CLIMATE−CARBON FEEDBACKS ASSOCIATED WITH CO_2 ANTHROPOGENIC EMISSIONS USING THE IPSL COUPLED MODEL: AN AMPLIFICATION EFFECT?

1. Introduction.

Over the last 150 years, the measured atmospheric CO_2 concentration increased by 25%, from 280 ppmv in 1860 up to 360 ppmv today. Actually, the CO_2 increase would be approximately twice if all CO_2 emitted by the human activities would remain in the atmosphere; in fact, about half of this emitted CO_2 is reabsorbed by the biosphere and the oceans.

The carbon cycle can be sketched as follow: atmospheric CO_2 fixed by the biosphere or by the oceans is released back to the atmosphere with a delay ranging from a few hours to a thousand of years depending on the concerned processes. Thus, in situation of near−equilibrium there is about as much carbon fixed than released. Indeed, on time−scales of a few centuries and without noticeable climatic change, one observes relatively constant CO_2 concentration, oceanic and biospheric uptakes being null on decadal average. The processes governing uptakes and releases of carbon depend on climate. Climate variations will modify carbon balance and thus atmospheric CO_2 concentration. On time−scales of several thousands of years, the paleodata show approximately a 20 ppmv/°C CO_2 concentration to global mean surface temperature sensitivity.

Today, the increase in atmospheric CO_2 enhances carbon up[take by plants and by the oceans (biospheric fertilization and increase of air−sea diffusive exchange). As carbon is released in the atmosphere with a delay (we consider here periods going from one year to a few centuries), the fast increase in CO_2 maintains an increase of the carbon uptake by the biosphere and the ocean. This is why only half of the CO_2 currently released by human activities remains in the atmosphere. Nevertheless recent studies suggest that the climatic change resulting from the greenhouse effect could reduce these CO_2 uptakes, and thus could introduce an amplifying effect (a positive feedback) between climate and carbon cycle.

2. Climate−carbon model coupling

Up to now, the climate−carbon feedback has been address with low−order physical and biogeochemial models, in particular to study the transitions between glacial and interglacial periods.

At IPSL (Institut Pierre Simon Laplace, Paris), we coupled three−dimensional models of the climate and of the carbon cycle in order to study the future climate and carbon cycle changes due to human activity. The climatic model is the coupled atmosphere−ocean general circulation model (AOGCM) IPSL−CM2. It was developed by teams of the LSCE, LMD and LODYC. The atmospheric GCM is LMD−5.3, the oceanic and sea−ice GCM is OPA−ICE, these two GCMs being interfaced via the OASIS coupler developed by CERFACS. The carbon cycle models are CASA/SLAVE for the biosphere and HAMOCC3 for the oceanic biogeochemistry. The two carbon models are forced with monthly mean values of climatic variables: solar flux, surface temperature and precipitation for the biosphere, surface flux and three−dimensional fields of temperature, salinity, velocity and vertical diffusion for the ocean biogeochemistry. The CO_2 concentration is homogeneous in the atmosphere and is updated once per year according to the budget between the imposed anthropogenic sources and the calculated uptakes by land and ocean. The CO_2 concentration for the year *t+1* is calculated as:

$$CO_2^{t+1} = CO_2^{t} + (ANT^{t} - BIO^{t} - OCN^{t})\,/2.12$$

where ANT^t is the annual CO_2 anthropogenic emissions (fossil fuel and deforestation), BIO^t and $OC\tilde{N}^t$ are respectively the carbon uptake by the biosphere and the ocean. The initial condition for CO_2 is pre−industrial ($CO_2^{t=0}$ = 286 ppmv).

Here, we focus on the study of the feedbacks between the climate and the carbon cycle. Thus, we only account for CO_2 as greenhouse gas (no CH_4, N_2O,... emissions). For the same reason the aerosols are not taken into account. For the anthropogenic emissions, we consider the fossil fuel and the land use change emissions. Several other processes were not considered because of their very strong uncertainties: vegetation geographical redistribution (due to the direct human pressure or due climate driven migration of species), additional fertilization effect from other non−CO_2 components (e.g. NO_x)

3. Recent evolution

A 240 years long control simulation, without anthropogenic CO_2 emission has been first performed. It allows us to check the model stability and the absence of climate and CO_2 drift. In parallel, a climate change simulation, forced by CO_2 emissions, from year 1860 to year 2100 allows a comparison with observations for the recent historical period (1860−2000) and future projection of the climate and the carbon cycle in the 21^{st} century. For this climate change run, the CO_2 emissions follow the IPCC recommendations: they are inferred from observations for the historical period and correspond to the scenario SRES−A2 (close to old scenario IS92−A) for the 21^{st} century.

This run reproduces extremely well the observed global mean surface temperature evolution and the CO_2 concentration long term trend (figure 1). Global warming is noticeable since the 1940's. However it is slightly larger than what observed, probably because of neglecting aerosols effects. The interannual variability of atmospheric CO_2 is well reproduced and is essentially driven by the biospheric uptake. These uptakes are mainly located in the tropical areas, and are well correlated with the southern oscillation ENSO. We also verified that the simulated climate variations over continents associated with the ENSO reproduced the current observations. On decadal time scale, the variability of the biosphere uptake still dominates, but the oceanic uptake variability is not negligible any more.

We only presented here, some global diagnostics , which illustrate the ability of our model to reproduce the global trend of climate and carbon cycle over the 150 last years as well as their interannual variability to give us some confidence to study the evolution of that coupled system in the future.

4. Future evolution

For the future part of the simulation, we used the IPCC SRES−A2 CO_2 emission scenario. We present results up to year 2050, the last 50 years of the simulation being still running (figure 2). The future CO_2 increase, is close, although slightly weaker, than what calculated for IPCC by the simplified Bern model (by year 2050, our CO_2 amounts to 500 ppmv whereas Bern simulation reaches 525 ppmv) . This difference is mainly due to the biospheric uptake, Bern biospheric uptake being weaker than ours (3 GtC/yr for Bern, 4GtC/yr for us by 2050). Ocean uptakes are similar (5.5 GtC/yr vs. 5.4 GtC/yr). One can see on figure 2a the geographical distribution of the land uptake. It is clearly positive, to the exception of the tropical regions (as described further down).

As CO_2 is the only greenhouse gas in this study, the radiative forcing is about 40% lower than a typical 1%/yr CO_2 increase (accounting for non−CO_2 forcing). Consequently, we simulate a lower warming than the mean of GCM simulations forced by IPCC IS92−A emissions. However, we find the now classical results : higher warming at high latitudes than in the tropics, higher warming on lands and sea−ice than on the oceans, higher precipitation in the tropics and at mid and high latitudes, but similar or lower precipitation in the sub−tropics, sea−ice decreases is large in the Arctic regions (35%) but rather small in the Antarctic.

5. Impact of climatic change on the carbon cycle

As the carbon models are coupled to the climate models in our simulations, we can study the feedback between climate and carbon cycle changes. In order to quantify this feedback, we ran one third simulation, called the constant climate run, with the same emissions as in the climate change run, but the climate taken from the control run. That is to say, the atmosphere does not see the CO_2 increase, and the carbon cycle only sees the CO_2 increase, but no climate change. One can see (figure 3a) that in such case, the calculated atmospheric CO_2 would be lower than in the coupled simulation (climate change run), that means that the uptakes are larger as the emissions are the same. By 2050, oceanic uptake is similar in the two simulations, but the biosphere uptake is drastically different, the uptake in the constant climate simulation being much larger than the one obtained in the climate change simulation (figure 3b and c). In the constant climate simulation, as there is no climate change, the biospheric uptake is only driven by the increase in atmospheric CO_2 (fertilization effect) and is efficient in all regions (figure 2b). Accounting for the climate change, reduces dramatically this uptake in the tropics (especially Africa and America), but tends to increase the uptake in the mid and high latitudes (figure 2c). At low latitudes, plant growth becomes limited by water availability as water stress increases because of an imbalance between the increase in evaporation and in precipitation. At high latitudes, higher temperature is beneficial to plant growth. In some regions of the tropics, the negative effect of climate change on plant growth is getting larger than the fertilization effect, switching these regions from carbon sinks to carbon sources.

6. Ocean compensates for the weakening of the biosphere

As stated before, ocean uptake shows little change under the climate change. Actually, the picture is slightly more complex. We can show that the climate change reduces slightly the ocean uptake of carbon, for a given atmospheric CO_2. However, the strong climate induced reduction of biospheric uptake in the climate change run leads to a larger CO_2 fraction in the atmosphere (figure 3a). This larger atmospheric CO_2 drives a larger geochemical uptake of carbon by the ocean. By year 2050 this additional geochemical ocean uptake, thanks to the weaker biosphere, over−compensates the climate induced reduction of ocean uptake. However, this compensation of the two effects may not hold in the long term. Indeed, in previous off−line simulations, done with the same models, but where the carbon models were forced by an a priori calculated climate change, we found that beyond $2xCO_2$, the ocean also starts to be negatively affected by the climate change (mainly because of weaker circulation). At $4xCO_2$, we calculated that climate change reduces oceanic carbon uptake by 35% and land uptake by 55%.

7. A long term unknown

The usual method adopted to estimate future climate change under given greenhouse gases emissions, as typically done by IPCC, is the following : a) Estimation of emission scenario based on socio−economic scenarios ; b) Conversion of emissions into concentration using biogeochemical models ran under present day climate ; and c) calculation of the corresponding climate change using GCMs.

Such approach clearly neglects the carbon cycle dependence to climate. As we showed here, the climate−carbon feedback is positive : by year 2050, atmospheric CO_2 is 10% higher if the climate change impacts on the carbon cycle. Therefore, the climate change itself is 10% higher than what would be obtained with the classical IPCC approach. The off−line simulations realized before these coupled simulations showed that this positive feedback keep increasing with time, being larger than 20% at $4xCO_2$.

In the present study, we deliberately neglected other key processes, such as vegetation dynamics (driven by climate or by direct human activity). So far, one other research group, at the Hadley Center, U.K., undertook coupled climate−carbon simulation. They account for vegetation dynamics and find a positive feedback that is even larger than ours as their tropical forests are dramatically shrinking because of the climate change (P. Cox, pers. comm.). Clearly, large uncertainties remain, mainly in the biosphere. However it seems obvious that we can not avoid to account for the climate change impact on the carbon cycle.

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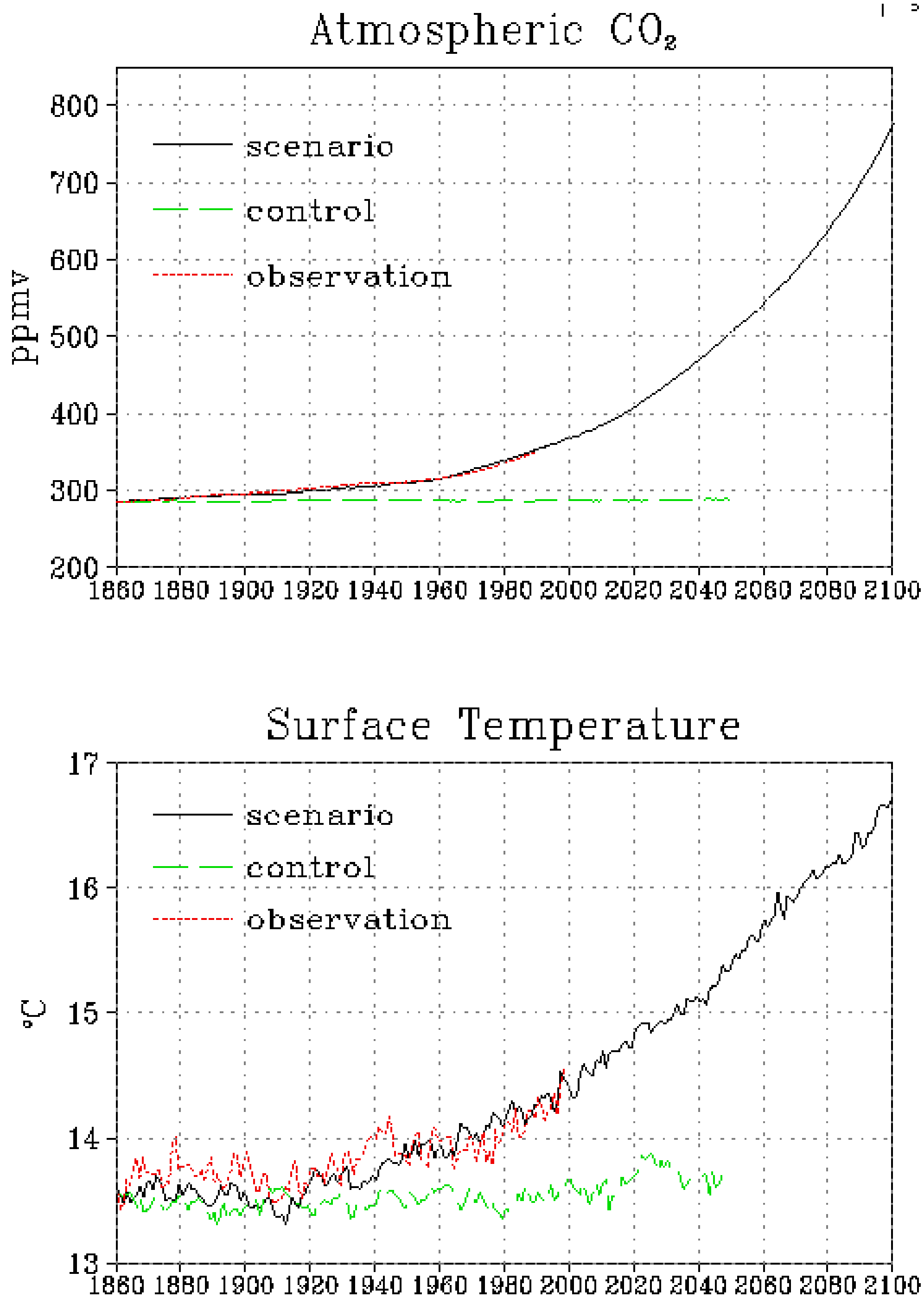

Figure 1. Time evolution of atmospheric CO_2 (ppmv, top) and global mean temperature (°C, bottom) from 1860 to 2050, as simulated by the IPSL coupled climate−carbon model. CO_2 emissions follow observation up to 1990, and are taken from IPCC (SRES−A2) for the 21st century. Dotted lines are observed CO_2 and global mean temperature.

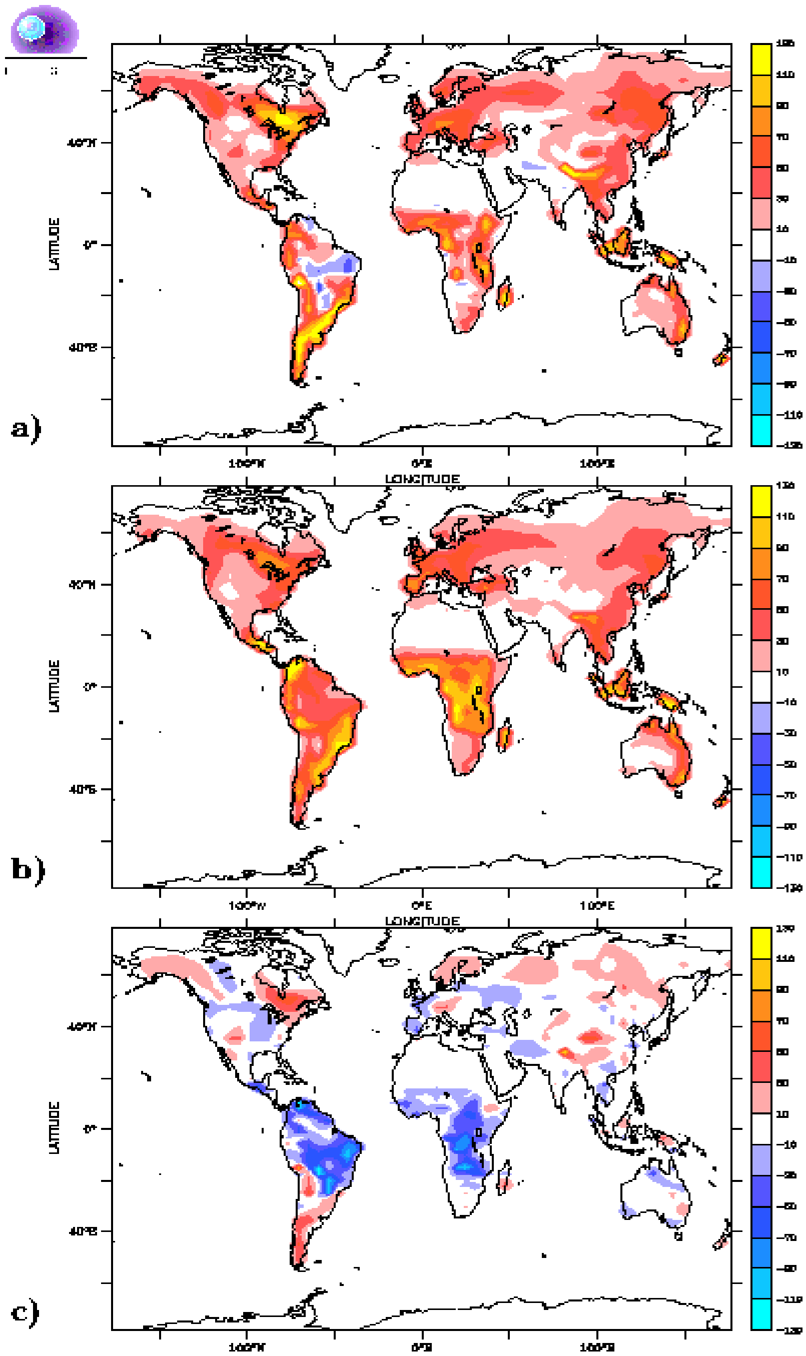

Figure 2. Biospheric uptake of carbon (gC/m2/yr). (a) difference between year 2050 and year 1860 in the climate change simulation, (b) difference between year 2050 and year 1860 in the constant climate simulation, and (c) difference, by year 2050 between the climate change simulation and the control climate simulation, isolating the climate impact on the biospheric carbon uptake.

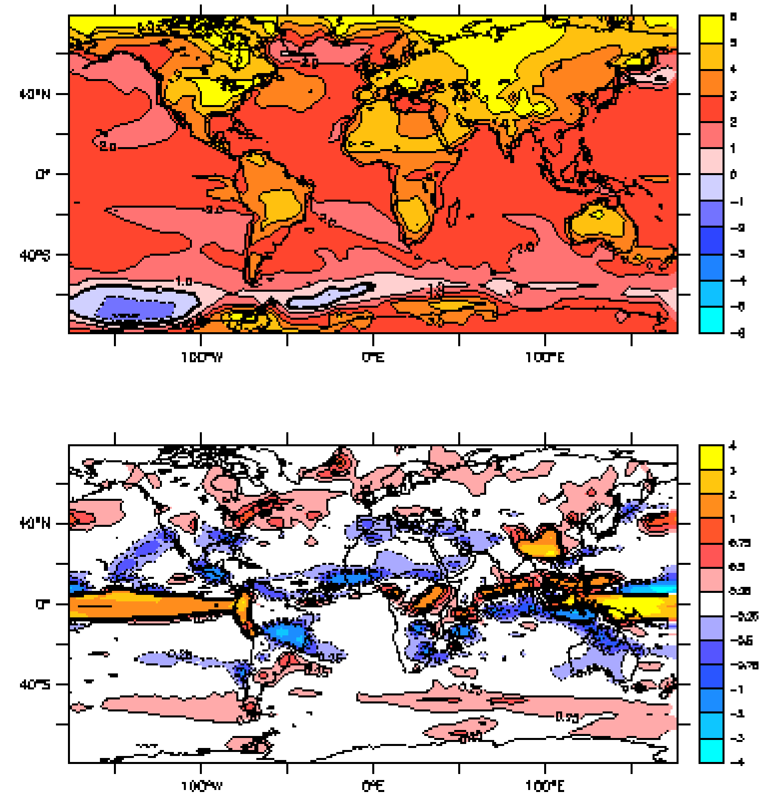

Figure 3. Temperature change (°C, top) and precipitation change (mm/yr, bottom) by year 2100, relative to preindustrial values, as simulated by the IPSL coupled climate−carbon model.

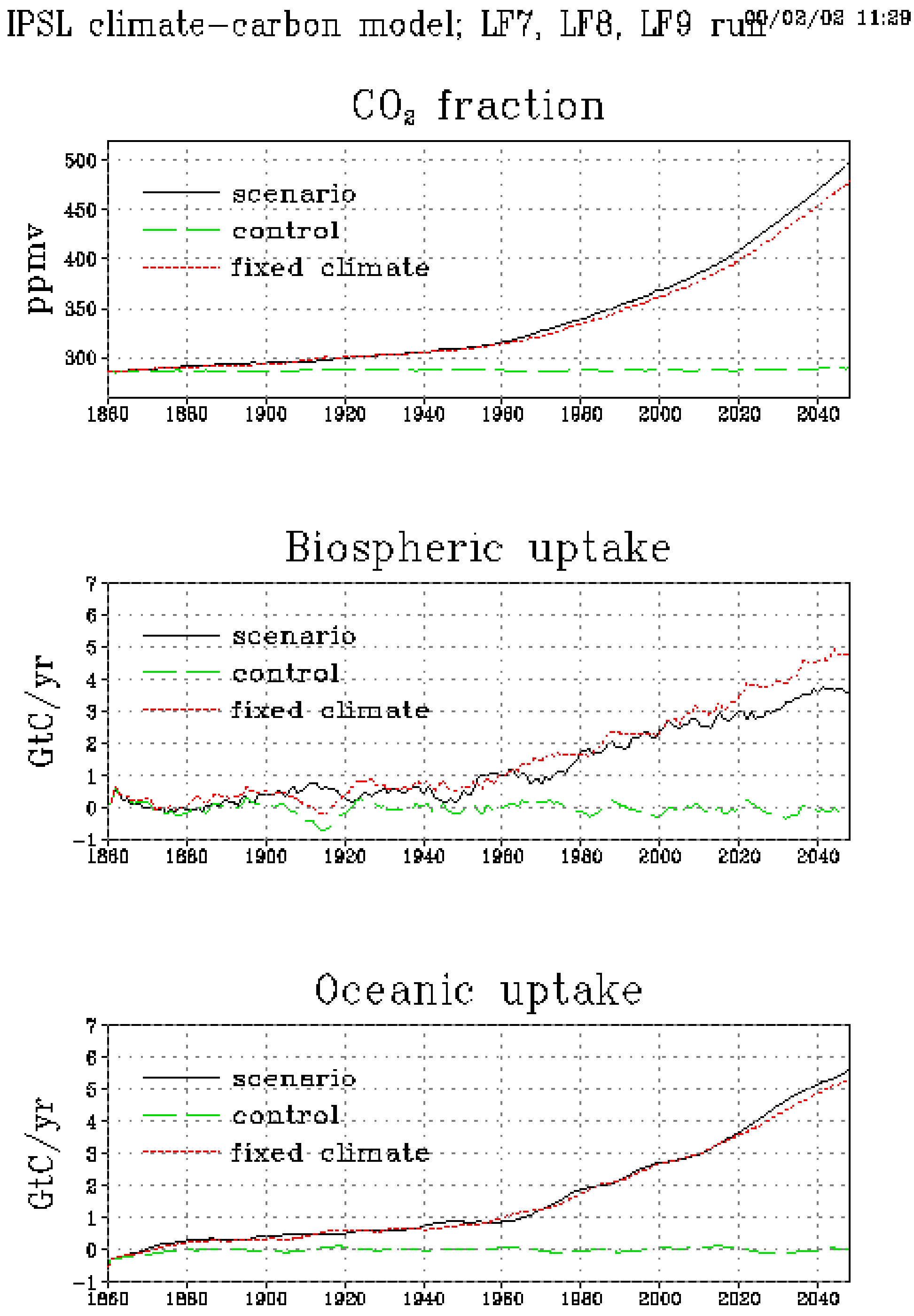

Figure 4. Time evolution of atmospheric CO_2 (ppmv, top), biospheric uptake (GtC/yr, middle), and oceanic uptake (GtC/yr, bottom) calculated with climate change impact on carbon cycle (climate change simulation, solid lines), or without accounting for the climate change (constant climate simulation, dotted lines). Also shown is the control run, with no anthropogenic emissions (dashed lines).