

Predictability Research

Predictability

General • The Predictability Research Division investigates the predictability and natural variability of weather and climate. The research covers a wide range of topics, which can be summarised in a number of themes.

The Division started with the theme 'Skill prediction and ensemble forecasting'. In a joint project with ECMWF (European Centre for Medium-Range Weather Forecasts) an ensemble prediction system for the European area has been developed for the short and early medium range. A second theme is 'Dynamics of weather and climate'. In this theme predictability is studied in the more theoretical context of isentropic contour dynamics models and low-dimensional models of climate. Finite predictability may be intrinsic or related to model limitations.

Research on climate variability and climatic change is the third main theme of the Division. It is centred around ECBILT, an intermediate-complexity climate model developed within the Predictability Research Division. In climate modelling we co-operate with various Climate Research Divisions (Atmospheric Research, Oceanographic Research and Climate Analysis), with our partners in CKO (Netherlands Centre for Climate Research) and with foreign institutes like the University of Louvain-La-Neuve, Belgium, and the Meteorological Institute of the University of Hamburg, Germany. The second version of ECBILT, containing an improved radiation scheme, became available in 2000. ECBILT has been applied to the study of a large number of scientific questions described in 'Predictability and natural variability of climate' and 'Reconstruction and modelling of past climate'. Topics include decadal climate variability, the effect of a variable solar forcing, ensemble scenario studies, modelling of low-frequency variability and the comparison to palaeo data, and the interpretation of recorded signals at Milankovitch timescales.

Part of the Division's funding comes from external agencies. The EU funded project SINTEX (Scale INTERactions EXPERiments) ended in 2000. In SINTEX the interaction between various timescales of natural variability has been studied. Two projects with respect to low-frequency variability and the comparison to palaeo data were funded by NOP (National Research Programme on global air pollution and climate change). Both involve a direct collaboration with geologists and palaeo-ecologists. A joint project with the Department of Mathematics of the University of Utrecht, funded by NWO (Netherlands Organisation for Scientific Research), is concerned with the fundamental properties of simple climate models. We actively participate in the Dutch

CLIVAR (Climate Variability and Predictability Research) programme called CLIVARNET.

Two international workshops were organised by the Division. In March 1999 about 30 scientists from Europe and the USA came to KNMI to discuss how climate modelling and palaeodata can be combined in the analysis of low-frequency climate variability. Co-organiser of this workshop was the GKSS Research Centre, Geesthacht, Germany. A workshop on dynamical system concepts in climate research was held in De Bilt in April 2000. This workshop was attended by about 50 scientists from Europe, Russia and the US.

Skill prediction and ensemble forecasting

Hersbach, Mureau, Opsteegh

The skill of a weather forecast varies from day to day. Information about the skill can be retrieved from the probability distribution function (PDF) of the forecast errors. Ensemble prediction systems are the most straightforward tools to generate such probability distributions. In an ensemble system the same forecast is repeated a large number of times from perturbed initial conditions. In order to limit the size of the ensemble a special type of perturbations is calculated which has optimal growth characteristics. An example of such optimal perturbations are the so-called Singular Vectors. The Singular Vectors with largest eigenvalues are the directions in phase space in which initial errors grow fastest during a predefined integration period and for a predefined area of interest. The area of interest can be the whole globe, but also a more restricted area like Europe. Singular Vectors, which are computed for a restricted area, are called Targeted Singular Vectors. In order to measure error growth properties a metric is needed. Here we have a choice. The Singular Vector properties will depend on this choice. Usually total energy is taken to measure differences.

In a joint project with ECMWF an ensemble system has been developed for the short and early medium range (up to day 5). This system is different from the operational ensemble prediction system (EPS) of ECMWF in that it makes use of Targeted Singular Vectors for the European area (TEPS). Such a system has a clear advantage: the full PDF of the forecast errors for Europe is generated more accurately. This especially applies for weather parameters (such as precipitation, 2-metre temperature and 10-m wind speed), for which the

skill is lower than for the large-scale flow. The Singular Vectors are generated with the T42 adjoint/tangent linear model, whereas an ensemble, consisting of 50 members, is integrated with the full T159 ECMWF non-linear model. Experiments have shown that an optimisation of the perturbations in terms of total energy results in the winter season in a modest improvement of the TEPS ensemble system with respect to the ECMWF EPS. However, in the autumn and spring cases, the impact of the targeted ensembles is significantly positive. This is caused by a better performance of TEPS with respect to low probability extreme-weather events. As a result, the range of cost/loss ratios for which a user has benefit is substantially larger for the targeted ensembles. The impact is maximal for day two and three and decreases thereafter. In 1999 TEPS was run on Fridays and Sundays. At those times evolved singular vectors were added operationally to the EPS system of ECMWF. These additional perturbations appear to dominate the performance of EPS, and therefore also the performance of TEPS for the first few forecast days. As an alternative, targeted singular vectors with an optimisation time of 12 h were introduced in TEPS. Although impact in scores with respect to EPS was more modest than for the cases considered in 1997, the frequency of outliers improved considerably. A paper has been submitted.

It was shown how the continuous ranked probability score (a rather new verification tool for probabilistic forecasts) can be decomposed into three parts and how each part is related to other well-known verification tools. A paper on this verification tool has been published in *Weather and Forecasting*.

Dynamics of weather and climate

Verkley, Pasmantier, Trieling, Vosbeek, Achatz, Crommelin, Timmermann, Opsteegh

Contour dynamics

In the summer of 1999 the post-doctoral research project 'The predictability of two-layer contour dynamics systems', funded by NWO came to an end by the departure of Dr. Trieling to the Vortex Dynamics Group of the Technical University Eindhoven. The project aimed at investigating to which extent it is possible to describe the process

of atmospheric cyclogenesis (synoptic development) using isentropic contour dynamics models. In isentropic contour dynamics models the vertical structure of the atmosphere is represented by one or more layers of uniform potential temperature (isentropic layers) and the horizontal structure (within the layers) by two or more regions of uniform potential vorticity (PV). Assuming hydrostatic and geostrophic equilibrium (simplified linear balance), the models are defined completely in terms of the positions of the potential vorticity fronts and can be integrated in time using the technique of contour dynamics.

The work has evolved into a state in which it has become clear that a so called two-and-a-half layer contour dynamics model with a single front of potential vorticity in each of the two active layers is sufficiently versatile to produce cyclogenesis. This model, consisting of three layers of uniform potential temperature - the upper layer assumed to be at rest - was investigated extensively. The project has resulted in two studies on baroclinic life cycles in a two-and-a-half layer contour dynamics system: one on the structure of zonal flows and another on infinitesimal and finite-amplitude perturbations of zonal flows.

Figure 1 shows an example from the second study. The shaded area marks the region in the lower layer in which the potential vorticity is lowest. The curve (contour) marks the potential vorticity front in the middle layer, with the higher value to the north of the contour. The initial state (shown in the first panel) is a zonal state in which both fronts are at 50 degrees north, with an amplitude of 5 degrees (north-south) and a phase difference of 50 degrees (east-west). The other panels show the states at intervals of one day. The figure shows an evolution that is typical of a baroclinic life cycle.

Monitoring atmospheric analyses

This project, begun in the summer of 1998, was funded by the BCRS (Netherlands Remote Sensing Board). The aim of the project is to devise a method by means of which it is possible, using a graphical interaction procedure, to modify the

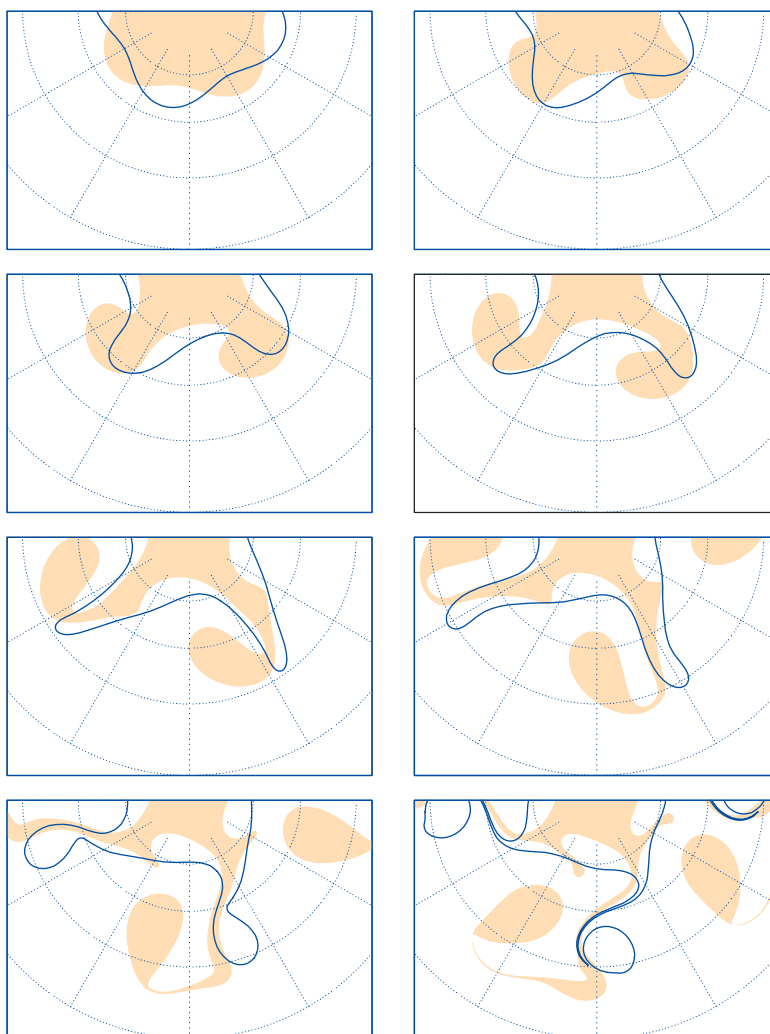


Figure 1. Life cycle of a cyclone in a two-and-a-half layer contour dynamics model. The panels (from top-left to bottom-right) show the state of the model at intervals of one day. The shaded region corresponds to low values of the potential vorticity in the lowest layer. The region north of the contour corresponds to high values in the middle layer. The top layer is motionless.

analysis of HIRLAM (High Resolution Limited Area Model) used at KNMI and to study the consequences of the modification in terms of the resulting forecast. The analysis is adjusted in terms of PV (potential vorticity) and a three-dimensional variational data-assimilation system (3DVAR) is

used to obtain a dynamically consistent modified analysis from the modified PV.

To give an idea of the present state of affairs we present an example of an analysis that is modified using this method (Figure 2). In panel (a) of the

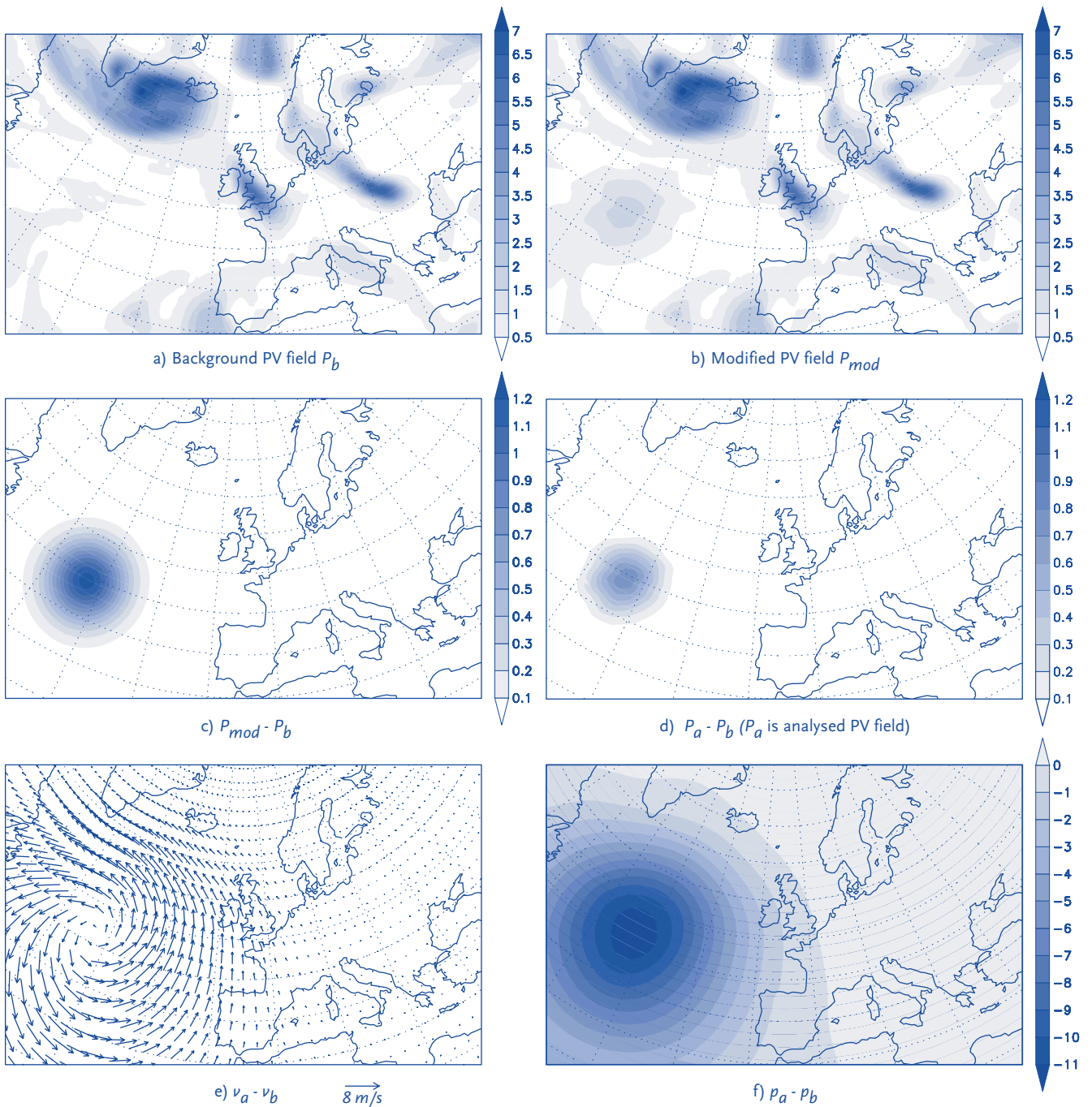


Figure 2. The background PV field (a), the modified PV field (b), the difference between the modified and the background PV field (c), the difference between the analysed and the background PV field (d), all on model level 15. The last two panels show for model

level 31 (the surface) the difference in velocity (e) and in pressure (f) between the background field and the modified analysis. The potential vorticity is shown in PV-units, the velocity in ms^{-1} and the pressure in hPa.

figure we show a PV field (background field) as analysed by HIRLAM. In (b) we show the modified PV field and in (c) the difference between the modified and background fields. Note that the difference is a rather large but localised source of PV. In (d) we show the modified analysis in terms of PV; the fact that (d) and (e) resemble each other to a considerable degree means that the procedure was able to modify the underlying dynamical fields in such a way that they reproduce the modified PV field. In (e) and (f) we show the difference between the analysis and the background of two of these underlying fields: the velocity and pressure field at the surface. The modified analysis can be used as an alternative initial state in a numerical forecast by HIRLAM.

In December 2000 the project was completed in terms of the BCRC report 'Manually adjusting a numerical weather analysis in terms of potential vorticity using three-dimensional variational data-assimilation'. The project has resulted in a system that functions as expected, although it needs further fine-tuning and optimisation. It has been established that the concept of potential vorticity in combination with variational data-assimilation can handle human interventions in the numerical forecasting process in a natural and effective way. It is intended to continue the work by testing the system on a few selected meteorological cases and to optimise the system in terms of computational speed and user-friendliness. In the future we expect to test the system in an operational forecasting environment to assess its effectiveness in daily operational practice.

Isentropic models

The main goal of this project is to provide a solid physical foundation for isentropic contour dynamics models of the atmosphere. The study of the dynamics of an isentropic layer in hydrostatic equilibrium - with the emphasis on the vertical profile of vertical velocity - appeared in the January 2000 issue of the Quarterly Journal of the Royal Meteorological Society. As a result of a referee's suggestion it was shown that the derived profile of vertical velocity is an exact solution of Richardson's equation when specialised to an isentropic layer.

In contrast with hydrostatic balance, geostrophic balance is not trivially applied to flow on a global domain. The problem was studied in the context of the simplest isentropic model that one can imagine: a single hydrostatic layer of air with uniform potential temperature. Such a model behaves very

much like a single-layer shallow water model, but is more appropriate as a simplified model of the atmosphere than a shallow-water (constant-density) model. The assumption that deviations of the Montgomery potential (or geopotential) from the state of rest are equal to the Coriolis parameter times the streamfunction was found to give a form of geostrophic balance that can be used globally. This simplification of linear balance can be used to derive, e.g., the equivalent barotropic vorticity equation on the sphere in a conceptually clear and physically consistent way.

The form of balance just mentioned was also used as a starting point in a Hamiltonian method, developed by Salmon, to construct global balanced models of the atmosphere that conserve energy, mass and potential vorticity. The method was applied to the single-layer isentropic model mentioned above. A comparison of the balanced model with the original unbalanced model makes clear that the balanced model is a very accurate approximation of the original model. The corresponding paper is now in press at the Quarterly Journal of the Royal Meteorological Society. It is planned to apply the method to isentropic models with more than one layer including the case in which the lowest layers are infinitesimally thin locally.

Statistical mechanical approach to 2D coherent structures

This concerns the study of the effects of the ever present and often neglected microscopic fluctuations on the macroscopic behaviour of the system under consideration. Three papers were published on the so-called statistical mechanics approach to the coherent structures observed in the asymptotic regime of two-dimensional flows. A fourth paper is in preparation. In this paper it is explained how and when it is possible that the inviscid theory correctly predicts the coherent structures generated by viscous two-dimensional flows. This represents an important step in bridging the gap between the theory and the behaviour of realistic, dissipative flows. A collaboration with Dr. A.H. Nielsen, RISØ Institute, Denmark, was started in order to apply some of the techniques developed in these papers to the results obtained in high-resolution numerical simulations.

Low order statistical-dynamical climate models

For two reasons it is an interesting objective to formulate low-dimensional models of the atmosphere which, in spite of their simplicity, retain

a considerable degree of realism in the description of mean states as well as internal variability. First, they are more transparent than the ever more complex state-of-the-art GCM's and thereby serve as tools for deepening our understanding of the behaviour of GCM's and the atmosphere itself. Furthermore, they are fast so that they can be used as part of intermediate complexity models by which we can examine the ultra-long timescales of the climate system. With this in mind, and based on previous encouraging work during the stay of Achatz at KNMI and after his return to the Leibniz-Institut für Atmosphärenphysik (Germany), a reduced model has been developed which is based on empirical orthogonal functions (EOF). Such models are able to describe complex systems with high efficiency. The novelty of the work undertaken here was that the non-linear dynamics of the model is based on the primitive equations (PE) so that also tropical dynamics is captured well. Furthermore the model goes beyond its predecessors by also describing a seasonal cycle. Basis is a new numerical PE algorithm, which retains internal gravity waves but is filtered with respect to the external wave type. This serves as framework for the definition of a PE-based total energy metric for the determination of the EOF's from some data set. The dataset used is a long run of ECHAM3 (Hamburg Version of the ECMWF Model). External forcing and linear dynamics of the model are empirical. They optimise instantaneous tendencies in the ECHAM3 data. Investigations of the behaviour of the model show good simulations of first and second moments in the ECHAM3 data and their respective seasonal cycles. Recurrent anomalies can be reproduced. This is especially the case for a small model version, based on as few as 30 patterns. The model is presently employed in studies on atmospheric dynamics. The possibility of using them as a dynamical core of an intermediate complexity climate model is presently under investigation.

By studying the properties of a two-layer quasi-geostrophic version of a low order dynamical-empirical EOF model, a link is established between atmospheric ultra-low frequency variability (ULFV) and the occurrence of homoclinic dynamics. Uncoupled atmosphere models possess significant variability on very long time scales (years to decades), which must be generated by internal atmospheric dynamics. The mathematical structure of this long-timescale variability is investigated. The ten-dimensional (10D) version of the model possesses both nonzero ultra-low frequency

variability and some realistic short timescales. The essence of the ultra-long timescale behaviour of the 10D model, which manifests itself as bursts in the atmospheric turbulent energy, can be represented by a 4D subsystem. In this subsystem, strong evidence for the existence of a homoclinic orbit is found. The chaotic dynamics generated by the homoclinic orbit explains the observed long-timescale features of the model. It is shown that hints of homoclinic dynamics can also be found in more complex models.

Low-order empirical climate models

The recurring theme in the investigations listed below is the construction, when possible, of empirical, low dimensional models. Another question is that of predictability, be it intrinsic or related to model limitations. In the empirical modelling of the dynamics of El Niño - Southern Oscillation (ENSO) a novel, nonparametric regression analysis was used to derive a set of reduced models from an intermediate-complexity atmosphere-ocean model of the tropical Pacific and from a state-of-the-art GCM. The analysis performed was focused on the dimensionality issue as well as on the role of nonlinearities. This empirical technique helps to identify key processes and to explain physical peculiarities of simulations. A publication will be published in the Journal of Physical Oceanography.

The results of a 330-year long model simulation performed with a coupled GCM as well as results from the simpler Zebiak-Cane ENSO model were used in order to compute the corresponding season-dependent, cyclic Markov chains. In this way, one obtains a lower bound for the predictive skill of dynamic ENSO models as well as the dependence of the ENSO predictability upon the initial state and the initial month. These calculations are now extended using longer simulations and available measurements. A collaboration was started with the Physics Department of the University of Rome in order to extract more information from these Markov chains.

The role of noise-induced transitions in the thermohaline circulation was studied using a multiplicative Langevin equation. It was shown that the intensity and other characteristics of the ubiquitous noise can lead to clear-cut changes in the mean state of the thermohaline circulation. The corresponding publication appeared in the Journal of Physical Oceanography.

Using a relatively simple threshold-model of ice volume forced by the envelope of the eccentricity modulated solar insolation it was possible to

reproduce the 100 ky cycles of the Late Pleistocene. A publication on this work has been submitted.

ECBILT: an intermediate-complexity climate model

Haarsma, Selten, Schaeffer, Wang, Weber, Opsteegh, Beersma

Models are an important tool in climate research. In recent years the so-called intermediate-complexity climate models are emerging to bridge the gap between comprehensive coupled GCM's on the one hand and low-order, conceptual models on the other hand. The Predictability Research Division has developed such an intermediate-complexity climate model (ECBILT), primarily for the investigation of extratropical climate variability on decadal and longer time scales. ECBILT contains a number of (subgrid-scale) processes in a parameterised form. In this respect it is similar to GCM's, albeit with a coarse spatial resolution and a high degree of simplification in its parameterisation package. Contrary to conceptual models, the number of degrees of freedom is much larger than the number of adjustable parameters. Tuning has to be done mainly on the level of the included processes. The simulated climate in the extratropics is reasonably realistic, with a good qualitative agreement to the observed location of the stormtracks and the dominant patterns of variability. Due to the coarse resolution the intensity of the variability is underestimated. ECBILT is computationally very efficient. It is possible to perform climate simulations in ensemble mode or to perform ultra-long simulations. Since it was first developed ECBILT has been applied for the study of a wide range of scientific questions. This will be described in the following paragraphs 'Predictability and natural variability of climate' and 'Reconstruction and modelling of past climate'.

ECBILT is being modified and improved in a continuing process. Here we co-operate with various Climate Research Divisions (Atmospheric Research, Oceanographic Research and Climate Analysis) as well as with (inter-) national partners. ECBILT has been coupled to the CLIO (Coupled Large-Scale Ice Ocean Model) ocean/sea-ice model of the University of Louvain-La-Neuve, Belgium. We participated in the workshop on Earth System Models of Intermediate Complexity (EMIC's) held at the Conference of the

European Geophysical Society (EGS) in Nice, France, in April 2000. A paper on the spectrum of climate models, ranging from comprehensive GCM's via EMIC's to pure conceptual models, has been submitted for review (first author: Dr. Martin Claussen, Potsdam Institute for Climate Impact Research, Germany). We recently joined an initiative of Prof. Klaus Fraedrich of the University of Hamburg to develop a European community climate model of intermediate complexity. This model will be embedded in a standard model environment, including pre- and postprocessing software, debugging tools and graphical packages. The model core will have a modular structure, which will make it relatively easy to exchange different physical parameterisation routines. Below we will describe the versions presently available (ECBILT₁ and ECBILT₂) and new developments. Frozen versions of ECBILT can be obtained through the CKO model support website.

ECBILT₁

This original configuration of ECBILT consists of an atmospheric quasi-geostrophic model (T₂₁, three levels) with a diagnostically computed correction for the ageostrophic terms. It contains parameterisations for the diabatic physical processes and a bucket land model. ECBILT₁ is coupled to a flat-bottom ocean model and a thermodynamic sea-ice model, both developed in the Predictability Division. This version is described in a *Tellus* (1998) paper. It has been updated so that orbital variations in the solar radiation can be taken into account.

ECBILT₂

In collaboration with the RIVM (National Institute of Public Health and the Environment) as well as the Divisions of Atmospheric Research and Climate Analysis a new radiation and cloud scheme has been developed. The radiation scheme is a linearisation of the radiation scheme of ECHAM₄ (Hamburg version 4 of the ECMWF model).

The cloud scheme is based on a simple parameterisation of cloud cover by prognostic model variables like relative humidity and vertical velocity. The radiation scheme now includes the possibility of studying the effects of variations in the concentration of trace gases like CO₂. ECBILT₂ is coupled to the MOM₃ (Modular Ocean Model) of GFDL (Geophysical Fluid Dynamics Laboratory), Princeton, USA. There also exists a version with the CLIO model (Coupled Large-Scale Ice Ocean model) of the University of Louvain-La-Neuve, Belgium. CLIO contains an ocean component as well as a thermodynamic/dynamic sea-ice component. We plan to extend ECBILT₂/CLIO with a land-ice component, in collaboration with University of Utrecht. This will bring the study of the initiation and termination of glaciations within reach.

ECBILT₃

New developments, which have started but are not yet completed, include:

1. Development of a boundary-layer scheme. In collaboration with Wageningen University, the Atmospheric Research Division and the RIVM a new boundary-layer scheme is developed. It will simulate the daily variation in the boundary-layer height and surface fluxes. To this end a daily cycle in solar irradiation will be included. The new boundary-layer scheme will be tested off line with Cabauw data and simulations with a 1-D version of RACMO (Regional Atmospheric Climate Model). This project is partly funded by NOP.
2. Development of a vegetation module. As part of a PhD project in collaboration with the RIVM a vegetation module is being developed to study climate-vegetation feedbacks.
3. Replacement of the quasi-geostrophic adiabatic code of ECBILT by a primitive equation code, which has been developed by the University of Hamburg.

Predictability and natural variability of climate

Haarsma, Selten, Schaeffer, Van Reenen, Wang, Opsteegh

Decadal variability in the midlatitudes has been investigated with ECBILT₁. We have focused on decadal variability in the North Atlantic and in the Southern ocean. In those regions the dominant patterns of covariability between sea surface temperature and 800 hPa geopotential height and their preferred time scales show good qualitative agreement with observations. The physical mechanisms of the simulated decadal variability have been investigated with a number of idealised experiments in which various feedback processes have been switched on and off. This analysis revealed that the midlatitude decadal variability is strongly associated with subsurface oceanic modes. These modes are generated by dominant, internal modes of the atmospheric circulation. The ocean sets the time scale. The feedback from the ocean to the atmosphere is not crucial for either the structure or the time scale of these decadal modes. This feedback, however, enhances the intensity of the decadal variability. The generation of the dominant time scale in the subsurface oceanic mode is different for the North Atlantic decadal mode and the Antarctic Circumpolar Wave (ACW). For the ACW the preferred time scale appears to be generated by the advective resonance mechanism. In this mechanism the ocean temperature can be

approximated by a passive tracer, which is advected by an ocean with a fixed velocity. The preferred time scale is set by the advection velocity of the ocean and the horizontal scale of the atmospheric mode. For the decadal variability in the North Atlantic the dynamical response of the ocean circulation to temperature anomalies and related anomalous salt advection appears to be crucial for the generation of the decadal time scale. Two papers on this subject have been published in the Journal of Climate. A PhD project has started to investigate the role of the salt anomalies and the possible interaction between the Pacific and the Atlantic more in detail. This will be done with ECBILT₂/MOM₃.

With ECBILT₁ we have investigated the effect of variable solar forcing on climate variability. For realistic amplitudes solar forcing dominates over internal variability in global mean surface air temperature beyond decadal time scales. On the regional scale the internal variability dominates on all time scales. Evidence is found for interaction between climate variations on different time scales. The simulated decadal variability in the North Atlantic appears to be sensitive to small low frequency fluctuations in the solar irradiance. A

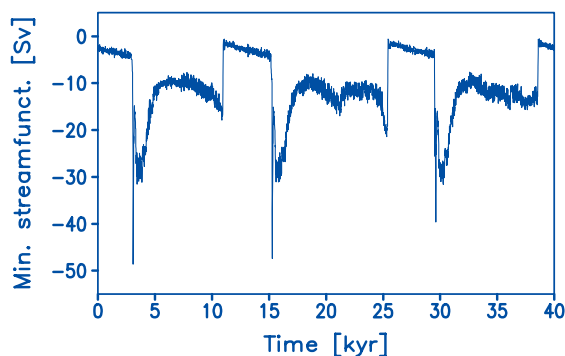


Figure 3. Extrema of the stream function of the meridional overturning (Sv) in the Southern ocean during a 40,000 years integration with ECBILT1.

paper has been published in Geophysical Research Letters. The time scale interaction has been discussed in a contribution to a book on solar variability and climate edited by Friis-Christensen.

With ECBILT1 a 40,000 year integration has been performed to study internal low-frequency behaviour. The model displays quasi-periodical behaviour on a time scale of about 10,000 years, characterised by rapid switches between two quasi-equilibrium solutions on decadal time scale (Figure 3). The mechanism is similar to the deep-decoupling oscillations observed in ocean models with mixed boundary conditions. The effect of sea-ice on the heat and freshwater fluxes appears to be crucial to generate this type of oscillation in a coupled atmosphere/ocean/sea-ice model. This experiment suggests the possibility of rapid transitions in the climate system. A paper will shortly appear in Climate Dynamics.

In collaboration with Dr. Hugues Goose of the University of Louvain-La-Neuve decadal variability over the Arctic ocean has been investigated with

ECBILT2/CLIO. A decadal oscillation in the Arctic ocean with a period of about 18 year is simulated. The geographical pattern and time scale are supported by the available observational evidence. A paper describing this oscillation will appear in Annals of Glaciology. Further analysis of the driving physical mechanism is underway.

With ECBILT2/CLIO, an ensemble of integrations has been performed for future concentrations of trace gases in the atmosphere up to the year 2100. The response of surface air temperature to the increasing concentrations of green house gases qualitatively resembles the results of similar runs performed with more comprehensive climate models. The simulated increase of surface air temperature falls in the lower range of published estimates. The thermohaline circulation decreases, the sea-ice cover in the Greenland-Iceland-Norwegian sea increases. The ensemble of integrations is being analysed to estimate changes in the occurrence of extreme events due to the change in the mean climate. A paper on this subject is in preparation.

Since regional climates tend to be influenced by a few dominant circulation structures, insight in the response of the statistics of these structures to changes in the forcing is crucial in understanding and predicting regional climate changes. The sensitivity of the statistics of the dominant extra-tropical circulation structures to changes in the diabatic heating is being studied in a quasi-geostrophic atmospheric model (the dynamical part of ECBILT1) in collaboration with Dr. Grant Branstator of NCAR (National Center for Atmospheric Research). The responses turn out to be highly non-linear. A dynamical interpretation of these sensitivities is underway.

Reconstruction and modelling of past climate

Weber, Van der Schrier, Tuenter

The palaeo research of the Predictability Division aims at developing a methodology for combining dynamical knowledge, based on the analysis of model simulations, and proxy data. This is done in close co-operation with climatologists, glaciologists, geologists and palaeo-ecologists. Research themes are the low-frequency variability of the present climate and the sensitivity of the climate system to

changes in the external forcing or in the boundary conditions. Both themes are highly relevant for detection and modelling of anthropogenic climate change. They are fully consistent with CLIVAR, PAGES (Past Global Changes) and the CLIVAR/PAGES intersection.

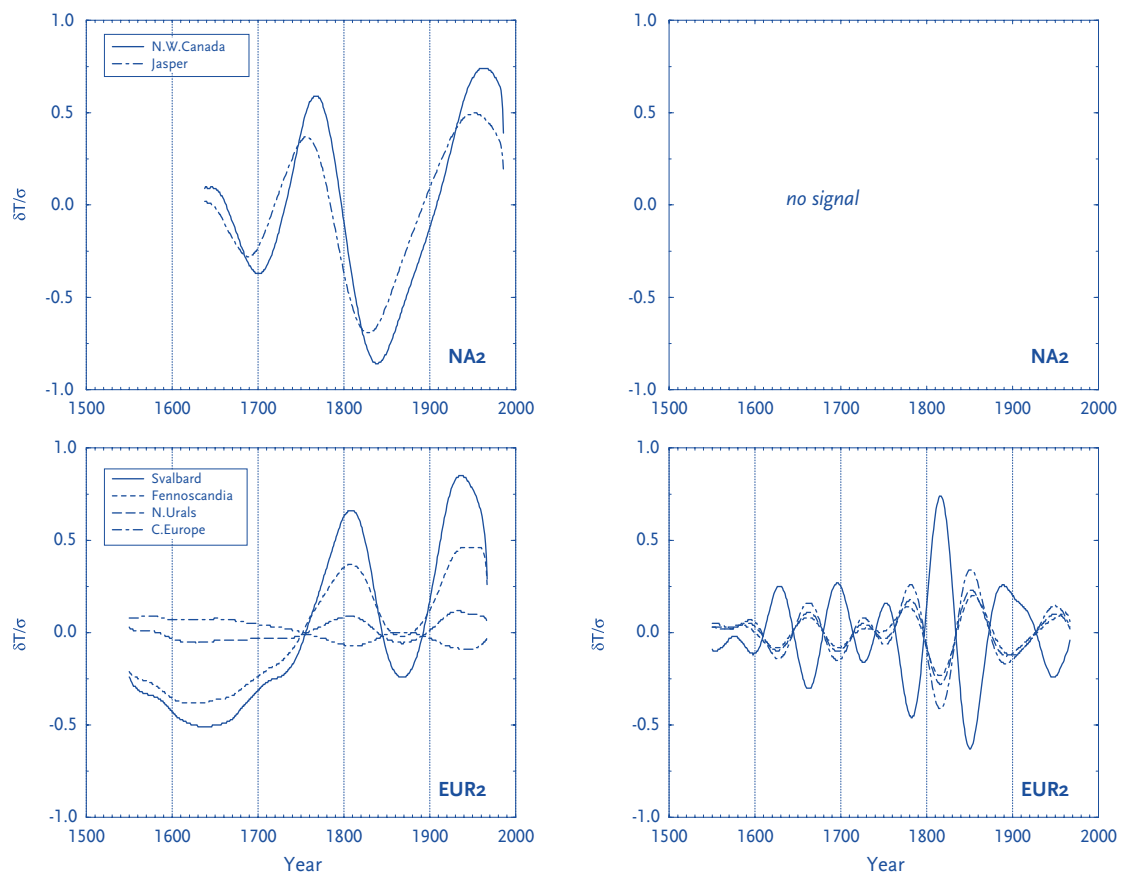


Figure 4. Low-frequency modes of temperature variability identified by MSSA in the reconstructed summer-season records of temperature for Europe (EUR2) and north-western North America (NA2). The specific locations are indicated in the legend. Shown

are the normalised anomalies, with the centennial mode in the left-hand panels and the multi-decadal mode in the right-hand panels. The multi-decadal mode is absent for NA2, as it only occurs in regions bordering the North Atlantic.

The project 'Patterns of low-frequency climate variability: a model-palaeodata comparison' ended in 2000. This was a collaboration between the Predictability Division, the Climate Analysis Division and Prof. Henry Hooghiemstra (Hugo de Vries Laboratory, University of Amsterdam). Focus of this NOP-funded project was on natural climate variability on interdecadal to centennial timescales. As a data base European early-instrumental timeseries and a proxy-based network covering North America and Europe were used. The latter incorporates high-quality climate reconstructions based on various palaeo proxies.

A combination of statistical techniques was applied, including principal component analysis and multivariate singular spectrum analysis (MSSA). On timescales longer than 50 years two statistically significant modes of temperature variability were identified, one on multidecadal and one on centennial timescales. Figure 4 gives the results for the summer data. The first mode is oscillatory, with a

timescale in the narrow range 60-80 years. The spatial pattern of this mode implies coherent oscillations over Europe and over north-eastern North America, with maximum amplitudes in Europe; over north-western North America this mode is absent. Its geographic shape suggests a connection to the North Atlantic Oscillation. A relation with solar forcing could not be detected. The second mode, which dominates low-frequency variability at high latitudes, describes temperature variations in a wide interval of timescales. The temporal pattern of this mode shows a multiple-phase 'Little Ice Age' and a prolonged 'Medieval Warm Period'. The interpretation of this mode is difficult, given its rather variable large-scale pattern and the uncertainty associated with centennial timescales in the proxy data. It was shown earlier that low-frequency variability patterns in early-instrumental temperature records are season-dependent. Due to a lack of seasonally resolved proxy data it is difficult to address this issue in a rigorous manner for the presently identified low-

frequency modes. In Europe, where long seasonal proxy series are available, both modes seem to be season-specific. A publication has appeared in *Journal of Geophysical Research*.

A simulation with ECBILT₁ of a thousand years, using present-day boundary conditions, was analysed with respect to patterns of variability in surface air temperature. Although the model fails to reproduce periodicity's identified in the proxy data, some encouraging similarity was found between spatial patterns of variability in the empirical and simulated summer data. A paper on the model analysis and model-data comparison is in preparation.

An international workshop on combining modelling and palaeodata in the analysis of low-frequency climate variability was co-organised with Dr. H. von Storch (GKSS Research Centre, Geesthacht, Germany), bringing together about 30 scientists from Europe and the US. A short report on the workshop theme appeared in the *American Geophysical Union Newsletter*, *Eos*.

Research on this theme continues with another NOP-funded project 'Sea level and climate variability on multi-decadal to centennial timescales'. This is a joint project of the Predictability Division and Oceanographic Research Division with Dr. Orson van de Plassche (Faculty of Earth Sciences, Free University Amsterdam). This two-year project started in 1999. The KNMI contribution to this project is to establish, from ECBILT₁ output, relations between coherent spatial patterns of North Atlantic sea level variability and prominent modes of the atmospheric circulation and other atmospheric parameters in the North Atlantic. A procedure to compute sea level diagnostically from ECBILT₁ was set up. A 1500-year long sea-level record for the North American East Coast, as reconstructed by Van de Plassche on the basis of salt marsh data, will be used in the model-data comparison. Hypotheses regarding the relation between sea level at the North American East Coast and climate in NW Europe, which have been formulated on the basis of reconstructed sea level and various other climate proxies, will be validated within the context of the model experiments.

The separation of solar-induced climate variations from other sources of climatic variability is a fundamental problem in the Earth sciences. By using concepts from dynamical systems theory, a technique has been devised which has the potential to distinguish explicitly between internally generated and externally forced climate variability. This

technique was applied to a long early-instrumental temperature record. A publication in *Geophysical Research Letters* is in press.

The mid-Holocene Optimum has been defined by the international Palaeo Modelling and Intercomparison Project (PMIP) as a key period for assessing the sensitivity of climate models to past changes in external forcing and boundary conditions. The climatic response as simulated by ECBILT₁ for the mid-Holocene Optimum was found to be comparable to results of state-of-the-art GCM's. A transient simulation of 10,000 year for the Holocene was recently completed. A short paper on the impact of the imposed orbital forcing on the ultra-low frequency behaviour of ECBILT₁ will appear in *Global and Planetary Change*. A more detailed analysis of the simulated climate change and climatic variability during the Holocene is in preparation. An off-line glacier model was used to estimate the Holocene evolution of a small number of maritime and continental glaciers. The glacier model generates synthetic glacier length records, which can be validated against known constraints for the Holocene epoch. A paper (co-author Prof. Hans Oerlemans, IMAU, University of Utrecht) is in preparation.

A PhD study on 'Modelling of astronomically forced variations in (circum)-Mediterranean climate' started at the end of 1999. This is a joint project with Dr. Frits Hilgen (Faculty of Earth Sciences, University of Utrecht). Mediterranean sedimentary records bear a clear signal of both the obliquity and precession cycle in the astronomical forcing, although the local forcing due to obliquity is very small compared to that due to precession. The aim of this study is to explain the 'observed' climatic response, which is found to be robust over the last 5 Million years. Results of time-slice experiments with ECBILT₁ show both a precession and an obliquity signal in the African monsoon and in the winter precipitation in southern Europe. The large-scale dynamical model response will be analysed in more detail in 2001.

On geological timescales the Earth's climate may be stabilised by the close coupling between climate and the biota. This is demonstrated mathematically by the Daisyworld model of Watson and Lovelock (1983). It is a highly idealised zero-dimensional Earth System model, based on albedo regulation due to vegetation changes. The steady state solution exhibits homeostasis over a large range of solar luminosities. A detailed analysis of Daisyworld

was carried out in order to determine to which extent this model is relevant for the real Earth System. It was shown that the basic assumptions of the Daisyworld model imply local temperatures, which are independent of incoming solar radiation. The property of fixed local temperatures and the associated heat transport mechanism do not seem to have parallels in the real climate. At the same

time, this property is crucial for the homeostatic behaviour of Daisyworld. A paper will appear in *Climatic Change*. An invited lecture on this work was given at the second Chapman Conference on the Gaia hypothesis in Valencia, Spain, in June 2000.

Articles, published in standard journals:

1999 Barkmeijer, J., R. Buizza and T.N. Palmer, 1999. *3D-Var Hessian singular vectors and their potential use in the ECMWF Ensemble Prediction System*. Quart. J. Royal Meteorol. Soc., **125**, 2333-2351.

Brands, H., S.R. Maassen and H.J.H. Clercx, 1999. *Statistical-mechanical predictions and Navier-Stokes dynamics of two-dimensional flows on a bounded domain*. Phys. Rev. E., **60**, 2864-2874.

Brands H., P.H. Chavanis, R.A. Pasmantier and J. Sommeria, 1999. *Maximum entropy versus minimum enstrophy vortices*. Physics of Fluids, **11**, 3465-3477.

Drijfhout, S.S., R.J. Haarsma, J.D. Opsteegh and F.M. Selten, 1999. *Solar-induced versus internal climate variability in a coupled Climate Model*. Geophys. Res. Lett., **26**, 205-208.

Grötzner, A., M. Latif, A. Timmermann and R. Voss, 1999. *Interannual to Decadal predictability in a coupled Ocean-Atmosphere General Circulation model*. J. Climate, **12**, 2601-2624.

Hersbach, J.P.Th. and P.A.E.M. Janssen, 1999. *Improvement of the short fetch behaviour in the wave ocean model (WAM)*. J. Atmos. Oceanic. Tech., **16**, 884-892.

Johnson, H.K., H.J. Vested, J. Hojtrup, S.E. Larsen and J.P.Th. Hersbach, 1999. *On the dependence of sea surface roughness on wind waves*. J. Atmos. Oceanic. Tech., **16**, 1780-1796.

Lenderink, G. and R.J. Haarsma, 1999. *On the mechanism of decadal oscillations in a coarse resolution ocean model*. Atmosphere-Oceans, **37**, 179-202.

Oortwijn, J., 1999. *Growth properties of optimal transition perturbations*. J. Atmos. Sci., **56**, 2491-2511.

Selten, F.M., R.J. Haarsma and J.D. Opsteegh, 1999. *On the Mechanism of North Atlantic decadal variability*. J. Climate, **12**, 1956-1973.

Shabalova, M.V. and S.L. Weber, 1999. *Patterns of temperature variability on multidecadal to centennial timescales*. J. Geophys. Res., **104**, 31023-31041.

Timmermann, A., 1999. *Detecting the nonstationary response of ENSO to Greenhouse warming*. J. Atmos. Sc., **56**, 2313-2325.

Timmermann, A., M. Latif, A. Grötzner and R. Voss, 1999. *Modes of climate variability as simulated by a coupled general circulation model. Part I: Enso-like climate variability and its low frequency modulation*. Clim. Dyn., **15**, 605-618.

Timmermann, A., J. Oberhuber, A. Backer, M. Esch, M. Latif and E. Roeckner, 1999. *Increased El Nino frequency in a climate model forced by future greenhouse warming*. Nature, **398**, 694-696.

Weber, S.L. and H. von Storch, 1999. *Future Challenges: Simulating Climatic Millennial Timescales and Combining Palaeoclimatic Evidence and GCM-based Dynamical Knowledge (workshop report)*. EOS Transactions, **80**, 380.

2000 Capel, H.W. and R.A. Pasmanter, 2000. *Evolution of the vorticity-area density during the formation of coherent structures in two-dimensional flows*. Physics of Fluids, **12**, 2514-2521.

Haarsma, R.J., F.M. Selten and J.D. Opsteegh, 2000. *On the mechanism of the Antarctic Circumpolar Wave*. J. Climate, **13**, 1461-1480.

Hersbach, J.P.Th., 2000. *Composition of the continuous ranked probability score for ensemble prediction systems*. Weather and Forecasting, **15**, 559-570.

Hersbach, J.P.Th., R. Mureau, J.D. Opsteegh and J. Barkmeijer, 2000. *A short-range to early-medium range ensemble prediction system for the European area*. Monthly Weather Review, **128**, 3501-3519.

Timmermann, A. and G. Lohmann, 2000. *Noise-induced transitions in a simplified model of the thermohaline circulation*. J. Phys. Oceanogr., **30**, 1891-1900.

Verkleij, W.T.M., 2000. *On the vertical velocity in an isentropic layer*. Quart. J. Royal Meteorol. Soc., **126**, 263-274.

Vosbeek, P.W.C., H.J.H. Clercx and R.M.M. Mattheij, 2000. *Acceleration of contour dynamics simulations with a hierarchical-element method*. J. Computer Phys., **161**, 287-311.

Reports and conference proceedings:

1999 Hersbach, J.P.Th., R. Mureau, J.D. Opsteegh, 1999. *An EPS for the short and early medium range*. In: Proceedings of the Workshop on predictability, ECMWF, Reading, United Kingdom, October 1997, 349-363.

Selten, F.M., R.J. Haarsma and J.D. Opsteegh, 1999. *On the mechanism of North*

Atlantic decadal variability. In: Proceedings of the first NRP-II Symposium on Climate Change Research, Garderen, The Netherlands, October 1998, 37-45.

Weber, S.L., 1999. *Low-frequency variability in long proxy record for surface air temperature*. In: Proceedings of the first NRP-II Symposium on Climate Change Research, Garderen, The Netherlands, October 1998, 53-59.

Weber, S.L. and H. von Storch, 1999. *Future Challenges: Simulating Climatic Millennial Timescales and Combining Palaeoclimatic Evidence and GCM-based Dynamical Knowledge*. Workshop report, EOS, 80, 380.

2000 Capel, H.W. and R.A. Pasmantier, 2000. *2D coherent structures: Maximum entropy on maximum mixing?* In: Proceedings of the Turbulence Workshop, Research Institute of Mathematical Science, Kyoto University, Japan, November 1999, 22-34.

Opsteegh, J.D. and H. Hersbach, 2000. *Objective verification of ensemble forecasting systems*. In: Proceedings of the seminar on diagnosis of models and data assimilation systems, ECMWF, Reading, United Kingdom, September 1999, 81-96.

Opsteegh, J.D., F.M. Selten and R.J. Haarsma, 2000. *Climate variability on decadal time scales*. NOP Report 410 200 060.

Verkleij, W.T.M., 2000. *Salmon's Hamiltonian approach to balanced flow applied to a one layer isentropic model of the atmosphere*. KNMI Scientific Report WR-2000-03.

Vosbeek, P.W.C., 2000. *Manual adjustments of numerical weather analyses*. In: Proceedings of the Meteorology at the millennium conference, Royal Meteorological Society, Cambridge, United Kingdom, July 2000, 181.

Vosbeek, P.W.C., W.T.M. Verkleij and A.R. Moene, 2000. *Manually adjusting a numerical weather analysis in terms of potential vorticity using three-dimensional variational data-assimilation*. BCRS Report NRSP-2 0101.

Weber, S.L., 2000. *A transient simulation of the Holocene climate with a coupled model of intermediate complexity*. In: Proceedings of the third pmip workshop (P. Braconnat, Ed), La Huardière, Canada, October 1999. wcrp-III WMO/TD-No. 1007, 197-201.

Weber, S.L. and M.V. Shabalova, 2000. *Patterns of low-frequency climate variability: a model-palaeodata comparison*. NOP Report 410 200 056.

Books and PhD-Theses:

1999 Haarsma, R.J., F.M. Selten, J.D. Opsteegh, Q. Liu and A. Kattenberg, 1999. *North Atlantic decadal climate variability in a coupled atmosphere ocean sea-ice*

model of moderate complexity. In: Beyond El Nino: Decadal and interdecadal climate variability (A. Navarra, Ed.), Springer Verlag, 277-301.

- 2000 Haarsma, R.J., S.S. Drijfhout, J.D. Opsteegh and F.M. Selten, 2000. *The impact of solar forcing on the variability in a coupled model*. In: Solar variability and climate, (E. Friis-Christensen et al., Eds.) Space Science Series of ISSI, Kluwer Academic Publishers.

Schrier, G. van der, 2000. *Aspects of the Thermohaline Circulation in a simple model*. PhD-Thesis, University of Utrecht, The Netherlands.

Number of international presentations: 1999: 17, 2000: 35.

Externally funded projects: national 5, international 1.

Education, organisation of workshops:

Several lectures have been organised for the forecasters to inform them about probabilistic forecasting. A presentation on objective verification of ensemble forecasting systems was given at the ECMWF seminar in September 1999 (Opsteegh and Hersbach, 2000). Similar lectures were given in a workshop on predictability for weather forecasters, which was organised three times in 2000 at KNMI.

D. Crommelin and M. Schaeffer were lecturers at the Buys Ballot symposium at Rolduc Abbey, Kerkrade, October 2000.

R. Haarsma was lecturer at the Symposium Weather and Climate, Technical University of Twente, Enschede, April 1999.

J.P.Th. Hersbach was lecturer at ABACUS, Mathematical Symposium Mathematics and the future, Technical University of Twente, Enschede, May 1999.

J.P.Th. Hersbach was lecturer at the Netherlands Union for Business and Weather Expectations (NVBW), Utrecht, September 1999.

J.D. Opsteegh is part-time professor of Dynamical Meteorology at the University of Utrecht.

R.A. Pasmantier was lecturer at the Eindhoven Student Union, April 2000.

A. Timmermann organised a CKO (Netherlands Centre for Climate Research) meeting, KNMI, De Bilt, February 1999 and May 2000.

A. Timmermann organised an international workshop on Dynamical System Concepts in Climate Dynamics, KNMI, De Bilt, April 2000.

W.T.M. Verkleij was lecturer at the course Synoptic Meteorology at KNMI, De Bilt, June 2000.

S.L. Weber co-organised with Prof. H. von Storch, GKSS Research Centre, Geesthacht, Germany, an international workshop on Climate variability on multi-decadal to millennial timescales, March 1999, KNMI, De Bilt.

S.L. Weber co-organised with F. Jansen, NIOZ, Texel, a CKO (Netherlands Centre for Climate Research) meeting, KNMI, De Bilt, June 1999.

S.L. Weber organised a mini-symposium for the Dutch Society for Professional

Meteorologists (NVBM) on Polar areas and the history of climate, KNMI, De Bilt, November 2000.

Other activities:

J.D. Opsteegh, member of the Climate Committee, Royal Netherlands Academy of Arts and Sciences (KNAW).

J.D. Opsteegh, member of the Board for Earth and Climate, KNAW.

J.D. Opsteegh, member of the Policy Advisory Committee - Earth Sciences (BAC-A), Earth and Life Sciences (ALW).

J.D. Opsteegh, member of the programme committee of the Centre for Climate Change and the Biosphere (CCB) of the Agricultural University of Wageningen.

J.D. Opsteegh, member of the programme committee of the Netherlands Earth Scientific Congress V.

J.D. Opsteegh, member of the programme committee of the Climate Conference 2001, Netherlands Centre for Climate Research (CKO).

J.D. Opsteegh, member of the Scientific Advisory Committee, ECMWF.

A. Timmermann, contributing author to IPCC Third Assessment Report, chapter 7, Physical Climate Processes and Feedbacks, section 7.6.4: El Niño – Southern Oscillation, authors: K. Trenberth, T. Palmer, A. Timmermann, M. Cane, R. Mugara.

S.L. Weber, member of the review committee of ALW.