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Transient CO_2 experiment using the ARPEGE/OPAICE non flux corrected coupled model

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Abstract. A transient CO_2 experiment using the ARPEGE/OPAICE coupled general circulation model with no flux correction has been performed at CERFACS. Despite a warm initial climate drift, the main features of the observed climate are reasonably captured in the control simulation. In particular, the simulated oceanic circulation is satisfactory. The transient CO_2 simulation shows a global warming of 1.6°C in surface air temperature at the time of CO_2 doubling. This value and the main geographical patterns of climate change are in agreement with previous studies using either flux corrected or non flux corrected models. The absence of flux correction does not prevent the too strong atmospheric water fluxes to produce an unrealistic freshening of the upper layer of the Northern North Atlantic which leads to a reduction of the thermohaline circulation in the control simulation. As a consequence, the weakening of the thermohaline circulation in response to the anthropogenic radiative forcing is less than expected.

Introduction

Over the last two decades, an important international effort has been undertaken to assess the potential anthropogenic impacts on global climate [*Houghton et al.*, 1995]. Most of the studies are conducted with coupled general circulation models (CGCM) and use flux correction to reduce the apparent effects of errors in formulation of the models [*Manabe et al.*, 1991; *Cubasch et al.*, 1991; *Murphy and Mitchell*, 1995; *Gordon and O'Farrel*, 1997]. Nevertheless, the use of flux correction raises some questions. In particular, the simulated climate variability has been shown to be negatively impacted by flux correction [*Greatbatch and Zhang*, 1995]. *Neelin and Dijkstra,* [1995] also showed that the use of flux correction may lead to artificial multiple equilibrium states in place of a unique solution for tropical climatology, while *Schneider,* [1996] claimed that the usual implementation of flux correction causes systematic error related to cold start. Moreover, the use of model without flux correction enables to detect biases in physical processes, which may concern not only the surface, but also the whole ocean and atmosphere. These considerations motivate the development of non flux corrected models, but only a few studies of anthropogenic climate change have been performed with such models [*Colman et al.*, 1995; *Washington and Meehl*, 1996; *Gregory and Mitchell*, 1997].

This note presents the main results of a transient CO_2 experiment performed with the ARPEGE/OPAICE coupled model, which has been specifically developed to be used without any flux correction.

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Coupled model and experiments

A detailed description of the coupled model can be found in *Guilyardi and Madec,* [1997]. Only the main changes with respect to this first version of the coupled model are reported here.

The atmosphere model is the ARPEGE-Climat model [*Météo-France/CNRM*, 1996] from Météo-France. A T31 spectral truncation is used, corresponding to a horizontal resolution of 3.75°. There are 19 vertical levels, including 3 levels in the stratosphere. The new version of the model includes a gravity wave drag parameterization and an increased convective entrainment. Moreover, the model now includes a four-layer prognostic soil scheme, with no restoring term. Model river flows are parameterized simply by taking all excess runoff in a river basin and discharging it instantly into the ocean at outflow grid points.

The ocean model is the OPAICE model developed at Laboratoire d'Océanographie DYnamique et de Climatologie (LODYC) [*Delecluse et al.*, 1993]. The grid resolution is roughly equivalent to a geographic mesh of 2 × 1.5 degrees, with 31 vertical levels (10 levels in the top 100 meters). An isopycnal parameterization of the lateral diffusivity is used in order to avoid spurious diapycnal fluxes in regions with sloping isopycnals. The model also includes a thermodynamical sea-ice model taking into account most of the relevant thermodynamical processes concerning ice and snow transformation. Three ice thickness classes have been used in order to represent the statistical distribution of the thickness in each mesh [*Filiberti et al.*, 1997].

The atmosphere and ocean models are coupled through the OASIS coupler developed at CERFACS [*Terray et al.*, 1995] which ensures the time synchronization of the two GCMs and performs the spatial interpolation of the coupling fields from one grid to another.

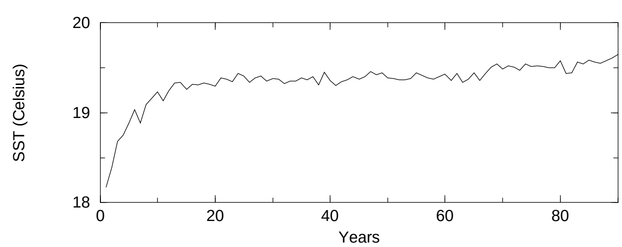

Figure 1. Time evolution of global sea surface temperature for the control simulation

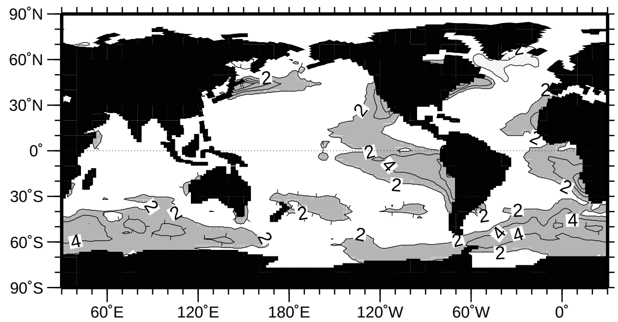

Figure 2. Difference in annual mean SST between control simulation and Levitus 82 atlas. 20-year average at the end of the simulation. Contours every 2°C, light shading under -2°C, dark shading above 2°C

The atmospheric initial state results from a forced integration of the atmospheric model by climatological Sea Surface Temperature (SST). The ocean is initially at rest, with temperature and salinity obtained from the *Levitus,* [1982] atlas. From this initial state, the coupled model has been integrated for a few years with a Newtonian restoring term for oceanic temperature and salinity at the surface and under the mixed layer. After a few years of integration, the wind-driven circulation is established and the sea-ice extent stabilizes close to observations. The coupled model is then integrated with no more internal restoring terms for a period of 130 years, the CO_2 concentration being held constant at the 1990 measured value (353 ppmv). The 80-year transient experiment, in which the CO_2 concentration is increased by 1%/year, is commenced when the initial surface drift of the control simulation stabilizes (*i.e.* after 15 years of free coupled simulation).

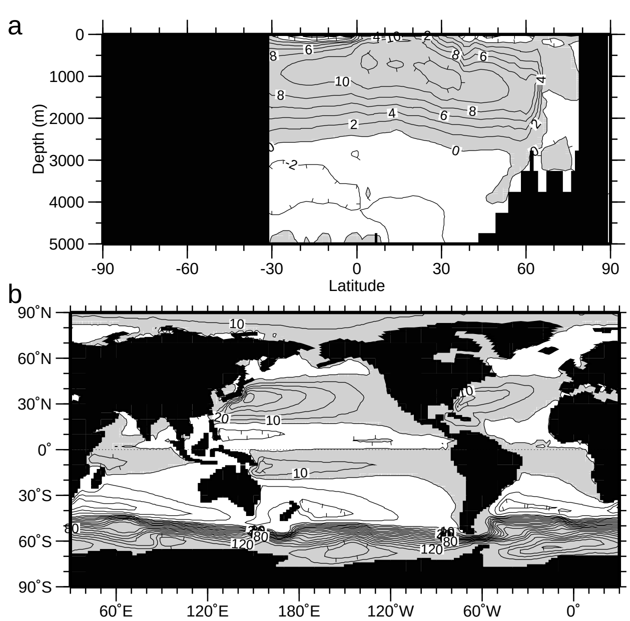

Figure 3. **a** Annual mean meridional overturning mass stream function (Sv) for the Atlantic. **b** Vertically integrated barotropic mass transport (Sv). 20-year average at the end of the control simulation

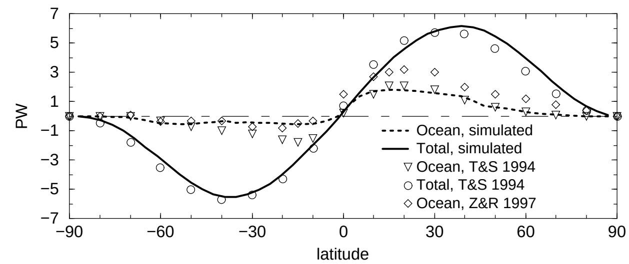

Figure 4. Northward heat transport. T&S 1994: Trenberth and Solomon 1994, Z&R 1997: Zhang and Rossow 1997. 20-year average at the end of the simulation

Control simulation

Due to the incompatibilities in the surface fluxes generated by the atmosphere and those expected by the ocean to maintain its surface temperature close to observations, a climate drift occurs when the components of climate system are coupled together. This is illustrated by the time evolution of globally averaged SST (Fig. 1). An initial warming of about +1.2°C occurs during the first 15 years, after which the SST distribution remains stable. The difference map between simulated SST and *Levitus,* [1982] atlas (Fig. 2) shows a warming mainly in the eastern tropical and subtropical oceans and in the southern Ocean. In the former region, the causes of the drift are a lack of marine stratocumulus and of coastal upwelling due to spurious values of wind curl off the coasts. This results in a weaker than observed east-west SST gradient in the tropics. The cooling in the Labrador and Irminger seas comes from an increased stratification due to too large atmospheric water flux. Furthermore, this freshening leads to the cessation of deep convection in the western North Atlantic, which reduces the strength of the thermohaline circulation. Finally, an imbalance of +1.2 W/m^2 at the top-of-atmosphere causes a secular drift of global ocean temperature of about +0.4°C/century.

The sea-ice cover is close to observations in the Arctic, although the amplitude of the seasonal cycle is too weak. In the Antarctic, only a reduced ice cover remains (about 15% of the observations) after the strong initial melting. The use of a thermodynamical sea-ice model promotes deep water formation in the Greenland and Norwegian seas and around Antarctic. Fig. 3a shows the overturning cell associated with the production of North Atlantic Deep Water (NADW), whose mean intensity is 14 Sv. This value lies within the estimated range of 13-18 Sv given by *Schmitz and McCartney,* [1993], and is comparable to results obtained with flux correction and equilibrium ocean spin-up [*Houghton et al.*, 1995]. A deep cell with an intensity of 6 Sv, associated with the production of Antarctic Bottom Water (AABW) is also present off the Antarctic.

The barotropic circulation (Fig. 3b) has been dramatically improved by the use of isopycnal lateral diffusion (*vs* horizontal). In the Atlantic, despite the coarse resolution of the model which does not allow the inertial boundary currents to be captured, the Gulf Stream intensity is of about 35 Sv at 34°N, to be compared to the estimate of 32 Sv for the Florida current [*Larsen*, 1992]. The Kuroshio intensity, of about 50 Sv is also in the estimated range [*Qiu and Joyce*, 1992], as well as the Antarctic Circumpolar Current trans-

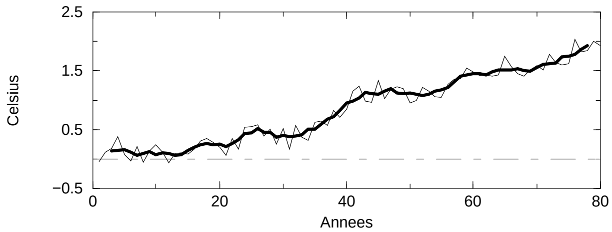

Figure 5. Time evolution of the difference in global air temperature at 2 meters between scenario and control experiments. Thick line: 5-year running mean

port through the Drake passage, of about 135 Sv, within the estimate range of 118-146 Sv from *Whitworth,* [1983].

The meridional heat transport is shown in Fig. 4. Two recent estimates have been plotted to emphasize the analysis uncertainties. The total (ocean + atmosphere) poleward energy transport is rather well captured. The energy transport by the ocean in the northern hemisphere is very close to the estimate from *Trenberth and Solomon,* [1994], but smaller than the estimate from *Zhang and Rossow,* [1997] using COADS surface turbulent fluxes climatology. The opposite occurs in the southern hemisphere where the simulated poleward oceanic heat transport is in better agreement with the latter estimate.

Climate change

The transient increase in atmospheric CO_2 produces a fairly linear increase of global surface air temperature as depicted in Fig. 5. At the time of CO_2 doubling, the global increase is +1.6°C with a trend, measured over the last 40 years, of about +0.25°C/decade.

The geographical distribution of changes in air temperature are presented in Fig. 6. An inter-hemispheric asymmetry appears clearly, the warming being larger in the northern hemisphere (+1.9°C) than in the southern hemisphere (+1.3°C). Moreover, land areas experience a greater warming than oceanic ones (except where sea-ice is present). The largest warming on land occurs at high latitudes (Siberia, northern North America), especially during fall and winter and is associated with a decrease of snow cover in these regions. At lower latitudes, the warming is strong over Asia, except India, and in the subtropical belts. The warming is weaker over the oceans (+1 to +2°C), apart from the Arctic where the retreat of sea-ice (-15% in annual mean) causes stronger changes, with important decadal variability. This warming is very important in fall and winter (up to +7°C), due to a strong melting in summer which delays the sea-ice formation and reduces its thickness. In the Antarctic, the sea-ice cover remains stable. Oceanic areas of reduced warming coincide with regions of strong mixing, *i.e.* Irminger basin and Southern Ocean.

A weakening of the strength of the thermohaline circulation occurs in the transient simulation (about 16 % in North Atlantic and 50 % around Antarctic). In the North Atlantic, this weakening may be linked to the freshening of sea surface that concerns the whole Arctic basin. The increase in atmospheric water flux (+0.174 mm/day over the 80-year period) is mainly responsible for this freshening, the sea-ice melting contribution being very weak (+0.006 mm/day).

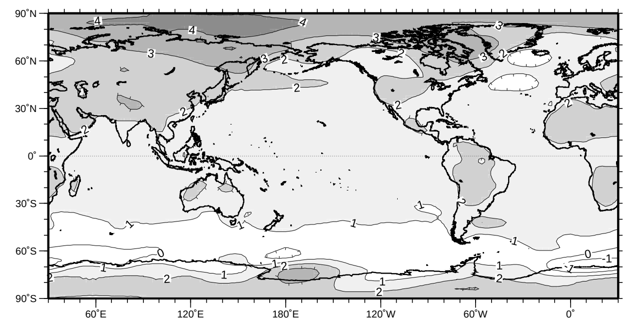

Figure 6. Difference in annual mean surface air temperature between scenario and control simulation. 20-year mean around the time of CO_2 doubling

The vertical structure of the warming (Fig. 7) shows a maximum of about +3°C in the upper tropical troposphere which can be attributed to an increase of latent heat released due to an enhanced hydrological cycle. At lower altitude, the warming is greater in the northern hemisphere. In the stratosphere, a generalized cooling occurs at all latitudes, due to enhanced radiative cooling to space. In the ocean, the warming is concentrated in the upper layers (down to 400 meter).

An enhancement of the hydrological cycle occurs, with a +3.6 % increase in the strength of precipitation and evaporation rates, at the time of CO_2 doubling. It is slightly more pronounced over land. The latitudinal dependence is characterized by an increase in net water flux over the equatorial regions and poleward of 50° and a decrease over subtropical regions, associated to a reduced soil water content, particularly pronounced over southern Europe and central Asia.

Discussion and conclusion

In this note we have presented the main results of the transient CO_2 experiment performed at CERFACS using the ARPEGE/OPAICE coupled model. A major achievement of the control simulation is the relatively small surface

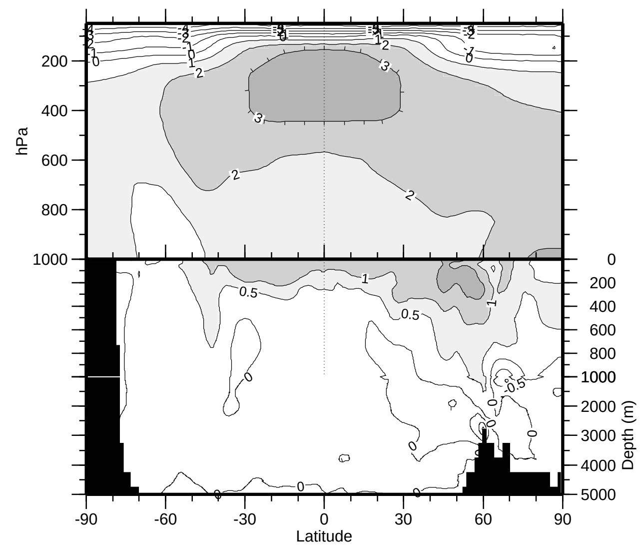

Figure 7. Zonally averaged change in annual mean atmospheric and oceanic temperature. 20-year mean around the time of CO_2 doubling.

drift and the rather satisfactory oceanic thermohaline and barotropic circulations. Also, although not discussed in the paper, the use of an isopycnal lateral diffusion ensures a reasonable water mass representation, in particular concerning the intermediate water masses [*Guilyardi*, 1997]. Flux correction may have a negative impact on this latter point, as imposing some fixed artificial fluxes may alter the water mass formation, due to inconsistencies between buoyancy fluxes and ocean dynamics, for instance in regions of strong lateral gradients [*Guilyardi*, 1997].

In the transient simulation, a global warming, of about +1.6°C, more pronounced in the northern hemisphere and over land is found as well as an increase in the hydrological cycle. Although the anthropogenic forcing is not fully realistic (e.g., lack of aerosols), this experiment is in broad agreement with previous studies made by other groups, using flux corrected or non flux corrected coupled models.

The effect of the absence of any flux correction may be assessed in the particular case of the weakening of the thermohaline circulation observed in the transient simulation. Indeed, it has been shown that the climate drift occuring at high latitudes in the control simulation suppresses deep water formation in Labrador and Irminger sea. The sea surface freshening that occurs in the transient experiment is similar to this climate drift, and results in a weakening of the thermohaline circulation. One can argue that if the initial bias were corrected, the convection in the Labrador and Irminger seas would be maintained in the control simulation. Thus, the deep water formation in these regions would be reduced in the transient experiment, the freshening due to anthropogenic forcing being particularly large there, and the thermohaline circulation affected to a larger extent.

Thus, it appears that the absence of flux correction terms enables us to better identify the causes of the initial drift of the simulation, e.g. the too large atmospheric water flux at high latitudes leading to irrealistic upper ocean freshening. These diagnostics point out the particular biases of the coupled model that need to be corrected in future simulations in order to reduce and hopefully eliminate this undesirable drift, which remains one area of uncertainty in this study.

Future work will be to assess the realism of the simulated climate variability by comparing with observations. If satisfactorily represented, the analysis of the natural variability in the decadal-interdecadal timescale range should allow the identification of the natural modes of simulated ocean-atmosphere variability and their modulation due to enhanced anthropogenic radiative forcing, shedding light upon the origin of present climate change.

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