REGIONAL MODELING AND EXTREMES

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INTRODUCTION

As a consequence of computer constraints on horizontal resolution in climate models, atmospheric models dedicated to costly experiments like anthropogenic scenarios have kept the same horizontal mesh size (between 200 and 300 km) over the last 20 years, despite the huge increase in computer power. However, there is strong demand in terms of local climate, since the taxpayers who support research activities are experiencing this climate, rather than general atmospheric circulation around the globe. In the early 1990s, specific models emerged, with a limited area or variable mesh, aimed at studying the issue of regional climate sensitivity over a particular region, ignoring what occurs over 90% of the earth. With increasing concern about extreme meteorological events, due to increased societal vulnerability as well as greater mass media coverage, the issue of extremes has been associated with that of local scales. Extreme phenomena exist in low resolution simulations, but their bulky spatial distribution makes them less credible than those simulated by regional models.

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Météo-France and the IPSL share the same numerical approach to regional modeling, namely variable resolution global modeling. This prevents their simulations from depending on another global simulation. The choice of algorithms and parameterizations of the respective models (ARPEGE and LMDZ) means they stand out somewhat in the European modeling landscape, where many regional models stem from a common ancestor, or from hybridizing two existing models. In the last five years, several simulations have been performed at both Météo-France and the IPSL, based on the IPCC 3rd assessment report or associated global coupled simulations. A large part of this chapter is devoted to their results. Simulations related to the 4th assessment report, in the framework of ESCRIME, only started in 2006. We shall mention here only preliminary results and perspectives.

MODELS

The ARPEGE-Climate model used at Météo-France is derived from the short-range operational forecast model. Both models provide the possibility of varying the mesh size between a pole of interest and its antipodes on the sphere (Déqué and Piedelievre, 1995). In the climate version, resolution varies between 50 km in the central Mediterranean Sea and 450 km in the southern Pacific. This ensures a resolution of at least 60 km over France. Vertical discretization is based on 31 terrain-following layers with variable depth. The time step is 30 min. The version used in the experiments conducted between 2001 and 2006 is version 3 (Gibelin and Déqué, 2003). Version 4, launched in 2003, offers no radical changes in physical parameterizations. Its novelty lies in the ARPEGE cycle (24 compared to 18 for version 3), some bug fixes, and a new grid with twice the number of grid points due to a lesser grid stretching. Simulations using sea surface temperatures (SST) from the IPCC-AR4 ocean-atmosphere coupled runs started in 2006.

The LMDZ model is also a variable mesh global general circulation model (Li, 1999). The version used in the IMFREX project is LMDZ3.3; this version is also used as a component of the IPSL global coupled system. A factor 2 zoom is applied to get a spatial resolution of about 160 km in France. The physical parameterizations include the Emanuel scheme for convection and ORCHIDEE for soil processes. An improved cloud scheme has recently been added.

FEDERATIVE PROJECTS

To avoid returning to the prehistory of regional modeling, we can mention the PRUDENCE project (http://prudence.dmi.dk/, see also Déqué et al., 2005, 2006), coordinated by the Danish Meteorological Institute. In this project, 10 regional models (Denmark, United Kingdom, France, Germany -2-, the Netherlands, Sweden, Switzerland, Italy and Spain) have simulated the response over Europe to the A2 scenario for 2071-2100 in relation to 1961-1990. SST forcing (and lateral boundary conditions for models other than ARPEGE) were provided by a simulation by the Hadley Center Model used in the IPCC-TAR. Regional models had a 50 km resolution. The focus of this project was societal impacts in various fields (agriculture, hydrology, economy) and the evaluation of uncertainties. Some models (including ARPEGE) have thus run another scenario (B2), another SST/lateral forcing, and other initial atmospheric conditions. It has been shown that the main source of spread, and therefore of uncertainty, came from the forcing. The ENSEMBLES project (2004-2009, http://www.ensembles-eu.org/) coordinated by the Met Office continues in this direction with an increased 25 km resolution (which has led Météo-France to replace ARPEGE by the ALADIN limited area model), adding new models (Norway and Czech Republic). ENSEMBLES attempts to attribute weights to the different simulations, using the climatic skill of simulations driven by 1958-2001 reanalysis (ERA40). ENSEMBLES regional scenarios are driven by IPCC-AR4 simulations.

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Studying extreme phenomena is one of the goals of PRUDENCE and ENSEMBLES, but this question was specifically addressed by the STARDEX project (http://www.cru.uea.ac.uk/projects/stardex/) coordinated by the University of East Anglia. In this project, a large number of indices for evaluating the intensity or frequency of climate extremes have been defined. These indices have been applied to 20th century climate datasets. The MICE project (http://www.cru.uea.ac.uk/cru/projects/mice/) also coordinated by the University of East Anglia has completed the study by analyzing extremes in IPCC-TAR low resolution scenarios. At the French level, the GICC IMFREX project (http://medias.cnrs.fr/imfrex) has focused on France and regional simulations with ARPEGE and LMDZ.

Most regional scenario studies are related to the atmosphere, but the GICC MEDWATER project (http://medias.cnrs.fr/medwater) has studied the response of a Mediterranean sea model to surface fluxes calculated by ARPEGE and LMDZ.

Here we have mentioned only completed or well-advanced projects. The projects that are just starting or about to start are described in the last section. There are also many projects (e.g. at the GICC) that use the results from the above-mentioned projects to a specific aim.

METHODS

The basis of regional studies is clearly a long model integration (10 to 30 years) possibly repeated (three members or more) under two conditions: the control (present climate) and the disturbance (possible future climate). The model response is the difference (not necessarily calculated by a simple subtraction) between the two cases.

In fact, using a regional model forced by observed conditions does not necessarily lead to sufficient accuracy at the local scale. Impact models (hydrology, biosphere) are sometimes highly sensitive to thresholds, and a modest departure between the control simulation and reality may lead to unacceptable results. Regional simulations must be followed by statistically-based correction and downscaling methods.

The first family of methods consists of using a transfer function between a physical variable as calculated by the model at a given time and place and a corresponding corrected variable. Déqué (2006) has studied a few simple methods from IMFREX results.

The second family consists of associating a given situation as a whole with a corresponding situation extracted from observation records. Here we no longer work with each variable independently. The notion of the weather regime (Sanchez-Gomez and Terray, 2005) means a change in climate can be characterized as a change in frequency, possibly associated with a modification of intra-regime variability (Boé et al., 2006). This approach has been used for impact studies on the river Seine's hydrology and on wind power potential at the end of the 21st century.

RESULTS

Due to the amount and diversity of results, the reader is invited to visit the above-mentioned Web sites. The response over France is a warming in all seasons, higher in summer than in winter. Winter precipitation decreases in the south and increases in the north. For the other three seasons, precipitation decreases everywhere. The response of strong winds is weak and relatively insignificant. There is an increase in summer droughts, in particular in the west. Less significant, an increase in high river run-off is seen in winter and spring.

Figure 1 shows the annual temperature increase over France

FIGURE 1 *Regional modeling of the ESCRIME-CNRM-A1B simulation with ARPEGE at variable resolution: average annual temperature over France (anomaly in Kelvin in relation to the 1961-1990 average).*

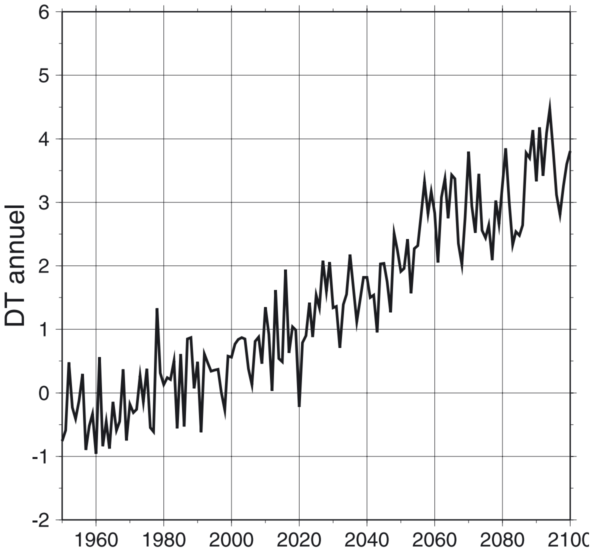
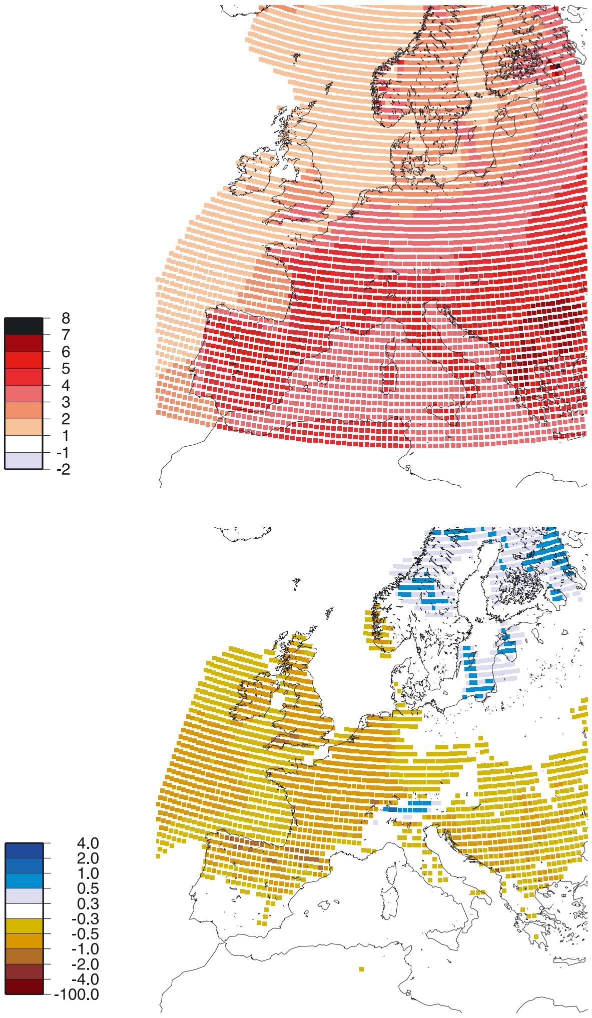


FIGURE 2 *Regional modeling of the ESCRIME-CNRM-A1B simulation over Europe with ARPEGE at variable resolution: response of temperature (a, K) and summer precipitation (b, mm/day) for 2071-2100 as compared to 1961-1990.*



in the A1B scenario (IPCC-AR4) with ARPEGE (regional climate version 4). Figure 2 shows the summer response over Europe for temperature and precipitation.

PERSPECTIVES

In the next few years, most numerical experiments carried out after the TAR will be updated by AR4 simulations (A1B, A2 and B1 scenarios). Building ensembles based on different sets of SSTs will allow a finer assessment of the frequency of extreme events. Until now the scenarios have concentrated on the late 21st century, in order to reduce the signal-to-noise problem due to natural variability. Faced with the urgent and understandable demand from society, modelers will now focus on the first half of the century, which is a more difficult exercise. The ENSEMBLES target period is 2020-2050, and projects like CECILIA or CIRCE (EU-FP6), REXHYSS (GICC), responses to the ANR's call for proposals, are also targeting this period. This implies performing ensemble simulations and abandoning the deterministic approach. Indeed, global averages at "short" climate range will be weak and of little interest for risk assessment. The spread of possible states is much more adapted, as Figure 1 suggests.

REFERENCES

- Boé J., L. Terray, F. Habets and E. Martin, 2006: A simple statistical-dynamical downscaling scheme based on weather types and conditional resampling. J. Geophys. Res., in press.
- Déqué, M., Jones, R.G., Wild, M., Giorgi, F., Christensen, J.H., Hassell, D.C., Vidale, P.L., Rockel, B., Jacob, D., Kjellström, E., de Castro, M., Kucharski, F., van den Hurk, B., 2005. Global high resolution versus Limited Area Model climate change projections over Europe: quantifying confidence level from PRUDENCE results. Clim. Dyn., 25, 653-670.
- Déqué, M., 2006: Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. Global and Planetary Change, in press.
- Déqué, M., Rowell, D.P., Lüthi, D., Giorgi, F., Christensen, J.H., Rockel, B., Jacob, D., Kjellström, E., Castro, M. ,van den Hurk, B., 2006. An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections. Climatic Change, in press.
- Gibelin, A.L., Déqué, M., 2003. Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. Clim. Dyn. 20, 327-339.
- Li, Z.X., 1999. Ensemble atmospheric GCM simulation of climate interannual variability from 1979 to 1994. J. of Climate, 12, 986-1001.
- Sanchez-Gomez, E. and L. Terray, 2005. Large-Scale Atmospheric Dynamics and Local Intense Precipitation Episodes. Geophys. Res. Letters, 32, L24711.

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RESPONSE OF THE WATER CYCLE TO ANTHROPOGENIC FORCINGS: WHAT HAVE WE LEARNT FROM THE LATEST IPCC SIMULATIONS?

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ABSTRACT

The purpose of this report is to make a brief assessment of the main studies that have been published since the Third Assessment Report of the IPCC about the hydrological response to anthropogenic climate change, and to describe the French contribution to this effort. This response is for many reasons much more difficult to predict than that of temperature. Beyond the unknowns related to the greenhouse gas emission scenarios, which mainly modulate the magnitude of the simulated anomalies, the global hydrological projections remain highly model-dependent. Such uncertainties are much more fundamental and problematic than those related to the forcings, since the response of one particular model cannot be inferred from the other models. In some cases, it is the very signs of the large-scale hydrological impacts that remain unknown. Uncertainties are, however, unevenly distributed. They are considerable as far as tropical precipitation is concerned, especially over West Africa. They are generally lower in the mid- and high latitudes, particularly over Europe, where most models predict a significant summer drying in the south and an increase in winter precipitation in the north. Globally speaking, hydrological contrasts are likely to increase in both space and time, which should lead to more frequent and severe floods and droughts. Nevertheless, many open questions remain about the very nature and regional distribution of the impacts, showing the need for better constraining the models' hydrological response. This urgent task is very difficult for two major reasons: 1) the large number and relative crudeness of the physical parameterizations that control the current state and the sensitivity of the water cycle, 2) the lack of convincing results about the detection of hydrological impacts due to observation inadequacies, to model deficiencies, to uncertainties in the anthropogenic forcings of the 20th century and to their potentially counteracting effects on precipitation.

GLOBAL RESPONSE

The long-term strengthening of the global water cycle in response to increasing amounts of greenhouse gases is no longer debatable. Models and observations indeed suggest that global warming is occurring at an almost constant relative humidity, i.e. with a strong increase in the lower tropospheric water vapor content. It must however be emphasized that this intensification is not associated with an acceleration of water vapor recycling, as has already been shown in previous CNRM climate scenarios (Douville et al., 2002). It is also remarkable that the increase in global precipitation has not yet been observed, due to the partial cover of the climatological network of rain gauges and to a decrease in tropical rainfall over land over the second half of the 20th century. This does not necessarily challenge the IPCC climate scenarios. On the one hand, the negative trend in tropical land precipitation is reasonably captured by some atmospheric GCMs, either forced by observed SSTs (Kumar et al., 2004) or coupled to an oceanic GCM and driven by observed concentrations of greenhouse gases (Wang and Lau, 2006). On the other hand, the relative agreement of coupled models in predicting an increase in global precipitation is only found at the end of the 20th century and disappears when focusing on land areas (Fig. 1). The main uncertainties that have been explored are those related to the parameterization of the direct and indirect effects of anthropogenic aerosols (Liepert et al., 2004, Ramanathan et al., 2006), to the spatial distribution of tropical

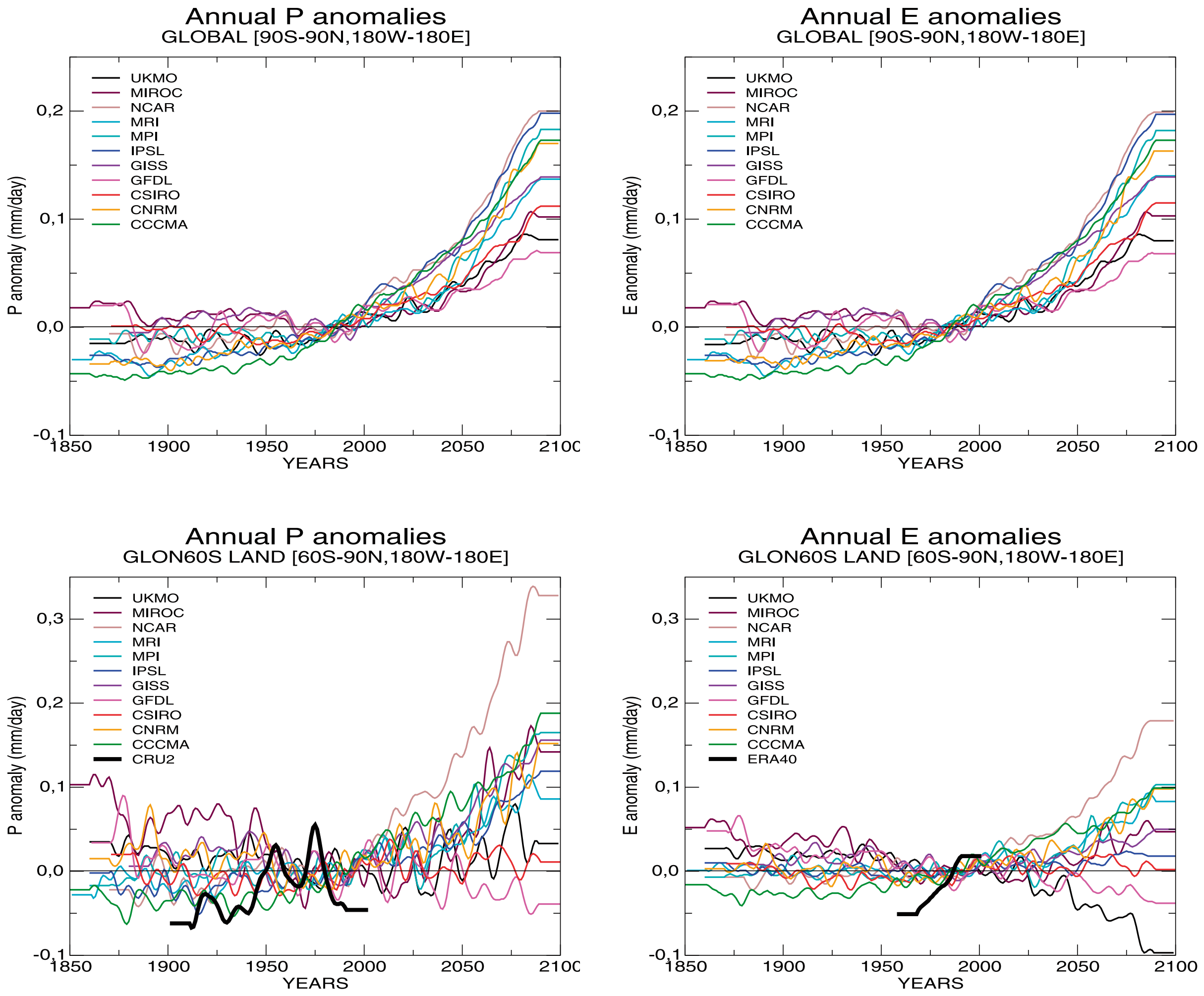
SSTs (Douville 2006a, Barsugli et al., 2006), and to the simulation of the teleconnections between precipitation and tropical SSTs (Douville et al., 2006, Joly et al., 2006).

The global evaporation response represents another open question. Most models predict higher surface ocean evaporation starting in the 20th century, but this trend is difficult to verify with the limited instrumental record (Liu and Curry, 2006). In contrast, the land response is highly model-dependent, not only as a result of the uncertainties in the precipitation anomalies, but also due to the implementation of new parameterizations in the models, such as the direct effect of atmospheric CO_2 on plant transpiration. By increasing their water use efficiency, this effect is supposed to limit the evapotranspiration of vegetated areas and has been shown to contribute to the increase in global continental runoff observed over the 20th century (Gedney et al., 2006). This result, however, relies on questionable observations and must therefore be considered with great caution. Another study, based on a multi-model ensemble of IPCC simulations, suggests on the contrary that the radiative effect of CO_2 is sufficient to explain the recent changes in the discharge of some of the world's main rivers, even if the detection of anthropogenic climate change was not thereby clearly demonstrated (Milly et al., 2005). Finally, as far as soil wetness is concerned, the climate scenarios are again highly model-dependent, but most of them suggest that greenhouse gas warming will cause a worldwide agricultural drought (Wang 2005).

In the face of such risks and uncertainties, it is urgent to think of methods to constrain the hydrological response of coupled GCMs in climate scenarios (Allen and Ingram, 2002). Paleoclimate simulations allow us to test the models' sensitivity to relatively strong external forcings. Such forcings are however quite different from those prescribed in the scenarios and the validation of such simulations is tricky due to the use of proxy observations. Detection-attribution studies are potentially more efficient, but the limited instrumental record available over the 20th century and the strong natural variability of precipitation are major obstacles. A recent study based on global and annual mean land precipitation shows that the anthropogenic signal is only detected in half of the selected models (Lambert et al., 2005). Model formulation appears to be more important for accurate precipitation simulation than the inclusion of a more complete set of forcings.

Beyond the comparison between observed and simulated

FIGURE 1 *Filtered anomalies (low-pass digital filter with a cut-off frequency at 10 years) of annual precipitation and evaporation in mm/day relative to 1971-2000 climatology in historical simulations and IPCC-AR4 A2 scenarios. Top: global averages. Bottom: global continental averages (excluding Antarctica). For information, changes in estimated continental precipitations based on CRU TS2.1 climatology are also plotted, along with the evolution of estimated continental evaporation based on ERA40 reanalyses (to be considered with great care).*



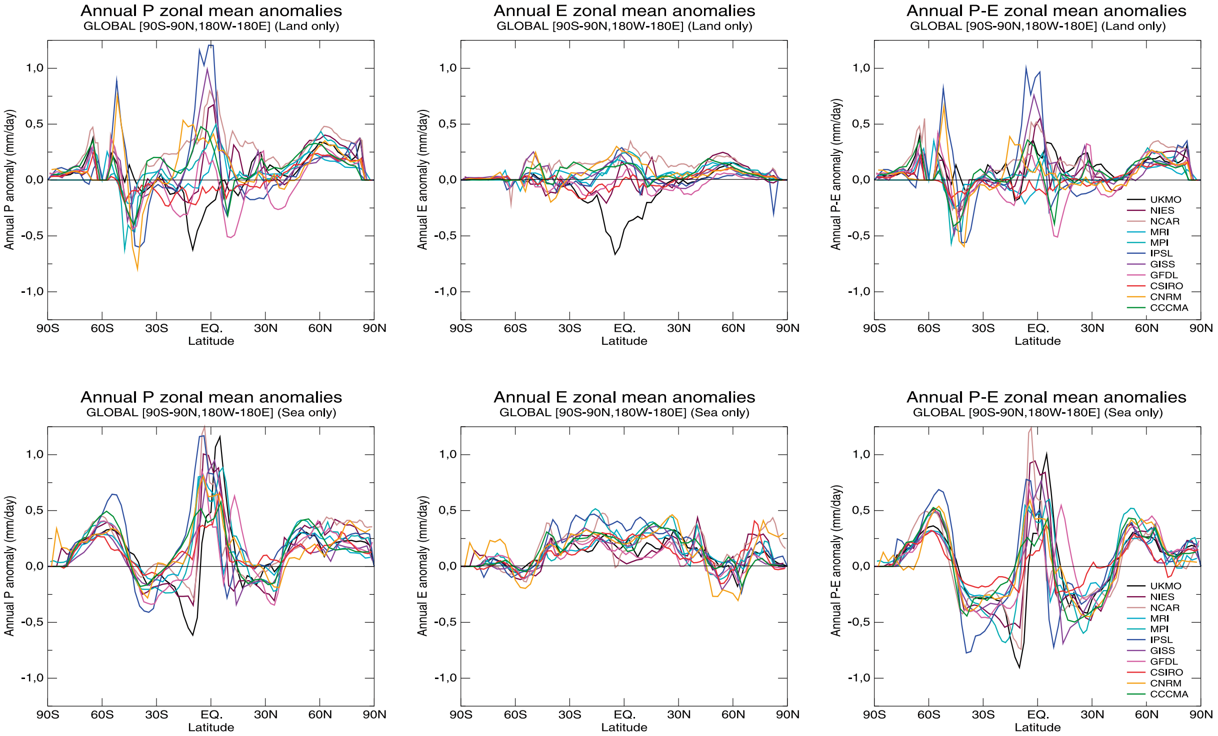
trends in hydrological variables, the validation of interannual variability appears as an interesting alternative to put the climate scenarios into perspective. Douville et al. (2006) show, for example, that the global precipitation-temperature relationships found at the interannual timescale have an apparent similarity with the hydrological model sensitivity to global warming. They suggest that ENSO, which dominates the natural variability of the global water cycle, could represent a useful surrogate for climate change to test the coupled GCMs. The study suggests that the most sensitive model, in terms of global land precipitation response over the 21st century, is an outlier. The method is however open to criticism since the ENSO-related SST anomalies show a much more heterogeneous spatial distribution than the 21st century climate scenarios. Douville et al. (2006) made an attempt to address this issue by stratifying the interannual anomalies according to their similarity with the tropical pattern of global warming. This original strategy is interesting, but remains inadequate for those models where climate change does not project onto the SST modes of interannual variability.

REGIONAL CONTRASTS AND TEMPORAL VARIABILITY

Zonally averaged (Fig. 2), the annual precipitation obtained in the SRES A2 climate scenarios performed for the IPCC-AR4 shows a relatively consistent model response (Douville et al., 2006): increased precipitation in the mid- and high latitudes related to a poleward shift of the storm tracks and of the associated precipitation maxima (Douville et al., 2002), decreased rainfall in the sub-tropics, and increased rainfall over the Inter-Tropical Convergence Zone. Over land, this zonal mean distribution of precipitation anomalies must however be tempered. There are also east-west contrasts and the multi-model spread is stronger. In the tropics, it is not only the magnitude but the very sign of the land anomalies that remains uncertain. In these regions, a large fraction of annual precipitation is related to the monsoon, especially over West Africa and South Asia. While the IPCC-AR4 scenarios generally show a weakening of these large-scale circulations, in keeping with former studies conducted at the CNRM (Douville et al., 2000b, Ashrit et al., 2003) and with some theoretical arguments (Held and Soden, 2006), monsoon precipitation does not necessarily decrease over the 21st century. Instead, it increases over South Asia, while the response is very uncertain over West Africa (Douville et al., 2006). Model deficiencies in simulating present-day monsoon climates are not the only reason for the model spread. Among the other factors, the influence of anthropogenic aerosols seems to be particularly relevant (Biasutti and Giannini, 2006, Held et al., 2006, Ramanathan et al., 2006), as well as the SST response of the tropical Pacific (Douville et al., 2006, Douville, 2006a), or to a lesser extent the potential biophysical feedbacks related to land surfaces (Douville et al., 2000a).

In the mid- and high latitudes, the precipitation response is less variable and shows an increase in annual mean accumulation (Douville et al., 2006). Model projections are particularly consistent over Europe, with a significant drying in the south and an increase in annual mean precipitation in the north, the boundary between these two regions being located between 45 and 50°N. Generally speaking, the regional precipitation

FIGURE 2 *Annual zonal mean anomalies for precipitation (P), evaporation (E) and moisture convergence (P-E) over land (top) and seas (bottom) in IPCC-AR4 A2 scenarios by comparing climatologies calculated over the last 30 years of the 20th and 21st centuries respectively.*



anomalies are more consistent in the IPCC-AR4 simulations than in the previous generation of climate scenarios (Giorgi and Bi, 2005). Changes in the surface water budget are however very uncertain. They depend not only on the projected precipitation anomalies, but also on the land surface modeling. For instance, the parameterization of the stomatal resistance of plants has a significant impact on the evapotranspiration response (Gedney et al., 2006), while the high-latitude runoff response is highly dependent on the permafrost modeling (Poutou et al., 2004). Moreover, in contrast with some GCM results and despite the significant surface warming observed over recent decades, there is no observational evidence of summer drying in the northern mid-latitudes (Robock et al., 2005) or of an increase in potential evaporation (Roderick and Farquhar, 2002) if one trusts the limited instrumental record available. Conversely, the gradual retreat of the northern hemisphere snow cover seen in post-1970 satellite measurements is captured by some models, as has already been highlighted in the former generation of CNRM climate scenarios (Douville et al., 2002).

Once again, detection-attribution studies represent a suitable tool for testing the models' sensitivity. Such studies are however preferentially conducted at a global scale. Some exceptions do exist, such as the ongoing efforts to detect hydrological anthropogenic impacts over West Africa, Europe or even France in the framework of the French DISCENDO project (http://www.cerfacs.fr/globc/Discendo). Such works can be complemented with detailed analyses aimed at understanding the main mechanisms that control the regional hydrological response in one particular climate scenario (Douville et al., 2002). In this respect, the most ambitious and original study is probably that of Rowell and Jones (2006) designed to partition some of the mechanisms of regional climate change in the case of the European summer drying found in the Hadley Center atmospheric GCM. By exploring the factors that contribute to the simulated precipitation anomalies, it is thus possible to make some assumptions about their robustness. The multi-model approach is another obvious methodology to reduce regional uncertainties through a probabilistic assessment of climate change, even if the metric to be used to define the models' reliability remains a matter of debate (Collins et al., 2005).

In addition to spatial heterogeneities, the hydrologic response of coupled GCMs to anthropogenic forcings also shows some temporal signatures. For instance, a strengthening of the annual cycle is found in the northern mid-latitude continents (Douville et al., 2002, Wang 2005), even if such a trend is difficult to detect in the observations (Robock et al., 2005). Many models also predict an increase in the interannual precipitation variability, particularly in the monsoon regions, as well as in the extrema of monthly precipitation in the mid- and high latitudes. Moreover, the analysis of daily model outputs indicates a possible increase in precipitation intensity, which has already been emphasized in the 20th century instrumental record over most extratropical land areas (Groisman et al., 2005, Klein Tank and Können, 2003). Such impacts are not surprising for those regions where seasonal precipitation is increased, given the asymmetric distribution of daily rainfall intensities. It would thus be interesting to distinguish the effect of changes in mean precipitation versus the effect of changes in the precipitation variance. We will not discuss here the impacts of anthropogenic forcings on extreme climate events, which are the focus of a specific chapter of this report. Note however that the anticipated strengthening of spatial and seasonal hydrological contrasts should lead to increasing probabilities of floods and droughts in many regions of the world. Note also that detection studies should take advantage of the ongoing analyses about daily precipitation intensities, since it has been suggested that changes in severe events could be more robust than changes in mean precipitation (Hegerl et al., 2004).

CONCLUSIONS

At present, about one third of the world's population lives in countries deemed to be "water-stressed". By strengthening the existing hydrological contrasts, in particular in precipitation distribution, global warming could make the situation even worse. However, climate change is only one of the drivers leading to changes in water resources and the evolution of the water demand related to demographic constraints is in many countries a much more serious concern (De Marsily et al., 2006). Moreover, even in the areas where annual precipitation is expected to increase, the increase in water resources is not warranted if rainfall is concentrated over a short season and if the storage capacity (dams) is not sufficient to take advantage of this excess precipitation. Therefore, the risk of more frequent and severe floods should not be underestimated, especially if the anticipated increase in precipitation intensity is confirmed.

The coordinated climate simulations performed for the IPCC Fourth Assessment Report represent an unprecedented effort by the scientific community to reach a consensus on the climatic consequences of recent and future anthropogenic forcings. This objective is however only partially achieved: the increasing number of models is useful in order to move towards a probabilistic approach to climate change, but favors the possibility of opposed model responses without providing any clear strategy to detect the outliers. Moreover, while the main hydrological impacts emphasized in the Third Assessment Report are confirmed by the IPCC-AR4 simulations (which is in itself a very encouraging result), the Fourth Report should not provide major new findings on this issue, except an evaluation of the climate change already underway and a much more detailed analysis of the impacts on climate variability and extreme events.

In summary, in spite (or because?) of the increasing complexity of the numerical tools, the hydrological impacts of global warming sometimes remain highly uncertain. Such uncertainties are however very unevenly distributed across the globe. The Mediterranean basin, for example, appears clearly as a very sensitive region, where water stress should increase dramatically. Many efforts will be necessary to go a step further in the localization and quantification of impacts. On the one hand, the large-scale atmospheric and oceanic response must be better defined as far as mean climate and climate variability are concerned. On the other hand, efficient downscaling tools must be developed to provide hydrological scenarios at a policy-relevant scale (see the related chapter in this report). In addition, the development of new satellite instruments aimed at monitoring various hydrological variables remains a priority for a better understanding of the evolution of the global water cycle and for constraining the models used in the climate scenarios.

Finally, it should be noted that the sensitivity of the water cycle is a central question among the many issues raised by anthropogenic climate change. It thus has obvious links with the other chapters of this report. Climate feedbacks related to the atmospheric branch of the water cycle, particularly to cloud cover, have been shown to contribute significantly to the spread in the projected global warming (Bony and Dufresne, 2005). The main modes of atmospheric variability (ENSO, NAO, etc.) have a major influence on the precipitation time series that have been observed over the 20th century in many regions of the world. Their response to global warming is therefore crucial to understanding and predicting that of the water cycle (Camberlin et al., 2004, Terray et al., 2004, Douville et al., 2006). In addition, the coupling between the water cycle and the carbon cycle also seems to be a major issue, both for simulating the variability of the CO_2 emissions (Ciais et al., 2005) or that of the continental water budget (Gedney et al., 2006). Finally, as far as detection-attribution studies are concerned, the strong natural variability of precipitation and its ambiguous response in the climate scenarios are a major obstacle for detecting an anthropogenic signal in the surface temperature time series at the regional scale. An empirical solution to this problem has however been proposed, consisting in taking advantage of the temperature-precipitation link at the interannual timescale to derive "corrections" in the temperature trends (Douville, 2006b). ■■■

REFERENCES

- Allen M.R. and W.J. Ingram (2002) Constraints on future changes in the hydrological cycle. *Nature*, 419, 224-228.
- Ashrit R.G., H. Douville, K. Rupa Kumar (2003) Response of the Indian Monsoon and ENSO-monsoon teleconnection to Enhanced Greenhouse Effect in the CNRM Coupled Model. *J. Meteorol. Soc. Japan*, 81, 779-803.
- Barsugli J.J., S-I. Shin, P.D. Sardeshmukh (2006) Sensitivity of global warming to the pattern of tropical ocean warming. *Climate Dyn.*, 27, 483-492.
- Biasutti M. and A. Giannini (2006) Robust Sahel drying in response to late 20th century forcings. *Geophys. Res. Letters,* 33, L11706, DOI :10.1029/2006GL026067.
- Bony S. and J-L. Dufresne (2005) Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. *Geophys. Res. Letters,* 32, L20806, DOI :10.1029/2005GL023851.
- Camberlin P., F. Chauvin, H. Douville, Y. Zhao (2004) Simulated ENSO-tropical rainfall teleconnections and their changes under enhanced greenhouse gases conditions. *Climate Dyn.,* 23, 641-657.
- Ciais P. and co-authors (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, 437, 529-533.
- Collins M. and the CMIP Modelling Groups (2005) El Niño- or La Nina-like climate change? *Climate Dyn.*, 24, 89-104.
- De Marsily G. et al. (2006) « Les Eaux Continentales ». Rapport sur la Science et la Technologie, Académie des Sciences, Editions Tech. & Doc.
- Douville H., Planton S., Royer J-F., Stephenson D.B., Tyteca S., Kergoat L., Lafont S., Betts R.A. (2000a): Importance of vegetation feedbacks in doubled-CO_2 time-slice experiments. *J. Geophys. Res.*, 105:14841-14861.
- Douville H., J-F. Royer, D.B. Stephenson, S.Tyteca, J. Polcher, P. Cox, N. Gedney, P. Valdes (2000b): Impact of CO_2 doubling on the Asian summer monsoon: robust versus model-dependent responses. *J. Meteorol. Soc. Japan*, 78, 421-439.
- Douville H., F. Chauvin, S. Planton, J-F. Royer, D. Salas-Mélia, S. Tyteca (2002) Sensitivity of the hydrological cycle to increasing amounts of greenhouse gases and aerosols. *Climate Dyn.*, 20, 45-68, DOI:10.1007/s00382-002-0259-3.
- Douville H. (2006a) Impact of regional SST anomalies on the Indian monsoon response to global warming in the CNRM climate model. *J. Climate,* **19**, 2008-2024.
- Douville H. (2006b) Detection-attribution of global warming at the regional scale: How to deal with precipitation variability? *Geophys. Res. Letters,* 33, L02701, DOI :10.1029/2005GL024967.
- Douville H., D. Salas-Mélia, S. Tyteca (2006) On the tropical origin of uncertainties in the global land precipitation response to global warming. *Climate Dyn.*, 26, 367-385, DOI:10.1007/s00382-005-0088-2.
- Gedney N., P.M. Cox, R.A. Betts, O. Boucher, C. Huntingford, P.A. Stott (2006) Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, 439, 835-838, DOI:10.1038/nature04504.
- Giorgi F. and X. Bi (2005) Updated regional precipitation and temperature changes for the 21st century from ensembles of recent AOGCM simulations. *Geophys. Res. Letters,* 32, L21715, DOI :10.1029/2005GL024288.
- Groisman P.Y., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, V.N. Razuvaev (2005) Trends in intense precipitation in the climate record. *J. Climate*, 18, 1326-1350.
- Hegerl G.C., Zwiers F.W., Stott P.A., Kharin V.V. (2004) Detectability of anthropogenic changes in annual temperature and precipitation extremes. *J. Climate*, 17, 3683-3700.
- Held I. and B.J. Soden (2006) Robust responses of the hydrological cycle to global warming. *J. Climate* (in press).
- Held I., T.L. Delworth, J. Lu, K.L. Findell, T.R. Knutson (2006) Simulation of Sahel drought in the 20th and 21st centuries. *PNAS*, 102, 17891-17896.
- Joly M., A. Voldoire, H. Douville, P. Terray, J-F. Royer (2006) African monsoon teleconnections with tropical SSTs in a set of IPCC-AR4 coupled models. *Climate Dyn.* (revised).
- Klein Tank A.M.G. and G.P. Können (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946-99. *J. Climate*, 16, 3665-3680.
- Kumar A., F. Yang, L. Goddard, S. Schubert (2004) Differing trends in the tropical surface temperatures and precipitation over land and oceans. *J. Climate*, 17, 653-664.
- Lambert F.H., N.P. Gillett, D.A. Stone, C. Huntingford (2005) Attribution studies of observed land precipitation changes with nine coupled models. *Geophys. Res. Letters,* 32, L18704, DOI :10.1029/2005GL023654.
- Liepert B.G., J. Feichter, U. Lohmann, E. Roeckner (2004) Can aerosols spin down the water cycle in a warmer and moister world? *Geophys. Res. Letters,* 31, L06207, DOI :10.1029/2003GL019060.
- Liu J. and J.A. Curry (2006) Variability of the tropical and subtropical ocean surface latent heat flux during 1989-2000. *Geophys. Res. Letters,* 33, L05706, DOI :10.1029/2005GL024809.
- Milly P.C.D., K.A. Dunne, A.V. Vecchia (2006) Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, 438, 347-350, DOI:10.1038/nature04312.
- Poutou E., G. Krinner, C. Genthon, N. De Noblet (2004) Role of soil freezing in future boreal climate change. *Climate Dyn.*, 23, 621-639.
- Ramanathan V., C. Chung, D. Kim, T. Bettge, J.T. Kiehl, W.M. Washington, Q. Fu, D.R. Sikka, M. Wild (2006) Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *PNAS*, 102, 5326-53333.
- Robock A., M. Mu, K. Vinnikov, I.V. Trofimova, T.I. Adamenko (2005) Forty-five years of observed soil moisture in the Ukraine: No summer dessication (yet). *Geophys. Res. Letters,* 32, L03401, DOI :10.1029/2004GL021914.
- Roderick M.L. and G.D. Farquhar (2002) The cause of decreased pan evaporation over the past 50 years. *Science*, 298, 1410-1411.
- Rowell D.P. and R.G. Jones (2006) Causes and uncertainty of future summer drying over Europe. *Climate Dyn.*, 27, 281-299, DOI:10.1007/s00382-006-0125-9.
- Terray L., M.E. Demory, M. Déqué, G. de Coetlogon, E. Maisonnave (2004) Simulation of the late twenty-first century changes in wintertime atmospheric circulation over Europe due to anthropogenic causes. *J. Climate*, 17, 4630-4635.
- Wang G. (2005) Agricultural drought in a future climate: results from 15 global climate models participating in the IPCC 4th Assessment. *Climate Dyn.*, 25, 739-753, DOI:10.1007/s00382-005-0057-9.
- Wang H. and K.M. Lau (2006) Atmospheric hydrological cycle in the tropics in twentieth century coupled climate simulations. *Int. J. Climatol.*, DOI : 10.1002/joc.1279.

POLAR REGIONS, CRYOSPHERE AND THERMOHALINE CIRCULATION

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POLAR REGIONS: A PART OF THE GLOBAL CLIMATE SYSTEM

A highly sensitive part of the climate system

High latitudes in both hemispheres hold most of the marine and land cryosphere (sea ice, snow, ice sheets and glaciers) and are, along with the Mediterranean Sea, the only region on earth where ocean convection occurs. This convection drives the global thermohaline circulation, also known as the 'conveyor belt'.

The global climate is currently warming up (0.6±0.2°C over the 20th century, IPCC, 2001), and in this context high northern latitudes are warming up even more rapidly: observed trends are as high as 1° per decade during the 1976-2000 period over a large part of Siberia, northern Canada and Alaska. This marked trend in continental areas can be partly explained by the retreat of land surface snow cover. However, IPCC-AR4 models do not fully reproduce this snow trend (Roesch, 2006).

Climate warming also took place from the early 1920s, but it was confined to the northern hemisphere. It peaked at a global average of about 0.5° during the 1930s and 1940s, but meanwhile the Arctic had experienced a warming of 1.7°C, which can be partly attributed to positive climate feedbacks involving sea ice (Bengtsson et al., 2004). However, this amplification of global warming was not observed in the Antarctic during the 20th century, except in the Antarctic Peninsula area.

Simulations of the 21st century (IPCC, 2001) also showed an amplification of global warming in the Arctic, which is less intense in the Antarctic. In the framework of CMIP2 (Coupled Models Intercomparison Project 2), CO_2 doubling experiments indicate that the warming of the Arctic is amplified by a factor of 1.5 to 4.5 compared to average global warming (Holland and Bitz, 2003). This amplification is essentially due to a sea ice albedo feedback, but the relatively large spread can be attributed to the initial sea ice cover and the diverse cloud responses, whereas land snow and ice sheets only play a secondary role. Furthermore, paleoclimatological simulations of the Last Glacial Maximum (LGM, 21000 years BP) carried out in the framework of PMIP2 (Paleoclimatological Models Intercomparison Project 2) indicate that the warming between the LGM and the preindustrial climate is amplified in polar regions compared to the magnitude of the simulated global warming over the same period (Masson-Delmotte et al., 2006), and that the correlation between the simulated temperature in polar regions and the average global temperature is high, hence confirming that temperature time series computed from ice-core measurements are good indicators of certain global climate variations.

Climate couplings involving sea ice

The sea ice cover in both hemispheres is characterized by a strong interannual variability, as a response to atmospheric and ocean forcings. Since 1972, satellites provide reliable sea ice extension data. These observations show that during the 1972-2002 period, no trend for the total surface of sea ice could be detected in the Antarctic, whereas over the same period, the extension of Arctic sea ice decreased by 0.9×10^6 km^2 (Cavalieri, 2003). This sea ice retreat has accelerated since the end of the 1990s, particularly during the summer (Stroeve et al., 2005). Positive feedbacks involving sea ice were highlighted by means of observations and modeling. For example, during the summer, the sea ice pack is looser as lots of open water areas appear. These leads have a low albedo and absorb a large part of the incoming solar shortwave radiation and warm up, enhancing the lateral melting of ice slabs and causing the open water fraction to increase further (Maykut and Perovich, 1987). Curry et al. (1995) have also documented other positive feedbacks. For example, sea ice albedo depends on the thickness of the considered slab, its deformation through dynamical processes and the nature of its surface (snow slab, meltwater ponds, etc.). In the same study it is stressed that the simulation of sea ice cannot be validated only by comparing modeled and observed thicknesses for the end of the 20th century, for example: it is also important to check that the sensitivity of modeled ice thickness to external climate forcings is correct, especially if the model is aimed at carrying out climate change simulations for the 21st century. Other papers suggest feedback mechanisms connecting the Arctic and the North Atlantic (Goosse et al., 2002, Goosse and Holland, 2005).

Climate coupling involving ice sheets and glaciers

The average sea level rose by 37 mm during the 1993-2005 period (Nerem et al., 2006), 40% of this variation being explained by the melting of glaciers and ice sheets. Moreover, a recent study shows that the flows of some major glaciers draining the Greenland ice sheet are accelerating, suggesting that their contribution to 21st century sea level rise may be currently underestimated (Rignot and Kanagaratnam, 2006). Based on both modeling and altimetry, there is increasing evidence that the Greenland mass balance has been significantly negative over the last decade (Krabill et al., 2004; Schutz et al., 2005; Zwally et al., 2005). This additional water input to the ocean might reduce the deep ocean convection in the Labrador Sea, slowing down the thermohaline circulation.

CRYOSPHERE AND THERMOHALINE CIRCULATION: PROJECTIONS FOR THE 21ST CENTURY

In this part, an overview is given of the different components of the cryosphere as modeled for IPCC-AR4. In general, such models are compared to observations spanning the last decades of the 20th century, and are also used to carry out projections indicating how the cryosphere may be affected by climate change.

Sea ice cover projections

Among the 20 sea ice models used in the framework of the most recent IPCC simulations, 11 consider a vertical discretization of sea ice slabs, 7 include an ice thickness distribution and 17 use advanced sea ice dynamics, which represents a significant improvement compared to IPCC-AR3 (IPCC, 2001). Even if the simulation of sea ice cover strongly depends on atmospheric and oceanic forcing, modeled sea ice covers in both hemispheres for 1981-2000 are clearly more realistic in IPCC-AR4 than in AR3, even if some significant biases are still present, particularly in the Antarctic (Arzel et al., 2006a). However, even if observations are still relatively sparse, it is very likely that the modeled thickness of sea ice during the same period is generally rather incorrect, in terms of geographical distribution or hemispheric average thickness. Hence, if many IPCC-AR4 models simulate a late summer ice-free Arctic Ocean during the second half of the 21st century (Arzel et al., 2006a), the decade when this might happen for the first time is highly uncertain. Finally, models seem to agree that in the Arctic, the annual average sea ice volume should decrease twice as rapidly as the average surface of the ice cover (Table 1).

TABLE 1 *Multi-model average of relative changes (%) in sea ice extent and volume between 2081-2100 and 1981-2000 for March, September and annual mean (AM) in both hemispheres.*

	Arctic			Antarctic		
	March	Sept.	AM	March	Sept.	AM
Sea ice thickness	-15.4	-61.7	-27.7	-49	-19.1	-24
Sea ice volume	-47.8	-78.9	-58.8	-58.1	-27.4	-33.7

A sea ice decline, initiated by anthropogenic climate change, could trigger a change in the climate regime, as observed in the IPCC-AR4/SRES-A1B simulation performed with the IPSL-CM4 model. In this experiment, the ocean outflow at Fram Strait, which is an important source of fresh water for the North Atlantic, undergoes a rapid and strong transition from a weak state towards a relatively strong state during the 1990-2010 period (Fig. 1). Arzel et al. (2006b) propose that a positive feedback in the atmosphere-sea ice-ocean system in the GIN-Barents Seas sector, initiated by the retreat of the sea ice in the Barents Sea as a result of the long-term warming of

FIGURE 1 *The time series of ocean outflow (left) and liquid freshwater export at Fram Strait (right), as simulated by IPSL-CM4, in Sverdrups (1Sv=$10^6 m^3/s$). The thin and bold lines respectively denote the pre-industrial experiment and the experiment covering the 20th century followed by an SRES-A1B scenario during the 21st century.*

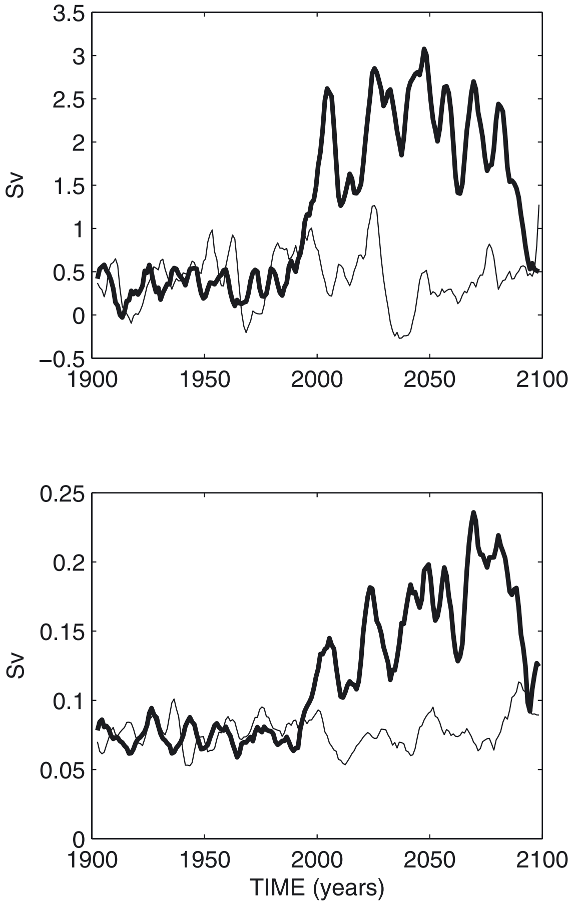
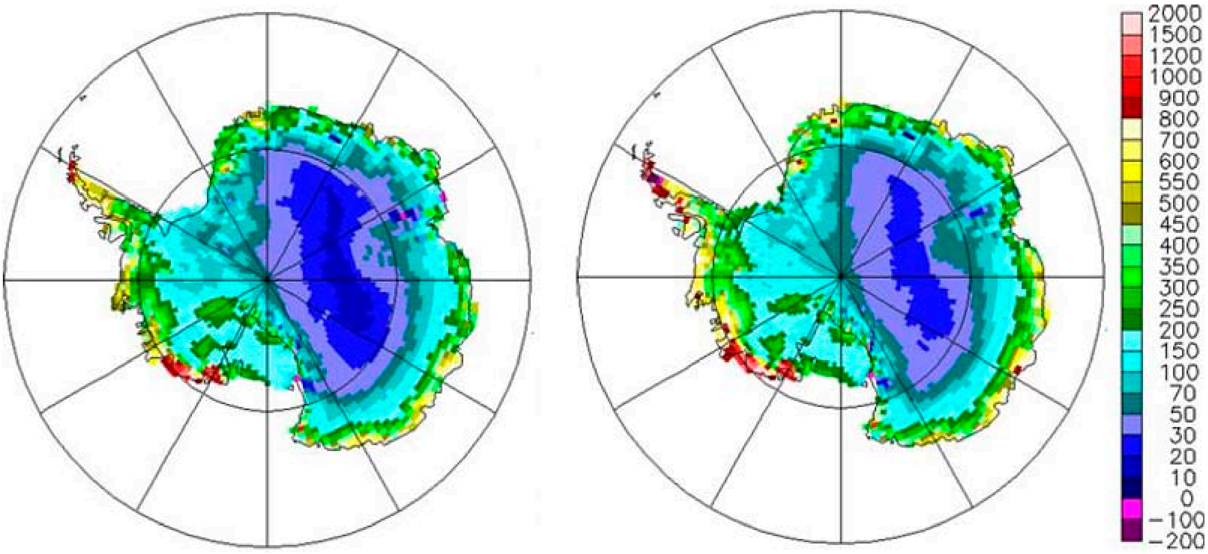


FIGURE 2 *Simulated surface mass balance for the Antarctic ice sheet (kg/m^2/an): 1981-2000 (left) and 2081-2100 (right), in the case of an SRES-A1B scenario.*



the Arctic climate during the late 20th century, is responsible for this behavior. Around the year 2080, the model predicts a second transition threshold beyond which the Fram Strait outflow is restored towards its original weak value. The long-term freshening of the GIN Seas is invoked to explain this rapid transition.

Ice sheets and glaciers mass balance projections

The change in the surface mass balance of the Antarctic ice sheet and its impact on the sea level was estimated for the end of the 21st century by regionalizing two IPSL-CM4 large-scale climate simulations with a 60 km resolution zoomed version of IPSL-CM4. These simulations respectively use boundary conditions provided by IPSL-CM4 for 1981-2000 and 2081-2100, and indicate that the Antarctic annual mass balance may increase by 32 mm water equivalent per year between the two selected periods, corresponding to a sea level decrease of 1.2 mm/year (Krinner et al., 2006a). Two more experiments were conducted, but contrary to previous simulations, in which sea surface boundary conditions produced by IPSL-CM4 were directly used, an anomaly method was preferred. The present-day simulations use observed sea surface conditions, while the simulations for the end of the 21st century use the change in sea surface conditions produced by the coupled simulations added to the present-day observations (Krinner et al., 2006b). It is shown that the use of observed oceanic boundary conditions clearly improves the simulation of the present-day Antarctic climate, compared to model runs using boundary conditions from a coupled climate model. Using this method, the simulated mean surface mass balance change over the grounded ice sheet from 1981-2000 to 2081-2100 is 43 mm water equivalent per year, which is equivalent to a eustatic sea-level decrease of 1.5 mm/year. This surface mass balance increase is largely due to precipitation changes, while changes in snow melt and turbulent latent surface fluxes are weak. The temperature increase leads to an enhanced moisture transport towards the interior of the continent because of the higher moisture-holding capacity of warmer air, but changes in atmospheric dynamics, in particular off the Antarctic coast, regionally modulate this signal.

A spatially-distributed snow and ice model simulating the surface mass balance of the Saint Sorlin Glacier (French Alps) over the 1981-2004 period was validated against *in situ* observational data (Gerbaux, 2005). The modeled mass balance globally reproduces field data, except over poorly-monitored areas where its specific pattern locally deviates from measurements extrapolated over too large distances. The same approach was then applied to simulate the glacier response during the 21st century, using forcing fields provided by several IPCC-AR4 SRES-B1 model simulations. The simulation shows a rapid decay of the glacier, and its total disappearance by the year 2070.

North Atlantic deep ocean convection and meridional ocean circulation changes

Twenty-first century simulations were performed by different models following SRES-A1B and suggest the North Atlantic Meridional Circulation may slow down by 0 to 50% (Schmittner et al., 2005). None of these simulations indicate that this circulation might collapse, a conclusion shared by Gregory et al. (2005) from the analysis of a set of experiments of a 1% per year increase in atmospheric CO_2 concentration to quadrupling level (4xCO_2). According to this study, changes in thermohaline circulation are mostly due to ocean surface heat fluxes rather than water flux changes. However, the models used in this work all neglect the impact of Greenland ice cap melting on the water flux. Hence two 4xCO_2 simulations were carried out with the IPSL-CM4 model (Swingedouw et al., 2006). The first one is the same as in Gregory et al. (2005), and in the second one, the water flux due to the melting of the Greenland ice sheet was modeled in an idealized way. In these experiments, the intensity of the thermohaline circulation index decreases by 21% and 47% respectively compared to present day conditions. In the latter case, the simulated surface temperature is up to 5 degrees colder in the Kara Sea than in the simulation with the effect of Greenland ice sheet melting.

The IPCC-AR4 climate simulations performed with CNRM-CM3 were also analyzed, showing that the thermohaline circulation index decreases by 8% over the 20th century. This trend can be explained by a marked freshening of the Labrador and Irminger Seas, causing a weakening of ocean deep convection in these regions. These changes in water mass characteristics are similar to those involved during the Great Salinity Anomaly. A significant melting of sea ice causes a freshening of the superficial ocean. This low-salinity water is advected through the Denmark Strait and spreads into the Irminger and Labrador Seas. This transport is due to the average current, but can also be partly attributed to the surface atmospheric circulation and induced surface ocean current anomalies. During the 21st century, the intensity of the thermohaline circulation decreases by about 40%, the differences between the scenarios depending on the level of warming in the North Atlantic. This considerable weakening of the Atlantic meridional overturning circulation is essentially due to a positive feedback involving a strengthening of the East-Greenland Current in response to an intensification of the Norwegian Current (Guemas and Salas-Mélia, 2006).

REFERENCES

- Arzel, O., T. Fichefet and H. Goosse (2006a) Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs. *Ocean Modelling*, **12**, 401-415. doi: 10.1016/j.ocemod.2005.08.002
- Arzel, O., T. Fichefet, H. Goosse and J.-L. Dufresne (2006b) Causes and impacts of Arctic freshwater budget changes over the 20th and 21st centuries in an AOGCM. *Climate Dynamics,* submitted.
- Bengtsson, L., V.A. Semenov and O.M. Johannessen (2004) The Early Twentieth-Century Warming in the Arctic - a Possible Mechanism. *J. Climate*, 17, 4045-4057.
- Cavalieri, D.J., C.L. Parkinson and K.Y. Vinnikov (2003) 30-year satellite record reveals contrasting Arctic and Antarctic decadal sea ice variability. *Geophys. Res. Lett.*, 30 (18). doi:10.1029/2003GL018931.
- Curry, J.A., J.L. Schramm and E.E. Ebert (1995) Sea Ice-Albedo Climate Feedback Mechanism. *J. Climate* 8, 240-247.
- Gerbaux, M. (2005) Reconstruction du bilan de masse des glaciers alpins et impact d'un changement climatique (in French). PhD, J. Fourier University, Grenoble, France, 132pp. http://lgge.obs.ujf-grenoble.fr/publiscience/theses/these-gerbaux.pdf).
- Goosse H., F.M. Selten, R. J. Haarsma and J.D. Opsteegh, 2002. A mechanism of decadal variability of the sea-ice volume in the Northern Hemisphere. Climate Dynamics 19, 61-83, DOI: 10.1007/s00382-001-0209-5
- Goosse, H. and M. Holland (2005) Mechanisms of decadal and interdecadal Arctic variability in the Community Climate System Model CCSM2. *J. Climate* 18, 3552-3570.
- J.M. Gregory, K.W. Dixon, R.J. Stouffer, A.J. Weaver, E. Driesschaert, M. Eby, T. Fichefet, H. Hasumi, A. Hu, J.H. Jungclaus, I.V. Kamenkovich, A. Levermann, M. Montoya, S. Murakami, S. Nawrath, A. Oka, A.P. Sokolov and R.B. Thorpe (2005) A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration. *Geophys. Res. Lett.*, 32, L12703, doi:10.1029/2005GL023209.
- Guemas, V. and D. Salas-Mélia (2006) Variability of the Atlantic Meridional Overturning Circulation in an Atmosphere-Ocean Global Coupled Model. *Ocean Modelling*, submitted.
- Holland, M.M. and C.M. Bitz (2003) Polar amplification in climate changes in coupled models. *Climate Dyn*, 21, 221-232.
- Intergovernmental Panel on Climate Change (2001). Climate Change 2001 (J.T. Houghton et al., Eds.), Cambridge Univ. Press, New York.
- Krabill, W., et al. (2004). Greenland ice sheet: increased coastal thinning. *Geophys. Res. Lett.*, 31(L24402): doi:10.1029/2004GLO21533.
- Krinner, G., O. Magand, I. Simmonds, C. Genthon and J. L. Dufresne (2006) Simulated Antarctic precipitation and surface mass balance at the end of the 20th and 21st centuries. *Climate Dyn*. doi:10.1007/s00382-006-0177-x.
- Krinner, G., B. Guicherd, K. Ox and C. Genthon (2006) Simulations of Antarctic climate and surface mass balance change from 1981-2000 to 2081-2100. *J. Climate*, submitted.
- Masson-Delmotte, V., M. Kageyama, P. Braconnot, S. Charbit, G. Krinner, C. Ritz, E. Guilyardi, J. Jouzel, A. Abe-Ouchi, M. Crucifix, R. M. Gladstone, C. D. Hewitt, A. Kitoh, A. N. LeGrande, O. Marti, U. Merkel, T. Motoi, R. Ohgaito, B. Otto-Bliesner, W. R. Peltier, I. Ross, P. J. Valdes, G. Vettoretti, S. L. Weber, F. Wolk and Y. Yu (2006) Past and future polar amplification of climate change: climate model intercomparisons and ice-core constraints. *Climate Dyn.* 26, 513-529. doi: 10.1007/s00382-005-0081-9
- Maykut, G. and D.K. Perovich (1987) The role of shortwave radiation in the summer decay of a sea ice cover. *J. Geophys. Res.* 92, C7, 7032-7044.
- Nerem, R.S., E. Leuliette and A. Cazenave (2006) Present-day sea level change, *C.R. Geosciences*. doi:10.1016/j.crte.2006.09.001.
- Rignot, E. and P. Kanagaratnam (2006) Changes in the velocity structure of the Greenland ice sheet. *Science*, 311, 986-990.
- Roesch, A. (2006) Evaluation of surface albedo and snow cover in AR4 coupled climate models. *J. Geophys. Res.* 111, D15111, doi: 10.1029/2005JD006473.
- Schmittner, A., M. Latif and B. Schneider (2005) Model projections of the North Atlantic thermohaline circulation for the 21st century assessed by observations. *Geophys. Res. Lett.* 32, L23710, doi:10.1029/2005GL024368.
- Schutz, B.E., H.J. Zwally, C.A. Shuman, D. Hancock and J.P. DiMarzio (2005) Overview of the ICES at Mission. *Geophys. Res. Lett.*, 32(L21S01), doi:10.1029/2005GLO24009.
- Stroeve, J. C., M. C. Serreze, F. Fetterer, T. Arbetter, W. Meier, J. Maslanik, and K. Knowles (2005), Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004. *Geophys. Res. Lett.*, 32, L04501, doi:10.1029/2004GL021810.
- Swingedouw, D., P. Braconnot and O. Marti (2006) Sensitivity of the Atlantic Meridional Overturning Circulation to the melting from northern glaciers in climate change experiments. *Geophys. Res. Lett.*, 33, L07711, doi:10.1029/2006GL025765.
- Zwally, H.J., M.B. Giovinetto, J. Lun, H.G. Cornejo, M.A. Beckley, A.C. Brenner, J.L. Saba and D. Yi (2005) Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992-2002. *Journal of Glaciology*