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Biogeosciences Discussions

Interactive comment on "Atmospheric CO_2 seasonality and the air-sea flux of CO_2" *by* P. R. Halloran

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Dear Editor:

The manuscript "Atmospheric CO_2 seasonality and the air-sea flux of CO_2," by P.R. Halloran, raises an issue worth investigating, particularly on the eve of coupled carbon-climate model submissions to the upcoming IPCC AR5 assessment. Indeed, I have completed complementary simulations with a fully coupled carbon-climate model (the Canadian Earth System Model, CanESM1) which shed further light on the issues raised by the author. This work, which is in preparation, focuses mainly on the sensitivity of terrestrial-atmosphere carbon exchange to the manner of CO_2 specification. However, in light of Halloran's results, I examined more carefully the ocean-atmosphere carbon exchange in the model output, and hope that sharing some results here may

be of interest to the author and others.

The author's principal result, presented in his Fig. 2, is supported mainly by the heuristic explanations offered in the main text at Sec. 3 paragraphs 2 and 3. The interdependencies between ocean CO_2 uptake (hereafter F, positive into ocean), sea-ice cover and solubility certainly sound reasonable. But as the old saw goes, the "proof is in the pudding," and one would like to know whether these relationships are the dominant ones in a model with fully interactive ocean-atmosphere CO_2 exchange. Moreover, according to the author's Fig. 2, the peak deficit in F at 60-70° N in run 3DC relative to run UNI is quite small: ~ 0.03 mol m^{-2} y^{-1} in the 1 x CO_2 case and ~ 0.08 for 2 x CO_2, compared with ~ 0.8 mol m^{-2} y^{-1} in the control. Thus the statistical significance of such modest changes is an outstanding question.

The results discussed here were obtained from a sequence of preindustrial 1850 control and follow-up historical period runs conducted with CanESM1. The characteristics of a 2000-year long carbon-coupled control run with fully prognostic atmospheric CO_2 (hereafter X_{CO2}) were described in Christian et al. (2010), where details of the terrestrial and oceanic biogeochemical components were also discussed. From this run, a second control run with some small differences in model parameterizations, but still with freely-varying CO_2, was initiated. The latter simulation, referred to as 3DC, was continued for 265 yr, the last 200 yr of which exhibited stable variations of X_{CO2}, temperature, and near-zero carbon fluxes between the atmosphere, land, and ocean. From the end of 3DC, a third control run was launched, hereafter UNI, identical to the 3DC experiment except that X_{CO2} was held fixed globally at a value of 287.9 ppmv, the mean value over the last 100 yr of 3DC. This run was continued for 150 years. The last 50 years of runs 3DC and UNI, by which time surface fields and fluxes have adjusted to the atmospheric CO_2 specification, were analyzed in the results below.

While the author's "0 x CO_2" experiment is clearly equivalent to our UNI run, the manuscript does not contain details of how the "1 x CO_2" experiment was conducted —e.g., what exactly were the monthly values of X_{CO2} used, and how did they vary with

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geographical location? In any event, it seems appropriate that the 3DC run described above, which generates an X_{CO2} seasonality consistent with the time-dependent land and ocean carbon fluxes, be compared with Halloran's "1 x CO_2" experiment. Simulations UNI and 3DC have the same global mean X_{CO2}, thus allowing one to isolate the effect of spatiotemporally varying X_{CO2} in 3DC. The equilibrium zonal mean F in CanESM1 is similar to that shown for HadGEM2-ES in Halloran's Fig. 1, except that the former possesses an unrealistically large Southern Ocean dipole; this, however, has no bearing on the results discussed here. The zonal mean annual cycle of X_{CO2}, over ocean points only, is shown in Fig. 1. The annual cycle of X_{CO2} over the Northern Hemisphere (NH) ocean is essentially determined by the seasonality of terrestrial primary production, with below-average concentrations in NH summer when photosynthesis is strongest.

The same is not true in the Southern Hemisphere (SH) extratropics, however, where the annual cycle in X_{CO2} reflects the dominance of air-sea gas exchange over land sources and sinks, due to the much higher fractional ocean coverage at high latitudes.

The key issue highlighted by the CanESM1 results is the large wintertime extratropical variability in air-sea CO_2 flux in both hemispheres. This can be seen in Fig. 2, which shows the annual cycle in F in the 3DC run (upper panel), the corresponding standard deviation (middle panel), and the difference in air-sea flux between the two runs, ΔF = $F_{3DC} - F_{UNI}$ (lower panel). The annual cycle of F (top) strongly resembles that of the X_{CO2} anomaly at nearly all latitudes, suggesting that local solubility largely determines whether the ocean acts as a source or sink. The seasonal pattern of variability in F (middle) mirrors the corresponding pattern of surface wind variability (not shown), which has strong maxima in Jan.-Apr. at $\sim^{\circ}$ N and in July–Oct. at $\sim^{\circ}$ S. The fact that these maxima correspond with the timing and latitude of strong CO_2 uptake is important.

In the absence of a significance calculation, the zonal and annual mean ΔF in the 1 x CO_2 case (not shown) displays a positive anomaly of magnitude $\sim$10% of the control

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value at 60° N, thus resembling Halloran's Fig. 2. However, the positive ΔF between Dec. and June in the NH extratropics is not significant due to the large variability in F at those latitudes (Fig. 2, upper and middle panels). The bottom panel of Fig. 2 shows that the only significant differences between 3DC and UNI occur in April at high southern latitudes (stronger uptake in 3DC) and in Sept.–Nov. from 10—60° N (weaker uptake in 3DC).

At higher latitudes where sea ice intrudes in NH winter, no significant differences between F in the two experiments are found in CanESM1 (which has fully prognostic sea ice), despite that fact that a weak annual cycle of F is present in the control. The latter is characterized by stronger uptake in Aug.–Jan. than in the remaining months (Fig. 2, upper), roughly coinciding with the period of minimum sea ice extent (<50% coverage at points south of 70° N).

In the SH, the ocean in run 3DC takes up significantly more CO_2 in March and April at 72° S (Fig. 2, lower), where the CO_2 concentration over ocean is near its annual maximum at that latitude (Fig. 1). In contrast to the NH, the SH annual cycle in X_{CO2} is dominated by air-sea gas exchange at high latitudes, due to the remoteness of land sources and sinks. Hence, increased solubility due to enhanced CO_2 concentration at this time results in a significant difference. However, it is notable that at no other time or latitude in the SH are favourable conditions for uptake found which would bias one type of X_{CO2} treatment over the other.

Halloran also investigates the effect of a doubled CO_2 annual cycle on air-sea flux. Follow-up CanESM1 simulations of the 1850–2000 period using both types of X_{CO2} specification (UNIh and 3DCh, where the latter includes specified monthly anthropogenic CO_2 emissions as input; see Arora et al. 2009) give some indication of the effect of an altered X_{CO2} annual cycle on F. In fully carbon-coupled simulations, the latter varies with geographical location, of course—indeed, it is a highly non-uniform function of latitude. Over the 1981-2000 period, e.g., the model gives an X_{CO2} annual cycle of slightly *lower* amplitude than the preindustrial control between 28 and

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65° N, while in the SH, it ranges from 1.1 to 7.2 times the preindustrial amplitude (as defined by the maximum minus minimum zonally averaged X_{CO2} anomaly over the year). Interestingly, no statistically significant differences ΔF are found at the 95% level between the 3DCh and UNIh simulations under contemporary conditions. This indicates that while the amplitude of the X_{CO2} annual cycle does increase by a sizable factor at some latitudes (notably in the SH subtropics), this does not coincide with an increase in ocean C uptake capacity. This could be due to the concommitant decrease in CO_2solubility caused by ocean warming, which becomes evident in the last 50 years of the 20^{th} century. Furthermore, in CanESM1, the variance of F does not change significantly over the historical period either.

In conclusion, while the physical mechanisms described by Halloran do appear to operate at some level in CanESM1, the sensitivity of air-sea CO_2 flux to the manner of CO_2 specification is not statistically significant at most times and locations. Where significant differences are found, they are due to different mechanisms than those emphasized in Halloran's paper. These results highlight the importance of using a fully coupled carbon-climate model to address questions of this sort. Of course, fully interactive simulations of the same design undertaken by other models would be advisable in order to settle the question of the sensitivity of ocean uptake to X_{CO2} specification once and for all.

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Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/8/C4479/2011/bgd-8-C4479-2011-supplement.pdf

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