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

(Contract no. ENV4-CT97-0497)

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Synthesis

Synthesis of the project

Overview

The overall objectives of POTENTIALS are to develop and use methods to identify and minimise 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. The techniques are nudging, a variational method and slow normal mode 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 which are present 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.

The main activities and results obtained in the project can be summarised as this:

- A substantial amount of work has been devoted to optimisation of the nudging assimilation. The main emphasis has been on identification of optimal relaxation time constants and on possible iterative (multiple) assimilation, i.e. a successive reduction of the tendency errors.
- The coding and testing of slow normal mode insertion (SNMI) has been finished. As mentioned above this improved methodology for estimation of tendency errors was given considerably more attention than originally planned. The SNMI described briefly below is a new method developed as part of POTENTIALS which should circumvent some of the problems associated with standard nudging.
- A new variational assimilation technique has been developed for the QG model. This technique identifies the optimal 12 hour average forcing residual which will bring the model from one observed state to the next (12 hours later).

- 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 been 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
- The tendency errors obtained via nudging have been used to guide and verify improvements of the physical parameterisation in ARPEGE and ECHAM. For both models two different parameterisation packages have been compared and a special analysis of the parameterisation of horizontal diffusion has proven the need for “negative” diffusion to correctly simulate the impact of non-linear interactions with unresolved scales.
- 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.

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 work carried out in each task is described.

<u>Task 1 (Identification of tendency errors):</u>

Three methods for identifying tendency errors have been studied within the project : the nudging technique, a variational estimation and the slow normal mode insertion (SNMI) method, developed during the project.

The nudging technique has been the basic technique for obtaining tendency errors and it was necessary to spend quite some time analysing the method. The principle behind the method is to relax the model under consideration towards a reference data set. Newtonian relaxation is used and the relaxation term is the estimate of the tendency error. Theoretical considerations show that this estimate is reasonable provided that the time constant used in the relaxation is chosen properly. It is questionable if the nudging technique can be used for obtaining instantaneous model tendency errors, whereas the method is well suited for determining time averages (on the time scale of a month to a season) of tendency errors.

Besides the theoretical considerations experimental studies of the ability of the nudging technique to obtain tendency errors have been performed. One of these experiments is a twin experiment, where the model is run for a given period and the model state is saved every six hours and used as the reference data set. Then the model is nudged towards the reference data set and the tendency errors obtained in this experiment will show the noise level of the method. The reason for storing the model state every six hours is that the observed data used later for obtaining the ‘real’ model

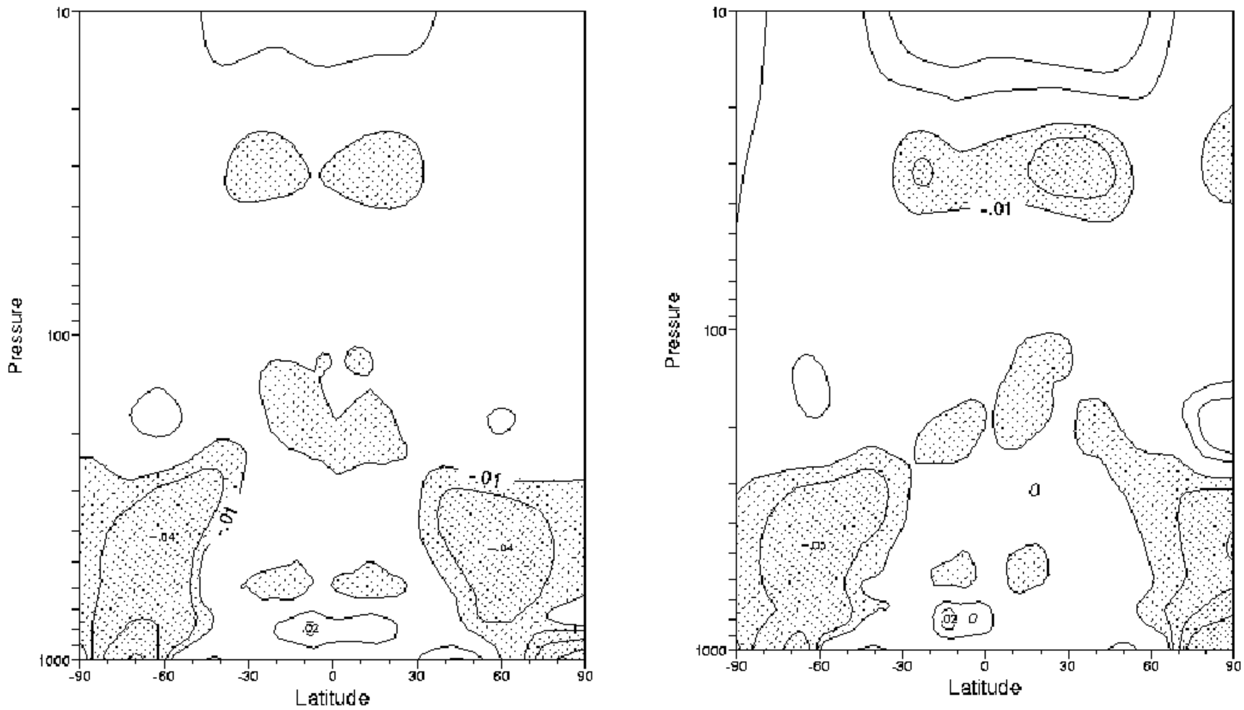

Fig. 1: Mean winter (left) and summer (right) temperature tendency in the “twin nudging” experiment. Contours: ±.01, ±.02, .and ±05 K/day; shading below -.01K/day

tendency errors are available with this time frequency. An interpolation of the 6-hourly data sets to a frequency equal to the time step used in the model is needed. Fig. 1 shows seasonal means of the zonal mean temperature tendency errors obtained in such a twin experiment with ARPEGE, version 3. The tendency errors in the twin experiment are indeed very small compared to the model tendency errors obtained using observed data as reference data.

Another way of testing the method is reconstruction of well known forcing errors, and 3 experiments along this line have been performed. The idea is to make a run with the standard version of the model and store the model state every 6 hours during the run. Then some modification (like turning off a parameterization scheme) is done to the model and the model is nudged towards the output from the standard run. The relaxation term is then an estimate of the known forcing error caused by the modification of the model. In one of the experiments the gravity wave drag (GWD) parameterization is turned off. This parameterization is acting only on the wind field. The forcing error in the wind field due to the missing gravity wave drag parameterization determined by nudging has a pattern quite similar to the true GWD forcing, but it is a little weaker. This is seen in fig. 2, where panel (a) shows the zonal mean of the zonal wind component of the true GWD forcing, and panel (b) shows the estimate of the zonal mean of the zonal wind component of the GWD forcing obtained by nudging. It turns out that when using the nudging technique a forcing error in the temperature field is also obtained, but the true GWD forcing is not acting on the temperature field. This means that, because the model is free to make some adjustments during the nudging assimilation, the forcing error is distributed into both the wind and the mass field.

Similarly, two other experiments were made in which the known forcing error would only appear in the temperature field : in one of the experiments was the radiation scheme turned of and in the other was the solar constant reduced. The conclusion from these two experiments was the same as for the GWD experiment : the pattern of the forcing error in the temperature field is well estimated, but the field is too weak. In these two experiments forcing errors in the wind field were not expected, but indeed some contribution was seen in the wind field. Generally speaking, using the nudging

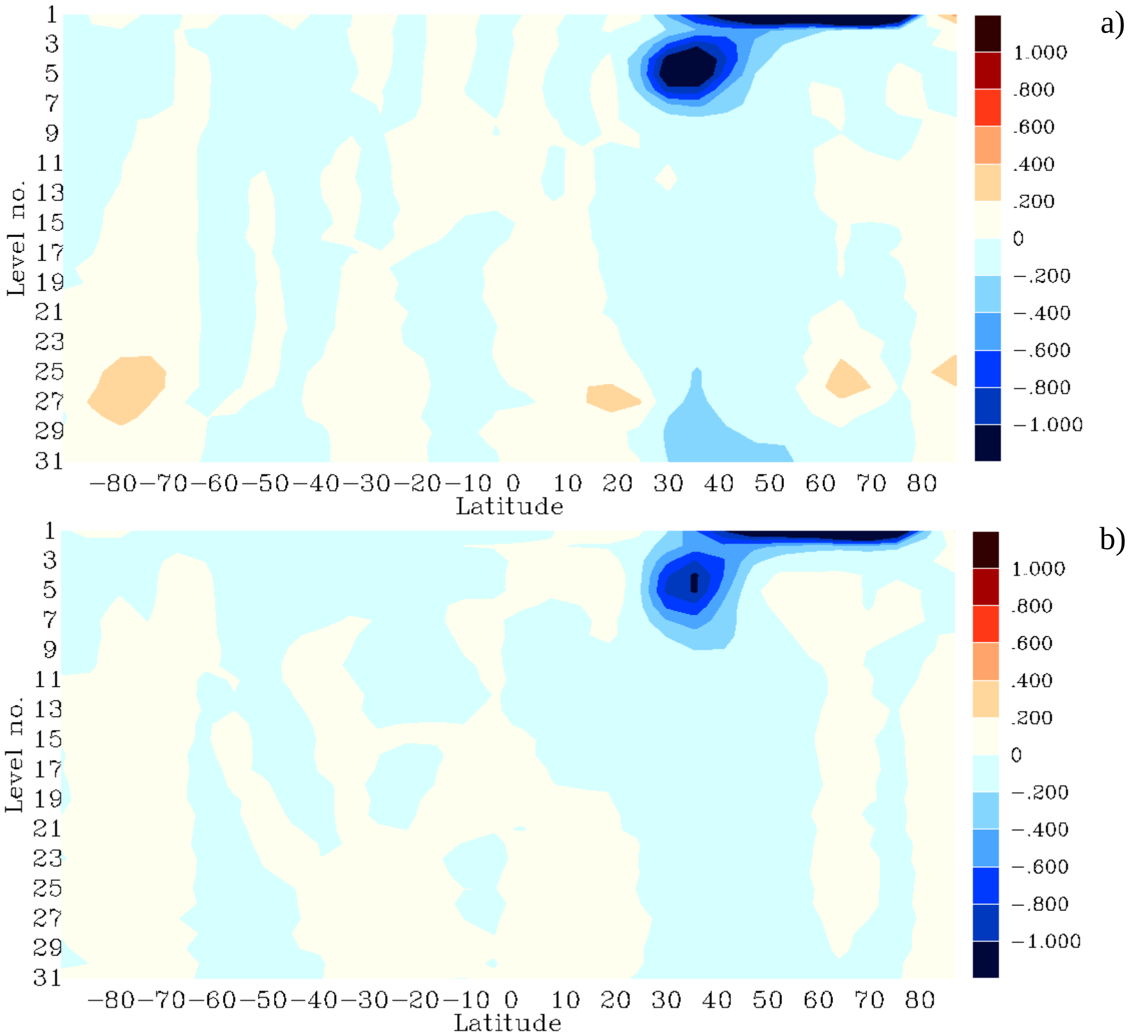

Fig. 2. Upper panel (a) shows the temporal average zonal mean GWD tendency contribution to zonal wind for a given month simulated with ARPEGE. Lower panel (b) shows the tendency contribution estimated via the nudging technique by assimilating data from the relevant month into a model version without gravity wave drag. Units: m/sec/day.

technique the known forcing errors were reasonably well estimated, but when interpreting the forcing errors it is important to be aware of the fact, that the forcing errors are distributed in both the mass and the wind field.

In order to determine the forcing errors of the models used in the project, the ECMWF reanalysis data (ERA) covering the period from 1979 to 1993 have been used as the reference data set. This data set has been assimilated using the nudging technique by the two atmospheric general circulation models ARPEGE, version 2 (resolution T42L31) and ARPEGE, version 3 (resolution T63L31) and by the primitive equation (PE) model used at CINECA (resolution T30L5). In this way global space/time maps of the tendency errors have been obtained and used for improvement of the three models.

At LMD, where a quasi geostrophic (QG) model (resolution T21L3) has been studied, tendency errors have been obtained by a variational method. The method gives very good results in estimating the tendency errors, and although the method is numerically expensive, it is recommended to study its application to the more complex GCMs.

When using the nudging technique humidity is not assimilated in order to avoid moisture spin-up problems, and also a rather weak nudging of the divergence field is necessary due to problems with gravity noise. Another more theoretical based way of solving these problems were developed within the project by the MPI participants. This new method is called slow normal mode insertion - SNMI. The main idea is to replace the slow modes of the model with the slow modes of the ERA data. In practical use of the method where the ERA data are only present every 6 hours the full insertion of the slow modes of the ERA data is only done at these times where the ERA data exist. At the time steps in between the slow normal modes of the model are relaxed towards the time interpolated slow normal modes of the reanalysis data with a weight decreasing to zero midway between the reanalysis times. The fast modes of the assimilating model develop freely and so do the soil variables and all prognostic variables of the hydrological cycle. Thereby, imbalances which project on the fast modes can not result in large spurious tendency errors as would be the case if also the fast modes were assimilated. As in a free run unbalanced fast modes are forced by nonlinear interactions and parameterized physical processes. This sets up fast oscillations which, however, are damped due to dissipation and the Asselin time filtering included in the time extrapolation scheme of the model. This damping works selectively, damping small scales and fast modes the most. After dying out of the oscillations the fast modes will be balanced. In this balance the field of vertical velocity will be consistent with the hydrological fields, which also develops freely, and a reason for a precipitation spin-up problem as observed in the ERA analyses is eliminated. The SNMI method has been tested on the ECHAM model and was compared with the nudging assimilation technique, which is not separating slow and fast modes. The superiority of the SNMI method has been demonstrated by validations of results from identical twin experiments as well as from long parallel ECMWF reanalysis (ERA) data assimilation experiments. Figure 3 shows the zonal average of the tendency error for temperature obtained by SNMI (top figure) and by nudging (bottom figure) of eight years of ERA data. In SNMI only imbalances projecting on the fast gravity modes are heavily damped, whereas using nudging tendency errors projecting on all gravity waves are damped heavily and even Rossby modes are damped moderately. Therefore stronger and supposedly more correct tendency errors are obtained by SNMI as compared to nudging.

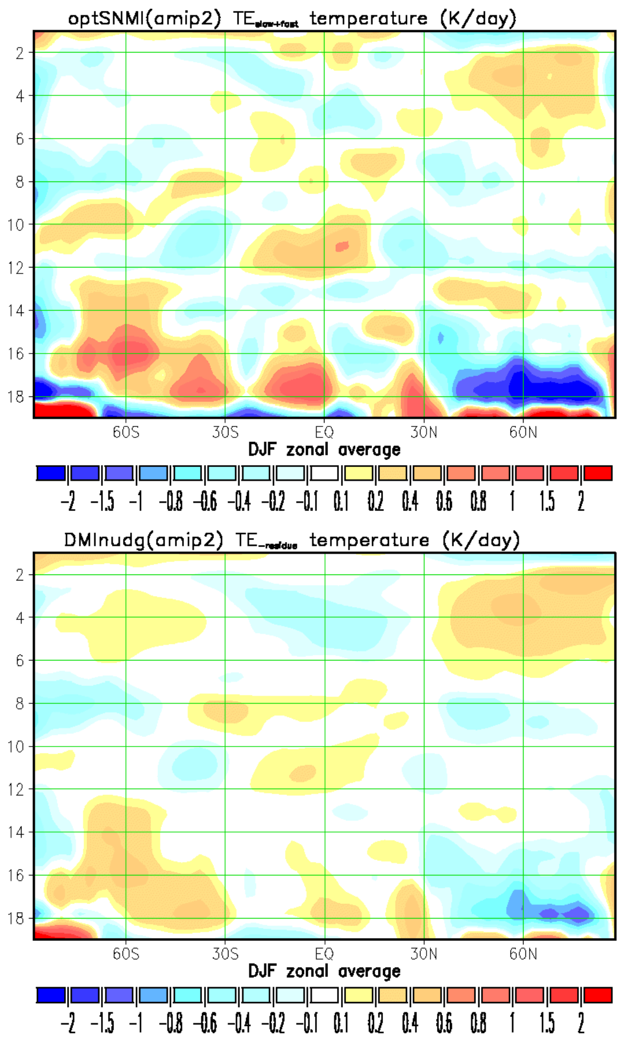

Fig. 3. Zonally averaged ECHAM4.5 systematic initial tendency errors (SITEs) for temperature based on eight years 81982-1989) of ERA assimilations using the optSNMI technique (upper cross section), and DMI nudging technique (lower cross section).

Task 2 (Objective tuning of physical parameterization):

The purpose of this task is to use the information about the tendency errors obtained in task 1 as guideline for improving the physical parameterizations in the models.

Partly within a previous EU-project (MILLENNIA, contract no. ENV4-CT95-0101) and partly within POTENTIALS a method for minimising the tendency errors was used to improve the description of horizontal diffusion in Eulerian versions of ARPEGE and ECHAM. The main result was that negative diffusive damping is needed for intermediate wave numbers in order to more correctly account for non-linear interactions with unresolved scales.

In the ECHAM model it was found that negative temperature tendency errors dominate the lower troposphere along the ice margin in the Atlantic sector of the arctic basin. This fact led to the conclusion that in agreement with newer observations the sea ice is too thick in the ECHAM model. At the lowest model level (see fig. 4c) the maximum excessive cooling is over the Greenland and Barents Seas. The excessive cooling will tend to create a thermal high pressure bias, a tendency which in fact is seen in. fig. 4d showing surface pressure systematic initial tendency errors. Taking into account a dominating eastward advection in a long free ECHAM simulation this is consistent with the position over the Kara Sea of a centre of systematically too high pressure (see fig. 4b). It was speculated that too large sea ice coverage and/or too thick sea ice in the model, in particular in the Greenland and Barents Seas, cause too little heating from the underlying ocean. Among the

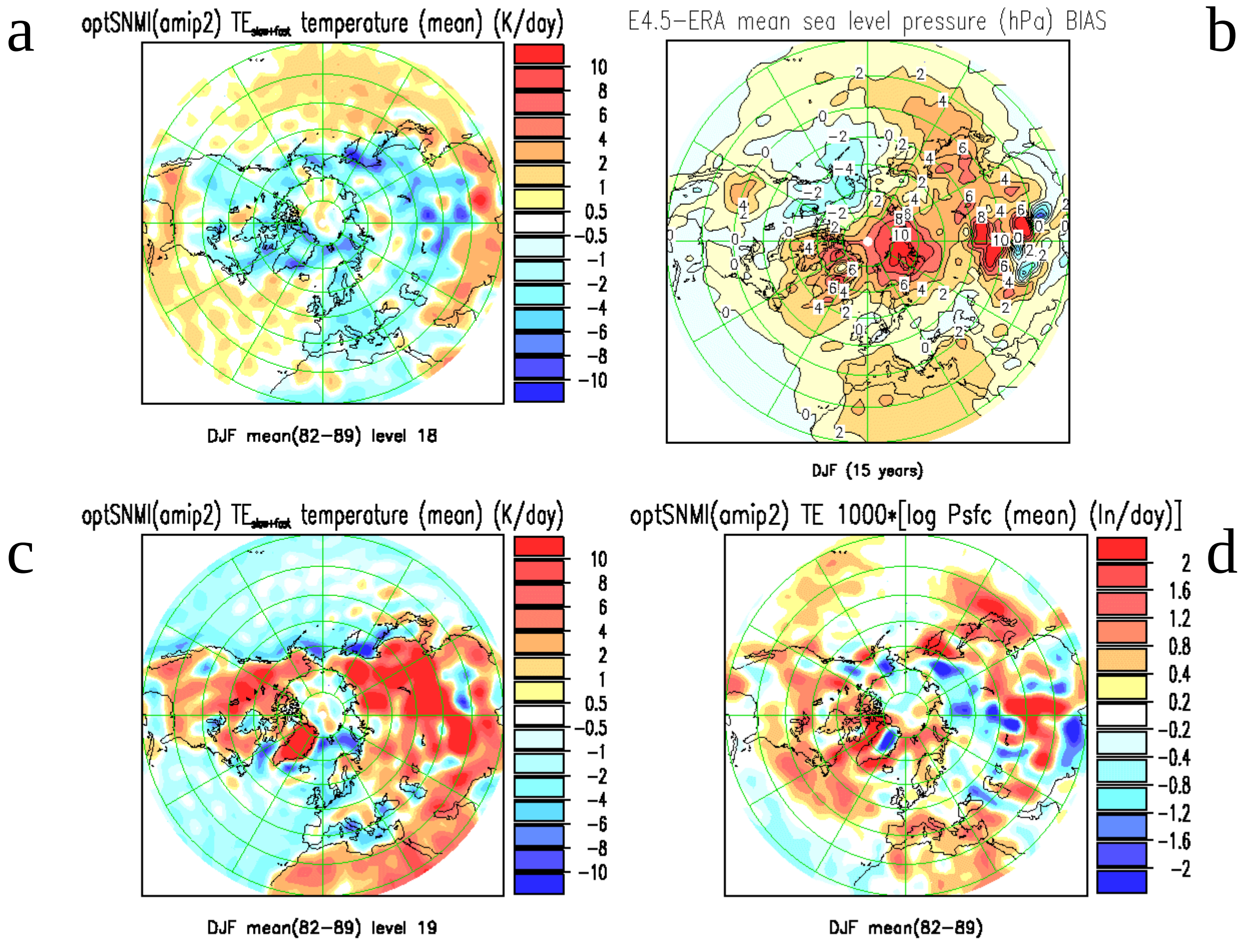

Fig. 4. Winter season SITEs based on eight years of optSNMI assimilation (a, c and d) and MSLP systematic errors based on 15 years of an ECHAM4.5 AMIP-2 simulation (b).

different processes influencing the temperature vertical diffusion is found to correlate the best (negatively) with the temperature tendency errors at the lowest levels, a fact which further supports this theory. To test this interpretation MPI started some AMIP runs in which more realistic thinner sea ice with less coverage is prescribed.

In the PE model used at CINECA the study of tendency errors inspired to several changes in tuning parameters in the physical parameterization schemes.

At CNRM the tendency errors estimated by the nudging technique have been used to judge whether a change in the dynamics or a change in the physics gave rise to improvements. An Eulerian advection scheme was compared to a semi-Lagrangian scheme, and the tendency errors were smallest for the semi-Lagrangian scheme. Two versions of a vertical diffusion scheme was tested. Version one used a constant boundary layer depth in the vertical profile of mixing length, whereas the other version had a depth varying with time and space. The tendency errors were almost identical except at the surface, where the incorrect warming in the polar regions (due to a too deep boundary layer) had disappeared in the version with variable depth. A change in the closure of the convection scheme resulted in a less realistic climate, and indeed the tendency errors were considerably larger.

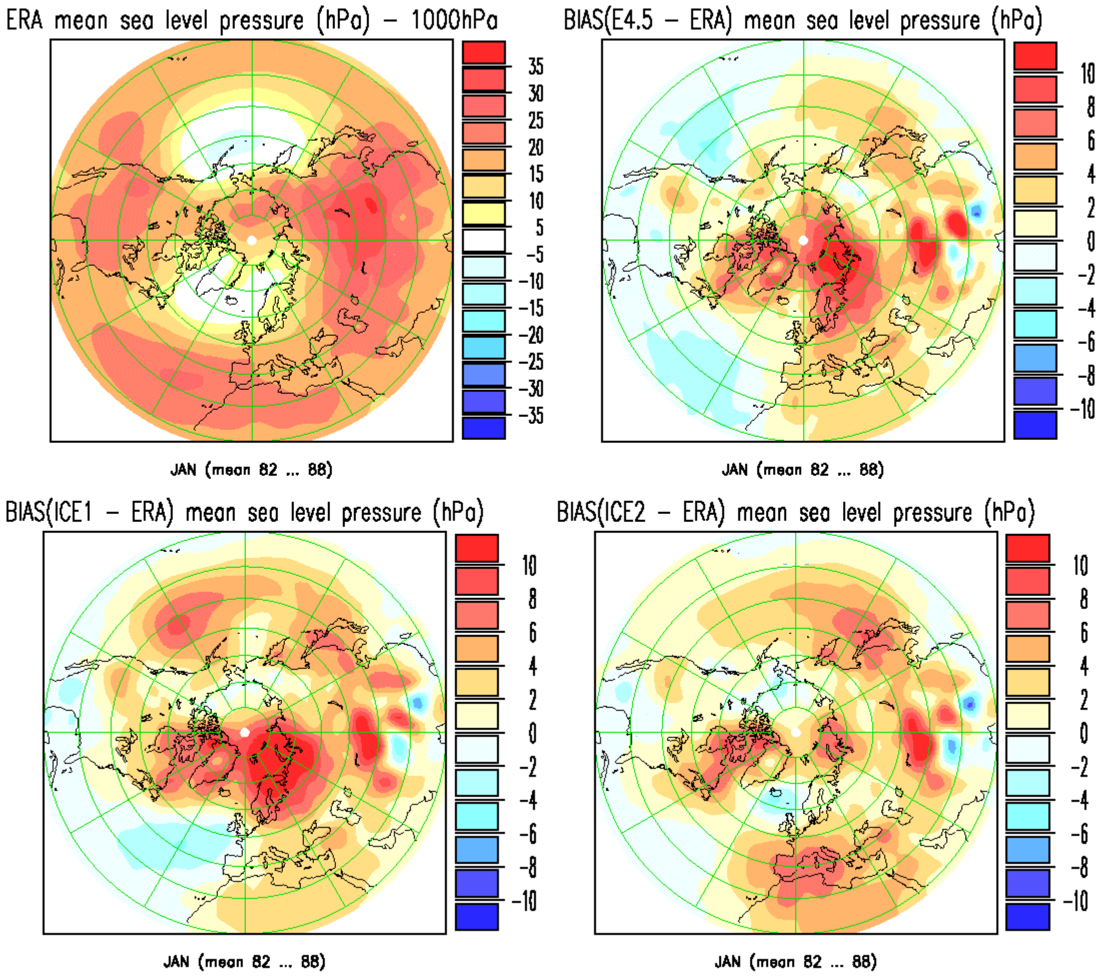

Fig. 5. Seven year mean ERA January MSLP distribution over the Arctic (upper left map), and corresponding systematic MSLP error patterns for the AMIP simulation (upper right map), for the ICE1 simulation (lower left map), and for the ICE2 simulation (lower right map).

Task 3 (Long runs with improved physical parameterisation):

The idea within this task is to study if the improvement of the physical parametrization schemes obtained in task 2 leads to an improvement in the description of the climate, when long runs are made with the improved versions of the models.

The modification of the horizontal diffusion in the ARPEGE and ECHAM models turns out to give a better estimation of the kinetic energy spectrum, and the low resolution versions (T21 and T30) of the models behave more similar to a high resolution (T106) version of the models.

As mentioned above MPI has started some AMIP runs in which more realistic thinner sea ice with less coverage is prescribed. A preliminary analysis of these runs shows that in particular a more realistic thinner ice reduces the systematically too high pressure north of Europe (compare upper right and lower right maps in fig 5). But at the same time occurred unexpectedly a band of low pressure across Europe and a too high pressure over the African coast. These experiments showed that it is not enough to change tendency errors just at one place on the Earth – remote effects have to be taken into account. Tendency errors must be reduced everywhere in order to benefit at a certain place from the effects of all remote tendency error reductions. For this purpose an iterative tendency error detection procedure is suggested.

With the PE model 100-year perpetual January experiments have been made with the control version and with the improved version of the model. Reduction of the systematic errors is seen in many areas for the fields wind, temperature and 500 hPa geopotential height and a satisfactory simulation of the low frequency variability was also achieved.

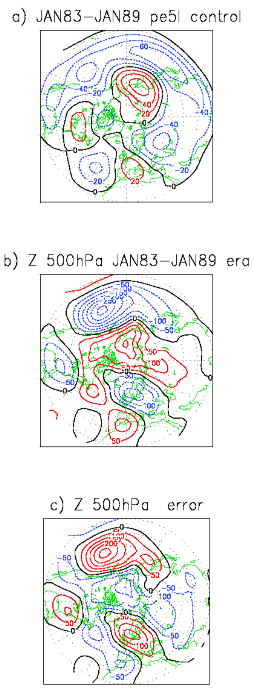

Fig. 6(left). 500 hPa geopotential height difference between January 1983 and January 1989. (a) Perpetual January control integrations of the 5-level model, difference between 1983 and 1989; (b) ERA 1983-1989; (c) error. Contour interval 20m in (a), 50m in (b) and (c).

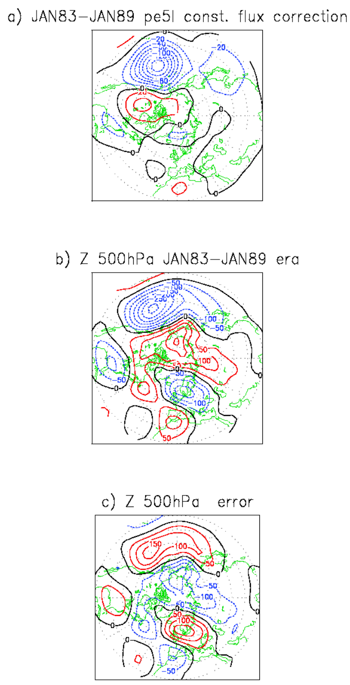

Fig.6(right) As in Fig.4(left) but for the 83/89 simulations in constant flux correction.

Task 4 (Flux corrected long term simulations):

The intention in this task is to use the tendency errors determined in task 1 for empirical correction of the models studied. The simplest way to correct the model is to use temporal means of the tendency errors as constant correction terms in the model equations. In the two versions of ARPEGE and in the PE model it has been tried to flux correct the model using monthly means of tendency errors. The correction terms were obtained by assimilating (using nudging) the ECMWF reanalysis data for the whole period covered by these data - 1979-1993. The monthly means were determined as averages over the 15 years covered by the ERA data.

With the PE model two kind of experiments (in perpetual) mode were performed. In one of these experiments climatological SSTs were used as boundary conditions, whereas in the other kind of experiment SSTs from years with large anomalies were applied as boundary conditions. One experiment with SSTs from January 1983 (warm ENSO) and one with SSTs from 1989 (cold ENSO) were made. In the experiment with climatological SSTs the flux corrected model behaves

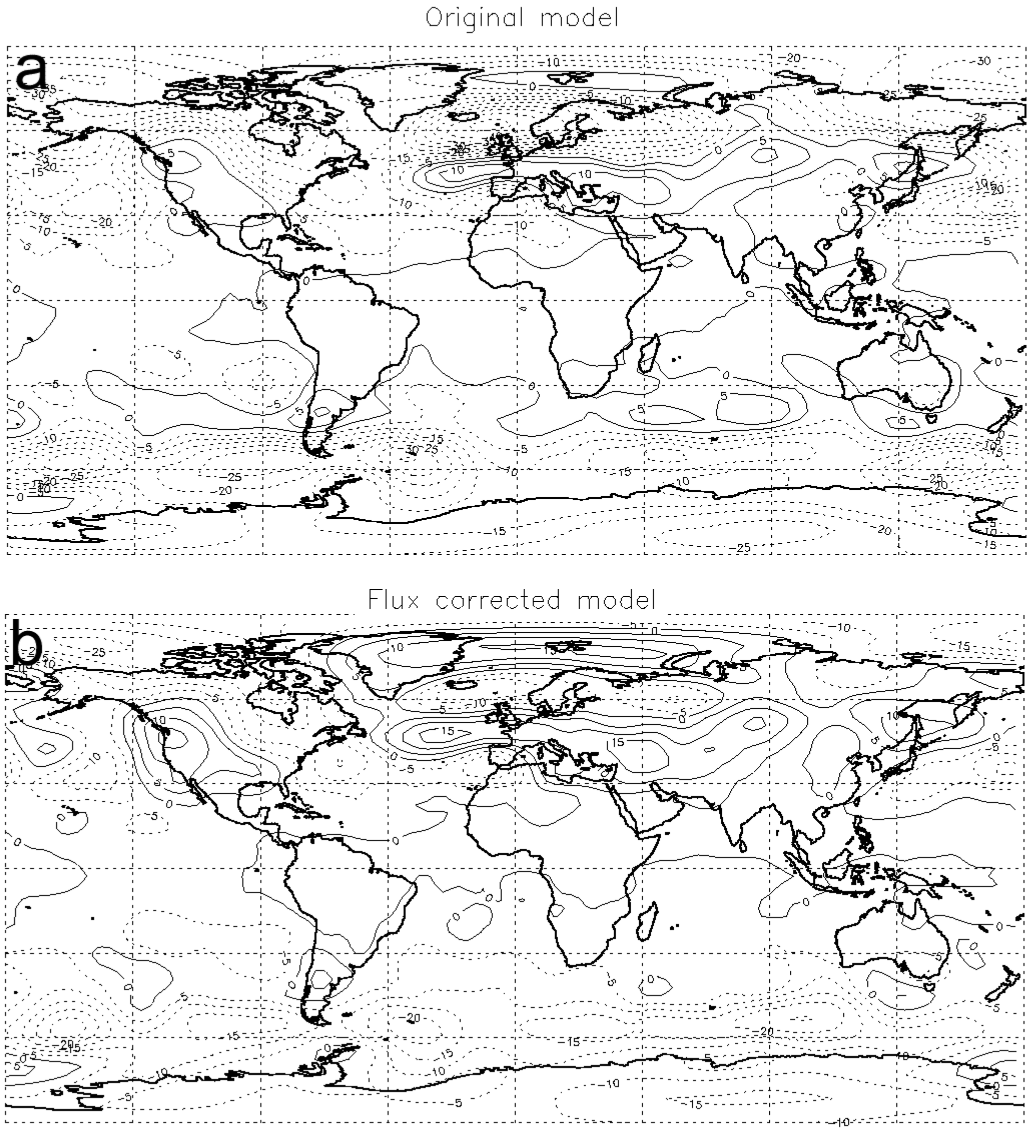

Fig. 7. (a) Systematic error of the standard deviation of the >10 days lowpass filtered 500 hPa geopotential height field averaged over the winters (DJF) 1979-80 to 1992-93 for the control model (ARPEGE climate version 2). Contour interval is 5m and dashed lines represent negative values. (b) Same as (a) but for the flux corrected model.

acceptable, but no major improvement is seen. But in the experiments with SSTs with large anomalies the corrected model is clearly showing better results than the control model with respect to systematic errors. Fig. 6 shows northern hemisphere 500 hPa geopotential height differences between January 1983 and January 1989. Fig. 6(left) shows the result for the standard model and

Fig. 8 On the left column, top to bottom: 500 hPa streamfunction climatology for the ECMWF operational analysis, DJF 1984-1994. Systematic error of the control 'Molteni' integration with the 3 level QG model. Systematic error of the empirical forcing integration. Central column, top to bottom: High frequency variability maps at 500 hPa for analysis, control and empirical forcing integration. Right Column, top to bottom: High frequency variability maps at 200 hPa for analysis, control and empirical forcing integration. In all panels contours are 2 10^6 m^2s^{-1}. On right and central column shading is over 10^7, on the right column shading is over 1.4 10^7. For reference, the geopotential high equivalent of the systematic error anomaly over the north Atlantic is of 126 meters in the control run and of 64 in the empirical forcing one.

6(right) the result for the flux corrected model. It is seen that the empirically forced model is more in accordance with observed differences.

With the two versions of the ARPEGE model the experiments were conducted as 9-member ensemble forecasts for each of the winters covered by the ERA data. For the version 3 of ARPEGE some improvements were seen in the systematic errors of the flux corrected model as compared to the control model. But the largest improvements were seen with version 2 of ARPEGE where the flux corrections were based on two assimilations. Here a large reduction in the systematic errors were obtained, but also the variability was improved in the flux corrected version of the model. The high frequency variability was improved quite substantially on the Northern Hemisphere, whereas the low frequency variability was improved on the Southern Hemisphere (see fig. 7).

The QG model used at LMD has been flux corrected with the correction terms being flow dependent, i.e. not constant in time. The correction used at a given time has been determined using the analogue method. The idea is have to a library of analysed atmospheric states and the corresponding tendency errors. At a given time step during a model integration the model state is compared with the analysed states and a number of the closest states are chosen. The average of the tendency errors corresponding to the chosen states are used as the correction term. Correcting the QG model this way the model shows a much better climatology and variability, at both high and low frequency. Fig. 8 shows the reduction of systematic error and the improvement of the reproduction of storm tracks.

Parameterization of tendency errors has also been used at LMD in a study of dimensionality of the dynamics. In order to do so a reduced model was constructed from the original QG model by projecting the equations of the QG model on its 10 leading EOFs. This model is a model of the sole large-scale and low frequency dynamics of the original model. The reduced model was flux corrected with flow dependent correction terms based on the tendency errors and shows then an indeed very good agreement with the original model concerning mean state and low frequency variability. This proves that the dynamics of the low frequency variability is low dimensional and that the trailing scales (neglected by the EOF filtering) can be parameterized in terms of the resolved scales. The time dependent parameterization of the tendency errors in terms of the flow has proven to be essential to obtain these results.

Task 5 (Seasonal prediction):

With the two versions of the ARPEGE model seasonal prediction experiments have been performed. The idea was to study to which extent an improvement of the mean state of the models would also lead to higher skill when the models were considered for seasonal prediction. The assumption is that an improved background flow will result in a more realistic response of the atmosphere to lower atmospheric boundary conditions like SSTs. The set-up for the seasonal prediction experiments was 9-member ensemble forecasts for the winter season (also for the summer season with ARPEGE, version 3). The individual forecast members were initiated on consecutive dates in late November (late May). To measure the skill of the forecasts temporal anomaly correlations and pattern correlations as well as mean anomaly correlations have been calculated.

For the version 3 of ARPEGE there is no noticeable improvement in skill using the flux corrected model for seasonal prediction. The improvements in systematic errors are also not that striking. This may be because the systematic errors are already rather small in version 3.

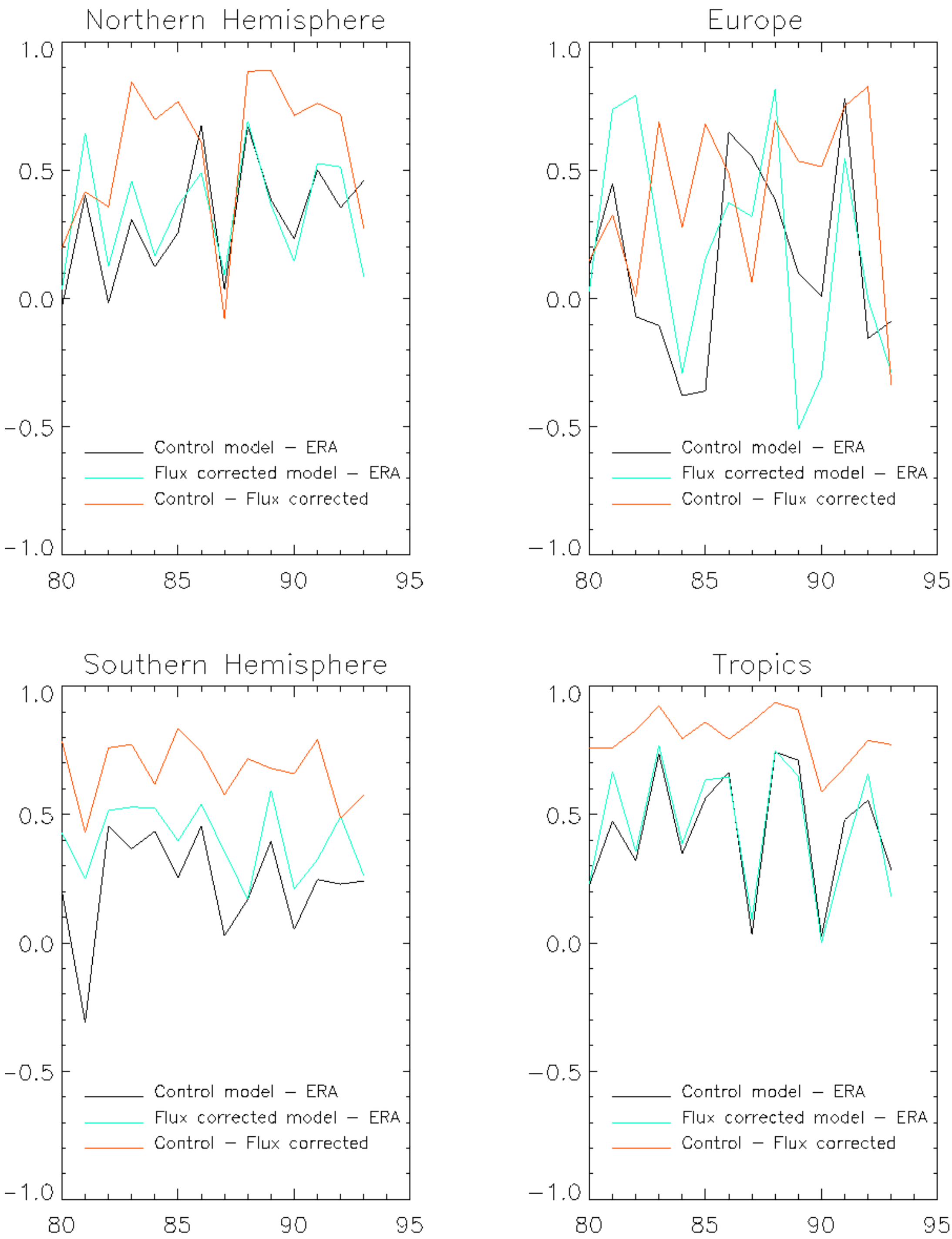

Fig. 9. Pattern correlations for four different areas between the control model and the ERA data, between the flux corrected model and the ERA data and between the control model and the flux corrected model. The model used is ARPEGE climate version 2.

In version 2 on the other hand substantial improvement of the systematic errors are seen in the flux corrected version of the model. Concerning seasonal prediction a general improvement of both the temporal correlation and the pattern correlation is seen on the Southern Hemisphere. Fig. 9 shows the pattern correlation for four different areas and it is seen that the correlation on the Southern Hemisphere is higher for the flux corrected model in all the years. In the other areas there is no sign that one model is better than the other. The improvement on the Southern Hemisphere may be related to the overall improvement in low frequency variability. As mentioned one reason for the larger improvement in version 2 could be that version 2 of the control model has larger systematic errors than version 3. Another reason may be that the flux corrections for version 2 are obtained by two assimilations which could mean that the correction terms are in better balance.

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