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Does atmospheric CO_2 seasonality play an important role in governing the air-sea flux of CO_2?

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Abstract. The amplitude, phase, and form of the seasonal cycle of atmospheric CO_2 concentrations varies on many time and space scales (Peters et al., 2007). Intra-annual CO_2 variation is primarily driven by seasonal uptake and release of CO_2 by the terrestrial biosphere (Machta et al., 1977; Buchwitz et al., 2007), with a small (Cadule et al., 2010; Heimann et al., 1998), but potentially changing (Gorgues et al., 2010) contribution from the ocean. Variability in the magnitude, spatial distribution, and seasonal drivers of terrestrial net primary productivity (NPP) will be induced by, amongst other factors, anthropogenic CO_2 release (Keeling et al., 1996), land-use change (Zimov et al., 1999) and planetary orbital variability, and will lead to changes in CO_2^{atm} seasonality. Despite CO_2^{atm} seasonality being a dynamic and prominent feature of the Earth System, its potential to drive changes in the air-sea flux of CO_2 has not previously (to the best of my knowledge) been explored. It is important that we investigate the impact of CO_2^{atm} seasonality change, and the potential for carbon-cycle feedbacks to operate through the modification of the CO_2^{atm} seasonal cycle, because the decision had been made to prescribe CO_2^{atm} concentrations (rather than emissions) within model simulations for the fifth IPCC climate assessment (Taylor et al., 2009). In this study I undertake ocean-model simulations within which different magnitude CO_2^{atm} seasonal cycles are prescribed. These simulations allow me to examine the effect of a change in CO_2^{atm} seasonal cycle magnitude on the air-sea CO_2 flux. I then use an offline model to isolate the drivers of the identified air-sea CO_2 flux change, and propose mechanisms by which this change may come about. Three mechanisms are identified by which co-variability of the seasonal cycles in atmospheric CO_2 concentration, and seasonality in sea-ice extent, wind-speed and ocean temperature, could potentially lead to changes in the air-sea flux of CO_2 at mid-to-high latitudes. The sea-ice driven mechanism responds to an increase in CO_2^{atm} seasonality by pumping CO_2 into the ocean, the wind-speed and solubility-driven mechanisms, by releasing CO_2 from the ocean (in a relative sense). The relative importance of the mechanisms will be determined by, amongst other variables, the seasonal extent of sea-ice. To capture the described feedbacks within earth system models, CO_2^{atm} concentrations must be allowed to evolve freely, forced only by anthropogenic emissions rather than prescribed CO_2^{atm} concentrations; however, time-integrated ocean simulations imply that the cumulative net air-sea flux could be at most equivalent to a few ppm CO_2^{atm}. The findings presented here suggest that, at least under pre-industrial conditions, the prescription of CO_2^{atm} concentrations rather than emissions within simulations will have little impact on the marine anthropogenic CO_2 sink.

1 Introduction

Rapid cooling, high biological activity, strong winds, and the pumping of surface waters to depth, make the high latitude oceans the planet's major atmospheric CO_2 sinks (Takahashi et al., 2009). Variability in the strength of these sinks is known to be large, but is presently poorly understood (e.g. Watson et al., 2009; Le Quere et al., 2007). Photosynthesis within the large, and extensively vegetated land masses of North America and Eurasia drive a major spring–summer CO_2 uptake in the Northern Hemisphere, with leaf fall and breakdown causing a compensating CO_2 release during autumn and winter (Machta et al., 1977). In high northern latitudes the amplitude of the CO_2^{atm} seasonal cycle presently

exceeds 15 ppm (Peters et al., 2007), and has increased significantly (+40 % between 1960's and 1990's) over recent years (Keeling et al., 1996). The sign of this change is consistent with the observed lengthening and intensification of the growing season and associated increase in net primary production, occurring in response to warming (White et al., 1999; Goulden et al., 1996), rising concentrations of atmospheric CO_2 (Lewis et al., 2004), and local increases in solar radiation intensity (Graham et al., 2003). Seasonality changes are also a potential driver of glacial–interglacial cyclicity (e.g. Gildor and Tziperman, 2000; Denton et al., 2005), as suggested by the close statistical coupling between variability in the Earth's obliquity, and glacial terminations (Huybers and Wunsch, 2005). High obliquity means high intra-annual variability in high-latitude insolation, and appears to be a precondition for deglaciation (Loutre et al., 2004; Huybers and Wunsch, 2005; Liu et al., 2008). To understand past change, and robustly investigate potential future change, we must therefore understand whether or not interactions between seasonality and the global carbon cycle can have a significant impact on the ocean sink. This challenge is of particular relevance right now because the decision has been made to prescribe CO_2^{atm} concentrations, rather than emissions, within the main Earth System Model simulations anticipated to contribute to the fifth IPCC climate assessment (Taylor et al., 2009). This decision has been made for good reason, because significant difficulties arise when attempting to undertake multi-model analysis of experiments with interactive carbon cycles seeing only common CO_2 emissions; each model will simulate a different evolution of the CO_2 airborne fraction, meaning that different models will experience different CO_2 radiative forcing histories. Despite being done for very sensible reasons, it is important to understand any potential implications of following this approach. One of the implications will be that the bulk of CMIP5 (5th Climate Model Intercomparison Project) experiments will not simulate or experience any seasonality in atmospheric CO_2 concentrations (Taylor et al., 2009). In this paper I explore the consequences of changes in CO_2^{atm} seasonality, examining conditions with no seasonal cycle, a pre-industrial seasonal cycle, and twice the pre-industrial seasonal cycle. I first explore the air-sea flux change occurring in response to a change in CO_2^{atm} seasonality by running a physical-biogeochemical ocean model (the ocean component of the HadGEM2-ES Earth System Model – see Sect. 2) with different CO_2^{atm} seasonal cycles. I then show that much of the air-sea CO_2 flux change resulting from a change in CO_2^{atm} seasonality can be reproduced within off-line calculations, and is therefore not governed by time-dependent processes, such as transport of carbon within the ocean. By holding variables constant within the off-line calculations, I identify the components of the system responsible for the seasonality-driven change in air-sea flux, and go on to suggest mechanism by which these changes could occur. Finally I quantify the net impact of a change in CO_2^{atm} seasonal cycle magnitude on the air-sea CO_2 flux, and consider the importance of simulating these processes interactively in climate-change simulations.

2 Methods

All calculations and simulations presented in this study are undertaken using, or using equations from components of, the 2nd Hadley Centre General Environmental Model, with Earth System components (HadGEM2-ES, Collins et al., 2011). Importantly for this investigation, HadGEM2-ES simulates a fully interactive and coupled ocean and terrestrial biogeochemistry (The HadGEM2 Development Team, 2011; Collins et al., 2011), and a fully coupled and well validated sea-ice component (McLaren et al., 2006). Improvements (with respect to the 3rd Hadley Centre Climate Model with low resolution but carbon cycle components HadCM3-LC, Cox et al., 2000) to the leaf phenology (Cadule et al., 2010) within the model now allow for good reproduction of the CO_2^{atm} seasonal cycle (Collins et al., 2011) (Fig. 1). Improvements to the physical-ocean and ocean-biogeochemistry within HadGEM2-ES lead to good agreement between the modeled and observed spatial pattern of air-sea CO_2 flux (Fig. 2).

TRIFFID (Top-down representation of interactive foliage and flora dynamics), the terrestrial carbon cycle component of HadGEM2-ES, contains five plant functional types and five soil carbon pools (Cox, 2001). Vegetation change is driven by carbon fluxes, with photosynthesis and respiration dependent on the climate and atmospheric CO_2 concentrations. The ocean biogeochemistry of HadGEM2-ES is simulated by the Diat-HadOCC sub-model, an extension of the original Hadley Centre Ocean carbon Cycle model (HadOCC) (Palmer and Totterdell, 2001) now including a diatom functional type, silica and iron cycling and dimethylsulphide production (Halloran et al., 2010) in addition to the generic macronutrient, phytoplankton, zooplankton and detritus simulated in the original version of the model.

Within this study, air-sea fluxes of CO_2 have been calculated using the following approach, and using values from Nightingale et al. (2000):

$$F = \frac{P_v}{(\frac{Sc}{660})^{-2}} \times ([CO_2]_{atm} - [CO_2]_{ocn}). \quad (1)$$

Where F is the air-sea CO_2 flux, P_v the piston velocity (a function of the surface atmosphere wind speed), Sc the Schmidt number, a function of surface ocean temperature, and $[CO_2]_{ocn}$ and $[CO_2]_{atm}$ the concentration of CO_2 in the ocean and atmosphere in equilibrium with the surface ocean, respectively.

Within this study, model formulations of two different levels of complexity (biogeochmical-physical ocean-model and off-line calculations) are used to identify and quantify the impact of changing CO_2 seasonality on ocean carbon uptake.

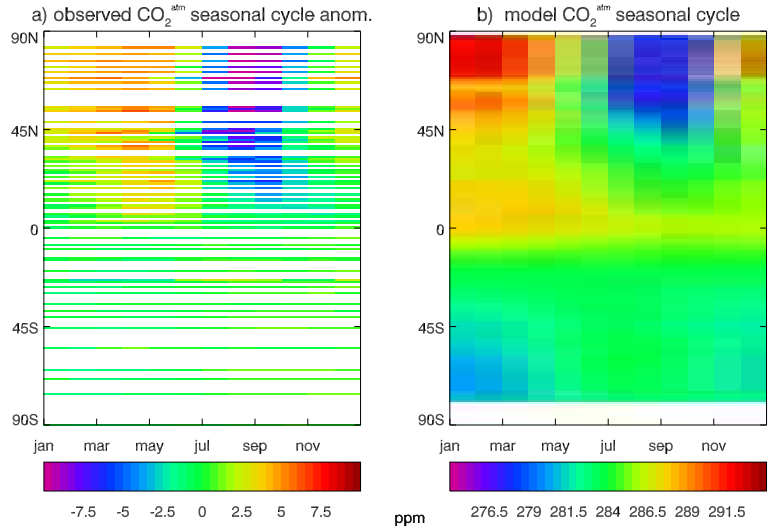

Fig. 1. **(a)** Observed atmospheric CO_2 seasonal cycle at latitudes with CarbonTracker flask measurement sites containing at least five years worth of data (Peters et al., 2007). Seasonal cycle calculated from detrended monthly values and presented as an anomaly from the annual mean at that latitude. **(b)** Pre-Industrial latitudinally averaged surface atmospheric CO_2 seasonal cycle simulated in the HadGEM2-ES model when run with interactive carbon cycle components. For consistency with calculations presented in this study, only CO_2 concentrations above the ocean have been considered. Note that although the relative magnitude of changed described by the color scale is identical in both panels, the left panel shows anomalies from zero, and the right, absolute values. This has been done to allow comparison between pre-industrial and detrended present-day values. The left panel shows the observed seasonal cycle at each latitude as an anomaly from its annual mean of zero, whereas annually averaged values for any given latitude in the right panel are not necessarily identical.

Results from fully coupled (ocean-atmosphere Earth System Model) simulations are used only to provide driving variables for ocean-model and off-line calculations, and to provide reference values against which to analyse the simulated air-sea CO_2 flux change. Model configurations and CO_2^{atm} forcings are documented in Table 1.

2.1 Ocean model experiments

A set of four ocean-model experiments are used to examine whether a change in the atmospheric CO_2 seasonal cycle has a net impact on the air-sea CO_2 flux, then to calculate the time-integrated air-sea CO_2 flux occurring in response to this change. Here the ocean component of HadGEM2-ES was run with monthly physical surface flux forcing data taken from the fully coupled pre-industrial control run (see below), are averaged to produce a repeating 12 monthly cycle. The atmospheric CO_2 concentrations seen by these experiments are transformations of the CO_2^{atm} simulated by the HadGEM2-ES model when run under pre-industrial forcings with a fully interactive ocean and terrestrial carbon cycle, and consequently where the CO_2^{atm} seasonal cycle is an emergent property of the model. Note that the temporal and spatial structure of CO_2^{atm} variability simulated by the Earth System Model compares well with that observed in the real world (Fig. 1). Manipulation of the seasonal cycle of CO_2^{atm} were achieved by multiplying the difference between individual monthly CO_2^{atm} values and the annual average CO_2^{atm} concentrations in each latitude-longitude box, by the specified factor (zero, one or two), and adding that to the annual mean value at that grid-point. Within this paper, "1× seasonal cycle" therefore refers to the seasonality simulated for the pre-industrial period within the HadGEM2-ES model when run with fully interactive carbon cycle components (Fig. 1b), "0× seasonal cycle" refers to a situation without any temporal variability, and "2× seasonal cycle" considers the annual variability at each point to be twice that simulated for the pre-industrial period. The chosen seasonal cycle magnitudes represent conditions as they may be specified in Earth System Model simulations with CO_2 prescribed as in the bulk of CMIP5 experiments (Taylor et al., 2009), as they would be simulated by a fully interactive Earth System Model for the pre-industrial, and at an arbitrarily chosen value representing a significant increase over the pre-industrial seasonal cycle to ensure a clear signal. The global annual average CO_2^{atm} seen by all simulations is adjusted to be exactly 286 ppmv; the pre-industrial CO_2^{atm} concentration specified in the fixed CO_2 control simulation.

2.2 Offline experiments

Secondly, I take the surface ocean and atmosphere physical and chemical fields relevant to CO_2 exchange (ocean and atmospheric CO_2 concentration, temperature, salinity, windspeed and sea-ice concentration) from the HadGEM2-ES coupled pre-industrial control run (i.e. a simulation without

Table 1. Specification of different model configurations and matrix showing which experiments (i.e. which CO_2^{atm} seasonal cycle forcing) have been undertaken using each configuration.

Forcing:	Constant CO_2^{atm} cycle	0× CO_2^{atm} cycle	1× CO_2^{atm} cycle	2× CO_2^{atm} cycle
CO_2^{atm} forcing description	all points = 286 ppmv	each point equals its annual average from pre-industrial simulation. global annual average = 286 ppmv	each point sees its seasonal cycle from pre-industrial simulation. global annual average = 286 ppmv	each point sees 2× magnitude of its seasonal cycle from pre-industrial simulation. global annual average = 286 ppmv
Model configuration	**Experiments undertaken**			
Fully coupled model	x		x	
Ocean-model	x	x	x	x
Off-line model		x	x	x

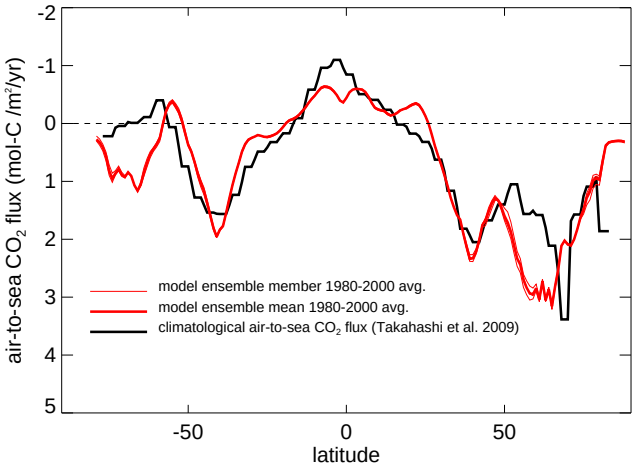

Fig. 2. Comparison of latitudinally averaged (above ocean) air-sea CO_2 fluxes calculated from an observation-derived climatology (Takahashi et al., 2009) (black), and from climate simulations using the HadGEM2-ES model (red). Earth system model simulations were forced using greenhouse gas, anthropogenic aerosol, volcanic aerosol, land-use change and solar cycle data from the years 1860–2005 (Taylor et al., 2009; Jones et al., 2011). The observation-based climatology has been calculated to represent the conditions in the year 2000, but to avoid sampling internal variability, the model results have been presented as a mean value from the years 1980–2000. The model's ensemble mean has been calculated as the average of three historical simulations started at 50 yr intervals from the pre-industrial control simulation, and is therefore considered to sample well the model's internal variability.

prescribed external forcings), and undertake air-sea CO_2 flux calculations offline (based on Eq. 1). Within my offline calculations, I have varied the values relating to the atmospheric CO_2 concentration, to simulate an increased or decreased CO_2^{atm} seasonal cycle magnitude (relative to pre-industrial). The different magnitude CO_2^{atm} seasonal cycles were calculated as described in Sect. 2.1. The calculations undertaken for this part of the study vary from those undertaken within the fully coupled model only in that monthly mean input values, rather than daily mean values, for physical and chemical fields where supplied. In all situations, using monthly mean values instead of continuous seasonal cycles will decrease the seasonal cycle's total magnitude, and therefore the magnitude of the results can be considered conservative. The result from these offline calculations will represent an instantaneous value for the air-sea CO_2 flux immediately after the seasonality change, rather than an estimation of the net ocean-atmosphere carbon exchange occurring in response to a change in CO_2^{atm} seasonality. These offline calculations have been designed to facilitate exploration of the mechanisms at play rather than accurately simulating the real-world air-sea CO_2 flux response.

2.3 Coupled ocean-atmosphere earth system model experiments

Surface atmosphere and ocean conditions required by the ocean-model and off-line simulations were provided from a pre-industrial control simulation using the fully coupled interactive carbon-cycle configuration of HadGEM2-ES (Jones et al., 2011). A minimum of 270 yr of control run simulation were used to produce all monthly and annual means. Where comparisons are made to the mean or standard deviation of the air-sea CO_2 flux simulated by the fully coupled Earth System model, the standard pre-industrial CMIP5 setup in which atmospheric CO_2 concentrations are specified at 286 ppmv throughout the year at every grid-point has been used. The decision to benchmark change against the prescribed atmospheric CO_2 concentration simulation was made because by definition these experiments will not contain feedbacks occurring in response to CO_2^{atm} seasonal cyclicity.

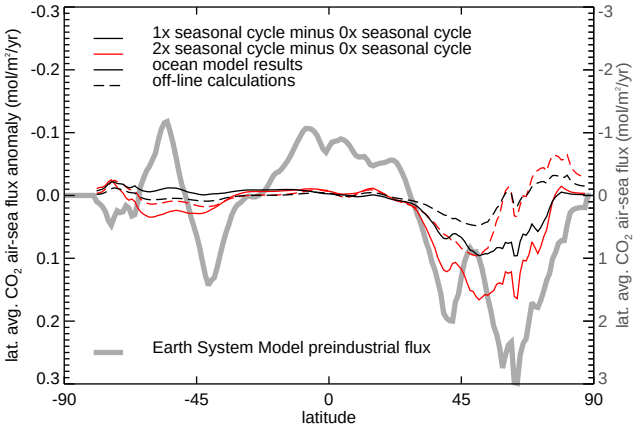

Fig. 3. Latitudinally averaged impact of changing atmospheric CO_2 seasonal cycle amplitude on the air-sea flux of CO_2 calculated as averages over the first perturbed year of ocean-model simulations (solid black and red lines), and instantaneously after the CO_2^{atm} perturbation using off-line calculations (dashed black and red lines). CO_2 air-sea flux difference calculated between the model's pre-industrial atmospheric CO_2 seasonal cycle and a situation with no seasonal cycle (black), and between two times the model's pre-industrial atmospheric CO_2 seasonal cycle and a situation with no seasonal cycle (red). Positive values represent a relative flux into the ocean. It can be seen that by increasing the seasonal cycle magnitude (but keeping the annually averaged value at individual points, and therefore globally, constant), the ocean takes up additional CO_2 in the mid-to-high latitudes, and takes up less CO_2 in the high latitudes. The enhanced relative CO_2 in- and out-gassing occurring in the mid and high Northern Hemisphere is a response to the larger seasonal cycle of atmospheric CO_2 in this hemisphere, and a tighter coupling between wind-speed, ocean CO_2 solubility, sea-ice change and atmosphere CO_2 concentration seasonality (see Figs. 8, 9 and 7 and accompanying text), relative to that in the low latitudes and Southern Hemisphere. The model-simulated latitudinally averaged pre-industrial air-sea flux of CO_2 is plotted in the dotted gray line for reference. Note the order of magnitude of increase in scale when considering the absolute air-sea flux, compared to that used for changes in flux.

Non-pre-industrial climate simulations have only been used for comparison of model-simulated air-sea fluxes with an observation-based climatology (Fig. 2). These simulations were undertaken according to the CMIP5 protocol, as described in Jones et al. (2011), and experience anthropogenic greenhouse gas and aerosol emissions and anthropogenically generated changes in land-use as well as natural volcanic and solar forcings. All coupled Earth System Model simulations used in this study are freely available from www.earthsystemgrid.org.

3 Results

The global spatial variability in the air-sea flux of CO_2 (Takahashi et al., 2009) highlighted here latitudinally (Fig. 2 black line) reflects a complex interplay of physical and biological processes. In a pre-industrial world, carbon would have been passed from the ocean to the atmosphere in areas of upwelling, then extracted from the atmosphere as biological activity took up carbon through photosynthesis and exported it to depth through sinking; as warm water moved poleward, CO_2 solubility increased and temperature driven changes in the partitioning of carbon between the reservoirs of carbonic acid, carbonate and bicarbonate allowed the water to hold more CO_2 prior to sinking to depth. The increase in the atmospheric concentration of CO_2 since industrialisation has moved this system out of equilibrium, reducing the out-gassing of CO_2 at upwelling regions, increasing the air-sea gradient of CO_2 elsewhere, modifying the temperature-driven uptake, and altering the balance of carbon species (Revelle and Suess, 1957). Despite the large anthropogenic perturbation to the system, the general features of the pre-industrial carbon cycle remain prominent, with out-gassing in equatorial upwelling zones, and in-gassing under highly productive regions such as the lower latitude Southern Ocean and mid-to high latitude Atlantic and Pacific, then temperature driven CO_2 uptake where surface waters move polewards and cool as in the North Atlantic (Takahashi et al., 2009). The close agreement between the present-day air-sea CO_2 flux calculated by the Earth System Model (Fig. 2 red-line), and the observational estimate of that flux (Fig. 2 black line) suggests that the HadGEM2-ES model is, to a first order, reproducing the dominant components of the natural carbon cycle operating over the timescales of interest.

3.1 Ocean model experiments

The first question to explore is whether a change in the CO_2^{atm} seasonal cycle will have an impact on the air-sea CO_2 flux. Looking at the average difference between an ocean-model simulation seeing no seasonality in CO_2^{atm} and one seeing the (Earth System Model's) pre-industrial CO_2^{atm} seasonal cycle ($1\times$ the seasonal cycle minus $0\times$ the seasonal cycle), and then the difference between no seasonal cycle and double the seasonal cycle (black and red solid lines respectively in Fig. 3), we see that, averaged over the first year of a simulations, the increase in the seasonal cycle amplitude promotes a relative flux of CO_2 into the ocean in the mid-to-high latitudes, and a small out-gassing of CO_2 at the highest latitudes. The average flux over the first year after the CO_2^{atm} seasonal cycle perturbation is approximately one order of magnitude smaller than the natural carbon cycle's latitudinal air-sea CO_2 flux variability (gray line in Fig. 3, note that the scale on the axis relating to this curve (right hand side) is an order of magnitude larger than that used to examine the change in CO_2 flux (left hand side)). Although

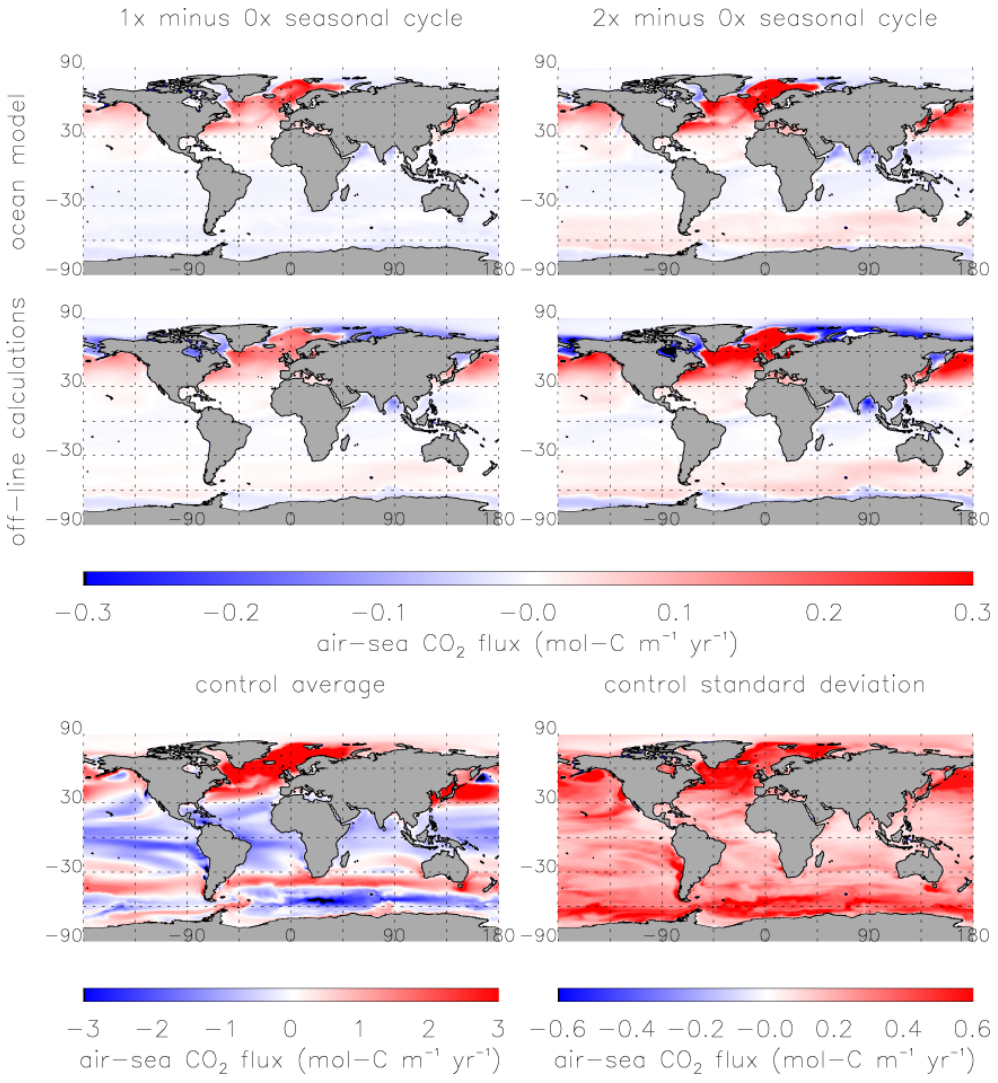

Fig. 4. Spatial maps showing the impact of changing atmospheric CO_2 seasonal cycle amplitude on the air-sea flux of CO_2 (top four figures), and the background (calculated from the first 200 yr of the control simulation) annually averaged air-sea flux and standard deviation in that flux (bottom two figures). Ocean model results (top row) have been calculated over the first 12 months after the CO_2^{atm} seasonal-cycle perturbation. Off-line calculations (second row from top) show an instantaneous estimate of the flux after the seasonal-cycle perturbation.

approximately the same pattern of response is seen in the Northern and Southern Hemispheres, the magnitude of the response is considerably larger in the Northern hemisphere; presumably reflecting the much larger seasonal cycle in the Northern Hemisphere (Fig. 1). Spatially, the change in air-sea CO_2 flux resulting from the change in CO_2^{atm} seasonality indicates that the switch from a relative in-gassing, to a relative out-gassing, occurs at the winter sea-ice edge (Fig. 4, top row), with an weak additional ocean CO_2 uptake occurring in the northern Indian Ocean. It is also interesting to note that the change from zero to one times the CO_2^{atm} seasonal cycle magnitude promotes a small out-gassing in the Southern Ocean, whereas the larger change, from zero to two times the CO_2^{atm} seasonal cycle magnitude, promotes in in-gassing (Fig. 3). The contrasting behavior depending on the magnitude of the seasonality change most likely reflects the non-linearity in the sensitivities of the opposing mechanisms at play (discussed in Sect. 3.2) to a change in CO_2^{atm} seasonal cycle magnitude.

The results above represent the difference between simulations where the intra-annual variability of the CO_2^{atm} concentration is being changed at each grid-point, but the annually averaged CO_2^{atm} at each point is remaining constant. It should however be noted that if one compares the ocean-model simulation with a constant CO_2^{atm} concentration throughout the year at each individual grid-point (as described above), to one with a constant CO_2^{atm} concentration in space as well as time (i.e. all grid points and all months having identical CO_2^{atm}, equal to the spatial and annual average value from the experiments described above (following CMIP5 protocol)), a

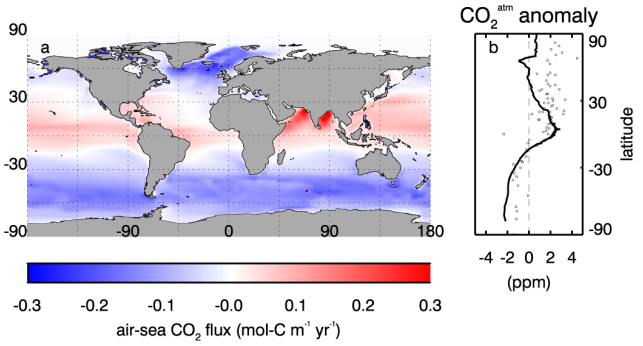

Fig. 5. Average air-sea CO_2 flux simulated during the first year after moving from the model ocean seeing a spatially and temporally homogeneous CO_2^{atm} concentration of 286 ppm to seeing annual mean (i.e. without a seasonal cycle) CO_2^{atm} simulated interactively by the HadGEM2-ES model, but still with a global mean of 286 ppmv (left). The latitudinal variability in annually averaged CO_2^{atm} calculated for the pre-industrial by the fully coupled HadGEM2-ES model (solid line), and observations (dots) presented as an anomaly from the globally averaged CO_2^{atm} during that model or observational year (right).

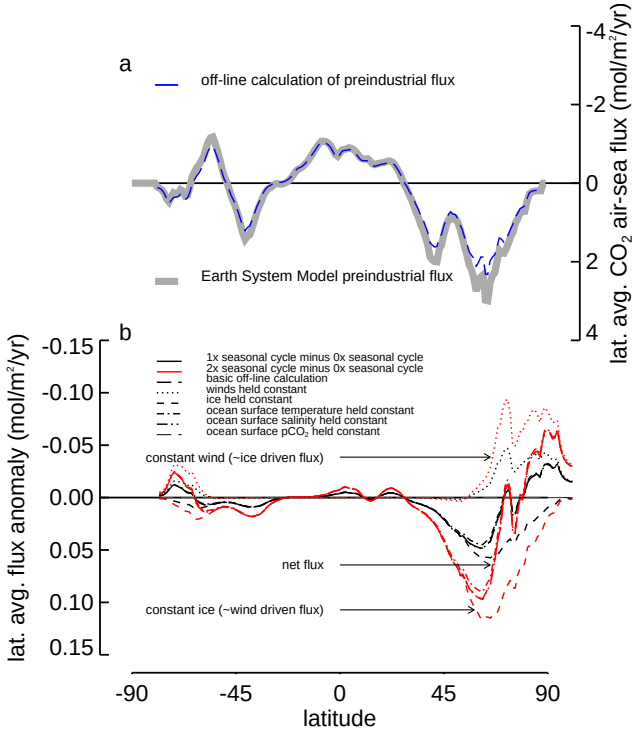

Fig. 6. **(a)** Latitudinally and annually averaged air-sea CO_2 flux simulated in (and calculated interactively by) the HadGEM2-ES pre-industrial interactive-CO_2 control simulation (gray), and off-line calculation of that air-sea flux from annually averaged temperature, salinity, wind-speeds, sea-ice concentrations, and atmosphere and ocean CO_2 concentrations (dashed blue line). **(b)** Offline calculations showing the impact on the air-sea CO_2 flux of changing the CO_2^{atm} seasonal cycle amplitude, presented as anomalies between that calculated with a pre-industrial CO_2^{atm} seasonal cycle (as calculated interactively by HadGEM2-ES) and no CO_2^{atm} seasonal cycle (black), and twice the pre-industrial CO_2^{atm} seasonal cycle, and no CO_2^{atm} seasonal cycle (red).

further difference in air-sea CO_2 flux arises (Fig. 5a). Here the change in air-sea CO_2 flux is occurring because the annually averaged CO_2^{atm} is not equal at all latitudes. Observationally, and to a large extent in the Earth System Model, we see that the average CO_2^{atm} concentration over the mid-to-high southern latitudes is 3–4 ppm lower than that in the Equatorial and Northern latitudes; presumably reflecting the large natural oceanic CO_2 draw-down occurring in the Southern Ocean (Fig. 5b). Note that comparison of the model and observations in Fig. 5b is complicated by the fact that ocean simulations have been undertaken with pre-industrial boundary conditions, and observations have been made in the present day, and consequently the observations will include an additional signature pertaining to the latitudinal distribution of anthropogenic CO_2 emissions – potentially explaining the disagreement between model and observations in the Northern Hemisphere.

3.2 Offline experiments

It is inherently difficult to isolate and identify the individual mechanisms behind any change within an Earth System Model because the model represents a myriad of processes which all interact with varying degrees of non-linearity. To isolate the variable(s) driving the change(s), one would ideally want to run a matrix of parallel simulations, each holding a different single variable constant; this is, however, often technically and/or computationally unfeasible. Here, I investigate to what degree we might be able to represent the changes identified within the ocean-model experiments in off-line calculations. Within such calculations one has the luxury of holding constant or manipulating individual variables, and consequently isolating their contribution to the overall process in question.

First I test whether it is possible to accurately reproduce the Earth System Model simulated natural air-sea flux using off-line calculations, given that it is not practicable to output data from the Earth System Model at the frequency at which it undertakes the calculations (every simulated hour). I find that using the same equations as those used in the Earth System Model (see Methods section), but using monthly-averaged, rather than hourly averaged input variables (ocean and atmosphere CO_2 concentrations, surface ocean temperature and salinity, wind-speed and sea-ice concentration) the offline calculation does a good job of replicating the Earth System Model simulated air-sea CO_2 flux (Fig. 6 top panel). Secondly, we must ask if the off-line calculations adequately recreate the change in the air-sea CO_2 flux simulated by the ocean-model as a response to a change in the CO_2^{atm} seasonal

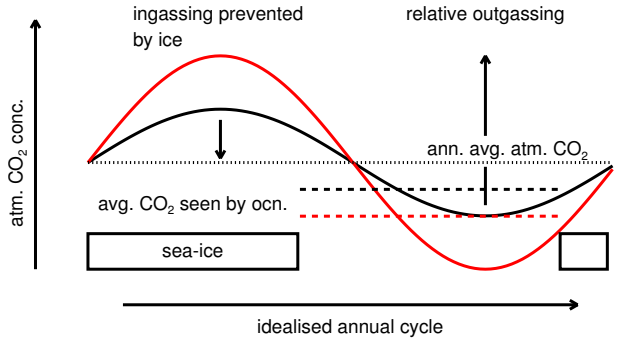

Fig. 7. Explanation of how a change in the magnitude of the atmospheric CO_2 seasonal cycle can change the air-sea CO_2 flux in seasonally sea-ice covered waters. During the year, high atmospheric CO_2 concentrations occur around the time of maximum ice-cover, and are therefore prevented from exchanging freely with the ocean, whereas at times of low atmospheric CO_2 concentration, there exists no barrier to exchange. The result of this synchronicity between the seasonal cycles of atmospheric CO_2 concentration and sea-ice extent is that the annually averaged atmospheric CO_2 concentration seen by the ocean is reduced relative to that its full annual mean value, as the amplitude of the atmospheric CO_2 seasonal cycle is increased. The solid black and red curves represent the idealised annual cycles in atmospheric CO_2 concentration at one and two times the seasonal cycle amplitude respectively. The dotted black line represents the full annually averaged atmospheric CO_2 concentration. The dashed black and red lines represent the partial average of atmospheric CO_2 concentrations for the two different seasonal cycle amplitudes, over the ice-free period.

cycle magnitude. This second question is tricky, because the off-line calculations are an estimate of the instantaneous response of the system, i.e. the response before the ocean has had any opportunity to come towards a new equilibrium; conversely, the ocean-model results can only tell us the average response over the first year (because a full seasonal cycle must be simulated), over which time the interactively modeled ocean will be rapidly moving towards a new equilibrium. Despite the fact that it is not possible to directly compare the two experiments, we can see if the features simulated by the ocean-model are recreated by off-line model, and indeed we find that they are (Fig. 4, comparing the top, and second-from-top rows), although in terms of the magnitude of the response and the detailed spatial structure, differences are unsurprisingly present (Fig. 3). Given the similarity of the spatial structures simulated by the on-line and off-line models, it is reasonable to assume that by identifying the mechanism driving the change in the off-line model, we will have a good appreciation of the mechanisms operating in a full Earth System Model, and then perhaps the real Earth System. Further, because the change in flux simulated by the on-line and off-line models are structurally similar, we can infer that to a first order the change is not driven by time-dependent processes, such as the transport of carbon within the ocean.

Working from the premise that the off-line calculations are sensibly representing the interactively modeled change in air-sea CO_2 flux occurring in response to a change in CO_2^{atm} seasonality, one can now explore the drivers of that change. I recalculate the change in air-sea flux moving from zero to one times the magnitude of the CO_2^{atm} seasonal cycle (black) and zero to two times the magnitude of the seasonal cycle (red); individually holding each of the components of the air-sea flux calculation constant at each grid-point throughout the annual cycle (variously dotted/dashed lines in Fig. 6b). I find that the change can be accounted for by the interaction of annual variability in wind-speed, sea-ice and to a much smaller degree, surface ocean temperatures with the annual cycle of atmospheric CO_2. Applying the annually averaged wind-speed to each month of the off-line simulation one finds that there is no change in the air-sea CO_2 flux between 60° S and 50° N (Fig. 6b dotted lines), telling us that the interaction of the seasonal cycle in CO_2^{atm} and wind-speed over these is the sole driver of the change over those latitudes. North of 50° N and south of 60° N the dotted line in Fig. 6b deviated from the zero line, representing the influence of all factors other than wind-speed on the change in air-sea CO_2 flux. It turns out that the deviation of the dotted line from zero in Fig. 6b is essentially representing the sea-ice driven contribution to the change in air-sea CO_2 flux, since individually holding all the other remaining variables constant has a negligible impact on the off-line calculation of the air-sea flux, the only minor exception being when holding temperature constant. When applying the annually averaged temperature at each point to each month in the off-line calculation, a small deviation from the results of the full off-line calculation occur between about 50 and 60° N (Fig. 6b dash-dot-dash line). I will next explore how and why the interaction between the seasonality of the identified variables and the seasonality of CO_2^{atm} concentrations might bring about the simulated change in air-sea CO_2 flux.

3.3 The mechanisms

In the high latitudes, particularly of the Northern Hemisphere, the seasonal cycles of CO_2^{atm} concentration and sea-ice extent vary approximately in phase. The reason for the synchronous change is that they share a common driving mechanism, light. During the winter months, little light is available for either photosynthesis or heating of the surface ocean; vegetation growth therefore slows or vegetation dies back causing a net release of CO_2, and (due to the cooling) sea-ice forms. Conversely, in the spring and summer, vegetation begins to draw-down CO_2 from the atmosphere, and, as more light reaches the ocean, sea-ice begins to melt. As a consequence of the seasonal cycles of CO_2^{atm} concentration and sea-ice extent varying in phase, when CO_2^{atm} is high, an ice-barrier limits CO_2 exchange with the ocean, and when sea-ice is not present, CO_2^{atm} concentrations are low and the air-sea pCO_2 gradient (and therefore CO_2 flux) is reduced.

Making the first order assumption that sea-ice is impermeable to CO_2 (although some CO_2 flux through continuous ice has been observed (e.g. Zemmelink et al., 2006)), the average CO_2^{atm} concentration that the ocean sees is therefore reduced relative to its full annual average (Fig. 7). A caveat here is that the seasonal melting of sea-ice can leave behind a stratified low-salinity lid which could limit the volume of water and modify the chemistry of that water, which may come into equilibrium with the atmosphere (Cai et al., 2010). The potential suppression of air-sea exchange in heavily stratified seasonally ice-covered waters may weight the net air-sea flux change towards that occurring in response to changes in the solubility mechanism. This component of the mechanism can not be addressed in the off-line model. I propose that the mechanism described here explains the change in air-sea CO_2 flux seen between the off-line model calculations with and without sea-ice concentrations held temporally constant.

In the mid-to-high latitudes, equatorward of the maximum seasonal extent of sea-ice, I find that the change in air-sea CO_2 flux resulting from a change in CO_2^{atm} seasonality is driven by two factors: the intra-annual variability in CO_2 solubility and the correlation between seasonal wind-speed and CO_2^{atm} change. By far the dominant mechanism is the co-variability of wind-speed and CO_2^{atm} (Fig. 6b). In common with the sea-ice mechanism, in the mid-to-high latitudes, particularly in the Northern Hemisphere, the seasonal cycle of surface wind-speed varies approximately in phase with the seasonal cycle of CO_2^{atm} concentrations (Fig. 8). Stronger winds when the CO_2^{atm} is highest allow a greater flux of CO_2 into the ocean (assuming under-saturation of CO_2^{ocn} persists) than would occur if wind-speed was highest when CO_2^{atm} concentrations were low. The correlation between wind-speed and CO_2^{atm} concentration throughout the year (Fig. 8) occurs because the winter-hemisphere decrease in insolation, which results in net respiration over photosynthesis, and therefore terrestrial CO_2 release, also drives an increased latitudinal thermal gradient, an increased equator-to-pole pressure difference, and increased wind-speeds. I propose that this wind-driven mechanism accounts for the difference between off-line calculations undertaken with temporally fixed and varying wind-speed, and therefore a large component of the CO_2^{atm} seasonality-driven air-sea CO_2 flux. Similarly, the seasonal cycle of CO_2 solubility varies approximately in phase with the seasonal cycle of CO_2^{atm} concentrations (Fig. 9). CO_2 solubility and the CO_2^{atm} concentration in the high (particularly northern) latitudes share a common driver, incident light (and therefore heat). A high CO_2 solubility when the CO_2^{atm} concentration is high, and a low CO_2 solubility when the CO_2^{atm} concentration is low, promotes an increased ocean-atmosphere pCO_2 gradient relative to a situation where high solubility occurs when CO_2^{atm} is low, and vice versa. The increased pCO_2 gradient increases the flux of CO_2. This solubility change mechanism can account for the air-sea CO_2 flux difference between the fixed and temporally varying temperature simulations seen between 50–60° N. Any change in CO_2^{atm} seasonality accentuating these relationships between sea-ice, wind-speed and temperature driven CO_2 variability, and the seasonality of CO_2^{atm} will enhance/reduce the importance of the discussed mechanisms.

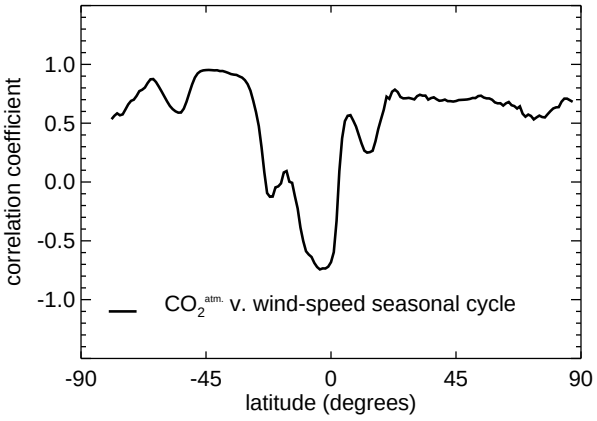

Fig. 8. Correlation coefficient between average monthly latitudinally averaged wind-speeds and CO_2^{atm} concentrations, as simulated in the fully coupled Earth System Model pre-industrial simulation.

Individually, none of these three mechanisms are likely to have a large impact on CO_2^{atm} concentrations. Assuming no feedbacks operate, after a change in seasonal cycle amplitude, the new equilibrium CO_2^{atm} concentration would be unlikely to shift by more than the high latitude CO_2 seasonal cycle amplitude change. Considering the sea-ice mechanism, the dashed black line in Fig. 7 represents the average atmospheric CO_2 concentration initially in equilibrium with the underlying seawater, the red dashed line then represents the average atmospheric CO_2 concentration after a change in seasonal cycle magnitude, but prior to reaching a new air-sea equilibrium. The ocean will undergo a relative release of CO_2 to the atmosphere until the atmospheric CO_2 concentration average over the ice-free period is in equilibrium with the seawater again. If we were to assuming that the air-sea CO_2 flux change has only a negligible effect on oceanic CO_2 concentrations, the new equilibrium would be reached when the dashed red line had raised to the concentration shown by the dashed black line, i.e. atmospheric CO_2 increased until the CO_2^{atm} experienced by the ocean during the ice-free months was again equal to the ocean CO_2 concentration. The problem with this reasoning is that the present high-northern-latitude ocean is not in equilibrium with the atmosphere, and is still taking up CO_2 until it sinks (Takahashi et al., 2009). The steady-state atmospheric CO_2 concentration resulting from a change in the magnitude of the CO_2^{atm} concentration seasonal cycle would therefore be a function of (to a first order) circulation, temperature change with latitude, the wind-driven rate of air-sea CO_2 exchange, time, and the spatial pattern of air-sea flux change (Volker et al., 2002). Consequently, this analysis of the off-line experiments will never completely represent the changes seen in ocean-model

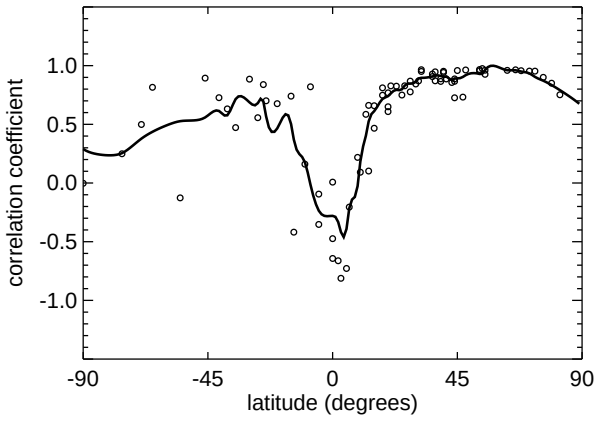

Fig. 9. Latitudinal dependence of the phase synchronicity between the seasonal cycle of atmospheric CO_2 concentrations and the solubility of CO_2 in seawater. Correlation coefficients between observed monthly averaged atmospheric CO_2 concentration seasonal cyclicity and the calculated monthly averaged seasonal cycle of CO_2 solubility in seawater are plotted against observation latitude. Points relate to all CarbonTracker flask measurement sites containing at least five years worth of data (Peters et al., 2007), as present in http://www.esrl.noaa.gov/gmd/ccgg/carbontracker on 11 August 2010. Atmospheric CO_2 observations were detrended using a third-order polynomial, fitted (using the least squares method) to all observations at each individual site. Detrended data were averaged into a typical annual cycle, then the correlation coefficient calculated between the 12 average months of atmospheric CO_2 data and 12 months of latitudinally averaged CO_2 solubility, calculated at the latitude corresponding to the relevant atmospheric CO_2 measurement site. CO_2 solubilities in seawater were calculated from World Ocean Atlas 2009 surface temperature and salinity climatologies (Locarnini et al., 2009; Antonov et al., 2009). The solid line depicts a cubic-spline interpolated 6-point moving average through all of the data. High correlation values indicate that the annual cycles in atmospheric CO_2 concentration and CO_2 solubility in seawater vary in phase at that latitude.

experiments, which themselves are still one step removed from fully coupled Earth System model experiments.

3.4 Towards the equilibrium response

Analysis of the off-line simulations allow us to understand the factors driving the air-sea CO_2 flux response to a perturbed CO_2^{atm} seasonal cycle, but does not allow us to ask whether changes in CO_2^{atm} seasonality might be responsible for significant cumulative changes in ocean carbon uptake; therefore, whether it is important for this reason to undertake coupled simulations with a fully interactive carbon cycle, rather than simulations essentially separating the ocean and terrestrial systems by prescribing atmospheric CO_2 concentrations. Examined as a global average, the deviations between the air-sea CO_2 flux in parallel sections of the zero and one-times CO_2^{atm} seasonal-cycle simulations, we see a maximum annually averaged out-gassing of carbon of 0.025Gt during the year after the seasonal cycle change is enforced (Fig. 10). Figure 10 presents the global air-sea CO_2 flux calculated with the ocean-simulation with each grid point seeing the annual average CO_2^{atm} for that grid-point simulated in the preindustrial fully-coupled control simulation (i.e. zero seasonal cycle) minus the control simulation with constant CO_2^{atm} seen by all grid-points (blue line). The out-gassing reflects the fact that in the Southern Ocean and high North Atlantic, the CO_2^{atm} seen by the ocean is less than the global average and consequently out-gassing occurs (see Sect. 3.4 and Fig. 5). The black and red line in Fig. 10 (difference between $1\times$ and $0\times$ seasonal cycle, and $2\times$ and $0\times$ seasonal cycle, respectively) do not show the signal of the background latitudinal CO_2 variability because they are presented as a difference of two simulations both containing this feature. The timescale over which this perturbation to the carbon cycle would come into equilibrium is unclear from simulations of the length undertaken here (50 yr), but a timescale of centuries appears likely. Given an average out-gassing of CO_2 of around $0.01\,Gt\,yr^{-1}$ over a couple of centuries, and assuming no mitigating terrestrial carbon cycle response, we might expect these processes to alter the background atmospheric CO_2 concentration by a small number of parts per million. The short timescale response is however considerably less than the inter-annual variability in the air-sea CO_2 flux (Fig. 10), so it is unlikely to contribute towards any rapid air-sea CO_2 flux changes or significant inter-annual variability.

4 Discussion

Despite being unlikely to alter global CO_2^{atm} concentrations significantly, the consequences of the operation of the sea-ice, wind-speed and solubility mechanisms, described here, under changing CO_2^{atm} seasonal cycle amplitude are interesting spatially and temporally. Firstly, an increase in the CO_2^{atm} seasonal cycle magnitude and a decrease in sea-ice extent (Intergovernmental Panel on Climate Change, 2007) over the coming decades, if acting alone, would cause the seasonal-solubility driven oceanic CO_2 uptake to increase and move to higher latitudes, and an increased intensity but reduced area, of seasonal-sea-ice driven relative out-gassing at the highest latitudes. Secondly, abrupt changes in the terrestrial biosphere, whether through natural variability (e.g. drought) or anthropogenic land-use change (e.g. deforestation), without necessarily impacting the annually averaged CO_2^{atm} concentration, could drive locally important changes in the high-latitude air-sea flux of CO_2. It is also possible that year-to-year changes in the CO_2^{atm} seasonal cycle, rather than in annually averaged CO_2 concentrations, could account for a small component of the observed, but largely unexplained high latitude air-sea CO_2 flux variability (e.g. Watson et al., 2009; Le Quere et al., 2007). A further point to note is that, assuming the CO_2^{atm} seasonality change is occurring in response to a change in some component of the climate

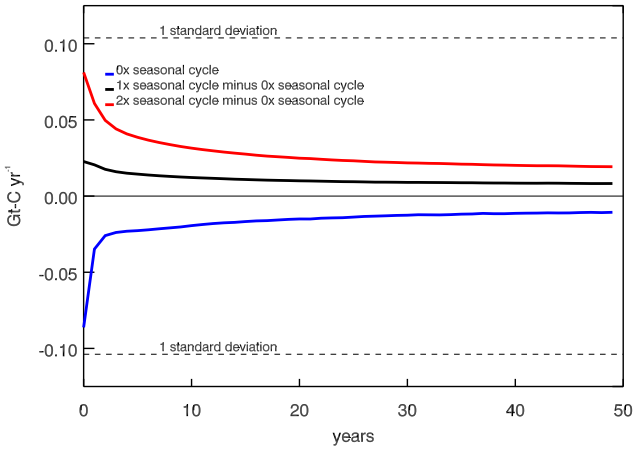

Fig. 10. Globally averaged air sea flux of CO_2 calculated as a difference between an ocean-model simulation seeing constant atmospheric CO_2 for 286 ppmv at all points, and spatially varying, but temporally constant (zero seasonal cycle) CO_2^{atm} (blue). Globally averaged air-sea flux of CO_2 calculated as a difference between the annual cycle of pre-industrial CO_2^{atm} generated by the Earth System Model control run (and adjusted so that the annual global mean is exactly 286 ppmv) (black). Globally averaged air-sea flux of CO_2 calculated as a difference between two times the annual cycle magnitude of pre-industrial CO_2^{atm} generated by the Earth System Model control run (and adjusted so that the annual global mean is exactly 286 ppmv, and the annual mean at each point equals the annual mean of that grid-point in the Earth System Model control run) (red). The dashed lines represent one standard deviation of the globally annually averaged air-sea CO_2 flux calculated over 270 yr of the fixed CO_2^{atm} pre-industrial Earth System Model control run.

system (rather than for example, an anthropogenically imposed change in land use), the ocean ecosystem, and factors impacting the air-sea flux (e.g. temperature and wind speed) may respond themselves to the climate forcing, modifying and potentially dominating the response to the change in CO_2^{atm} seasonality.

One aspect of the seasonality and air-sea flux feedback mechanisms not discussed here is that of shifts in seasonal cycle phase, rather than amplitude. Various mechanisms, such as changing precipitation pattern or intensity, could shift the CO_2^{atm} cycle phase independently from the sea-ice and seawater CO_2 solubility cyclicity. The theory behind how changing CO_2 seasonal cycle amplitude impacts on the CO_2 air-sea flux, presented here, could equally be used to understand the response of the air-sea CO_2 flux to changing CO_2^{atm} seasonal cycle phase. A relative shift in the phase of the seasonal cycles of CO_2^{atm} concentration, and sea-ice extent or wind-speed or seawater CO_2 solubility may have the capacity to produce much larger changes in ocean in/out-gassing than changes in CO_2^{atm} concentration seasonal cycle amplitude. A relative shift in phase between these variables might be expected if a change in phase of the CO_2^{atm} seasonal cycle, as observed over the last few decades (Keeling et al., 1996), was to occur in response to changing CO_2 fertilisation of the terrestrial biosphere, rather a change in temperature (which may be expected to impact all of the cycles in the same sense).

Presently, the seasonal cycle in earth system model CO_2^{atm} concentrations is often considered a way of diagnosing and bench-marking changes in model terrestrial net primary production (e.g. Cadule et al., 2010; Heimann et al., 1998), rather than as critical prognostic variability in its own right. Given the identification of mechanisms by which CO_2^{atm} may feed back (at least locally) on air-sea CO_2 fluxes, it is important that the terrestrial biosphere components of earth system models consider the seasonal cycle of CO_2^{atm} as more than a diagnostic tool, and are developed, validated, and explored accordingly.

5 Conclusions

Despite being a prominent and dynamic feature of the carbon cycle, the climatic influence of the CO_2^{atm} concentration seasonal cycle has, to the best of my knowledge, not previously been explored. In Northern Hemisphere seasonally ice-covered waters, the air-sea flux change seen here appears to occur as a consequence of the synchronicity between the CO_2^{atm} and sea-ice seasonal cycle. Equatorward of the maximum sea-ice extent, the change in air-sea flux appears to results from of synchronicity between the seasonal cycles of CO_2^{atm} and the seasonal cycles of wind-speed and seawater CO_2 solubility. The operation of the described mechanisms could allow the sign of the net air-sea flux change to switch depending on the maximum sea-ice extent. Despite demonstrating that changes in the amplitude of the CO_2^{atm} seasonal cycle can impact the mid-to-high latitude air-sea flux of CO_2, at least at a global level the impact of this change is marginal.

Given the small impact on globally averaged air-sea CO_2 fluxes found to occur in response to a change from a spatially and temporally constant CO_2^{atm} to the observed seasonal cycle, it appears that little error will be introduced to simulations, via the mechanisms discussed in this paper, by the decoupling of ocean and terrestrial carbon cycle components through the prescription of CO_2^{atm} concentrations, rather than allowing the modeled carbon cycle to generate its own CO_2 concentration, seasonality and distribution from specified CO_2 emissions.

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