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Validation and Analysis of Regional Present-day Climate and Climate Change Simulations over Europe

by

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Abstract

In the European Commission (EC) project "Regionalization of Anthropogenic Climate Change Simulations, RACCS, recently terminated, 11 European institutions have carried out tests of dynamical and statistical regionalization techniques. The outcome of the "dynamical part" of the project, utilizing a series of high resolution LAMs and a variable resolution global model (all of which we shall refer to as RCMs, Regional Climate Models), is presented here. The performance of the different LAMs had first, in a preceding EC project, been tested with "perfect" boundary forcing fields (ECMWF analyses) and also multi-year present-day climate simulations with AMIP "perfect ocean" or mixed layer ocean GCM boundary conditions had been validated against available climatological data. The present report involves results of a validation and analysis of RCM present-day climate simulations and anthropogenic climate change experiments. Multi-year (5 - 30 years) present-day climate simulations have been performed with resolutions between 19 and 70 km (grid lengths) and with boundary conditions from the newest CGCM simulations. The climate change experiments involve various 2xCO2 -1xCO2 transient greenhouse gas experiments and in one case also changing sulphur aerosols. A common validation and inter-comparison was made at the coordinating institution, MPI for Meteorology. The validation of the present-day climate simulations shows the importance of systematic errors in the low level general circulation. Such errors seem to induce large errors in precipitation and surface air temperature in the RCMs as well as in the CGCMs providing boundary conditions. Over Europe the field of systematic errors in the mean sea level pressure (MSLP) usually involve an area of too low pressure, often in the form of an east-west trough across Europe with too high pressure to the north and south. New storm-track analyses confirm that the areas of too low pressure are caused by enhanced cyclonic activity and similarly that the areas of too high pressure are caused by reduced such activity. The precise location and strength of the extremes in the MSLP error field seems to be dependent on the physical parameterization package used. In model pairs sharing the same package the area of too low pressure is deepened further in the RCM compared to the corresponding CGCM, indicating an increase of the excessive cyclonic activity with increasing resolution. From the experiments performed it seems not possible to decide to what extent the systematic errors in the general circulation are the result of local errors in the physical parameterization schemes or remote errors transmitted to the European region via the boundary conditions. Additional errors in precipitation and temperature seems to be due to direct local effects of errors in certain parameterization schemes and errors in the SSTs taken from the CGCMs. For all seasons many biases are found to be statistically significant compared to estimates of the internal model variability of the timeslice mean values. In the climate change experiments statistically significant European mean temperature changes which are large compared to the corresponding biases are found. However, the changes in the deviations from the European mean temperature as well as the changes in precipitation are only partly significance and are of the same order of magnitude or smaller than the corresponding biases found in the present-day climate simulations. Cases of an interaction between the systematic model errors and the radiative forcing show that generally the errors are not canceling out when the changes are computed. Therefore, reliable regional climate changes can only be achieved after model improvements which reduce their systematic errors sufficiently. Also in future RCM experiments sufficiently long time-slices must be used in order to obtain statistically significant climate changes on the sub-continental scale aimed at with the present regionalization technique.

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1.0 Introduction

For meaningful climate change impact studies accurate local climate simulations of possible future forcing scenarios are needed. Of particular importance in this context is the simulation of severe weather phenomena. A prerequisite for such simulations is that the numerical models used explicitly resolves physiographic features, such as the land-sea distribution and those smaller scales of the orography, which are of importance for the local climate. This requires a high resolution. A high resolution is also needed to simulate sufficiently accurate the development of weather systems, and in particular those which give rise to severe weather phenomena. Due to limited computer power the resolution that can be used in the global coupled atmosphere-ocean models (CGCMs) used for long climate simulations (at present spectral T42 or grid lengths of about 300 km) is far from sufficient. Therefore different less expensive approaches to obtain simulations of higher resolution are presently being developed. Each of these approaches build on the time-slice technique in which a certain period (say 10 years) in a long CGCM simulation is being repeated using a high resolution atmospheric model which takes initial and sea surface boundary conditions from the CGCM simulation.

- The first approach is to use a higher resolution global model, an AGCM.
- A second approach is to use a variable resolution global model in which the highest resolution is over an area of interest.
- A third approach is to use a high resolution limited area model (LAM) centered over an area of interest and taking also lateral boundary conditions from the low resolution CGCM simulation.

Presently it is possible by the first approach to do sufficiently long time-slice experiments with a resolution of T106 (maximum grid length in the transform grid, dmax=125 km) (e.g. Wild et al., 1995a,c and Déqué and Piedelievre, 1995).

In specific experiments the second approach has so far been used with a resolution which vary between T220 and T106 over Europe (dmax between 60 and 125 km) and decreases down to T18 (dmax=740km) in the southern Pacific Ocean. With the presently available computer power the 60 km grid length is about the maximum resolution that can be reached using this approach.

The third approach was pioneered by Dickinson et al. (1989) and it was used in the first regional climate change experiments for Europe by Marinucci and Giorgi (1992) and Giorgi et al.(1992). With boundary fields from a T42 spectral model (or an equivalent grid point model) LAM simulations with grid lengths (dmax) between 30 and 60 km are presently being produced. Using boundary conditions from such LAM simulations (Christensen et al., 1997, 1999) or from T106 time-slice simulations (Marinucci et al.,1994) even higher resolution LAM simulations (grid lengths 20-30 km on a smaller integration area) are feasible. Thus by the double nested LAM approach the highest resolutions can be reached, though for a small area only.

In the EC project "Regionalization" (1 January 1993 - 31 March 1995) and its follow-on project "Regionalization of Anthropogenic Climate Change Simulations, RACCS" (1 May 1994 - 30 September 1996), both coordinated by the lead author to the present report, 11 European insti-

tutions have carried out tests of the second and the third approach aiming specifically at climate simulations for Europe. The main objective of these projects was to further develop and test the dynamical regionalization techniques, utilizing a series of high resolution LAMs and a variable resolution global model (all of which we shall refer to as RCMs, Regional Climate Models).

The performance of the different LAMs should first be tested with "perfect" boundary forcing fields (ECMWF analyses) by validation against the analyses and surface observations from the period in question. These tests might reveal model deficiencies which one should then try to remove. Accordingly, several LAMs have been tested in this way using boundary conditions from a common period, 1 January 1990 - 31 August 1991. A common validation over Europe of several such "perfect" boundary simulations for July 1900 and January 1991 was performed at the Danish Meteorological Institute, DMI and presented in Christensen et al.(1997), in the following referred to as CEA97. In addition a long 10 year "perfect" boundary simulation was made at the Hadley Centre, UKMO (Noguer et al., 1998).

A second step should be to perform multi-year high resolution present-day climate simulations with the LAMs nested in AMIP GCM simulations (Gates,1992), i. e. GCM simulations with observed monthly SST and sea-ice distributions. The variable resolution global model should also be tested with these "perfect" ocean boundary conditions. The regional simulations should then be evaluated against available climatological data, i.e. analyses (gridded data) and if necessary surface station data. The estimated accuracy of the present-day climate simulations would constitute first estimates of (i.e. upper bounds of) the accuracy that can be expected in regionalization of CGCM time-slice simulations of future climate, produced with the same nesting techniques. This validation might reveal further deficiencies of the regional models which should then, if possible, be eliminated before they were utilized in the third project step to be dealt with in the present report.

In reality the first two steps were carried out more or less in parallel. A validation and intercomparison of three "step two" RCM simulations, i. e. 5 - 10 year high resolution regional simulations for Europe performed with more or less "perfect ocean" boundary conditions, were carried out at the Max Planck Institute for Meteorology, MPI and presented in Machenhauer et al. (1996), in the following referred to as MEA96. In addition in Noguer et al. (1998) is recently reported a separate UKMO study of the above mentioned 10-year "perfect" boundary simulation and the 10 year "perfect ocean" simulation which were also included in Machenhauer et al. (1996). These two simulations were validated in parallel in order to try to partition errors between those externally forced by the driving data and those internally generated by the RCM.

The third project step involves the validation and analysis of RCM present-day climate simulations and anthropogenic climate change experiments with boundary conditions from fully coupled GCMs (CGCMs). Multi-year present-day climate simulations have been performed with six RCMs with resolutions (grid lengths) between 20 and 60 km and with boundary conditions from simulations made with the newest versions of the UKMO and MPI CGCMs in T42 or equivalent grid lengths resolutions. With four of the RCMs also multi-year 2xCO2 Experiments have been performed. The RCMs were "driven by", i.e. used boundary conditions from, time-slices of transient CGCM climate change simulations with changing greenhouse gas concentrations, and in one of the experiments also changing sulphur aerosol concentrations. The RCMs involved were the HadRM2 model, run at UKMO, the HIRHAM4 model, run at MPI in a 55km resolution and at DMI double nested in a 19km resolution (VHIRHAM4), the variable resolution AGCM, ARPEGE T63s, run at Météo-France. In addition but only for the presentday climate simulations the CLAMBO model, run at the Regional Meteorological Service of the Emilia Romagna Region (SMR-ER) and the RegCM2 model (the newest version of the MM4 model used at NCAR), run at University of L'Aquila (UNIVAQ). The purpose of these experiments has not so much been to estimate possible future climate changes on a regional scale in Europe, we did expect large uncertainties, but rather the intension was to get more precise estimates of the uncertainties and to try to find the reasons for the uncertainties. A common validation and inter-comparison has again been made by the coodinating institution, MPI, the results of which are presented in the present report.

Here we shall at first summarize the main results obtained in the previous common validations presented in CEA97 and MEA96.

The limited area models (LAMs) included in the CEA97 validation of "perfect boundary" simulations were the same as in the present assessment except that two versions of HIRHAM, one with the older ECHAM3 physical parameterization package and one with the new ECHAM4 package (see Section 1.1), were included and VHIRHAM were not. Additionally two more LAMs participated, namely, the German/Swiss EUROPA model run at ETH, Zurich and the PROMES model run at University of Complutense, Madrid.

The "perfect ocean" RCM simulations validated in MEA96 were made with three of the RCMs included in the present assessment, i.e. the global variable resolution model, ARPEGE T63s, run at Météo-France and two LAMs, the HadRM2a model run at UKMO and the HIRHAM3 model run at MPI. For comparison also the two coarse resolution GCM simulations that were used for boundary conditions to the LAM simulations, UKMO GCM and ECHAM3, and a homogeneous coarse resolution version (ARPEGE T42) of the Météo-France GCM were included in the MEA96 validation. In the Météo-France and the MPI simulations observed (AMIP) SST and sea-ice distributions were used whereas in the UKMO simulations SST and sea-ice distributions which were close to the observed seasonally varying climatology were extracted from a flux corrected mixed layer ocean model coupled to the AGCM. Each of the three RCMs use the same physical parameterization package as the corresponding AGCM.

In MEA96 maps of decadal mean biases for surface air temperature and precipitation in Europe were presented for each season. Relative large values of mean seasonal biases averaged over sub-areas of 100,000 - 1,000,000 km2 size (see Figure 0.2) were found for all six models. Many of them were found to be of a significant magnitude compared to the variations found between sub-area mean values in different ECHAM3 AMIP simulations and compared to variations of observed decadal mean values. For the three RCMs the largest negative and positive sub-area biases were for temperature -2.6K and +4.6K and for precipitation -61% and +114% (per cent of the observed precipitation), respectively. The biases were generally of the same order or larger than the changes expected in various climate change scenarios for the coming 100 years. Furthermore, often the biases of the different RCMs for the same sub-area were found to differ significantly. In 64% of the cases were the sub-area temperature bias smaller in the RCM than in the GCM simulations but for precipitation this percentage was smaller, i. e. only 45%. These

results raised serious doubts on the reliability of the results of coming climate change experiments on this sub-area scale using the dynamical down-scaling techniques. Therefore, the main emphasis was placed on an analysis aiming at finding likely reasons for the large biases.

As a result of this analysis a significant part of the time-slice mean temperature and precipitation biases seemed to be systematic and caused by systematic errors in the simulated general circulation over Europe, though without parallel perfect boundary condition experiments it was not possible to quantify the proportion. The errors in the circulation in each of the RCMs were found to resemble rather closely those in the corresponding GCM. A common pattern of continental scale mean sea level pressure (MSLP) systematic errors were found over Europe in all three pairs of models with areas of too high pressure to the north and to the south and areas of too low pressure to the east and to the west between which either a north-south ridge or, more often, an west-east trough is established. There are, however, significant differences, at subcontinental scale, between the systematic errors of the different models which apparently causes differences in the induced biases in temperature and precipitation. In all three model pairs the systematic MSLP errors are largest in the winter season and weakest in the summer.

The UKMO models simulated too low pressure in an east-west belt situated south of approximately 55°N north of which the gradient of the pressure bias indicated a systematic easterly low level error flow. i. e. reduced westerlies. The too low pressure, deeper in the RCM than in the driving GCM, found in connection with the storm tracks were thought to indicate increased cyclonic activity which partly explain rather large positive precipitation biases, which were found over most Europe, largest in the RCM, fed by erroneous moisture advection from the Atlantic or the Mediterranean in the southern part of the belt. From the separate UKMO study, Noguer et al. (1998), evidence were presented that even when the GCM and RCM simulates the observed flow a large precipitation bias is evident, again larger in the RCM. This implies systematic errors in the release of precipitation in the UKMO models. The circulation biases were thought to influence also the temperature biases but they seemed to be caused mainly by local effects of defects in the physical parameterization schemes.

In the ARPEGE models the belt of too low pressure was deeper and more northerly situated, between 55°N and 65°N, resulting in too strong westerly flow between this belt and areas of too high pressure over parts of the Mediterranean and southern Europe. The too strong mean advection of moist air from the Atlantic and increased cyclonic activity were thought to explain excessive precipitation and a reduced seasonal temperature variation over most of Europe. The too high pressure to the south seemed, due to increased subsidence, to explain reduced precipitation over parts of or the whole southern Europe.

Finally, in the MPI simulations in the winter and spring seasons a north-south orientated ridge between the two centers of too high pressure was found giving a southerly error flow over western Europe and in the spring also a northerly error flow over eastern Europe, in both cases with an easterly error flow over northern Europe. The too high pressure seemed to explain too dry areas over southern Europe, the southerly error flow seemed to explain positive temperature and precipitation biases over parts of Europe and the easterly error flow to the north seemed to explain the too cold areas over north-eastern Europe, partly carried southward by the southerly error flow in the spring season. In the summer and autumn seasons the MPI model error pattern were rather similar to that of the ARPEGE models, although with less extremes. That is, enhanced cyclonic activity and advection from the Atlantic seemed to explain too wet and in the summer season also too cold conditions over northern Europe and too high pressure over southwestern Europe seemed to contribute to negative precipitation biases there.

As mentioned above the systematic errors in each of the RCMs resemble rather closely those in the corresponding AGCM, but a clear tendency of intensified troughs of too low pressure, which were interpreted as increased cyclonic activity, were noted with the increased resolution from the AGCMs to the RCMs. Except for that, in the area of interest (Europe) the systematic errors were found to be rather insensitive to the increased resolution and they were speculated to be due to errors in the forcing by the physical parameterizations, either locally in the area of interest or elsewhere on the Globe (perhaps in the tropics) and then transmitted, in the LAMs via the boundary conditions, to our area.

In addition to temperature and precipitation biases belived to be caused by systematic errors in the general circulation also biases were identified in MEA96 and CEA97 which seemed to be caused by errors in the physical parameterizations directly influencing temperature and precipitation locally.

Thus, in MEA96 warm and dry biases over south-eastern Europe in the summer and autumn season were found to be connected with the soil moisture drying out too rapidly during spring and summer, most likely due mainly to deficiencies in the parameterization of radiation and hydrological processes. It was speculated that the drying out process was intensified in the models due to an overestimation of the solar radiation reaching the ground as observed for ECHAM3 and several other models by Wild et al. (1995b). The excessive heating would lead to too strong evaporation in the spring resulting in a too fast drying-out. The dry soil would then lead to positive feedbacks, firstly of reduced evaporation (and evaporative cooling) and subsequently reduced precipitation (and reduced cloud shading) resulting in further drying out (and heating). Secondly the heating would lead to "heat low" formation, especially in the RCMs, which enhances the decoupling of the region from the westerly advection of moist/cool Atlantic air. In addition the enhancement of these biases in the RCMs compared to those in the GCMs were ascribed to the stronger orographical sheltering of the regions in question.

In CEA97 it was found that most of the models validated showed a similar warming and drying in the south-eastern Europe in the summer month July 1990. It was furthermore found that the biases were reduced substantially in the HIRHAM4 simulation compared to HIRHAM3 and by surface heat budget calculations with the HIRHAM model versions it was proven that the excessive incoming solar radiation in HIRHAM3, largely absent in HIRHAM4, did contribute significantly to the process, although it was argued that also increased soil water holding capacities in HIRHAM4 had lead to the improvements. That some drying-out and excessive heating occurred also in the HIRHAM4 simulation showed that the positive feedback processes may be initiated also without the excessive solar radiation.

Another common feature amongst many of the model simulations validated in CEA97 was a cold bias in winter (1 - 3 K over large areas). It was believed that this results from the underestimation of incoming long-wave radiation at the surface (caused by inaccuracies in the param-

eterization of the water vapour continuum) identified by Wild et al. (1995b) in the ECHAM3 and in the radiation schemes of many other models. That this was a major factor in explaining the cooling were supported by surface heat budget calculations with the HIRHAM model versions and the fact that the correction of this error in the HIRHAM4 physics leads to improved (sometimes even positive) biases. It has not been possible to detect similar effects of the underestimation of incoming long wave radiation in the HIRHAM3 and ARPEGE simulations in MEA96. The reason seems to be that this effect is obscured by stronger effects of the systematic errors in the general circulation. However, some widespread cold biases in the UKMO simulations found in MEA96 for all seasons seem to be ascribed to an underestimation of the incoming long wave radiation.

Finally, as mentioned above even without systematic circulation biases the study by Noguer et al. (1998) seems to show that the UKMO models suffer from too excessive release of precipitation, most excessive in the RCM. In Jones et al. (1995) it was shown that the enhancements of precipitation were accompanied by increased (resolved) vertical velocity variance which show that the increase at least partly was in the non-convective precipitation scheme. (Release of precipitation by unresolved vertical velocity variance is parameterized in the convective precipitation schemes). In MEA96, assuming that this is the case also in other models the increased vertical velocity variance were belived to be mainly at synoptic scales connected to the increased cyclonic activity evidenced by the large organized areas of lower surface pressure in the RCMs observed in all cases studied. The extra-tropical cyclonic activity is maintained by baroclinic instability and the increase with increasing resolution were believed to be caused by sharper baroclinic zones (fronts) made possible in higher resolution models. The cases of enhanced precipitation with increasing resolution reported by Noguer et al. (1998) without such areas of reduced surface pressure indicate that at least in the UKMO model the increased vertical velocity variance may also be mainly at smaller scales, maybe even down to the two grid length scale, created by small scale orographical and diabatic forcing, aliasing and maybe numerical instabilities

As mentioned above it was far from in all cases that the sub-area biases in MEA96 were improved when going from the GCM to the RCM simulations. The reasons why were discussed in MEA96 and shall be summarized here. A direct effect of increased resolution should be expected in the simulation of orographical precipitation. It was demonstrated, by comparing the RCM and their respective coarse resolution GCM simulations, that such improvements were experienced in some cases but only when the mean flow over the mountain range in question were not too unrealistic. Large systematic errors in the general circulations could even lead to deteriorations with increasing resolution. Another undesirable effect of better resolved mountains was mentioned above, namely, increased drying out and heating over south-eastern Europe in summer and autumn due to more realistic mountains and therefore better sheltering against moist Atlantic air. In the GCMs the heating and drying process were even compensated by spurious up-slope orographical precipitation in the areas in question released by the unrealistic smooth model mountains. Another deteriorating effect has also been mentioned, namely, that typically the troughs of too low pressure intensify with increasing resolution. It means according to our assumptions that the too strong cyclonic activity and also the strength of the erroneous advections by the mean error flow increase with resolution which leads to increased

temperature and precipitation biases. These are probably the reasons why only 46% of the subarea precipitation biases were found to be smaller in the RCMs than in the GCMs.

In the remaining part of this introductory Section 1 we will describe the model versions used (Sub-section 1.1), the simulations performed (Sub-section 1.2) and the climatological data used in the validation and analysis of the simulations (Sub-section 1.3). In Section 2 the biases in the precipitation and surface air temperature simulated in the various present-day climate simulations will be presented and their significance will be tested, i.e. it is tested to what extent the biases can be separated from estimated internal model variations. Also their relation to resolution, physical parameterization and systematic errors in the general circulation will be discussed. At the end of Section 2 further discussions of these results and comparisons with the results obtained in CEA97 and MEA96 are carried out. In Section 3 we analyze the changes in precipitation and surface air temperature found in various climate change experiments. It is shown that they are related closely to the changes in the general circulation. The changes are also compared with the biases found in the corresponding present-day climate simulations and their statistical significance (or lack of that) are investigated. Finally, in Section 4 the main results are summarized and our conclusions and outlooks are presented.

1.1 Models

1.1.1 The UKMO CGCM

The UKMO atmospheric models are described in some detail in Jones et al. (1995), hence only a brief description will be given here. Both the RCM (HadRM2) and the AGCM (HadAM2) belong to the UKMO Unified Forecast / Climate Model (UM) system. They are primitive equation grid point models using a terrain-following hybrid vertical coordinate (Simons and Burridge, 1981) and a split-explicit time extrapolation scheme. The prognostic variables are represented on 19 vertical levels. The horizontal coordinate system is the spherical latitude-longitude system. The resolution of the AGCM is 2.75° x 3.75° (=250 km spacing at 50° N). The physical parameterization package includes all the usual processes. Minor changes were made in the convection component of HadAM2 and HadRM2 relative to the models of Jones et al. (1995) (HadAM2a and HadRM2a), the rate of evaporation of convective precipitation was increased as was the frequency of convective snow showers. This lead to a globally better simulation and in particular a reduction in the large positive moist bias in the driving GCM described here, HadCM2. In the previous UKMO simulations (Jones et al. (1995) and those included in MEA96), the atmospheric GCM was run coupled to a 50 m mixed layer ocean model and a thermodynamic sea-ice model. In the current simulations the CGCM consists of the same AGCM (with the modifications just mentioned) coupled to a full OGCM. The ocean model is based on the Bryan-Cox primitive equation model (Bryan, 1969a, Cox, 1984). It has 20 depth layers in the vertical and uses the same horizontal grid as the AGCM. The ocean component also includes a sea-ice model which represents ice thermodynamics according to Semtner (1976), parameterization of ice concentration according to Hibler (1979) and a simple representation of ice dynamics based on Bryan (1969b). Coupling between atmospheric and oceanic components is performed daily. For a full description see Johns et al. (1997).

1.1.2 The HadRM2 Model

The UKMO RCM, HadRM2, is a limited area version of the UM atmospheric model covering a domain shown in Figure 0.1. The domain has been reduced compared to the version (HadRM2a) used in MEA96 (Fig. 1.2 in that report) and is the same as the version (HadRM2b) used in CEA97. It is placed around the equator in a rotated system in order to have a quasi-homogeneous grid. Therefore no filtering of short wave lengths along latitude circles near the poles are needed, as in the AGCM where a Fourier filtering must be performed to keep reasonable length of time steps. The horizontal resolution is 0.44° X 0.44° (about 50 km grid lengths). Apart from horizontal resolution the physical and dynamical formulations of HadRM2 are identical to those in the AGCM described above. Exceptions are certain details of the filtering (see above) and horizontal diffusion (Jones et al. 1995). Thus, the vertical hybrid coordinate, the vertical levels and the finite difference schemes are the same as in the AGCM.

In a one-way nesting technique, the RCM is driven at its lateral and lower sea surface boundaries by time series of data achieved from a previous integration of the UKMO CGCM. At the lateral boundaries the relaxation to the AGCM prognostic variables are made with linearly decreasing weight inward over a zone of four grid length. The AGCM values used at the lateral boundaries are obtained by linear interpolation in time from values saved every six hours. The values used at the sea point lower boundaries are interpolated from the CGCM fields saved every 5 days.

A short description of the HadRMa and HadRMb model versions may also be found in Jones et al. (1995) and Noguer at al. (1998) or in MEA96 and CEA97, respectively.

1.1.3 The ARPEGE T63s Model

The Météo-France AGCM is a climate version of the spectral ARPEGE-IFS atmospheric model developed by Météo-France and ECMWF. A description of the climate version is given in Déqué et al., 1994. It is a primitive equation spectral model using also a terrain-following hybrid vertical coordinate. The physical parameterization package is mainly that of the Météo-France operational model, with some additions such as treatment of the ozone concentration as a 3-D prognostic variable and a soil-vegetation scheme with rainfall interception. As in the operational model a deep soil temperature must be prescribed. It has also a higher vertical resolution in the stratosphere (20 levels out of the 30 above 200hPa). The model offers the possibility of varying the horizontal resolution by a stretching which maintains local isotropy, i.e. the angles are preserved. A pole of stretching determines the point of maximum resolution and a stretching factor how much the resolution is increased in that point. The Météo-France RCM used here is called ARPEGE T63s. It is a stretched version of the ARPEGE climate model with a T63 resolution, pole of stretching in the Tyrrherian sea (40° N, 12° E) and a stretching factor of 3.5. The resulting horizontal resolution is shown in Figure 1.2 (the middle map) of MEA96. It varies between T106 and T 220 over Europe and decreases down to T18 in the southern Pacific. The grid length in the transform grid varies between about 60 km at the pole of stretching and 750 km at the anti-pole. When we refer to "the corresponding GCM" we mean a usual homogeneous T42 resolution version of the ARPEGE model with a grid length in the transform grid of about 300 km.

The model version used in the present simulations is slightly different from that used in the "perfect ocean" (AMIP) simulations analyzed in MEA96:

- The number of vertical levels is 31 instead of 30 and the distribution of the layer depths is more regular in the lower stratosphere through the use of an analytical function discretized in equal intervals.
- There is a new additional non uniform horizontal diffusion; then the standard spectral diffusion has been reduced by a factor of two. The divergence equation is now better linearized for the semi-implicit scheme.
- The critical humidity profile has been slightly modified (more low clouds) to improve the cloud radiative forcing over Europe.
- Two modifications have been introduced in the convection scheme. The first one takes into account the evaporation of precipitation in sub-cloud layers. The second one introduces a dependency with height for the entrainment rate with higher entrainment in the lower part of the cloud.
- The soil-vegetation scheme has been modified (Mahfouf et al., 1995): a bottom run-off is introduced (gravitational drainage), the rainfall interception is limited for high convective rates. A new distribution of the fraction of sand and clay is used. The tables for the fraction of vegetation, roughness length, albedo, soil depth, minimum stormal resistance and leaf area index have been updated.
- The roughness length for the thermal exchange coefficients is taken to 10% of the standard dynamical roughness length.

More detailed descriptions of the ARPEGE model versions used in the previous and the present experiments may be found in Déqué and Piedelievre(1995) and Deque et al. (1998), respectively.

In the present experiments the ARPEGE T63s is run with SST, sea-ice and land deep soil temperature fields derived from output of the UKMO CGCM.

1.1.4 The MPI CGCM

The atmospheric component of the MPI CGCM (ECHAM4) used in the present experiments is the most recent version of a series evolving from the ECMWF model. A detailed description of this version is given in Roeckner et al. (1996a) whereas the previous version ECHAM3, which was used in the simulations analyzed in MEA96, is described in Roeckner et al. (1994) and DKRZ (1994). As with the previous versions ECHAM 4 is a spectral model based on the primitive equations using a leap-frog / semi-implicit time stepping scheme with a weak time filter. Most prognostic variables, vorticity, divergence and temperature in 19 irregularly spaced layers and logarithm to surface pressure are represented by spherical harmonics with triangular truncation at wave number 42 (T42).Unlike the previous versions the water vapour and cloud water in ECHAM4 are represented only in grid point space (in the transform grid) and they are advected using a semi-Lagrangean scheme (Williamson and Rasch, 1994). Also the physical parameterizations of ECHAM4 have undergone a number of changes with respect to the previous version:

• The radiation code from the ECMWF (Mocrette 1991) has been adopted with some modifications such as the consideration of additional greenhouse gases (methane, nitrous oxides and 16 CFCs) and various types of aerosols, revision of the water vapour continuum (Giorgetta and Wild, 1996) and revision of the single scattering properties of cloud droplets and ice crystals and of the parameterization of their effective radii.

- A high-order closure scheme, based on prediction if turbulent kinetic energy, is used to compute the turbulent transfer of momentum, heat, water vapour and cloud water within and above the atmospheric boundary layer (Brinkob and Roeckner, 1995).
- As in ECHAM3, the convective mass flux scheme of Tiedtke is applied, but with some modifications. The closure for deep convection and organized entrainment has been modified to be based on buoyancy instead of moisture convergence, and organized detrainment is computed for a spectrum of clouds detraining at different heights (Nordeng, 1996).
- In contrast to ECHAM3 the cloud water detrained in cumulunimbus anvils and also in nonprecipitating cumulus clouds is used as a source term in the stratiform cloud water equation.
- The formulation of the surface schemes are identical in ECHAM3 and ECHAM4, but two parameters in the soil moisture scheme, both functions of the soil moisture, are changed (see e. g. Wild et al.,1995a). The effects of these changes are to reduce the evaporation from bare soil at low values of the soil moisture and the evaporation from dry vegetated soil at medium and low values.
- A new global data set of fields of land surface parameters is used in ECHAM4 (Claussen et al., 1994), constructed from the major ecosystem complexes of Olson et al. (1983). These changes must have affected the thermodynamic and hydrological processes simulated in the surface scheme. In particular, the new geographically varying field of soil moisture capacity with averaged values in Europe of about 35 cm instead of a constant value of 20 cm, together with the parameter changes mentioned above, must have contributed to a reduced tendency of excessive summer dryness.

The MPI oceanic model component, OPYC3, is the newest version of the model described in Oberhuber (1992 and 1993). It consists of three sub-models: for the interior ocean, the surface mixed layer and the sea-ice, respectively. The model for the interior ocean employs the primitive equations in form of the conservation laws for momentum, mass, heat and salt in 11 isopy-cnic layers. Horizontal and vertical diffusion and convection are parameterized. The mixed layer model computes entrainment and detrainment rates into and out of the layer according to a budget equation for the turbulent kinetic and mean potential energy. The sea-ice model solves equations for ice momentum, ice and snow thickness and their concentration. The thermodynamic part consists of a prognostic computation of the temperature profile. Poleward of 36°, the horizontal resolution is identical to the atmospheric model (the T42 transform grid). Equatorward of 36° the meridional grid spacing is gradually decreased down to 0.5° at the Equator.

1.1.5 The HIRHAM4 and VHIRHAM4 Models

The RCM of MPI and DMI used here is called HIRHAM4. It combines the adiabatic part of the HIRLAM model, developed by the Nordic, Dutch and Irish meteorological services, with the ECHAM4 physical parameterization package (Christensen et al., 1996). A detailed description of the adiabatic HIRLAM part is given in Källén(1996). The previous version, HIRHAM3, which was used in MEA96 had implemented the ECHAM3 parameterization package (Christensen and Meijgaard, 1992). As the previous versions HIRHAM4 is a limited area primitive equation grid point model. The vertical hybrid coordinate, the vertical levels and the vertical finite difference schemes are the same as in ECHAM4. Also the HIRHAM4 uses a rotated lat-

itude-longitude grid. The resolution of the present simulations made at MPI is 0.51°x0.51° corresponding to a grid length of about 55 km. The domain covered, shown in Figure 0.1, is the same as that used in CEA97 but reduced (approximately halved) compared to that used in MEA96. The prognostic fields are relaxed to those of an ECHAM4 / OPYC3 simulation made in advance in a 10 grid lengths lateral boundary zone with decreasing weight inward into the integration area. (the fractional weight given to the ECHAM4 fields in this zone is shown in Figure 1.3 of MAE96). An inflow/outflow dependent scheme is used for specific humidity and no relaxation is made of prognostic cloud water content. The ECHAM4 boundary fields are interpolated in space and time from 6-hourly output of the CGCM simulation. Beside the changes in physical parameterization from model version 3 to 4 also an important change was made in the horizontal diffusion. Namely, that no diffusion were made in points where the slope of the model surface exceeds a critical value. This change was introduced in order to avoid up-slope diffusion of water vapour giving rise to excessive precipitation at the mountain tops. Simulations with a very high resolution version, called VHIRHAM4, with a grid length of 0.17° or about 19 km have been made at DMI for the area over Scandinavia shown in Figure 0.1. The VHIRHAM4 simulations took boundary conditions from the HIRHAM4 simulations. A short description of the two HIRHAM model versions (3 and 4) referred to here is given in CEA97. It should be noted, however, that the HIRHAM3 version used in MEA96 differs somewhat from the HIRHAM3 version described in CEA97. In the former version a much larger area (Fig. 1.2 in MEA96) and a 30-point boundary relaxation zone were used (Fig. 1.3 of MAE96). Furthermore, the following changes were introduced in the ECHAM3 soil-vegetation scheme used in the MEA96 HIRHAM3 version. The constant soil moisture holding capacity were increased from 20 cm to 35 cm and the new ECHAM4 "forest" and "vegetation" fields (with substantially reduced values of coverage over Europe) were introduced. These changes anticipated the changes to HIRHAM4 which have been introduced with the implementation of the ECHAM4 soil-vegetation fields.

1.1.6 The CLAMBO Model

CLAMBO is a climate version of the LAMBO now operational for short range forecasting at SMR-ER. It is based on a sigma version of the ETA-model (Mesinger et al., 1988, Black, 1988, Janjic, 1990) which is operational at the US National Centre for Environmental Prediction. It is a split-explicit grid point primitive equation model using a lat-long grid and a sigma vertical coordinate with a 0.25° x 0.25° horizontal resolution and 20 vertical layers. The domain (30°N - 60°N, 35°W - 30°E) is shown in Figure 0.1. It uses a non-linear fourth order horizontal diffusion scheme (Black, 1988). Most of the physical parameterization schemes have been taken over from the ETA model: A second order closure turbulence scheme (Mellor and Yamada, 1974), large scale precipitation released if the relative humidity exceeds a certain threshold, shallow and deep convection using the Betts and Miller (1986) adjustment scheme, soil temperature predicted with a 2 layer scheme (Deardoff, 1978) and soil water content described by a balance equation (Miyakoda and Sirutis, 1984), no effects of vegetation are included. In the present version the only part of the model not derived from the ETA-model is the one treating the radiative processes. They are parameterized by the Météo France scheme (Ritter and Geleyn, 1992). The Davies (1996) boundary relaxation scheme is used with boundary fields linearly interpolated from 6 hourly MPI CGCM output.

1.1.7 The RegCM2 Model

The RegCM2 model is an augmented version of the NCAR/Pennsylvania State University limited area model, MM4, coupled to the soil-vegetation model BATS (Dickinson et al., 1986). The previous version of this model was used in CEA97 where it was referred to simply as MM4. A short description of that previous version was included in CEA97 and a detailed description of the present version, RegCM2, may be found in Giorgi et al. (1993a,b). The RegCM2 is a splitexplicit grid point primitive equation model using a regular grid on a Lambert conformal map, here with a resolution of about 70 km, and a sigma vertical coordinate, with 16 layers. The area covered is shown in Figure 0.1. The main difference of the physics schemes in RegCM2 and those in the MM4 version used in CEA97 are:

- The RegCM2 includes a boundary layer scheme that adopts a non local eddy diffusivity formulation (Holtslag and Boville, 1993), while the MM4 in CEA97 adopted a local formulation. This produces an enhanced vertical transport of moisture which improves the model vertical moisture profile.
- The RegCM2 adopts the mass flux cumulus parameterization of Grell (1993), which produces better heating and moisture profiles than the Kuo scheme used in CEA97.
- The explicit cloud water scheme which is used in RegCM2 reduces occurrence of numerical grid point storm events compared to the formulations based on instantaneous precipitation of condensed water.

Also preliminary tests at UNIVAQ gave improved simulations of precipitation with the new schemes.

A Newtonian boundary relaxation scheme including a diffusion term (Anthes et al., 1987) in a 6 point lateral boundary zone and an inflow/outflow formulation for humidity (Giorgi et al., 1993b) is used with boundary fields linearly interpolated from 12 hourly MPI CGCM output.

1.2 Climate simulations performed

1.2.1 The MPI CGCM present-day climate simulation

The procedure used in the MPI CGCM present-day climate simulations is described in Roeckner et al.(1996b). Prior to coupling, the MPI OGCM (OPYC3) has been spun up for about 1000 years by prescribing a combination of observed and T42 ECHAM4 simulated fluxes. A flux correction technique is applied in order to avoid a large climate drift when the restoring boundary conditions then are replaced by the fluxes computed in the AGCM. As the techniques employed previously still resulted in relatively large drifts, i. e. a global mean SST drift of typically 0,5 K within the first 100 years, and as seasonal corrections tends to reduce and/or spectrally modify ENSO variability an alternative approach is applied. It differs from the traditional one basically in two respects. 1) The flux correction is computed by a gradual updating and it is gradually introduced during a 100 year spin-up of the CGCM, and 2) only the annual mean of heat and freshwater is corrected while the respective annual cycles and the wind stress (and other couplings variables as well) remain unchanged. In the subsequent 100 year CGCM presentday climate simulation relatively small drift was found with a cooling trend of the global annual mean temperature of about 0.1K and also a realistic level of ENSO variability (Roeckner et al., 1996b). The CGCM simulation can be considered as a simulation of the present-day climate as the concentrations of atmospheric greenhouse gases (as well as the solar constant) are prescribed according to present-day conditions (IPCC, 1990).Moreover both the OGCM spin-up and the computation of the flux corrections are based upon the currently observed SST distributions.

1.2.2 RCM simulations driven by the MPI CGCM present-day climate simulation

The MPI CGCM present-day climate experiment was initialized at year 90 of the 100 year coupled spin-up run and after having integrated 60 years 6 hourly output for a 10 year time-slice, year 151-160, were prepared for boundary conditions to RCM simulations. This time-slice is called ECHAM4 CTL(10). A HIRHAM4 simulation (with the 55 km resolution) covering domain 1 in Figure 0.1 was made at MPI for the last 9 years of the 10 year period. Subsequently, a VHIRHAM4 simulation covering Scandinavia (domain 2, with the 19 km resolution) was run at DMI for the same period using boundary conditions derived from the HIRHAM4 simulation. We refer to these simulations as HIRHAM4 CTL(9) AND VHIRHAM4 CTL(9), respectively. In addition two 5 year simulations were made with the CLAMBO, covering the domain 3, and with the RegCM2, covering the domain 4, both using boundary conditions derived from the first half of the MPI CGCM present-day climate time-slice, i. e. the years 151-155. They are referred to as CLAMBO CTL(5) and MM4 CTL(5), respectively.

1.2.3 The MPI CGCM scenario simulation

A new 230 year simulation with gradually increasing greenhouse gas (GHG) concentrations was made with the MPI CGCM described above and time-slices of this simulation were provided for boundary conditions to various RCM simulations. In this simulation, changes in aerosols were not taken into account. It will be referred to in the following as the MPI GHG simulation. It was decided to start the simulation in 1860 and use observed greenhouse gas concentrations until 1990, whereafter the concentrations should increase according to the IS92a scenario (IPCC, 1992 with amendments of the concentrations of CFCs according to IPCC, 1995). The simulation was started with initial conditions, including greenhouse gas concentrations, from year 100 of the present-day climate integration, i. e. at the end of the coupled spinup run. It would have been more desirable to be able to start with initial conditions representative of the time around 1860. However, this could not be done as it would have required CGCM fields that had been spun up using SSTs (and other fields needed) which were representative of a time around 1860. Such fields are, however, not available and it would not be possible to produce reliable ones as sufficient observations of SST from that time do not exist. Thus, as the simulation had to be started up with conditions representative of the present-day climate it was decided to adjust the greenhouse gas concentrations used in the simulation so that the *radiative* forcing (change of net radiative flux induced at the tropopause) were the same as it would have been had the initial concentrations been the 1860 ones. These "adjustments" were made using the approximate relations between radiative forcing and concentration that were used for construction of scenarios in the IPCC 1990 Assessment (IPCC, 1990, Table 2.2). Thus, for the CO2 concentration C(t), for instance, since the expression for the radiative forcing F is logaritmic, $F=6.3 \ln(C/Co) W/m2$, the adjustment involve a multiplication with the ratio between the 1990 concentration and the 1860 concentration, i. e. C'(t)=(C(1990)/C(1860))C(t). Although, the simulation of a period with a certain radiative forcing cannot be strictly representative of the

period actually having that radiative forcing (it will be too warm, globally at least, since initially it was too warm and since the greenhouse gas concentrations were too high during the simulation up to that time) it may never the less be assumed that the *climate changes* computed from the scenario simulation are similar to those that would have been simulated with the correct conditions. For that to be true the assumption is that the simulated changes are insensitive to the deviations of the model state in the present simulation from that in a more ideal one. This should be kept in mind when interpreting the results. The radiative forcing actually computed in the MPI GHG simulation and the simulated globally averaged surface air temperature changes are shown in Figure 0.3 (Roeckner, personal communication).

1.2.4 RCM simulations driven by the MPI CGCM scenario simulation

Two 10 year time-slices with 6 hourly output, a "control" simulation around 1990, called ECHAM4 sca(10), and an anomaly simulation around 2075, ECHAM4 SCA(10), were made available for RCM simulations. The latter time-slice were chosen so that during it the IS92a equivalent CO2 concentration is doubled with respect to the 1990 value. The "equivalent concentrations" referred to here take into account beside the radiative forcing by CO2 also the forcing by the other greenhouse gases included in the model's radiation scheme. The two time-slices are indicated in Figure 0.3. Two HIRHAM4 simulations covering domain 1 in Figure 0.1 (with 55 km resolution) were made at MPI for the last 9 years of both 10 year periods, i. e. both that around 1990 and that around 2075. These simulations will be called HIRHAM4 sca(9) and HIRHAM4 SCA(9), respectively. Subsequently, a VHIRHAM4 simulation covering Scandinavia (domain 2, with the 19 km resolution) were run at DMI for the second period around 2075 using boundary conditions derived from the HIRHAM4 SCA(9) simulation. We call that simulation VHIRHAM4 SCA(9).

1.2.5 The UKMO CGCM present-day climate simulation

To produce a quasi-stable and realistic present-day climate simulation required also at the Hadley Centre the use of a long spin up integration and the use of flux corrections at the atmosphere-ocean interface. Spinning up the coupled system was done mostly in coupled mode. The ocean was integrated from rest with initial potential temperature and salinities imposed from the Levitus (1982) climatology. The integration then alternated between a relaxation phase and a flux correction phase. In the former an annual cycle of monthly reference sea-surface temperature (SST) and salinity (SSS) fields are used to keep the system close to climatological sea surface values (and hence avoid climate drift). During this phase flux corrections of heat and fresh water required to maintain the reference sea surface climatology are calculated. These are then used in the following flux correction phase being added to the atmosphere fluxes passed to the ocean on coupling. This process was continued for 500 years after which the ocean was very close to equilibrium. A final relaxation phase of the spin up was used to provide flux corrections to be used for the present-day climate and scenario simulations. These are necessary for if omitted the model quickly develops large systematic errors which would greatly complicate analysis of climate change simulations produced with the model. As it was done at MPI, given the use of current sea surface conditions in the calculation of the flux corrections also a current value of the equivalent carbon dioxide concentration were used, here the observed value at around 1950 (323 ppm), rather than a pre-industrial value. However, again the two transient climate

change simulations performed, which both were using the same initial state as this present-day climate simulation, included equivalent CO2 concentrations adjusted so that the radiative forcing were as observed from 1860 to 1990 and thereafter values increasing by 1% per year were used. Hence, when using the present-day climate simulation as a control simulation we may assume that the differences between this control simulation and an anomaly simulation represent the climate change relative to 1860. Full details of the set up and design of the present-day climate simulation can be found in Jones et al.(1997).

1.2.6 RCM simulation driven by the UKMO CGCM present-day climate simulation

The HadRM2 model described above was nested in a 30 year period of the above CGCM present-day climate simulation, from year 146 to 175 counted from the start of the integration (in the following referred to as UKMO RCM CTL(30) and UKMO GCM CTL(30), respective-ly). The period was chosen around the time when the CO2 concentration in the SUL anomaly simulation (see below) reached double the value used in the present simulation. See Jones (1997) for more details.

1.2.7 The UKMO CGCM scenario simulations

Output from two different scenario simulations produced with the UKMO CGCM were used in the present assessment. Both are described in Mitchell et al. (1995). The first one, called GHG, is a simulation with gradually increasing equivalent CO2 concentration and the second one, called SUL, is a simulation which also takes into account a direct effect of increasing sulphate aerosol concentrations. Both were started from the same initial conditions as the presentday climate simulation (see above). For both, the observed increases in the anomalous forcings were imposed for the first 130 years (from 1860 to 1990) and then the integrations were continued (to 2100) with the forcings increased according to a 1% per year increase in the equivalent CO2 concentration and in the case of SUL with changes in surface albedo determined from concentrations of sulphate aerosols based on IPCC scenario IS92a. In Figure 0.3 the global annual mean radiative forcing and surface air temperatures in these simulations are reproduced from Mitchell et al. (1995) where more details of these simulations may be found.

1.2.8 RCM simulations driven by the UKMO CGCM scenario simulations.

Two 10 year time-slices of global SST fields were prepared for Météo-France from the GHG simulation. These were a "control" simulation for the years 1985-95 (UKMO GCM sca(10) in the following) and a "2 x CO2" simulation for the years 2055-65 (UKMO GCM SCA(10)). The latter time-slice is around the time of doubling equivalent CO2 concentration with respect to the 1990 value. Both time-slices are indicated in Figure 0.3. In this GHG experiment the global mean radiative forcing for the 1990 - 2060 period between the two time-slices is 4.1 W/m2 and the corresponding surface air temperature increase is 2.2K, as also indicated in the figure. At Météo-France the time-slices from the UKMO CGCM were used in two 10 year ARPEGE T63s simulations, called ARPEGE T63s sca(10) and ARPEGE T63s SCA(10), respectively.

From the SUL simulation a 30 year time-slice of 6 hourly boundary fields, from 2006 to 2035, were prepared for the UKMO RCM, HadRM2. The time-slice is around the time when the ad-

justed equivalent CO2 concentration in the scenario simulation has reached two times the value used in the present-day climate simulation. This time-slice, UKMO GCM SCA(30), is also indicated in Figure 0.3. Differences between the CGCM present-day climate simulation and this anomaly simulation should represent the climate change between 1860 and 2020. In this SUL experiment the global mean radiative forcing for this period is 2.6 W/m2 and the corresponding surface air temperature rise is 1.2K, as also indicated in the figure. The HadRM2 simulation using this output for boundary conditions is referred to as the UKMO RCM (or HadRM2) SCA(30) simulation. See Jones (1997) for more details.

A survey of all the RCM simulations assessed in the present report are shown in the following table:

RCM simulation(years)	Driving simulation(years)	Constituents changed	Concentrations used
Time-slice period	Time-slice period	Type of simulation	
HadRM2 CTL(30)	UK GCM CTL(30)	No changes	equiv.CO2 = 1950 value
Year 146 -175	Year 146 -175	Present-day Climate Simul.	
HadRM2 SCA(30)	UK GCM SCA(30), SUL	Equiv. CO2 and aerosols	Adjusted values
2006 - 2035	2006 - 2035	Scenario Simulation	equiv.CO2 = 2 x 1950 value
ARPEGE T63s sca (10)	UK GCM sca(10), GHG	Equivalent CO2	Adjusted values
1986 - 1995	1986-1995	Control (for next simulation)	equiv.CO2 = 1990 value
ARPEGE T63s SCA(10)	UK GCM SCA(10), GHG	Equivalent CO2	Adjusted values
2056-2065	2056-2065	Scenario Simulation	.equiv.CO2 = 2 x 1990 valu
HIRHAM4 CTL(9)	ECHAM4 CTL(10)	No changes	1990 greenhouse. gas conc
Year 152-160	year 151-160	Present-day Climate Simul.	
HIRHAM4 sca(9)	ECHAM4 sca(10), GHG	Greenhouse gases	Adjusted values
1986-1994	1986-1995	Control (for text simulation)	1990 greenhouse. gas conc
HIRHAM4 SCA(9)	ECHAM SCA(10), GHG	Greenhouse gases	Adjusted values
2071 -2079	2071 -2080	Scenario Simulation	equiv.CO2 = 2 x 1990 value
VHIRHAM4 CTL(9)	HIRHAM4 CTL(9)	No changes	1990 greenhouse. gas conc
Year 152-160	Year 152-160	Present-day Climate Simul.	
VHIRHAM4 SCA(9)	HIRHAM4 SCA(9), GHG	Greenhouse gases	Adjusted values
2071 -2079	2071 -2079	Scenario Simulation	equiv. CO2 = 2 x 1990 valu
CLAMBO CTL(5)	ECHAM4 CTL(10)	No changes	1990 equiv. CO2 conc.
Year 151-155	Year 151-160	Present-day Climate Simul.	
RegCM2/MM4 CTL(5)	ECHAM4 CTL(10)	No changes	1990 equiv. CO2 conc.
Year 151-155	Year 151-160	Present-day Climate Simul.	

RCM Simulations

Climatological data

1.3.1 Climatological data

The the present day climate simulations and the ARPEGE sca(8) control simulation, will be validated against climatology. As in MEA96 simulated surface pressure and upper air fields will be evaluated against ECMWF climatology based on 14 years of operational analyses (1979, 1981-1993).

The main emphasis will be put on the validation of simulations of precipitation and surface air temperature. Here we evaluate against new climatological data for Europe produced by the Climate Research Unit (CRU) of University of East Anglia, Hulme et al. (1995). Actually daily minimum and maximum temperature were analyzed by Hulme et al.(1995) and from these the daily mean surface air temperature we are using was defined as a simple average. A preliminary version of these data was used in MEA96. The deviations between this version and the final version used here are, however, insignificant. The data covers land points in Europe in a 0.5° x 0.5° latitude-longitude grid (in the following referred to as the CRU grid). Here land points are defined as grid cells with a non-zero fraction of land, whereas in the models land points are defined as grid cells with more than 50% land. This climatology is based on data from the period 1961-90, for temperature and precipitation using 1500 and 2300 stations, respectively. Interpolation of the station data to the CRU grid was done by fitting a partial thin plate smoothing spline (e.g. Hutchinson, 1991), in which elevation is included along with latitude and longitude as a predictor of the climate surface. For each parameter the data in each grid cell are given for a minimum, an area mean and a maximum value of the height of the surface topography. We have, however, mainly used the data determined for the mean height of the orography. This mean orography, shown in Figure 1.1 of MEA96, most closely matches the orography of the RCM models, some of which are shown also in the same figure. The land-sea masks used in subsequent figures were obtained by interpolating the model land sea masks (fields of fractions of land, having the value 1 in land points and 0 in sea points) to the CRU grid and then selecting as land points only those points with more than 50% land which are also land points in the CRU data.

For each variable Hulme et al. (1995) validated the performance of their method of analysis at 100 independent observation sites. They found for January and July that the mean absolute error (MAE) for maximum and minimum temperature was between 0.5°C and 0.8°C and for precipitation between 9% and 12%. For precipitation they also compared the mean-elevation CRU climatology with the Legates/Willmott climatology (the version not corrected for gauge-undercatch; Legates and Willmott, 1990). The Legates/Willmott climatology has previously often been used for validation of regional climate simulations (e.g. Jones et al.,1995 and Déqué and Piedelievre, 1995). Over most lowland areas of "greater Europe" the agreement is generally good between Legates and the mean-elevation CRU fields, over many of the larger mountainous areas, however, large differences, both absolute and relative, are apparent, in all cases the CRU climatology being wetter than Legates. This is broadly as expected, since in upland areas

where precipitation is generally largest, gauge locations are biased towards lower elevations (Legates had no elevation dependency in his interpolation scheme therefore could not correct for this bias). Hulme et al. (1994) concludes that the CRU estimates for many of the mountain areas in mainland Europe (e.g. the Alps, Norway, the Balkans) are likely to be more realistic than those of Legates. It should be noted, however, that the precipitation observations used in the CRU analysis have not been corrected for gauge biases due to wetting, evaporation or strong wind (especially important with snow fall). Also biases due to irregular horizontal and vertical distributions (i. e. over sampling of valley stations in mountainous regions) have not been accounted for. Thus specifically precipitation on model up-slopes and mountain tops must even in the CRU analysis be underestimated, especially in winter.

For monthly mean temperatures and precipitation the CRU data set includes also fields of anomalies in the same $0.5^{\circ} \ge 0.5^{\circ}$ grid over the "greater European" area for each month in the 34 year period 1961 to 1994 (Barrow et al., 1993). They are based on previous more coarse mesh global analyses (for temperature at 5° latitude by 5° longitude resolution (Jones, 1994) and for precipitation at 2.5° latitude and 3.75° longitude resolution (Hulme, 1994)). They will be used in the following to define the observed (or natural) variability in certain sub-areas of Europe against which averaged time-slice biases for each sub-area can be compared. The sub-areas are defined in Figure 0.2. They are the same sub-areas which were used in MEA96. In the design of the boundaries between the sub-areas we have tried to avoid cancellations of biases with opposite sign within the sub-areas. Thus, typically biases of both precipitation and temperature have different signs on the western up-slope of mountain ranges than on the eastern down-slope. We have therefore placed the sub-area boundaries at the summit of the Scandinavian and the former Yugoslavian mountain ranges. For similar reasons other boundaries, i. e. around the Alps, were placed so that lowland and mountain areas were separated.

In order to eliminate or at least reduce the effect of differences between the CRU mean orography and the model orographies we compute biases from surface air temperatures reduced to mean sea level (MSL). In MEA96 and CEA97 a standard lapse rare of 6.5K per km was used. As, however, some biases, apparently spurious ones, seemed to be caused by the standard lapse not being representative in all cases we have used the CRU climatological temperatures at the minimum and the maximum height in each grid cell to compute averaged "observed" lapse rates for each calendar month and each sub-area. A pronounced seasonal variation with very little geographical variation was found. The average of the 9 sub-area values are listed in the following table:

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OKT	NOV	DEC
5.01	5.66	6.01	5.97	5.88	5.84	5.53	5.22	5.33	5.24	5.21	4.94

Averaged observed lapse rates for Europe (in K per km)

During the year this averaged lapse rate vary more than 1K per km with high values in spring and early summer and with low values in autumn and early winter. All monthly values are lower than the standard lapse rate. The deviation of the monthly sub-area values from these averaged values are in most cases less than 0.05K per km (only two exceptions, one at 0.06K and the other at 0.07K). In the present report we have used these monthly averaged European values instead of the standard lapse rate.

1.3.2 Significance tests

The models as well as the real climate system exhibits even without changes in the radiative forcing variations on all time-scales. In the assessment of the model performance we want to distinguish between biases due to such internal variations and real systematic errors of a model. A model bias is computed as the difference between a mean value over a time-slice of a model simulation of certain length (N1 years) and a corresponding mean value over a time-slice of analyses of the real atmosphere, possibly of another length (N2 years). Both time-slices are assumed to be randomly picked. We want to estimate *limits of significance*, i.e. the magnitude a bias must exceed in order that it is unlikely to be due to random internal variations of the model and of the real atmosphere. If the limit of significance is exceeded we assume that the bias represents a systematic model error. Similarly, when considering changes in biases from an old to a newer model version or changes in model stages of the same model version subject to different radiative forcings (i.e. estimated climate changes) we want to estimate which changes that are significant and which changes may be due to the internal variations of the model and the real atmosphere.

Thus, for each of the sub-areas and each season we have determined *limits of significance* for temperature and precipitation, by which we mean biases or changes larger than which they are unlikely to be caused by a random sampling of time-slices varying with the model's, respectively the real atmosphere's, internal variability.

As measures of the models internal variability we have for each sub-area and each season computed standard deviations of the time series of yearly mean values and of 5-, 10- and 30-year running mean values based upon the 300 year MPI CGCM present-day climate simulation. Additionally, from the available 34-year time series of observed (CRU) data, we have computed corresponding standard deviations for yearly and for 5- and 10-year running mean values. These standard deviations are listed in the following Tables 3A and 3B:

Table 3A: Standard deviations for running mean values of sub-area averaged surface air temperatures for four seasons (tenths of K)

Temperature (0.1 K)	Ν	NE	W	С	Ε
CRU Data, 1 year	20/09/08/09	28/12/09/12	10/06/07/06	16/08/07/07	24/13/09/10
CRU Data, 5 years	12/09/04/09	17/07/04/04	05/04/03/03	09/04/03/03	14/05/04/04
CRU, Data10 years	06/03/02/03	08/04/03/03	03/02/02/01	05/02/01/02	06/03/02/02
ECHAM4, 1year	19/11/08/10	29/16/09/13	12/09/09/07	16/11/08/08	28/17/08/13
ECHAM4, 5 years	09/06/04/05	14/07/05/07	05/04/04/03	06/05/04/04	12/08/04/06
ECHAM4, 10 years	07/04/03/04	10/05/04/05	04/03/03/02	05/03/03/02	08/05/03/04
ECHAM4, 30 years	04/02/02/03	06/02/02/04	02/02/02/01	03/02/02/01	05/02/02/02
Temperature (0.1 K)	Alps	SW	S	SE	Total
Temperature (0.1 K) CRU Data, 1 year	Alps 12/08/08/07	SW 08/07/07/07	S 08/07/06/07	SE 12/10/06/08	Total 13/07/05/06
Temperature (0.1 K) CRU Data, 1 year CRU Data, 5 years	Alps 12/08/08/07 06/04/04/04	SW 08/07/07/07 03/05/04/04	S 08/07/06/07 03/02/04/05	SE 12/10/06/08 04/03/03/04	Total 13/07/05/06 08/03/03/03
Temperature (0.1 K) CRU Data, 1 year CRU Data, 5 years CRU, Data10 years	Alps 12/08/08/07 06/04/04/04 03/02/03/03	SW 08/07/07/07 03/05/04/04 02/03/03/04	S 08/07/06/07 03/02/04/05 02/01/03/04	SE 12/10/06/08 04/03/03/04 03/02/02/03	Total 13/07/05/06 08/03/03/03 04/02/01/02
Temperature (0.1 K)CRU Data, 1 yearCRU Data, 5 yearsCRU, Data10 yearsECHAM4, 1year	Alps 12/08/08/07 06/04/04/04 03/02/03/03 16/12/09/09	SW 08/07/07/07 03/05/04/04 02/03/03/04 10/09/08/07	S 08/07/06/07 03/02/04/05 02/01/03/04 13/09/08/08	SE 12/10/06/08 04/03/03/04 03/02/02/03 17/12/07/10	Total 13/07/05/06 08/03/03/03 04/02/01/02 15/10/05/07
Temperature (0.1 K)CRU Data, 1 yearCRU Data, 5 yearsCRU, Data10 yearsECHAM4, 1yearECHAM4, 5 years	Alps 12/08/08/07 06/04/04/04 03/02/03/03 16/12/09/09 06/06/04/04	SW 08/07/07/07 03/05/04/04 02/03/03/04 10/09/08/07 04/04/04/03	S 08/07/06/07 03/02/04/05 02/01/03/04 13/09/08/08 05/04/04/04	SE 12/10/06/08 04/03/03/04 03/02/02/03 17/12/07/10 07/05/03/05	Total 13/07/05/06 08/03/03/03 04/02/01/02 15/10/05/07 06/04/02/03
Temperature (0.1 K)CRU Data, 1 yearCRU Data, 5 yearsCRU, Data10 yearsECHAM4, 1yearECHAM4, 5 yearsECHAM4, 10 years	Alps 12/08/08/07 06/04/04/04 03/02/03/03 16/12/09/09 06/06/04/04 04/04/03/03	SW 08/07/07/07 03/05/04/04 02/03/03/04 10/09/08/07 04/04/04/03 03/03/02/02	S 08/07/06/07 03/02/04/05 02/01/03/04 13/09/08/08 05/04/04/04 03/02/03/03	SE 12/10/06/08 04/03/03/04 03/02/02/03 17/12/07/10 07/05/03/05 04/03/02/03	Total 13/07/05/06 08/03/03/03 04/02/01/02 15/10/05/07 06/04/02/03 04/03/02/02

(DJF/MAM/JJA/SON)

Without going into a detailed comparison between observed (CRU) and modeled (ECHAM4) standard deviations we shall note some general features starting with the yearly seasonal mean values, labeled "1 year":

For temperatures the model sub-area standard deviations fall between 0.7K and 2.9K. The values varies with season with largest values in winter and smallest in summer or autumn. The values are generally largest in "NE" and "E" and are decreasing towards west and south. The CRU values correlate well with the model values within a similar range and thus, their seasonal and spatial variations are similar to those of the modeled values. Generally the observed standard deviations are sightly smaller than those of the model. The only exceptions are in winter in "N" and in summer in "E" when the observed inter-annual variations are larger than the modeled ones.

Table 3B: Standard deviations for running mean values of sub-area aver-
aged precipitation for four seasons in per cent of observed values

Precipitation (%)	Ν	NE	W	С	Ε
CRU Data, 1 year	32/25/17/20	19/20/17/14	21/19/19/17	23/19/17/18	19/19/17/19
CRU Data, 5 years	17/10/06/08	10/06/08/08	08/09/09/08	10/09/06/06	10/06/09/08
CRU Data, 10 years	09/05/03/03	06/04/06/04	05/06/06/04	06/05/04/02	05/03/09/03
ECHAM4, 1year	14/15/10/10	28/24/12/20	17/17/14/13	28/22/13/23	23/19/10/20
ECHAM4, 5 years	06/06/05/04	12/10/08/08	07/08/07/06	11/10/06/10	10/09/05/09
ECHAM4, 10 years	04/04/03/03	08/07/06/06	05/06/05/04	08/07/04/07	07/06/03/06
ECHAM4, 30 years	03/02/02/02	05/04/03/04	03/03/03/02	05/03/02/05	05/03/01/03

(DJF/MAM/JJA/SON)

Precipitation (%)	Alps	SW	S	SE	Total
CRU Data, 1 year	23/18/17/24	37/27/35/34	26/18/28/20	26/18/17/23	12/07/08/08
CRU Data, 5 years	11/06/06/12	14/11/15/16	15/07/10/09	18/06/08/10	05/03/03/03
CRU, Data10 years	06/03/05/05	09/08/10/10	09/04/07/05	11/03/06/07	02/01/01/01
ECHAM4, 1year	21/13/07/18	31/23/27/21	20/21/25/17	26/20/10/26	11/10/06/09
ECHAM4, 5 years	09/06/03/08	14/10/12/09	09/09/11/08	10/09/04/12	05/05/03/04
ECHAM4, 10 years	06/04/02/05	10/07/08/06	06/06/08/05	07/06/03/09	03/03/02/02
ECHAM4, 30 years	04/02/01/03	05/04/06/04	04/04/04/02	04/03/02/06	02/01/01/02

For precipitation the model standard deviation varies between 6% and 31% of the observed 30 -year mean precipitation (see Table 2). The spatial variation is somewhat different from that of the temperature standard deviations. The values varies with season, again with largest values in winter and smallest in summer or autumn. The seasonal variation is largest in the central and eastern sub-areas where the observed variances generally are smaller than the modeled ones. In all these sub-areas the summer season is, however, an exception with the observed variation being the largest. In the western sub-areas and in "N" and "Alps" the inter-annually variation is more uniform throughout the year with values of standard deviations generally increasing toward the south and with observed values larger than the modeled ones.

Concerning the standard deviations computed from time series of running n-year mean values they should theoretically be equal to the standard deviation of the (yearly) seasonal mean values divided by the square root of n, n being 5, 10 or 30. This may be seen in the tables to be the case in practise, approximately.

Assuming normal distributions "Students" t-tests are used to estimate which precipitation and

temperature biases or changes are statistically significant at the 95% level (P). In all cases we used the following condition for a significant difference between two mean values X1 and X2 over periods of N1 and N2 years, respectively:

$$|X_1 - X_2| > t(n, P) \cdot \sqrt{\frac{N_1(N_1 - 1)\sigma_1^2 + N_2(N_2 - 1)\sigma_2^2}{n} \cdot \left\langle \frac{1}{N_1} + \frac{1}{N_2} \right\rangle}$$

where t(n,P) is the "Students" t distribution as a function of n = N1+N2-2 degrees of freedom and P=95% and the sigmas are estimated standard deviations of the mean values.

In these estimations we have assumed that the above standard deviations determined from the 300-year long MPI CGCM simulation are representative also for the other model simulations considered here (all of which were available only for much shorter periods). We also assume that the model standard deviations are independent of the changes between the different model versions we consider and are also independent of the changes in radiative forcing considered. As the standard deviation of modeled 30 year mean values (HadRM2) we use the above listed directly computed MPI CGCM standard deviations based on time series of running 30-year mean values. As the standard deviation of modeled 9 and 10-year simulations (present HIRHAM4, present and previous (in MEA96) Météo-France and UKMO simulations) we use those based on MPI CGCM time series of running 10-year mean values and as the standard deviation of modeled 46 month and 5-year simulations (present and previous (in MEA96) HIRHAM3 simulations and the present CLAMBO and RegCM2 simulations) we use those based on MPI CGCM time series of running 5-year mean values. As the model standard deviations increase with increasing length of model time-slices used it is obvious that so do the *lim*its of significance. Thus, smaller biases and changes will be estimated as significant for the "5year simulations" than for the rest of the experiments, especially the UKMO experiments. As the biases of temperature and precipitation we consider here are each a difference between a modeled mean value (X1) over a certain period (N1 years) and an observed climatological mean value (X2) over a 30 year period (N2) we need standard deviations for a population of observed 30-year mean values. Since we have available time series of only 34 years of observed (CRU) values the standard deviation of observed 30-year mean values cannot be computed directly, so instead the above mentioned theoretical relation to the standard deviation of the observed yearly seasonal mean values were used.

2.0 Systematic errors in the present-day climate simulations

We shall consider in this section fields of biases of mean sea level pressure (MSLP), surface air temperature and precipitation. When referring to a bias for a given season we mean the deviation from climatology of a sample averaged value, i. e. the deviation from the ECMWF or the CRU climatology of the seasonal mean value averaged over all years in the time-slice period considered. A systematic error is a bias which is essentially independent of the sample (the time-slice) chosen, i.e. has a statistical significant magnitude. We call the MSLP biases system-

atic errors because they seem to a large extent to be systematic for a certain model. This has been demonstrated at least for 10 year time-slices of ECHAM3 and ECHAM4 model simulations (Klaus Arpe, personal communication). We shall see that also the temperature and precipitation biases considered here to a large extent are systematic.

We have available results from five regional present-day climate simulations. Namely, HadRM2 CTL(30), HIRHAM4 CTL(9), VHIRHAM4 CTL(9), CLAMBO CTL(5) and RegCM2 CTL(5). Since no present-day climate simulation is available with ARPEGE T63s we include in the following instead the ARPEGE T63s sca(10), i.e. the 1986-1995 time-slice of the scenario simulation (which also serves as a control for the ARPEGE T63s SCA(10) simulation in a climate change experiment). When interpreting the results it must be taken into consideration that the ARPEGE T63s sca(10) simulation is not really a present-day climate simulation. Together with the regional model simulations we consider also the simulations performed with the corresponding driving models.

As in CEA97 and MEA96 maps of all fields will be presented on the common verification area, 35°N - 75°N and 15°W - 35°E, shown in Figure 0.1. We shall refer to this as the CRU domain.

2.1 General performance of the models

In Figures 1.1 - 1.8 we present from four of the RCM simulations maps of seasonally averaged values of the *mean MSLP*, the *standard deviation of band pass filtered* (2.5 - 6 *days*) 500 hPa *heights* (Blackmon, 1976) and *the systematic errors in MSLP*. Also shown is the ECMWF MSLP climatology. The four RCM simulations included in these figures are the HadRM2 CTL(30), ARPEGE T63s sca(10), HIRHAM4 CTL(9) and VHIRHAM4 CTL(9). In the same figures are shown similar fields for the CGCM/RCM time-slice simulations used for boundary conditions. In Figures 3.3 and 3.4 the same fields are shown for the two remaining RCM simulations, CLAMBO CTL(5) and RegCM2 CTL(5), respectively.

As in MEA96 we present here the maps of *the systematic errors in MSLP* because of their inherent information about the errors in the general circulation, defined here as the mean horizontal and vertical motions of the lower troposphere. It is well known that in reality to a large extent the general circulation determines the time averaged surface air temperature and precipitation fields. This is the case especially for a region as Europe situated next to the Atlantic Ocean in the west wind belt. To the extent that the parameterization of physical processes works as in reality this should be the case also for the models. Systematic errors in the circulation patterns should therefore together with errors in the physical parameterization explain the biases in the temperature and precipitation patterns, our primary interest here. As shown in MEA96 and summarized in the introduction, systematic errors in the simulations considered there in the horizontal and vertical mean motions and in the eddy transport of heat and moisture seem to explain large errors in temperature and precipitation over all parts of Europe. We shall summarize shortly how we think the involved mechanisms work:

Between the regions of too high pressure and those of too low pressure in the MSLP bias maps we find areas of relatively *large pressure bias gradients*. Assuming gradient flow, with frictional modifications in the PBL, these are areas with erroneous horizontal advection of heat and

moisture by the mean flow in the lower troposphere. When the erroneous advection is enforcing (or weakening) an advection from the Atlantic, for instance, it intensifies (or weakens) the advection of moist air which typically leads to increased (or decreased) cloudiness and precipitation. An erroneous advection of Atlantic air usually also imply an erroneous transport of heat which together with errors in cloudiness, may lead to errors in the surface air temperature. Such temperature biases may be large, especially in the extreme seasons, winter and summer. In the winter time too much cloud will tend to lead to too high temperatures since the increase in the downward longwave radiation is larger than the decrease in solar radiation reaching the surface. This cloud effect will increase the positive temperature biases and thus it will work in the same direction as the advection of heat from the Atlantic. In summer the direct effect of the advection of cold air from the Atlantic is also normally enhanced by the cloud effect. This is because in summer too much cloud cover must reduce the incoming solar radiation more than it increases the downward longwave radiation at the surface.

An area of *too high pressure* indicates too much subsidence and hence reduced precipitation and generally also reduced cloudiness. When the cloudiness is reduced the surface air temperature will typically be reduced in winter and increased in summer due to changes in the local radiation balance. On the other hand an area of too low pressure will indicate excessive rising motions and hence increased precipitation and probably also increased cloudiness. Increased cloudiness will typically lead to increased temperature in winter and reduced temperature in summer. When situated in connection with the North Atlantic storm track, as in the cases considered here, an area of too low pressure indicates increased extra-tropical "cyclonic activity" in the form of too manny and/or too deep low pressure systems. Such increased cyclonic activity will lead to increased precipitation, created not only by the large scale ascending motions but also by convection connected to the individual cyclones. It must also result in an increased eddy transport of heat and moisture toward the north and thus tend to create precipitation and temperature biases in the northern part of and to the north of the area of too low pressure. Typically in winter, for instance, an increased cyclonic activity will result in an excessive supply of heat and moisture in the southern part of a belt of too low pressure due to excessive advection from the Atlantic and in an increased eddy transport of heat and moisture toward the north. Thus, if sufficiently strong the excessive cyclonic activity will lead to an extension of the positive temperature and precipitation biases to the whole belt of too low pressure and even somewhat north of it where the easterly mean error flow counteract the excessive northward transports due to reduced westerly advection of heat and moisture from the Atlantic. If, however, the excessive cyclonic activity is less excessive the effect of the reduced westerlies north of the belt of too low pressure may dominate and lead to negative precipitation and temperature biases.

The position of the cyclone tracks in reality, i.e. in the ECMWF analyses, as well as in the model simulations are indicated by the fields of *standard deviation of band pass filtered 500 hPa heights* which are superimposed on the MSLP fields in Figures 1.1 to 1.8. Let us call this standard deviation the "*storm track parameter*". A belt of high values of this parameter shows approximately the preferred position of the cyclone tracks. Unfortunately, the fields of storm track parameter shown here were computed at the institutions producing the respective simulations using different procedures and they are therefore generally not comparable. Because of this we shall use the maps of the storm track parameter presented here only as an indication of the location of the storm tracks in the simulations and in the ECMWF analyses. That an area of too low pressure located in connection with the cyclone track is caused by increased cyclonic activity, as argued above, has been confirmed in a separate investigation (Machenhauer et al., 1998) involving a time-slice of the present-day coupled ECHAM4/OPYC3 climate simulation considered here and several AMIP simulations with the ECHAM4 model in different resolutions. In that study the same procedure (i.e. Blackmon, 1976) were used to compute fields of the cyclone track parameter for 1000 and 500 hPa for both the ECMWF re-analyses (ERA) and the model simulations. They are therefore comparable and in all the cases considered areas of enhanced cyclone track parameter (compared to that in the ERA) were found connected to the areas of too low pressure over Europe, thus indicating that these are indeed caused by enhanced cyclonic activity. Similarly, the areas of too high pressure to the north and the south were found to be areas of reduced cyclone track parameter indicating that they are caused by reduced cyclonic activity.

As found in MEA96 the continental scale of the systematic MSLP error pattern seems to be more or less similar for all models, at least over greater Europe, but it deviates substantially on a sub-continental scale. These deviations seem to depend on which packages of physical parameterization are used in the models. Thus, sub-continental deviations are found between the error pattern of ECHAM3 in MEA96 and ECHAM4 in the present paper. The systematic MSLP errors over Europe need not be caused by local errors in the parameterization schemes, they may even be caused mainly by errors in the forcing somewhere outside Europe, maybe in the Tropics, in this case imposed on the RCMs used here via their boundary conditions (MEA96). This would explain why the UKMO and MPI LAMs have systematic errors which are very similar to those of their driving models and also as we found in MEA96, why those of ARPEGE T63s are similar to those of an ARPEGE T42. It may, however, also be explained by similar local effects in model pairs sharing the same parameterization package. Thus, local deficiencies in the parameterization schemes may influence the dynamics of the synoptic systems which, for instance, may lead to a too slow filling of the low pressure systems that then could explain the observed areas of too low pressure at the end of the storm tracks. The locally increased resolution over Europe in the RCMs has relatively small large scale effects on the pattern of systematic MSLP errors (MEA96). A clear systematic change found with increasing resolution is, however, a further reduction of the pressure in the areas of too low pressure connected to the storm tracks, indicating a further spurious increase in the cyclonic activity. This could be due to the sharper baroclinic zones which are possible locally with the higher resolution. When a LAM and its driving GCM use different physical parameterization packages, as in the present CLAMBO and RegCM2 simulations which are both driven by MPI CGCM simulations, we shall see that larger deviations in the systematic MSLP error patterns may develop between the LAM and the driving CGCM. This indicates that local effects of the parameterization schemes may be important. Presently we can only guess about the reasons for the systematic errors in the MSLP and the related general circulation patterns over Europe, which seem to cause large systematic errors in the surface air temperature and precipitation patterns. A coming more detailed study will be devoted to finding these reasons. Here we shall try to deduce their effects only.

Whereas the simulations verified in MEA96 were run with near climatological or observed SST and sea-ice distributions these fields are in the present simulations determined from CGCM present-day climate simulations (except for the ARPEGE T63s and the driving CGCM simulation). The seasonal mean biases of the SSTs (with respect to a climatology determined from 10 years of AMIP data) in the three CGCM simulations used are shown in Figures 4.1 and 4.2. In all simulations we see non-negligible SST biases. These biases must influence the simulations of temperatures and precipitation over land and thus add another source of errors to those mentioned above. As explained in the previous section the UKMO and MPI CTL-simulations should be representative of the present-day climate as the driving models spin-up and subsequent simulations are performed with present-day conditions. The UKMO GCM sca(10) simulation, the sea surface parameters of which are used in the APEAGE T63s sca (10) simulation, is, however not. As explained above it is a time-slice of a transiently increasing CO2 scenario simulation which were started in equilibrium with present conditions and were run with the increasing radiative forcing observed between 1860 and 1985. Consequently it was run 125 years with too high equivalent CO2 concentrations. As expected, it is seen in the figures (based on just the first 8 years of the 10 year period used in the APEAGE T63s sca (10) simulation) that this simulation throughout the year has relatively large positive SST biases, at many places between 1K and 3K (the negative biases north of 75°N are probably not influencing Europe significantly). But even the two ordinary present-day climate simulations show non-negligible SST biases around Europe. They are smallest in the UKMO simulation, except for the northwestern corner of the CRU-area which probably is too far away to influence Europe. In this simulation the biases are generally numerically below 2K but at places higher values are seen. Some seasonal variations are seen, especially in the Baltic and Mediterranean seas. In the MPI simulation, the seasonal variation of the biases is much more pronounced, with extremes around Denmark and in the Mediterranean numerically up to between 3K and 5K, and even larger in the Black sea. That such large amplitude seasonal SST bias variations can develop in the MPI simulation must be because the flux corrections are not varied with season. It seems obvious that such large SST biases must influence the simulations of temperatures and precipitation significantly over Europe.

Maps showing the CRU seasonal averaged *climatological precipitation and surface air temperature (reduced to MSL)* are included in Figures 2.1 - 2.8 (the top-most maps). In the same figures are shown the seasonally averaged *biases in precipitation and surface air temperature* for four RCM simulations and the driving CGCM simulations. Similar biases for the remaining two RCMs are presented in Figures 3.1 and 3.2. Both the observed CRU values of surface air temperature and the various simulated values have been reduced to mean sea level (MSL), using the CRU based seasonally varying lapse rates (Section 1.3.1), before subtracting the former from the latter. We thereby approximately correct for the temperature differences due to height differences between the model orographies and the CRU orography.

As mentioned above we divide the European land area within the CRU domain into 9 sub-areas, shown in Figure 0.2. In Tables 1.1 - 1.4 and 2.1 - 2.4 are listed the magnitude of the mean seasonal *temperature and precipitation biases* averaged over the land points in each of the 9 sub-areas. Also shown are biases averaged over all land points in Europe (Total). It is the same sub-areas that were used in MEA96. In MEA96 a simple averaging of the point values in the lati-

tude-longitude CRU grid were used but here we have taken into account the variation of grid cell areas with latitude. This affects noticeably only the absolute sub-area mean values whereas it has negligible effects on biases and changes. Figures 5.1 and 5.2 show among others the same information in graphical form. Using the definitions of significance presented in Sub-section 1.3.2 the biases found to be significant on the 95% level are marked with bold types in Tables 1.1-1.4 and 2.1-2.4.

Temperature biases (X)	Worst case bias of CRU(10)s /CRU(5)s	Worst case devia.of MPI CGCM(30)s /CGCM(10)s /CGCM(5)s	HadRM2 (30 years)	ARPEGE T63s (10 years)	HIRHAM4 (9 years)	CLAMBO (5 years)	RegCM2 (5 years)
X<1K	100/81%	100/81/78%	47% (47%)	64% (45%)	64% (50%)	25%	36%
1K <x<2k< td=""><td>00/11%</td><td>00/16/11%</td><td>39% (42%)</td><td>22% (19%)</td><td>31% (36%)</td><td>25%</td><td>11%</td></x<2k<>	00/11%	00/16/11%	39% (42%)	22% (19%)	31% (36%)	25%	11%
2K <x< td=""><td>00/08%</td><td>00/03/11%</td><td>14% (11%)</td><td>14% (36%)</td><td>5% (17%)</td><td>50%</td><td>53%</td></x<>	00/08%	00/03/11%	14% (11%)	14% (36%)	5% (17%)	50%	53%
Extr.(X), K Sub-area Season Significant	0.9/3.3 E,/NE DJF/DJF	1.0/2.3/4.1 NE/E/NE DJF/DJF/DJF	-2.8 (-2.6) N (NE) JJA (JJA) 75%	-3.3 (4.6) S (NE) SON (DJF) 61%	-2.2 (4.6) Alps (SE) MAM (JJA) 44%	-5.7 E DJF 86%	-7.4 E MAM 71%
biases							
Precipitation biases (X)	Worst case bias of CRU(10)s /CRU(5)s	Worst case devia.of MPI CGCM(30)s /CGCM(10)s /CGCM(5)s	HadRM2 (30 years)	ARPEGE T63s (10 years)	HIRHAM4 (9 years)	CLAMBO (5 years)	RegCM2 (5 years)
Precipitation biases (X) X<20%	Worst case bias of CRU(10)s /CRU(5)s 100/78%	Worst case devia.of MPI CGCM(30)s /CGCM(10)s /CGCM(5)s 100/94/89%	HadRM2 (30 years) 34% (22%)	ARPEGE T63s (10 years) 42% (36%)	HIRHAM4 (9 years) 50% (33%)	CLAMBO (5 years) 64%	RegCM2 (5 years) 4%
Precipitation biases (X) X<20% 20% <x<40%< td=""><td>Worst case bias of CRU(10)s /CRU(5)s 100/78% 00/19%</td><td>Worst case devia.of MPI CGCM(30)s /CGCM(10)s /CGCM(5)s 100/94/89% 00/06/08%</td><td>HadRM2 (30 years) 34% (22%) 22% (45%)</td><td>ARPEGE T63s (10 years) 42% (36%) 36% (31%)</td><td>HIRHAM4 (9 years) 50% (33%) 22% (28%)</td><td>CLAMBO (5 years) 64% 14%</td><td>RegCM2 (5 years) 4% 28%</td></x<40%<>	Worst case bias of CRU(10)s /CRU(5)s 100/78% 00/19%	Worst case devia.of MPI CGCM(30)s /CGCM(10)s /CGCM(5)s 100/94/89% 00/06/08%	HadRM2 (30 years) 34% (22%) 22% (45%)	ARPEGE T63s (10 years) 42% (36%) 36% (31%)	HIRHAM4 (9 years) 50% (33%) 22% (28%)	CLAMBO (5 years) 64% 14%	RegCM2 (5 years) 4% 28%
Precipitation biases (X) X<20% 20% <x<40% 40%<x< td=""><td>Worst case bias of CRU(10)s /CRU(5)s 100/78% 00/19% 00/03%</td><td>Worst case devia.of MPI CGCM(30)s /CGCM(10)s /CGCM(5)s 100/94/89% 00/06/08% 00/00/03%</td><td>HadRM2 (30 years) 34% (22%) 22% (45%) 44% (33%)</td><td>ARPEGE T63s (10 years) 42% (36%) 36% (31%) 22% (33%)</td><td>HIRHAM4 (9 years) 50% (33%) 22% (28%) 28% (39%)</td><td>CLAMBO (5 years) 64% 14% 22%</td><td>RegCM2 (5 years) 4% 28% 68%</td></x<></x<40% 	Worst case bias of CRU(10)s /CRU(5)s 100/78% 00/19% 00/03%	Worst case devia.of MPI CGCM(30)s /CGCM(10)s /CGCM(5)s 100/94/89% 00/06/08% 00/00/03%	HadRM2 (30 years) 34% (22%) 22% (45%) 44% (33%)	ARPEGE T63s (10 years) 42% (36%) 36% (31%) 22% (33%)	HIRHAM4 (9 years) 50% (33%) 22% (28%) 28% (39%)	CLAMBO (5 years) 64% 14% 22%	RegCM2 (5 years) 4% 28% 68%
Precipitation biases (X) X<20% 20% <x<40% 40%<x Extr.(X),% Sub-area Season Significant</x </x<40% 	Worst case bias of CRU(10)s /CRU(5)s 100/78% 00/19% 00/03% 20/43 SE/N DJF/DJF	Worst case devia.of MPI CGCM(30)s /CGCM(10)s /CGCM(5)s 100/94/89% 00/06/08% 00/00/03% 15/38/41 SW/SW/SW DJF/DJF/DJF	HadRM2 (30 years) 34% (22%) 22% (45%) 44% (33%) 98 (108) NE (NE) MAM (MAM) 80%	ARPEGE T63s (10 years) 42% (36%) 36% (31%) 22% (33%) 95 (114) NE (NE) MAM (MAM) 64%	HIRHAM4 (9 years) 50% (33%) 22% (28%) 28% (39%) 123 (105) E (NE) DJF (MAM) 64%	CLAMBO (5 years) 64% 14% 22% 65 SE JJA 36%	RegCM2 (5 years) 4% 28% 68% 90 SW JJA

Table 4: Percentage distributions of all sub-area biases

To get a first rough estimate of the overall performance of the different RCM models we show in the above Table 4 for each of the models the percentage distribution of all 36 sub-area biases (nine sub-areas in four seasons) on classes of small, medium and large biases. Also shown for each simulation are the numerically largest biases and the sub-area and season where and when it was found. For the three models included in the MEA96 assessment the numbers obtained there are added in parenthesis.

We are interested in comparing the sub-area biases with the amplitudes of natural variations and modeled variations. We therefore also show in the tables distributions of worst case "observed" time-slice biases obtained from the available 34 year CRU time series, i.e. 5 year mean and 10 year mean sub-area deviations from the 1961-1990 CRU climatology. For each averaging period these distributions were determined as follows. The data for each year in the available 34-year CRU time series of monthly precipitation and temperature were at first averaged over seasons and the sub-areas. Then from the resulting 34-year time series for each sub area and each season running 5-year mean values (30 values) and running 10-year mean values (25 values) were computed.We then searched for that 5-year period, respectively 10-year period, which had the absolute largest mean bias. These 36 "worst cases" (4 seasons with 9 sub-areas) were then stratified in classes and the numbers were converted to percentage of the total number (36). The resulting distributions shown in the second column of the tables may be considered as the worst case of randomly picked 5- or 10-year time-slice simulations with a "perfect" model (the CRU analyses).

It is seen that all the 10-year worst case "perfect model" biases fall within the bias classes called "small", i. e. temperature biases numerically less than 1K and precipitation biases numerically less than 20% of the observed values. The extreme values are seen to be close to these limits. Thus, this result indicates that for randomly selected time-slices with a length of the order of 10 years larger biases in any sub-area than the "small class" magnitudes are unlikely to occur in a perfect model. Similarly it is seen that several medium and even large biases may be found in randomly chosen 5-year time-slices.

With less perfect models the sampling errors might, however, be different if the model's variability deviates from that of the CRU data. We have tried to estimate if that is the case, although only for one of our simulations, the MPI CGCM present-day climate simulation ECHAM4 CTL(300), for which we have available the long time series necessary. From this 300-year model simulation we have computed distributions of worst case time-slice deviations, i.e. 5-year, 10-year and 30-year mean sub-area deviations from the long term 300-year mean values. For each averaging period the distributions of precipitation and temperature deviations were determined as described above for the observed CRU time series, except that here deviations from the 300 year mean values rather than biases are considered. The resulting distributions shown in the third column of the tables may be considered as worst case biases of randomly picked 5-, 10-, or 30-year time-slice simulations with a "real" model with no long term mean biases.

It is seen that all the 30-year worst case model biases fall within the bias classes called "small", even the extreme values are seen to be close to or less than these limits. This result indicates that for randomly selected time-slices with a length of the order of 30 years larger biases than the "small class" magnitudes are unlikely to be picked from a real model simulation with no long term biases. In randomly chosen 10-year time-slices a few medium biases and even a large

bias may occur whereas several medium and even large biases may be found in randomly chosen 5-year time-slices. These distributions are very similar to the "perfect model" distributions, a fact that leads to the conclusion that sampling errors, even with a less perfect model, can explain only relatively small biases in any of our sub-areas. Therefore, larger biases must generally be systematic errors.

The following columns in the tables for the distributions of the RCM model simulations show clearly that generally the biases found are much larger than those explainable by random timeslice sampling. That sampling errors are of secondary importance is supported also by the relatively large biases found for the 30 year HadRM2 simulation, for which the sampling errors should be very small. These facts indicates then that at least the sub-area biases of medium and large magnitude classes are really systematic errors. In these estimations we have assumed that the above worst case distributions determined from the 300-year long MPI CGCM simulation are representative also for the other model simulations considered here, for which we have available simulations only over much shorter periods.

The numbers in parenthesis in the fourth to sixth columns are those found for the simulations in MEA96. It is seen that the HadRM2 simulation is slightly worse compared to the simulation HadRM2a in MEA96. For temperature the number of medium size biases has decreased and the number of large biases has increased. For precipitation the number of small errors has increased at the expense of medium size errors but a similar increase has occurred for the large biases. On the other hand both the ARPEGE and the HIRHAM simulation has improved somewhat. For both temperature and precipitation the ARPEGE numbers of large errors have decreased while the numbers have increased for both medium and small biases. In the case of HIRHAM the improvement is even more convincing as both the number of medium and large values has decreased and consequently the number of small biases has increased. This is the case for both temperature and precipitation which leaves HIRHAM with the best distributions among the present three RCM simulations. The reasons for the changes compared with the previous simulations are discussed in Section 2, in particular in Sub-section 2.7.

In the new simulations it is still so that far from all RCM sub-area biases are reduced compared to those in the driving CGCM. The percentage of sub-area biases which are smallest in the RCM simulation are for temperature (precipitation) 75% (28%), 56% (28%) and 39% (56%) in the HadRM2, ARPEGE T63s and HIRHAM4, respectively. The corresponding numbers for the previous simulations are 86% (28%), 53% (58%) and 53% (50%). Thus, except for the AR-PEGE temperature and HIRHAM precipitation biases, the number of improved RCM sub-area biases have decreased in the new simulations. It should be noted that for the ARPEGE simulations the new and the previous numbers are not strictly comparable as the "corresponding" GCM is not the same. Concerning the changes in sub-area precipitation between the GCMs and the corresponding RCMs they are found in most cases to be positive. Thus, averaged over Europe we find that the mean annual precipitation are increased 27%, 18%, and 21% in the HadRM2, ARPEGE T63s and HIRHAM4, respectively. As most biases in the GCMs are already positive the increases in precipitation often result in deteriorations.

In the above tables it is seen also that for the simulations with the two remaining RCMs, CLAMBO and RegCM2, the numbers in columns seven and eight show generally much larger

biases than for the other three models, although this is not the case for the precipitation biases of CLAMBO which are surprisingly small.

In spite of a general improvement of the sub-area biases for two of the RCMs we still find very large sub-area biases for all the models. Shown in the tables in the fourth rows are the largest found for each of the models. For precipitation they are convincingly larger than the corresponding "worst case" extremes. This is the case also for temperature for the 30-year simulation whereas the extreme values from the 10- and 5-year simulations are only sightly larger than the "worst case" extremes. We find as listed in the last row of Table 4 that for the model simulations considered here between 44% and 86% of the temperature biases and between 36% and 93% of the precipitation biases are of a statistically significant magnitude. Thus, also when using this measure we find that for all models a large portion of the biases must be characterized as systematic errors.

As so many of the biases are estimated to be highly significant we find it of interest to cary out an analysis of their possible causes and also in that connection to investigate if the model chances that has taken place since the simulations in MEA96 might explain the changes in performance. An exposure of the causes of the systematic errors is the prerequisite of the model improvements needed to reduce or eliminate them. As we did in MEA96 we shall, by a detailed analysis of the temperature and precipitation biases in Figures 2.1 - 2.8, show that a large part of the biases seemingly are explained by the systematic errors in the general circulation (deduced from Figures 1.1 - 1.8) and by the SST biases in the simulations (shown in Figures 4.1 and 4.2). The remaining biases (also, in general, large) then, are explained by defects in the physical parameterization schemes and in the GCMs especially by a too coarse resolution orography. (In Figures 4.1 and 4.2 the seasonal SST bias maps for the UKMO GCM sca (10) simulation are based on the first 8 years only of the full 10-year time-slice used. Inclusion of all 10 years would lead to insignificant modifications only).

2.2 The HadRM2 simulation

<u>Winter</u>

In the present UKMO simulations the systematic MSLP error fields (Figs. 1.1 and 1.2) are very similar to those found in the MEA96 simulations except that here the averaged pressure in the verification area is lower. The GCM systematic MSLP error field has an east-west belt of too low pressure in connection with the cyclone track along approximately 50°N with too high pressure to the north and south (Fig. 1.1). The pattern is similar in the RCM simulation except that here the pressure is lower in the belt of too low pressure (Fig. 1.2). This indicates an excessive cyclonic activity in this belt, which is increasing from the low resolution GCM to the high resolution RCM.

The excessive precipitation and generally positive temperature biases found most places (Figs. 2.1 and 2.2), except to the south in areas of too high pressure and at the west coasts of UK and Norway, seems to be explained partly by the too strong cyclonic activity and by errors in the low level mean advection. However, also specific systematic errors of the UKMO models are influencing the simulated climatology significantly. Such an error is the mean SST biases shown in Figures 4.1 and 4.2 with mainly positive biases except in the summer season, in par-
ticular in the Baltic and the Black Seas. Also validations of the simulated HadGM2 humidity fields have shown that the model troposphere is too moist. This means that the air advected from the Atlantic by the westerly mean low level flow in the HadCM2 as well as in the HadRM2 (through its western boundary) is too moist and too warm. Also the excessive radiative cooling and enhanced precipitation release in the UKMO models, must have influenced the results. Concerning this excessive radiative cooling we reported previously that in CEA97 the January temperature biases of the RCM were generally negative all over Europe which were explained by systematic errors in the radiation scheme, i. e. too weak downward long wave radiation at the surface. Also in the winter season simulations analyzed in MEA96 the temperature biases were generally negative, especially in the GCM simulation, which was explained similarly. The enhanced precipitation release in the UKMO models is as argued above believed to be due to excessive small scale vertical velocity variance developing in the models, in particular in the RCM.

The bias in the low level mean flow in southern Europe is westerly (Figs. 1.1 and 1.2), thereby intensifying the advection of very warm and very moist Atlantic air over the land surface in this region (here the ocean is in the mean about 5K - 10K warmer than the land at MSL).

At European medium latitudes the zonal mean flow is unbiased westerly and transports the slightly too moist and slightly too warm Atlantic air in over central Europe. The mean SST biases in the Atlantic at these latitudes (Fig. 4.1) are mostly between 0.5K and 1K, except in a thin band along the French coast where it is between 1K and 2K. This seems not enough to explain the positive temperature biases over land (Fig. 2.1 and 2.2) at these latitudes (many places 1K - 2K), also because the excessive radiative cooling tend to cool the land surface. Likewise it seems not possible that the advection by the mean flow of the slightly too moist Atlantic air (judging from the small SST biases) can supply enough excessive moisture to explain the positive precipitation biases over land, especially as these are largest in eastern Europe

In northern Europe the bias in the low level mean flow is easterly (Fig. 1.1 and 1.2), thereby decreasing the advection of warm and moist Atlantic air over the land surface in this region (here in reality the ocean is in the mean about 2K - 5K warmer than the land at MSL). This should result in a cooling over land. To judge from the mean SST biases, Fig. 4.1, the Atlantic air of the models can be up to 2K too warm which will tend to reduce the effect of the too weak advection. The large cold biases at the west coasts of UK and Norway (Figs. 2.1 and 2.2) indicate that the total effect of the errors in the advection by the mean flow is a cooling, although also the too strong radiative cooling must have contributed to the cold biases there. It seems likely also to assume also that the combined effects of the reduced mean advection speed and the increased moisture content of the air advected are reduced moisture fluxes from the Atlantic as indicated by the negative precipitation biases at the west coasts of UK and Norway (Figs. 2.1 and 2.2). This means that also the positive temperature and precipitation biases on the eastern side of the Scandinavian mountains (Sweden in particular) cannot be explained by errors in the advection by the mean flow. Therefore, it seam that a transport of heat and moisture to both medium and high latitude inland regions is necessary in order to explain the temperature and precipitation biases there. This is assumed to be carried out as meridional eddy transports brought about by the excessive cyclonic activity in connection with the east-west bands of too low pressure in both the GCM and the RCM. Thus, we think that part of the excessive heat and moisture advected from the Atlantic at low latitudes supplemented with excessive heat and moisture evaporated from the too warm Black and Baltic Seas are transported to medium and high latitudes while the moisture is released as precipitation by the organized vertical motions in connection with the excessive cyclonic activity and by small scale vertical velocity variance, resulting in the excessive precipitation and positive temperature biases there. It should be mentioned that most likely the heating in the far north is enhanced by the well know positive snow-albedo feed-back process.

The more excessive precipitation in the RCM than in the GCM may be explained by the more effective transport of moisture and release of precipitation caused by the increased cyclonic activity, in the UK models apparently intensified by the more efficient release in the RCM of precipitation by excessive small scale vertical velocity variance. The positive precipitation biases in the RCM simulation are higher in all sub-areas (Table 1.1) than in MEA96 which may be explained by the positive SST biases (Fig. 4.1) and more moist boundary conditions. The maximum sub-area bias is 65% in "E" whereas it was 52% in MEA96.

The dry areas to the south seems to be due to excessive subsidence in the areas of too high pressure there which reduces all kinds of precipitation releases.

Except in "W" all RCM sub-area precipitation biases are found to be statistically significant.

As mentioned above, in the winter season simulations analyzed in MEA96 the temperature biases were generally negative, especially in the GCM simulation, which was explained by the spuriously reduced long wave downward radiation. Due to similar systematic errors as described above for the present simulations reduced negative and even small positive biases were found east of the Scandinavian mountains, over central Europe and over parts of south-eastern Europe. As we have seen, a similar pattern of temperature biases are found in the present simulations, but here more pronounced, most likely due to the positive SST biases. Here this has resulted in improved sub-area biases compared to those in MEA96. Apart from the west coasts of Norway and UK, already dealt with, the negative temperature biases are limited to the too dry and therefore presumably less cloudy areas around the Mediterranean Sea. Although less extended the negative biases are still large. Thus, the mean biases in sub-area "S" are -5.0K and -2.0K in the GCM and RCM, respectively. The corresponding biases in MEA96 were - 5.8K and -1.8K. We explain the increased positive or decreased negative temperature biases in the RCM compared to the GCM by the larger release of latent heat and probably more clouds in connection with the more excessive precipitation generally found in the RCM.

In the RCM only the sub-area temperature bias in "S" is significant

Spring

As in MEA96, south of an area of too high pressure an east-west belt of too low pressure covers the central and southern part of the verification area in both the GCM and the RCM simulation (Figs. 1.3 and 1.4). Also as in the MEA96 simulations, the temperature biases are generally negative (Figs. 2.3 and 2.4) due presumably to the above mentioned defect in the radiation scheme. Exceptions in the present simulations are costal areas at the Black Sea and the northern Baltic Sea apparently caused by the too warm SSTs there (Fig.4.2). Most other places along the coasts

of Europe the SST biases are negative which must also have contributed to the negative temperature biases over land. This effect seems small, however, as the temperature biases are of the same magnitude as in MEA96, the largest ones being -3.8K and -2.1K in the GCM and the RCM, respectively, both in sub-area "S". All RCM sub-area temperature biases are found to be significant.

The precipitation biases resembles those in the winter season and may be explained in the same way. They are generally positive and also of a magnitude similar to those in the MEA96 simulation. The largest (relative) sub-area biases are 71% in the GCM and 98% in the RCM, both in "NE". All RCM sub-area precipitation biases are found to be significant.

<u>Summer</u>

The patterns of precipitation and temperature biases are pretty similar to those in the MEA96 simulations and they may be explained in almost the same way. The belt of too low pressure covers almost the whole verification area, with central deficits somewhat larger than in the MEA96 simulations (Figs. 1.5 and 1.6). Again this indicates excessive cyclonic activity which may explain the positive precipitation biases found everywhere except over parts of the eastern and south-eastern Europe (Figs. 2.5 and 2.6). These dry areas also have positive temperature biases whereas elsewhere they are negative. The positive precipitation biases are generally larger than in MEA96 and as usual largest in the RCM (74% in "SW" in the RCM where it was 49% in MEA96) in agreement with the higher cyclonic activity indicated by the lower pressure over most of the verification area and the more efficient release of precipitation by small scale vertical velocity variance. The negative temperature biases may be explained by the defect of the radiation scheme mentioned earlier but here enforced by the mainly too cold SSTs surrounding Europe (Fig 4.2). Therefore, they are generally larger numerically than in MEA96, in the RCM in sub-area "N" for instance the bias is -2.8K whereas it was -2.5K there in MEA96.

The positive temperature and negative precipitation biases over eastern / south-eastern Europe is caused by the positive drying-out / heating feed-back process described in the introduction. Due to deficiencies in the hydrological and radiational schemes this is leading to a too fast dry-ing-out of the soil and an excessive heating of the soil. Similar phenomena were detected in CEA97 and MEA96 for all model simulations studied there and thus also for the UKMO simulations. The drying and heating is less pronounced in the present UKMO simulations than in those studied in MEA96. This is especially the case in the RCM simulation. The negative SST biases and the higher cyclonic activity, also in the presiding winter seasons, may explain that. Except for "E" and "SE" is that the case also for all the sub-area temperature biases.

<u>Autumn</u>

The systematic errors in the MSLP fields (Figs. 1.7 and 1.8) resembles again those in the MEA96 simulations, although the belts of too low pressure situated over central and southern Europe are slightly deeper and the patterns of too high pressure to the north are less high. The same general features as in MEA96 are observed. The temperature biases (Fig. 2.7 and 2.8) are generally negative, caused presumably by the defect in the radiations scheme. Largest exceptions are again near the Black Sea and the northern part of the Baltic Sea both of which have

too high SSTs. Smaller positive SST biases are seen along the Atlantic coast where they probably have lead to reductions in magnitude of the negative temperature biases over land. The negative SST biases in the Mediterranean may explain the increased magnitude of the negative biases south of the Alps, in the RCM for instance in sub-area "S" it is -2.2K where it was -1.9K in MEA96. All RCM sub-area temperature biases are found to be significant. The precipitation biases resembles again those found in the winter season, although generally they are smaller and may be explained in the same way. Compared to MEA96 the generally positive precipitation biases has increased north of the Alps and decreased south of the Alps which may be explained by the SST biases mentioned above. The largest bias in the RCM is now 45% in subarea "NE", approximately the same magnitude as the largest one in the MEA96 simulation which were in "SW". Except that in "N" all the RCM sub-area precipitation biases are found to be significant.

2.3 The ARPEGE T63s simulation

In the present series of simulations we have not included a present-day climate simulation with a homogeneous low resolution ARPEGE simulation, i. e. a simulation with a regular T42 model, as was done in MEA6. Instead we present results of the UKMO coupled model simulation, the "UKMO GCM sca(10)" simulation, which has produced the SST and sea-ice distributions used in the present ARPEGE T63s simulation. The mean anomaly fields of the SSTs are shown in Figures 4.1 and 4.2 (only the first 8 years of the available 10-year SST data were used in the figures). Compared to those used in the UKMO GCM CTL(30) simulation (same figures) we see that they are warmer in all seasons, generally by 1 - 2K. This should be expected as mentioned before. The UKMO GCM CTL(30) simulation is a real present-day climate simulation whereas the UKMO GCM sca(10) simulation considered here is from a scenario simulation that was initialized with present-day conditions and then integrated 125 years with too high (adjusted) equivalent CO2 concentrations. Although the ARPEGE T63s use the same SSTs and sea-ice fields this model's systematic errors are quite different from those of the GCM. We shall therefore consider them separately.

In spite of the differences in SSTs (and equivalent CO2 concentrations) we should expect many similarities between the UKMO GCM sca(10) simulation and the UKMO GCM CTL(30) simulation since they were produced with the same GCM. We do in fact find quite similar systematic errors in the MSLP for all seasons as seen in Figures 1.1 to 1.8. As a consequence we see that also the patterns of precipitation biases are very similar (Figs. 2.1 - 2.8) as are also the magnitude of the sub-area precipitation biases (Tables 1.1 - 1.4 or Fig. 5.1). The differences between the sub-area precipitation biases are generally statistically insignificant, indicating that the differences may be due to inter-decadal model variations. Also the pattern of temperature biases are quite similar (Figs. 2.1 - 2.8). The magnitude of the mean values are, however, different. On the average for the whole Europe the sca(10) is seen to be warmer by 0.9K - 1.5Kwhich, of course, is explained by the warmer SSTs in that simulation. The largest differences between the two simulations are found in the winter season in the northern sub-areas due to the enhancement of the heating by the snow-albedo feed-back. Similar effects of the warmer SSTs must be expected in the ARPEGE T63s simulation which we shall next consider, season for season:

Winter

The pattern of systematic MSLP errors (Fig. 1.2) is similar to that in the AMIP simulation in MEA96, but the position of the extremes have changed slightly and their magnitudes are somewhat smaller. A trough of too low pressure with its axis at 55° -60°N extends from the Atlantic over Europe north of an area of too high pressure over the eastern Mediterranean. The much too strong zonal flow transports warm and moist air from the Atlantic into most of Europe. This explains the positive precipitation and temperature biases found at most places (Fig. 2.2). In the north the positive temperature and precipitation biases on the eastern side of the Scandinavian mountains (Sweden) must be caused by the northward eddy heat and moisture transport due to the enhanced cyclonic activity and also by the mean error flow advection of relatively moist and warm air around the center of too low pressure. Generally the magnitude of the biases are smaller than in the AMIP simulation although the positive SST biases in the present simulation tend to increase them. This reduction must be caused by the reduction of the strength of the zonal error flow. The maximum sub-area precipitation bias in the present simulation (Table 1.1) is still large, 76% in "NE" whereas in the AMIP simulation the maximum was 89% in "S". Also the temperature biases (Fig. 2.2) are somewhat reduced (Table 2.1) over most of Europe compared to the AMIP simulation, +3.1K in "E" where it was +4.0K in the AMIP simulation.

As in the AMIP simulation areas of negative precipitation biases are found at the west coasts of Norway and Scotland, caused by reduced westerlies or even reversed cross-mountain low level flow, and at the costal land areas of the Mediterranean Sea, caused by excessive subsidence in the area of too high pressure. The bias is -17% in "S", slightly smaller (numerically) than in the AMIP simulation. Negative temperature biases are seen in approximately the same areas where we have negative precipitation biases. It seems likely that these biases are due to the cloud cover effect (reduced cloud cover where negative precipitation biases) described previously. This is probably intensified due to defects in the radiation scheme, maybe similar to those in the UKMO scheme. Compared to the AMIP simulation the magnitude of the negative temperature biases have decreased slightly (-1.2K in "S" where it was -1.8K in the AMIP simulation). Except in "N", "W", and "SW" are the sub-area temperature biases significant and except for "N", "S", and "SE" are the precipitation biases significant too.

Spring

The pattern of systematic errors in the MSLP field (Fig.1.4) is somewhat different from that in the AMIP simulation. In that simulation the westerlies were too strong over the whole Europe down to the Alps, south of which a centre of too high pressure was situated. In the present simulation the positive MSLP bias to the south is reduced and so is the strength of the excess zonal flow which only extends up to about 55°N. At about this latitude a belt of too low pressure is situated north of which the error flow is reversed. The positive SST biases (Fig. 4.1) are smaller than in the winter season and in particular in the Atlantic south of 55N they are less than 1K. North of the Alps the positive precipitation biases (Fig. 2.4 and Table 1.2) are reduced compared to those in the AMIP simulation. They are still large, however, in "NE" reduced from 114% to 95%. This is in agreement with the reduced but still strong advection from the Atlantic

and the excess cyclonic activity in the belt of too low pressure. Due to this advection also the temperature biases are slightly positive here, but only up to about 60°N. Normally the ocean is slightly warmer than the land but here this difference is increased because of the positive SST biases in the Atlantic. Thus the excess advection from the ocean leads to excessive heating. Also the large positive SST biases in the Black Sea is causing larger positive temperature biases in the surrounding areas. In the north the error flow from the east (reduced westerlies) must explain the negative temperature biases there, in spite of the positive SST biases in the North Atlantic. South of the Alps the magnitude of the negative precipitation biases have decreased from the AMIP to the present simulation, in "S" from -21% to -5%, due to the reduced MSLP bias there. As in the AMIP simulation here to the south also the temperature biases are relatively small (Fig. 2.4 and Table 2.2), except for the (most likely) spurious negative biases connected with mountains. Defects in the radiation scheme may have resulted in an all over cooling which has been an additional cause of these negative biases, and those in the north as well. Except in "W", "C","E", and "SE" are the sub-area temperature biases significant and except for "N", "SW", and "S" are the precipitation biases significant too.

Summer

In the AMIP simulation a ridge of too high pressure south of about 50°N extended from the Atlantic over southern Europe north of which the westerly flow were too strong. In the present simulation the pattern is similar except that the pressure is decreased allover in the verification area and a belt of too low pressure is now centered along a line in the Atlantic running from south-west to north-east just off the coasts of Scotland and Norway (Fig.1.6). As a result the excessive advection of cold and moist air from the Atlantic is less strong and therefore the negative temperature biases (Fig. 2.6 and Table 2.3) and positive precipitation biases (Fig. 2.6 and Table 1.3) are reduced substantially over north-western Europe. The positive SST biases (Fig. 4.2) must also have contributed to the reduction of the biases. Most extreme are the decrease of the temperature bias in "NE" from -3.3K to -0.6 and the decrease of the precipitation bias in "N" from 110% to 26%.

South of the Alps the heating and drying-out process has increased, in "S" the temperature bias has increased slightly from -0.9K to +1.0K and the precipitation bias has increased (numerically) from -23% to -51%, also because of the reduced advection from the Atlantic but in addition due to the mostly positive SST biases, especially those in the Black Sea (Fig. 4.2). Except in "Alps" and "SW" are the sub-area precipitation biases significant but of the small temperature biases are only the biases in "C", "Alps", "S", and "SW" significant.

<u>Autumn</u>

The systematic MSLP errors in the AMIP simulation were dominated by a strong positive bias centered over central and southern Europe north of which the flow were too westerly. In the present simulation the positive bias centre has decreased substantially and the northern negative bias has moved south forming a negative centre between Scotland, Norway and the Faeroe Islands (Fig. 1.8). Thereby the belt of too strong westerlies has weakened and moved southward,

although not so much as in the spring and summer season. As a result the mainly positive precipitation (Fig. 2.8 and Table 1.4) biases have decreased in the northern sub-areas (in "N" from 34% to -18%) and increased in the central sub-areas (in "C" from -7% to 25%). Also the negative precipitation biases in the southern sub-areas have generally decreased numerically, in "SE" from -28% to -11%. They remain relatively large, however, in the other sub-areas: -16% and -28% in "SW" and "S", respectively. As in the AMIP simulation the sub-area temperature biases (Table 2.4) are all negative and numerically relatively large. They have increased slightly numerically in most sub-areas from the AMIP to the present simulation in spite of the fact that the SST biases (Fig. 4.2) around Europe are positive. (The largest bias is, however, slightly smaller numerically, -3.3K in sub-area "S" where it was -4.0K in the AMIP simulation). The most likely explanation of the negative temperature biases seems to be defects in the radiation scheme, similar to those in the UKMO scheme, which are compensated only partly by the excessive warm air advection from the Atlantic. All the sub-area temperature biases are significant and except for "NE" and "E", but only three precipitation biases are significant: "N", "C", and "S".

2.4 The HIRHAM and VHIRHAM simulations

Winter

The MSLP systematic errors in the ECHAM3 and HIRHAM3 AMIP simulations were very similar, both with two connected positive bias centers, one over the eastern Mediterranean and one north-east of the verification area. A negative centre was situated in the Atlantic west of the verification area. This gave positive temperature and precipitation biases due to the erroneous advection of heat and moisture from south-south-west over most of Europe except over south-eastern Europe where some erroneous subsidence lead to too dry and slightly too cold conditions. It seems likely that these cold biases were due to the cloud cover effect (reduced cloud cover where there are negative precipitation biases) described previously which probably was intensified due to the defects in the ECHAM3 radiation scheme, i.e. here reduced downward longwave radiation at the surface.

In the present simulation we find that the systematic MSLP errors (Figs. 1.1 and 1.2) are changed substantially, obviously due to the changes in the physical parameterization from the ECHAM3 to the ECHAM4 version and perhaps also due to the use of SST and sea-ice fields generated by the coupled OPYC3 ocean model instead of the observed (AMIP) ones. In the present ECHAM4 simulation the southern centre of too high pressure has moved westward to the Iberian Peninsula (Fig. 1.1). Between this center and the center of too high pressure northeast of the verification area we see a roughly east-west orientated belt of relatively low pressure. The pattern resembles now that in most other simulations, in particular the UKMO simulation (same figure), except that here the belt is at a more northerly position, at about 60°N over west-ern Europe. In the MEA96 simulations they differed considerably. The systematic MSLP errors in the HIRHAM4 and VHIRHAM4 simulations (Fig. 1.2) are very similar to those in the ECHAM4, except that in both simulations the pressure as usual has decreased further in the belt of relatively low pressure. This indicates too strong cyclonic activity in these belts, in particular

in the high resolution simulations around the southern part of the Scandinavian Peninsula.

The small scale ridge of too high pressure over Scandinavia and the troughs on each side of it increase with increasing resolution. This ridge/trough "error pattern "is created by the westerly flow, crossing the mountain chain. Its increase with resolution, due to the increase in height of the mountain chain and perhaps roughness with increasing resolution, is seen in all seasons. Similar patterns are seen in the ARPEGE and in the RSCS II simulations although with less amplitudes. It is difficult to say if it is in fact error patterns as they could also be due to a too smooth MSLP analysis. We know, in fact, that the analyses are somewhat too smooth.

The map of seasonal SST biases with respect to the AMIP SSTs (Fig. 4.1) shows generally too warm SSTs, 0.5K - 3.0K, especially near Denmark and in the Mediterranean. Exceptions are a too cold northern part of the Baltic sea and areas with negative biases to the north. The latter biases are, however, too far away to influence Europe significantly.

In the belt of too low pressure and in the too strong zonal flow south of it we find as expected positive precipitation and temperature biases (Figs. 2.1 and 2.2). As the error flow transports warm and moist air deeper into Europe in the HIRHAM4 simulation the positive precipitation and temperature biases extends more toward the east and are larger than in the ECHAM4 simulation. In the AMIP simulations the positive temperature and precipitation biases over central Europe were substantially smaller than those found in the present simulations. Thus, in the HIRHAM simulations the bias in sub-area "E" has increased from 56% and 1.1K to 123% and 1.6K in the present simulation. The main reason must be the changes in the systematic circulation errors but also the too high SSTs in the Atlantic must have contributed to these bias increases es. Also around the Black Sea have the too high SSTs in the present simulations obviously caused excessive temperature biases.

The positive temperature and precipitation biases in the northern part of the belt of too low pressure on the eastern side of the Scandinavian mountains (Sweden) must be caused by the northward eddy heat and moisture transport due to the enhanced cyclonic activity and the advection by the mean error flow of relatively moist and warm air around the center of too low pressure, just as in the ARPEGE simulation. Here the too low SSTs in the Baltic Sea must have reduced these biases.

Over Finland/Russia both the temperature and the precipitation biases show significant differences between the ECHM4 and the HIRHAM4 simulations. The biases in "NE" are -0.5K/58% in ECHAM4 and 1.9K/91% in HIRHAM4. In this respect the ECHAM4 resembles more the AMIP simulations in MEA96. The differences can be explained by the differences in the systematic flow errors. In the HIRHAM4 simulation the trough of too low pressure extends so far east that the effects of the intensified mean advection from the Atlantic and the eddy transports due to increased cyclonic activity influence also Finland/Russia. On the other hand in the ECHAM4 these influences reach not so far east and furthermore the easterly error flow which weakens the advection from the Atlantic is stronger and covers more of the Finland/Russia area. This explains the negative temperature biases and less positive precipitation biases found over Finland/Russia. It illustrates that even seemingly small differences in the systematic MSLP errors may cause large differences in temperature and precipitation biases. The VHIRHAM simulation covers only the northern sub-areas, "N" and "NE". With the increasing resolution from ECHAM4 to VHIRHAM4 we see in "N" a monotone decrease of temperature bias from +2.4K to -0.7K and an increase in precipitation bias from -17% to +40%, also monotone. A similar variation with resolution were seen in the AMIP simulations. As mentioned earlier, the CRU analyses most likely underestimate the precipitation, especially for snow and at up-slopes and tops of mountains. Therefore the precipitation in the CRU analysis is most likely underestimated in sub-area "N". We do not know how much, but 40% may not be unrealistic in the winter season. Thus, our results do indicate an improvement in orographical precipitation with increasing resolution, which apparently is explained by the increasing realism of the mountains with increasing resolution when, as here, the bias in the cross-mountain flow is relatively small. Turning now to the decreasing temperature with increasing resolution in "N" the only explanation we can think of is connected with the eddy heat transport by the traveling extra-tropical cyclones. The cyclone track parameter patterns (Fig. 1.1 and Fig. 1.2) indicate that in the models the main track is south of Norway whereas in the ECMWF analyses it is north-west of Norway along its coast. For sub-area "N" the Scandinavian mountains must shelter against the northward heat transport connected with cyclones moving south of Norway whereas cold air advection from the Norwegian Sea on the western side of the cyclones unhindered can reach the area. The sheltering effect of the mountains must increase with increasing resolution due to the increasing height of the mountains. This process imply a decreasing temperature with increasing resolution whereas other resolution dependent processes we can think of have the opposite effect. Thus, the more southerly low level mean flow, the increasing release of latent heat and the supposed increasing cloud cover with increasing precipitation all tend to increase the temperature with increasing resolution. Apparently these processes are more than counteracted by the sheltering effect of the mountains.

Only in "W", "C", and "SE" are the HIRHAM sub-area temperature biases significant but except for "Alps" and "SW" are all the precipitation biases significant.

Spring_

Also in the spring season has the systematic MSLP error pattern changed from that in the AMIP simulations. In the north the positive bias has weakened and the one in the south has moved westward and is intensified. The western negative bias has almost vanished and the eastern one has increased slightly. The pattern of the HIRHAM4 (and VHIRHAM4) systematic MSLP error is rather similar to that of the ECHAM4 simulation (Figs. 1.3 and 1.4) and that is the case also for the temperature and precipitation bias patterns (Figs. 2.3 and 2.4). The too low pressure over eastern and central Europe indicate increased cyclonic activity which explain the enhanced precipitation there and north of that area. To the north reduced westerlies give negative biases on the western slope of the Scandinavian Peninsula. In the AMIP HIRHAM simulation the maximum precipitation biases were in "E" and "NE", 100% and 105%, respectively. These have been reduced slightly in the present simulation to 89% and 96%, respectively (Table 1.2).

Approximately the same area that has excessive precipitation is also too cold which may be explained by the easterly error flow, i. e. decreased warm advection by the westerlies, north of the center of too low pressure and increased southward cold advection mainly by the eddies to the east and by the mean error flow over central and southern Europe. Here we have in the present simulations relatively large negative biases in some sub-areas. In the HIRHAM4 simulation for instance -2.2K and -1.5K in "Alps" and "SE", respectively (Table 2.2). These are obviously enhanced due to the negative SST biases in the Baltic Sea (Fig.4.1). On the other hand due to different errors in the mean circulation the temperature biases in the AMIP simulations were mostly positive and rather small over central and southern Europe.

The temperature biases over the most western part of Europe (UK, western France and the Iberian Peninsula) are small but generally positive (In HIRHAM4 +0.4K in "W"). The biases are caused by advection from the Atlantic where the SSTs are higher than the land surface air temperatures (it is normally so and besides the SST biases are slightly positive (Fig. 4.1)) or in the south because of reduced cloud cover in the areas of too high pressure. In the same areas plus countries along the Mediterranean coasts, i. e the areas surrounding the area with positive precipitation and negative temperature biases, the simulations are mostly too dry which can be explained by the too high pressure surrounding the center of too low pressure

Similarly to the winter season we see in "N" that with the increasing resolution from ECHAM4 to VHIRHAM4 the temperature bias decreases from -0.3K to -3.1K and the precipitation bias increases from -10% to +32%, both monotonously. These variations may be explained as for the winter season.

Except in "NE", "W", and "SW" are the HIRHAM sub-area temperature biases significant and except for "W","C", "Alps" and "SW" are the precipitation biases significant too.

Summer

In the AMIP simulations the MSLP systematic error fields for the summer season were relatively slack. For the present simulations they have more structure. The ECHAM4 error field (Fig. 1.5) show a belt of too low pressure across the verification area with a center over southern U.K. A center of too high pressure is situated over the eastern Mediterranean. In the HIRHAM4 (and VHIRHAM4) the negative bias center over England has expanded, mainly northward (Fig. 1.6). In the area of too strong westerlies south and south-east of the pressure bias center over England we see as expected positive precipitation and negative temperature biases in ECHAM4 (Fig. 2.5) due to the advection from the Atlantic. This is the case also in the HIRHAM4 (and VHIRHAM4) simulation but here the cold and moist air is advected by the mean error flow around the more northerly center over England, giving positive precipitation and negative temperature biases also over the Scandinavian Peninsula and Finland (Fig. 2.6). The map of SST biases with respect to the AMIP SSTs (Fig. 4.2) shows generally too cold SSTs, biases down to - 5.0K, especially near Denmark and in the Mediterranean. Exceptions with positive biases are areas to the north-west which, however, probably are too far away to influence Europe significantly. Obviously the large negative SST biases around Europe must have contributed to the negative biases over land in all three model simulations. It should be mentioned that the negative temperature biases over land around the Baltic Sea in the ECHAM4 simulation are partly fictive. They are caused partly by the fact that also air temperatures at sea grid points have been used in the bilinear interpolation to the CRU grid. This will tend to spread the negative biases

in the SSTs (Fig. 4.3) to coastal land points within one grid length from a sea point in ECHAM4. Due to a much smaller grid length this effect is negligible in HIRHAM4 (the SSTs were interpolated at first to the HIRHAM4 grid using only ECHAM4 sea points) and VHIRHAM4.

As in the winter and spring season we see in "N" that with the increasing resolution from ECHAM4 to VHIRHAM4 the temperature bias decreases, here from -0.2K to -3.4K, and the precipitation bias increases, here from -41% to 10%, both monotonously. These variations may be explained as for the winter season except that here in the summer the cloud cover effect must contribute to the decreasing temperatures. Preliminary analyses have in fact shown that the total cloud cover increases from HIRHAM4 to VHIRHAM4 in "N". Even in summer a certain underestimation of the CRU climatological precipitation amounts must be expected so that the precipitation simulated by VHIRHAM4 may be realistic.

The positive temperature and negative precipitation biases, mainly over south-eastern Europe, are due to the excessive summer drying-out /heating process described previously. Here we note that, as expected, they have been reduced considerably compared to those in the AMIP simulations (e.g. the HIRHAM4 bias is 1.2K in "SE" where it was 4.6K in the AMIP simulation). The improvements must be due to changes in soil parameters and the improved radiation scheme in the ECHAM4 physics as discussed in the introduction. However, also the negative SST biases (Fig. 4.2) must have contributed to the reduction of the biases.

About half the HIRHAM sub-area biases are significant: for precipitation those in "E", "Alps", "S", and "SE" and for temperature those in "N", "NE", "Alps", "SW", and "SE".

<u>Autumn</u>

In the AMIP simulations a belt of too low MSLP were crossing the verification area from the north-western corner to the south-eastern one. South of that a ridge of too high MSLP were covering south-western Europe. Both the belt of too low pressure and the ridge were slightly stronger in the HIRHAM3 than in the ECHAM3 simulation. This gave too dry conditions south-west of the belt of too low pressure and too much precipitation north-east of that belt. The temperature biases were generally positive and relatively small.

In the present simulations we see also a belt of too low pressure (Figs. 1.7 and 1.8) but here orientated east-west and deeper than in the AMIP simulation, again deepest in the HIRHAM4 simulation. The center of too high pressure over the Mediterranean is much weaker than the ridge in the AMIP simulations. The enhanced subsidence near the center of too high pressure and the dry and hot soil left over from the summer season can explain the too dry, e.g. -35% precipitation bias in "S" in HIRHAM4 (Table 1.4), and too warm conditions over southern Europe (Figs. 2.7 and 2.8). This is an improvement compared to the AMIP simulation (-57% in "S" in HIRHAM3), due partly to the weaker positive MSLP bias and probably also partly due to the reduced drying-out / heating process in the summer season.

As usual, in the belt of too low pressure and north of it east of the mountains the precipitation biases are positive. This is explained by the enhanced cyclonic activity and the excess advection from the Atlantic connected with the belt of too low pressure. As this is deepest in the HIRHAM4 simulation the biases are largest there. In HIRHAM4 the precipitation bias in "E"

is +70% which is an increase compared to the AMIP simulation where it was only +14%. Except for spots of negative biases in connection with mountains the temperature biases are generally positive but rather small in central and northern Europe. The main reason must be the excessive advection from the Atlantic. Normally, at the latitudes in question and this time of the year the ocean is only slightly warmer than the land but here this temperature difference is enhanced due to the SST biases (Fig.4.2).

In the north the error flow from the east, i. e. reduced westerlies there, may explain the negative temperature biases there and the negative precipitation biases on the western slopes of the mountains. Also in the autumn, as in the other seasons, we see in "N" that with the increasing resolution from ECHAM4 to VHIRHAM4 the temperature bias decreases, here from +1.0K to -2.6K, and the precipitation bias increases, here from -31% to -1%, both monotonously. These variations may be explained as for the winter season. Due to the expected underestimation of the CRU climatological precipitation amounts in this case even the VHIRHAM4 seems to have underestimated the precipitation in "N".

Only three of the temperature sub-area biases are of a significant magnitude: these are "N", "Alps", and "S". For precipitation all sub-area biases are significant except those in "W" and "SW".

2.5 The CLAMBO simulation

Winter

The MSLP systematic errors of the five year CLAMBO simulation are shown in Figure 3.3. As in the driving ECHAM4 simulation (Fig.1.1) a center of too high pressure is situated over south-west Europe, but here it is much stronger (+14 hPa whereas it is + 5 hPa in ECHAM4). As expected, the enhanced subsidence and advection from the Atlantic due to this error pattern result, except over mountains, in too dry conditions over southern Europe, -42% in "SW", and generally in too wet conditions over central Europe, +23% in "C", (Table 1.1, Fig. 3.1). Note the positive precipitation biases over the mountains in southern Europe (Fig. 3.1). They must be caused by a spurious up-slope transport of heat and moisture to the model mountain tops by diffusion along the terrain following model surfaces. When averaging over sub-areas they will tend to compensate the negative biases in-between the mountain areas. We see the same pattern all year round (Fig 3.1) which explains the relatively small sub-area precipitation biases as seen in Table 4.

The large negative temperature biases, Fig. 3.1, e.g. -5.7K in "E", (Table 2.1) are not as expected from the MSLP bias pattern. The enhanced advection from the Atlantic should normally, as in the ECHAM4 and HIRHAM4 simulations, lead to positive temperature biases. Most likely the excessive cold temperatures are due to defects in of the cloud/radiation schemes used in the model. Also in the prefect boundary simulation presented in CEA97, the January 1991 simulation with the CLAMBO model, showed very large negative temperature biases. It was suggested in CEA97 that the reason could be a systematically too weak downward long-wave radiation similar to that which had been found in the previous ECHAM3 radiation scheme. The excessive values of the biases in the CLAMBO January 1991 simulation compared to those found in the

HIRHAM3 simulation do, however, indicate that this is not the whole explanation. Most likely the biases are also due to lack of tuning of the radiation scheme to its use in the CLAMBO model (the same scheme developed by Ritter and Geleyn (1992) has been used also in the present ARPEGE T63s simulations) It seems as if the lack of tuning has lead to a further decrease in downward longwave radiation.

The much larger deviations from the ECHAM4 MSLP systematic error pattern than in the HIRHAM4 simulation (Fig. 3.3 and Figs. 1.1/1.2) is probably caused by the large negative temperature biases in the CLAMBO simulation. When the temperatures drops in the limited area model inward directed pressure gradient forces must develop at the boundaries. This may then lead to spurious inward directed fluxes of mass in the boundary relaxation zone which can explain that the average pressure in the LAM domain becomes too large.

All sub-area temperature biases are significant whereas only three of the precipitation sub-area biases are significant, namely those in "C", "SW", and "S".

Spring

The systematic errors in MSLP resembles those in the winter season. Again stronger positive biases over south-western Europe than in the ECHAM4 and the HIRHAM4 simulations. As expected, the enhanced subsidence and advection from the Atlantic due to this error pattern result in too dry conditions over southern Europe (-12% in "SW"), except over mountains (+33% in "Alps"), and generally too wet conditions over central Europe, +16% in "C", (Table 1.2, Fig. 3.1). Over most of the eastern part of Europe the temperature biases are negative (-3.1K in "E"). As these large temperature biases cannot be explained by erroneous mean advection it seems reasonable to assume again that they are due to defects in the radiation/cloud parameterization schemes which maybe have been intensified by the effect of too much cloud cover in connection with the excess precipitation here. The temperature biases (Table 2.2, Fig.3.1) over the most western part of Europe (UK, France and the Iberian Peninsula) are generally positive (+0.8K in "W") which can be explained by the excessive advection from the too warm Atlantic. Normally, the too strong advection from the Atlantic should not affect the temperature biases significantly as the climatological surface temperatures are quite similar over land and ocean at the latitudes covered by CLAMBO. The ECHAM4 SSTs used in the simulation are, however, warmer than the climatological ones (Fig. 4.1).

Except in "C" and "SW" are all the sub-area temperature biases significant but of the precipitation biases only the one in the "Alps" is significant.

Summer_

Compared to the HIRHAM4 simulation (Fig. 1.6) we see a deeper negative MSLP bias covering most of Europe (Fig. 3.3). The temperatures are extremely high all over Europe with the largest positive bias, +7.5K, in sub-area "SE" (Table 2.3) and the precipitation is very low (e.g. -65% in "SE") with the exception of some mountain areas (only - 3% in "Alps"). The dry and hot conditions must have been developed by the positive drying-out feed-back process described previously. In the CLAMBO simulation this process apparently is intensified, most likely due to too strong solar radiation as in previous HIRHAM3 simulations, but here obviously further intensified, probably due to lack of tuning of the radiation scheme. The hot temperatures must have led to reduction of the surface pressure (the heat low formation process) which then has contributed to the large negative MSLP biases.

All sub-area temperature biases are significant and except "Alps" and "SW" so are the precipitation biases.

<u>Autumn</u>

Compared to the HIRHAM4 simulation (Fig. 1.8) the too high MSLP to the south (Fig. 3.3) is intensified and the belt of too low pressure is weakened (Fig. 3.3). The too high pressure is less pronounced and situated further south than in the winter and spring seasons. As in the winter and spring seasons the enhanced subsidence and advection from the Atlantic due to this error pattern result in too dry conditions over southern Europe (-20% in "S"), except over mountains (+52% in "Alps"), and generally too wet conditions over central Europe (+12% in "C") (Table 1.4, Fig. 3.1). Except for the south-eastern part of Europe the temperature biases (Table 2.4, Fig.3.1) are generally negative (-1.4K in "SW"). As these negative temperature biases cannot be explained by erroneous advection it seems reasonable to assume again that they are due to defects in the radiation/cloud parameterization schemes. As in the spring, normally, the too strong advection from the Atlantic should not affect the temperature biases as the climatological surface temperatures are quite similar over land and ocean at the latitudes covered by CLAMBO. The SSTs used in the simulation (Fig. 4.2) are, however, warmer over the Atlantic than the climatological ones so that the advection from the Atlantic must have reduced the cold temperature biases.

Except in "C" and "SE" are all the sub-area temperature biases significant but of the precipitation biases only that in "Alps" is significant.

2.6 The RegCM2 simulation

Winter

The MSLP systematic error field of the five year RegCM2 simulation is shown in Figure 3.4. As in the driving ECHAM4 simulation (Fig.1.1) a center of too high pressure is situated over south-west Europe, but here it is much stronger (+11 hPa whereas it is + 5 hPa in ECHAM4). Also the belt of too low pressure to the north-east is similar to that in the driving ECHAM4 simulation, but again much deeper. As expected, the enhanced subsidence due to this error pattern result in too dry and probably due to reduced cloud cover also too cold conditions over southern Europe, -75% and -2.7K in "S". At mid latitudes we find generally too wet and warm conditions, +17% in "C" and +2.9K in "W", (Table 1.1 and 2.1, Fig. 3.2) due to the enhanced advection from the warm Atlantic. The positive SST biases in the driving model must have contributed to the positive temperature and precipitation biases over land. The cold biases in the south-eastern and the north-eastern corner of the integration area indicate a too strong general long wave radiative cooling in the model which may have contributed also to the large negative bias in "S". The relatively large positive precipitation bias in "E", i. e. +47%, is apparently coursed by a spurious release of precipitation near the boundary zone (data from the 7 point boundary zone are not included in the figures).

Only in "W", "C" and "S" are the sub-area temperature biases significant but except for "C" and "SE" is that the case for all the precipitation biases.

<u>Spring</u>

The systematic errors in MSLP resembles those in the winter season (Fig, 3.4). Again a strong positive bias is situated over south-western Europe. In the interior of the LAM area the pattern is very much different from that in the driving ECHAM4 simulation (Fig. 1.3) although they may fit at the outermost boundaries (not shown). As expected, the enhanced subsidence due to this error pattern result in too dry conditions over southern Europe, -69% in "SW", which is decreasing toward north-east, -22% in "E", (Table 1.2, Fig. 3.2). Over central and eastern Europe we find large negative temperature biases which increases toward the eastern boundary, -7.4K in both "E" and "SE" (Table 2.2, Fig.3.2). As these large temperature biases cannot be explained by erroneous advection it seems reasonable to assume that they are due to defects in the radiation/cloud parameterization schemes. The temperature biases over the most western part of Europe (UK, the western France and the western Iberian Peninsula) are generally positive though small (+1.2K in "SW") which might be explained by the excessive advection from the south and west, in the latter case from the too warm Atlantic (Fig. 4.1).

All the sub-area temperature and precipitation biases are significant.

Summer

In the interior of the LAM area the pattern of MSLP errors (Fig. 3.4) is again very much different from that in the driving ECHAM4 simulation (Fig. 1.5) although it may fit at the outermost boundaries (not shown). Whereas the MSLP biases were generally negative in the HIRHAM4 simulation we see here a slack generally positive MSLP bias pattern covering most of Europe (Fig. 3.4). The temperatures are extremely high all over central and southern Europe with the largest positive bias, +5.9K, in sub-area "SW" (Table 2.3) and the precipitation is very low all over Europe (-90% in "SW"). The dry and hot conditions must have been developed by an excessive positive drying-out / heating feed-back process. In the ResCM2 simulation this process apparently is intensified, most likely due to too strong solar radiation due to defects in the radiation scheme as in previous HIRHAM3 simulations, but here obviously further intensified due the too high pressure.

All temperature and precipitation biases are significant.

<u>Autumn</u>

Compared to the driving ECHAM4 simulation (Fig. 1.7) the too high MSLP to the south is intensified, the center value from 2 hPa to 5-6 hPa, and the belt of too low pressure is weakened (Fig. 3.4). The enhanced subsidence due to this error pattern results in too dry conditions over most Europe, especially to the south where the center of too high pressure is situated (-80% in "S" and -23% in "C") (Table 1.4, Fig. 3.2). In the north-eastern part of the integration area the temperature biases (Fig.3.1) are generally negative (-2.4K in "E", Table 2.4,) which we assume must be due to defects in the radiation/cloud schemes as they cannot be explained by erroneous advection. This is the case, however, for areas around the too high pressure pattern where excessive southerly and westerly advection seems to have caused the positive temperature biases seen in Figure 3.2 and Table 2.4 (+2.1K in "SW"). As in the spring, normally, the too strong westerly advection should not affect the temperature biases significantly as the climatological surface temperatures are quite similar over land and ocean at the latitudes covered by RegCM2. The ECHAM4 SSTs used in the simulation (Fig. 4.2) are, however, warmer over the Atlantic than the climatological ones so that the excess westerly advection leads to positive temperature biases.

In only "E", "SW", and "S" are the sub-area temperature biases significant. All the precipitation biases are significant.

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2.7 Comparisons with previous simulations

In the present Sub-section we shall consider the changes in biases of temperature and precipitation of the present RECS, ARPEGE and HIRHAM simulations compared to the corresponding "perfect ocean" simulations we validated in MEA96. In doing so we shall concentrate mainly on statistically significant changes, by which we mean changes that are so large that it is unlikely they could be due just to internal model variations in essentially unchanged models, or in other words exclude that they could be differences between random samples from the same population. Significance is again based on the 95% "Students" t-test assuming that the standard deviations we have estimated from the MPI CGCM simulation (Table 4) are representative also for the RCM simulations. We summarize and extend the explanations we propose for the changes in biases in order to validate further the applicability of the explanations we have suggested here and in MEA96 for the reasons of the biases in the various simulations. Note that as all biases are defined relative to the same CRU data, changes of biases are equivalent to changes in the simulated time-slice mean values.

Compared to the validation performed in MEA96 of simulations with previous versions of the models an important change is that in the present validation the SSTs used are simulated by CGCMs rather than being observed AMIP SSTs or mixed-layer ocean SSTs close to climatology. The seasonal mean biases of the SSTs in the CGCM simulations with respect to the AMIP climatology (Figs. 4.1 and 4.2) were found in all cases to be non-negligible. They are smallest in the UKMO control simulation, generally numerically below 2K but at places higher values are found, in particular in the Black sea. Some seasonal variations are seen, especially in the Baltic and Mediterranean seas, with too cold SSTs in summer and too warm SSTs in winter. In the MPI simulation, a similar seasonal variation of the biases is much more pronounced, with extremes around Denmark and in the Mediterranean sea numerically up to between 3K and 5K, and even larger values in the Black sea. These large amplitude seasonal variations in the MPI simulation can develop because the flux corrections are not varied with season. The UKMO 1990 scenario simulation, used in the ARPEGE T63s simulation, has throughout the year relatively large positive SST biases, at many places between 1K and 3K. The seasonal variation and horizontal pattern of the biases are similar to that found in the UKMO control simulation but the preceding 125 year simulation with increased (too high) GHG concentrations seems to have added a more or less homogeneous bias of about 0.5 - 1.5 K.

It was shown in Table 4 that statistically the sub-area temperature and precipitation biases for the UKMO RCM simulation have increased slightly in magnitude compared to those found in the MEA96 simulation (increased number of large biases). This deterioration is most likely due to the SST biases in the present HadRM2 simulation and moister boundary conditions from the driving GCM. The effects of the SST biases are seen most clearly in the UKMO simulations because there only few other model changes were made. The only major changes are a slightly reduced size of the RCM domain and an extension of the integration period from 10 years to 30 years. Essentially the same atmospheric model versions are used as in the MEA96 validation, no significant changes have been made though they did have a significant global impact on the driving GCM, HadCM2. As a consequence we found that direct and indirect effects due to the SST and humidity biases were easily detectable.

We found in many cases that the SST and humidity biases lead to deteriorations. Let us mention the most important cases: In the winter season increased temperature and precipitation biases at high and middle latitudes were ascribed to the too high SSTs in the Atlantic. Except for the temperature increases in "W" (+0.9K) these changes were, however, not found to be significant, even the large temperature increase in "NE" (+2.3K) were not significant due to the large variability in "NE". Likewise, in the spring and autumn seasons increased positive temperature biases in coastal areas at the northern part of the Baltic Sea and at the Black Sea were ascribed to positive SST biases there. In the Autumn season also increased negative temperature biases south of the Alps seemed to be explained by negative SST biases in the Mediterranean and a relatively large increase in the positive precipitation biases north of the Alps were explained by the positive SSTs in the Atlantic. No significant sub-area temperature changes were, however, connected with these probable SST induced changes.

Cases were found also in the HadRM2 simulations where the introduction of SST biases seems to have resulted in compensations of errors. Thus, in the autumn the negative temperature biases were found to be decreased over western Europe and also a negative precipitation bias in "W" was found to decrease significantly (16%), both changes presumably due to the positive SST biases in the Atlantic. South of the Alps the large positive precipitation biases were also reduced (significantly in "SW" and "S", 31% and 19%, respectively) presumably due to the negative SST biases in the Mediterranean.

The changes in the MSLP bias pattern, and thereby the general circulation, were relatively small in the HadRM2 simulations showing that these biases are indeed systematic errors. Some changes, thought to be due to changes in the general circulation, were, however, seen. Thus, large significant precipitation increases in "E", "Alps", and "SE" in the spring (increases of 29%, 10%, and 17%, respectively), caused presumably by wormer and moister air from the Atlantic transported and released more efficiently by the increased cyclonic activity in the present simulation as indicated by up to 5 hPa lower pressure in these sub-areas than in the former simulation, has obviously lead to a deterioration. Looking for a local reason of this change we found that it could be due to the influence of the 4-5K too warm Black Sea (Fig. 4.1) acting as an increased heat and humidity source. This source south of and east of the sub-areas in question must have intensified the baroclinic zone there as indicated in the map of surface air temperature biases, Fig. 2.2. Also significant changes in sub-area biases over central and southern

Europe in the summer season (temperature decreases of about 1-2K and precipitation increases of about 20-40%) seemed to be explained by larger MSLP biases in the present HadRM2 simulation, i. e. by a lower pressure (3-5 hPa) in those areas. The increased cyclonic activity indicated by the lower pressure should explain the enhanced precipitation which in the model in this region this time of the year must be more of the heat-low type. The reduced temperatures could then be due to the associated increased cloud cover, but an additional cause was thought to be the up to 2K too cold SSTs around Europe (Fig. 4.1). The lower pressure which presumably is the main reason for these significant changes appears not to be caused by local changes in the SSTs. They may, however, still be caused by changes in the forcing due to the SST biases, just induced from somewhere else on the globe, e. g. in the Tropics.

Although the SST biases are generally larger in the ARPEGE and the HIRHAM simulations their effects are less easily detectable in these simulations due to larger changes in the systematic errors of the general circulation caused by the changes in the physical parameterizations. The effects of the relatively large SST biases may even be larger than in the HadRM2 simulations but they are often masked or even compensated by other large changes.

It was shown in Table 4 that all over the sub-area temperature and precipitation biases for the present ARPEGE T63s simulation have decreased in magnitude compared to those found in the AMIP simulation. Due to the larger differences in SSTs and the model changes described in Sub-section 1.1.3 we find more changes to be significant than for the UKMO simulations. The most significant changes are in both temperature and precipitation for the winter and summer seasons. The main reason is in both seasons a reduction of the large biases in the zonal flow. Averaged over Europe the biases in precipitation and temperature are improved from 31% and 2.0K to 25% and 1.1K in winter and from 28% and -1.8K to 10% and -0.1K in summer. Thus, when averaged over Europe the biases are rather small in the present simulation. However, in individual sub-areas we still have some large biases as seen in the tables (1.1, 1.2 and 3). The effects of the generally higher SSTs in the present simulation must have counteracted the improvements in temperature in winter and increased the improvement of the temperature in summer. This is in agreement with the larger improvement in summer than in winter. The significant changes are primally in "N" and "NE" but in the summer season also in "C" and "E". The cause of the dominating factor, the reduced zonalization, can be either the changes in the parameterizations or the influence of the SST biases, or both. As seen in Figure 4.1 and 4.2 the positive SST biases increases toward the north and this gradient in the excess heating will tend to reduce the north-south temperature difference and thus lead to a reduction of the zonal flow. The changes in the horizontal diffusion mentioned in Sub-section 1.1.3 may, however, also have had a positive effect.

Also in the spring a reduced zonalization and thus reduced advection of moisture from the Atlantic in northern and central Europe seems to explain reduced positive precipitation biases there (in "N" and "E" significant changes of -81% and -20%, respectively). At the same time the precipitation is increasing significantly in southern sub-areas (+29% in "SW"), which is explained by the elimination of the excessive high MSLP there in the AMIP simulation. For the autumn similar explanations were given of large significant reductions of precipitation in northern Europe and significant increases in some central and southern European sub-areas. In summer, in sub-area "S" and "SE", we see a clear increase in the excessive drying and heating, in "S" a significant temperature increase of 1.9K and a precipitation decrease of 28%. This deterioration which results in rather large precipitation and temperature biases seems to be due to the introduction of a bottom runoff in the moisture surface scheme, but it must also be influenced by the reduced advection from the Atlantic and the positive SST biases, especially those in the Black Sea.

Turning finally to the MPI simulations we saw in Table 4 that also the present HIRHAM simulation shows a general reduction of biases compared with the AMIP simulation validated in MEA96. Of the three RCMs this model has undergone the most extensive changes in the physical parameterizations (Section 1.1). This is the main reason for the many significant changes in its simulation of temperature and precipitation, most of which are improvements. However also the relatively large SST biases must have contributed to the changes in performance.

In the winter season we find significant increases in precipitation biases in "W", "C", "E", "Alps", and "SE" which are accompanied by only small changes in the temperature biases. The precipitation increases is explained by increased moisture advection from the Atlantic to these areas. The reason for the temperature not being affected must be a compensation of two effects: the increase in mass of the advected air is compensated by its lower temperature as the air is coming from a more motherly direction. Also the effect of the positive SSTs (Fig. 4.1) must be compensated by the more motherly advection. In "SE" the precipitation bias has changed sign because the centre of too high pressure moved toward the west reducing subsidence and opening up for the advection from the Atlantic. Except improvement in "W" and "Alps" these changes in precipitation represent deteriorations, especially those in "C" and "E".

In the spring we find significant increases in the precipitation in "S" and "SE" explained again by the movement of the southern centre of too high pressure toward west. Significantly lower temperatures in central and southern sub-areas and increased precipitation in "N" are also explained by changes in the circulation, i. e. increased advection from the north and from the west, respectively. In some sub-areas these changes are improvements, in others they are not.

Some large improvements are achieved in the summer season. These improvements are explained mainly by improved physical parameterizations. Large positive temperature biases in the southern sub-areas are almost eliminated and the deficit in precipitation in "SW" is significantly reduced. This is explained by a general reduction of the excessive summer drying and heating process due to changes in the surface and radiation schemes. These improvements in temperature and precipitation are, however, also helped by the negative SST biases (Fig. 4.2) and an increased westerly advection bias which also explain significant increases in precipitation and decreases in temperature in "W" and "C", also improvements.

Also in summer in "N" and "NE" increased easterly advection biases, i. e. decreased westerlies, leads to significantly decreased precipitation and increased temperatures, which also are improvements. The negative SST biases has counteracted the increase in temperature to the north and increased the decrease in the south and they may be the reason why we still have negative temperature biases in the sub-areas "N", "NE" and now also in "C". Thus, it seems that some of the improvements in the primary weather elements are caused by increased errors in the gen-

eral circulation and by the SST biases.

The autumn simulation has also benefited from the changes in the physical parameterizations as well as by changes in the circulation, almost like in the summer season. Significant increases in precipitation and decreases in temperature are found in central and southern sub-areas, in most cases improvements, exceptions are new large positive precipitation biases in "C" and "E" which represent deteriorations. The changes are explained by the changes in the surface and radiation schemes helped by increases in the westerlies but here in the autumn are the temperature changes counteracted by the positive SST biases in the Atlantic. To the north in "N" and "NE" reduced westerlies explain decreased precipitation, a small but significant deterioration in "N" and a slight improvement in "NE". The changes in circulation which explain these changes in biases of the primary weather elements are in this case not due to increased MSLP errors but just due to changes in the position of extremes with almost the same magnitude.

3.0 Analysis of climate change experiments

We shall in this section consider the climate changes over Europe simulated with four of the RCMs driven by output from 1 x CO2 and 2 x CO2 CGCM time-slice simulations as described in Section 1.2. The four different RCM climate change experiments we analyze for Europe are all based on the IS92a scenario (IPCC, 1992) (the UKMO simulations only approximately). One experiment were performed with the HadRM2 model taking boundary conditions from a 30 year time-slice of a recent UKMO CGCM experiment. It is designed to simulate changes in long term mean values from 1860 to 2020 due to effects of increasing greenhouse gas and a direct effect of sulphate aerosols. The 30 year HadRM2 present-day climate simulation verified in Section 2 were used as the control simulation. We call this experiment and the corresponding one for the driving GCM model the SUL experiments whereas the remaining experiments, where only changes in greenhouse gases were included, are referred to as the GHG experiments. One of the GHG experiments were performed with the ARPEGE T63s model using SST and deep soil temperatures based on two 10 year time-slices of a transient GHG simulation performed with the UKMO CGCM. It should simulate the changes between 1990 and 2060. The 1990 time-slice is used here as the control simulation. It was also validated in Section 2. A second GHG experiment were performed with the HIRHAM4 model taking boundary conditions from two 9 year time-slices of a transient GHG simulation performed with the ECHAM4 model. It should simulate the changes from 1990 to 2075. Finally, a third GHG experiment consists of simulations with the double nested VHIRHAM4 model taking boundary conditions from two 9 year HIRHAM4 simulations. This last experiment, covering only Scandinavia, use as the control simulation the present-day climate simulations validated in Section 2. It should simulate changes over the period 1860-2075. Thus, the four climate change experiments considered represent all different forcings over different periods. However, at least the ARPEGE and HIRHAM experiments should be comparable as the forcings and periods are pretty similar.

Similarly to what we did in the preceding section with biases we define sub-area changes as significant if they exceeds estimates of internal model variability based on a 95% "Students" t test. For the 9- and 10-year time-slice simulations we use standard deviations of decadal mean

values determined from the MPI CGCM (Table 4). Similarly, for the 30-year simulations we use standard deviations of 30-year mean values determined from the MPI CGCM. The magnitude of the changes will be compared also with the magnitude of the corresponding biases found in the preceding section of the present-day climate simulations. We shall see that with a few exceptions in all GHG experiments the sub-area temperature changes are significant and of the same order of magnitude or larger than the corresponding biases in the present-day climate simulations. This is due to a large more or less homogeneous heating contribution caused by the radiative forcing and it is saying nothing about the eventual significance of smaller regional deviations created by advection, snow-albedo feed back processes and interactions with seasonal variations in moisture and cloud cover. To study such questions we consider separately for each season the averaged temperature changes for Europe as a whole and the sub-area deviations from these mean values. In order to indicate which of the sub-area temperature deviations that are statistically significant the changes in question have been underlined in Tables 2.1 - 2.4.

3.1 The HadRM2 SUL experiment

Of the CGCM climate change experiments providing boundary conditions for the RCM experiments considered here the UKMO SUL experiment represent the smallest radiative forcing. The CO2 doubling is with respect to a relatively small value, the 1950 equivalent CO2 concentration and the doubled value is an adjusted equivalent CO2 concentration. Furthermore, the direct effect of the sulphur aerosols included in this experiment reduces the forcing (Fig. 0.3). Differences between the anomaly simulation UKMO GCM SCA(30) (the time-slice around 2020) and the control simulation UKMO GCM CTL(30) (the present-day climate simulation) should represent the climate change between 1860 and 2020. The global mean radiative forcing for this period is only 2.6 W/m2 and the corresponding surface air temperature rise is 1.2K, as also indicated in Figure 0.3. This is much smaller changes than in the "GHG only" experiments also considered here which have forcings between 4.1 and 6.7 W/m2 and global warmings of between 2.2 and 3.4K. Over Europe the reductions due to the aerosols included in the SUL experiment are even stronger than in the global mean (Mitchell et al., 1995). On the other hand the longer time-slice period, 30 years, in the SUL experiment imply that smaller changes become significant. Boundary conditions from these UKMO CGCM time-slices were used in two corresponding HadRM2 simulations

Winter

The changes of MSLP in both the CGCM and the RCM (HadRM2) experiment, Figure 6.1, are very small and so are the changes in precipitation, Figure 7.1, they can hardly be seen in the figures. None of the RCM precipitation sub-area changes, Table 1.1, reaches the level of significance and in the GCM only the increase in "S" is significant. All these changes are much smaller than the corresponding biases of the present-day climate simulations. The sub-area temperature changes in the RCM are between 1.0K and 1.8K, quite similar to those in the GCM. They are of a significant magnitude in all sub-areas except in "E", Table 2.1, and are generally of the same order of magnitude as or larger than the corresponding biases. A separation

show, however, that whereas the mean change of temperature for Europe is significant and larger than the bias in both the GCM and RCM experiment none of the sub-area deviations from this mean value are significant and they are generally smaller than the corresponding biases of the present-day climate simulations. Even though the changes in MSLP are small the patterns of precipitation and temperature changes are consistent with it. The small increases in precipitation over southern Spain and at the whole Mediterranean coast is consistent with the lower pressure in south-west giving increasing southerly advection from the sea. Also the small decreases in precipitation and relatively small temperature increases in "W", "SW" and "C" can be ascribed to the weakening of the westerlies there. In "N", and "NE" the relatively large temperature increases must be due to the snow-albedo feed-back.

Spring

The changes in MSLP, Figure 6.2, are more pronounced than in the winter season with a center of more than 2 hPa increase in pressure over eastern Europe and a center of more than 2 hPa decrease in pressure over the Atlantic, the latter extended in a trough toward the northern Scandinavia. The patterns of precipitation and temperature changes are consistent with these MSLP changes. Small increases in precipitation in "SW, "W", "N" and "NE", two of them significant in the RCM, and at the Mediterranean coast (Fig. 7.3, Table 1.2) are due to the decrease in pressure and the changes in advection there. The increase in pressure in the east causes the decrease in precipitation in "S", "SE", and "E". The latter two are significant in both the GCM and RCM. All of the sub-area temperature changes reaches the level of significance, Table 2.2. The changes are, however, generally smaller than or of equal magnitude as the corresponding biases of the present-day climate simulations. Also the mean change of temperature for Europe is significant in both the GCM and RCM experiment and of equal magnitude as the corresponding biases. The temperature increase is largest in the north, in the RCM in "NE" 2.3K, due to the snow-albedo feed-back and decreases toward the south, in the RCM and GCM respectively to 1.1K and 1.0K in "SE". The sub-area deviations from the European mean values in "N" and "NE" are significant and so are the deviation in the GCM in "SE", but in all cases they are smaller than the biases. The changes in circulation is seen also to influence the pattern of temperature changes. Thus, we see that the increased advection from the south in "S", "Alps" and "C" explain the larger temperature increases there, e.g. 1.7K in "Alps" in the RCM, than east and west of these sub-areas, although the lower temperature increase around the Black Sea (Fig. 7.3) apparently is due to the relative small temperature increase in that sea (Fig. 8.1).

Summer

The changes of MSLP in both the GCM and the RCM experiment, Figure 6.3, are very small and so are the changes in precipitation, Figure 7.5, they can hardly be seen in the figures. The temperature changes (Fig. 7.6) are pretty homogeneous, the sub-area changes in the RCM are between 1.1K and 1.5K, quite similar to those in the GCM. The precipitation sub-area changes in "W"", "Alps", and "S", Table 1.3, reaches the level of significance and for the temperature, Table 2.3, all of them does. The mean change of temperature for Europe is significant in both the GCM and RCM experiment but only the sub-area deviations from the mean value in "S" and "SE" in the GCM are significant. The changes are, however, generally smaller than or of equal magnitude to the corresponding biases of the present-day climate simulations. Even

though the changes in MSLP are small the patterns of changes are consistent with it. Thus, the small, but significant, increase in precipitation and the relatively small temperature increase in "S" and "SE" are consistent with the increased southerly advection from the Mediterranean Sea.

<u>Autumn</u>

Again the changes of MSLP in both the GCM and the RCM experiment, Figure 6.4, are very small and so are the changes in precipitation, Figure 7.7, they can hardly be seen in the figures. The temperature changes (Fig. 7.6) are pretty homogeneous, the sub-area changes in the RCM are between 1.1K and 1.5K, quite similar to those in the GCM. Except "S" in the RCM none of the precipitation sub-area changes, Table 1.4, reaches the level of significance but all of the temperature changes does, Table 2.4. The mean change of temperature for Europe is significant in both the GCM and RCM experiment. Except for the European mean temperature change the changes are generally smaller than or of equal magnitude to the corresponding biases of the present-day climate simulations. Even though the changes in MSLP are small the patterns of changes are consistent with it. The small increase in precipitation and the relatively small temperature increase in north-western Europe as well as the negative deviation from the European mean value in "W" in the RCM are significant, and the decreased precipitation in southern Europe, significant in the RCM in "S", is consistent with the advection of smaller temperature changes from the Atlantic and the increased northerly advection.

3.2 The ARPEGE T63s GHG experiment

Of the climate change experiments considered here the UKMO CGCM GHG experiment, providing SSTs for the ARPEGE T63s experiment, represents a medium radiative forcing (Fig. 0.3). The CO2 doubling is with respect to the 1990 value, and no effects of sulphur aerosols are included in this experiment. Differences between the time-slice around 2060 (the anomaly simulation UKMO GCM SCA(10)) and the time-slice around 1990 (the control simulation UKMO GCM sca(10)) should represent the climate change between 1990 and 2060. The global mean radiative forcing in the UKMO GCM simulation for this period is 4.1 W/m2 and the corresponding global surface air temperature rise is 2.2K, as also indicated in the figure. These are much larger changes than in the SUL experiment. SSTs from the two time-slices of the UKMO GHG simulation were used in two corresponding ARPEGE simulations. In ARPEGE also climatological deep soil temperatures (DSTs) must be specified. For the control time-slice the same field was used as in the AMIP simulation validated in MEA96 and for the anomaly timeslice monthly anomaly fields were added. These anomalies were monthly time averaged difference fields between corresponding surface air temperatures in the two time-slices of the UKMO simulation. A time filter was applied to the monthly anomalies to account for the depth of the soil layer with climatological temperatures. The 1990 CO2 concentration, 354 ppmv, used in the ARPEGE control run were not completely consistent with the averaged adjusted equivalent CO2 concentration, 477 ppmv, used in the control time-slice of the UKMO simulation. In the ARPEGE 2060 time-slice simulation the CO2 concentration was doubled to 708 ppmv while the concentration used in the UKMO simulation was 954 ppmv. Sensitivity experiments have shown that the precise values of the CO2 concentrations in the ARPEGE simulation is not that important and it is assumed therefore that the inconsistency with the values used in the driving

GCM simulations must have influenced the surface variables only negligibly. Since the climate changes deduced from the UKMO GHG experiment differ substantially from those of the AR-PEGE experiment, due presumably to different physical parameterization packages, we shall for each season analyze them separately. (In Figures 6 -8 the climate change maps for the UKMO CGCM GHG experiment are based on the first 8 years only of the full 10-year time-slices used. Inclusion of all 10 years would lead to insignificant modifications only. All 10 years were used in the experiments and they were included in the maps for the ARPEGE GHG experiment as well as in the Tables 1 and 2 for both experiments)

Winter

The UKMO CGCM GHG experiment

For this experiment Figure 6.1 show a center of decreased pressure in south-west, more than 9 hPa, with a trough to a weaker center in north-east. It also shows a center of increased pressure in south-east, more than 4 hPa. The changes in the precipitation is in agreement with these MSLP changes. The precipitation increases in south-west in the center of decreased pressure and along the trough line to the north-eastern center due to increased cyclonic activity (Figure 7.1). The precipitation also increase at the coast of the western Mediterranean Sea due to increased advection from south. The increases in "SW", "S", and "NE" are significant. In connection with the center of increased pressure in the south-east we see an area of reduced precipitation due to the increased subsidence there. The maximum sub-area change is +40% in "NE" (Table 1.1).Generally, however, the precipitation changes are smaller than or of the same order as the biases of the control simulation.

We find as expected a large-scale pattern of temperature changes here in the winter season, with the largest temperature increase in north-east due to the snow-albedo feed-back (Fig. 7.2). The pattern seems, however, to be modified locally due to the other changes. The southward shift (compare with the ECHAM4 field, same figure) is probably caused by the increase in precipitation just north of the maximum, which can have pushed the boundary of permanent snow southward. Furthermore, a secondary maximum is formed over southern Europe due to the increased advection there from the south. The sub-area changes are between 2.0K and 4.2K (Table 2.1). They are statistically significant in all sub-areas except "NE" and they are generally substantially larger than the corresponding bias in the control simulation. An exception is in "S" where a bias in the control simulation of -4.3K is almost compensated by a change of +4.0K. The mean change of temperature for Europe is significant and much larger than the corresponding bias but only the sub-area deviations from this mean value in "W", caused by advection of smaller changes from the Atlantic, is significant and several of the biases are much larger than the corresponding deviations.

The ARPEGE experiment

The changes in MSLP are very different from those in the UKMO experiment (Fig. 6.1). Over southern and central Europe the pressure has decreased while north of about 58°N the pressure has increased. This pattern of pressure changes is in agreement with the changes in precipitation (Figure 7.1) with increases over southern and central Europe and decreases over northern Europe. The sub-area increases in "C", "E", "Alps", "S", and "SE" are all significant with the

largest one, 38%, in "S". Except for the sub-areas "S", and "SE" the changes are, however, smaller than the biases in the control run.

A large temperature increase due to the snow-albedo feed-back process is as expected seen in north-east (Fig. 7.2), +2.3K in "NE" (Table 2.1). The effect of the westerly advection over north-west Europe of smaller changes from the Atlantic is to reduce the changes there, the minimum sub-area change is + 1.1K in "W". Due to the excessive westerlies already in the control simulation (Figure 1.2) this reduction is particular strong in this experiment and goes deeply into Europe. The sub-area changes are significant over central and southern Europe but generally of the same order of magnitude as the biases of the control run. They are in all sub-areas smaller than in the UKMO GHG experiment. The averaged increase for the whole Europe is 1.9K whereas it was 3.3K for the UKMO experiment. The excessive maritime influence in the present experiment explains why the changes are smaller than those in the UKMO GHG experiment. The averaged European change is significant and larger than the corresponding bias but none of the sub-area deviations from this mean value are significant and many biases are much larger than the corresponding deviations.

Spring

The UKMO GCM experiment

In this experiment only relatively small changes has taken place in the MSLP pattern (Fig.6.2). The pressure has increased slightly over central and southern Europe along a ridge-line from north-west to south-east and decreased slightly around that area. As a consequence only small changes are found in the precipitation (Fig 7.3): Small decreases in southern sub-areas, around - 10% (Table 1.2), and small increases in the remaining sub-areas, +2% to + 24%, only the change in "NE" being significant and all of them of the same order of or smaller than the biases of the control simulation.

The sub-area temperature changes are between 1.8K and 2.9K (Table 2.2), all of them significant and generally larger than the biases of the control run. The pattern is relatively homogeneous, except that north-east of the ridge-line the increased advection from north-west has obviously reduced the temperature increases and south-west of that line the increased southeasterly advection has increased the changes (Fig. 7.4). The averaged European change is significant and larger than the corresponding bias but none of the sub-area deviations from this mean value are significant and several biases are much larger than the corresponding deviations.

The ARPEGE experiment

The MSLP changes in this experiment (Fig. 6.2) are larger and again completely different from those in the UKMO GCM experiment. A center of reduced pressure, more than 3 hPa, is situated over southern Scandinavia with a trough line extending east- an westward from the center. This pattern of change is somewhat similar to the pattern of systematic errors in the control run (Fig. 1.4). The precipitation has increased (Fig 7.3) in the trough due to enhanced cyclonic activity and to the south of it due to increased westerly mean advection (41% in "E", Table 1.2). To the south-west where the pressure has increased as expected reductions in the precipitation are seen (- 30% in "SW"). The sub-area precipitation increases in "C", "E", and "SE" as well

as the decrease in "SW" are significant but they are generally of the same order as or smaller than the biases of the control simulation.

The sub-area temperature changes are between 1.7K and 3.4K, all of them significant and generally much larger than the biases of the control run. South of the trough-line the excessive westerlies in the control siumulation (Figure 1.4) which is further enforced by the incremental advection from west explains reduced temperature increases and north of that line the incremental easterly advection leads to increased changes (Fig. 7.4). For the present season there is no all over tendency for the temperature increase to be smaller than in the UKMO GHG experiment, the averaged increase for the whole Europe is 2.4K in both experiments. The averaged European change is significant and larger than the corresponding bias but none of the small subarea deviations from this mean value are significant and several biases are larger than the corresponding deviations.

<u>Summer</u>

The UKMO GHG experiment

Only relatively small changes has taken place in the MSLP pattern (Fig.6.3). The pressure has decreased over north-eastern Europe and small, insignificant increases are found over UK and over central and southern Europe. As a consequence only small changes are found in the precipitation (Fig 7.5), small increases in "N", "NE", and "E" in connection to the area of decreased pressure and small decreases in the rest of the sub-areas (Table 1.3). The changes are, except for "SE", not significant and of the same order of magnitude as the biases in the control run.

The sub-area temperature changes (Table 2.3) are between 1.0K and 3.7K, with the largest increases over southern Europe. All of the changes are significant and except for the small changes in the northern sub-areas and "E" they are much larger than the biases of the control run. The averaged European increase is also significant and large compared to the corresponding bias. The negative sub-area deviations from this mean value in "N" and "NE" are found to be significant although smaller than the corresponding biases and significant are also the positive deviations in "SW", "S", and "SE" but of the same order of magnitude as the corresponding biases. That the largest temperature increase occur to the south (Figure 7.5) should be expected due to a normal distribution of clouds with less clouds over the southern part of the continent in the summer season. Therefore, to the south the greenhouse effect become large, also because of relatively high values of the specific humidity there. The small temperature increase in the northern sub-areas are explained by the advection from the Atlantic in the control simulation (Figure 1.6) which is further intensified by the changes (Figure 6.3).

The ARPEGE experiment

The changes in MSLP (Figure 6.3) are somewhat similar to those in the driving UKMO experiment, with decreased pressure to the north-east. Consequently, the precipitation changes (Figure 7.5) are similar to those in the UKMO experiment with small increases in precipitation in "N", "NE", and "E" and small decreases in the rest of the sub-areas (Table 1.3). Only the decreases in "Alps" and "SE" are significant and all of them are of the same order of magnitude as or smaller than the biases of the control simulation. Also the pattern of temperature changes (Figure 7.6) resembles those of the driving UKMO experiment but they are generally slightly smaller. For the whole Europe the change is 2.0K whereas it is 2.4K in the UKMO experiment (Table 1.3). The sub-area temperature changes are between 1.0K and 3.4K, again with the largest changes over southern Europe. Except for the small increase in "NE" all the changes are significant and they are generally much larger than the biases of the control run. The averaged European increase is also significant and large compared to the corresponding bias. The positive deviations in "SW" and "S" from this mean value are found to be significant. As in the driving UKMO experiment the north-south gradient in the heating is enhanced due to reduced cloud cover in central and southern Europe in the perturbed simulation and increased westerly advection in northern Europe. The generally smaller temperature increase to the north are explained by the excessive advection from the Atlantic here in the control simulation (Figure 1.6) which is further intensified by the changes (Figure 6.3).

<u>Autumn</u>

The UKMO GCM experiment

The MSLP changes (Fig. 6.4) are relatively large with a center of reduced pressure of more than 4 hPa in north-east from which a trough-line extends toward south-west over Scandinavia and UK to west of Spain and with a center of increased pressure over the Mediterranean Sea. As a consequence the precipitation (Fig.7.7) has increased in and around the trough-line, in particular south of it and it has decreased in connection with the center of increased pressure to the south. Only the positive sub-area precipitation changes in "N", "NE", and "W" are significant and all of them are generally of the same order of magnitude as or smaller than the biases of the control simulation.

The temperature changes (Fig. 7.8) are largest in south-western Europe. The sub-area changes (Table 2.4) are between 1.1K in "N" and 3.7K in "SW". The former must be reduced due to advection of smaller changes from the Atlantic, increased advection from the north and probably increased cloud cover. The large temperature increase to the south must be due to small and reduced cloud cover and moisture over southern Europe. All of the changes, except that in "NE", are significant and they are generally of the same order of magnitude as or larger than the biases of the control run. The averaged European increase is significant but of the same order of magnitude as the corresponding biases in the control simulation and the only sub-area deviations from this mean value that are significant are those in "N" and "SW".

The ARPEGE experiment

The changes in the MSLP are very different from those of the UKMO experiment. A center of increased pressure is centered over the English Channel and to the north the pressure has decreased (Fig. 6.4) giving increased advection from the west in northern Europe and from easterly directions over southern Europe. As a consequence the precipitation has increased over northern UK and Scandinavia and decreased over south-western Europe (Fig. 7.7). The subarea increases in "N" and "NE" and the decreases in "Alps" and "S" are significant but all of them are generally of the same order of magnitude as or smaller than the biases of the control simulation (Table 1.4).

As in the UKMO GHG experiment the temperature changes (Fig. 7.8) are largest in south-west-

ern Europe. The reduced heating over north-eastern Europe may be explained by the excessive maritime influence originally in the control simulation (Figure 1.8) which is intensified by the changes (Figure 6.4) and probably increased cloud cover. The large temperature increase to the south must be due to small and reduced cloud cover and moisture over southern Europe. The sub-area changes (Table 2.4) are between 1.6K in "E" and 2.9K in "SW". The excessive maritime influence explains why as in winter and summer the changes are smaller generally than those in the UKMO GHG experiment. For the whole Europe the temperature change is 2.0K whereas it is 2.8K in the UKMO experiment. All of the sub-area changes are significant, they are generally of the same order of magnitude as or larger than the biases of the control run. There is a clear tendency for the changes to compensate the biases. The averaged European increase is significant bur of the same order of magnitude as the corresponding bias. Only the positive sub-area deviation in "SW" is significant but the deviations are generally small compared to the corresponding biases.

3.3 The HIRHAM and VHIRHAM GHG experiments

Of the CGCM climate change experiments considered the MPI GHG experiment, providing boundary conditions for the present RCM experiments, represents the largest radiative forcing and global warming (Fig. 0.3). Two experiments are considered.

The first one, called the *HIRHAM experiment*, is a CO2 doubling experiment similar to the UKMO GHG experiment. As in that experiment the CO2 doubling is with respect to the 1990 value, and also no effects of sulphur aerosols are included. In this experiment we consider the differences between a time-slice around 2075 (the anomaly simulation ECHAM4 SCA(9)) and a time-slice around 1990 (the control simulation ECHAM4 sca(9)). The global mean radiative forcing for the 1990 - 2075 period simulated is 4.5 W/m2 (Fig. 0.3) and the corresponding global warming is 2.5K, as also indicated in the figure. This is again much more than in the UKMO SUL experiment and a little more, about 10% more, than the UKMO GHG experiment. Boundary conditions from the two time-slices in this MPI GHG doubling experiment were used in two corresponding HIRHAM4 simulations.

The second MPI GHG climate change experiment, called the *VHIRHAM experiment*, is composed of a time-slice from the MPI CGCM present-day climate simulation (the control ECHAM4 CTL(9)) and a 2075 time-slice (the ECHAM4 SCA(9)). Differences between the anomaly simulation and the present-day climate simulation considered in this experiment represent the climate change between 1860 and 2075. The global mean radiative forcing for this period is 6.7W/m2 (Fig. 0.3) and the corresponding surface air temperature rise is 3.4K, as also indicated in the figure. These are larger changes than in any of the other climate change experiments considered. Boundary conditions from the two ECHAM4 time-slices were used in two corresponding HIRHAM4 simulations each of which provided boundary conditions for two VHIRHAM simulations.

The HIRHAM experiment (1990 - 2075):

Winter

In both ECHAM4 and HIRHAM4 positive MSLP changes are found in south-west and negative changes in north-east and north giving increased advection from the north-west in northern and

eastern Europe turning over northerly to an easterly direction over south-western Europe (Fig. 6.1). These circulation changes give increased precipitation at the north-west coasts of Scandinavia, UK and at the cost of the Baltic Sea (Fig. 7.1). The largest increase in HIRHAM is 42% in "E" (Table 1.1). This and the increases in "N" and "NE" are the only sub-area changes which are significant in HIRHAM. In the area of positive pressure changes and south of it the precipitation has decreased, in HIRHAM -22% in "SW", due to enhanced subsidence and dry advection from the east. All sub-area changes are of the same order of magnitude as or smaller than the biases in the corresponding present-day climate simulations.

The temperature increases, Figure 7.2, are largest in northeast due to the snow-albedo feedback and smallest in southern Europe. The general westerly flow has advected smaller changes from the Atlantic over western Europe. The largest sub-area changes are in "NW", +6.3K and +5.2K and the smallest are in "S", +2,5K and +2.6K in ECHAM and HIRHAM, respectively (Table 2.1). All the sub-area changes are significant and much larger than the biases in the corresponding present-day climate simulations. The effect of the increased north-westerly advection in northern and eastern Europe must have been to reduce the warming there. The averaged European increases are significant and large compared to the corresponding bias but only the sub-area deviations from the mean values in "SW" and "S" are significant and the deviations are of the same order of magnitude or smaller than the corresponding biases in the control simulation.

Spring

In both ECHAM4 and HIRHAM4 an area of positive MSLP changes (Fig. 6.2) are found in central and southern Europe and negative changes are found north and south of that area giving increased advection from the west in northern Europe and from easterly directions over southwestern Europe. These circulation changes give increased precipitation at the north-west coasts of Scandinavia, UK and at the Baltic Sea (Fig. 7.3). The largest increase in HIRHAM is 34% in "N" (Table 1.2). In the area of positive pressure changes and south of it the precipitation has decreased due to enhanced subsidence and dry advection from the east. In HIRHAM the change is -30% in "SE". The HIRHAM sub-area increases in "N", "NE, and "E" and the decreases in "S" and "SE" are significant. All sub-area changes are of the same order of or smaller than the biases in the corresponding present-day climate simulations.

The temperature increases, Figure 7.4, are largest in southern Europe probably due to reduced cloud cover and increased easterly advection but still relatively large in the north-east due to the snow-albedo feed-back. The largest sub-area changes are in "Alps", 4.5K in HIRHAM (Table 2.2). The effect of the westerly advection and its increase in northern Europe has been to reduce the warming in western costal areas there, the smallest sub-area change is in "N", +2.9K in HIRHAM. All the changes are significant and much larger than the biases in the corresponding present-day climate simulations. The averaged European increases are significant and much larger than the corresponding biases but none of the sub-area deviations from the mean values are significant and they are of the same order or smaller than the corresponding biases.

Summer

In both ECHAM4 and HIRHAM4 positive (or reduced negative) MSLP changes (Fig. 6.3) are

found in an east-west belt at about 55°N and negative changes are found north and south of that belt giving increased advection from the west in northern Europe and from easterly directions over southern Europe. These circulation changes give increased precipitation at the north-west coasts of Scandinavia, UK and Finland (Fig. 7.5). The largest increase in HIRHAM is 15% in "N" (Table 1.3). In the area of positive pressure changes and south of it the precipitation has decreased due to enhanced subsidence and dry advection from the east. The largest decrease in HIRHAM is -26% in "SW" (Table 1.3). In HIRHAM the decreases in "C", "E", "Alps", "SW", and "SE" and the increase in "N" are significant. Generally the sub-area changes are of the same order of magnitude as the biases in the corresponding present-day climate simulations. In "S" and "SE", however, the positive biases are much larger than the changes, which is unusual and furthermore rather exceptionally we find that the reductions in "C" (-24%) and "SW"(-26%) are much larger than the corresponding biases.

As usual in the summer season the temperature increases, Figure 7.6, are largest in southern Europe due to a strong greenhouse effect there because of little clouds and high values of specific humidity. In the present case the heating is enhanced due to the increased easterly advection. The largest sub-area changes are in "SE", in HIRHAM +5.7K (Table 2.3). The effect of the westerly advection in northern Europe, which in this case is further increased, is to reduce the warming in western costal areas there. We find the smallest sub-area changes in "N", +2.6K in both HIRHAM and ECHAM. All the sub-area changes are significant and much larger than the biases in the corresponding present-day climate simulations. The averaged European increases are significant and the positive deviations from these mean values in "Alps", "SW", "S", and "SE" as well as the negative ones in "N" and "NE", plus "W" in HIRHAM, are significant. Generally the sub-area deviations are of the same order of magnitude as or larger than the biases in the corresponding present-day climate simulations, which again is unusual.

<u>Autumn</u>

In both ECHAM4 and HIRHAM4 positive MSLP changes (Fig. 6.4) are found in an east-west band at about 50°N and negative changes are found north and south of that belt giving increased advection from the west in northern Europe and from easterly directions over southern Europe. These circulation changes, which are rather similar to those in the Spring, give increased precipitation at the north-west coasts of Scandinavia, UK and at the Baltic Sea (Fig. 7.7). The largest increase in HIRHAM is 55% in "NE" (Table 1.4). In the area of positive pressure changes and south of it the precipitation has decreased due to enhanced subsidence and dry advection from the east. The largest decrease in HIRHAM is -36% in "SE". The decreases in "SW", "SE" and the increases in both northern sub-areas are significant in HIRHAM. Most sub-area changes are of the same order of magnitude as or smaller than the biases in the corresponding present-day climate simulations. Rather exceptionally, however, the HIRHAM changes in "N" (+36%) and "SE" are much larger than the corresponding biases.

The temperature increases, Figure 7.8, are largest in southern Europe due to reduced cloud cover and increased easterly advection and also relatively large in the north-east due to the snow-albedo effect. The largest sub-area changes are in "Alps", in HIRHAM +5.6K (Table 2.4). The effect of the normal, in this case increased, westerly advection at mid latitudes has been to reduce the warming in western costal areas there, the smallest sub-area change is in "W", +3.2K

in HIRHAM. All the changes are significant and much larger than the biases in the corresponding present-day climate simulations. The averaged European increases in both ECHAM and HIRHAM are significant and much larger than the corresponding bias. In HIRHAM the positive deviations from these mean values in "Alps" and "S" are significant and so is the negative one in "W". Most sub-area deviations are of the same order of magnitude as or smaller than the biases in the corresponding present-day climate simulations. Rather exceptionally, however, the negative deviation in HIRHAM in "W" (-1.5K) is numerically much larger than the corresponding bias.

The VHIRHAM experiment (1860 - 2075)

Winter

In Figure 6.1 in both the VHIRHAM4 and the driving HIRHAM4 experiment positive MSLP changes are found in north-west and negative changes in the east giving increased advection from the north in northern Europe. This gives precipitation changes (Fig. 7.1) which are qualitatively similar to those in the *HIRHAM experiment*. The incremental flow here is, however, more parallel to the Norwegian coast, especially in the VHIRHAM experiment. The increase in precipitation rate is therefore smaller in VHIRHAM in both "N" and "NE" (Table 1.1). Both these sub-area changes are insignificant and much smaller than the biases in the present-day climate VHIRHAM simulation.

The VHIRHAM sub-area temperature changes, +3.4K in "N" and +4.8K in "NE" (Table 2.1), are smaller than the corresponding HIRHAM changes in the *HIRHAM experiment* which must be due to the differences in the advection. In the present experiment the incremental advection is more northerly. The changes are significant and much larger than the biases in the present-day climate simulation.

Spring

The changes in MSLP are rather similar to those in Spring in the *HIRHAM experiment*. In Figure 6.2 both the VHIRHAM and the driving HIRHAM4 experiment have decreased pressure over northern Scandinavia indicating increased cyclonic activity there and increased advection from the west in the remaining part of the VHIRHAM area. These circulation changes give increased precipitation at the north-west coasts of Scandinavia, UK and at the cost of the Baltic Sea (Fig. 7.3). The increase in VHIRHAM in "N" is 31% which is larger than in HIRHAM in the *HIRHAM experiment*. The reason must be the lower pressure and therefore the higher level of cyclonic activity and the steeper orography here. The changes in both "N" and "NE" are significant. The VHIRHAM sub-area changes are of the same order of or smaller than the biases in the corresponding present-day climate simulation.

The temperature increases, Figure 7.4, resembles those in the *HIRHAM experiments* but here they are larger, as should be expected. Again, the effect of the increased westerly advection in northern Europe has been to reduce the warming in western costal areas. As the strength of the incremental westerly advection is much weaker in the VHIRHAM experiment than in the HIRHAM experiments (Fig. 6.2) this reduction of the warming is less in VHIRHAM which gives larger changes, e.g. +5.0K in "N". Both VHIRHAM sub-area changes are significant and much larger than the biases in the corresponding present-day climate simulation.

Summer

The changes in MSLP (Fig. 6.3) are rather similar to those in summer in the *HIRHAM experiment* except that the band of higher pressure crossing Europe is moved somewhat southward. In the north the changes in precipitation in the HIRHAM experiments are rather similar but the increases in the VHIRHAM experiment are larger (Fig. 7.5), +28% in "N" (Table 1.3), due probably to the steeper orography. This VHIRHAM change in "N" is significant and both subarea changes are larger than the biases in the corresponding present-day climate simulations.

All over the temperature increases, Figure 7.6, are larger than in the *HIRHAM experiment* in agreement with the larger radiative forcing. The warming in Scandinavia is largest in VHIRHAM probably due to the scheltering effect of the steeper orography and more release of latent heat, i. e. due to the Foehn effect. The largest VHIRHAM sub-area changes are in "N", +4.4K (Table 2.3). Both sub-area changes are significant and somewhat larger than the biases in the corresponding present-day climate simulation.

<u>Autumn</u>

The changes in MSLP (Fig. 6.4) are again rather similar to those in autumn in the *HIRHAM experiment* except that the pressure rise in the band of increasing pressure over central and southern Europe is smaller. In the north the changes in precipitation in the HIRHAM experiments are rather similar but the increases in the VHIRHAM experiment seems larger (Fig. 7.7). The sub-area change in "N" is indeed larger but the change in "NE" is +40% (Table 1.4), a somewhat smaller value than in the HIRHAM experiment (55%). Both VHIRHAM sub-area changes are significant. In "N" the change is much larger but in "NW" it is much smaller than the corresponding bias in the present-day climate simulation.

The all over heating is larger than in the *HIRHAM experiment* due to the larger radiative forcing. The warming in Scandinavia is largest in VHIRHAM, again probably due to the scheltering effect of the steeper orography and more release of latent heat, i. e. due to the Foehn effect. The largest VHIRHAM sub-area change is in "NE", +4.6K (Table 2.4). Both sub-area changes are significant and larger than the biases in the corresponding present-day climate simulation.

3.4 Discussion

As expected the changes in surface air temperature and precipitation were largest in the GHG experiments. We shall consider these experiments at first.

The GHG experiments

Regarding the changes in precipitation in these experiments it is remarkable that the pattern of changes (Figures 7.1, 7.3, 7.5, 7.7) in all cases seems to be explained by the changes in the low level general circulation, i. e. by the changes in MSLP (Figures 6.1 - 6.4). We find that the precipitation reduces due to increasing subsidence in areas where the pressure increases, that it increases due to increasing rising motion, presumably in connection with increasing cyclonic activity, in areas where the pressure decreases, but in most cases the precipitation changes is found to be a result of increasing or decreasing mean advection from the Atlantic. This is in

agreement with the fact that the biases in the present-day climate simulations to a large extent seems to be explained similarly by systematic errors in the general circulation.

In the preceding sub-sections we found that only the largest sub-area precipitation changes are significant compared with the estimated internal variability of the ECHAM model, which we assume is representative also for the other models considered here. For the ARPEGE and HIRHAM experiments we find that 42% and 50% of the sub-area biases, respectively, are significant. This finding indicates that in many cases we cannot rule out that the detected changes in precipitation are the result of random decadal internal model variations. In other words, we cannot be certain that all the changes in the pattern of precipitation in these experiments over Europe are systematic changes which result from the radiative forcings imposed on the models.

Furthermore we found that the sub-area changes in precipitation generally are smaller than or of the same order of magnitude as the corresponding biases. Thus, we find that the distribution on the classes of changes:

small (X < 20%), medium (20% < X < 40%), large (X >40%)

for the ARPEGE experiment is	72% (42%),	25% (36%),	3% (22%),
and for the HIRHAM experiment	is58% (50%),	36% (22%),	6% (28%).

The numbers in parentheses are the corresponding distribution of the biases (shown also in Table 4). For the driving models the changes are generally smaller. This raises doubts on the reliability of the changes calculated or in other words it raises doubts on to what extent the changes calculated would take place in reality if the atmosphere were forced in the same way as the models are in the experiments.

Another indication of lack of reliability of the computed changes in precipitation is the completely different patterns of changes obtained with models exposed to similar radiative forcing. The main reason for these differences seems to be the different physical parameterization packages of the models. Thus, we find that generally the pattern of precipitation changes are very similar for the ECHAM and its nested model, HIRHAM whereas the pattern of changes in experiments with the UKMO GCM and the ARPEGE model are quite different from each other and from those of the ECHAM and HIRHAM experiments. These similarities and differences in patterns of precipitation changes are consistent with the respective patterns of general circulation changes. Differences in the dynamical part of the models seems not to be important in this respect as indicated by the relatively small differences between the ECHAM and HIRHAM changes. It would be of interest to know whether the different climate changes are due to local differences in the forcing by the parameterized physical processes (i.e.differences over or near Europe) or if they are due to remote differences in the forcing (the effect of which is then transmitted to Europe, in the LAMs via the boundary conditions). Unfortunately, it seems not possible on the basis of an analysis of the present experiments to determine this question.

In the GHG experiments we find a common large scale heating pattern which seems to be caused by direct or indirect thermodynamic effects of the radiative forcing. This pattern is modified by advection. Neglecting at first the influence of advection we explain as follows the common large scale pattern. In winter the largest temperature increase is situated over north-eastern Europe due to the snow-albedo feed-back process which has its maximum in the area between the snow limit before and after the change. In summer the direct influence of the long wave radiative forcing will give maximum heating over southern Europe. Here normally a ridge of high pressure is situated with few clouds and an enhanced positive humidity feed-back due to high temperatures. Cloud free conditions will obviously enhance the direct effect of increasing greenhouse gas (including water vapour) concentrations whereas large amounts of clouds, as in winter, will reduce the effect. The southern maximum is therefore replaced in the winter season by a minimum. In Spring and Autumn we have a combination of weakened features from both of the extreme seasons.

In the long term mean heat balance which determines the mean temperature at a certain place the mean advection of heat constitutes an important contribution. A change in mean advection will therefore contribute to a change in the temperature. We may write a change in advection of heat as follows

> -(**V2.** grad(T2) - **V1.** grad T1)= -((**V1**+**V2**)/2. grad(T2-T1) + (**V2-V1**). grad((T2+T1)/2))

where \mathbf{V} is a horizontal velocity vector, T is a temperature and where index 2 refers to after and index 1 refers to before the change. Thus, the velocity field as well as the temperature field may have changed.

The first term on the right hand side is the contribution from advection of temperature changes by the average wind. This term explains the smaller heating found in all GHG experiments over the western parts of Europe caused by advection of smaller heating rates from the Atlantic by the normal westerlies. Over the ocean the temperature changes (T2-T1) are generally smaller than over land. This is especially the case over the northern Atlantic. grad(T2-T1) is therefore large at the Atlantic coasts and here the mean wind (V1+V2)/2, normally westerlies, advects smaller temperature changes in over the land. The magnitude of the resulting reduction of the GHG warming near the European west coasts differs from experiment to experiment and is influenced in particular by systematic errors in the general circulation.

If in a model experiment the systematic errors in advection were exactly the same in the control simulation and in the perturbed simulation then they would cancel out when computing the changes and they would have no influence on the accuracy of the calculated mean temperature changes. As we shall see below such an assumption of cancellation of systematic errors cannot always be valid, at least not on the sub-continental scales considered here. In these examples large systematic errors in the general circulation are seen to result in large errors in the calculated changes. We cannot claim that there is a one to one correspondence between systematic errors and errors in the calculated changes. On the bases of the examples considered it seems evident, however, that significant effects of systematic errors can be ruled out only if the systematic errors are much smaller than the changes computed. If this is not the case the reliability of the changes computed must be considered questionable due to possible detrimental impacts of the systematic errors.

As a first example where systematic errors in the mean wind obviously results in too excessive reductions of warming over land consider the DJF season of the ARPEGE experiment. Here,

the systematic circulation errors in the control experiment are large (Fig. 1.2), i. e. too strong westerlies. Compared with that the changes in circulation are relatively small (Fig. 6.1). We see a clear reduction of the warming (Fig.7.2) over western and central Europe, unusually deep into the continent, where the too strong westerlies bring in smaller temperature changes from the Atlantic. This is an example showing that cancellation of errors in climate change experiments is not a valid assumption. Since the westerlies are approximately equally strong in the control and the perturbed simulations let us assume that the circulation errors are equal and therefore cancel out. Never the less the too large westerlies leads to excessive reductions of the temperature changes over land. A certain cancellation of errors in the advection do occur. If the error in the wind is assumed unchanged in this idealized case and equal to delta(V) and we assume no errors in the temperature fields then the error in the control simulation is delta(V). grad(T1)and the error in the perturbed simulation may be written delta(V). grad((T2 - T1) + T1). The error that cancels out is delta(V). grad(T1), the initial advection error, but a part of the error in the perturbed simulation remains, namely delta(V). grad(T2 - T1), advection by the error wind field of the temperature change. This remaining error can obviously be large as indicated by the present example. Here in the present example the only way to reduce the error in the computed change is by reducing delta(V), the systematic wind error in the control simulation. We see that smallness of the error in the computed climate change depends on smallness of the systematic errors in the general circulation of the control simulation.

As a second example where errors in the mean wind field obviously results in too small reductions over land consider the UKMO GHG experiment for the winter season. In Figure 1.1 it is seen that the simulated low level atmospheric flow has a strong easterly bias over northern Europe where the computed change in circulation is small (Fig. 6.1). Thus, the westerlies seem to be equally much too weak in the perturbed and the control simulation. As a consequence we see in Scandinavia unusually small reductions of the temperature changes due to advection from the Atlantic (Fig. 7.2). Again in this example we see that although the systematic circulation error may cancel out the effect of these errors on the temperature do not.

The second term on the right hand side of the equation above is a contribution from advection of the mean temperature field by the field of velocity changes. As an example: increasing westerlies in the winter season will, with unchanged Atlantic temperatures, lead to a cooling over land. We have shown in the preceding sub-sections that this form of change in advection explains additional deviations from the basic patterns of temperature changes, some that could easily be identified in the maps of temperature changes. The most clear example is also from the winter season of the UKMO GHG experiment. In the control simulation the systematic error of the circulation is relatively small over southern Europe (Fig. 1.1), whereas here the perturbed simulation show a strong southerly wind (Fig. 6.1). As this is in an area where the northsouth gradient in both simulations is large an unusual secondary maximum is created over southern Europe in the pattern of temperature changes (Fig. 6.1). As demonstrated above the changes in precipitation seem to a large extent to be explained by changes in the general circulation. For the changes in temperature it has been possible to identify only some effects of changes in circulation though it seems likely that they affect the temperature changes as much as they affects the changes in precipitation. However, for temperature it is difficult to distinguish the effects of changes in circulation from the dominating thermodynamic effects of the

radiative forcing and the strong influence of advection of smaller temperature changes from the Atlantic.

We have seen that with a few exceptions in all GHG experiments the sub-area temperature changes are significant and of the same order of magnitude or larger than the corresponding biases in the present-day climate simulations. It should be noted that this is due to the large more or less homogeneous heating contribution caused by the radiative forcing and it is saying nothing about the significance of the smaller regional deviations created by changes in advection, snow-albedo feed back processes and variations in cloud cover and moisture. To clarify the significance of such regional differences we have considered separately for each season the averaged temperature changes for Europe as a whole and the sub-area deviations from these mean values.

The averaged temperature changes for Europe (Tables 2, column "Total") were seen to be significant for all the GHG model experiments in all seasons and the corresponding biases in the present-day climate simulations were seen to be smaller than the changes, in most cases much smaller. This means that the averaged seasonal European warming computed in these experiments most likely is not just the result of internal model variations. Smallness of the corresponding biases gives, however, no guarantee that the computed changes are realistic responses to the radiative forcing imposed in the experiments. In fact, as the computed changes in the different GHG experiments are different all of them are unlikely to be realistic possible futures. As pointed out previously the global radiative forcing imposed in the different GHG experiments are pretty similar. In spite of that the averaged European warming in the different experiments differ much more than the global warming does in the two basic CGCM experiments. This seems to be the result of differences in the heating of the Atlantic and different biases in the zonal flow. Averaged over all four seasons of the year the mean European temperature increase in the GHG experiments are 2.1K, 2.7K, 4.1K and 4.1K for the ARPEGE, UKMO CGCM, HIRHAM and MPI CGCM, respectively (Tables 2.1 -2.4). For UKMO CGCM this is slightly more (0.5K) than the global mean value of 2.2K (Fig. 0.3). This should be expected because the European value is calculated over land which is heated relatively more, although it is under influence of the northern Atlantic which is heated relatively less (Figs. 8.1 and 8.2). For the same reasons we find that the MPI CGCM mean European change is 1.6K larger than its global mean change, 2.5K. Compared to UKMO CGCM the MPI CGCM (called ECHAM4 in figures and tables) simulates between 1K and 2K larger heating in the northern Atlantic which explains, at least partly, that for this model the mean change over Europe is relatively high, i.e. 1.4K larger than that of the UKMO CGCM. The mean change of HIRHAM is very similar to that of its driving model whereas that of ARPEGE is 0.6K smaller than that of UKMO CGCM. This smaller heating in ARPEGE seems mainly to be caused by the larger systematic errors in the zonal flow in this model causing enhanced advection of smaller changes from the Atlantic. The slightly smaller values of the CO2 concentrations in the ARPEGE time-slice simulations than in the UKMO simulation, and thereby the smaller change in concentrations, (see Section 2.0.2) have probably had only a negligible effect.

The sub-area temperature changes for which the deviations from the European mean changes are significant were underlined in Tables 2.1 -2.4. In the winter season we find significant neg-
ative deviations which we ascribed to advection of smaller changes from the Atlantic ("W" in UKMO GCM and ARPEGE) and extensive cloud cover ("SW" and "S" in ECHAM and HIRHAM) while the relatively large positive deviations to the north connected with the snowalbedo feed-back process are not found to be significant as here the estimated decadal model variability is also high (Table 4). In the summer season in all cases and in some cases also in the autumn season we find significant positive sub-area deviations in southern European subareas which we ascribed to the normal seasonal reduced cloud cover and an efficient water vapour feed-back due to the high temperatures there. In "W" and/or the northern sub-areas we find also in the summer corresponding significant negative deviations which we ascribe to advection of smaller changes from the Atlantic and to extensive cloud cover. That the temperature increase depends upon the cloud cover was explained by a maximal greenhouse effect in a cloud free column. The deviations of the changes are generally of equal magnitude as or smaller than the corresponding biases in the present-day climate simulations, although in a few cases, mainly significant ones, the changes are much larger.

Thus, although we find in the GHG experiments analyzed here that the mean warming over Europe is highly significant and generally much larger than the corresponding biases in the present-day climate simulations we see that only some large spatial deviations of the temperature changes on the sub-area scale, ascribed to advection of smaller changes from the Atlantic and the normal seasonal variation of cloud cover, do pass our test of significance. Unlike the sub-area changes in precipitation we find none of the sub-area temperature deviations that can be ascribed to changes in the general circulation to be significant. Even the changes that are significant are generally not larger than the corresponding biases. Therefore, in general, as for the precipitation changes, their reliability is questionable. This is being supported also by the fact that although some general large scale features are common the smaller scale (the sub-area scale) spatial variations of the changes are generally quite different in the different model experiments.

In the HIRHAM experiment in the summer season we find exceptions from the general results described above and at the same time another example where cancellation of systematic errors most likely is not taking place. Thus, here quite exceptionally significant precipitation changes were found in five central and southern European sub-areas and furthermore the largest changes in the sub-areas "C" and "SW" (Table 1.3) were found to be much larger than the corresponding systematic errors. In this experiment we found also significant temperature deviation changes in four central and southern European sub-areas and the sub-area changes were quite exceptionally found to be of the same order of magnitude or larger than the corresponding systematic errors. We found also in this season the highest degree of agreement between the patterns of temperature deviation and precipitation changes in the different GHG experiments. The maps in Figures 7.6 and 7.5 show in all of them relative temperature decreases and increasing precipitation in the north and relative temperature increases and decreasing precipitation to the south. This agreement is seen clearly also in Tables 2.3 and 1.3. Now, it is interesting to note that in the HIRHAM experiment the pattern of summer precipitation change (Fig. 7.5) resembles the summer bias pattern (Figure 2.6) but with the areas of largest decrease in precipitation shifted north- and eastward. (This is true also for the changes in the HIRHAM experiment which is used for boundary conditions in the VHIRHAM experiment, same figure). Thus, it seems that

the radiative forcing in the experiment results in an extension toward north and east of the overly dry areas to cover more of the continent than it did in the control simulation. Since the models do have dry biases in the present-day climate simulations the positive drying/heating feed-back process is apparently operating too strongly, that is, the model's long term mean response to the natural increase in solar radiative forcing in the Spring is too much heating and drying-out over the south-eastern part of Europe. With the increased longwave radiative forcing in the present perturbed simulation the heating and drying-out process seems to have proceeded further. There is a clear tendency that it is not areas that have already been dried out in the present day climate simulation that is being dried out. Instead adjoined areas are being dried out in the climate change experiment. The same tendency is seen in the ARPEGE climate change experiment. It seems reasonable to assume, firstly, that the climate change heating and drying-out is the result of a model defect, namely the too strong drying/heating feed-back process and secondly that the climate changes would be different had the models not had this defect. Although it is not possible to figure out how the climate changes would be with a perfect model with no systematic errors a reasonable guess in this case would be that some climate change drying-out/heating would occur, but weaker and situated instead over the south-eastern Europe in areas where the present-day climate simulations were drying too much in the Spring.

It is seen that even in the HIRHAM case where our test convincingly indicates that the sub-area changes in precipitation and temperature deviation for central and southern Europe are significant and where the largest sub-area changes also exceeds the corresponding biases by a sub-stantial amount are the realism of the changes highly questionable. The problem is indicated by the fact that other sub-area biases are large compared to the corresponding changes, in this case especially the precipitation biases in "S" and "SE". Thus, it seems that here we have an example where a large systematic error in the control simulation is growing and expanding in the perturbed simulation and therefore do not cancel out giving the correct changes when the simulated fields are subtracted from each other.

The UKMO SUL experiments

As expected, the climate changes simulated in these experiments were found to be much smaller than in the GHG experiments. The longer time-slices, 30 years instead of about 10 years, is, however, to some extent compensating for that.

Even though the changes in MSLP are small the patterns of precipitation changes and even in some cases those of the temperature changes are, as far as it can be seen in the maps, found to be consistent with the changes in the general circulations.

Concerning the changes in precipitation none of the mean seasonal changes for the whole Europe exceeds 5% and none of the sub-area changes exceeds 30%, most are less than 10%. Only 19% and 22% of the sub-area changes for respectively the GCM and the RCM experiment passed the test of significance and all of the precipitation changes were smaller (often much smaller) than or equal in magnitude to the biases in the corresponding present-day climate (control) simulations. Thus, we must conclude that in spite of the long integration period the detected small changes in sub-area precipitation may be the result of random internal model variations. And even if they should be systematic changes their realism is questionable.

For Europe as a whole the annual mean temperature increases are 1.3K and 1.4K for the GCM and the RCM, respectively (Tables 2.1 -2.4). This is slightly more than the global mean value of 1.2K for the GCM (Fig. 0.3). This should be expected because it is over land and because of the influence from the northern Atlantic which is heated relatively less (Figs. 8.1 and 8.2). All the seasonal sub-area temperature changes are significant. However, they are generally of the same order of magnitude as the corresponding biases in the control runs, in some cases smaller, especially to the south, and in some cases larger, especially to the north, so in general their realism is questionable.

As we are interested in the significance and realism of the spatial variations on the sub-area scale we considered again separately the averaged temperature changes for Europe as a whole and the sub-area deviations from these mean values. Doing so we find that the averaged temperature changes for Europe (Tables 2, column "Total") are significant for all seasons, but the corresponding biases in the control simulation are of the same order of magnitude as the changes computed, except the unusually small biases in the winter season. Thus, the averaged European warming computed is significant in all four seasons but their accuracy is questionable because of the relatively large biases.

For the deviations of the sub-area temperature changes from the European mean changes we find that, except for 5 and 3 cases respectively for the GCM and RCM experiment, none of them are passing our test of significance and with a few exceptions all of the sub-area deviations are found to be smaller than the corresponding biases, usually much smaller. The pattern of temperature changes is much more homogeneous than in the GHG experiments. Of the characteristic features seen in these experiments only the maximum to the north connected with the snow-albedo feedback process in winter and spring are found in the SUL experiments (Figures 7.2 and 7.4) as indicated also by the significant deviation changes in "N" and "NE" in the Spring (Table 2.2). Thus, although the total warming in the European sub-areas are highly significant the same is generally not the case for the spatial variations on the sub-area scale and thus it is uncertain if the spatial variations found in the experiments are systematic model changes. Furthermore, because of the relatively large biases the realism of the deviation change es are highly questionable.

4.0 Summary and conclusions

4.1 The present-day climate simulations

We have analyzed six different RCM simulations of the present-day climate in Europe. Four simulations were performed with four LAMs having grid lengths between 25 and 70 km, most of them around 50 km. The 30-year UKMO HadRM2 simulation took boundary conditions from a recent UKMO CGCM control simulation whereas the 9-year simulation with the HIRHAM4 model and two five year simulations with the CLAMBO and the RegCM2 models took boundary conditions from a similar MPI CGCM simulation. A fifth present-day climate simulation was made with the double nested 19 km VHIRHAM4 covering Scandinavia only. It used boundary conditions from the 50km HIRHAM simulation. A sixth RCM simulation was

performed with the variable resolution ARPEGE T63s model having a grid length down to about 60 km over Europe and using SSTs based on a 10-year time-slice from a transient UKMO CGCM GHG scenario simulation centered around 1990. This scenario run was started in 1860 from present conditions and then integrated with prescribed greenhouse gas concentrations corresponding to the observed radiative forcing. Thus, at 1990 in the simulation the radiative forcing had increased since 1860 to twice the real 1990 value. The SSTs in the 1990 time-slice are therefore too warm, on the average 0.5 - 1.5K. Never the less, lacking a real present-day climate simulation with the ARPEGE T63s model it was decided to validate it together with the other RCM simulations mentioned and to try to separate out the effects of this additional heating.

In the validation of the decadal mean biases of averaged sub-area surface air temperatures and precipitation in the HIRHAM and the ARPEGE simulations we defined levels of significance based on 95% "Students" t -tests using standard deviations determined directly from running 10-year mean values of the 300 year long MPI CGCM present-day climate simulation. Similar limits of significance were defined for the 30-year mean biases determined from the HadRM2 simulation and for the 5-year mean biases of the CLAMBO and RegCM2 simulations based on 30-year and 5-year mean values of the same MPI CGCM present-day climate simulation, respectively. We introduced similar definitions of significance of changes between previous and present simulations building on the same standard deviations.

In the present validation we found that the sub-area biases of surface air temperature and precipitation in Europe in many cases are of a significant magnitude (Table 4). Thus, we found that the larger biases are indeed systematic errors. It was shown in Table 4 that statistically the subarea temperature and precipitation biases for the UKMO RCM simulation have increased slightly in magnitude compared to those found in the MEA96 simulation performed in a previous study whereas the biases for the ARPEGE and HIRHAM simulations have decreased.

Our explanations of the biases are the same as those presented in the previous validations in MEA96 and CEA97. Thus, the systematic errors in the general circulation seem again to cause a substantial part of the biases in the primary weather elements and two sets of systematic defects in physical parameterization schemes seems responsible for additional significant errors. Firstly, a too weak downward longwave radiation at the surface explain in some models a tendency for negative or reduced positive temperature biases and secondly, deficiencies in the hydrological and in most models probably also the radiational scheme explain a too fast spring-summer drying-out and heating of the soil over south-eastern Europe. An important additional reason for biases in the present simulations is the imposed SST biases and too moist boundary conditions in at least one of the RCMs due to imperfect simulation in the deriving CGCM models.

A common typical pattern of large scale systematic mean sea level pressure (MSLP) errors were found over Europe in all models considered with areas of too high pressure to the north and to the south and areas of too low pressure to the east and to the west between which most often an west-east trough of too low pressure is established. The precise location of the centers and trough-line varies from model to model, sometimes with the eastern center dominating and sometimes with the western one dominating. This apparently causes substantial sub-continental differences in the induced biases in temperature and precipitation. In all cases the systematic MSLP errors are largest in the winter season and weakest in the summer.

It was argued in MEA96 That an area of too low pressure located in connection with the cyclone track is caused by increased cyclonic activity. This has been confirmed in a separate investigation (Machenhauer et al., 1998b) involving analyses of a series of MPI GCM 10-15 years time-slice simulations. Included were the present-day climate simulation considered here and several AMIP simulations with the ECHAM4 model in different resolutions. For each simulation 500 and 1000 hPa patterns of systematic errors in geopotential and in the so-called cyclone track parameter (i.e. Blackmon, 1976) were analyzed. In particular over Europe it was found that in all cases areas of too low pressure were connected to areas of enhanced cyclone track parameter, thus indicating that these are indeed caused by enhanced cyclonic activity. Similarly, the areas of too high pressure to the north and to the south were found to be areas of reduced cyclone track parameter indicating that they are caused by reduced cyclonic activity.

Enhanced cyclonic activity was thought to lead to the release of an increased amount of precipitation and also to an increase in northward eddy transports of heat and moisture. This seems to be consistent with the observed temperature and precipitation bias patterns. Also the observed increase in simulated precipitation with increasing resolution when going from a CGCM to the corresponding nested LAM (on a yearly basis for the whole Europe 27% and 21% for the UKMO and MPI models, respectively, see Tables 1.1-1.4) seems to be consistent with the increase in cyclonic activity with increasing resolution which is indicated by the observed extension and deepening of the areas of too low pressure with increasing resolution (Figures 1.1. -1.8). However, for the UKMO model, stronger small scale vertical motions and excessively moist boundary conditions are also important factors.

The deviations between the patterns of systematic errors in the general circulation in different models seem to depend on which packages of physical parameterization are used in the models. Thus, sub-continental deviations are found between the error pattern of ECHAM3 analyzed in MEA96 and of ECHAM4 analyzed in the present paper. The systematic MSLP errors over Europe need not be caused by local errors in the parameterization schemes, they may even be caused mainly by errors in the forcing outside Europe, maybe in the Tropics, in this case imposed on the RCMs used here via their boundary conditions (MEA96). This would explain why the UKMO and MPI LAMs have systematic errors which are very similar to those of their driving models and also as we found in MEA96, why those of ARPEGE T63s are similar to those of an ARPEGE T42. It may, however, also be explained by similar local effects in a GCM and a RCM sharing the same parameterization package. Thus, local deficiencies in the parameterization schemes may influence the dynamics of the synoptic systems which, for instance, may lead to a too slow filling of the low pressure systems that then could explain the observed areas of too low pressure at the end of the European storm track. The locally increased resolution over Europe in the RCMs has relatively small large scale effects on the pattern of systematic MSLP errors (MEA96). A clear systematic change found with increasing resolution is, however, the above mentioned further reduction of the pressure in the areas of too low pressure connected to the storm tracks, indicating a further spurious increase in the cyclonic activity. This could be due to the sharper baroclinic zones which are possible locally with the higher resolution.

When a LAM and its driving GCM use different physical parameterization packages, as in the

present CLAMBO and RegCM2 simulations which are both driven by MPI CGCM simulations, we have seen that larger deviations in the systematic MSLP error patterns may develop between the LAM and the driving CGCM. This indicates at least that local effects of the parameterization schemes are important.

Presently we can only guess about the reasons for the systematic errors in the MSLP and the related general circulation patterns over Europe, which seem to cause large systematic errors in the temperature and precipitation patterns. A coming more detailed study will be devoted to finding these reasons. Here we have tried to deduce their effects only.

Concerning the defects in the physical parameterization schemes, as referred to in the introduction, it has been shown by Wild et al.(1995b) that the solar radiation reaching the ground is overestimated and the incoming longwave radiation at the surface is underestimated in the cloud / radiation schemes of ECHAM3 and several other models. These deficiencies, largely absent in the ECHAM4 schemes, were shown in CEA97 and MEA96 to contribute significantly to temperature and precipitation biases in several model simulations. Thus, the excessive summer drying and heating found in most simulations validated in CEA97 and MEA96 were explained as effects of deficiencies in the surface schemes and to a large extent also the excessive solar radiation. In the present simulation we still see the drying-heating problem, most clearly in the RCMs. In the ARAEGET63s simulation the associated biases have increased compared to the simulation in MEA96. This deterioration which results in rather large precipitation and temperature biases seems to be due to the introduction of a bottom runoff in the moisture surface scheme, but it must also be influenced by a reduced advection from the Atlantic and positive SST biases, especially in the Black Sea. In the HIRHAM4 simulation some large improvements are achieved. These improvements were expected due to the change from ECHAM3 to ECHAM4 physics. Large positive temperature biases in the southern sub-areas are almost eliminated and the deficit in precipitation is significantly reduced due to changes in the surface and radiation schemes. The improvements are, however, also helped by negative SST biases (Fig. 4.2) and an increased westerly advection bias which also result in other improvements, i. e. significant increases in precipitation and decreases in temperature in UK and central Europe.

Negative precipitation biases in many of the January model simulations validated in CEA97 and in all seasons in the UKMO simulations in MEA96 were explained as effects of a too weak downward longwave radiation. In the present simulations this deficiency was found still to result in significant biases. It contributes to relatively large negative biases in several seasons in both the UKMO and the ARPEGE simulation and it seems active in both the CLAMBO and the RegCM2 simulations.

The deterioration of the UKMO RCM biases compared to those in MEA96 was found, at least mainly, to be due to the SST biases and moister boundary conditions in the present HadRM2 simulation. The effects of some moderate SST biases (Figures 4.1 - 4.2) are seen most clearly in the UKMO simulations because here almost the same atmospheric model versions are used as in the MEA96 validation. The SST biases were found to be substantially larger in the AR-PEGE T63 and the HIRHAM4 simulations (in the former case in the form of a superimposed general heating of 0.5 - 1.5K and in the latter case as large seasonal variations around Europe

tending to reduce the yearly cycle) but here their effects were less easily detectable due to other model changes.

As mentioned above the biases in temperature and precipitation in the ARPEGE T63 and the HIRHAM4 simulations are reduced compared to those in MEA96. For ARPEGE T63 the main reason seems to be reduced zonalization in all seasons. This seems to be explained by a south-north gradient in the SST biases but also changes in the horizontal diffusion may have contributed. The superimposed too high SST biases all year round leads to increased advection of heat and moisture from the Atlantic which compensates for the improvements in winter and increases them in summer.

In the case of the present HIRHAM4 simulations substantial changes have occurred in the systematic errors of the general circulation to patterns more similar to the those typical for the other models. In some cases this has lead to improvements and in others to deteriorations. The most serious deterioration in the HIRHAM simulation is in the winter and autumn seasons when increased advection from the Atlantic has lead to significant increases in the positive precipitation biases in central and eastern Europe. This was enhanced also due to large positive SST biases in these seasons. On the other hand, large improvements were found in winter and spring when the southern centre of too high pressure had moved toward the west resulting in significant increases in the precipitation in southern and south-eastern Europe.

Among the present RCM simulations it is remarkable that the simulations in which we see the largest differences in MSLP between that of a driving GCM and that of its nested LAM are those with LAMs which have a physical parameterization package which is different from that used in the driving GCM. Such RCM simulations are the CLAMBO and the RegCM2 simulations, both of which are driven by the MPI CGCM. In most of the year for these LAMs the MSLP biases are increased substantially compared to those in the GCM. This seems to be caused by the different parameterization packages which result in the build up of differences across the lateral boundary zones. Both the CLAMBO and the RegCM2 simulations show a distinct tendency to develop large negative temperature biases. In the CLAMBO simulation it is the case in the autumn, winter and spring seasons, most extremely in winter. The too weak downward longwave radiation seems to be further reduced in CLAMBO due to lack of tuning of the radiation scheme. The MSLP bias patterns are somewhat similar to the HIRHAM4 patterns except for a much higher pressure in the interior of the CLAMBO domain in these three seasons. These higher pressures were explained by the inward pressure gradients which must develop in the upper model atmosphere in the lateral boundary zone due to the too cold model atmosphere. In the RegCM2 simulation we found similarly too high pressure in the same three seasons although it is not straightforward to ascribe that solely to the excessive radiative cooling. Thus, in the RegCM2 simulation a boundary relaxation scheme which is different from that used in the other LAMs may have contributed to the exceptionally large deviations of the MSLP patterns from those of the MPI CGCM simulations. In both the CLAMBO and the RegCM2 simulations the too high pressure explains the excessive dry conditions. In the CLAMBO simulation this is compensated by excessive precipitation at mountain tops so that the CLAMBO gets surprisingly small averaged sub-area precipitation biases. In the summer simulation of both the CLAMBO and the RegCM2 model we find excessive positive temperature and negative precipitation biases which were explained by too strong solar radiation at the surface combined with defects in the surface schemes. Again it seems that in the CLAMBO radiation scheme this defect is enhanced due to lack of tuning. Also in this season CLAMBO has excessive precipitation at mountain tops which compensates the general negative biases and thus gives relatively small sub-area biases.

Similar excessive precipitation in the mountain regions are seen in the UKMO RCM simulation. It may be due to spurious horizontal diffusion of moisture along model surfaces to the top of the mountains. However, whether this is the right explanation or to what extent the biases are due to a general underestimation of the observed precipitation in mountainous regions is not clear. As discussed in CEA97 this is a question requiring more intensive studies.

A clear sensitivity to resolution was found for the integrated precipitation amount in sub-area "N", the western slope of the Scandinavian mountains, simulated with the ECHAM, HIRHAM and the VHIRHAM model. The VHIRHAM simulation covers only the Scandinavian Peninsula and surroundings. With the increasing resolution from ECHAM4 to VHIRHAM4 we see in "N" a monotone increase in precipitation bias in autumn, winter and spring, the three seasons with some cross-mountain low level flow and not too large biases in the flow. The biases in the VHIRHAM simulation in "N" in winter, spring and autumn are +40%,+32% and -1%, respectively. As mentioned earlier, the CRU analyses most likely underestimate the precipitation, especially for snow and at up-slopes and tops of mountains. Therefore the precipitation in the CRU analysis is most likely underestimated in sub-area "N". We do not know how much, but 30 - 40% may not be unrealistic in the winter and spring season. A bias of -1% in the autumn may even represent some underestimation of the simulated amounts. Thus, our results do indicate an improvement in orographical precipitation with increasing resolution, which apparently is explained by the increasing realism of the mountains with increasing resolution. This issue is further discussed in Christensen et al. (1999) in which also the improvements with resolution of several other components of the hydrological cycle in Scandinavia are demonstrated

4.2 The climate change experiments

We analyzed four different RCM climate change experiments for Europe, all based on the IS92a scenario (IPCC, 1992), UKMO experiments only approximately (see Figure 0.3). One SUL experiment was designed to simulate changes in long term mean values from 1860 to 2020 due to effects of increasing greenhouse gas and a direct effect of sulphate aerosols. It was performed with the HadRM2 model taking boundary conditions from a 30 year time-slice of a recent UKMO CGCM experiment centered around 2020 and using the 30 year HadRM2 present-day climate simulation as a control simulation. Three GHG experiments including only changes in greenhouse gases were analyzed. One of the GHG experiments was performed with the ARPEGE T63s model using SST and deep soil temperatures from two 10 year time-slices of a transient GHG simulation performed with the UKMO CGCM. It should simulate the changes between 1990 and 2060. The 1990 time-slice is used here as a control simulation. A second GHG experiment was performed with the HIRHAM4 model taking boundary conditions from two 9 year time-slices of a transient GHG simulation form two 10 year time-slices of a transient GHG simulation. The HIRHAM4 model taking boundary conditions from two 9 year time-slices of a transient GHG simulation performed with the HIRHAM4 model taking boundary conditions from two 9 year time-slices of a transient GHG simulation performed with the HIRHAM4 model taking boundary conditions from two 9 year time-slices of a transient GHG simulation performed with the HIRHAM4 model taking boundary conditions from two 9 year time-slices of a transient GHG simulation performed with the ECHAM4 model. It

simulates the changes from 1990 to 2075. Finally, a third GHG experiment consists of simulations with the double nested VHIRHAM4 model taking boundary conditions from two 9 year HIRHAM4 simulations. This last experiment, covering only Scandinavia, uses as the control simulation the present-day climate simulations. It simulates changes over the period 1860-2075. Thus, the four climate change experiments considered represent all different forcings over different periods. However, at least the ARPEGE and HIRHAM experiments should be comparable as the forcings and global temperature responses are pretty similar in these experiments (see Figure 0.3). Along with the RCM climate change experiments we considered also the corresponding CGCM experiments. The purpose of these experiments has not so much been to estimate possible future climate changes on a regional scale in Europe, we expected large uncertainties with the present models, but rather the intension was to get more precise estimates of the uncertainties and their reasons with the purpose to learn which model improvements are needed for sufficiently accurate future climate change computations.

If in a model experiment the systematic errors were exactly the same in the control simulation and in the perturbed simulation then they would cancel out when computing the changes and they would have no influence on the accuracy of the calculated mean changes. Examples were given in the preceding section showing that this popular assumption of cancellation of errors cannot be valid always, at least not on the sub-continental scales considered here. In these examples large systematic errors in the general circulation, temperature and precipitation are seen to result in large errors in the calculated changes of temperature and precipitation. We cannot claim that there is a one to one correspondence between systematic errors and errors in the calculated changes. It seems reasonable, however, to assume that significant effects of systematic errors can be ruled out only if the systematic errors are small compared with the changes computed. If this is not the case the reliability of the changes computed must be considered questionable due to possible detrimental impacts of the systematic errors. As the model equations are non-linear the errors in a certain parameter may result from interactions between errors in other parameters. Small errors in a certain parameter is therefore not sufficient to warrant high accuracy of the changes of that parameter.

Concerning the changes in precipitation in the experiments it is remarkable that the pattern of changes in all cases seem to be explained by the changes in the general atmospheric circulation, i.e. by the changes in MSLP. We found that the precipitation reduces in areas where the pressure increases due to increasing subsidence, that it increases where the pressure decreases due to increasing updraft, presumably connected with increasing cyclonic activity, but in most cases the precipitation changes were found to be the result of increasing or decreasing advection of moist air from the Atlantic. This is supported by the fact that the biases in the present-day climate simulations were partially caused by systematic errors in the general circulation.

In the GHG experiments considering decadal mean values we found that 40-50% of the subarea precipitation changes are significant compared with the estimated internal decadal variability of the models. This means that the main features in the patterns of precipitation changes are significant. The sub-area changes are generally smaller than or of the same order of magnitude as the corresponding biases. In spite of similar forcings we found that generally the pattern of MSLP changes often are very different in the two "whole Europe" GHG experiments and consequently so are the patterns of precipitation. In the SUL experiments only about 20% of the sub-area precipitation changes passed the test of significance. The changes were generally very small but as 30-year mean values are considered the main extremes in the patterns of precipitation changes are also here found to be significant. All of the precipitation changes in the SUL experiments were smaller (often much smaller) than or of equal magnitude as the biases in the corresponding present-day climate (control) simulations. Thus, we must conclude that although the main features in the pattern of simulated changes in precipitation are statistically significant the computed sub-area mean precipitation changes cannot be considered reliable responses to the radiative forcings imposed in any of the experiments.

In all the GHG experiments the averaged warming over Europe was found to be highly significant but of different magnitude. They are generally much larger than the corresponding biases in the present-day climate simulations. For the SUL experiments the averaged European warming is much smaller than those in the GHG experiments but as 30-year mean values are considered we found that also they are significant in all four seasons. They are, however, of the same order of magnitude as the biases in the corresponding control simulations; in the summer and the winter seasons they are even smaller.

The deviations from the mean European warming in the GHG experiments were found to be organized in a common large scale heating pattern caused by direct or indirect thermodynamic effects of the radiative forcing and effects of advection. In the winter the largest temperature increase is situated over north-eastern Europe due to the snow-albedo feed-back process which has its maximum in the area between the snow limit before and after the change. However, due to the large internal decadal model variability in the northern sub-areas these deviations were found not to be significant. In summer the direct influence of the long wave radiative forcing gives maximum heating over southern Europe where in the normal ridge of high pressure few clouds and high specific humidity due to high temperatures tends to enhance the direct greenhouse effect. In the winter season the southern maximum is replaced by a minimum because then large amounts of clouds reduce the greenhouse effect there. In Spring and Autumn we find a combination of weakened large scale features from both of the extreme seasons. These heating patterns are then further modified by advection. Thus, the smaller heating found in all GHG experiments over the western parts of Europe are explained by advection of smaller heating rates from the Atlantic by the normal westerlies. Weaker direct and indirect effects of the changes in the general circulation may be responsible for the smaller scale deviations found in the pattern of temperature changes in the different GHG experiments.

We find that the large sub-area deviations from the European mean temperature change described above which are connected to the advection of small changes from the Atlantic and connected to the seasonal variation of cloud cover, do pass our test of significance. However, even the deviations that are significant are generally not larger than the corresponding biases.

For the SUL experiments the pattern of temperature changes is much more homogeneous than in the GHG experiments and we found in general that the small sub-area deviations from the European mean temperature changes we compute are insignificant and smaller than or of the same order of magnitude as the corresponding biases. Some deviations were, however, found to be significant. Namely, deviations connected with the snow-albedo feed-back process to the north in spring, deviations connected with advection of small changes from the Atlantic to the west in autumn and deviations connected with reduced cloud cover to the south in spring and summer. The deviations were, however, found generally to be smaller than the biases.

That the averaged seasonal temperature changes for Europe were found to be significant for all the GHG model experiments show that the different European warmings computed in these experiments most likely is not the result of internal model variations. In spite of similar radiative forcings we find different averaged European warmings when using different models (in the annual mean ranging from 2.1K to 4.1K). This indicates systematic differences in model sensitivity which mainly seems to be the result of the influence of different warmings of the Atlantic Ocean and different systematic errors in the advection from the Ocean. Also the different patterns of significant changes of precipitation and temperature in the GHG experiments indicate systematic differences in model sensitivity which must be explained by different changes in the general circulation, different errors in the advection from the Atlantic Ocean, different warmings of the Ocean and different local effects of the local physical parameterization over Europe. The importance of changes in the general circulation were seen clearly especially for the changes in precipitation. Differences in the circulation changes were thought to be caused by different errors in the physical parameterization schemes of the different models.

In the summer season GHG experiments we find exceptions from the general results and at the same time one of the examples where cancellation of systematic errors most likely is not taking place. Thus, in the HIRHAM experiment we find significant precipitation changes in two central and three southern European sub-areas and also significant temperature deviation changes in the three southern European sub-areas. Furthermore these sub-area changes are quite exceptionally found to be of the same order of magnitude as or larger than the corresponding systematic errors. In this season we find also quit exceptionally a high degree of agreement between the patterns of precipitation and temperature changes in all the different GHG experiments. The radiative forcing in the experiments was found to result in an intensification and extension of the overly dry and hot areas to cover more of the continent than it did in the control simulation. A similar response was seen in the ARPEGE experiment although with smaller changes. The explanation adopted was that the climate change heating and drying-out process is proceeding too "willingly" just as this process does in the present-day climate simulations. We concluded that the climate changes most likely would be completely different had the models not had the dry and hot biases to start with. Obviously, in the present cases the large systematic errors which are most likely present in both the control and the perturbed simulations are different and thus do not cancel out giving the correct changes when subtracted from each other. Thus, even in such cases where our test convincingly indicates that large changes in precipitation are significant and where these changes also exceeds the corresponding biases we find that the realism of the changes are highly questionable. The problem is indicated in this case by large systematic errors in areas neighboring to the area with the large changes. This indicates again that the systematic errors need to be small compared to the changes in order to exclude that they significantly influence the climate changes.

4.3 Outlooks

We have seen that the mean European warming computed in the different climate change experiments in all seasons and experiments were found to be significant. We are interested, however, also in sub-continental deviations from the European mean, i.e. deviations on our sub-area scale.

We found that generally in the GHG experiments the main changes in precipitation and temperature on the sub-area scale passed our test of significance. Particular features in the pattern of temperature changes, namely the winter time maxima connected to the snow-albedo feedback process, were not found to be significant. Thus, even with the large radiative forcing in the GHG experiments it seems desirable to consider changes of mean values over longer time-slices. Time-slices of 15-years would probably be sufficient. In coming experiments taking into account the influence of sulphur aerosols (SUL experiments) we will probably have to use 30year time-slices and go beyond year 2020, in order to have sufficiently large changes on the subarea scale to exclude the possibility that the changes we compute are due to internal model variations. That a sufficiently large period and time-slice have been chosen could be tested using output from the driving models (since anyway we assume that the internal model variation is the same in the driving and nested model).

We found also that in order to have sufficient confidence in the computed changes the systematic errors in the present-day climate simulations must be small compared to the climate changes. Of the experiments analyzed here this is generally the case only for the mean European warming in the GHG experiments. Again, we are interested in particular in changes of precipitation and temperature on the sub-area scale which generally were found to be smaller than or of equal magnitude to the corresponding systematic errors. Consequently, before reliable experiments can be produced we will have to reduce the systematic errors sufficiently. This must be done by improving the physical mechanisms simulated in the models rather than by carrying out an excessive tuning of the models that may not be valid in a changed climate.

The work on such reductions of biases are now carried out in particular in two EC projects PO-TENTALS (Project On Tendency Evaluations using New Techniques to Improve Atmospheric Long-term Simulations) and MERCURE (Modeling European Regional Climate: Understanding and Reducing Errors). In POTENTIALS which is coordinated by Eigil Kaas, DMI the aim is to reduce the systematic errors in the general circulation of the GCMs since similar systematic errors in RCMs with the same physical parameterization package as the GCMs, as we have seen, severely degrades the performance of the RCMs. The plan is to try to diagnose the errors in the physical forcings and then to change the physical parameterizations to eliminate, as far as possible, these errors. This is the strategy also in the MERURE project coordinated by Richard Jones, UKMO except that here RCMs will be used, mainly with "perfect" boundary conditions, and the aim is to reduce the "local" systematic model errors over Europe which were identified in the present RACCS project; in particular the common errors leading to the excessive summer drying and heating over southern and eastern Europe and the increase in excessive cyclonic activity with increasing resolution.

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Precipitation DJF	Ν	NE	W	C	E	Alps	SW	S	SE	Total
CRU (30) [mm/day]	4.0	1.2	3.5	1.7	1.3	3.1	2.6	3.4	1.8	2.2
UKMO GCM CTL (30) - CRU (30) [%]	-13.2	67.7	-22.6	30.9	44.4	2.4	-15.1	-34.3	13.6	3.9
UKMO GCM SCA (30) - CTL (30) [%]	-3.2	2.0	0.2	-1.3	-0.5	10.9	11.7	12.9	9.8	4.6
UKMO RCM CTL (30) - CRU (30) [%]	15.4	60.5	3.3	53.7	64.8	41.1	31.5	15.2	34.5	30.2
UKMO RCM SCA (30) - CTL (30) [%]	-1.6	9.0	-0.8	-3.6	0.8	7.2	10.9	4.5	4.2	3.0
UKMO GCM sca (10) - CRU (30) [%]	-18.4	55.5	-25.4	29.3	36.8	3.6	-31.5	-36.1	25.0	0.4
UKMO GCM SCA (10) - sca (10) [%]	10.6	39.9	12.9	4.6	18.9	18.0	36.8	22.0	-8.1	15.4
ARPEGE T63s sca (10) - CRU (30) [%]	-19.3	75.6	30.0	72.1	68.9	27.1	32.2	-16.5	-8.8	24.7
ARPEGE T63s SCA (10) - sca (10) [%]	-12.0	0.4	11.3	31.9	30.5	25.1	16.5	37.8	37.4	21.1
ECHAM4 CTL (9) - CRU (30) [%]	-16.5	57.5	-10.0	62.1	60.8	-13.4	-40.1	-38.5	28.9	8.8
ECHAM4 SCA (9) - sca (9) [%]	10.1	35.2	6.8	13.9	26.9	-2.5	-21.6	-0.4	23.9	10.4
HIRHAM4 CTL (9) - CRU (30) [%]	15.9	91.1	8.9	104.2	122.5	9.3	-16.1	-25.4	35.5	35.0
HIRHAM4 SCA (9) - sca (9) [%]	25.5	32.3	7.8	20.6	42.0	4.5	-21.9	-3.6	8.3	11.3
VHIRHAM CTL (9) - CRU (30) [%]	40.0	76.2								
VHIRHAM SCA (9) - CTL (9) [%]	5.2	22.7								
CLAMBO CTL (5) - CRU (30) [%]			-13.4	22.8	-5.2	17.7	-41.9	-34.5	-23.7	
MM4 CTL (5) - CRU (30) [%]			-27.8	16.9	46.5	-55.9	-75.3	-75.1	-20.8	

Table 1.1: Sub-area means of seasonal ensemble averages of multi-year time series for precipitation for winter season (DJF). Included are climatological values, CRU(30) [mm/day], and a series of models: biases of control simulations (e.g. UKMO GCM CTL (30) - CRU (30)) and simulated climate changes (e.g. UKMO GCM SCA (30) - CTL (30)). Biases and climate changes are in percent of climatological value. Bold numbers indicate significant values.

Precipitation MAM	N	NE	W	С	Е	Alps	SW	S	SE	Total
CRU (30) [mm/day]	2.6	1.1	2.5	1.8	1.4	3.7	2.1	2.3	1.8	1.9
UKMO GCM CTL (30) - CRU (30) [%]	2.3	71.3	-12.7	19.3	32.7	2.3	9.8	18.4	41.1	20.2
UKMO GCM SCA (30) - CTL (30) [%]	6.0	10.6	5.4	1.9	-11.9	4.5	9.6	3.4	-11.5	0.5
UKMO RCM CTL (30) - CRU (30) [%]	23.7	97.6	9.8	41.7	81.0	41.8	48.5	79. 8	63.8	52.5
UKMO RCM SCA (30) - CTL (30) [%]	11.0	12.8	9.3	-0.4	-15.3	3.8	16.2	-9.8	-17.8	-1.0
UKMO GCM sca (10) - CRU (30) [%]	4.5	74.0	-4.2	26.0	32.6	2.0	-0.2	14.3	36.5	20.0
UKMO GCM SCA (10) - sca (10) [%]	8.9	23.6	2.0	5.4	11.3	4.9	-7.8	-9.4	-11.6	2.1
ARPEGE T63s sca (10) - CRU (30) [%]	9.6	95.0	38.5	71.8	87.6	28.5	15.4	-5.0	26.4	42.7
ARPEGE T63s SCA (10) - sca (10) [%]	-2.7	21.1	14.9	28.0	40.9	10.5	-29.6	-2.1	22.0	14.2
ECHAM4 CTL (9) - CRU (30) [%]	-10.4	64.7	-19.3	30.3	32.7	-21.5	-30.5	-3.0	29.0	9.6
ECHAM4 SCA (9) - sca (9) [%]	19.1	48.9	6.2	-2.8	16.1	-3.9	-4.4	-23.0	-23.0	2.4
HIRHAM4 CTL (9) - CRU (30) [%]	19.1	96.0	-6.3	52.9	88.5	3.3	-20.0	3.2	39.0	32.4
HIRHAM4 SCA (9) - sca (9) [%]	34.0	33.1	7.6	-7.0	20.7	-10.1	-5.2	-24.5	-29.6	-1.3
VHIRHAM CTL (9) - CRU (30) [%]	31.6	74.6								
VHIRHAM SCA (9) - CTL (9) [%]	41.4	46.6								
CLAMBO CTL (5) - CRU (30) [%]			-6.3	16.1	-9.4	33.1	-12.4	7.9	-3.7	
MM4 CTL (5) - CRU (30) [%]			-33.9	-30.9	-22.0	-64.0	-68.8	-57.6	-26.9	

Table 1.2: As Table 1.1 but for spring season (MAM).

Precipitation JJA	N	NE	W	С	Е	Alps	SW	S	SE	Total
CRU (30) [mm/day]	3.1	2.2	2.4	2.2	2.5	4.2	1.1	1.4	2.2	2.2
UKMO GCM CTL (30) - CRU (30) [%]	14.1	12.9	-1.3	9.7	-25.2	-10.8	14.5	30.0	-7.8	-0.4
UKMO GCM SCA (30) - CTL (30) [%]	-2.5	-2.7	-9.6	-3.3	1.5	7.7	11.7	26.7	6.5	1.8
UKMO RCM CTL (30) - CRU (30) [%]	43.2	44.5	23.0	18.1	1.2	8.2	74.4	56.4	-0.2	22.1
UKMO RCM SCA (30) - CTL (30) [%]	1.9	4.2	-9.5	0.6	2.1	8.3	5.4	25.5	-2.8	2.1
UKMO GCM sca (10) - CRU (30) [%]	12.9	11.6	-10.9	-1.9	-23.5	-22.2	-3.9	8.7	-9.5	-6.0
UKMO GCM SCA (10) - sca (10) [%]	9.4	12.4	-6.2	-4.5	1.3	-6.6	-15.0	-16.7	-16.6	-3.5
ARPEGE T63s sca (10) - CRU (30) [%]	26.1	40.2	23.3	26.8	13.0	-10.6	-14.3	-51.4	-28.5	9.9
ARPEGE T63s SCA (10) - sca (10) [%]	5.5	7.5	-6.2	-7.9	6.8	-9.3	-22.3	-16.6	-14.2	-4.2
ECHAM4 CTL (9) - CRU (30) [%]	-41.0	-23.9	-37.4	-3.9	-28.2	-35.2	35.9	21.7	-12.6	-16.7
ECHAM4 SCA (9) - sca (9) [%]	6.0	-0.3	-6.5	-17.4	-18.2	8.0	-25.3	25.5	-4.6	-7.3
HIRHAM4 CTL (9) - CRU (30) [%]	11.8	10.2	-0.3	10.3	-14.7	-25.0	-12.2	-33.5	-44.9	-9.1
HIRHAM4 SCA (9) - sca (9) [%]	14.9	8.9	-1.1	-23.7	-14.7	-17.6	-25.9	-13.5	-17.9	-11.8
VHIRHAM CTL (9) - CRU (30) [%]	10.0	9.6								
VHIRHAM SCA (9) - CTL (9) [%]	28.3	15.4								
CLAMBO CTL (5) - CRU (30) [%]			-34.6	-40.2	-40.5	-3.3	-12.6	-56.8	-65.4	
MM4 CTL (5) - CRU (30) [%]			-69.1	-74.3	-81.1	-80.4	-90.0	-82.9	-84.0	

Table 1.3: As Table 1.1 but for summer season (JJA).

Precipitation SON	N	NE	W	С	E	Alps	SW	S	SE	Total
CRU (30) [mm/day]	4.8	1.9	3.6	2.1	1.8	3.6	2.3	3.3	1.7	2.4
UKMO GCM CTL (30) - CRU (30) [%]	-21.4	32.4	-34.6	-2.1	-2.2	-6.5	-25.2	-22.6	5.9	-10.5
UKMO GCM SCA (30) - CTL (30) [%]	4.8	7.4	2.3	4.3	6.0	7.6	-5.6	3.4	3.1	3.4
UKMO RCM CTL (30) - CRU (30) [%]	1.9	44.7	-11.1	13.7	25.9	27.7	14.6	24.7	36.2	15.9
UKMO RCM SCA (30) - CTL (30) [%]	6.1	9.1	4.1	7.7	6.5	5.5	-5.0	-10.6	1.1	3.2
UKMO GCM sca (10) - CRU (30) [%]	-21.8	33.4	-36.9	-1.0	4.6	-3.4	-32.4	-18.0	14.5	-8.4
UKMO GCM SCA (10) - sca (10) [%]	14.4	23.9	14.0	11.6	6.6	-10.3	0.8	-15.1	-23.3	3.5
ARPEGE T63s sca (10) - CRU (30) [%]	-17.7	37.2	-1.9	25.0	11.4	3.4	-15.8	-27.9	-10.9	-0.4
ARPEGE T63s SCA (10) - sca (10) [%]	26.7	19.5	-1.4	-13.8	-8.0	-25.2	-16.8	-17.1	-9.4	-5.2
ECHAM4 CTL (9) - CRU (30) [%]	-30.9	32.9	-18.8	21.1	13.6	-25.5	-15.4	-41.2	5.9	-4.1
ECHAM4 SCA (9) - sca (9) [%]	21.3	50.1	3.1	-12.6	-11.3	-8.0	-7.2	-7.1	-36.5	-0.9
HIRHAM4 CTL (9) - CRU (30) [%]	-14.0	59.8	4.2	67.0	70.2	16.7	12.3	-35.4	25.4	25.2
HIRHAM4 SCA (9) - sca (9) [%]	35.8	54.9	7.8	-9.7	-11.8	-13.6	-21.7	-16.4	-35.5	-1.9
VHIRHAM CTL (9) - CRU (30) [%]	-0.7	57.3								
VHIRHAM SCA (9) - CTL (9) [%]	38.5	39.8								
CLAMBO CTL (5) - CRU (30) [%]			3.2	12.2	5.8	51.5	10.7	-19.8	-5.3	
MM4 CTL (5) - CRU (30) [%]			-31.1	-23.6	-40.0	-56.2	-73.1	-80.1	-54.2	

Table 1.4: As Table 1.1 but for autumn season (SON).

Temperature DJF	N	NE	W	С	E	Alps	SW	S	SE	Total
CRU (30) [C]	-3.9	-9.4	5.1	1.5	-4.5	3.8	9.9	8.8	1.8	0.8
UKMO GCM CTL (30) - CRU (30) [C]	-3.0	0.2	0.1	1.1	0.3	-1.3	-1.1	-5.0	-0.5	-0.7
UKMO GCM SCA (30) - CTL (30) [C]	1.6	1.8	0.8	1.1	0.8	1.5	1.0	1.6	1.3	1.2
UKMO RCM CTL (30) - CRU (30) [C]	-0.3	1.0	0.5	0.6	-0.1	0.3	-0.4	-2.0	0.0	-0.2
UKMO RCM SCA (30) - CTL (30) [C]	1.5	1.8	1.0	1.2	1.3	1.4	1.1	1.4	1.3	1.3
UKMO GCM sca (10) - CRU (30) [C]	-0.8	2.2	1.1	1.8	0.2	-0.3	-0.6	-4.3	0.0	0.1
UKMO GCM SCA (10) - sca (10) [C]	2.3	2.9	2.0	3.1	4.2	3.8	2.9	4.0	3.5	3.3
ARPEGE T63s sca (10) - CRU (30) [C]	0.1	1.9	0.4	2.2	3.1	1.2	-0.7	-1.2	2.5	1.1
ARPEGE T63s SCA (10) - sca (10) [C]	1.4	2.3	1.1	1.5	1.8	2.0	1.8	2.4	2.2	1.9
ECHAM4 CTL (9) - CRU (30) [C]	2.4	-0.5	1.2	2.2	-1.3	0.0	0.5	-1.7	0.8	-0.4
ECHAM4 SCA (9) - sca (9) [C]	3.8	6.3	3.1	3.2	4.8	3.0	2.8		3.1	3.9
HIRHAM4 CTL (9) - CRU (30) [C]	0.6	1.9	1.3	2.1	1.6	0.9	0.6	-0.6	1.2	0.9
HIRHAM4 SCA (9) - sca (9) [C]	3.8	5.2	3.2	3.1	4.3	3.0	<u>2.9</u>	<u>_2.6</u>	3.1	3.6
VHIRHAM CTL (9) - CRU (30) [C]	-0.7	1.0								
VHIRHAM SCA (9) - CTL (9)[C]	3.4	4.8								
CLAMBO CTL (5) - CRU (30) [C]			-2.8	-4.2	-5.7	-1.6	-3.6	-5.1	-4.6	
MM4 CTL (5) - CRU (30) [C]			2.9	2.2	0.3	0.6	-0.2	-2.7	-0.5	

Table 2.1: As Table 1.1 but for surface air temperature reduced to MSL. Units for all values is °C. Underlined values (e.g. ECHAM4 SCA (9) - sca (9) for the areas "SW" and "S") indicate a significant different climate change signal than the corresponding mean change over Europe in column "Total".

Temperature MAM	N	NE	W	С	E	Alps	SW	S	SE	Total
CRU (30) [C]	2.9	1.2	8.6	8.7	6.9	12.0	15.0	14.4	11.8	8.9
UKMO GCM CTL (30) - CRU (30) [C]	-3.8	-1.5	-0.6	-0.9	-1.2	-2.8	-2.2	-3.8	-1.8	-1.8
UKMO GCM SCA (30) - CTL (30) [C]	<u> </u>	<u>2.2</u>	1.1	1.5	1.0	1.6	1.3	1.3	<u> </u>	1.4
UKMO RCM CTL (30) - CRU (30) [C]	-1.9	-1.0	-0.7	-1.3	-1.0	-2.2	-1.8	-2.1	-1.2	-1.4
UKMO RCM SCA (30) - CTL (30) [C]	<u> </u>	<u>2.3</u>	1.2	1.6	1.3	1.7	1.4	1.5	1.1	1.5
UKMO GCM sca (10) - CRU (30) [C]	-2.1	0.1	0.2	-0.1	-0.8	-1.8	-0.9	-2.8	-1.1	-0.9
UKMO GCM SCA (10) - sca (10) [C]	2.4	2.5	1.8	2.1	2.6	2.3	2.9	2.2	2.2	2.4
ARPEGE T63s sca (10) - CRU (30) [C]	-0.8	-1.1	0.3	0.2	0.3	-1.3	-0.6	-1.0	0.2	-0.4
ARPEGE T63s SCA (10) - sca (10) [C]	2.9	3.4	1.7	2.0	2.1	2.4	2.8	2.5	2.1	2.4
ECHAM4 CTL (9) - CRU (30) [C]	-0.3	-1.9	0.6	-0.1	-1.6	-2.1	0.1	-1.5	-1.5	-1.4
ECHAM4 SCA (9) - sca (9) [C]	2.8	3.0	3.0	3.6	3.3	4.3	4.0	4.2	4.1	3.5
HIRHAM4 CTL (9) - CRU (30) [C]	-1.0	-0.8	0.4	-0.8	-1.3	-2.2	0.5	-1.2	-1.5	-1.1
HIRHAM4 SCA (9) - sca (9) [C]	2.7	2.9	3.2	3.5	3.0	4.5	4.2	4.3	3.9	3.5
VHIRHAM CTL (9) - CRU (30) [C]	-3.1	-2.8								
VHIRHAM SCA (9) - CTL (9)[C]	5.0	5.2								
CLAMBO CTL (5) - CRU (30) [C]			0.8	-0.2	-3.1	-1.6	0.5	-0.7	-1.2	
MM4 CTL (5) - CRU (30) [C]			0.7	-2.2	-7.4	-4.2	1.2	-4.1	-7.4	

Table 2.2: As Table 2.1 but for spring season (MAM).

Temperature JJA	N	NE	W	С	E	Alps	SW	S	SE	Total
CRU (30) [C]	13.1	14.0	14.9	17.5	17.6	20.5	23.7	23.6	21.4	18.5
UKMO GCM CTL (30) - CRU (30) [C]	-4.0	-3.1	-0.2	-0.5	0.9	-2.0	-1.4	-2.5	0.4	-0.9
UKMO GCM SCA (30) - CTL (30) [C]	1.3	1.3	1.4	1.3	1.2	1.2	1.3	<u> </u>	<u> </u>	1.2
UKMO RCM CTL (30) - CRU (30) [C]	-2.8	-2.7	-0.6	-1.0	-0.8	-1.8	-1.7	-1.3	0.2	-1.2
UKMO RCM SCA (30) - CTL (30) [C]	1.3	1.2	1.1	1.3	1.5	1.4	1.3	1.0	1.3	1.3
UKMO GCM sca (10) - CRU (30) [C]	-2.7	-1.7	1.0	0.8	2.0	-0.6	0.9	-0.9	1.5	0.4
UKMO GCM SCA (10) - sca (10) [C]	<u> </u>	<u> </u>	2.3	2.3	1.8	2.8	3.7	<u> </u>	<u>3.3</u>	2.4
ARPEGE T63s sca (10) - CRU (30) [C]	-0.5	-0.6	-0.1	-0.6	-0.2	-0.8	0.2	1.0	1.3	-0.1
ARPEGE T63s SCA (10) - sca (10) [C]	1.1	1.0	1.7	1.8	1.2	2.6	<u> </u>	<u>3.2</u>	2.6	2.0
ECHAM4 CTL (9) - CRU (30) [C]	0.2	0.2	1.9	0.4	1.1	-0.7	-0.4	-0.6	0.1	0.1
ECHAM4 SCA (9) - sca (9) [C]	<u>_2.6</u>	<u> </u>	3.7	4.6	4.0		5.4		<u>4.8</u>	4.1
HIRHAM4 CTL (9) - CRU (30) [C]	-1.1	-1.3	0.6	-0.5	0.2	-1.0	0.9	0.3	1.2	0.0
HIRHAM4 SCA (9) - sca (9) [C]	<u> </u>	2.5	<u> </u>	4.5	4.1	5.7	5.3	5.6		4.4
VHIRHAM CTL (9) - CRU (30) [C]	-3.4	-3.3								
VHIRHAM SCA (9) - CTL (9)[C]	4.4	3.8								
CLAMBO CTL (5) - CRU (30) [C]			4.9	5.7	5.7	3.4	3.1	5.1	7.5	
MM4 CTL (5) - CRU (30) [C]			2.3	1.4	-1.3	2.2	5.9	2.7	2.7	

Table 2.3: As Table 2.1 but for summer season (JJA).

Temperature SON	N	NE	W	С	E	Alps	SW	S	SE	Total
CRU (30) [C]	4.8	2.9	10.7	10.2	7.5	13.1	17.5	17.2	12.7	10.5
UKMO GCM CTL (30) - CRU (30) [C]	-2.8	-1.2	-0.5	-0.4	-0.9	-2.5	-1.6	-4.7	-1.4	-1.5
UKMO GCM SCA (30) - CTL (30) [C]	1.3	1.5	1.1	1.2	1.4	1.4	1.3	1.3	1.4	1.3
UKMO RCM CTL (30) - CRU (30) [C]	-1.4	-1.1	-0.3	-0.6	-1.2	-1.2	-1.2	-2.2	-1.2	-1.2
UKMO RCM SCA (30) - CTL (30) [C]	1.3	1.5	<u> </u>	1.1	1.4	1.4	1.3	1.4	1.5	1.3
UKMO GCM sca (10) - CRU (30) [C]	-0.9	0.9	0.4	0.6	0.9	-1.6	-0.7	-3.8	-0.1	-0.2
UKMO GCM SCA (10) - sca (10) [C]	<u> </u>	1.5	2.4	3.0	2.8	3.5	<u> </u>	3.4	3.1	2.8
ARPEGE T63s sca (10) - CRU (30) [C]	-0.9	-0.4	-0.9	-0.9	-0.4	-1.9	-2.4	-3.3	-1.6	-1.5
ARPEGE T63s SCA (10) - sca (10) [C]	1.9	1.8	2.0	2.1	1.6	2.3	<u>2.9</u>	2.4	1.8	2.0
ECHAM4 CTL (9) - CRU (30) [C]	1.0	-0.8	0.8	1.1	-0.1	-0.5	-0.2	-1.3	0.2	-0.5
ECHAM4 SCA (9) - sca (9) [C]	<u>3.9</u>	5.1	<u> </u>	4.4	4.9	5.1	4.5	4.9	4.9	4.7
HIRHAM4 CTL (9) - CRU (30) [C]	-1.4	-0.8	0.2	0.1	0.1	-0.9	-0.1	-0.8	0.4	-0.4
HIRHAM4 SCA (9) - sca (9) [C]	4.1	4.3	3.2	4.4	4.5	<u> </u>	4.8	<u> </u>	5.5	4.7
VHIRHAM CTL (9) - CRU (30) [C]	-2.6	-1.9								
VHIRHAM SCA (9) - CTL (9)[C]	4.4	4.6								
CLAMBO CTL (5) - CRU (30) [C]			-0.9	-0.6	-1.5	-1.1	-1.4	-1.1	0.1	
MM4 CTL (5) - CRU (30) [C]			0.1	-0.4	-2.4	0.0	2.1	-1.2	-0.6	

Table 2.4: As Table 2.1 but for autumn season (SON).



Figure 0.1: The validation area and integration areas of limited area models: 1. HIRHAM4, 2. VHIRHAM4, 3. RECS II, 4. CLAMBO, 5. RegCM2, 6. The validation area.



Figure 0.2: Sub-areas for Europe shown on the HIRHAM4 orography.



Figure 0.3: Global surface air temperature and radiative forcing for the three climate change experiments performed by the Hadley Center, UKMO (from Mitchell et al., 1995) and the MPI (Roeckner, personal communication). Curves marked GHG are from transiently increasing greenhouse gas scenarios and those marked SUL are from a scenario in which also a direct effect of changing sulphate aerosols is included. Marked are the time-slices during which boundary conditions were provided for RCM experiments. The global warming and radiative forcing in these experiments are indicated.



DJF

50

70

30

30

DJF

30

30

60

DJF

 \bigcirc

20

Figure 1.1: Left coulmn: MSLP multi-year ensemble averages for winter season (DJF) of ECMWF analyses and GCM control simulations [2.5 hPa] (solid lines) and standard deviation of bandpass filtered 500 hPa height [10 m] (shaded). Right coulmn: Systematic errors of MSLP [1 hPa].





Figure 1.2: As Figure 1.1 but for RCMs.





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- 10

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Figure 1.3: As Figure 1.1 but for spring season (MAM).





Figure 1.4: As Figure 1.2 but for spring season (MAM)





Figure 1.5: As Figure 1.1 but for summer season (JJA).





Figure 1.6: As Figure 1.2 but for summer season (JJA)





Figure 1.7: As Figure 1.1 but for autumn season (SON).




Figure 1.8: As Figure 1.2 but for autumn season (SON)



[°C]

Figure 2.1: Multi-year ensemble averages for winter season (DJF). Left coulmn: Precipitation [mm/day]. Right coulmn: Surface air temperature reduced to MSL [°C]. Upper panels: Climatologie. Lower panels: Biases of GCMs.



Figure 2.2: As Figure 2.1 but for RCMs



[°C]

Figure 2.3: As Figure 2.1 but for spring season (MAM).



Figure 2.4: As Figure 2.2 but for spring season (MAM)



[°C]

8

Figure 2.5: As Figure 2.1 but for summer season (JJA).



Figure 2.6: As Figure 2.2 but for summer season (JJA)



SON

30

30

30

30

[°C]

Figure 2.7: As Figure 2.1 but for autumn season (SON).



Figure 2.8: As Figure 2.2 but for autumn season (SON)



Figure 3.1: Biases of seasonal ensemble averages of 5 year control simulation with CLAMBO model. Left coulmn: Precipitation [mm/day]. Right coulmn: Surface air temperature reduced to MSL [°C].



DJF

70

30

30

JJA

SON

30

70

[°C]

Figure 3.2: As Figure 3.1 but for the MM4 model.



Figure 3.3: Left column: MSLP five year ensemble averages of CLAMBO control simulations [2.5 hPa]. Right column: Systematic errors of MSLP (control – ECMWF analyses) [1 hPa], zero line omitted.



Figure 3.4: Left column: MSLP five year ensemble averages of MM4 control simulations [2.5 hPa]. Right column: Systematic errors of MSLP (control – ECMWF analyses) [1 hPa], zero line omitted.



Figure 4.1: Seasonal ensemble averages of multi-year sea surface temperatures (SST) fields. AMIP analyses and biases for time-slices of three CGCM "control" simulations. Left coulmn: Winter season (DJF). Right coulmn: Spring season (MAM).



[°C]

[°C]

Figure 4.2: As Figure 4.1 but for summer (JJA) left and for autumn (SON) right seasons.



Figure 5.1: For each season and each sub-area (see Figure 5.1 in MEA96) precipitation biases [in percent of climatological values] of different "observed" and simulated time series. In column 1 and 2 (from left) are shown estimated ranges of observed and simulated variation of decadal mean values (see legend of Table 1.1). The ranges are shaded. The next 9 columns show the biases for the models in the following order: 3 UKMO GCM (30), 4 UKMO RCM, 5 UKMO GCM (8), 6 ARPEGE T63s, 7 ECHAM4, 8 HIRHAM4, 9 VHIRHAM, 10 CLAMBO and 11 MM4. Odd numbered columns from 3 to 7 contain results of GCMs providing boundary conditions for the RCM in the following column. In each column is the bias of a control run marked with a solid line, and that of the scenario run by a stipled line. In column 7 and 8 is drawn also the bias of an additional "control" run (sca (9)) taken from scenario runs with present day (1990) forcing.







SON



Figure 5.2: As Figure 5.1 but for surface air temperature reduced to mean sea level and showing absolut changes.



DJF

30

30

30

- <u>5</u>

30

5-

DJF

60

DJF

DJF 30

Figure 6.1: Climate changes for the winter season (DJF) (scenario – control) of MSLP ensemble averages for "driving" models **left coulmn** and "nested" models **right coulmn**.



Figure 6.2: As Figure 6.1 but for spring season (MAM)



Figure 6.3: As Figure 6.1 but for summer season (JJA)



Figure 6.4: As Figure 6.1 but for autumn season (SON)



[mm/day]

Figure 7.1: As Figure 6.1 but for precipitation.



Figure 7.2: As Figure 6.1 but for surface air temperature reduced to MSL.



Figure 7.3: As Figure 6.2 but for precipitation.



Figure 7.4: As Figure 6.2 but for surface air temperature reduced to MSL.



Figure 7.5: As Figure 6.3 but for precipitation.



Figure 7.6: As Figure 6.3 but for surface air temperature reduced to MSL.



Figure 7.7: As Figure 6.4 but for precipitation.



Figure 7.8: As Figure 6.4 but for surface air temperature reduced to MSL.



Figure 8.1: Climate changes of multi-year seasonal ensemble averages of sea surface temperatures (SST) fields. Left coulmn: Winter season (DJF). Right coulmn: Spring season (MAM).



50 N 30

SON

50

50

60

[°C]

4 5 8

30

SON

30

SON

Figure 8.2: As Figure 8.1 but for summer season (JJA) left and for autumn season (SON) right.

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