RT4: Understanding the processes governing climate variability and change, climate predictability and the probability of extreme events

Coordinators: UREADMM, CNRS-IPSL

Aim:
The purpose of this Research Theme is to advance understanding of the basic science issues at the heart of the ENSEMBLES project. The work will focus on the elucidation of the key processes that govern climate variability and change, and that determine the predictability of climate on timescales of seasons, decades and beyond. Particular attention will be given to understanding linear and non-linear feedbacks in the climate system that may lead to climate "surprises", and to understanding the factors that govern the probability of extreme events. Improved understanding of these basic science issues will contribute significantly to the quantification and reduction of uncertainty in seasonal to decadal predictions and projections of climate change.

RT4 will exploit the ENSEMBLES integrations performed in RT2A as well as undertaking its own experimentation to explore key processes within the climate system. It will link strongly with RT5 on the evaluation of the ENSEMBLES prediction system and will feed back its results to RT1 to guide improvements in the earth system models and, through its research on predictability, to steer the development of methods for initialising the ensembles.

Primary Objectives:
O4.a: To establish the coordination mechanisms within RT4, and to develop methodologies for the coordinated experimentation.

O4.b: To investigate and quantify feedbacks in the Earth system, and their potential to lead to abrupt climate change or other climate "surprises" in existing transient climate change simulations.

O4.c: To determine the impact of climate change on climate variability, and to investigate the mechanisms that govern regional patterns of climate change, including ocean heat uptake.

O4.d: To develop methodologies which will elucidate the climate processes that determine the probabilities of extreme weather events, and the ways in which these probabilities may change in a changing climate.

O4.e: To develop the tools, and to exploit existing seasonal to decadal hindcasts, for identifying and understanding the sources of predictability in current and future climates.

Current state of knowledge
In a previous European project about cloud feedbacks ("Cloud feedbacks and Validation", project ENV4-CT95-0126), clear differences in the behaviour of clouds with temperature in different models were pointed out, especially in subsidence regions (Bony et al. 2004). However, in that project neither the appropriate data nor the simulations were available to determine which

behaviour was the most realistic. In WP4.1 we will use new reanalyses (ERA-40), more extended satellite datasets and new model integrations to address this issue.
At the moment only 2 groups in the world performed fully coupled climate-carbon cycle simulations, and a complete analysis of the large differences obtained in the magnitude of the climate-carbon cycle feedback still has to be done. New simulations will be performed within ENSEMBLES with a strict protocol that will allow work in WP4.1 to provide a better comparison. No other EU project has so far funded this activity.
Research on the stability of the THC using complex state-of-the-art climate models is in an early stage. There is a real need to close the gap between the results from reduced complexity models, which show evidence of multiple stable states and have been one of the main drivers behind abrupt climate change, and full climate models which show a more gradual response to climate forcing. The IPCC TAR showed a range of responses in state-of-the-art models from a marked slowing down of the THC to almost no change at all. There is a clear need to reduce uncertainty in the projections of THC behaviour in the coming century. Since EU WATCHER has not been funded, there is a clear need for ENSEMBLES to address this important topic. This will therefore be a focus for research within WP4.1.
In the recent past, an increasing interest in the effects of the mean climate changes on the natural climate variability has developed. Thus, in a number of studies and research projects the possible impacts of the climate change on the main modes of the natural variability has been considered. For example, simplified models have been used to investigate how the frequency and the intensity of ENSO can be affected by changes in the mean state of the equatorial Pacific (e.g., Fedorov and Philander, 2000); whereas, coupled GCMs have been used to analyze what are the possible changes in the oscillation induced by the greenhouse gas forcing (e.g., Timmermann et al. 1999, 2001; Collins 2000). In the EU project PREDICATE, it has been shown that "the strong interdecadal variability over the North Atlantic/European region has the potential to mask an anthropogenic climate signal for many decades". But, the mechanisms underlying this low-frequency mode of the climate variability are still unclear.
In the EU project PROMISE, climate scenario experiments performed with a CGCM have suggested that the anthropogenic climate change might induce a more intense monsoon activity and variability both in Africa and India. However, the uncertainties in the results are still very high. One of the primary factors of uncertainty is that different CGCMs can produce different regional changes even when the external (anthropogenic) forcing is the same. Giorgi et al. (2001) have shown that a comprehensive assessment of the regional change projections can be based on the collective information from an ensemble of CGCM simulations. The ENSEMBLES multi-model system, enabled by the PRISM infrastructure, offers a unique opportunity for WP4.2 to investigate the mechanisms that govern the natural climate variability and to assess the effects that human induced climate change might have on them.
Recent EU projects such as PRUDENCE, STARDEX and MICE have made progress in developing statistical methods for describing and exploring extremes. However, to make more progress in exploiting multi-model climate simulations, a more rigorous probability model-based approach needs to be developed. This is one of the aims of WP4.3 and will lead to improved assessments of the incidence of extreme events and their characteristics. Furthermore research on the relationship between climate regimes and extreme events is in its infancy and WP4.3 will enable a much more comprehensive study.
The PROVOST, and DEMETER projects have shown that climate models have some skill in predicting seasonal fluctuations, in particular in the tropics, although weak but not negligible skill exists also in the extra-tropics, for instance over Europe. The PROVOST and DEMETER projects have used global SST-forced AGCMs and CGCMs integration ensembles, respectively. They have also both shown that the multi-model ensemble approach provides a pragmatic and efficient solution to account for model uncertainty in the seasonal prediction problem.

The PREDICATE project has shown that there is potential decadal predictability for the tropical and extra-tropical parts of the North Atlantic European region. On interannual-to-decadal time scales, the North Atlantic European climate is influenced by ENSO but also by Atlantic SST. PREDICATE also suggested that the thermohaline circulation is an active player in modulating Atlantic SSTs on long time scales and that changes in the THC can dominate an anthropogenic climate signal. WP4.4 will extend these studies and provide new assessments of the predictability using a new generation of coupled models run over both seasonal and decadal timescales.

Scientific/technical questions:

- What non-linear feedbacks in the earth system may contribute to abrupt climate changes or climate 'surprises'?
- What processes and phenomena contribute to regional variations in the patterns of climate change?
- How will the major modes of natural climate variability (e.g. ENSO, NAO) change with anthropogenic climate change?
- How can the probability of extreme events be estimated?
- What is the relationship between climate regimes and extreme events?
- How will the nature and probability of extreme events change with anthropogenic climate change?
- How predictable is the climate system, and which factors influence the predictability on different timescales?
- What is the importance of ocean initial conditions in defining future climate change scenarios?

WP4.0: Management of RT4

Leader: UREADMM (Julia Slingo), CNRS-IPSL (Herve Le Treut, Pierre Friedlingstein).
Participants: INGV (Silvio Gualdi), CERFACS (Laurent Terray)

The RT4 coordinators and work package leaders of WP 4.1–4.4 will provide management and coordination of activities within RT1. Integration across the RT will be achieved through a series of workshops and by coordinated time slice experiments. These experiments will be designed to investigate and understand the factors controlling climate at selected time periods (e.g. 1850, 2000, 2050). The experiments will be conducted with both atmospheric GCMs and coupled GCMs. Specific experiments will be designed to investigate issues such as the role of specific feedbacks, sensitivity to resolution, and sensitivity to oceanic initial conditions. The following groups will participate in the coordinated experimentation: U. Reading, CERFACS, CNRM, INGV, NERSC, Uni-Kiel.

Task 4.0.a: Ensure that deliverables and milestones for the project are met in a timely fashion and that progress reports, as specified by the ENSEMBLES Project Co-ordinator, are provided.

Task 4.0.b: Set-up and management of an internal web site for the RT, which will hold information such as contact details, minutes of meetings and progress reports, design of and results from the coordinated time slice experiments. Details of publications relevant to RT4 will also be maintained.

Task 4.0.c: Organization of a workshop during the first year of the project to discuss the key science issues for RT4, and to agree priorities for years 2-5 (Month 12).

Task 4.0.d: Arrange meetings with those groups participating in the coordinated time slice experiments to design the integrations and formulate a detailed plan (Month 18).

Task 4.0.e: At later stages in the project, organise meetings as required of the whole RT and those that are participating in the coordinated experimentation. The purpose of these meetings will be to exchange results and discuss priorities for future activities. Where feasible, these will be combined with the annual meetings of the whole ENSEMBLES consortium.

Task 4.0.f: Ensure that linkages with other RTs are maintained and that results relevant to other RTs are communicated in a timely fashion.

WP4.1: Feedbacks and climate surprises
Leader: CNRS-IPSL (Pierre Friedlingstein).
Participants: METO-HC (Cath Senior, Pete Cox), DMI (Eigil Kaas), INGV (Silvio Gualdi), CNRS-IPSL (Pierre Friedlingstein, Herve Le Treut), UCL-ASTR (Thierry Fichefet)

WP4.1 has two main objectives, (a) to quantify the role of different feedbacks in the Earth system on the climate predictions uncertainty, and (b) to investigate the risk of abrupt climate changes. Several feedbacks are already accounted for but poorly understood and therefore poorly represented in actual OAGCMs (examples are clouds, water vapor, surface hydrology), but new feedbacks may appear when other components of the Earth system are introduced in the ESMs (climate-carbon, climate-chemistry-aerosols, land use, ...). Therefore it becomes increasingly important to understand and quantify these feedbacks, comparing several models simulations, and using common methodologies to decompose these feedbacks into combinations of sensitivities that, where possible, can be evaluated against observations. Progress in understanding these processes is essential for building improved earth system models and for reducing uncertainties in future climate predictions.

The second objective of WP4.1 will investigate the risk of climate surprises, mainly associated with the stability of the ocean thermohaline circulation and its response to changes in fresh water fluxes and thermal forcing in the coupled atmosphere-land-cryosphere-ocean system. WP4.1 will make use of several Earth System Models to improve our assessments of the likelihood of such abrupt climate changes occurring in the future.

We will use first the 20C ENSEMBLES simulations with prescribed greenhouse gases only, with natural forcings only, with anthropogenic and natural forcings. Then, we will analyze 21C ENSEMBLES simulations. For Task 4.1.b, we will start by using existing coupled climate-carbon cycle simulations (Hadley and IPSL), then we will use ENSEMBLES simulations

Evaluation datasets for WP4.1:

Dataset	Short description	Period covered	Use
ERA-40	Atmospheric reanalysis	1957-present	Variability of the atmospheric circulation, definition of dynamic regimes
NCEP-2	Atmospheric	1948-present	Ditto

	reanalysis		
ISCCP	Clouds, radiation	1984-present	Cloud and cloud radiative forcing evaluation, analysis of sensitivities and feedbacks
SSM/I	Precipitable water	1988-present	Water vapour evaluation, analysis of sensitivities and feedbacks
GPCP	Precipitation	1979-present	Precipitation evaluation
HadISST	SST	1860-present	Variability of the SST, analysis of sensitivities and feedbacks
	Atmospheric CO2	1860-present	Evaluation of coupled climate carbon cycle models

Task 4.1.a: Analysis and evaluation of the physical processes involved in the water vapour and cloud feedbacks.
How do changes in cloud, water vapour and radiation contribute to climate sensitivity in the ENSEMBLES simulations?
How can observations and model simulations of the current climate be used to reduce uncertainty in the climate sensitivity?

Current climate models provide much contrasted results about the change in cloud cover in a warmer climate. This radiative effect is made more complex by the direct and indirect effects of aerosols. In particular, models that predict a decrease of the low-level cloudiness are likely to predict a higher climate sensitivity than others. In such areas as the Northern Atlantic or Indian oceans, anthropogenic aerosols have been shown to affect significantly the low cloud optical properties through the so-called aerosol indirect effect, whose treatment may vary strongly from a model to the other. The behaviour of low-level clouds also depends on both the large-scale atmospheric circulation and the thermodynamic structure of the lower troposphere. By compositing cloud properties in dynamical regimes in models and in observations over the 20th century, we will be able to assess the thermodynamic relationship between changes in cloud and in surface and boundary-layer properties simulated by the models under given dynamical conditions (Bony et al. 2004). This will provide a strong constraint on the sign of cloud radiative feedbacks. Such an assessment will help to determine the level of confidence that can be associated with each ENSEMBLES model. By considering the models that successfully pass the observational tests described above, we will narrow the range of climate sensitivities and thereby reduce the uncertainty of climate change predictions.
In a previous European project about cloud feedbacks ("Cloud feedbacks and Validation", project ENV4-CT95-0126), clear differences in the behaviour of clouds with temperature in different models were pointed out, especially in subsidence regions (Bony et al. 2004). However, in that project neither the appropriate data nor the simulations were available to determine which behaviour was the most realistic. In WP4.1 we will use new reanalyses (ERA-40), more extended satellite datasets and new model integrations to address this issue.
Research will be conducted to compare the physical processes involved in climate change scenarios and in the 20th century interannual to decadal variability. We will infer from observations collected during the 20th century the sign of the relationship between temperature and cloud changes on interannual to decadal timescales. The characterization of cloud changes will address the changes of their radiative impact, and whenever possible the mechanisms that

may explain those modifications will be described, including the potential role of the aerosols. Based on the model-model and model-observations comparisons, this WP will determine the uncertainty of climate change predictions associated with the water vapour and cloud feedbacks in climate models. Characterization of the temperature, water vapour, clouds types and radiation responses to anthropogenic climate forcings will be performed, and the linkage with changes in the precipitation patterns will be documented. These diagnostics will therefore provide an estimation of the uncertainty affecting impact studies. That will allow us to establish a relationship between the magnitude of the global climate sensitivity produced by the different models and the characteristics of water vapour, cloud and radiation changes in the models.

Deliverables:
- More confident assessments of the sign and magnitude of cloud radiative feedbacks under climate change.
- Papers addressing:
  - New assessments of climate sensitivity and its relationship with cloud and water vapour feedbacks
  - Intercomparison of cloud and water vapour feedbacks in the ENSEMBLES models.

Task 4.1.b: Quantification of the climate-carbon cycle feedback, with a specific focus on terrestrial carbon cycle sensitivity to climate change.
What factors contribute to carbon-cycle feedbacks and how can we use observations to constrain model simulations?
How will carbon-cycle feedbacks affect assessments of future climate change?

Hadley Centre and IPSL performed coupled climate-carbon simulations, they obtained a positive feedback but there was a factor of 4 between the Hadley Centre response and the IPSL response. The sensitivity of the terrestrial biosphere to climate is the main source of uncertainty. There is a need to better understand the vegetation and soil response to climate change and variability. The ability of coupled climate-carbon model to produce both a realistic historical trend and a realistic ENSO variability in term of carbon cycle will be crucial. This will be done with ENSEMBLES simulations were both models are forced with the same emission scenario and land use change scenario for the past and the future, following a detailed protocol.

At the moment only 2 groups in the world performed fully coupled climate-carbon cycle simulations, a complete analysis of the large differences obtained in the magnitude of the climate-carbon cycle feedback still has to be done. New simulations will be performed within ENSEMBLES with a strict protocol that will allow better comparison. No other EU project has so far funded this activity.

Using several climate-carbon coupled model simulations spanning over the 20th and 21st century, we will characterise the model results in terms of sensitivity and feedback factors, in order to isolate the uncertainty arising from the climate response to CO_2, and ocean and land responses to CO_2 and climate. Comparison with observed trends and variability on interannual to decadal timescales of climate, atmospheric CO_2 and carbon fluxes should allow us to reduce the uncertainty in the role of the climate-carbon cycle feedback in the future.

Deliverables:
- Reduced uncertainty in the processes involved in climate-carbon cycle feedbacks leading to improved models.

- More confident assessments of the role of climate-carbon cycle feedbacks in future climate scenarios.
- Papers addressing:
  - Carbon–climate feedback processes in the ENSEMBLES models
  - Influence of the carbon cycle of future climate scenarios

Task 4.1.c: Explore the effects of non-linear feedbacks in the atmosphere-land-ocean-cryosphere system and the risks of abrupt climate change/climate surprises
What processes influence the stability of the THC under climate change?
What are the relative role of freshwater and thermal forcing?

The focus of this task will be the stability of the thermohaline circulation (THC). An analysis of the global water mass transformation during climate change will be performed using the ENSEMBLES simulations. This will focus on future changes in freshwater fluxes to the ocean, from melting of sea-ice or polar ice sheets and from changes in precipitation. The response of the ocean in terms of salinity structure and NADW formation will be evaluated with the ENSEMBLES models over the 21st century and possibly the third millennium. Based on the ENSEMBLES scenarios an assessment of the stability of the THC will be made.

Research on the stability of the THC using complex state-of-the-art climate models is in an early stage. There is a real need to close the gap between the results from reduced complexity models, which show evidence of multiple stable states and have been one of the main drivers behind abrupt climate change, and full climate models which show a more gradual response to climate forcing. The IPCC TAR showed a range of responses in state-of-the-art models from a marked slowing down of the THC to almost no change at all. There is a clear need to reduce uncertainty in the projections of THC behaviour in the coming century. Since EU WATCHER has not been funded, there is a clear need for ENSEMBLES to address this important topic.

Deliverables:
- New assessments of the likelihood a shutdown or major slow down of the THC in the coming century(ies).
- Papers addressing:
  - Relative roles of freshwater and thermal forcing for the stability of the THC
  - Intercomparison of the response of the THC to anthropogenic forcing in the ENSEMBLES models

WP4.2: Mechanisms of regional-scale climate change and the impact of climate change on natural climate variability
Leader: INGV (Silvio Gualdi).
Participants: CERFACS (Laurent Terray), UREADMM (Julia Slingo, Rowan Sutton), CNRM (Jean-Francois Royer), NERSC (Helge Drange), IfM (Mojib Latif), ICTP (Franco Molteni), MPIMET (Marco Giorgetta)

The purpose of this work package is to advance understanding of the mechanisms that govern modes of natural climate variability and the regional characteristics of climate change. Climate variability can occur on all time-scales, both as a response to changes in the external forcing (natural or human-induced) and as a result of complex interactions between components of the climate system. In order to quantify and predict changes in climate regimes as a result of an external forcing (e.g., greenhouse gases), it is necessary to understand the processes that determine the natural, internal variability of the system, and then to assess how these may be modified by the effects of external forcings.

The uptake of heat by the oceans plays a key role in determining the rate of climate change and the regional variations in greenhouse gas warming. The mechanisms that determine these regional variations, for example the lower levels of warming in the extratropical oceans, need to be understood. Furthermore, the ocean heat uptake also determines the magnitude of sea-level rise due to thermal expansion, whereas regional details in sea-level change depend on the local climate and ocean circulation.

WP4.2 has synergies with EU FP6 DYNAMITE, which we will seek to exploit. The overall objectives of DYNAMITE are to address the fundamental processes involved in ENSO and the NAO, including the role of ocean biology. So DYNAMITE will provide the underpinning research on which ENSEMBLES can build, noting that WP4.2 addresses modes of variability other than just ENSO and the NAO and will use a wider range of coupled models.

The characteristics of global and regional modes will be analysed in existing climate simulations and in the ENSEMBLES prediction system. The relationships between modes of large-scale, low frequency variability and variability on shorter time and space scales will be investigated. Results from the different models will be compared, and will be evaluated by comparison with analyses of observational data. In order to improve our understanding of the ocean's response to anthropogenic forcing, the processes that govern the ocean uptake of heat will be investigated. Coordinated sensitivity experiments will be conducted to identify causal mechanisms and to explore the role of coupling between different components of the earth system. This work package will link strongly with the model evaluation activities of RT5.

Evaluation datasets for WP4.2:

Dataset	Short description	Period covered	Use
NCEP/NCAR	Atmospheric reanalysis	1948-present	Characterisation of modes of climate variability
ERA-40	Atmospheric reanalysis	1957-present	Ditto
CRU (Climate Research Unit)	Precipitation and surface temperature over land	1901-1995	Regional changes and variability in surface climate
CMAP	Precipitation	1979-present	Relationship between modes of variability and the hydrological cycle
HadISST	SST	1930-2002	Longer term indices of SST variability
NOAA AVHRR	Outgoing longwave radiation	1974-present	Independent information on convective anomalies particularly in the tropics.
EU ENACT	Ocean analyses	1958-2000	Description of the ocean behaviour associated with modes of climate variability
SODA	Ocean analyses	1950-1995	Ditto
TOGA-TAO	In situ buoy measurements in tropical Pacific	1983-2004	Evolution of El Nino events in the ocean.

Task 4.2.a: Analysis of the mechanisms involved in modes of natural climate variability
What are the physical mechanisms that produce and maintain the main modes of natural climate variability from seasonal to decadal time scales and govern their mutual interactions?

Based on existing simulations performed under PREDICATE and DEMETER, followed by the ENSEMBLES control integrations, modes of natural (internal) climate variability (e.g. NAO, ENSO) will be analysed on timescales from seasons to decades. The mechanisms involved in these modes will be explored with an emphasis on scale interactions and on the interaction between different modes of variability (e.g. ENSO with the NAO). For the Euro-Atlantic region, the interaction between Tropical Atlantic Variability, NAO and the Meridional Overturning Circulation, will be explored and the exchanges between the Arctic and mid-latitudes in the North Atlantic will be quantified. Similarly, the main processes of climate variability in the Indo-Pacific region, such as monsoons, Indian Ocean Zonal Mode, ENSO and Pacific Decadal Oscillation will be studied.

The statistical properties of these modes of variability on decadal and longer timescales will be investigated by means of both complex and intermediate ESMs. In particular, the characteristics of the models that determine the amplitude and the periodicity of ENSO will be explored by exploiting the modularity of the ENSEMBLES models enabled by the PRISM infrastructure. The potential effects of low-frequency changes in ENSO on the teleconnections with the Indian Ocean, the North Atlantic and the European region will be studied.

Deliverables:

- Characterization of the modes of natural climate variability and analysis of the physical mechanisms underlying these modes and their interaction.
- Papers addressing:
    - Tropical modes of variability in ENSEMBLES models
    - Extratropical modes of variability in ENSEMBLES models

Task 4.2.b: Assessment of the sensitivity of natural (internal) modes of climate variability modes to changes in the external forcing
How are the modes of natural climate variability influenced by externally forced changes of the mean climate?

Present-day and future climate scenarios produced by the ENSEMBLES prediction system will be used to investigate the effects that changes in the mean climate might have on the dominant modes of variability from seasonal to decadal timescales. Special emphasis will be given to possible changes in the North Atlantic and Indo-Pacific climate induced by greenhouse gas forcing. In addition, simulations performed with an entire atmosphere (from the surface to the thermosphere) model coupled with chemistry will allow us to explore the effects of the 11-year solar cycle on the atmospheric variability. The results will be underpinned by large ensembles of long simulations performed with intermediate models (e.g. SPEEDY developed at ICTP), which will provide a dynamically-based estimate of the reliability and significance of regime statistics derived from complex ESMs.

Deliverables:

- Improved understanding of the relationship between the mean climate and climate variability.
- Papers addressing:

- Reliability and significance of regime statistics
- Impacts on the modes of natural climate variability induced by changes in the mean climate produced by greenhouse gas forcing;
- Impacts on the natural climate variability induced by the 11-year solar cycle.

Task 4.2.c: Regional climate change, the mechanisms of ocean heat uptake and local sea level change.
What are the characteristics of the regional and large-scale changes in surface climate, and which processes determine these changes?

Processes and feedbacks in the atmosphere and surface system that determine regional and large-scale patterns of change in surface climate and the hydrological cycle will be analysed. Research will be conducted to understand the physical mechanisms that control the variability of soil moisture and snow mass for different climate conditions (present-day and scenario). Sensitivity experiments will be performed in order to assess how air-sea coupling can modulate the land surface feedbacks. The processes of global ocean heat uptake during climate change will be investigated. In addition, the mechanisms determining the geographical patterns of sea-level change due to changes in ocean density and circulation will be analysed in the ENSEMBLES models.

Deliverables:

- Improved understanding of the processes that influence regional patterns of climate variability and change
- More confident assessments of future regional climate variability and change, including sea level rise.
- Papers addressing:
    - Regional and large-scale changes in surface climate
    - Physical processes determining the characteristics of regional climate change
    - Geographical patterns of sea-level rise

WP4.3: Understanding Extreme Weather and Climate Events
Leader: UREADMM (David Stephenson)
Participants: NERSC (N. Kvamsto), KNMI (Frank Selten), CERFACS (Laurent Terray), INGV (Silvio Gualdi), IfM (Mojib Latif), AUTH (Panagiotis Maheras), UEA (Jean Palutikof), UNIFR (Martin Beniston)

Many of the most serious impacts of climate variability and change arise from changes in the frequency and characteristics of extreme events. The objective of the WP is to study extreme events from a meteorological perspective rather than through their impacts, which will be addressed in RT6. Events of interest include extremes in wind speed, temperature, and precipitation. This requires the correct diagnosis of extreme events from model output, and therefore methods for estimating tail probabilities using data from multi-model climate model ensembles must be developed. These methodologies will also be used in RT5 to evaluate extremes in the ENSEMBLES regional model simulations.

Recent EU projects such as PRUDENCE, STARDEX and MICE have made progress in developing statistical methods for describing and exploring extremes. However, to make more progress in exploiting multi-model climate simulations, a more rigorous probability model-based approach needs to be developed. Task 4.3a will develop such tools which will then be deployed in tasks 4.3b and 4.3c. Task 4.3b will use the tools to investigate the extent to which large-scale factors influence local extremes. Task 4.3c will use the tools to make the best possible predictions about the future probability of extreme events.

An important component of the research will be to investigate how the probability of extreme events is related to the characteristics of weather systems and larger scale patterns of variability and change, such as climate regimes. A specific priority will be to understand better the role of the North Atlantic storm track. This research will in turn facilitate studies to learn how extreme events are likely to behave in the future and what the uncertainty is in the ENSEMBLES predictions (e.g. due to model horizontal resolution, etc.).

Table of evaluation datasets for WP4.3:

Datasets	Short description	Period covered	Use
NCEP /NCAR	Atmospheric reanalysis (daily values)	1948-present	Development and testing of the extremes statistical models and for use in validating the results of the control runs of the model simulations.
ERA-40	Ditto	1957-present	Ditto
ECA daily observations	Ditto	20th century	Ditto

Task 4.3.a: Development and use of methodologies for the estimation of extreme event probabilities
Which are the best methods for inferring probabilistic tail information from multi-model ensembles of climate model simulations?

Statistical methods for estimating extreme event probabilities using multi-model ensembles of climate simulations will be developed in collaboration with partners in RT5. These methods will be capable of exploiting all the gridded field information from ensembles of simulations with different models. In addition to inclusion of spatial covariates (i.e. latitude and longitude) the statistical models will be able to incorporate large-scale circulation such as mode/regime indices. The methods will be tested by application to observed/reanalysis data sets (table above) and to existing model simulations such as those produced by the PRUDENCE project and long simulations available at KNMI.

Deliverables:

- Development of Spatial Extreme Value (SEV) Models - Statistical methods for identifying regimes and estimating extreme-value tail probabilities using multi-model gridded data. Reports will be written up on this and disseminated to all partners and software will be made freely available. CGAM and KNMI will address question 1 by developing and testing statistical methods for estimating extreme event probabilities using multi-model ensembles of climate simulations. Spatial extreme value models will be developed in collaboration with partners in WP5.4 that is capable of using gridded field information from ensembles of simulations with different models. In addition to inclusion of spatial covariates (i.e. latitude and longitude) the model will be able to incorporate large-scale circulation such as mode/regime indices. These tools will then be used to answer question 2 in WP4.3. During the first 18 months of ENSEMBLES, KNMI will also deliver a standard method for weather regime analysis to be applied to the ensembles produced in the project in order to be able to intercompare the climate integrations in this aspect and a standard method to reveal the relation between local weather extremes and the large-scale weather regimes. These methods will be developed using a 62 member ensemble of NCAR CCSM scenario integrations over the years 1940-2080 produced by KNMI in Summer 2003 (see www.knmi.nl/onderzk/CKO/Challenge_live).

- Analysis of extremes in observations/reanalyses - An analysis of which factors are the most important in determining extreme events in Europe obtained by applying the techniques developed in WP4.3a to the observed data sets (see table above). Oceanic (e.g. SST and THC) and atmospheric (large-scale flow) factors will be investigated. Extremes in both Northern and Southern Europe will be addressed. CERFACS, INGV, KIEL, AND NERSC will use the tools developed by CGAM and KNMI to start to analyse the extremes in the ensembles of coupled and time-slice runs. Results will be written up as a joint publication.

Task 4.3.b: Exploring the relationships between extreme events, weather systems and the large-scale atmospheric circulation/climate regimes
How do different large-scale factors influence weather extremes?

The statistical models for weather regime analysis will be used to diagnose the relationship between local weather extremes and large-scale weather and climate regimes in both observations (re-analysis) and model simulations produced in the framework of ENSEMBLES. An analysis of which factors are the most important in determining extreme events in Europe will be completed using the multi-model ensemble of coupled and time-slice simulations. Oceanic (e.g. SST and THC) and atmospheric (large-scale flow) factors will be investigated. Extremes in both Northern and Southern Europe will be addressed.

Deliverables:

- Analysis of extremes in the control simulations of the coupled runs - CERFACS and KIEL will address question 2 by focussing on the role of SST and oceanic phenomena such as the THC as factors controlling extremes. INGV will investigate the relationship between extreme events occurring in the Euro-Mediterranean region and modes of large-scale climate variability, such as the NAO. A comparison of the results obtained from a control run and scenario experiments will allow to assess how forced climate changes may affect the links between large-scale variability and extreme events over Southern Europe and the Mediterranean. NERSC will address question 2 but will focus more on extremes in Northern Europe related to the Atlantic storm track. Publications will be written up describing the results of these analyses.

Task 4.3.c: The influence of anthropogenic forcings on the statistics of extreme events
How are extreme events likely to behave in the future?

The methodology for identifying extreme events will be applied to the climate change scenarios produced by the ENSEMBLES prediction system. The characteristics of extreme events under climate change (e.g. intensity, return period) will be assessed. The effects of climate change on the links between large-scale variability and extreme events will be analysed with particular reference to the Euro-Atlantic sector. The dependence of the results on model formulation, particularly horizontal resolution, will be studied.

Deliverables:

- Analysis of extremes in future scenario simulations of the coupled runs – The SEV model will be used to infer the changes in the extremes between the control and the future scenario simulations. Best estimates of future changes in various types of extremes will be summarised. In addition, more detailed impact-type extremes studies will probe deeper the sensitivity of the most significant changes. Publications will be written up describing the results of these analyses.

WP4.4: Sources of predictability in current and future climates
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The primary focus will be to advance understanding of the physical processes that give rise to predictability of both the first (initial condition) and second kind (boundary condition). The importance of both sources of predictability will be investigated on timescales from seasonal to multidecadal and over a wide range of space scales. The primary focus will be to advance understanding of the physical processes that give rise to predictability. This will be achieved through carefully designed sensitivity experiments coupled to the analysis of the core multi-model simulations performed within RT2A.
The objective of ENSEMBLES WP4.4 is to improve the understanding of the physical processes by which various Earth's surface components (ocean, land surface) influence the atmosphere. For instance, ENSEMBLES wants to study the influence of the various ocean basins on predictability (mechanisms, time scales, non-linearities…). How do the various regional SST modes interact with each other (linear or nonlinear interaction)? Another new question addressed within ENSEMBLES is the influence of land surface (soil moisture and snow thickness) and stratospheric circulation anomalies on the atmosphere on seasonal-to-interannual time scales. These potentially very important aspects have not been addressed within the previous European projects.
Another new objective within ENSEMBLES is to improve the understanding of the interaction between anthropogenic climate change and natural climate variability modes (for instance the THC or ENSO). Does climate change influence predictability of climate fluctuations (what are the relevant processes, time scales…)? Is the level of decadal predictability dependent upon the initial oceanic conditions (for instance the phase of the THC)? What is the importance of oceanic initial conditions versus external forcing in climate change prediction?
For the first 18 months, we will use existing integrations (those performed within the PREDICATE and DEMETER projects) as well as the coordinated sensitivity experiments (planned within RT4). The core multi-model simulations performed within RT2A will be used in the second part of the project (the last 42 months).

Table of evaluation datasets for WP4.4:

Datasets	Short description	Period covered	Use
NCEP /NCAR	Atmospheric reanalysis	1948-present	Observed regimes, interannual variability and validation of simulated weather and climate circulation regimes
ERA-40	Ditto	1957-present	Observed regimes interannual variability and validation of simulated weather and climate

			regimes. Study of the stratospheric influence upon tropospheric predictability. Parameters of the land surface analysis used in boundary conditions of the sensitivity experiments related to the land surface hydrology.
NCAR SLP dataset	Sea level pressure	1900-2002	Observed regimes interannual variability and validation of simulated weather and climate circulation regimes
CRU SLP dataset	Ditto	Ditto	Ditto

Task 4.4.a: Sources of atmospheric and oceanic predictability at seasonal to interannual timescales (predictability of the first kind, influence of initial conditions)
Which are the main global and regional SST modes associated with predictability at seasonal to interannual time-scales? How do they interact?
Is there any source of predictability associated with land surface anomalies (soil moisture, snow cover and thickness)? Which are the main physical processes involved?

These questions will be addressed through carefully designed sensitivity experiments and statistical analysis of the persistence of SST, soil moisture and snow mass anomalies in the core ENSEMBLES simulations as well as their relationships with large-scale climate modes. The coordinated sensitivity experiments include forced AGCM integrations with observed SSTs in some ocean basins and the climatology elsewhere. This will enable to separate the influence of the different ocean basins upon potential predictability of the main large-scale atmospheric modes.

The predictability associated with the different ocean basins will be quantified and the interaction between these different sources of predictability for the various timescales will be studied. Sources of predictability associated with land surface anomalies (soil moisture, snow cover and thickness) for both tropical and extra-tropical regions will be investigated. These studies will use coordinated sensitivity experiments in conjunction with the core multi-model ENSEMBLES simulations.

Deliverables:

- Improved assessments of the seasonal to interannual predictability associated with SST variability.
- Better understanding of the processes that impart predictability to the climate system from the land surface.
- Papers addressing:
  - Predictability associated with different ocean basins and the interaction between them
  - Land surface anomalies as a source of predictability

Task 4.4.b: Sources of atmospheric and oceanic predictability on decadal to multi-decadal timescales (predictability of the first and second kind, influence of both the initial and boundary conditions)

Is there any influence of initial oceanic conditions (in particular the state of the THC) upon predictions of natural climate variability at interannual to decadal time scales?
Do ocean initial conditions matter for climate change projections?
What is the influence of anthropogenic forcing upon the levels of predictability for the main natural modes of variability (ENSO, NAO, THC)?

The influence of the initial ocean state (for instance the phase of the thermohaline circulation) upon decadal predictability will be assessed through ensembles of coupled experiments having the same initial oceanic state and different atmospheric initial conditions. Greenhouse gas (GHG) integrations will also be conducted in order to quantify the relative roles of initial and boundary values. In particular, it will be analysed how stable the THC is and how sensitive it is to the initial conditions.

The influence of initial oceanic conditions upon predictions of natural climate variability (for both atmosphere and ocean) at interannual to decadal time scales will be investigated using the ENSEMBLES prediction system. In collaboration with RT2A, the sensitivity of the ENSEMBLES climate change predictions to initial conditions, particularly low-frequency ocean characteristics such as the state of the thermohaline circulation (THC) will be investigated. The influence of interactions between natural modes of variability and anthropogenic forcing (e.g. low-frequency modulation of the ENSO variability) on the levels of predictability will be assessed.

Deliverables:
- Improved estimates of the importance of ocean initial conditions on decadal and longer timescale predictions.
- First assessments of the effects of climate change on the predictability of the major modes of climate variability.
- Papers addressing:
  - Decadal predictability associated with ocean initial conditions
  - Influence of ocean initial conditions on climate change scenarios
  - Effect of climate change on predictability of natural modes of variability

Task 4.4.c: Exploring the role of the stratosphere in extra-tropical atmospheric predictability
Is there any influence of stratospheric circulation anomalies upon mid-to-high latitude climate variability and its predictability at various time scales?

This question will be addressed by comparing hindcast ensembles (including models with different parameterisations and different representation of the stratosphere as well as different forcings) to reanalysis data to determine the necessary elements in reproducing the change over the last four decades in the NH troposphere and stratosphere circulation regimes. The ENSEMBLES scenario integrations will be analysed for future changes in tropospheric as well as stratospheric regime shifts.

The vertical structure of tropospheric and stratospheric weather/climate regimes and their use in prediction studies of mid-to-high latitude climate variability at various timescales will be investigated through a combination of reanalysis and model studies. The sources of predictability associated with stratospheric circulation anomalies (such as a strong or weak vortex) and their links to extremes in the underlying annular modes such as the Northern Annular Mode (NAM) or the Southern Annular Mode (SAM) will be studied.

Deliverables:

- Improved understanding of the role of the stratosphere in climate variability and predictability
- Assessment of the potential shifts in stratospheric regimes under climate change and their influence on the troposphere.
- Papers addressing:
    - Relationship between tropospheric and stratospheric weather and climate regimes and implications for predictability.
    - Influence of climate change on stratospheric regimes and their links with the troposphere.