

# CLIMATE CHANGE AND THE CARBON CYCLE

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## INTRODUCTION

Atmospheric CO<sub>2</sub> concentration is one of the most important factors likely to determine the climate of the 21st century. In projecting future climate change, the majority of experiments with comprehensive ocean-atmosphere general circulation models (OAGCMs) still use prescribed CO<sub>2</sub> concentration scenarios. This implies that the climate change simulated by the OAGCM has no impact on the carbon cycle and therefore on the atmospheric CO<sub>2</sub> trajectory. However, the atmosphere-land and atmosphere-ocean fluxes of CO<sub>2</sub> are known to be sensitive to the climate. For example, the growth rate of atmospheric CO<sub>2</sub> varies with the El Niño Southern Oscillation (e.g. Bousquet et al., 2002), and is also believed to have been affected by the climate disturbance arising from the Pinatubo volcanic eruption (Jones and Cox, 2001, Lucht et al., 2002).

The first two OAGCM climate projections to include an interactive carbon cycle (Cox et al., 2000; Dufresne et al., 2002) showed that the climate-carbon cycle feedback is positive (i.e. amplifying the externally induced disturbance), but the magnitude of the feedback varied markedly between them (Friedlingstein et al., 2003). In the context of the Coupled Climate-Carbon Cycle Model Intercomparison Project (C<sup>4</sup>MIP) and for the upcoming 4th IPCC assessment report, a new coupled climate-carbon model has been developed at the Institut Pierre-Simon Laplace (IPSL\_CM4\_LOOP) and has been used to perform carbon-climate simulations over the historical period and the 21st century.

## MODEL DEVELOPMENT

The IPSL\_CM4\_LOOP model couples the latest version of the IPSL ocean-atmosphere GCM (Marti et al., 2005) used for the IPCC-AR4 simulations (Dufresne et al., 2005) to the land carbon cycle model ORCHIDEE (Krinner et al., 2005) and the ocean carbon cycle model PISCES (Aumont and Bopp, 2006). ORCHIDEE is a global vegetation model which calculates the energy and hydrology budgets, carbon assimilation, alloca-

tion and decomposition for 13 PFTs. The model accounts for four litter pools and three (fast, slow and passive) soil carbon pools. PISCES is a global ocean carbon model that includes a simple marine ecosystem model, with four plankton functional groups (nanophytoplankton, diatoms, microzooplank-

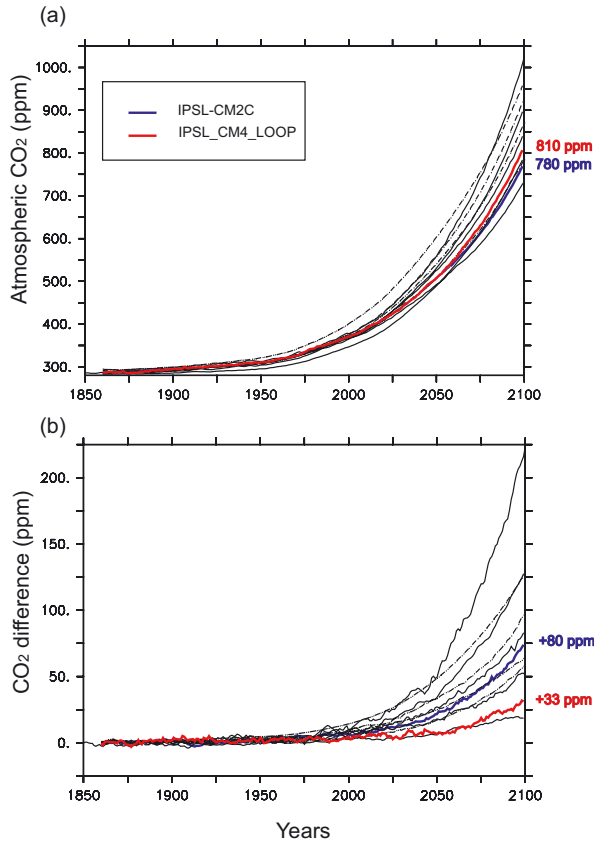
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In the ocean, the sea-surface warming and the stratification of oceanic surface layers explain most of the reduced carbon uptake. On land, the increased soil respiration due to the warming explains most of the reduced carbon uptake.

ton and mesoplankton). Nutrient co-limitation of phytoplankton growth is a function of N, P, Si and Fe.

The climate-carbon model is forced by the observed anthropogenic fossil fuel emissions for the historical period (Marland et al., 2005) and the IPCC SRES-A2 emission scenario for the 2000-2100 period. It also includes land-use associated CO<sub>2</sub> emissions provided by Houghton and Hackler (2002) for the historical period and by the IMAGE integrated model for the 21st century (Leemans et al., 1998). We carried out two simulations, one "coupled" simulation in which climate change affects the carbon cycle, and one "uncoupled" simulation in which CO<sub>2</sub> is treated as a non-radiatively active gas (so that the carbon cycle experiences no CO<sub>2</sub>-induced climate change). The difference between these two runs defines the effect of the climate on the carbon cycle and hence on atmospheric CO<sub>2</sub> that is fundamental for the climate-carbon feedback.

**FIGURE 1** a) Concentration of simulated atmospheric CO<sub>2</sub> (ppm) from 1860 to 2100 by the coupled climate-carbon models, C4MIP, b) The impact of climate-carbon feedback on simulated atmospheric CO<sub>2</sub> (ppm). The IPSL models are shown in color.



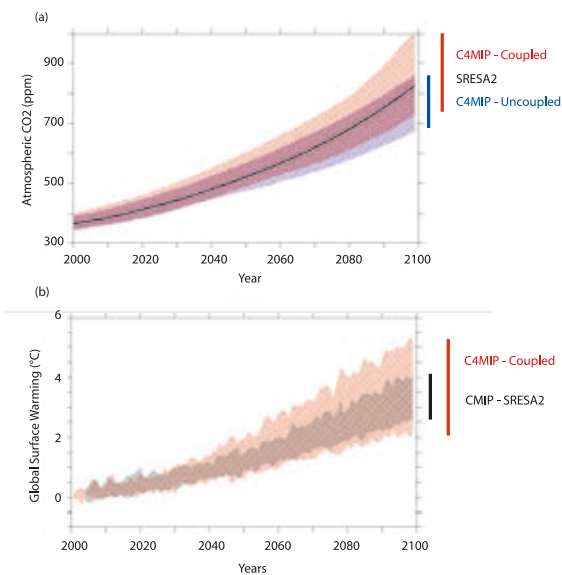
## THE CLIMATE-CO<sub>2</sub> FEEDBACK

In the coupled simulation, atmospheric CO<sub>2</sub> concentration reaches 807 ppm in 2100 (Figure 1.a) and is close to observations over the historical period. When comparing the coupled and uncoupled simulated atmospheric CO<sub>2</sub>, our model shows 33 ppm more CO<sub>2</sub> in 2100 for the coupled simulation (Figure 1.b), confirming the initial findings of a positive climate-carbon cycle feedback. A feedback analysis shows that both the land and the ocean carbon cycles contribute to this positive feedback. In the ocean, the sea-surface warming and the stratification of oceanic surface layers explain most of the reduced carbon uptake. On land, the increased soil respiration due to the warming explains most of the reduced carbon uptake. When compared to the other C4MIP results, the IPSL\_CM4\_LOOP simulation falls in the lower range of the additional atmospheric CO<sub>2</sub> induced by this feedback, which is found to be between +20 and +200 ppm (Friedlingstein et al., 2006, Figure 1.b). This would lead to additional warming ranging between 0.1 and 1.5°C in 2100.

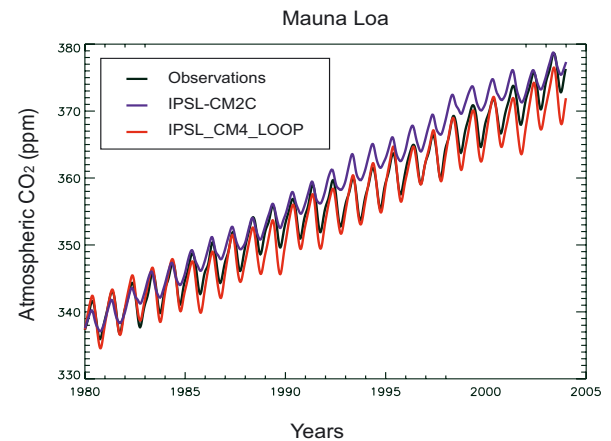
### Towards a more comprehensive validation

To reduce the considerable uncertainty arising from this positive feedback, a more comprehensive validation is needed. We propose to take advantage of the large data set of atmospheric CO<sub>2</sub> concentrations put together by the NOAA-CMDL laboratory (Globalview-CO<sub>2</sub>, 2006). The land and ocean carbon fluxes computed by IPSL\_CM4\_LOOP have been trans-

**FIGURE 2** a) Concentration of atmospheric CO<sub>2</sub> simulated by the C4MIP models for the coupled (red) and uncoupled (blue) simulation along with the imposed concentration for standard IPCC AR4 models for the SRES-A2 scenario (black), b) global surface warming simulated by the C4MIP models for the coupled simulation (red) and by standard IPCC AR4 models for the SRES-A2 scenario (black).



**FIGURE 3** Comparison between the concentration of atmospheric CO<sub>2</sub> simulated by IPSL-CM2-C and IPSL\_CM4\_LOOP and that observed at the Mauna Loa station for the 1979-2003 period.



ported into the atmosphere using the atmospheric transport model LMDZ4 and observed winds for the 1979-2003 period. Figure 2 shows the comparison at Mauna Loa station (19.5°N, 155.6°W) between observed concentrations and the simulated concentrations from IPSL-CM2-C (Dufresne et al., 2003) and IPSL\_CM4\_LOOP. Differences between the two models are striking in terms of mean trend and amplitude of the seasonal cycle. IPSL\_CM4\_LOOP shows a much better agreement in terms of the amplitude of the seasonal cycle.

We have also taken advantage of the recent data set of oceanic anthropogenic carbon put together by Sabine et al., 2005, and have compared this data set to the IPSL\_CM4\_LOOP results. Globally, Sabine et al. (2005) estimate that the ocean has taken up 106 PgC since pre-industrial times, whereas our model predicts an oceanic absorption of 96.5 PgC from 1860 to 1995.

## PERSPECTIVES

Simulations with non-CO<sub>2</sub> greenhouse gases, aerosols, solar and volcanic forcing are ongoing. We will estimate the role of these additional forcings in terms of the realism of the simulated climate and carbon cycle over the 20th century as well as the amplitude of the climate-carbon feedback over the 21st century. These IPSL\_CM4\_LOOP simulations along with other C4MIP model runs are compared to atmospheric CO<sub>2</sub> and oceanic anthropogenic carbon observations. ■■■

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# DETECTION AND ATTRIBUTION AT THE REGIONAL SCALE: THE CASE OF FRANCE

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## INTRODUCTION

The climate-scale detection and attribution studies presented here are not directly based on the simulations performed within the framework of the preparation of the AR4 report. They are in fact studies focusing on the series of climate observations in France and their comparison with the results of numerical simulations made using regional climate models. While awaiting the release of new regional climate simulations (currently underway at the CNRM, CERFACS and IPSL) that are constrained by the global coupled simulations performed for the AR4, the regional climate scenarios produced for previous projects have been analyzed (GICC-IMFREFX, PRUDENCE, DISCENDO, etc.).

The detection of climate change can be defined as the process to demonstrate that the climate has changed in a certain statistical sense, without giving the reason for this change. The attribution of the causes of this climate change consists in establishing the most likely causes of this climate change with a certain confidence level defined in the statistical sense. In practice, attribution implies demonstrating that the detected change is consistent with an estimated climate response to a given combination of natural and anthropogenic forcings, and inconsistent with alternative, physically plausible explanations, which exclude a significant part of this combination of forcings (IDAG 2005, IPCC 2007).

The now classical approach to the detection and attribution of climate change is the optimal fingerprint method proposed by Hasselmann (1997) then first applied to temperature observations at the planetary scale (Hegerl et al., 1997; Allen and Tett, 1999; Tett et al., 2002). More recently a new class of methods based on Bayesian inference has been implemented (Hasselmann, 1998; Schnur and Hasselmann, 2005), but the research conducted within the French community refers to the more classical approach.

At the international scale, studies using the fingerprint method, first applied to near-surface temperatures, have been extended at the global scale to tropospheric temperatures from satellite observations (Thorne et al., 2003), to the thermal content of

the ocean (Barnett et al., 2001, 2005), to surface pressure (Gillet et al., 2005) and very recently to precipitation (with less robust results than those for temperatures, Lambert et al., 2004). Work has also begun on the detection of extreme events (Hegerl et al., 2004; Stott et al., 2004).

Furthermore, only a few studies have concentrated on the detection of climate change for temperatures at sub-regional scales (typically that of a country like France). Among these studies, only those conducted within our community have used the fingerprint methodology. Another original aspect of the studies carried out within our community was to also consider the case of precipitation and the occurrence frequencies of weather regimes at the regional scale.

## DETECTION STUDIES

Detection studies carried out at the scale of France have benefited from data series for average monthly temperatures and precipitation covering the whole of the 20th century, standardized according to the methodology proposed by Mestre (2000). The regional climate simulations used to date come from the regional climate model ARPEGE-Climat at variable resolution (60 km over Europe). The estimation of the internal variability needed for the statistical test rejecting the null hypothesis for the detection was obtained using the data series themselves, but limited to the 1900-1970 period, assumed to be less contaminated by the climate change signal. It should be noted that this contamination leads to a lower probability of detection (a more conservative test).

The first detection study carried out at the French scale was that of Spagnoli et al. (2002). It was applied to the analysis of 30-year trends in average minimum and maximum daily temperatures in summer and winter. It revealed a detection of minimum daily temperature trends in summer, but not of maximum summer temperatures nor of any winter temperatures.

A later analysis put forward a physical interpretation of this detection. The hypothesis was proposed that via changes in

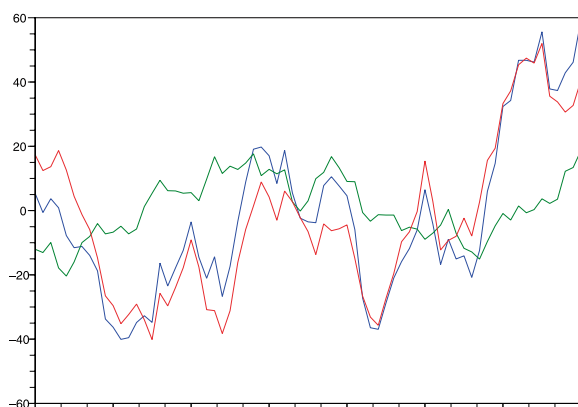
evapotranspiration, the spatial variation of soil water content could amplify warming in the drier regions and limit it in wetter regions. This mechanism is present in the simulation of the regional climate model (Planton et al., 2005). A positive correlation between the soil wetness index simulated for the current climate and reconstructed from observations over the 1971-2000 period agrees with this physical interpretation of detection. More recently, the comparison of wetness indexes calculated by the regional climate model for the current climate and over a period of 23 years based on the SAFRAN-ISBA-MODCOU hydrological model for the 1983-2005 period (correlation of spatial averages of around 20%) also falls in line with this hypothesis.

The same kind of detection study as the one carried out on temperatures was also conducted based on standardized data for winter precipitation in France. The analysis also focused on the 30-year trends for this parameter. As with temperatures, the data are first centered in space in order to study only the trend for the geographical distribution of precipitation. But whereas for temperatures the effect of this operation was to limit the possibility of a detection due to the strong average warming signal, it in fact increases the chances of a detection for precipitation as the evolution of simulated average rainfall, serving to estimate the trend linked to climate warming, is weak in comparison with the variability of the trends observed. The analysis shows the detection of a change signal for the spatial distribution of rains with a confidence level of over 90% from 1990.

An attempt at interpreting this detection by a change in the occurrence frequency of climate regimes in the North Atlantic proved unsuccessful. Figure 1 illustrates this result by showing the evolution of the detection variable associated with winter rains, that of the contribution to this variable of precipitation explained by the variability in the frequency of climate regimes (obtained by means of a linear regression of precipitation over the data for the frequency of climate regimes produced within the framework of the EMULATE project), and the residual term obtained by difference. The evolution of the detection variable is largely explained by that of the residual term, especially at the end of the period.

This implies the presence in recent observations of a signifi-

**FIGURE 1** Evolution of the detection variable for winter rain in France (in blue), of the contribution to the detection variable linked to the frequency variability of climate regimes in the North Atlantic (in green) and of the residual term (in red).



cant signal on the 30-year trend for precipitation, in line with the one calculated by the model for anthropogenic climate change conditions, and not explained simply by the occurrence variability of different climate regimes (especially the NAO).

## ATTRIBUTION STUDIES

### Temperatures

The first attribution studies were carried out as part of the Discendo project on the detection and attribution of climate change at the regional scale. The approach taken in this project is based on the use of variable resolution atmospheric models (with high resolution over the area of interest) and the consideration of the boundary oceanic conditions (sea surface temperatures – SST) as an additional forcing to anthropogenic forcings (greenhouse gases – GHG – and sulfate aerosols – SUL) and natural forcings (solar – SOL – and volcanism – VOL). The first idea is to detect climate changes in relation to internal atmospheric variability and to variability linked to ocean fluxes (whether of an internal nature or linked to anthropogenic and/or natural factors). In other words, this method aims to detect a direct response of the forcings considered (GHG, SUL, SOL, VOL) on the atmosphere, in addition to the one potentially associated with ocean warming due to the same forcings (Sexton et al., 2001). This approach is advantageous if the signal-to-noise ratio is higher than that of the classical approach based on coupled ocean-atmosphere models. Giving SSTs the role of an additional forcing reduces the internal variability of the system considered to the internal atmospheric variability, but also removes the oceanic contribution (linked to SSTs) from the estimation of the anthropogenic signal. The other advantage is that it is not completely based on the use of coupled models and it avoids complex drift and bias issues.

The second idea concerns the attribution methodology: it is based on the performance of ensemble simulations that differ in terms of the combination of forcings applied. The first ensemble is forced only by SSTs observed over the 1950-1999 period and the other forcings (GHG, SUL, NAT – SOL + VOL) are constant and fixed at their 1950 value. For the other ensembles, the observed changes in anthropogenic and natural forcings are added sequentially. The ensemble averages of the simulations performed constitute the climate signals and the internal variability – noise – is built from the intra-ensemble variability (the differences between each simulation and the corresponding ensemble average). These two ingredients are then used in the fingerprint method, which can also be seen as a simple regression method with several parameters. The observations ( $\mathbf{y}$ ) can be represented by a linear combination of the forcings considered  $\mathbf{x}_1$  (SST),  $\mathbf{x}_2$  ( $G=[SST, GHG]$ ),  $\mathbf{x}_3$  ( $GS=[SST, GHG, SUL]$ ) and  $\mathbf{x}_4$  ( $GS-NAT=[SST, GHG, SUL, NAT]$ ) plus a remainder representing the internal variability,  $\mathbf{u}$ :

$$\mathbf{y} = \sum \beta_i \mathbf{x}_i + \mathbf{u}$$

with  $\beta_i$  the adjustment coefficients (or signal amplitudes) esti-

mated by the regression. The detection of the signals considered thus depends on the following null hypothesis test,  $H_0: \beta = 0$ . The impossibility of rejecting  $H_0$  means that the signal amplitudes (associated with the forcings considered) in the observations are not different from 0 at the chosen statistical confidence level (95%). The attribution part of the analysis seeks to ascertain whether the amplitudes are consistent with the vector identity ( $H_0: \beta = 1$ ). If  $H_0$  cannot be rejected, then it is possible to attribute the change observed to the combined effect of the different forcings considered. Furthermore, the plausibility of this reconstruction is verified by a statistical consistency test: we check that the remainder  $\mathbf{u}$  is consistent with the internal variability represented here by the intra-ensemble variability. The individual contribution of each forcing is calculated using a linearity hypothesis on the combinations of different forcings (Gillett et al., 2004). It should be noted that here  $\mathbf{y}$ ,  $\mathbf{x}_i$  and  $\mathbf{u}$ , unlike in the works mentioned in the previous paragraph, are spatio-temporal vectors (we attempt to detect a fingerprint that varies in time and not a simple linear trend). Note also that the amplitude of the signals considered is weaker than in the previous approach (where the signal is obtained by difference between the future climate – 2070-2099 – and the present climate).

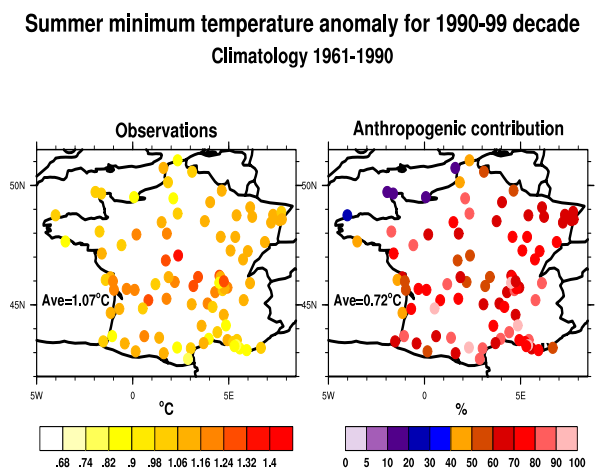
The methodology has been applied to decadal anomalies in minimum and maximum summer temperatures over the 1950-1999 period (Terray and Planton, 2006). The observed warming for minimum temperatures can be explained by the combination of the oceanic signal with the direct effects due to GHGs and SULs ( $\beta \neq 0$  and  $\beta = 1$ , Fig. 2). It should also be noted that here the SUL forcing is essential to detecting a combination of signals. The oceanic signal seems to be strongly linked to a variability mode known as the Multidecadal Atlantic Oscillation (MAO) whose origin is probably internal to the ocean. The shift to a positive phase of this oscillation in the last decades of the 20th century contributed to a slight increase in

the main warming due to anthropogenic effects (GHG + SUL). The detection of maximum temperatures is less robust, but the combined effects of SSTs and GHGs are detected even if the model seems to slightly underestimate the response of these forcings in relation to observations.

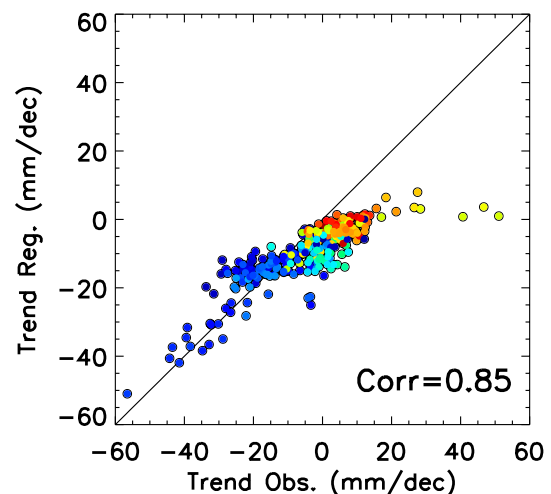
### Precipitation and surface pressure

A different approach was taken for precipitation. The results of detection and attribution studies for winter precipitation (extended winter, from November to March) using the same methodology as the one used for temperatures (see previous section) do not allow us to clearly conclude on detection, and even less on the attribution of changes observed for decadal anomalies over the 1950-1999 period, unlike the results mentioned in part b. Based on this observation, the idea was to separate the precipitation signal into a dynamic part (linked to the evolution of occurrence frequencies for weather regimes) and a thermodynamic residual, which can partly be linked to changes in the water vapor content and to other causes. To carry out this separation, disintegration techniques based on atmospheric circulation regimes at the daily scale (weather regimes) and developed for impact studies (see chapter on Regional Modeling and Extremes) were used to construct a transfer function between the occurrence frequencies of weather regimes and precipitation over France (Boé and Terray, 2006). The dataset used for weather regimes is the set for surface pressure at daily frequency over the North Atlantic and Europe developed as part of the European EMULATE project. The regimes considered here differ from those used in section b, firstly by the temporal aspect (daily, not monthly), and secondly by the construction method. The approach taken here consists in determining discriminant regimes not only for the large scale, but also for the sensitive climate variable in question. To do so, we apply mathematical classification

**FIGURE 2** Ellipses representing the estimation of the joint distribution of amplitudes for all combinations of two signals (linked to SST forcings and/or to anthropogenic factors, GHG and SUL) at a confidence level of 95%. The variables considered are the minimum and maximum summer temperatures for France. Each ellipse is centered on the optimal estimation of amplitudes marked by a black cross and their size reflects the uncertainty associated with the amplitudes of the two signals identified in the colored labels. The horizontal and vertical bars indicate the unidimensional distributions of amplitudes for each of the signals at a confidence level of 95%.



**FIGURE 3 a.** Linear precipitation trends (in mm/decade) for the 299 stations in France over the 1951-2000 period observed on the x axis and reconstructed by regression on the occurrences of regimes on the y axis. The color scale represents the latitude of the station, from north (red) to south (blue);

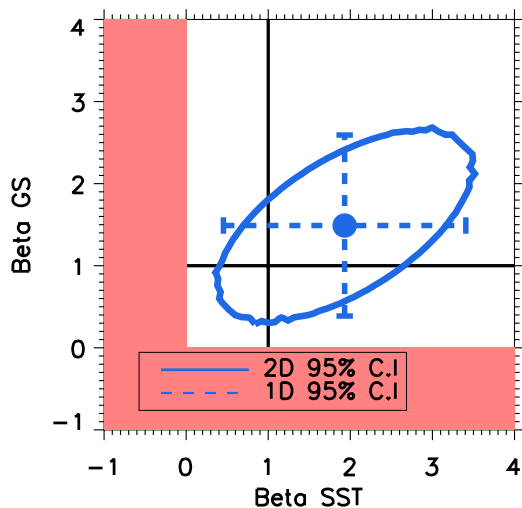


tools simultaneously to both variables (surface pressure and precipitation). The analysis shows that it is then possible to reconstruct by multiple regression and with a high level of accuracy (correlation of 0.85) the precipitation trends observed over France based on only fluctuations in occurrence frequencies of the eight weather regimes found (figure 3a). The stations where the trend is underestimated by the reconstruction are all found in the north-east of France. These differences in data observed for the north-east can be reduced by taking intra-regime changes into account in the regression method (Boé and Terray, 2006). The final stage thus consists in applying the methodology described in the previous paragraph for detecting and possibly attributing the changes in occurrence frequencies due to oceanic forcings (SST) and anthropogenic forcings (GHG and SUL). The detection vector here is made up of decadal averages of the occurrence frequencies of the eight types of weather. The results (figure 3b) show that it is possible to detect the effect of the combined GHG-SUL forcing and SSTs on the changes in occurrence of weather regimes and associated precipitation.

## CONCLUSION

The studies carried out within our community are the first to suggest that it is possible to detect in the observations of minimal summer temperatures in France a spatial fingerprint of anthropogenic climate change at sub-regional scales. Attribution studies show that most of this warming is due to the combined action of GHGs and SULs, to which is added a small contribution linked to the MAO mode. This result is important as it questions the certainties displayed since the TAR on the minimum spatial scale for the detection of the anthropogenic signal (5 000 km). The analyses carried out seem to indicate that the nonlinearities between the climatology of soil water content and temperature anomalies, via changes in evapotranspiration, are responsible for the spatial structure of

**FIGURE 3** b. Ellipse representing the estimation of the joint distribution of amplitudes for the combination of the two signals (SST and GHG-SUL) at a confidence level of 95%. The variable considered is the occurrence frequency of regimes. The ellipse is centered on the optimal estimation of amplitudes marked by a blue circle. See key to figure 2 for the confidence intervals.



warming. The examination of the climatology of simulated soil wetness and its comparison with the SIM analyses suggest that the mechanism at work in the model may also play an important role in observations. Furthermore, studies on precipitation show that it is also possible to detect an anthropogenic signal on the winter trends of the last 30 years. The separation of the precipitation signal into a dynamic part (linked to fluctuations in the occurrence of discriminant weather regimes for precipitation) and a remainder show that this dynamic component almost completely captures the observed trend. The fingerprints of the SST signals and the GHG-SUL combination are detected in observations of the occurrence of regimes.

Furthermore, these results as a whole constitute a detailed validation of the ability of the regional model to reproduce different aspects of the sensitivity of the European climate to anthropogenic forcings and may serve to better constrain regional projections for the climate of the 21st century. ■■■

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## ACKNOWLEDGEMENTS

The people listed below actively contributed to the development of the coupled models used for the IPCC scenarios, to the experiments conducted, the circulation of results or the scientific analyses presented in this document: Olivier Arzel, Jacques Bellier, Rachid Benshila, Sandrine Bony, Laurent Bopp, Olivier Boucher, Jean-Philippe Boulanger, Pascale Braconnot, Alain Braun, Patrick Brockmann, Patricia Cadule, Christophe Cassou, Arnaud Caubel, Fabrice Chauvin, Francis Codron, Nathalie deNoblet, Sébastien Denvil, Michel Déqué, S. Dominiak, Hervé Douville, Jean-Louis Dufresne, Laurent Fairhead, Thierry Fichefet, Marie-Angèle Filiberti, Marie-Alice Foujols, Claude Frankignoul, Pierre Friedlingstein, Guillaume Gastineau, Christophe Genthon, Josephine Ghattas, Anne-Laure Gibelin, Katarina Goubanova, Jean-Yves Grandpeix, Eric Guilyardi, Didier Hauglustaine, Frédéric Hourdin, Abderaman Idelkadi, Soumaya Jamili, Masa Kageyama, Gherart Krinner, Alexandre Laigné, Alban Lazar, Phu Le Van, Claire Lévy, Laurent Li, François Lott, Gurvan Madec, Eric Maisonnave, Pascal Marquet, Olivier Marti, Sébastien Masson, David Salas y Melia, Ionela Musat, Serge Planton, Johannes Quaas, Annie Rascol, Catherine Ritz, Jean-François Royer, Victoria Serafini, Florence Sevault, Samuel Somot, Didier Swingedouw, Claude Talandier, Laurent Terray, Pascal Terray, Hubert Teysse, Sophie Tyteca, Sophie Valcke, Nicolas Viovy, Aurore Voldoire.

The ESCRIME project would also like to thank the IDRIS, Météo-France and CEA data centers, without which this unprecedented climate modeling effort by the French community would not have been successful.



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