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Atmospheric CO_2 seasonality and the air-sea flux of CO_2

P. R. Halloran

Met Office Hadley Centre, FitzRoy Road, Exeter, Devon, EX1 3PB, UK

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Correspondence to: P. R. Halloran (paul.halloran@metoffice.gov.uk)

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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), 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. Here I describe two separate mechanisms by which co-variability of the seasonal cycles in atmospheric CO_2 concentration, ocean temperature, and sea-ice extent could potentially lead to rapid changes in the air-sea flux of CO_2 at high latitudes. One mechanism responds to an increase in CO_2^{atm} seasonality by pumping CO_2 into the ocean, and the other by releasing CO_2 from the ocean (in a relative sense). The relative importance of the two mechanisms is determined by the seasonal extent of sea-ice, the net sign of their operation may therefore have interesting implications for glacial-interglacial and future climate change. 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. The decision to prescribe CO_2^{atm} concentrations within model simulations for the fifth IPCC climate assessment (Taylor et al., 2009) may therefore result in an underestimation of changes in marine CO_2 sources and sinks.

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

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(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 been increasing significantly in an apparent response to rising atmospheric CO_2 concentrations (+40 % between 1960's and 1990's) (Keeling et al., 1996). 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 interactions between seasonality and the global carbon cycle. In this paper I present two novel mechanisms linking changes in seasonality with changes in the magnitude of oceanic CO_2 sources and sinks.

2 Methods

Pre-industrial climate simulations (i.e. simulations without prescribed exernal forcings) were undertaken using the earth system model HadGEM2-ES, with fully interactive and coupled ocean and terrestrial biogeochemistry (Martin et al., 2011; Collins et al., 2011), and a fully coupled and well validated sea-ice component (McLaren et al., 2006). Improvements to the leaf phenology within the model now allow for good reproduction of the CO_2^{atm} seasonal cycle (Collins et al., 2008), and improvements to the physical and ocean-biogeochemistry model lead to good agreement between the modelled and observed spatial pattern of air-sea CO_2 flux (Fig. 1).

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Within the HadGEM2-ES model, air-sea carbon fluxes are calculated as a function of the atmospheric and ocean CO_2 concentrations, the seawater temperature and salinity (influencing the CO_2 solubility and the transfer velocity), windspeed, and sea-ice concentration, as described for a previous model version by Palmer and Totterdell 2001. To allow me to calculate the impact on air-sea fluxes of changes in the seasonal cycle of atmospheric CO_2 concentrations, without the need to spin up new model simulations to equilibrium with those seasonal cycles, I have extracted the physical and chemical fields described above calculated for the model's pre-industrial state, and undertaken air-sea CO_2 flux calculations offline. 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. The different magnitude CO_2^{atm} seasonal cycles were calculated by multiplying the difference between individual monthly CO_2^{atm} values and the annual average CO_2^{atm} concentrations in each latitude-longtitude box, by the specified factor (zero, one or two), and adding that to the anual mean value at that point. Within this paper, "1x seasonal cycle" therefore refers to the seasonality simulated for the preindustrial period within the model, "0x seasonal cycle" refers to a situation without any temporal variability, and "2x seasonal cycle" considers the annual variability at any each point to be twice that simulated for the preindustrial period. The calculations undertaken for this study vary from those which would be undertaken within the model only in that, annual, rather than daily mean, values for physical and chemical fields where used, and the surface wind field was calculated from wind mixing energy rather than taking values directly from the model's atmosphere. 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 of these calculations will be an instantaneous value for the air-sea CO_2 flux immediately after the seasonality change, rather than an estimation of the net ocean-atmophere carbon exchange occuring in response to a change in CO_2^{atm} seasonality. Calculation of the net carbon exchange at equilibrium will require long simulations with fully coupled earth system models.

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3 Results

Investigating the consequences of artificially doubling the amplitude of the seasonal cycle simulated within a pre-industrial earth-system-model (HadGEM2-ES (Martin et al., 2011; Jones et al., 2011; Collins et al., 2008)) climate, and calculating the instantaneous change in the air-sea flux of CO_2, I find two contrasting impacts. The first is a relative out-gassing from the high latitude oceans, the second is a relative in-gassing from the mid-to-high-latitude oceans (Fig. 2). These two effects will initially be considered separately.

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. 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 reduced relative to its full annual average (Fig. 3).

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 the intra-annual variability in CO_2 solubility. In common with the sea-ice mechanism, in the mid-to-high latitudes, particularly in the Northern Hemisphere, the seasonal cycle of CO_2 solubility varies approximately in phase with the seasonal cycle of CO_2^{atm} concentration (Fig. 4). The exchange of CO_2 between the atmosphere and the ocean occurs to bring the concentrations in each media towards equilibrium. Air-sea CO_2 concentration equilibrium occurs between the partial pressure of CO_2 in seawater multiplied by the solubility of CO_2 in that seawater, and the CO_2^{atm} concentration

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multiplied by the solubility of CO_2 in the seawater below. The solubility of CO_2 in seawater is a function of seawater temperature and, to a lesser degree, salinity. Again, CO_2 solubility and the CO_2^{atm} concentration in the high (particularly northern) latitudes share a common driver, incident light (and therefore heat). Having 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, and both CO_2 concentration and solubility always having positive values, an increase in the CO_2^{atm} seasonal cycle magnitude will cause an increase in the annually averaged product of the two quantities (Fig. 5). Raising the CO_2^{atm} concentration in potential equilibrium with seawater will cause an increased CO_2 gradient into the ocean, and promote a relative increase in the air-to-sea CO_2 flux.

Individually, neither of these two effects 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. 3 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. Assuming 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 of the dashed black line. 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. The net change in the air-sea flux

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of CO_2 resulting from a seasonal cycle shift under various conditions must therefore be quantified using coupled earth system models. A further caveat 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 supression of air-sea exchange in heavily stratified seasonally ice-covered waters may weight the net air-sea flux change towards that occuring in response to changes in the solubility mechanism.

Despite, under a pre-industrial climate configuration, being unlikely to alter global CO_2^{atm} concentrations by more then a few ppm, the consequences of the operation of the sea-ice and solubility mechanisms under changing CO_2^{atm} seasonal cycle amplitude have important implications 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, will 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. These shifts will impact the location and magnitude of high latitude ocean acidification (Steinacher et al., 2009). 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 significant step changes or inter-annual variability in the high-latitude air-sea flux of CO_2. It is possible that year-to-year changes in the CO_2^{atm} seasonal cycle, rather than in annually averaged CO_2 concentrations, could accounting for the observed, but largely unexplained high latitude air-sea CO_2 flux variability (e.g. Watson et al., 2009; Le Quere et al., 2007). Finally, the combination of these mechanisms have potentially interesting implications for glacial-interglacial cycling.

As previously discussed, the termination of glacial periods tends to occur at times of high orbital obliquity (Huybers and Wunsch, 2005). High obliquity causes increased high latitude insolation seasonality. A large seasonal cycle in high latitude insolation will cause high seasonal variability in sea-ice cover and high seasonal variability in

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CO_2 uptake and release by the terrestrial biosphere. The balance between the two identified mechanisms will be sensitive to the maximum annual sea-ice extent. When sea-ice is extensive, the described sea-ice mechanism dominates over the described solubility mechanism, and vice versa. During warm periods, with high seasonality, the solubility mechanism will be strong, and will pump CO_2 into the ocean, whereas during cold periods of high seasonality, the dominant mechanism will switch, and (in a relative sense) pump CO_2 into the atmosphere. The combination of these mechanisms would potentially allow the termination of a glacial to skip a number of periods of high obliquity, as is observed (Huybers and Wunsch, 2005), and only induce CO_2 release, potentially triggering warming feedbacks (e.g. Gildor and Tziperman, 2000) and deglaciation, once the glacial world has cooled enough to reach a sea-ice determined threshold. Given a slow cooling, and therefore a slow increase in maximum sea-ice extent, this mechanism also offers a possible explanation for the switch between a ~40 kyr and ~100 kyr glacial-interglacial periodicity at around 900 kyr before present (Raymo and Nisancioglu, 2003). To test whether the combination of these mechanisms could contribute to the timing of glacial terminations would require an appreciation of the spatial and intra-annual variability in glacial CO_2^{atm} concentrations. The limited temporal resolution of most palaeoclimate proxies makes this a difficult, but potentially important, challenge. Furthermore, it will be important to understand the past spatial and sub-annual variability in CO_2 solubility and sea-ice extent. Although a uniform increase in CO_2 solubility under a colder climate would make little difference to the mechanisms discussed, changes in the distribution of the reduced solubility due to reorganisation of ocean circulation may significantly amplify or reduce the climatic importance of this mechanism. Once validated for a glacial world, earth system models containing fully interactive and coupled carbon-cycle components, could be run to test whether the described mechanisms could play a role in the pacing of obliquity-driven glacial terminations.

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Presently, the seasonal cycle in earth system model CO_2^{atm} concentrations is often considered a way of diagnosing and benchmarking changes in model terrestrial net primary production (e.g. Cadule et al., 2010), rather than as critical prognostic variability in its own right. Given the potential sensitivity of the climate system to seasonality-drive changes in the air-sea flux of CO_2, it is important that the terrestrial biosphere components of earth system models consider the seasonal cycle of CO_2^{atm} as a critical component of the model, and develop, validate, and explore models accordingly.

Given the findings presented here, care must be taken when analysing model experiments where the CO_2^{atm} concentration is prescribed without either seasonal or spatial variability. Experiments of this design will contribute heavily to the conclusions reached in the IPCC's 5th climate assessment (Taylor et al., 2009). Although it will be possible to diagnose the seasonal carbon fluxes simulated within these model experiments, the individual model carbon-cycle components will not be able to feed back on each other through the mechanisms described. It is therefore imperative that fully coupled carbon cycle simulations are run and explored to quantify the feedbacks missing from the main body of simulations, and if nothing else, to show that feedbacks, such as those discussed here, are small. The feedbacks described here may help us understand the complex issue of high-latitude ocean CO_2 uptake in response to retreating sea-ice extent.

4 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. I demonstrate 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. In seasonally ice-covered waters, the air-sea flux change occurs 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 occurs as a result of synchronicity

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between the CO_2^{atm} and seawater CO_2 solubility seasonal cycles. The operation of the described mechanisms allows the net air-sea flux sign to switch depending on the maximum sea-ice extent, making the combination of these mechanisms of particular relevance to contemporary and glacial-interglacial climate change. 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, can 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 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. I have made no attempt in this study to quantify the magnitude of the highlighted carbon cycle feedbacks at steady state. To determine whether the described mechanisms could play a significant role in past or future carbon cycle change will require the spin up of (ideally) fully coupled earth system models to equilibrium with different amplitude (and potentially phase) atmospheric CO_2 seasonal cycles. If shown to be significant, the climatic impact of the seasonality-driven carbon cycle response must then be quantified.

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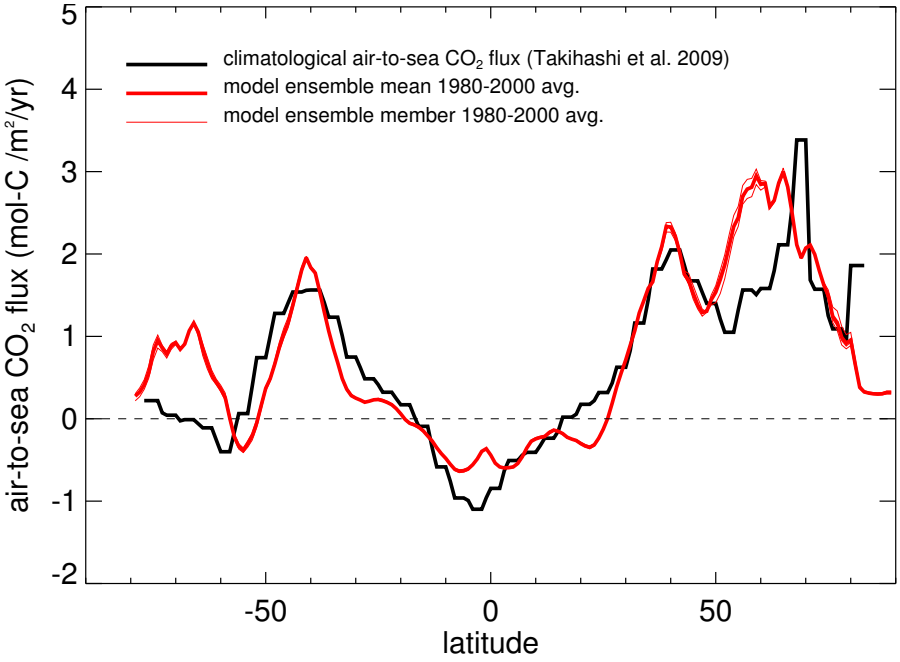

Fig. 1. Comparison of latitudinally averaged global air-sea CO_2 fluxes calculated from an observation-derived climatology (Takahashi et al., 2009) (black), and from climate simulations using the HadGEM2-ES model (red). Earth System model simulations were forced using greenhouse gas, anthropogenic aerosol, 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 preindustrial control simulation, and therefore considered to sample well the model's internal variability.

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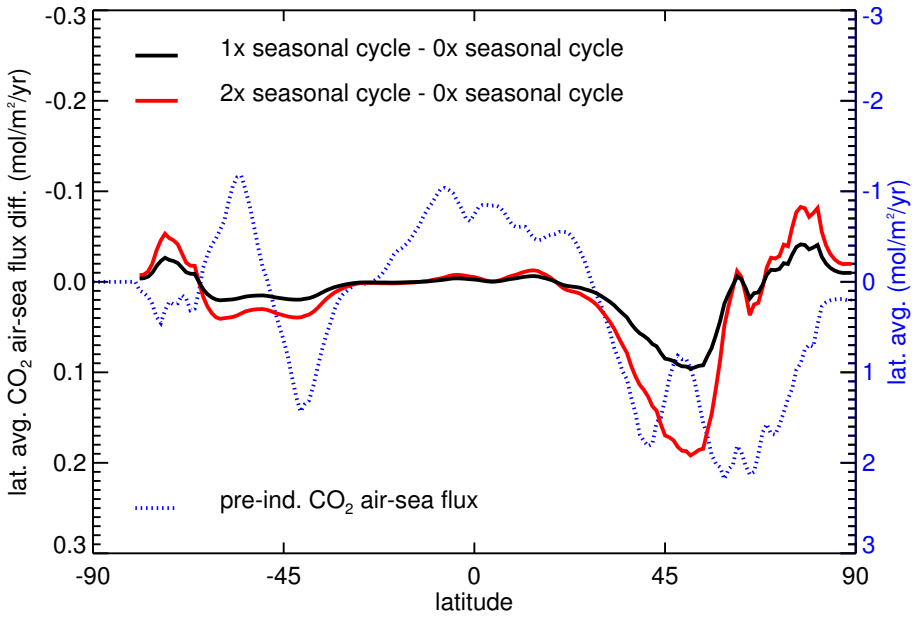

Fig. 2. The impact of changing atmospheric CO_2 seasonal cycle amplitude on the simulated air-sea flux of CO_2. Latitudinally averaged values of the CO_2 air-sea flux difference calculated between (black) the model's preindustrial atmospheric CO_2 seasonal cycle and a situation with no seasonal cycle, and between (red) two times the model's preindustrial atmospheric CO_2 seasonal cycle and a situation with no seasonal cycle. All values are calculated using common surface ocean CO_2 fields, so represent the flux prior to equilibration. 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 ocean CO_2 solubility, atmosphere CO_2 concentration and sea-ice seasonality (see Fig. 4 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 blue 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.

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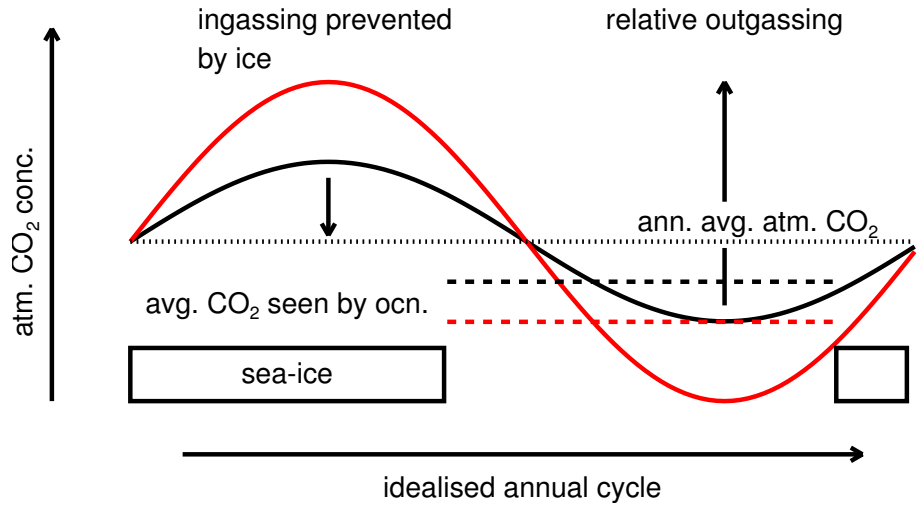

Fig. 3. Explanation of how a change in the magnitude of the atmospheric CO_2 seasonal cycle can change the air-sea CO_2 flux in seasonally sea-ice covered waters. During the year, high atmospheric CO_2 concentrations occur around the time of maximum ice-cover, and are therefore prevented from exchanging 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.

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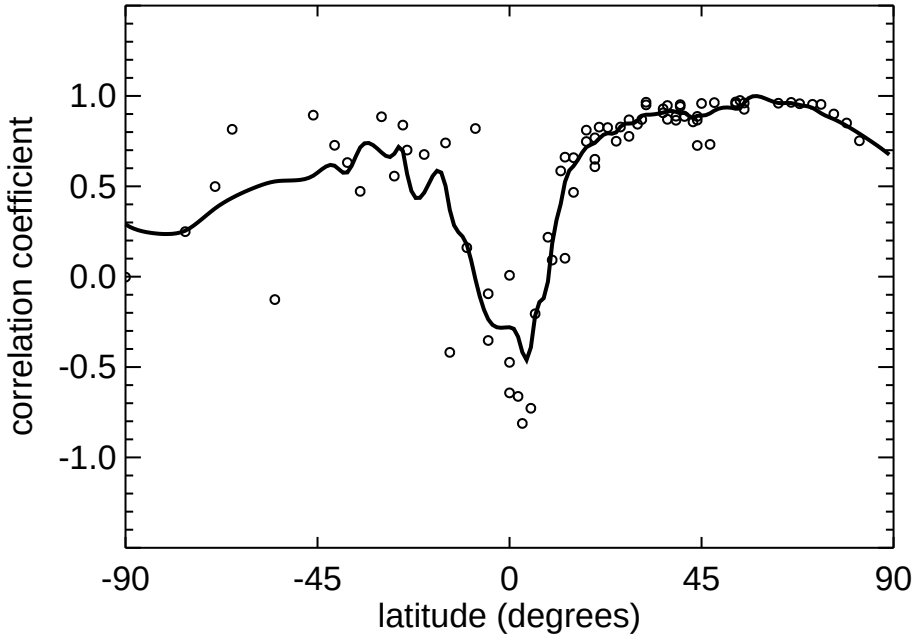

Fig. 4. Latitudinal dependence of the phase synchronicity between the seasonal cycle of atmospheric CO_2 concentrations and the solubility of CO_2 in seawater. Correlation coefficients between observed monthly averaged atmospheric CO_2 concentration seasonal cyclicity and the calculated monthly averaged 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 11/8/2010. 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.

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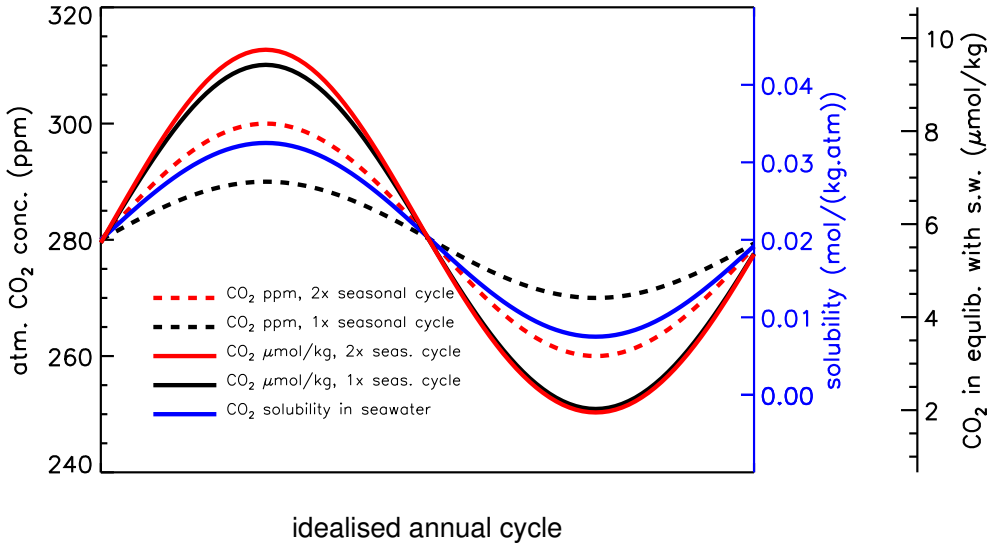

Fig. 5. Cartoon explaining how a change in the magnitude of the atmospheric CO_2 seasonal cycle can change the air-sea CO_2 flux due to coupling between the seasonal cycles of seawater CO_2 solubility and atmospheric CO_2 concentrations. Where the atmospheric CO_2 seasonal cycle and seasonal cycle of solubility are in phase, an increase in the magnitude of the atmospheric CO_2 seasonal cycle results in an annual average increase in the atmospheric CO_2 concentration in equilibrium with the underlying seawater. Dashed black and red lines represent an idealised atmospheric CO_2 cycle at 1x the normal seasonal cycle, and 2x the normal seasonal cycle respectively. The blue line represents the solubility of CO_2 in the underlying seawater throughout an idealised annual cycle. The solid black and red lines represent the atmospheric CO_2 concentration in equilibrium with seawater (the product of the atmospheric mole fraction and the solubility, assuming a total pressure of 1 atmosphere) for 1x and 2x the atmospheric CO_2 cycle amplitude respectively. The elevation of the solid red line, over the solid black line (CO_2 at 2x and 1x seasonal cycle) in the first half of the year is not cancelled by an equal decrease in the second half of the year, and consequently the annually averaged atmospheric ρCO_2 seen by the ocean is elevated by the increase in the seasonal cycle amplitude. The elevated atmospheric ρCO_2 will drive a relative flux of CO_2 into the ocean.

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