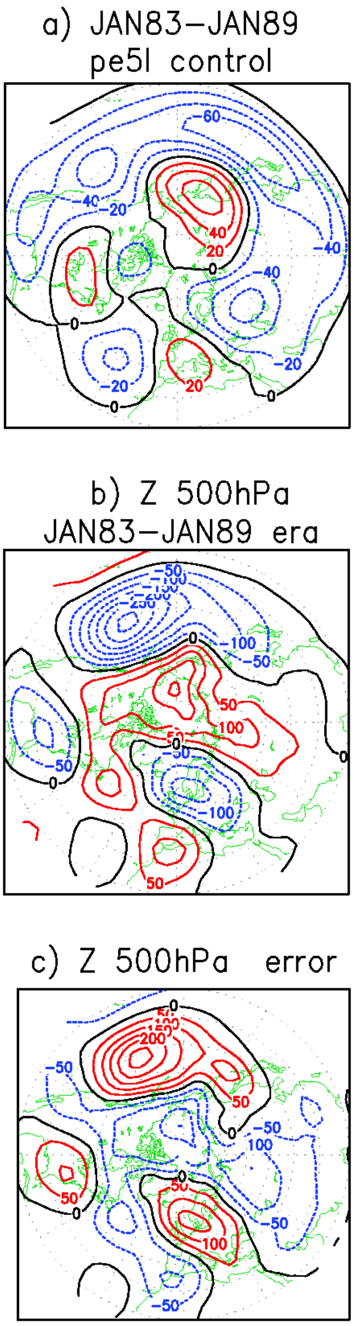

Fig.11 500 hPa geopotential height difference between January 1983 and January 1989. (a) Perpetual January control integrations of the 5-level model, difference between 1983 and 1989; (b) ERA 1983-1989; (c) error. Contour interval 20m in (a), 50m in (b) and (c).

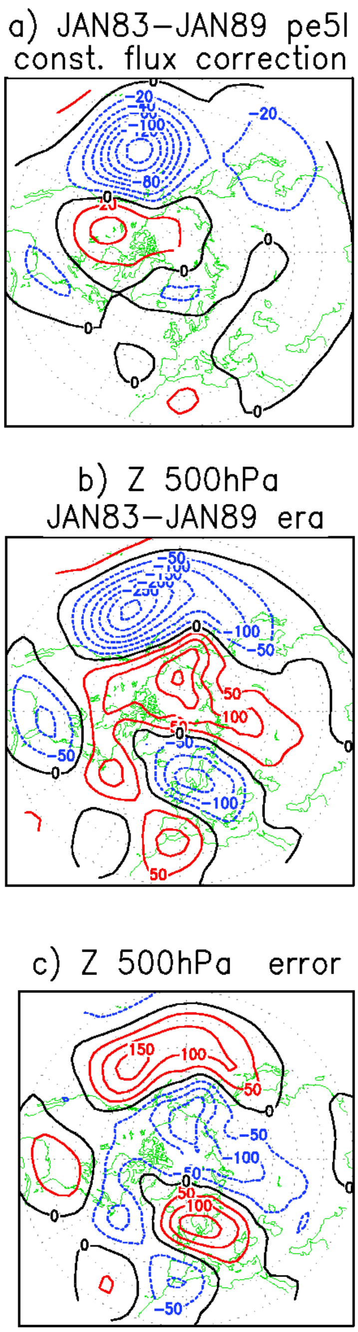

Fig.12 As in Fig.11 but for the 83/89 simulations in constant flux correction.

4. Experiments with opposite SST anomalies.

Results of several experiments (see for example Peng et al. 1995) seem to indicate that even slightly different climatic flow can lead to very different responses to SST anomalies. Thus it is very important to have small systematic errors (as small as possible) in order to obtain a realistic response to lower boundary forcing like SST anomalies.

In the light of this findings (and of the encouraging results described in Section 3 where the empirical correction gives rise to some improvement in the model systematic error), two pairs of experiments with large and opposite SST anomalies have been carried out. The first pair consists in two control perpetual January integrations with the sea surface temperatures of January 1983 [warm ENSO] and January 1989 [cold ENSO]. These simulations have been compared to companion integrations performed in constant flux correction (i.e. with the empirical forcing shown in Fig.5).

The difference between control simulations (83-89), reanalysis and the systematic error are shown in terms of geopotential height at 500 hPa in Fig.11. The same fields, but for the pair of integrations in constant flux correction, are displayed in Fig. 12. It can be seen that the empirically corrected model performances are very good when compared to the control integrations. The PNA-like structure which characterises the American-Pacific sector has been captured by the empirically corrected model (Fig.12a) (even though the amplitude of the negative anomalies over Pacific is weaker of about 150m), while the control exhibit a very modest (60m) Pacific negative centre. As far as the Euro-Atlantic sector is concerned there is no improvement

5. Plans for future work

Future development of this study (next six months) will follow two lines of investigation:

1. improve the nudging technique applied (trying to nudge the surface pressure as well) in order to reduce the systematic error in the constant flux correction integrations.
2. use tendency errors information to improve the physical parameterisations (task 2e) and perform a very long integration for investigation of ultra low frequency variability. (task 3d)

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