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Abstract. The Atlantic and Arctic Oceans are critical components of the global carbon cycle. Here we quantify the net sea–air CO₂ flux, for the first time, across different methodologies for consistent time and space scales for the Atlantic and Arctic basins. We present the long-term mean, seasonal cycle, interannual variability and trends in sea–air CO₂ flux for the period 1990 to 2009, and assign an uncertainty to each. We use regional cuts from global observations and modeling products, specifically a pCO₂-based CO₂ flux climatology, flux estimates from the inversion of oceanic and atmospheric data, and results from six ocean biogeochemical models. Additionally, we use basin-wide flux estimates from surface ocean pCO₂ observations based on two distinct methodologies. Our estimate of the contemporary sea–air flux of CO₂ (sum of anthropogenic and natural components) by the Atlantic between 40° S and 79° N is −0.49 ± 0.05 Pg C yr⁻¹, and by the Arctic it is −0.12 ± 0.06 Pg C yr⁻¹, leading to a combined sea–air flux of −0.61 ± 0.06 Pg C yr⁻¹ for the two decades (negative reflects ocean uptake). We do find broad agreement amongst methodologies with respect to the seasonal cycle in the subtropics of both hemispheres, but not elsewhere. Agreement with respect to detailed signals of interannual variability is poor, and correlations to the North Atlantic Oscillation are weaker in the North Atlantic and Arctic than in the equatorial region and southern subtropics. Linear trends for 1995 to 2009 indicate increased uptake and generally correspond between methodologies in the North Atlantic, but there is disagreement amongst methodologies in the equatorial region and southern subtropics.
1 Introduction

The ocean is the dominant removal pathway of anthropogenic CO$_2$ from the atmosphere on centennial timescales (Khatiwala et al., 2009; Sabine et al., 2004). Estimates for the present-day global ocean anthropogenic CO$_2$ sink have converged to $-1.9$ to $-2.4$ Pg C yr$^{-1}$ (Wanninkhof et al., 2012), the same magnitude as the mean net global CO$_2$ sink in the terrestrial biosphere. Contemporary net sea–air CO$_2$ fluxes reflect a combination of natural processes and anthropogenic CO$_2$ uptake, and spatially integrated CO$_2$ fluxes at ocean basin scales provide important metrics of the ocean carbon cycle and anthropogenic CO$_2$ transient (Gruber et al., 2009; Takahashi et al., 2009). The current best estimate for the global contemporary sink is $\sim1.7$ Pg C yr$^{-1}$ (Gruber et al., 2009), with the difference between this and the anthropogenic sink primarily being a natural outgassing of carbon input by rivers (0.45 Pg C yr$^{-1}$; Jacobson et al., 2007).

In this manuscript, a contribution to the Regional Carbon Cycle Assessment Project (RECCAP; Canadell et al., 2011), we review the state of our understanding of contemporary carbon fluxes between the atmosphere and ocean for the Arctic and Atlantic. Previous work has indicated that the net annual sea–air CO$_2$ flux for the Arctic and Atlantic is negative (into the ocean). Modeling studies and ocean inversions have suggested that nearly all of this net flux is driven by the uptake of anthropogenic CO$_2$ (Gruber et al., 2009). The tropical region is an annual mean source of CO$_2$ to the atmosphere, whilst the mid and high latitudes are annual mean sinks of CO$_2$. The few CO$_2$ flux estimates existing for the Arctic concur that the region is an annual mean sink.

At the global scale, interannual variability (IAV) in sea–air flux has been well established to be dominated globally by the El Niño/Southern Oscillation (ENSO) cycle (Feely et al., 2006; Ishii et al., 2009; McKinley et al., 2003; McKinley et al., 2004; Peylin et al., 2005), whilst the impact of variations in the dominant mode of North Atlantic variability, i.e. the North Atlantic Oscillation, has remained difficult to quantify (Gruber et al., 2009; McKinley et al., 2004; Peylin et al., 2005; Thomas et al., 2008). Trends in ocean carbon uptake have become of significant interest in recent years because of a concern that climate-driven feedbacks may be limiting ocean carbon uptake (Canadell et al., 2011; Le Quéré et al., 2010; Lovenduski et al., 2008; McKinley et al., 2011; Schuster et al., 2009). In this study, we review in detail these previous results with respect to mean CO$_2$ uptake, its interannual variability, and its recent trends for 5 key subregions of the Arctic and Atlantic.

1.1 The Arctic

The Arctic Ocean is a complex region of sea–air CO$_2$ fluxes due to its unique characteristics. Its biogeochemical cycle is dominated by its lateral inputs, including nutrient-rich inputs through the Barents Sea (North Atlantic) and Chukchi Sea (North Pacific), which lead to high biological production and consequent undersaturation of surface CO$_2$ (Omar et al., 2007), and carbon-saturated riverine (Anderson et al., 2009) and meltwater inputs from the surrounding land masses. These inputs have a disproportionate effect on the Arctic Ocean as it encompasses only 3% of the global ocean’s total area, but received $\sim10\%$ of total global runoff. A significant proportion (53%) of the Arctic basin consists of continental shelf margins, whose inorganic and organic carbon content is highly variable and notoriously difficult to assess. Finally, much of the ocean is covered by seasonal sea ice, which restricts carbon fluxes in winter, while high rates of primary production over inflow shelves lead to undersaturated open water in summer months (e.g. Bates, 2006).

The dynamics of the Arctic Ocean make estimates of the sea–air CO$_2$ flux very difficult, with large uncertainties. However, it is generally agreed that the ocean as a whole is a year-round CO$_2$ sink (Bates and Mathis, 2009, and references therein) with high seasonal variability due to the sea-ice cycle and related biological activity (Bates, 2006; Kaltin and Anderson, 2005). For example, there are areas of the Arctic Ocean such as the Chukchi Sea and Barents Sea where there is large CO$_2$ uptake per unit area (e.g. Bates, 2006; Omar et al., 2007) due to very high rates of summer-time pelagic phytoplankton primary production. Early assessments of the rate of sea–air CO$_2$ exchange in the Arctic Ocean using indirect mass balance approaches suggested that the integrated net sea–air CO$_2$ flux for the entire Arctic Ocean was in the range of $-0.024$ to $-0.129$ Pg C yr$^{-1}$ (Anderson et al., 1990, 1994). A more recent review of available sea–air CO$_2$ flux and supporting seawater carbonate chemistry data gave a range of $-0.06$ to $-0.199$ Pg C yr$^{-1}$ for the Arctic Ocean (Bates and Mathis, 2009). Such studies used a scaling-up approach where relatively sparse and often very localized data were translated into estimates for each region of the Arctic Ocean. A more recent estimate of CO$_2$ fluxes (Arrigo et al., 2010) indicated a flux of $-0.118$ Pg C yr$^{-1}$ for the period 1998–2003. A model study of the carbon cycle of the Arctic (Manizza et al., 2011) estimates the flux of CO$_2$ for the Arctic Ocean north of 65° N to be $-0.059$ Pg C yr$^{-1}$. This estimate comes from an ocean carbon cycle model embedded in a high-resolution ocean circulation model of the Arctic Ocean with applied reanalyzed forcing corresponding to the 1992 to 2001 period. For the Siberian Sea, Anderson et al. (2009) state an outgassing of $+0.010$ Pg C yr$^{-1}$ – which is higher than any of the Bates and Mathis (2009) quoted values, which range from $-0.0059$ to $+0.0003$ Pg C yr$^{-1}$ – which brings down the high end of the estimate for the net sea–air flux from $-0.199$ to approximately $-0.175$ Pg C yr$^{-1}$. Based on these reported values, the long-term mean Arctic Ocean sea–air CO$_2$ flux is $-0.06$ to $-0.18$ Pg C yr$^{-1}$, or $-0.12 \pm 0.06$ Pg C yr$^{-1}$.

There is insufficient data available to provide a quantitative assessment of interannual variability or long-term trends in CO$_2$ flux in the Arctic, although the dynamic nature of
the region suggests that the former would be relatively large. Speculation over the future trend of the carbon flux in this region has suggested that the net CO$_2$ sea–air flux in the Arctic will grow more strongly negatively associated with further sea-ice loss. It is important to note that previous synthesis and model studies of the Arctic Ocean CO$_2$ flux were based on data collected prior to the major summertime sea-ice loss event in 2007 (Bates and Mathis, 2009) – a transformation in the sea-ice extent of the Arctic that has continued to the present day. More recent surveys conducted suggest that there may not have been an increase in CO$_2$ uptake since the 2007 sea-ice loss event (Cai et al., 2010). Thus, estimates of the current Arctic Ocean CO$_2$ flux remain highly uncertain given that there are competing processes either reducing or increasing the rate of sea–air CO$_2$ transfer (e.g. Bates and Mathis, 2009). Processes acting to reduce the CO$_2$ flux into the ocean include warming, increased sea-ice melt and freshwater contributions to the polar mixed layer, and enhanced riverine discharge of dissolved organic carbon and subsequent remineralization to CO$_2$. In contrast, greater areal extent of summertime sea-ice-free open water, increase in pelagic phytoplankton primary production (e.g. Arrigo et al., 2008) and translocation of marine ecosystems in response to changes in sea ice act oppositely to potentially increase CO$_2$ uptake. Complicating future assessment of the trajectory of the Arctic Ocean CO$_2$ flux is the loss of multi-year sea ice and its replacement by thinner first-year sea ice, which has implications for winter sea–air CO$_2$ transfer across sea ice. Similarly, changing optical regimes below thinning sea ice may also significantly change rates of pelagic phytoplankton primary production (Arrigo et al., 2012) and uptake of CO$_2$ on the polar shelves and sea-ice retreat zones of the Arctic.

1.2 The subpolar North Atlantic

The subpolar North Atlantic, between 50$^\circ$ N and 80$^\circ$ N, is a strong sink for atmospheric CO$_2$. Takahashi et al. (2009) estimated it at $-0.27$ Pg C yr$^{-1}$, equivalent to 15% of the total global oceanic CO$_2$ uptake. This strong sink is a result of a sizeable natural CO$_2$ sink, being roughly doubled by the uptake of anthropogenic CO$_2$ (Gruber et al., 2009). In fact, this area constitutes one of the most intense anthropogenic CO$_2$ sinks per unit area (Mikaloff Fletcher et al., 2006). Coupled physical–biogeochemical models indicate a sea–air flux variability of approximately 0.1 Pg C yr$^{-1}$, and illustrate that the opposing effects of variability in sea surface temperature (SST), convective fluxes, and biology dampen the sea–air flux variability (Bennington et al., 2009; Le Quéré et al., 2000; McKinley et al., 2004; Thomas et al., 2008; Ullman et al., 2009).

In recent years, observational studies have suggested that the net CO$_2$ flux into the ocean has declined in the subpolar North Atlantic, weakening by about 50% in the southeastern part of the subpolar gyre from $-0.20$ Pg C yr$^{-1}$ in the mid-1990s to $-0.09$ Pg C yr$^{-1}$ in the mid-2000s (Schuster et al., 2009). Across the subpolar region, a summer rise in the partial pressure of sea surface CO$_2$ ($p$CO$_2$) was identified as between 2.3 and 3.5 µatm yr$^{-1}$ between 1982 and 1998, whilst the atmospheric CO$_2$ rise over the same time period was 1.5 µatm yr$^{-1}$ (Lefevre et al., 2004). Furthermore, between the winters of 2001 and 2008, an even faster rise of surface water $p$CO$_2$ of the order of 5.8 ± 1.1 µatm yr$^{-1}$ to 7.2 ± 1.3 µatm yr$^{-1}$ was reported (Metzl et al., 2010). These studies identified a decrease of the ocean–atmosphere $p$CO$_2$ difference ($\Delta p$CO$_2$), suggesting a decrease in the carbon sink, as has also been highlighted in other studies (Corbière et al., 2007; Olsen et al., 2006; Omar and Olsen, 2006).

However, coupled physical–biogeochemical models and atmospheric inversions do not suggest a declining sink in the subpolar gyre from the mid-1990s to the mid-2000s. An atmospheric inversion study (Rödenbeck, 2005) tentatively suggested an increase in CO$_2$ uptake between 50$^\circ$ N and 80$^\circ$ N of 0.03 Pg C yr$^{-1}$ (0.15 to 0.18 Pg C yr$^{-1}$) during this time. A regional physical–biogeochemical model (Ullman et al., 2009) identified a similar increase of 0.04 Pg C yr$^{-1}$ (0.22 to 0.26 Pg C yr$^{-1}$) in the carbon uptake over the same period and same region, with the first-order mechanism being reduced convective supply of dissolved inorganic carbon (DIC) from depth. Thomas et al. (2008) find a slight decrease in the CO$_2$ uptake by the ocean in the eastern subpolar gyre from 1996 to 2004, due to a surface ocean $p$CO$_2$ increase slightly exceeding the atmospheric CO$_2$ growth rate of 1.6 ppm yr$^{-1}$. Thomas et al. (2008) attribute this to a decrease in horizontal advection of low DIC waters from the subtropics between 1997 and 2004, and they note that recent trends are primarily driven by decadal timescale climate variability.

Comparison of these studies suggesting declines in carbon uptake is difficult because of their lack of coherence in time and space. For example, the observations are sparse and tend to be concentrated along shipping lanes where Volunteer Observing Ships (VOS) operate, and models are coarse in spatial resolution and crudely parameterize critical biological processes. Further, it is critical to distinguish whether the significant decadal climate variability in this region is responsible for observed changes, as opposed to long-term trends. McKinley et al. (2011) addressed these issues by using an updated $p$CO$_2$ database (Takahashi et al., 2009) to estimate $p$CO$_2$ trends in three North Atlantic basin-scale biomes for a range of time frames between 1981 and 2009. They illustrated that in the subpolar region it takes at least 25 yr for the driving force of ocean carbon uptake to be predominantly anthropogenic carbon accumulation in the atmosphere, and that the shorter-term changes reported from observations are best interpreted as the result of decadal variability and not by long-term declines in ocean carbon sequestration (e.g. Gruber et al., 2009).

Variability in the subpolar carbon sink is due to the various and opposing influences of the decadal climate variability, with the North Atlantic Oscillation (NAO) being the dominant mode of climate variability here. A negative NAO phase
is characterized by less extreme wind events in winter in the subpolar gyre (Marshall et al., 2001). A shift from a positive to negative NAO during the mid-1990s to the mid-2000s resulted in increased \( p\text{CO}_2 \) in this region, primarily caused by warmer surface waters in the subpolar gyre (Corbière et al., 2007). Additionally, the strength of the subpolar gyre circulation decreased in the 1990s (Hakkinen and Rhines, 2009), allowing the advection of warmer waters to penetrate the subpolar region and reducing the \( p\text{CO}_2 \) uptake here (Schuster and Watson, 2007). However, at the same time, the decline in the NAO led to reduced convective mixing of high DIC waters from depth, and this lowered \( p\text{CO}_2 \) and promoted increased carbon uptake (Ullman et al., 2009). A reduction in biological activity is another factor that could explain change in \( \text{CO}_2 \) uptake (Lefèvre et al., 2004). However, the NAO explains only about 30% of the climate variability (Marshall et al., 2001). Metzl et al. (2010) attribute a fast rise of surface water \( p\text{CO}_2 \) observed in the early 2000s to seawater carbonate chemistry changes that are unlikely to be caused by NAO variability. Whether NAO driven or not, the fact that the \( \text{CO}_2 \) sink is influenced by these multiple, vigorous and opposing mechanisms makes a precise determination challenging, and makes elucidation of effects, particularly as they vary on interannual to decadal timescales, prone to both observational and model uncertainty.

### 1.3 The subtropical North Atlantic

The subtropical and temperate North Atlantic from 14°N to 50°N is a significant sink for atmospheric \( \text{CO}_2 \), with an estimated net sea–air \( \text{CO}_2 \) flux of \(-0.22\) Pg C yr\(^{-1}\) in 2000 (Takahashi et al., 2009). Similar to the subpolar North Atlantic, this large flux is interpreted to be a consequence of a superposition of a large uptake of anthropogenic \( \text{CO}_2 \) with a large sink of natural \( \text{CO}_2 \), with the latter driven by a net heat loss and an efficient biological pump (Gruber et al., 2009). The trends and year-to-year variations in these net sea–air fluxes have been observed both in the western subtropical Atlantic at the Bermuda Atlantic Time Series (BATS, e.g. Bates, 2007), and in the eastern subtropical Atlantic at the European Station for Time Series in the Ocean (ESTOC, e.g. González-Dávila et al., 2007). Interannual variability in the subtropical \( \text{CO}_2 \) flux can also be illustrated by combining data from BATS with those from the nearby Station S that has existed since 1983 (Bates, 2007; Gruber et al., 2002; Keeling, 1993), with the most recent results finding a peak-to-peak range of \(+0.2 \text{ to } 0.3\) Pg C yr\(^{-1}\) (Bates, 2007) when scaled to the northern subtropical gyre. In the eastern subtropical gyre at ESTOC, a weak sink is observed in some years, e.g. 2002, whereas in other years, e.g. 2003, the net sea–air flux is close to zero (Santana-Casiano et al., 2007). Year-to-year variability in the carbon sink at both sites is significantly correlated with sea surface temperature and mixed layer depth anomalies (González-Dávila et al., 2007; Gruber et al., 2002; Santana-Casiano et al., 2007). These were found to be correlated to the NAO without a time lag at BATS (Gruber et al., 2002), but with a 3-yr time lag at ESTOC (Santana-Casiano et al., 2007). With a coupled physical–biogeochemical model, Oschlies (2001) illustrated mechanistically that during high (low) NAO phases, the subtropics were subject to less (more) winter mixing, bringing up less (more) nutrients to the surface, thereby dampening (strengthening) the seasonal cycle of sea–air fluxes of \( \text{CO}_2 \) and hence resulting in weaker (stronger) carbon sinks – a prediction confirmed by the observations from BATS (Gruber et al., 2002).

The nearly 30-yr-long time series of observations at BATS/Station S also indicate that the long-term mean \( \text{CO}_2 \) sink has remained relatively steady (Bates, 2007). At ESTOC, the rise of surface water \( p\text{CO}_2 \) between 1996 and 2006 \((1.55 \pm 0.43 \mu\text{atm yr}^{-1})\) was also comparable to the rise in atmospheric \( \text{CO}_2 \), implying that the long-term mean oceanic sink has also remained relatively constant (González-Dávila et al., 2007). However, the model of Ullman et al. (2009) indicates a steadily increasing sink for \( \text{CO}_2 \) in the subtropics between 1992 and 2006, in addition to variable climatically driven changes in convective mixing, biological fluxes and freshwater forcing. Some observational studies have suggested a decreasing \( \text{CO}_2 \) sink in recent years. A slight weakening of the oceanic sink for carbon was found in the eastern North Atlantic subtropical waters and the Canaries Current between 2000 and 2008 (Padin et al., 2010). Moreover, Watson et al. (2009) showed that significant interannual variability of the sea–air flux of \( \text{CO}_2 \) existed throughout the subtropical and temperate zones \((30–45°N)\) between 2002 and 2007. Similar to the subpolar biome, McKinley et al. (2011) found decadal climate variability is the best explanation for these observed changes in the subtropics over short temporal extents.

With respect to longer timescale trends, climate-change modeling studies indicate that warming-induced reduction of \( \text{CO}_2 \) solubility will decrease the ocean carbon uptake, particularly early in the Anthropocene (Sarmiento and Le Quéré, 1996) and with pronounced effects in the North Atlantic (Le Quéré et al., 2010). Observations indicate that since 2007 this long-term negative feedback has begun to modify carbon uptake in the North Atlantic subtropical gyre (McKinley et al., 2011).

### 1.4 The equatorial Atlantic

The equatorial Atlantic is subject to equatorial upwelling (Andrie et al., 1986), seasonal variations (warming/cooling, seasonal migration of the Intertropical Convergence Zone), interannual variability probably linked to ENSO events (Philander, 1986), and river discharge (Jacobson et al., 2007). The equatorial Atlantic from 14°N to 15°S is the second most intense source of oceanic \( \text{CO}_2 \) flux into the atmosphere after the equatorial Pacific, due to frequent upwelling of cold, \( \text{CO}_2 \)-rich water in the eastern Atlantic which then propagates.
westward, increasing the fugacity (and therefore flux rate) as it warms (Oudot et al., 1995). Takahashi et al. (2009) estimated the total flux in this region to be \(+0.10 \text{Pg C yr}^{-1}\) for 2000, although this is likely to be an underestimate because there is a strong north–south gradient of oceanic \(^{13}C\) levels, with values in the south up to four times larger than in the north, which is not well reproduced by the climatology (Koffi et al., 2010; Parard et al., 2010). Taking this gradient into account leads to estimates of the flux in this region equating to a source of \(+0.22 \text{Pg C yr}^{-1}\) (Parard et al., 2010). This outgassing is today only half as large as it used to be in pre-industrial times, since the outgassing of natural \(^{13}C\) is substantially counteracted by a strong uptake of anthropogenic \(^{13}C\) (Gruber et al., 2009). These authors also suggested that a substantial part of the natural outgassing is the result of the large input of organic matter by rivers, which is then remineralized in this region and subsequently lost to the atmosphere (see also Jacobson et al., 2007). There are few data, and thus estimates of interannual variability or long-term trends have not previously been made; also, previous analyses of coupled physical–biogeochemical models have not addressed this region. The RECCAP equatorial Atlantic region has been set to be between \(18^\circ\)S and \(18^\circ\)N, and therefore includes the equatorial Atlantic (\(5^\circ\)S to \(5^\circ\)N) and the northern and southern tropical Atlantic.

1.5 The subtropical South Atlantic

The subtropical South Atlantic is a sink for atmospheric \(^{13}C\). Half of this sink appears to be driven by the uptake of anthropogenic \(^{13}C\) and the other half by the uptake of natural \(^{13}C\) (Gruber et al., 2009). The region is scantily sampled. According to Ito and co-workers (Ito et al., 2005), the isotherm of \(23^\circ\)C in the South Atlantic Tropical Gyre (sSTG) is the boundary between oceanic waters acting as a sink or a source of atmospheric \(^{13}C\). Thus, the western sSTG, north of \(31^\circ\)S, acts as a source (\(+0.6 \text{ mol m}^{-2} \text{ yr}^{-1}\)) in boreal spring and as a small sink (\(-0.2 \text{ mol m}^{-2} \text{ yr}^{-1}\)) in autumn, as estimated from observations between 2000 and 2008 (Padin et al., 2010). Further south, the region acted as a \(^{13}C\) sink of \(-0.9 \text{ and } -2.2 \text{ mol m}^{-2} \text{ yr}^{-1}\) in boreal spring and autumn, respectively (Padin et al., 2010). Similar behavior is observed in the eastern subtropical South Atlantic (González-Dávila et al., 2009; Santana-Casiano and González-Dávila, 2009); North of \(20^\circ\)S the waters were a source in 2006/2007 (\(+0.33 \text{ mol m}^{-2} \text{ yr}^{-1}\)), and south of \(20^\circ\)S the waters were a sink in 2006/2007 (\(-0.45 \text{ mol m}^{-2} \text{ yr}^{-1}\)) between \(24^\circ\)S and \(20^\circ\)S, and \(-1.89 \text{ mol m}^{-2} \text{ yr}^{-1}\) between \(32^\circ\)S and \(29^\circ\)S. Estimates of interannual variability or long-term trends are rare. The interannual variability in the eastern part of the southern subtropical Atlantic has been shown to be large, predominately caused by strong upwelling events (González-Dávila et al., 2009). One study of cruises conducted between 2000 and 2008 in the western part of the subtropical South Atlantic did not reveal any significant long-term trend of \(^{13}C\) uptake in this area (Padin et al., 2010); previous analyses of coupled physical–biogeochemical models have not addressed this region.

2 Methods

Consistent with the RECCAP methodology, we use global “Tier 1” methodologies for our primary analysis (Canadell et al., 2011). These are sea–air \(^{13}C\) fluxes from (1) a sea surface \(^{13}C\) climatology, (2) ocean inversions, (3) atmospheric inversions, and (4) ocean biogeochemical models. Additionally, we use flux estimates based on the gridded product of monthly sea surface observations of \(^{13}C\) from the Surface Ocean \(^{13}C\) ATLAS (SOCAT) and fluxes estimated at the regional scale based on the \(^{13}C\) database analysis of McKinley et al. (2011). In the subtropical North Atlantic, we also compare fluxes based on sea surface \(^{13}C\) observations at BATS and at ESTOC.

Throughout, when referring to “fluxes”, it refers to contemporary fluxes, i.e. the total flux that is the sum of natural fluxes, fluxes resulting from riverine inputs, and the perturbation due to anthropogenic carbon accumulation in the atmosphere (Gruber et al., 2009).

2.1 Tier 1 RECCAP methodologies

The ocean \(^{13}C\) climatology is that produced by Takahashi et al. (2009) for the reference year 2000, based on \(^{13}C\) observations mostly collected between the 1990s and the 2000s. The \(^{13}C\) flux was estimated by Wanninkhof et al. (2012) using Cross-Calibrated Multi-Platform wind speeds (CCMP, Atlas et al., 2011). Uncertainty is estimated conservatively as 50% of the long-term mean regional flux (Gruber et al., 2009; Takahashi et al., 2009).

Eleven atmospheric inversions are included in the analysis (Table 1), retrieved from the TRANSCOM website (https://transcom.lsce.ipsl.fr/). Atmospheric inversions use atmospheric transport models and measured atmospheric \(^{13}C\) levels to assess sources and sinks. All fluxes were reported as flux densities in units of \([\text{mol m}^{-2} \text{ yr}^{-1}]\), and we converted fluxes in units of \([\text{Pg C yr}^{-1}]\) based on each model’s unique land/ocean mask. As the individual atmospheric inversions use the \(^{13}C\) climatology and/or ocean inversions as Bayesian priors, their results are not fully independent from these other methodologies.

Six ocean biogeochemical models are included in the analysis, retrieved from the RECCAP website (http://www.globalcarbonproject.org/reccap/products.htm); details are given in Table 2. Ocean biogeochemical models are numerical solutions for ocean circulation and biogeochemical processes that allow for calculation of ocean \(^{13}C\) from total alkalinity (TA) and dissolved inorganic carbon (DIC). Outputs included in this study are monthly \(^{13}C\) fluxes of hindcast scenarios forced with historical
Table 1. RECCAP atmospheric inversions included in this study.

<table>
<thead>
<tr>
<th>Model abbreviation</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSCE_an,v2.1</td>
<td>1996–2004</td>
</tr>
<tr>
<td>LSCE_var,v1.0</td>
<td>1990–2008</td>
</tr>
<tr>
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<td>1995–2008</td>
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<tr>
<td>NICAM_NIWA</td>
<td>1990–2007</td>
</tr>
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atmospheric boundary conditions (winds and fluxes of heat and freshwater) and atmospheric $\rho$CO$_2$ concentrations (identified as “ANTH” in the archive). Developers of the CCSM-ETH and UEA simulations submitted alternate model versions to the RECCAP archive, but they are not considered here because they were submitted to allow for sensitivity analyses to study the impact of different formulations of the gas-transfer velocity (CCSM-ETHk19) or the impact of different atmospheric forcings (UEA). All fluxes were reported in units of flux density [mol m$^{-2}$ yr$^{-1}$] and converted to fluxes in units of [Pg C yr$^{-1}$] based on each model’s unique land/ocean mask.

For a complete closure of the carbon budget with respect to land and globe, carbon fluxes from rivers must be included in ocean model fluxes if those models do not already include them: BER, CSI, BEC, and ETHk15. For these we use the regional annual mean estimates of Jacobson et al. (2007), based on the 11 region TRANSCOM mask. In that study, the Arctic and north subpolar is one region with a total estimate of 0.064 Pg C yr$^{-1}$ river input, so it must be subdivided for our study (see geographical subregions in Sect. 3.3 below). Following Rachold et al. (2004), we attribute 0.030 Pg C yr$^{-1}$ of this to the Arctic and the remainder to the North Subpolar. The net carbon input from rivers into the open ocean is assumed to outgas completely to the atmosphere within the regions of input (Gruber et al., 2009; Jacobson et al., 2007).

The ocean inversion product of Gruber et al. (2009) is used. The ocean inversion constrains surface sea–air fluxes based on estimates of the interior ocean circulation and the divergence of surface DIC. Results are taken from the native set of 23 regions of Gruber et al. (2009), with the long-term mean and average for flux estimates for years 1995, 2000, and 2005 as provided in the RECCAP archive. We use the best-estimate fluxes reported by Gruber et al. (2009), which are weighted mean results of a set of inversions using 10 different ocean general circulation models that are used to estimate transport of tracers through the ocean. The fluxes for 2000 and 2005 were computed by scaling the anthropogenic CO$_2$ fluxes reported for 1995 by Gruber et al. (2009) by a factor of 1.109 for the year 2000 and by a factor of 1.23 for 2005, commensurate with the anthropogenic CO$_2$ flux scaling used in the inversion (Mikaloff Fletcher et al., 2006). The uncertainties are those reported by Gruber et al. (2009). These results were provided for each region in units of [Pg C yr$^{-1}$], and flux densities in units [mol m$^{-2}$ yr$^{-1}$] were estimated using the RECCAP area mask (Table 3).

2.2 Observations

From SOCAT (Pfeil et al., 2012; Sabine et al., 2012), we use the gridded monthly unweighted sea surface CO$_2$ fugacity ($f$CO$_2$) product of version 1.5 (http://www.socat.info/), which is on a 1° latitude × 1° longitude grid. Data cover the time period from 1990 to 2007. In order to produce a basin-wide estimate of the flux based on the gridded SOCAT product, a multi-parameter regression (MPR) was performed using NCEP/NCAR Reanalysis sea surface temperature (Kalnay et al., 1996), SeaWiFS chlorophyll $a$, total alkalinity from the climatology of Lee et al. (2006), and mixed-layer depth from the climatology of De Boyer Montegut et al. (2004) as independent parameters. The MPR was performed separately for each of the Atlantic RECCAP regions (see Sect. 3.3 below), including all available years. The root mean square error (RMSE) of the SOCAT MPR was 19.9 µatm, computed by comparing the regression-derived values with the original SOCAT product for the Atlantic. No chlorophyll $a$ data were available in the Arctic, so this region is excluded from the SOCAT MPR. Because SeaWiFs chlorophyll $a$ was not available until the end of 1997 and SOCAT v1.5 ends in 2007, the SOCAT MPR product is produced for years 1998 to 2007. It should be noted that the independent parameters used do not explicitly allow for the increase of surface $f$CO$_2$, and the SOCAT MPR is therefore excluded from the trend analysis (Sect. 4.4).

SOCAT MPR flux values were calculated using the standard formulation:

$$F = ks\Delta f CO_2,$$

where $k$ is the gas transfer velocity, $s$ the solubility, and $\Delta f CO_2$ the difference between the atmospheric and oceanic $f$CO$_2$. The gas transfer velocity $k$ was calculated using the wind formulation by Wanninkhof (1992) with bomb $^{14}$C corrections by Sweeney et al. (2007). Wind speed data, taken from the 6-hourly CCMP Wind Vector Analysis dataset (Atlas et al., 2011), were provided for the RECCAP project (Wanninkhof et al., 2012). The solubility $s$ was calculated according to the method presented by Weiss (1974), using the in situ temperature and salinity values recorded with each measurement. Atmospheric $x$CO$_2$ values were obtained from the reference matrix of GLOBALVIEW (varying over time and latitude; GLOBALVIEW-CO$_2$, 2011), regribed and converted into $f$CO$_2$ using NCEP/NCAR sea level pressure and sea surface temperatures (Kalnay et al., 1996). This resulted in varying atmospheric $f$CO$_2$ over time, latitude,
and longitude, due to the variability of sea level pressure and sea surface temperature. \( \Delta f \text{CO}_2 \) was then computed as sea surface \( p\text{CO}_2 \) minus atmospheric \( p\text{CO}_2 \). It is worth noting here that the non-ideal behavior of \( \text{CO}_2 \) gas is corrected for in \( f \text{CO}_2 \); the \( \Delta f \text{CO}_2 \) is generally indistinguishable from the \( \Delta p\text{CO}_2 \), provided atmospheric \( f \text{CO}_2 \) is used in the former. Uncertainty is estimated as 50% of the regional mean flux for the SOCAT fluxes.

Additionally, we include an analysis of regional \( \text{CO}_2 \) fluxes and trends based on the observed in situ \( p\text{CO}_2 \) database of Takahashi et al. (2009) using the method of McKinley et al. (2011) adapted to the regions for this analysis (Sect. 2.3). In our North Subpolar region, we also include \( p\text{CO}_2 \) calculated from direct observations of DIC, TA, SST, and salinity between Iceland and Newfoundland (SURAT-LANT) of Metzl et al. (2010). In this approach, in situ observations of surface ocean \( p\text{CO}_2 \) are collapsed onto a single time series for each region, and then a harmonic seasonal cycle and a linear trend is fit. The validity of the resulting estimate of the \( p\text{CO}_2 \) trend is tested through a comparison of \( p\text{CO}_2 \) trends calculated with the same method using the output from the RECCAP ocean biogeochemical models, subsampled at the times and locations of the field observations, compared to \( p\text{CO}_2 \) trends derived from the complete model fields. Results vary by region, with at least 50% and up to 100% of the models confirming that the methodology can capture \( p\text{CO}_2 \) trends. \( p\text{CO}_2 \) fluxes are estimated with ocean \( p\text{CO}_2 \) estimated for each month based on the function fit above; atmospheric \( p\text{CO}_2 \) based on GLOBALVIEW-CO\(_2\) (2011), integrated over each region; CCMP wind speeds (Wanninkhof et al., 2012) integrated over each region and including the wind speed variance; and HadISST SST (Rayner et al., 2003). Uncertainties of the fluxes are calculated from the same calculations as above but with the trend replaced by the ±1σ confidence intervals of the trend fit.

At BATS, we calculate surface \( p\text{CO}_2 \) using sea surface measurements of DIC, TA, SST, and salinity, applying CO2SYS (Lewis and Wallace, 1998) with the dissociation constants by Mehrbach et al. (1973), refitted by Dickson and Millero (1987). Data cover the time period from 1990 to 2009. At ESTOC, we use sea surface \( p\text{CO}_2 \) measurements from 1995 to 2009. Fluxes are estimated at BATS and ESTOC in the same way as for SOCAT MPR. For the seasonal cycle, we compare BATS and ESTOC flux densities [mol m\(^{-2}\) yr\(^{-1}\)] to the other methodologies. For interannual variability, and only for the purpose of comparison, we show BATS and ESTOC fluxes in Pg C yr\(^{-1}\) where the area of the entire subtropical region has been used to convert flux densities to fluxes. This is an illustrative comparison to address the issue of how representative these two time series are of the entire subtropical basin.

### 2.3 Geographical subregions

For the purpose of this study, the Arctic and Atlantic are divided geographically into 5 different regions (Table 3, Fig. 1). The North Subtropics, Equatorial, and South Subtropics are regions 6, 7 and 8, respectively, of the 11-region TRANSCOM mask (Gurney et al., 2008), whilst the Arctic and North Subpolar are regions 1 and 2, respectively, of the 23-region mask of the Ocean Inversion Project...

<table>
<thead>
<tr>
<th>Model abbreviation</th>
<th>Model</th>
<th>Reference</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSI</td>
<td>CSIRO</td>
<td>Lenton and Matear (2007)</td>
<td>1959 to 2009</td>
</tr>
<tr>
<td>BEC</td>
<td>CCSM-BEC</td>
<td>Thomas et al. (2008)</td>
<td>1990 to 2009</td>
</tr>
<tr>
<td>ETHk15</td>
<td>CCSM-ETH</td>
<td>Graven et al. (2013)</td>
<td>1990 to 2007</td>
</tr>
<tr>
<td>UEAncep</td>
<td>NEMO-PlankTOM5 NCEP</td>
<td>Le Quéré et al. (2007)</td>
<td>1990 to 2009</td>
</tr>
</tbody>
</table>

**Table 2.** Details of the ocean biogeochemical models included in this study.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Latitude boundaries</th>
<th>Longitudinal boundaries</th>
<th>Area [10(^{12}) m(^2)]</th>
</tr>
</thead>
<tbody>
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<td>Arctic</td>
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<td>excl. Baffin Bay and Nordic Seas (SW of 76° N, 19° E)</td>
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</tr>
<tr>
<td>North Subpolar</td>
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<td>West of 19°E</td>
<td>8.63</td>
</tr>
<tr>
<td>North Subtropics</td>
<td>18° N to 49° N</td>
<td></td>
<td>23.68</td>
</tr>
<tr>
<td>Equatorial</td>
<td>18° S to 18° N</td>
<td></td>
<td>23.49</td>
</tr>
<tr>
<td>South Subtropics</td>
<td>44° S to 18° S</td>
<td>West of 19°E</td>
<td>18.44</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>83.84</td>
</tr>
</tbody>
</table>

**Table 3.** Latitudinal boundaries of subregions in the Arctic and Atlantic.
In Table 3 are the latitudinal and longitudinal boundaries and standard region areas using the RECCAP area mask prepared by N. Gruber on the basis of a global 1° topography and provided in the RECCAP archive (http://www.globalcarbonproject.org/reccap/). There is no single set of region boundaries used by studies of Atlantic and/or Arctic CO₂ fluxes, hence the boundaries used here are sometimes different than those in other publications. Despite the non-biogeochemical nature of the boundaries used here, we employ the above terminology throughout for ease of reading; nevertheless, the reader should be aware that, for example, our subpolar region is not identical to the subpolar gyre.

2.4 Statistics

A quantitative best-estimate flux for the atmospheric inversions and ocean biogeochemical models is derived at by combining all model results of each of these respective methodologies, and computing a cross-model median and median absolute deviation (MAD) for the flux [Pg C yr⁻¹] for each month and region. These fluxes were then converted into flux densities [mol m⁻² yr⁻¹] using the total region area (last column Table 3). Given the variable start and end years for atmospheric inversions, median results are only considered from 1995 to 2008.

When averaging in time for the derived medians of the atmospheric inversions and ocean biogeochemical models and for the other four methodologies that offer only one realization each, a temporal mean is calculated. For the atmospheric inversions, we assume that these mean fluxes are representative of the full period of interest, 1990 to 2009.

Interannual variability for low-frequency (multi-annual) variability is calculated by applying a 12-month box filter to each realization of each methodology. High-frequency (sub-annual) interannual variability, presented only in the Supplement, is calculated for each realization of each methodology by removing a climatological seasonal cycle. For the atmospheric inversions and ocean biogeochemical models, medians are taken after filtering. For consistency with previous studies, uncertainty in the interannual variability is estimated as a standard deviation for each methodology, following the calculation of the median in the case of the atmospheric inversions and ocean models. For trends, we fit a linear trend to the low-frequency variability for each methodology, and present the 95% confidence interval on this fit. Throughout this manuscript, the term “standard error propagation” indicates the square root of the sum of squares. This is a conservative estimate of the uncertainty that does not explicitly exclude the possibility of correlated errors in the estimates.

We develop a “best” estimate of the mean fluxes in each region as an average of the pCO₂ climatology and of the ocean inversion. These two methodologies are selected because they are two independent data-based estimates. Ocean forward models have substantial uncertainties and spread across individual realizations, but are our only basis for future projection, so these comparisons are also important. Atmospheric inversions are critical tools by which terrestrial CO₂ fluxes are estimated, and so comparison to these results is also of great value.

3 Results

3.1 Long-term mean

Figure 2 shows the long-term temporal mean (LTM) CO₂ flux density [mol m⁻² yr⁻¹] at 1° × 1° resolution for the Tier 1 methodologies: the pCO₂ climatology, the weighted mean of the ocean inversions, the median of the atmospheric inversions, and the median of the ocean biogeochemical models; additionally, we show the long-term temporal mean of the gridded SOCAT product and the SOCAT MPR.

All show the strong LTM sink at high latitudes and the net source near the equator. In the main Arctic basin, the flux is near zero or set to zero due to (i) ice cover in the models, (ii) the climatology being only equatorwards of 80° N, (iii) limited number of observations in the SOCAT gridded product, and (iv) chlorophyll a not being available year-round for the SOCAT MPR.

In Fig. 3 and Table 4, the 1990 to 2009 long-term temporal mean CO₂ flux [Pg C yr⁻¹] is presented by region and by methodology. For each region, the methodologies agree as to the sign of the flux, and generally also as to the magnitude when the uncertainty is considered. The Arctic has a neutral flux or a small sink of up to −0.05 ± 0.03 Pg C yr⁻¹. The North Subpolar region has the widest range of estimates, ranging from −0.07 to −0.30 Pg C yr⁻¹. The sink in the North Subtropics ranged from −0.13 Pg C yr⁻¹ to −0.34 Pg C yr⁻¹. The Equatorial region is a source, with fluxes ranging from 0.10 Pg C yr⁻¹ to 0.15 Pg C yr⁻¹. The South Subtropics is a sink of atmospheric CO₂, ranging...
The zonal Atlantic mean seasonal cycles of the CO$_2$ flux densities [mol m$^{-2}$ yr$^{-1}$] are presented in Fig. 4 for the Tier 1 methodologies: $p$CO$_2$ climatology, atmospheric inversion median, and the ocean biogeochemical model median; additionally, we show the result for the observations-based SOCAT MPR. The ocean inversions only give annual mean fluxes, and thus are not shown. The fluxes in the South Subtropics, Equatorial region, and North Subtropics follow the mainly temperature-driven increase in $p$CO$_2$ in the warmer summer months, which results in outgassing in summer. Polewards of 44° N, the SOCAT MPR (Fig. 4d) shows an outgassing in winter, similar to an observational study for 2005 (Chierici et al., 2009; Olsen et al., 2008; Watson et al., 2009). This is also evident to a minor degree by the $p$CO$_2$ climatology (Fig. 4a), yet is not found in the other Tier 1 methodologies.

The spatial mean seasonal cycles of the CO$_2$ flux densities [mol m$^{-2}$ yr$^{-1}$] for each region are shown in Fig. 5 for Tier 1 methodologies: $p$CO$_2$ climatology, median of atmospheric inversions, and median of ocean biogeochemical models; additionally, we include results from the SOCAT MPR and $p$CO$_2$ database methods (all regions except the Arctic). We include BATS and ESTOC in the North Subtropics.

In Table 5, we present the correlation coefficients for the seasonal cycles in each region.

In the Arctic (Fig. 5a), all three methods have near zero fluxes for most of the year due to ice-cover, and a small drawdown in summer, which leads to good correlation of the $p$CO$_2$ climatology to the atmospheric inversions and ocean biogeochemical models (Table 5a). The ocean biogeochemical models and atmospheric inversion cycles do not correlate well.

In the North Subpolar region (Fig. 5b), the seasonal cycle is the most intense of all the regions. There is agreement in the shape and amplitude of the seasonal cycle of the ocean biogeochemical models and the $p$CO$_2$ climatology, with a seasonal cycle influenced by a mixed temperature-driven and biologically driven $p$CO$_2$ cycle in this region (Bennington et al., 2009; Takahashi et al., 2002). However, the seasonal cycle of the ocean biogeochemical models is more dominated by the temperature component in summer compared to that of the $p$CO$_2$ climatology. The SOCAT MPR shows the opposite seasonal cycle (Fig. 5b), with an efflux in winter and a sink in summer, indicating a biologically dominated mean seasonal cycle. This pattern is consistent with detailed studies in the subpolar gyre (Chierici et al., 2009; Olsen et al., 2008; Rödenbeck et al., 2012; Watson et al., 2009). However, the mean SOCAT MPR sink is much lower than that of the other methodologies (Fig. 3b). It should be noted, however, that the SOCAT MPR only extends to 65° N, and hence does not cover the whole of the RECCAP subpolar region. This predominantly biologically driven season cycle is also evident in the $p$CO$_2$ database approach, which is notable because, even though a significant amount of data is common between SOCAT and Takahashi et al. (2009), the data treatment to derive the RECCAP regions’ surface $p$CO$_2$ values are quite different (Sect. 2.2). Finally, the atmospheric inversions have a seasonal cycle that is significantly out of phase with the ocean models, with their median peaking in September, most possibly due to the significant terrestrial influence in this region bordered by large continents. The spread of
their seasonal cycle is very large, with a lack of consistency in the shape of the cycle across the set (not shown).

With a boundary defined simply by the latitude of 49° N, the RECCAP North Subpolar region is not well-defined based on the actual physical and biogeochemical state of this region (McKinley et al., 2011; Sarmiento et al., 2004). The choice of this boundary is historical, out of the TRANSCOM effort, and we use it for consistency with the overall RECCAP process. Yet, this choice means that the seasonal cycle from the methodologies with full spatial coverage (ocean models, pCO2 climatology) are not dominated by biological activity, i.e. winter convective mixing brings DIC into surface waters and biological productivity removes it in summer, as it should be. That fluxes are closer to zero in summer suggests a strong temperature control, likely due to the inclusion of the northern reaches of the subtropical gyre (Fig. 4).

In the North Subtropics (Fig. 5c), all methodologies are well correlated, with the correlation coefficient, R, ranging from 0.94 to 1, such that we can consider this cycle to be well-known. Nevertheless, we note that amongst the Tier 1 methodologies, the ocean biogeochemical models have a larger efflux in late summer and fall than in the

Biogeosciences, 10, 607–627, 2013
www.biogeosciences.net/10/607/2013/
Table 5. Correlations of seasonal cycle for each region and each methodology. Significant correlations ($p < 0.05$) are in bold.

<table>
<thead>
<tr>
<th>Region</th>
<th>Methodology</th>
<th>$p$ CO$_2$ climatology</th>
<th>Atmospheric inversions</th>
<th>Ocean models</th>
<th>SOCAT MPR</th>
<th>$p$ CO$_2$ database</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Arctic</td>
<td></td>
<td>$p$ CO$_2$ climatology</td>
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<td>(e) South Subtropics</td>
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<td>SOCAT MPR</td>
<td>1</td>
<td></td>
<td></td>
<td>0.99</td>
</tr>
</tbody>
</table>

Fig. 4. Zonally averaged long-term mean seasonal cycle of Atlantic sea–air CO$_2$ flux density [mol C m$^{-2}$ yr$^{-1}$ per degree of latitude], based on the Tier 1 methodologies: (a) $p$ CO$_2$ climatology, (b) median of atmospheric inversions, and (c) median of ocean biogeochemical models; additionally we show (d) the observations based SOCAT MPR. The $p$ CO$_2$ database is not shown because it is not a gridded product.
3.3 Interannual variability (IAV)

Figure 6 shows the low-frequency IAV and trends for Tier 1 methodologies for the atmospheric inversions, ocean biogeochemical models, and the pCO₂ database. High-frequency IAV can be found in the Supplement. Note that fluxes at BATS and ESTOC in [Pg C yr⁻¹] assume the same flux intensities of each site at each grid point in the whole RECCAP subtropical region.

In Table 6, the amplitude of the interannual variability (IAV) is presented for each approach, calculated as the temporal standard deviation. SOCAT MPR IAV is compared here even though it is not shown in Fig. 6. Variability is smallest in the Arctic (0.003 to 0.005 Pg C yr⁻¹) and largest in the North and South Subtropics (up to 0.026 Pg C yr⁻¹). The atmospheric inversions suggest the largest variability, and the SOCAT MPR the smallest. The integrated Arctic/Atlantic regional sink varies by ±0.055 Pg C yr⁻¹ for the atmospheric inversions, ±0.029 Pg C yr⁻¹ in the ocean biogeochemical models, ±0.015 Pg C yr⁻¹ in the SOCAT MPR, and ±0.046 Pg C yr⁻¹ in the pCO₂ database.

Correlation of the low-frequency interannual variability is presented in Table 7 by region. On the whole, correlations are low. In some regions and between some methods, there are significant and positive correlations, but there is not a consistent pattern of strong positive correlations between methods across all regions. For the whole Atlantic and Arctic, the highest positive correlation (0.87) is between the SOCAT MPR and the pCO₂ database, and this is due to high positive correlations in the North Subpolar and South Subtropics regions. As for the seasonal cycle, this is encouraging because though these estimates are derived from very similar datasets of in situ pCO₂, the methodologies used to interpolate through space and time are quite different.

It is notable that the NAO has highest correlations to the Tier 1 results in the Equatorial and South Subtropics regions, but generally weak and insignificant correlations across the North Atlantic.

In the North Subtropics, BATS positively correlates to all the other methodologies, which suggests that this location is somewhat representative of carbon fluxes across the gyre. Lower and insignificant correlations at ESTOC indicate that it is less representative of the large-scale behavior.

Atmospheric inversions may mistakenly attribute interannual variability of terrestrial fluxes to oceanic flux variability, because the atmospheric signals are dominated by the larger terrestrial variability. However, when individual realizations of the atmospheric inversions and ocean biogeochemical models are correlated (not shown), some strong and statistically significant correlations (p < 0.05) are found in all regions. Thus, even though the medians across the methodologies do not necessarily correlate strongly (Table 7), some of the individual realizations of atmospheric inversions and ocean biogeochemical models do share signals of multi-year variability.

The seasonal cycles of the South Subtropics (Fig. 5e) agree well across methodologies, with correlations all being statistically significant. We note the similar patterns of the mean seasonal cycles shown by the atmospheric inversions and the pCO₂ climatology, which should be largely due to the atmospheric inversions using these same climatological CO₂ fluxes as priors and there being very limited atmospheric pCO₂ data in the temperate Southern Hemisphere to move results away from the priors.
3.4 Linear trends of the sea–air CO$_2$ flux

Table 8 presents the linear trends of the sea–air CO$_2$ flux for 1995–2009 in each region from the atmospheric inversions, ocean biogeochemical models, and observation-based trends from the $p$CO$_2$ database. The SOCAT MPR is not included as its time-period is shorter than this.

For 1995 to 2009, linear trends are generally negative, indicating an increasing sink, or indistinguishable from zero. The exception is the Equatorial Atlantic and South Subtropics where positive trends for the atmospheric inversion indicate increasing outgassing, while for the same regions the ocean biogeochemical model trends are neutral and the $p$CO$_2$ database trends are negative. For the whole Atlantic and Arctic, the atmospheric inversions suggest a steady sink while the ocean models and $p$CO$_2$ database suggest an increasing sink, with the basin scale difference driven by the Equatorial region. The strong increasing trend for the $p$CO$_2$ database is dominated by the trend in the South Subtropics where data are extremely limited. Even in other regions, the $p$CO$_2$ database method suggests the largest trends, and these should be considered upper-bound estimates for the trends.
Table 7. Correlations of low-frequency interannual variability for each region between methodologies. Correlation to the monthly NAO index, smoothed with a 12-month filter, are included for all regions. For the North Subtropics, we include correlations to BATS and ESTOC. All correlations are at zero time lag. Significant correlations ($p < 0.05$) are in bold. Time periods for each methodology are as noted in Table 6.

<table>
<thead>
<tr>
<th>(a) Arctic</th>
<th>Atm. inversions</th>
<th>Ocean models</th>
<th>SOCAT MPR</th>
<th>$pCO_2$ database</th>
<th>NAO</th>
<th>BATS</th>
<th>ESTOC</th>
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because this approach estimates the fluxes from a repeating harmonic seasonal cycle and a steadily changing linear trend in $pCO_2$ over the full time period, i.e. interannual variability in $pCO_2$ is suppressed (Sect. 2.2).

4 Discussion

Taking the sum of the “best” estimates for each region (selected as the $pCO_2$ climatology and the ocean inversion), the 1990 to 2009 long-term mean sea-air flux for the Arctic + Atlantic is estimated to be $-0.61 \pm 0.06$ Pg C yr$^{-1}$, which makes the region responsible for 36% of the global contemporary uptake of $-1.7 \pm 0.10$ Pg C yr$^{-1}$ as estimated by ocean inversion (Gruber et al., 2009).

4.1 The Arctic

Our assessment of the long-term mean flux in the Arctic is derived from previous literature due to the poor representation of the Arctic in the Tier 1 RECCAP methodologies and basin-scale data products that are the focus of this paper. This estimate is a net sea-air flux of $-0.12 \pm 0.06$ Pg C yr$^{-1}$. With respect to the seasonal cycle, there is some agreement in the Tier 1 methodologies as to the shape of this cycle, indicating the largest seasonal drawdown in summer when sea ice is at a minimum, a result that is mechanistically sensible. Given concerns about the Tier 1 methodologies in their ability to represent the long-term mean flux in the Arctic, we cannot put much weight on their assessment of the amplitude of the seasonal cycle, interannual variability, or the long-term
trends in CO$_2$ flux. Multi-annual timescales are also not captured by direct observations, and thus much more work is needed to fully elucidate sea–air CO$_2$ fluxes and their variability in the Arctic.

Estimates of primary production based on satellite data suggest that decreases in sea-ice extent could have increased the productivity of Arctic waters in the recent years (Arrigo and van Dijken, 2011; Pabi et al., 2008). This could have enhanced the strength of the biological pump of the Arctic Ocean, and driven an increased CO$_2$ sink (McGuire et al., 2010), an effect also shown in model simulations (Zhang et al., 2010). However, this effect may be muted by countering impacts on upper ocean carbon chemistry of warming and freshening. With data, Cai et al. (2010) showed that part of the Western Arctic has decreased its CO$_2$ uptake capacity due to the change in ocean carbon chemistry despite a decrease in sea-ice area. Additionally, ocean acidification may trigger unexpected changes in the biological pump and in CO$_2$ uptake (Bates and Mathis, 2009). The simultaneous occurrence of multiple and contrasting processes (both physical and biogeochemical) in the Arctic significantly complicates our understanding and prediction of the direction and magnitude of the trend of its CO$_2$ sink.

### 4.2 The North Subpolar

The North Subpolar region is a substantial sink for atmospheric CO$_2$ of $-0.21 \pm 0.06$ Pg C yr$^{-1}$ over the RECCAP period, 1990–2009, despite its small area. Analysis of the ocean inversion (Gruber et al., 2009) suggests that about half of the total long-term mean flux is driven by the uptake of anthropogenic CO$_2$, and the remainder is due to the natural carbon cycle. The latter is a consequence of reinforcing tendencies from net ocean cooling, which increases the uptake of atmospheric CO$_2$ by increasing the ocean’s solubility, and from a relatively efficient biological pump. This uptake tendency is slightly reduced by the outgassing of carbon supplied by rivers to the ocean.

Mechanistic understanding of the seasonal cycle in the North Atlantic subpolar gyre is as follows: strong biological drawdown in spring, and continued drawdown through summer that opposes the temperature-driven cycle, followed by efflux of respired CO$_2$ with winter mixing (Olsen et al., 2008; Takahashi et al., 2009; Watson et al., 2009). Estimates of the seasonal cycle of the CO$_2$ flux in the North Subpolar region agree between the $p$CO$_2$ database and the ocean biogeochemical models, but include a significant CO$_2$ efflux in the summer that is a subtropical, temperature-driven signal. The RECCAP North Subpolar region, derived from the TRANSCOM project, includes a significant portion of the subtropical gyre, and thus these estimates are affected by the imposed regional boundaries. The atmospheric inversions have a very broad set of estimates for the seasonal cycle, leading to a median with maximum drawdown in September, which is long after the subpolar spring bloom. The two methods based on in situ $p$CO$_2$ data have maximum CO$_2$ uptake at the time of the bloom, and then a relatively flat cycle through the rest of the year. We recommend that future assessments use regional boundaries that are defined by biogeochemical provinces (McKinley et al., 2011; Sarmiento et al., 2004) as opposed to lines of latitude.

Interannual variability in the North Subpolar region is small, ranging from 0.004 to 0.016 Pg C yr$^{-1}$ (Table 6). There is limited correlation between the methodologies (Table 7), which we partially attribute to regional boundaries being sub-optimal. Maximum correlations come between the $p$CO$_2$ database and the other methodologies, which is due largely to the fact that wind speed variability is the only source of interannual variability in the $p$CO$_2$ database approach. There are no strong correlations of the variability with the NAO. Trends in CO$_2$ uptake for 1995–2009 are neutral or negative, indicating a steady or increasing sink. These trends are best interpreted as a response to decadal timescale climate variability, given their short time frames (McKinley et al., 2011).

### 4.3 The North Subtropics

The North Subtropical region is a significant long-term sink for atmospheric CO$_2$ at $-0.26 \pm 0.06$ Pg C yr$^{-1}$ between 1990 and 2009, driven by a substantial uptake flux of anthropogenic CO$_2$ and a natural CO$_2$ uptake driven in turn by net heat loss and the biological pump. This sink ($-0.93$ mol C m$^{-2}$ yr$^{-1}$) is substantiated by the observation-based flux estimates in the western subtropical Atlantic at BATS between 1983 and 2005 ($-0.8 \pm 0.2$ mol m$^{-2}$ yr$^{-1}$ and $-1.2 \pm 0.3$ mol m$^{-2}$ yr$^{-1}$; Bates, 2007); the sink in the eastern subtropical Atlantic at ESTOC was lower between 1995 and 2004 at $-0.05 \pm 0.03$ mol m$^{-2}$ yr$^{-1}$ (Santana-Casiano et al., 2007). The seasonal cycle in the subtropics is mainly temperature driven, with an efflux in summer and

Table 8. Linear trends of the spatially integrated sea–air CO$_2$ flux for each region and whole Arctic + Atlantic, 1995 to 2009 [Tg C yr$^{-1}$ decade$^{-1}$], for the atmospheric inversions, the ocean biogeochemical models and the $p$CO$_2$ database. Trends are a linear fit to the low-frequency median flux IAV (i.e Fig. 6), with $2\sigma$ confidence. Trends distinguishable from zero are indicated in bold.

<table>
<thead>
<tr>
<th>Region</th>
<th>Atmospheric inversions</th>
<th>Ocean biogeochemical models</th>
<th>$p$CO$_2$ database</th>
</tr>
</thead>
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<td>$-2.4 \pm 1.5$</td>
<td>$-9.0 \pm 1.6$</td>
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<td>$17 \pm 26$</td>
<td>$-34 \pm 14$</td>
<td>$-290 \pm 7.4$</td>
</tr>
</tbody>
</table>
an uptake in winter, being influenced to a small degree by low biological activity. All methodologies show the same patterns, which are significantly correlated (Table 5c). The ocean biogeochemical models show maximum summer efflux being notably larger and later compared to that of other methodologies. This class of ocean biogeochemical models tends to underestimate biological productivity in the stratified subtropical gyre. This leads to excessive late summer and fall surface ocean $pCO_2$ and too large an efflux at this time of year, and this also biases the long-term mean uptake of the ocean biogeochemical models to be too low (Table 4, Fig. 3). The eastern subtropical region shows a smaller mean of the ocean biogeochemical models to be too low (Table 4, $p_{f}$ deficient subtropical gyre. This leads to excessive late summer tends to underestimate biological productivity in the strati- methodologies. This class of ocean biogeochemical models ocean biogeochemical models show maximum summer ef-

- $\text{CO}_2$ of $0.12 \pm 0.04 \text{Pg C yr}^{-1}$ between 1990 and 2009, with estimates by the different methodologies being indistinguishable from each other. This efflux in the equatorial Atlantic is approximately 6 times smaller than the outgassing in the tropical Pacific (Gruber et al., 2009). The Atlantic efflux of our study is, however, significantly lower than the ones estimated between $5^\circ$ S and $5^\circ$ N between 1982 to 1984 (Andrie et al., 1986), between $10^\circ$ S–$6^\circ$ N, $10^\circ$ W–$10^\circ$ E between 2005 and 2007 (Koffi et al., 2010), and at $6^\circ$ S, $10^\circ$ W in 2007 (Parard et al., 2010). The RECCAP Equatorial Atlantic region includes the equatorial Atlantic ($5^\circ$ S to $5^\circ$ N), the northern tropical Atlantic and the southern tropical Atlantic; this leads to an overall small efflux in the whole RECCAP region ($18^\circ$ S to $18^\circ$ N) by cancelling the source south of the Equator and the sink north of the Equator (González-Dávila and Santana Casiano, 2012). Additionally, the region suffers from a scarcity of observations, both oceanic and atmospheric, such that significant upwelling events (Andrie et al., 1986) cannot be captured by the observations, and might be under-represented in the models, contributing to the small efflux.

A seasonal cycle in the RECCAP Equatorial is not discernible, as it includes opposing cycles from the Northern and Southern Hemisphere, and the correlations between most methodologies are not statistically significant (Table 5d). Interannual variability in the tropical Atlantic is probably linked to ENSO events, with warm events in the tropical Atlantic following the occurrence of El Niño events in the Pacific (e.g. Philander, 1986), leading to higher than usual $pCO_2$ in the equatorial Atlantic associated with higher SST in boreal winter (Andrie et al., 1986). However, it is not clear whether the $CO_2$ flux would be significantly different, as the increase of surface $pCO_2$ caused by warming might be counterbalanced by weaker trade winds. The $CO_2$ flux trend estimates (Table 8) varied in sign and statistical significance; due to the lack of sufficient atmospheric and oceanic observations, we put highest confidence into the estimate by the ocean biogeochemical models, i.e a steady source for 1995 and 2009.

### 4.5 The South Subtropics

The RECCAP South Subtropics, $44^\circ$ S to $18^\circ$ S, is a significant long-term sink for atmospheric $CO_2$ at $-0.14 \pm 0.04 \text{Pg C yr}^{-1}$ between 1990 and 2009. It includes areas of net outgassing and net uptake of atmospheric $CO_2$, bounded along the $23^\circ$ C isotherm (Ito et al., 2005), visible between $30^\circ$ S and $20^\circ$ S in both the long-term mean flux (Fig. 2) and the mean seasonal cycles (Fig. 4). Observations in both the western South Subtropics (Padin et al., 2010) as well as the eastern South Subtropics (González-Dávila et al., 2009; Santana-Casiano and González-Dávila, 2009) show this pattern. The South Subtropics seasonal cycle is again mainly temperature driven, with an efflux in summer and an uptake in winter; all methodologies show this pattern, and being highly correlated (Table 5e), we therefore
know the South Subtropics seasonal cycle with high confidence in this RECCAP region. Interannual variability in this region is large (Fig. 6e), possibly caused by strong upwelling events in the eastern part (González-Dávila et al., 2009). CO₂ flux trend estimates (Table 8) again vary in sign and significance. As this region also suffers from a scarcity of observations, both oceanic and atmospheric, we put highest confidence into the trend estimate by the ocean biogeochemical models which indicates a steady sink over 1995 and 2009.

5 Conclusions

We have summarized and compared sea–air CO₂ fluxes estimated for the Atlantic and Arctic across many realizations of the dominant methodologies presently in use to quantify regional and global carbon budgets: pCO₂ climatology, ocean inversion, atmospheric inversions and ocean biogeochemical models. Original results based on newly released large databases of in situ pCO₂ observations are also compared. Across the approaches, mean fluxes within the four Atlantic subregions generally agree within uncertainties, but seasonal cycles agree only in the subtropical regions of both hemispheres. We find little detailed agreement with respect to interannual variability or trends.

Our estimate for the 1990–2009 long-term net sea–air CO₂ flux in the Atlantic between 40° S and 79° N is $-0.49 \pm 0.05 \text{Pg C yr}^{-1}$, derived from an average of the two independent data-based approaches (pCO₂ climatology and ocean inversion). Literature sources indicate the Arctic flux was $-0.12 \pm 0.06 \text{Pg C yr}^{-1}$. Combining these, our “best” estimate of the 1990–2009 CO₂ flux in the Atlantic and Arctic is $-0.61 \pm 0.06 \text{Pg C}$. The interannual variability of the Atlantic and Arctic basins together ranged from 0.02 to 0.06 Pg C yr⁻¹ between 1990 and 2009, based on all models and data resolving this timescale. Trends of the sea–air CO₂ flux varied between time periods and methodologies used. Giving highest confidence to trends derived from ocean biogeochemical models, due to their mechanistic nature, the Atlantic and Arctic sink trend was $-0.03 \pm 0.01 \text{Pg C yr}^{-1} \text{decade}^{-1}$ (increasing sink) between 1995 and 2009.

Atlantic and Arctic carbon uptake needs to be better quantified and mechanistically understood through observations, process studies and integrated modeling efforts. One relatively simple improvement that can be made in future syntheses is to use regions defined based on biogeochemical characteristics (McKinley et al., 2011; Sarmiento et al., 2004), not straight latitudinal or longitudinal lines. A clear target for near-term process research should be to better constrain the mechanisms driving the seasonal cycle of sea–air CO₂ flux in the subpolar North Atlantic. This single region experiences the most intense carbon uptake of the globe, and if we are to understand how the global carbon sink will change under the influence of a warming climate, we must better understand the most basic pattern of variation in this critical region. Fluxes in the Arctic are quantitatively smaller, but the baseline flux is very poorly quantified and changes are rapidly progressing, so there is much work to do. In the North Subtropics, continued observations at time series stations and with VOS programs are important, as ongoing observations appear sufficient to monitor the carbon sink and potentially lead to identification of climate feedbacks on carbon uptake. The Equatorial and South Subtropics have received far less research attention. While we can be hopeful that process understanding derived elsewhere can translate effectively to these regions through ocean models, a minimum requirement will be significantly more observations for validation of model results.

Supplementary material related to this article is available online at: http://www.biogeosciences.net/10/607/2013/bg-10-607-2013-supplement.pdf.

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References


