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On the construction of a regional atmospheric climate model

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ON THE CONSTRUCTION OF A REGIONAL ATMOSPHERIC CLIMATE MODEL

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Abstract

A Regional Atmospheric Climate Model which combines the physical parametrization package of the General Circulation or Climate Model (ECHAM) used at the Max Planck Institute for Meteorology in Hamburg, and the dynamics package of the Nordic - Dutch - Irish Limited Area Model (HIRLAM), has been developed. The objectives of the project are formulated, and the developing strategy is described in some detail mainly as a guidance for the potential user with a limited knowledge of either of the two models. Furthermore, the necessary changes applied to both model packages in order to obtain a *working* code are described. Finally, preliminary results of the very first experiments are presented and briefly discussed.

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INTRODUCTION

Available computing resources impose strong restrictions on the design of a global circulation or climate model. The resolution needed to represent the horizontal and vertical scales will always be limited. Presently, the information from a global circulation model (GCM) is obtained on a rather coarse grid, typically about (250 km)^2, which is certainly insufficient to provide an unambiguous prediction of climate variables on regional scale, i.e. $\approx$ (50 km)^2. Furthermore, the chosen resolution strongly determines the way physical processes in the atmosphere are parametrized. Apart from that, the level of sophistication of these parametrizations is far from optimal, again in view of the need to keep the model manageable. One may argue the validity of the simplifications applied in the description of physical processes, but once again the coarse resolution of global models prevents a clear answer to such doubts. In this perspective the construction of a **R**egional **A**tmospheric **C**limate **MO**del (RACMO) is very interesting, since it allows one to extract more detailed information about the evolution of climate variables and the underlying physical processes (Giorgi and Mearns, 1991).

A potential way to obtain more detailed knowledge on regional scale is via the nesting method (Dickinson et al., 1989; Giorgi, 1990). A limited area model (LAM) is nested in a GCM in the sense that the initial fields and lateral boundary conditions are supplied to the LAM by the GCM. Recently, such an approach has been initiated at DMI. At this institute a lot of experience is gained in working with the HIRLAM (**HI**gh **R**esolution **L**imited **A**rea **M**odel) model, since this model is in operational use for almost three years. Meanwhile, the first experiments with the nesting technique were started. The lateral boundaries for these experiments were generated from ECMWF analyses supplied at 6 hour intervals. Likewise the initial conditions were based on ECMWF analyses. The integrations were carried out successfully for a summer and a winter month. This type of experiments led to a better understanding of the behaviour of the HIRLAM model in general and gave valuable insight about the shortcomings of the operational version, when the model was run in climate mode. The ultimate goal is to run the model nested in a global circulation model, which is running in climate mode. The ECHAM model is well suited for this purpose, since it represents the state of the art in climate simulations, and it would be very attractive to do the nesting experiments with a combination of the two models. Within such a project detailed knowledge of the model performance forms an essential prerequisite in order to assign any scientific impact to the outcome of *scenario experiments* obtained with the nesting technique. Hence, the model behaviour will also be studied by running the RACMO in forecast mode with boundary conditions taken from the ECMWF analyses. If it is possible to show that the deviations of the model results from the analyses themselves are insignificant by some well-defined measure, one might be able to draw definite conclusions about the impact of the RACMO on a GCM experiment.

A recently initiated research project at KNMI is directed to model intercomparison and validation. The aim is to improve the understanding of the behaviour of the various physics modules and their role in mutual interactions. It is intended to examine the impact of parameterization schemes as well as to investigate modifications of existing modules or to develop and test physics modules based on new concepts and insights. For this purpose the ECHAM3 physics package linked to the HIRLAM model may serve as a RACMO baseline model. This model in itself is already quite valuable since it combines a treatment of the HIRLAM dynamics with the physics package of an up-to-date climate model. To investigate the impact of the physics modules, studies of various well-documented cases in the recent past are planned, such that the results of the model can be validated against observations. The selected cases will be simulated by running the model based on initial and boundary fields supplied by an ECMWF analysis. The model output will also be compared with the operational HIRLAM runs for the same cases.

The paper is organised as follows. First we formulate the objectives and point out the working strategy. Thereafter, the essentials of the nesting technique are described; special attention is paid to the treatment of the liquid water variable at the boundaries. In the subsequent section the contents of the ECHAM3 physics package are briefly summarized. In the last section the results of the first experiments with the RACMO are discussed. Finally, an appendix includes a list of all the fields, which are generated by the physics package of the RACMO.

OBJECTIVES

In order to be consistent with the treatment of the physics in a driving GCM, it is required to use the same physical parameterization in the LAM. It would be desirable, therefore, to have the ECHAM3 physics in a coded form which can easily be integrated into the HIRLAM environment. However, the coding structures of both models differ widely. The present note describes in detail how a RACMO is constructed, guided by the objective that in the near future it must be possible to run the HIRLAM (level2) model with a call to the ECHAM3 physics.

The structure of the ECHAM3 code is such, that information about all fields is transferred between the various routines by means of a rather CRAY specific memory manager and by the use of pointer statements. The organization of the HIRLAM (level2) model, however, is entirely different. In order to be portable it is coded in a way which is known as *plug compatible* or *pluggable*. Furthermore, the RACMO as we intend to use it will be run on a CONVEX system. Therefore, the physics package of the ECHAM3 code must be transformed into a form that meets the requirements of the HIRLAM code. Briefly stated: No CRAY specific coding and fully *pluggable*.

Once a recoded ECHAM3 physics package is available, the HIRLAM code itself requires some minor adaptations, in order to cope with the additional fields needed to handle the ECHAM3 physics. Apart from the aspects concerning the organization, all relevant climatological fields need to be provided in order to completely specify the initial state and the boundary conditions. However, a treatment of this problem is outside the scope of the present note.

Finally, another technical difference between the HIRLAM and ECHAM physics packages is noted. There is a possibility in HIRLAM to allow for a less frequent calculation of tendencies related to physical processes than the general time stepping prescribes. In running the operational HIRLAM version it was demonstrated, that it is sufficient to call the physics only every third time step (Hansen-Sass, *personal communication*). Since the ECHAM3 physics package is far more elaborated in terms of cpu-time, it would be very attractive to have a similar option in the HIRLAM/ECHAM model as well.

WORKING STRATEGY

The main strategy which was followed in order to rearrange the ECHAM3 physics package into a framework fitting into the structure of the HIRLAM model can be formulated in terms of a few major steps. The ECHAM3 physics package needed recoding into a form that is *pluggable*, implying that all relevant information for the different physics subroutines is specified through dummy list calls rather than through the use of common blocks or pointer statements. One of the physics modules was already close to that stage, i.e. the mass-flux scheme for convective cloud parameterization (Tiedtke,1989). Any use of pointers and allocation of memory in the ECHAM3 model is basically CRAY specific although CONVEX now supports most of these features. However, it turned out to be desirable in the HIRLAM/CONVEX environment to abandon their use. This is a natural consequence of the transformation of the code into the *plug compatible* form. When the arrays are specified in the dummy list for the call to the routine, there is no need to allocate memory nor specify any pointer position for that variable.

Furthermore, it appeared necessary to change any dependency on latitude circles within the code. In a GCM, latitude circles are often regarded as unit blocks in terms of which the physics part of the code can be parallelized. Such a procedure can of course not be followed in parallelizing a limited area model, and hence all loops inside the physics routines running over longitude assuming a given latitude circle were altered into one big loop for the whole HIRLAM area of integration. A few loops in the physics routines show explicit dependence on the latitude circle, for instance the calculation of the solar angle. These parts required additional recoding, since latitude varies from point to point in the HIRLAM model.

Parallel to the link between the two codes a separate way to set up the physics package was chosen. A one-column version was formulated and put on top of the basic physics management routine PHECHAM. The one-column version showed to be a powerful tool in checking whether the recoding of the various physics routines was carried out properly. By just prescribing realistic values for the prognostic fields and their tendencies, the physics package could be tested simply and quickly, without suffering from the unpleasant requirement of a tremendous amount of memory. In this way we could come to an exact definition of the routine PHECHAM, which eventually turned out to be the gateway between the HIRLAM model and the ECHAM3 physics.

Once the recoding was done, a first RACMO version of the linked HIRLAM and ECHAM3 codes could be generated. The compiled version was, however, extremely memory demanding, even on a rather modest integration area (110×100 points using 16 vertical levels - known as the DK-HIRLAM area - required $> 500 Mbyte$ in virtual memory on a CONVEX 3240, out of which $\approx 90\%$ was actually used). To reduce the memory requirement, the concept of *work space* was introduced in an entirely similar way as was done in the HIRLAM (level2) model. The *work arrays* are introduced at the call to the physics routines. They are used throughout the physics package to cover all fields (both single-level as multi-level) which are neither used for time-stepping nor for diagnostics. The size of the work arrays is chosen such as to yield an optimum between small memory demand and still efficient vectorization. A typical array size for a single-level field is 165. The number of times the physics package is looped over corresponds to the ratio of the number of grid points and the *work-space* size. After this final revision the compiled code required a reasonable amount of memory ($\approx 100 Mbyte$ of virtual memory with about 70% required in real memory for an area as mentioned above. Most of the unused virtual memory is due to the dimensioning of fields intended for use in the semi-lagrangean version, which is kept in core, although not addressable in the present setup).

The last important modification is to allow the physics routines to be called less frequently than the dynamical time stepping prescribes. Typically this would be every third time step. However, a few of the ECHAM3 routines are organized such, that the time stepping including an Asselin time filtering is done inside the routines (surface schemes), and for this reason they cannot be bypassed at any time step. This is not crucial, since neither of the routines are particularly expensive in terms of cpu demand. But the rest of the physics routines could be rearranged to handle this (in principle this option has been implemented, but the Sundqvist scheme (Sundqvist 1978) does not seem to work properly in this environment, and therefore this scheme is still called every times step). The main technical problem is to update the accumulative fields properly.

The changes in the HIRLAM code have been organized in such a way that the full standard library is maintained. It should be mentioned at this point though, that the version of the HIRLAM (level2) code that has been used for the present developments is a preliminary version, based on what was available by late November 1991. An up-grading to a later version of the HIRLAM level2 system will be undertaken later. The demand has then been only to involve a limited number of routines for modifications. To deal with this, it was decided to add two new common blocks to the HIRLAM system. One common block 'COMECH' contains all extra field variables which are not already in the HIRLAM system, and a second common block 'COMECH2' covers the remaining parameters necessary for the ECHAM physics. Following the *work space* strategy also enforce an updating of the common block 'COMWRK'. Apart from a rather obvious need for reading and writing of non standard HIRLAM fields, these modifications have involved only three of the main HIRLAM routines. But a future option in the HIRLAM system will be to use a semi-lagrangean technique, and then further modifications will be asked for. However, due to the structure of the HIRLAM code itself, and the present strategy, it should be quite straight forward to modify any scheme in HIRLAM that should replace the eulerian time integration to match the call to the ECHAM3 physics package.

NESTING

Nesting implies that the boundary fields of the LAM are specified by a GCM. In that sense the GCM governs the large-scale flow in the LAM. Consequently, at scales comparable or beyond the resolution of the GCM the quality of the LAM-results will be crucially dependent on the choice of area, grid size and again the physical parametrization *and* the quality of the GCM itself. Improvement of quality therefore must first of all be sought at smaller scales where LAM-results are expected to provide detailed and interesting information of climate variables. But equally important it may turn out that for a carefully chosen area (i.e. large enough), the LAM may be able to improve on the large scale flow of the model atmosphere as well, because of the higher resolution.

In practice the nesting procedure involves the relaxation of the prognostic fields in the boundary zone. Presently, relaxation inside HIRLAM towards boundary fields generated from the ECMWF forecasts model is carried out in two steps. First a linear interpolation in time between two adjacent boundary fields is carried out for each of the prognostic fields. Secondly a relaxation towards these time interpolated fields is made according to

$$\psi_j^r = \alpha_j \psi_j^b + (1 - \alpha_j)\psi_j^m,$$

where ψ^r, ψ^b and ψ^m denote respectively the relaxed field, the boundary field provided by the GCM, and the model field determined in the current time step. The relaxation function is defined as

$$\alpha_j = 1 - tanh\frac{2j}{N-4},$$

where j and N refer to the distance to, and the width of the boundary zone in units of grid-distances. (In HIRLAM $N = 10$.) The relaxation procedure is applied to the fields at time step t_{n+1}, after the integration, but prior to the use of the Asselin time filter.

In Fig. 1 a rotated lat/lon cylindrical map projection is shown over Europe. The area inside the highlighted box represents a LAM integration area, whereas the remainder without any loss of generality may be considered as representing the rest of the world in a GCM. The figure shows the mean sea level pressure in hPa and the 850 hPa temperature situation on the 22nd of January 1991 at 18 Z. The fields inside the LAM area are the results of a 6 hours forecast using HIRLAM, based on ECMWF analysis as boundaries. In the outer part, the fields are generated from the corresponding ECMWF analysis, that was used as boundary field. The analysis fields have been interpolated to the same horizontal resolution and the same vertical levels as used within the LAM. Note the effect of the increased resolution inside the LAM area, which is most evident on the frontal system SW of Greenland. Note also how the two fields in general are smoothly joined at the boundary, despite the somewhat different interpolation procedures involved in the production of the fields in the two different areas. The boundary relaxation zone itself is not shown exactly. But it is located inside the LAM area and have a linear size of $\approx 10\%$ of the LAM linear size.

The presence of the prognostic liquid water variable in the LAM poses a particular problem. When a boundary defining GCM, such as the ECMWF model, does not provide liquid water, its relaxation must be deduced from the other variables such as specific humidity, temperature and pressure. But even when a GCM contains liquid water as a prognostic variable, such as the ECHAM model, relaxation of liquid water in a similar way as is done with the standard prognostic fields may be insufficient to yield a balanced description of the water-related fields in the boundary zone. The first and also most simple solution is to circumvent the problem by ignoring the relaxation of the liquid-water field. This may be shown to have only a small total effect on the model behaviour, since the liquid water only accounts for a minor part of the total moisture budget. However, such an approach will emphasize the problem related to the interpretation of precipitation fields in the entire integration area.

Instead, it may prove better to determine liquid water and cloud fraction from the already *relaxed* specific humidity, temperature and pressure fields with the same condensation scheme which is used in the internal region of the LAM. In this way cloud fraction and liquid water in the boundary zone are consistently coupled to the other model variables. This approach is expected to have an additional positive influence on the model behaviour for numerical reasons. It can be shown that in this way unrealistically steep gradients in the liquid-water field are avoided in the bounday zone.

The condensation scheme in the ECHAM model is based on a formalism developed by Sundqvist (1978). In the scheme the specific humidity is expressed as

$$q_v = bq_{sat}(T,p) + (1-b)q_e,$$

where b and q_e are respectively the cloud fraction and the specific humidity in the dry environment. The latter quantity is taken proportional to the saturation specific humidity,

$$q_e = U_0 q_{sat}.$$

To determine the relative humidity U_0 two options are used,

$$\text{option 1} \quad : \quad U_0 = U_{00}, \tag{1}$$

$$\text{option 2} \quad : \quad U_0 = b + (1-b)U_{00}, \tag{2}$$

where the threshold relative humidity U_{00} is considered to be a function of height and stability only. Presently option 1 is used in the ECHAM model. In this option the cloud fraction b becomes

$$b^m = \frac{q_v^m - U_{00}q_{sat}^m}{(1-U_{00})q_{sat}^m} = \frac{U^m - U_{00}}{1-U_{00}},$$

where the index m refers to LAM quantities. We relax the cloud fraction in the boundary zone according to

$$b^r = \frac{U^r - U_{00}}{1-U_{00}},$$

where U^r is the relaxed specific humidity,

$$U^r = \frac{q_v^r}{q_{sat}(T^r,p^r)}.$$

The relaxed liquid water content is determined by assuming that the in-cloud liquid water content $q_{c\ell}$ remains constant in the relaxation procedure. Then the grid-box mean liquid water content relaxes according to

$$q_\ell^r = b^r q_{c\ell} = b^r \frac{q_\ell^m}{b^m},.$$

where b^m and q_ℓ^m denote respectively the cloud fraction and grid-box mean liquid water content (at time step t_{n+1}), which result from the model calculation. The assumption states that the relaxation of liquid water is only due to a change in cloud fraction. In this way the effect of advection of vapour and liquid water across the boundary is implicitly taken into account. Precipitation, which mainly affects the in-cloud water content is presently ignored.

The expression for q_ℓ^r is also used when $b^r \neq 0$, while $b^m = 0$. In that case also $q_\ell^m = 0$ and one must consider $\lim_{b\to 0} q_{c\ell}$. However, the value of this limit is not unique and depends on the history of the system. For reasons of simplicity it is proposed to assume this limit to be zero, which corresponds with a relaxed value $q_\ell^r = 0$.

When $b^r = 1$ the expression for q_ℓ^r must be extended with the excess of q_v^r over q_{sat}^r:

$$q_\ell^r = b^r \frac{q_\ell^m}{b^m} + q_v^r - q_{sat}(T^r, p^r),$$

where instantaneous rain-out is assumed. This situation is however not very likely to happen.

The proposed relaxation method behaves smoothly at the transition from boundary zone to internal region, where the coefficients α vanish. In the internal region b^r must be equal to b^m, otherwise the condensation scheme is not implemented properly. Consequently, $q_\ell^r = q_\ell^m$, which ensures that no spurious liquid water gradients are introduced due to the relaxation method.

PHYSICS

Hereafter it is very briefly pointed out how the ECHAM3 physics package is organized. The basic prognostic variables of the model are geopotential height (Z), horizontal wind components (u and v), temperature (T), specific humidity (q), and liquid water content (x). Given a prognostic quantity a, the model in principal calculates its evolution according to

$$a(t + \Delta t) = a(t) + (\frac{\partial a}{\partial t})\Delta t.$$

where the total tendency can be expressed as

$$\frac{\partial a}{\partial t} = (\frac{\partial a}{\partial t})_{dyn} + (\frac{\partial a}{\partial t})_{phys}$$

The dynamical or adiabatic tendency,

$$(\frac{\partial a}{\partial t})_{dyn} = -u\frac{\partial a}{\partial x} - v\frac{\partial a}{\partial y} - w\frac{\partial a}{\partial z}$$

is calculated in the dynamics package: in the RACMO it will be generated by the HIRLAM model. The physical or diabatic tendency is generated by the physics package and contains the contributions from all relevant physical processes:

$$(\frac{\partial a}{\partial t})_{phys} = \sum_i (\frac{\partial a}{\partial t})_{physical\ process\ i}.$$

In the ECHAM3 physics package the following physical processes can be distinguished (HAMBURG, 1992):

1. radiation (Hense et al., 1982; Rockel et al., 1986; Eickerling, 1989)

2. vertical diffusion (Louis, 1979; Louis et al., 1982)
3. gravitational wave drag (Laursen and Eliassen, 1989)
4. deep convection Kuo, 1965, 1974; Kuo and Anthes, 1984; Tiedtke, 1989)
5. large scale condensation (Sundqvist, 1978;Roeckner and Schlese, 1985; Roeckner et al. 1990)
6. surface processes (Sellers, 1986; Blondin, 1989; Dümenil and Todini, 1991)

(Part of the following outline of the ECHAM physics package is taken from HAMBURG, 1992, paragraph 1.1.3)

- The radiation module is based on the Cologne radiation scheme. The fundamental output quantities of the module are the emissivity per layer related to thermal radiation (EMTER) and the transmissivity per layer related to solar radiation (TRSOL). Routine RADHEAT is invoked to compute radiative diagnostics as well as to update the temperature tendency per layer due to radiative processes.
  The characteristics of the radiation scheme are:
  - two-stream approximation
  - six spectral intervals in the terrestrial part
  - four spectral intervals in the solar part
  - gaseous absorbers: H2O, CO2 and O3 (prescribed)
  - aerosols: prescribed
  - clouds: computed cloud optical depth and cloud
  - emissivity: function of cloud water path (Stephens, 1978)
  - continuum absorption: included
  - cloud overlap: maximum for contiguous cloud layers and random otherwise
  - diurnal cycle: included
  - radiation time step: variable (in ECHAM3 set to two hours)
- The vertical diffusion module (VDIFF) represents a first order local diffusion scheme, in which turbulent diffusivity coefficients are formulated in terms of local gradients of the mean variables. Tendency contributions to all prognostic quantities are calculated.
  Characteristics of the vertical diffusion scheme are:
  - surface fluxes of momentum, heat and moisture are calculated with transfer coefficients depending on the roughness length and the bulk Richardson number.
  - above the surface layer, an eddy diffusivity approach with coefficients depending on wind shear, thermal stability, and mixing length (Blackadar, 1962).
  - above the PBL (planetary boundary layer): vertical diffusion only for unstable stratification
  - "moist" Richardson number
- The gravity wave drag module (GWDRAG) is taken from the ECMWF model, cycle 31.
  The characteristics of the gravity wave drag scheme are:
  - linear second order scheme applied only at a critical wave number
  - gravity wave drag (Palmer et al.,1986; Miller et al.,1989)
  - surface stress due to gravity waves, which are excited by stable stratified flow over irregular terrain, is calculated from linear theory and dimensionality considerations.

  - orographic forcing prescribed as a directionally dependent sub grid-scale orographic variance computed from the high resolution US Navy data set
  - vertical structure of momentum flux induced by gravity waves calculated from a local wave Richardson number, which describes the onset of turbulence due to convective instability and the turbulent breakdown approaching a critical level
  - the GWD scheme is not used at T21 resolution

- To account for deep convective processes two options are available: the mass-flux scheme (CUCALL) as proposed by Tiedtke (1989), or a combination of a zeroth-order Kuo-scheme (KUO0) with a shallow convection scheme (SCV). The mass-flux scheme calculates tendency contributions to all prognostic quantities, though the liquid water tendency is only due to stratiform processes. The KUO0/SCV module generates only T and q tendencies. The characteristics of the deep convective schemes are:
  - convective cloud formation in a conditional unstable layer between the lifting condensation level and the level of non-buoyancy
  - simple cloud model: moist adiabate through the lifting condensation level
  - total moisture convergence in the cloud colum is used for heating and moistening of the cloud environment shallow convection (Tiedtke, 1983, 1989)
  - enhanced turbulent transport of sensible and latent heat through cloud base and cloud top of shallow moist convectively unstable layers
  - stratocumulus regime: cloud top entrainment vertical diffusion

- The condensation routine (LWCOND) is meant to describe cloudiness and precipitation due to large scale processes. The prognostic relation for liquid water and the closure relation for cloudiness are taken from Sundqvist (1978). Tendency contributions to T, q and x are calculated.
  The characteristics of the condensation scheme are:
  - cloud water transport equation
  - sub grid-scale condensation and cloud formation with different thresholds for convective and stratiform clouds (Krueger et al., 1989)
  - temperature dependent partitioning of liquid/ice phase (Matveev, 1985)
  - rain formation by auto-conversion of cloud droplets (Sundqvist, 1978)
  - sedimentation of ice crystals (Heymsfield, 1977)
  - evaporation of cloud water
  - evaporation of precipitation

- The surface module (SURF) is taken from the ECMWF model and modified to solve a five-layer model in order to be suitable for climate studies. No tendencies are calculated, instead the prognostic equations for surface and deep soil temperatures and moisture contents are solved.
  The characteristics of the land-surface scheme are:
  - heat transfer: diffusion equation solved in a 5-layer model with zero heat flux at the bottom (10m)
  - water budget equation for three reservoirs: soil moisture, interception reservoir (vegetation), snow
  - vegetation effects: stomatal control on evapo-transpiration and interception of rain and snow

- run-off scheme: based on catchment considerations including sub grid-scale variations of field capacity over inhomogeneous terrain
- sea-ice temperature

At KNMI a research version has been developed with the option of selecting alternative physics. A vertical diffusion module was made available based on a non-local formulation of the mixing of heat and moisture in the boundary layer (Holtslag and Boville, 1993). Here the concept of ***pluggability*** showed its usefulness. The new module could straightforwardly be linked to the RACMO by constructing an interface routine which, besides simple, transfers all relevant variables from the physics management routine PHECHAM to the diffusion module. Similarly, an alternative radiation package (Morcrette, 1989, 1991) was included in the research version of the RACMO. The incorporation of a recently developed radiation package taking into account variable concentrations of aerosols and trace gases is in preparation (van Dorland).

FIRST EXPERIMENTS

As already mentioned, a first test of the RACMO performance can be obtained by driving the model with analyses. The model is initialized from a single analysis, and during the run new boundaries also based on analyses are supplied every six hours. Such a procedure is believed to provide the most ideal boundaries to the model, and a measure of the model performance is found by comparing the results of a month-long integration run with the driving fields themselves.

A number of such experiments has already been undertaken at DMI, using the operational HIRLAM (level1) model, driven by ECMWF analysis fields. The operational HIRLAM system is maintained on two areas at DMI. One of them, referred to as the DK-LAM, turned out to be very adequate for these pioneering experiments. The entire operational model set-up related to a run for this area was copied. The integration area is defined by the inner box on Fig. 1.

The DK-LAM area is a rotated lat/lon coordinate system with the pole rotated 65° along the geographical longitude 180°. The area is defined by a 110 times 100 points grid, with a horizontal resolution of 0.51° by 0.51°, corresponding to about 50 km by 50 km. In the vertical a 16 level version with hybrid coordinates is used. The corresponding pressure levels for a reference pressure of 1013.25 hPa is found in table 1.

We carried out similar experiments with the first working version of the RACMO or HIRLAM-HAM model. The integration area was kept identical to the DK-LAM area, but the number of vertical levels was increased to the 19 levels used in the ECHAM3 experiments at MPI in Hamburg. These levels may also be found in table 1.

One way to compare the model results with the analyses is in terms of so called area-mean biases. Monthly mean biases have been calculated for two experiments utilizing the DMI operational physics package and the ECHAM3 package respectively. Here, the bias is defined as the difference between the area-averaged monthly-mean fields of the model and of the corresponding

ECMWF analyses, interpolated to the same horizontal grid and vertical levels. Figures 2-4 compares the temperature, specific humidity, and u-wind component bias of the two experiments for the month of January 1991. It is immediately evident, that the ECHAM3 physics signifies a considerable improvement compared to the operational physics, in particular when referring to temperature and humidity. The slight tendency towards a more "zonal" flow in the ECHAM3 experiment may be less significant. However, the results require a more refined analysis in order to be conclusive.

It should be added here, that the ECHAM3 physics experiment was carried out without any tuning of the different subroutines. Such a tuning is very likely to be required in a few of the routines. In particular in the Sundqvist scheme (LWCOND) this seems unavoidable (Erik Roeckner ***personal communication***). Furthermore, liquid water at the boundaries is simply put to zero, instead of using the liquid water relaxation scheme which is outlined in the paragraph on *Nesting*.

These preliminary results seem to demonstrate, that the objectives of the present project are already achieved quite satisfactorily. The more elaborated physics of the ECHAM model is better suited for climate studies than the operational HIRLAM model. The presently constructed RACMO ***will*** form the essential tool for experiments, which are planned at DMI and KNMI. Since the tool is ready, these experiments, described in the Introduction section, can be started with very soon.

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We like to thank the staff of the Meteorology Department of the Max Planck Institute in Hamburg for giving permission to use the ECHAM3 model. In particular, we like to thank Ulrich Schlese of MPI for actually making available the ECHAM3 source code, and for supporting us so many times in explaining the tiniest details of the model.

APPENDIX: LIST OF FIELD VARIABLES

Here we list the fields which are maintained as prognostic or diagnostic fields in the present version of the RACMO. The list contains the internal code name used in the ECHAM3 physics package and their meaning. It is also indicated when this field exists in the HIRLAM code as well (in it's present version). In some cases, however, the correspondence may not be exactly one to one. It is furthermore indicated whether the field is a single- or multi-level field, and whether the field needs an external initialization. If the latter is not necessary the relevant field is initialized either in the routines RESETP or INISOIL, or otherwise calculated each time step inside the physics routines. Parentheses indicate, that the initialization may not be important or that there will be a major difference in initialization when running the model in climate mode or forecast mode. The values of the fields are given in SI-units. If a field is indicated to be accumulative, the units listed are expressed without the time-unit related to the integration (see for example precipitation). The fields that are time integrated inside the physics routines are indicated by a (1) in the ECHAM internal name. The (M) indicates that the field must be updated at each time step, although that may be redundant. Most of the fields are stored in history files at the write-out times used in the present RACMO version.

ECHAM internal name	HIRLAM internal name[1]	level type	variable [units]	accu-mulat-ive	Initi-aliz-ation
Prognostic fields					
UM	U	m	X comp. of wind [m/s]		ext.
VM	V	m	Y comp. of wind [m/s]		ext.
TM	T	m	Temperature [K]		ext.
QM	Q	m	Specific humidity [kg/kg]		ext.
XM	CW	m	Liquid water content [kg/kg]		(ext.)
Tendencies of prognostic fields					
VOM	DUDT	m	∂(X comp. of wind)/∂t [m/s^2]		
VOL	DVDT	m	∂(Y comp. of wind)/∂t [m/s^2]		
TE	DTDT	m	∂(Temperature)/∂t [K/s]		
QE	DQDT	m	∂(Specific humidity)/∂t [kg/kg/s]		
XE	DCWDT	m	∂(Liquid water cont.)/∂t [kg/kg/s]		
KE		m	Dissipated kinetic energy rate [J/s]		
Pressure, geopotential and vertical velocity					
APP1/		m	Full-level pressure [Pa]		
APM1		m			
APHP1/		m	Half-level pressure [Pa]		
APHM1		m			
	PS	s	Surface pressure (= APHM1(NLEV+1))		ext.
ALPSM1	ALNPS	s	Logarithm of surface pressure ALPSM1 =ln(PS)		
ALPSE	DPSDT	s	Time-derivative of logarithm of surface pressure ALPSE = ∂(ln(PS))/∂t [s^{-1}]		
ALNPR		m	Logarithm of ratio of half-level pressures		
GEOM1		m	Full-level geopotential [m^2/s^2]		
GEOSPM	PHIS	s	Surface geopotential [m^2/s^2]		ext.
VERVEL	EDOT	m	Vertical velocity dp/dt [kg/m/s^3]		

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1) The variable names listed in the column "HIRLAM internal name" refer to the names used in the HIRLAM routine PHCALL.

ECHAM internal name	HIRLAM internal name	level type	variable [units]	accu-mulat-ive	Initi-aliz-ation
Surface characteristics					
LOLAND		s	Land/sea switch		
ALB(M)	ALBEDO	s	Surf. background alb. [fract.]		ext.
VGRAT		s	Vegetation ratio [fract.]		ext.
FOREST(M)		s	Vegetation type		ext.
SLM(M)	FRLAND	s	Land sea mask [fract.]		ext.
LOGLAC		s	Glacier switch		
GLAC(M)		s	Glacier mask [fract.]		
SEAICE	FRICE	s	Sea-ice cover [fract.]		ext.
SICED		s	Sea-ice depth [m]		
AZ0(M)	ROUGH ROUSEA	s	Surface roughness [m]		ext.
Surface fields					
TS(M)(1)	TS/TSEA	s	Surface temperature [K]		ext.
WS(M)(1) 2)	SW	s	Surface soil wetness [m/m]		ext.
WL(M)(1)		s	Skin reservoir content [m]		(ext.)
SN(M)(1)	SN	s	Snow depth [m]		ext.
Deep soil fields					
TD3,4,5(M)(1)		s	Soil temperatures [K]		ext.
TD(M)(1)	TSD	s	Deep soil temperature [K]		ext.
TDCL(M)(1)	TSDCLI	s	Lower boundary clim. soil temp. [K]		ext.
WD(M) 3)	SWD	s	Deep soil wetness [m/m]		ext.
Surface diagnostics					
TSMAX(M)		s	Maximum surface temperature [K]	acc.	
TSMIN(M)		s	Minimum surface temperature [K]	acc.	
TSURF(M)		s	Surface temperature [K]	acc.	
TSKIN(M)(1)		s	Skin temperature [K]		
TEFF(M)		s	Eff. sea-ice skin temperature [K]	acc.	
TSN(M)(1)		s	Snow temperature [K]		
DSNAC(M)		s	Snow depth change [m]	acc.	
SNMEL(M)		s	Snow melt [m/s]	acc.	
RUNOFF(M)		s	Surface runoff [m/s]	acc.	

2) Throughout the ECHAM physics package the surface moisture content WS(M)(1), the deep moisture content WD(M) and the field capacity WSMAX are expressed in decimeters and referenced to a depth of 0.7 dm.

3) Never used.

ECHAM internal name	HIRLAM internal name	level type	variable [units]	accu-mulat-ive	Initi-aliz-ation
Surface energy fluxes (and derivative)					
THFL		s	Sensible+latent heat flux [W/m^2]		
DHFT		s	d(Total heat flux)/d(Surf. temp.) [W/m^2/K]		
SRFL		s	Short wave radiation flux [W/m^2]		
TSLIN(M)		s	Residual surf. heat budg. [W/m^2]	acc.	
AHFLI		s	Latent heat flux over ice [W/m^2]		
AHFL(M)	LATF	s	Surface latent heat flux [W/m^2]	acc.	
AHFS(M)	SENF	s	Surface sensible heat flux [W/m^2]	acc.	
Surface moisture and liquid water kinematic fluxes and derivatives					
QHFL		s	Vapour flux [kg/s/m^2]		
DHFQ		s	d(Moist. flux)/d(Surf. moist) [kg/s/m^2/m]		
DHFQS		s	d(Moist. flux)/d(Snow cover fract) [kg/s/m^2]		
DHFQW		s	d(Moist. flux)/d(Skin res. cont.) [kg/s/m^2/m]		
CVGHL		s	(Veg.)/(Veg.+bare soil) moist. flux [fract.]		
XHFL		s	Liquid water flux [kg/s/m^2]		
RSFL		s	Large scale rain flux at surface [kg/s/m^2]		
SSFL		s	Large scale snow flux at surface [kg/s/m^2]		
RSFC		s	Convective rain flux at surface [kg/s/m^2]		
SSFC		s	Convective snow flux at surface [kg/s/m^2]		
Surface layer diagnostics					
DEW2(M)		s	2m Dew point temp. [K]	acc.	
TEMP2(M)		s	2m Temp. [K]	acc.	
T2MAX(M)		s	2m Maximum temp. [K]	acc.	
T2MIN(M)		s	2m Minimum temp. [K]	acc.	
USTAR3(M)		s	u_*^3 [m^3/s^3]	acc.	
USTR(M)		s	U-stress [Pa]	acc.	
VSTR(M)		s	V-stress [Pa]	acc.	
U10(M)	U10	s	10m U-velocity [m/s]	acc.	
V10(M)	V10	s	10m V-velocity [m/s]	acc.	
VDIS(M)		s	Boundary layer diss. [W/m^2]	acc.	
WIND10(M)		s	10m Wind speed [m/s]	acc.	
WIMAX(M)		s	10m Max. wind speed [m/s]	acc.	
Boundary layer diagnostics[4]					
PBLH		s	Boundary layer height [m]		
OBUKL		s	Obukhov length [m]		

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4) Not present in baseline physics package.

ECHAM internal name	HIRLAM internal name	level type	variable [units]	accu- mulat- ive	Initi- aliz- ation
Deep convection diagnostics					
NBASEC(M)		s	Cloud base (level)	acc.	
NTOPC(M)		s	Cloud top (level)	acc.	
TOPMAX(M)		s	Max. conv. cloud tops level	acc.	
ARPRC(M)		s	Convec. precipitation [m/s]	acc.	
Cloud and liquid water large scale condensation diagnostics					
ACLC(M)	TOTCOV	m	Cloud cover [fract.]		
ACLCAC(M)		m	Cloud cover [fract.]	acc.	
ALWC(M)		m	Liquid water cont. [kg/kg]		
ALWCAC(M)		m	Liquid water cont. [kg/kg]	acc.	
ACLCOV(M)		s	Tot. cloud cover [fract.]	acc.	
ALWCVI(M)		s	Vert. integr. liq. wat. [kg/m^2]	acc.	
QVI(M)		s	Vert. integr. spec. hum. [kg/m^2]	acc.	
Precipitation and evaporation					
APRC(M)	ACCPRC	s	Convec. precipitation [m/s]	acc.	
APRL(M)	ACCPRL	s	Large scale precipitation [m/s]	acc.	
APRS(M)		s	Snow fall [m/s]	acc.	
EVAP(M)		s	Evaporation [m/s]	acc.	
Radiation (diagnostics)					
ALBEDO(M)		s	Surface albedo [fract.]		
ACLCV(M)		s	Total cloud cover [frac.]		
EMTER(M)		m	Emissivity (long wave) [frac.]		
TRSOL(M)		m	Transmissivity (short wave) [frac.]		
SRADS(M)		s	Surf. sol. rad. [W/m^2]	acc.	
SRADSU(M)		s	Upward surf. sol. rad. [W/m^2]	acc.	
SRAD0(M)		s	Top sol. rad. [W/m^2]	acc.	
SRAD0U(M)		s	Upward top sol. rad. [W/m^2]	acc.	
TRADS(M)		s	Surf. therm. rad. [W/m^2]	acc.	
TRADSU(M)		s	Upward surf. therm. rad. [W/m^2]	acc.	
TRAD0(M)		s	Top therm. rad. [W/m^2]	acc.	
Gravity wave drag (diagnostics)					
VAROR		s	Orographic variances [m^4/s^4]		ext.
VAR (1-4)		s	Directional orographic variances [m^4/s^4]		ext.
USTRGW(M)		s	U-grav wave stress [Pa]	acc.	
VSTRGW(M)		s	V-grav wave stress [Pa]	acc.	
VDISGW(M)		s	Gravitational wave dissipation [W/m^2]	acc	

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Table 1

HIRLAM model levels†

Operational version [*hPa*] *16 levels*	ECHAM3 version [*hPa*] *19 levels*
...	10.0
25.0	30.0
...	50.4
75.3	73.4
...	102.6
127.8	...
...	141.2
185.6	190.1
251.2	252.4
325.9	325.6
409.3	409.0
500.0	500.0
594.6	594.9
689.0	689.4
778.2	778.5
857.0	857.1
921.0	921.0
967.4	967.4
995.7	995.7
1009.3	1009.3

†Referring to a reference pressure of 1013.25 hPa.

FIGURE CAPTIONS

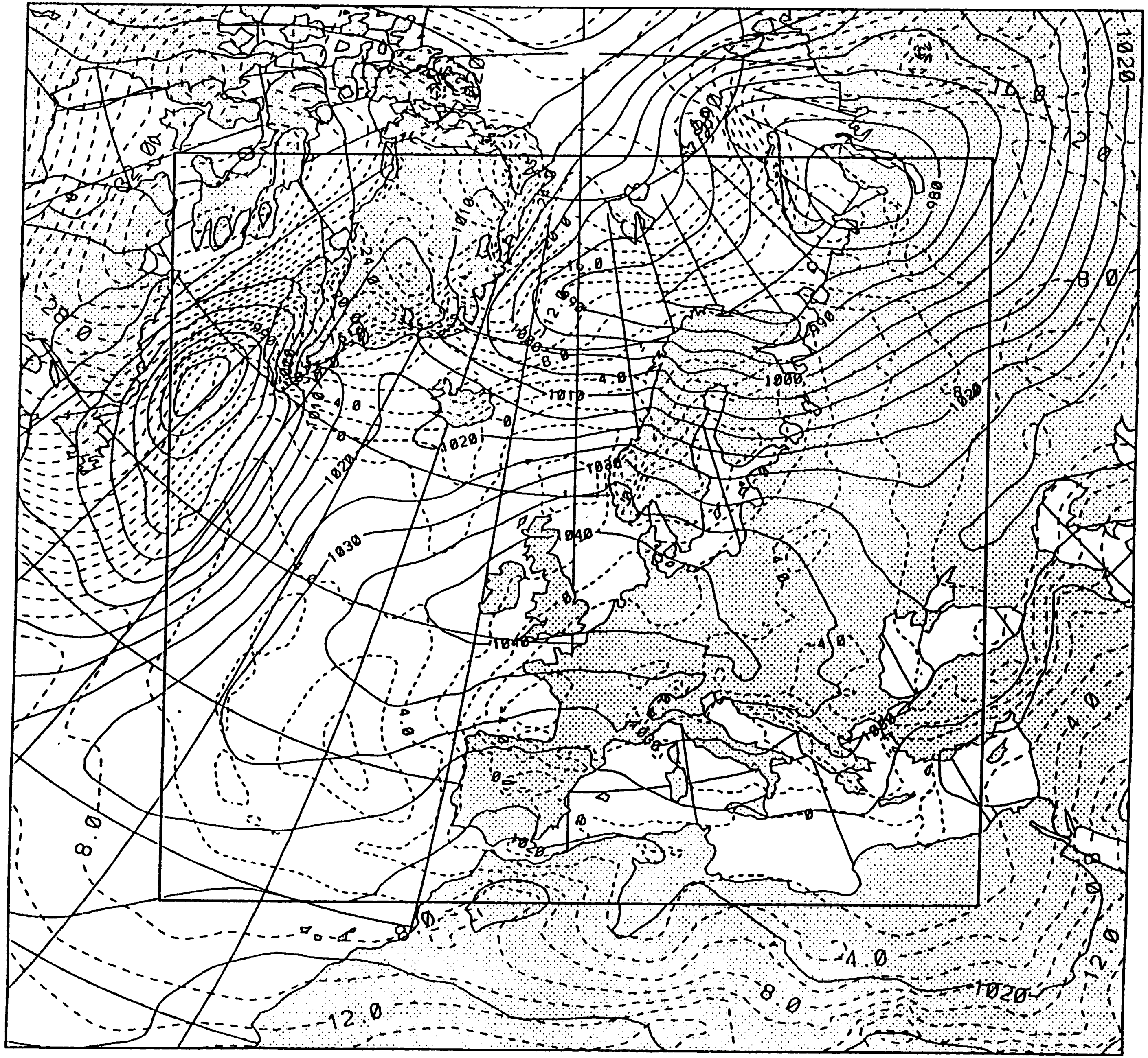
Fig. 1. Illustration of the nesting technique. A LAM is run within the highlighted box, driven by boundary fields supplied by a GCM. The fields are smoothly joined in a boundary zone. Here a 6 hours forecast within the small area is shown, along with the driving GCM (ECMWF analysis) fields outside the LAM area. Full lines are mean sea level pressure in hPa, and dashed lines are 850 hPa temperatures.

Fig. 2. Temperature bias for January 1991 for HIRLAM experiments driven by ECMWF analyses. The bias is defined as the difference between the area-averaged monthly-mean temperature profiles of the model and of the corresponding ECMWF analyses. Upper diagram shows result for operational HIRLAM physics, as used at DMI. Lower diagram is for ECHAM3 physics. Full line shows bias for the whole internal integration area, i.e. inside boundary relaxation zone. Dotted lines are for land points only, and dashed lines are for sea points.

Fig. 3. Same as Fig. 2, but for specific humidity.

Fig. 4. Same as Fig. 2, but for zonal wind.

HIRLAM FORECAST 91012212 + 06



Mean sea level Pressure
850 hPa Temperature

Figure 1

Figure 2

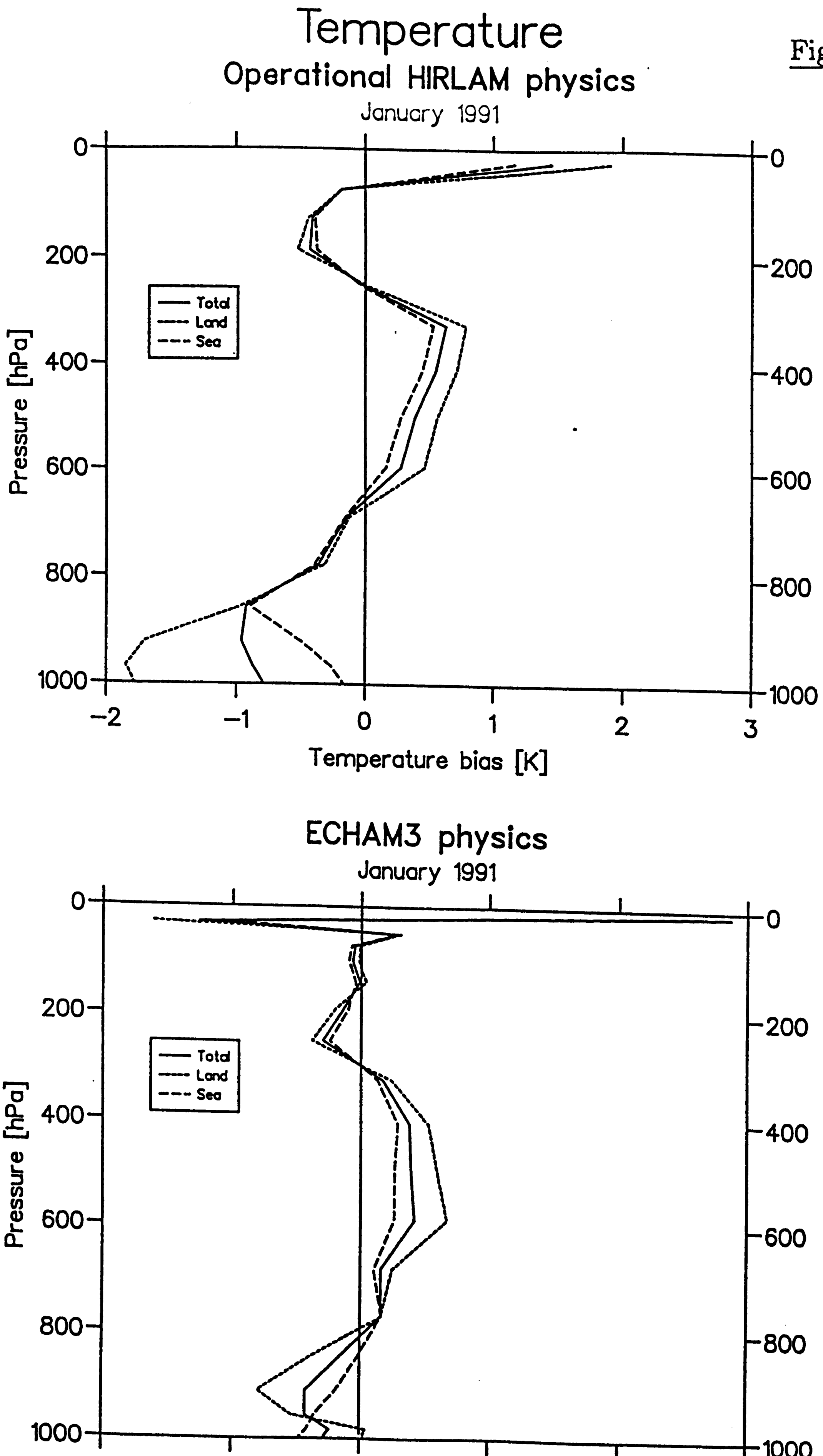
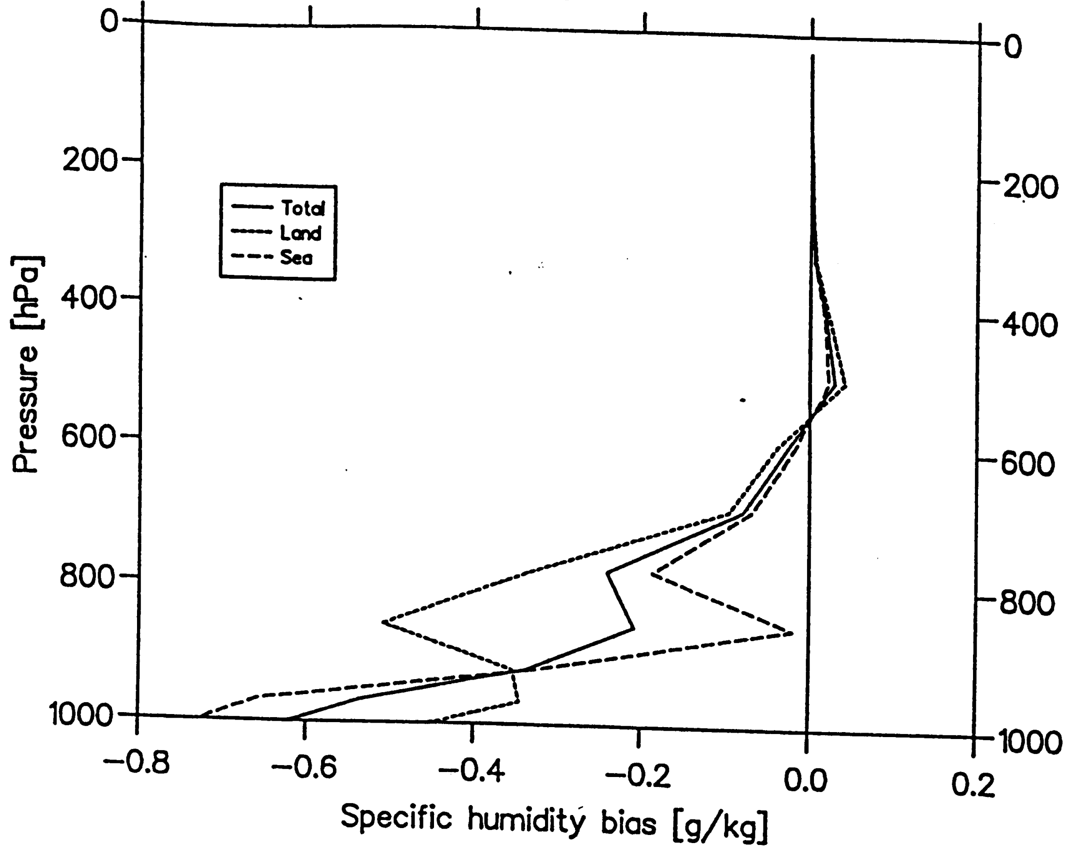

Temperature
Operational HIRLAM physics
January 1991
Pressure [hPa]
Temperature bias [K]
0
200
400
600
800
1000
−2
−1
0
1
2
3
Total
Land
Sea
ECHAM3 physics
January 1991
Pressure [hPa]
Temperature bias [K]
0
200
400
600
800
1000
−2
−1
0
1
2
3
Total
Land
Sea

Figure 3

Specific Humidity

Operational HIRLAM physics
January 1991



ECHAM3 physics
January 1991

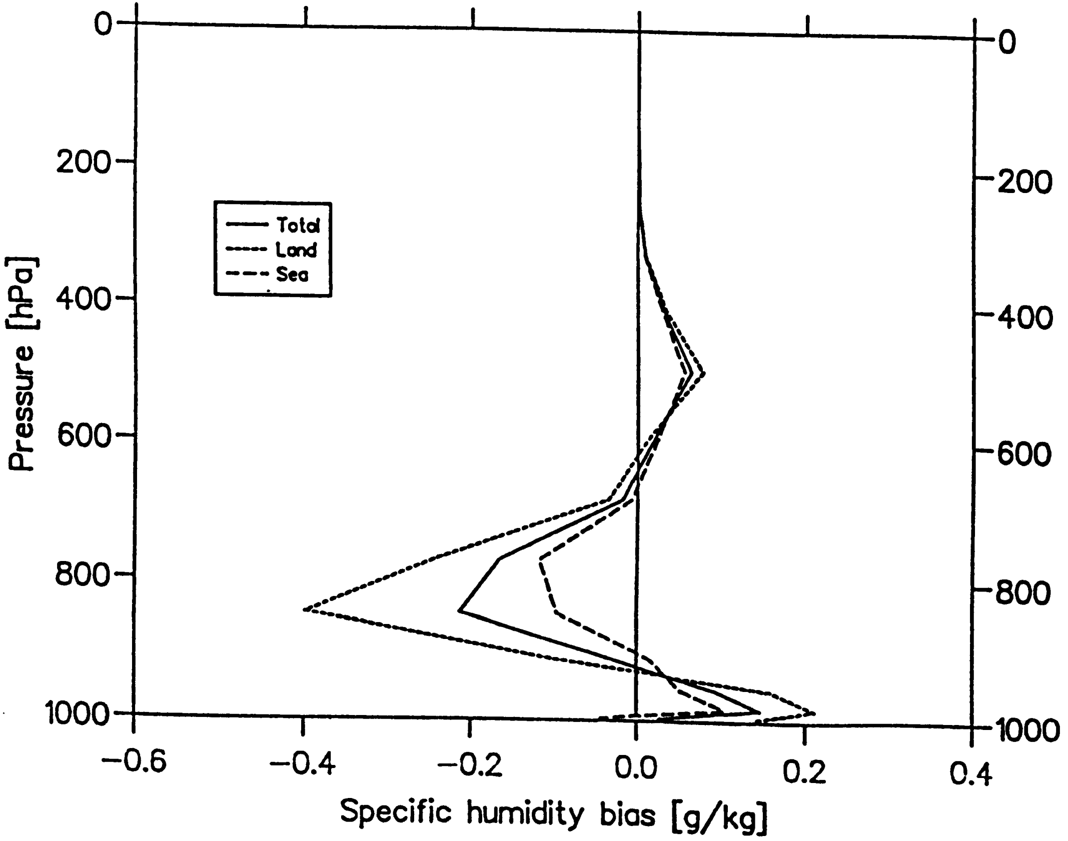
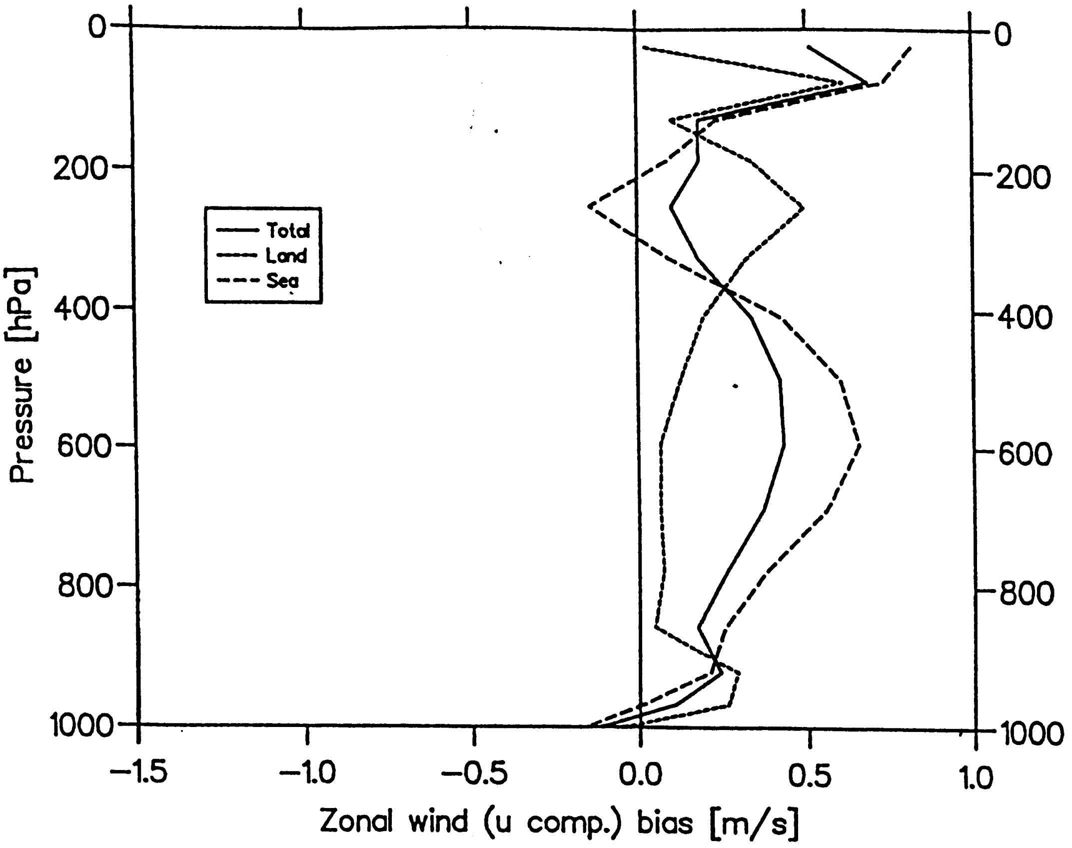


Figure 4

Zonal wind

Operational HIRLAM physics

January 1991



ECHAM3 physics

January 1991