AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL061223

Key Points:
- Recent evolution of ocean carbon sink is attributed to rising atmospheric CO_2
- Climate change impacts on air-sea CO_2 exchanges are detected in tropical oceans
- Variability in polar oceans hampers the detection climate impacts on CO_2 fluxes

Supporting Information:
- Readme
- Text S1

Correspondence to:
R. Séférian,
rseferian.cnrm@gmail.com

Citation:
Séférian, R., A. Ribes, and L. Bopp (2014), Detecting the anthropogenic influences on recent changes in ocean carbon uptake, *Geophys. Res. Lett.*, *41*, 5968–5977, doi:10.1002/2014GL061223.

Received 16 JUL 2014
Accepted 8 AUG 2014
Accepted article online 11 AUG 2014
Published online 27 AUG 2014

Detecting the anthropogenic influences on recent changes in ocean carbon uptake

Roland Séférian[1,2], Aurélien Ribes[1], and Laurent Bopp[2]

[1]CNRM-GAME/GMGEC, Toulouse, France, [2]IPSL/LSCE, Gif-sur-Yvette, France

Abstract Anthropogenic greenhouse gas emissions have modified the rate at which oceans have absorbed atmospheric CO_2 over the last centuries through rising atmospheric CO_2 and modifications in climate. However, there are still missing pieces in our understanding of the recent evolution of air-sea CO_2 exchanges related to the magnitude of their response to anthropogenic forcings versus that controlled by the internal variability. Here, to detect and attribute anthropogenic influences on oceanic CO_2 uptake between 1960 and 2005, we compare an ensemble of Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model simulations forced by individual drivers to ocean-only model reconstructions. We demonstrate that the evolution of the global oceanic carbon sink over the last decades can be understood without invoking climate change, attributing rising atmospheric CO_2 as prominent driver of the oceanic sink. Nonetheless, at regional scale, the influence of climate change on air-sea CO_2 exchanges seems to emerge from the internal variability within the low-latitude oceans.

1. Introduction

One of the greatest sources of uncertainty for future climate predictions is the response of the global carbon cycle to climate change [*IPCC*, 2013]. The growth of atmospheric CO_2 acts on the ocean carbon sink in two contrasting ways: it strengthens the ocean carbon sink by increasing the difference in the partial pressure of CO_2 between the atmosphere and the ocean, but also weakening that sink from associated global warming caused by anthropogenic CO_2 and other greenhouse gases [*Sarmiento et al.*, 1998; *Plattner et al.*, 2001; *Friedlingstein et al.*, 2006; *Cadule et al.*, 2009]. The mechanisms invoked to explain this weakening refer to changes in CO_2 solubility [*Roy et al.*, 2011], biology [*Bopp et al.*, 2013] and ocean circulation and ventilation [*Séférian et al.*, 2012; *Schwinger et al.*, 2014]. The reduction in the ocean carbon sink can be ultimately exacerbated by a contribution from the changing buffer capacity of ocean water [*Egleston et al.*, 2010], as the inorganic carbon content of surface waters increases in response to the ocean circulation slowdown.

Up to present, the oceanic uptake of CO_2 has reduced the rate at which anthropogenic carbon accumulates in the atmosphere [*Sabine et al.*, 2004]. The magnitude of this carbon sink is presently estimated to roughly one fourth of the anthropogenic CO_2 emissions [*Le Quéré et al.*, 2013; *Wanninkhof et al.*, 2013]. However, as the ocean carbon sink is sensitive to climate as well as atmospheric CO_2, models predict a future weakening of the CO_2 uptake rate in response to ongoing climate change, resulting in a positive carbon-climate feedback [*Friedlingstein et al.*, 2006]. The effort to identify this climate-carbon feedback promoted the investigation of trends in ocean carbon uptake [*Le Quéré et al.*, 2007; *Schuster and Watson*, 2007; *Thomas et al.*, 2008; *Schuster et al.*, 2009; *Metzl et al.*, 2010; *Watson et al.*, 2011] in order to detect substantial deviations from the expected response to rising atmospheric CO_2. However, the causes of the recent variations in the ocean carbon uptake over the last decades are still poorly understood [*Le Quéré et al.*, 2007; *Lovenduski et al.*, 2008; *McKinley et al.*, 2011; *Bates*, 2012].

Over the past 10 years, numerous studies tried to explain observed decadal changes in ocean carbon uptake from atmospheric or oceanic data taking a regional approach. For example, recent variability in oceanic carbon uptake in the North Atlantic sector was attributed to either changes in stratification or to the modification of the horizontal currents in response to a shift in the North Atlantic Oscillation regime [*Thomas et al.*, 2008; *Schuster et al.*, 2009]. The decrease of the Southern Ocean carbon sink, on the other hand, was explained by the strengthening of the westerlies in response to increasingly positive phases of the Southern Annular Mode [*Lovenduski et al.*, 2008]. However, the fact that these previous studies differed in their methodology and region of focus makes drawing conclusions at the global scale difficult.

Here, we present a first application of detection and attribution (D&A) methods to changes in ocean carbon uptake over the last decades. In this framework, *detection* refers the process of demonstrating that an observed change cannot be explained by internal climate variability in a statistical sense. The *attribution* of a change to a cause requires, in addition, the demonstration that the detected change is consistent with the expected response to known external forcings and not consistent with other alternative physically-plausible explanations.

Instrumental records of oceanic carbon-related data go back to the early 1960s. They are unevenly distributed with five times more data collected each month in the Northern Hemisphere than in any other oceanic regions [*Bakker et al.*, 2012]. The scarcity of observations impairs our capability to detect a weakening of the ocean carbon sink over the past decades in response to anthropogenic climate impacts [*Fay and McKinley*, 2013]. To circumvent this issue, we use gridded reconstructions of ocean carbon fluxes provided by the seven ocean biogeochemical models as pseudo-observations over the 1960–2005 period. These model reconstructions have contributed to the Regional Carbon Cycle Assessment and Processes [*Canadell et al.*, 2011] (RECCAP) project as a part of the Global Carbon Project [*Le Quéré et al.*, 2013] (GCP).

2. Materials

2.1. RECCAP Reconstructions

The RECCAP initiative provides a set of reconstructions from 1959 to 2005 performed with seven ocean biogeochemical general circulation model forced by atmospheric reanalyses of the National Center for Environmental Prediction (NCEP, [*Kalnay et al.*, 1996]). The reconstructions of ocean carbon fluxes in the RECCAP initiative are estimated from MICOM-HAMOCC5.1 [*Assmann et al.*, 2010], CCSM-BOGCM [*Matear and Lenton*, 2008], CCSM-BEC [*Doney et al.*, 2009], CCSM-ETHk15, CCSM-ETHk19 [*Graven et al.*, 2012], NEMO-PISCES [*Aumont and Bopp*, 2006], and NEMO-Planktom5 [*Buitenhuis et al.*, 2010]. Even if some of the models that are used here are based on similar original codes (it is the case for the models derived from CCSM model), we consider them as independent from each other since all the ocean biogeochemical models are based on different representations of the marine biogeochemistry. Of the nine available reconstructions, three were carried out with NEMO-Planktom5 using three different wind products: ECMWF (European Centre for Medium-Range Weather Forecasts, [*Dee et al.*, 2011]), NCEP, and CCMP (cross-calibrated multiplatform, [*Atlas et al.*, 2011]). Here, we have chosen to keep only one of these three reconstructions in order to ensure consistency in the model distribution. The seven remaining reconstructions produced by the seven ocean biogeochemical models forced with the same atmospheric forcing product are used here, as pseudo-observations, to detect and attribute anthropogenic influences on the oceanic sink of CO_2 from 1960 to 2005.

2.2. Coupled Model Intercomparison Project Phase 5 (CMIP5) “Fingerprints” Simulations

We used several ensembles of simulations from CMIP5 Earth system models to distinguish between the effect of increasing atmospheric CO_2, the effect of climate, the combined effects of both, and the internal variability on the ocean carbon fluxes. The GEO ensemble represents the influence of rising anthropogenic CO_2 into the atmosphere without accounting for its contribution to the radiative forcing (hereafter, the geochemical forcing). The CLIM ensemble considers only change in climate due to external forcings without accounting for their contributions to geochemical forcing (hereafter, the climate forcing). External forcings include anthropogenic CO_2 and other anthropogenic greenhouse gases and aerosols as well as natural forcings like natural aerosols, volcanoes and variations of the solar irradiance. The ALL ensemble integrates the influences of both the geochemical and the climate effect on the ocean carbon uptake. We evaluate the internal variability (IV) of ocean carbon fluxes by considering more than 13,000 years of control simulations including experiments in which external forcings are set to their preindustrial values and those in which atmospheric CO_2 is prognostically computed by the model without anthropogenic emissions. The size of each ensemble is, respectively, 7 for GEO, 5 for CLIM, 21 for ALL, and 297 for IV.

2.3. Data Processing

The ensembles of simulations, ALL, GEO, CLIM, RECCAP, and IV were processed as follows. We interpolated model outputs on a regular 1° × 1° grid. Carbon uptake was computed at global and regional scales by spatially integrating ocean carbon fluxes from 1960 to 2005. Regional budgets are calculated for the North Atlantic and North Pacific domains (north of 30°N); the low-latitude Atlantic and Pacific which includes the

Indian ocean (30°S and 30°N) and the Southern Ocean which includes all oceanic domains south of 30°S. The mean seasonal cycle was removed from both regional and global time series in order to compute yearly anomalies of ocean carbon uptake from 1960 to 2005. These time series were reduced to 10 time steps corresponding to temporal averages over 10 non-overlapping periods of ~4.5 years. We used a similar methodology for the 13,000 years of preindustrial simulation, except that these simulations were split into 297 time segments of 45 years before computing the 10 year averaged time series.

3. Detection and Attribution Methods

3.1. Detection Procedure Based on Long-Term Trend Analysis

The first step of our detection and attribution approach consists of a simple consistency test focusing on long-term trend analysis over the whole period. Here, we analyze the long-term contribution of the anthropogenic forcings to ocean carbon fluxes with respect to the long-term variations driven by the internal variability. We compared the linear trends computed from the time series of ocean carbon uptake at the global scale and in five oceanic domains. The probability density functions (pdf) of these long-term trends are described by a Gaussian distribution. The *p*-value results from a consistency test comparing long-term trends of the RECCAP's multi-model mean trends, $y_,$ to the distribution of the trends estimated from the GEO, CLIM, and ALL ensembles, $X_,$ as follows:

$$\frac{y-\overline{x}}{\sigma_x\sqrt{\frac{n+1}{n}}}\sim T_{n-1}$$

where $\overline{x}$ and σ_x are the mean and standard deviation of the sample *X*. In this statistical test, a high [low] *p*-value indicates that trends of the RECCAP's multi-model mean are consistent [inconsistent] with the underlying distribution of the GEO, CLIM, and ALL ensembles. We compared the trends of the RECCAP, GEO, and CLIM ensemble means to the distribution of the estimated internal variability using the same protocol.

3.2. Fingerprint Analysis

To assess the relative contribution of each external forcing to the multi-decadal evolution of the ocean carbon uptake at both regional and global scales, we applied a detection and attribution analysis based on the Regularized Optimal Fingerprint (ROF [*Ribes et al.*, 2013]). A detection and attribution procedure is performed using a regression model where pseudo-observations *Y* are decomposed into the sum of scaled model-simulated responses to the geochemical and the climate external forcings *g* plus internal climate variability ε_Y as $Y=\sum_{i=1}^{2}\beta_i g_i+\varepsilon_Y$. In this statistical model, we assume that model-simulated responses to external forcings are not perfectly known. They are potentially modulated by the internal variability (ε_g), so that $\widetilde{g}_i=g_i+\varepsilon_g$. Scaling factors, β, are unknown and estimated by regressing pseudo-observations onto individual fingerprints using a total least square regression (TLS [*Allen and Stott*, 2003]). Confidence intervals on β are estimated for 90% significance level (see [*Allen and Stott*, 2003; *Ribes et al.*, 2013] for further details). Simultaneously, the TLS algorithm also provides estimates for ε_Y and ε_g, which are used to test goodness of fit (see section 3.3). Fingerprints of the GEO or the CLIM forcings have been evaluated from the ensemble mean of the corresponding set of simulations. Finally, more than 13,000 years of control simulation from the CMIP5 Earth system model ensemble (see supporting information) have been used to determine internal variability of ocean carbon fluxes.

The analysis was applied twice over the 10 non-overlapping periods between 1960 and 2005. The first application considers each oceanic domain individually, whereas the second integrates all regions together in order to capture global spatiotemporal information.

For GEO and CLIM, scaling factor β statistically inconsistent with 0 (meaning its confidence interval does not include 0) indicates that the response to the corresponding forcing is detected, confirming that this forcing has a significant influence on the observed changes. The influence of the corresponding forcing in the RECCAP reconstructions is similar in magnitude with that simulated by CMIP5 models when β is equal to 1. β smaller [larger] than 1 suggests that the CMIP5 model tends to overestimate [underestimate] the RECCAP reconstructions.

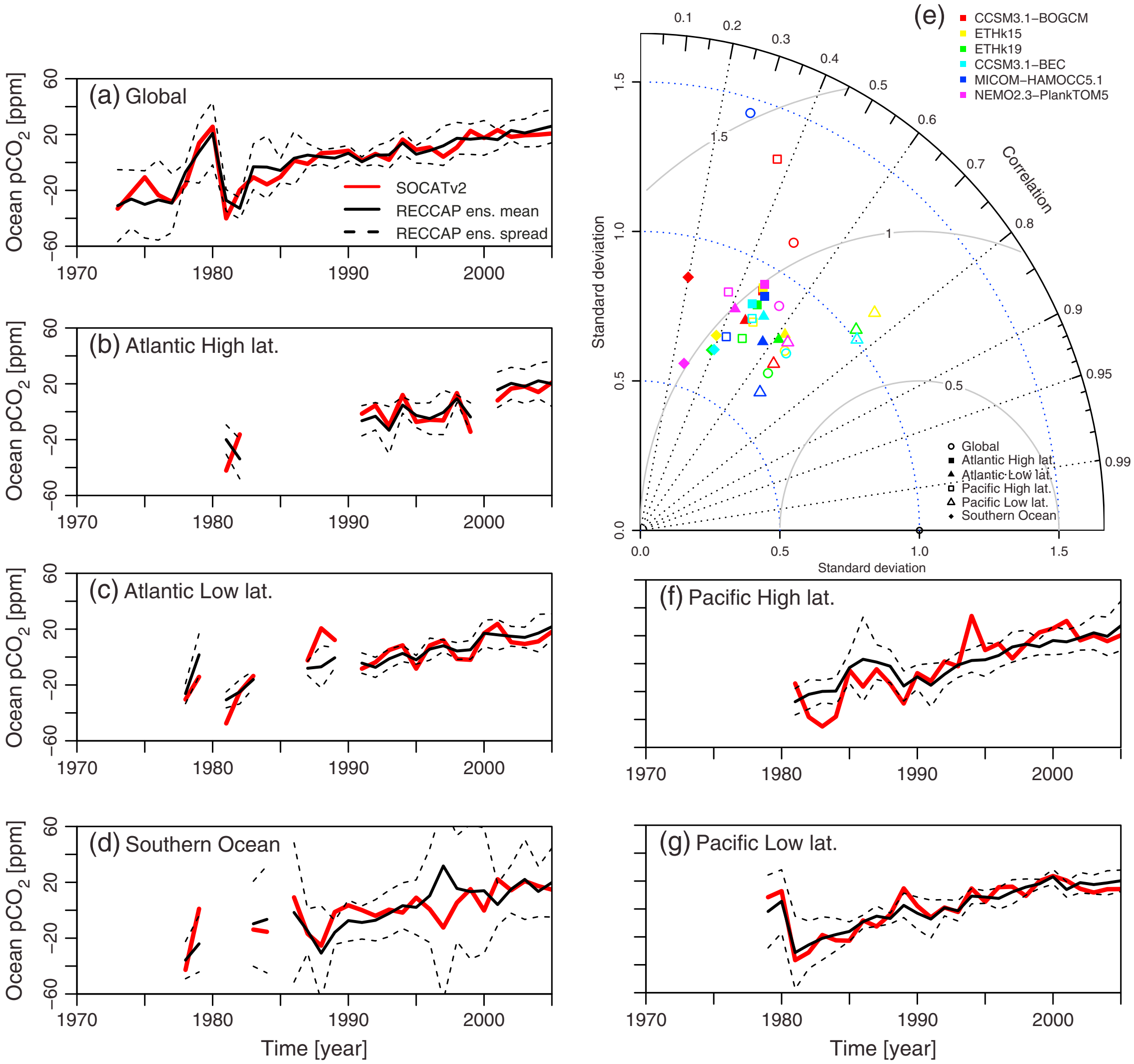

Figure 1. SOCATv2 and Regional Carbon Cycle Assessment and Processes (RECCAP) 1970–2005 time series of oceanic pCO_2 anomalies. Annual anomalies (in ppm) averaged at global scale and over the five oceanic domains as performed in the optimal fingerprint analysis. Observed time series of oceanic pCO2 of SOCATv2 are represented in red thick line. The reconstructed time series of oceanic pCO_2 is estimated from the RECCAP ensemble including all the models expect NEMO-PISCES; the ensemble mean is represented in solid black line while the 5%–95% confidence interval is given in dashed thin lines. Taylor diagram (e) compares spatiotemporal reconstructions of the six available RECCAP models to the SOCATv2 observations from 1970 to 2005. Available RECCAP reconstructions have been subsampled in time and space accordingly to the SOCATv2 observations.

3.3. Residual Consistency Test

The final step in our detection and attribution procedure is a residual consistency test to check whether the estimated residuals ε_Y and ε_g are consistent with the assumed internal variability (IV). This test was derived from the two residual consistency tests introduced by *Allen and Tett* [1999] and *Allen and Stott* [2003] and relies on two different estimates of the null-hypothesis distribution (i.e., based on the estimated internal variability, implementation details are provided in [*Ribes et al.*, 2013]). The overall statistical model can be considered suitable if this test is passed. If not, then at least one of the initial assumptions should be revised. Rejection may occur, for example, if the IV is too low or response patterns to external forcings are not correct.

4. Evaluation of the RECCAP Ensemble

Here, we evaluate the accuracy of the available RECCAP reconstructions that are used in our statistical framework as pseudo-observations. For this purpose, we use *in situ* observations of ocean fCO_2 from the SOCATv2 database [*Bakker et al.*, 2014], which span the years 1970 to 2011. We estimate *in situ* pCO_2 from the

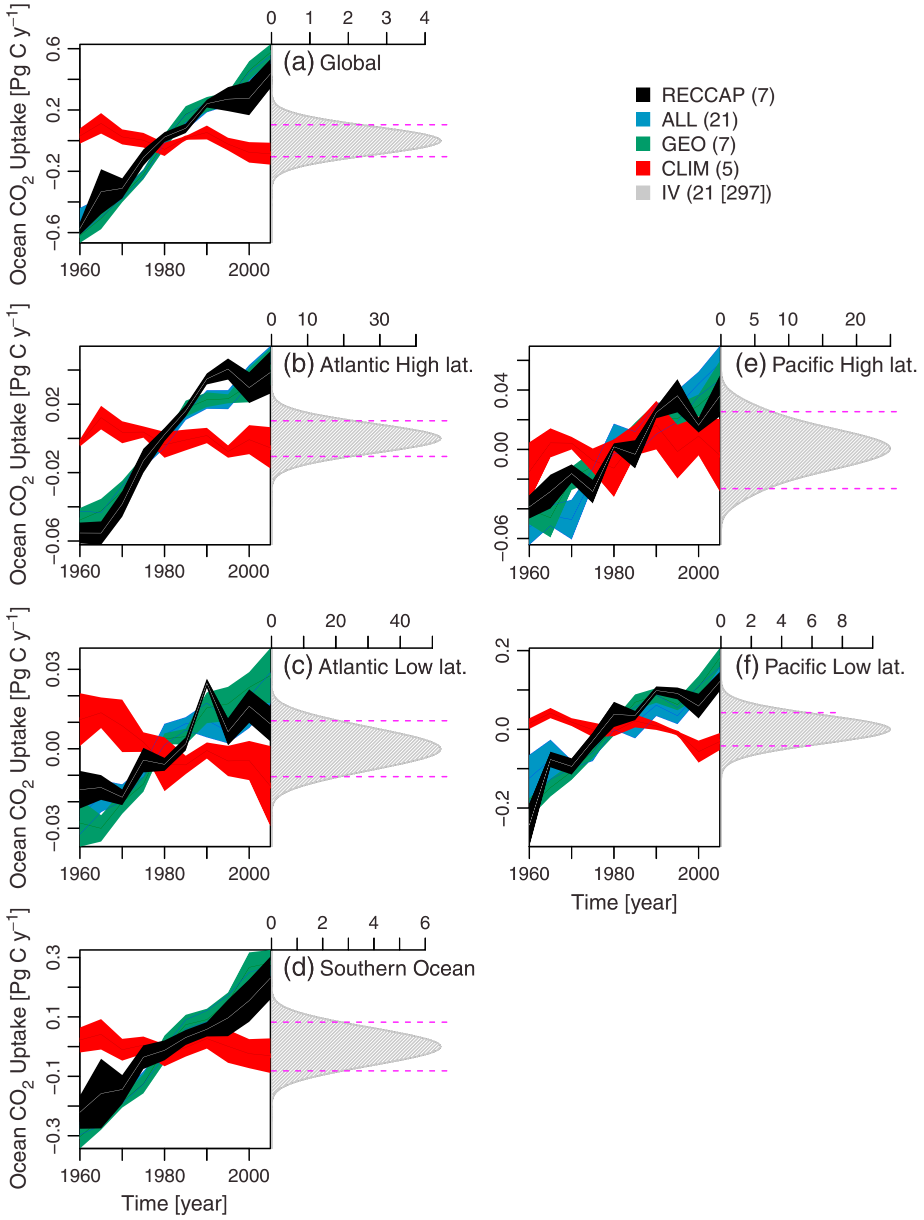

Figure 2. Coupled Model Intercomparison Project Phase 5 (CMIP5) and RECCAP 1960–2005 time series of ocean CO_2 uptake anomalies. Annual anomalies (in Pg C y^{-1}) averaged over 10 non-overlapping periods as performed in the detection and attribution (D&A) analysis. Blue and black shading represents the 5%–95% confidence interval of each 5 year mean historical ensemble (ALL) of CMIP5 models and RECCAP reconstructions, respectively. Green and red shading indicate the 5%–95% confidence interval of each 5 year mean as computed from the CMIP5 multi-model ensemble considering individual responses due to the geochemical forcings (GEO) and the climate forcings (CLIM). Internal variability (IV) of the ocean CO_2 uptake is represented with the probability density function (grey hatched) and the corresponding 5%–95% quantiles (dashed magenta lines) as computed from the 297 non-overlapping time segments of the CMIP5 preindustrial simulations. The size of each ensemble used is bracketed.

SOCATv2 fCO_2 database using a fixed 1/0.996 conversion factor. The six available RECCAP reconstructions for pCO_2 (including all the models except NEMO-PISCES) have been subsampled in order to keep consistency with the same spatiotemporal coverage as the observations. Correlations, standard deviations, and root-mean squared errors of the year-to-year spatial distribution of averaged anomalies of pCO_2 for the observations and the reconstructions are summarized on the Taylor Diagram (Figure 1e). The reconstructed pCO_2 agrees reasonably well with the observed pCO_2: the correlations and standard deviations essentially

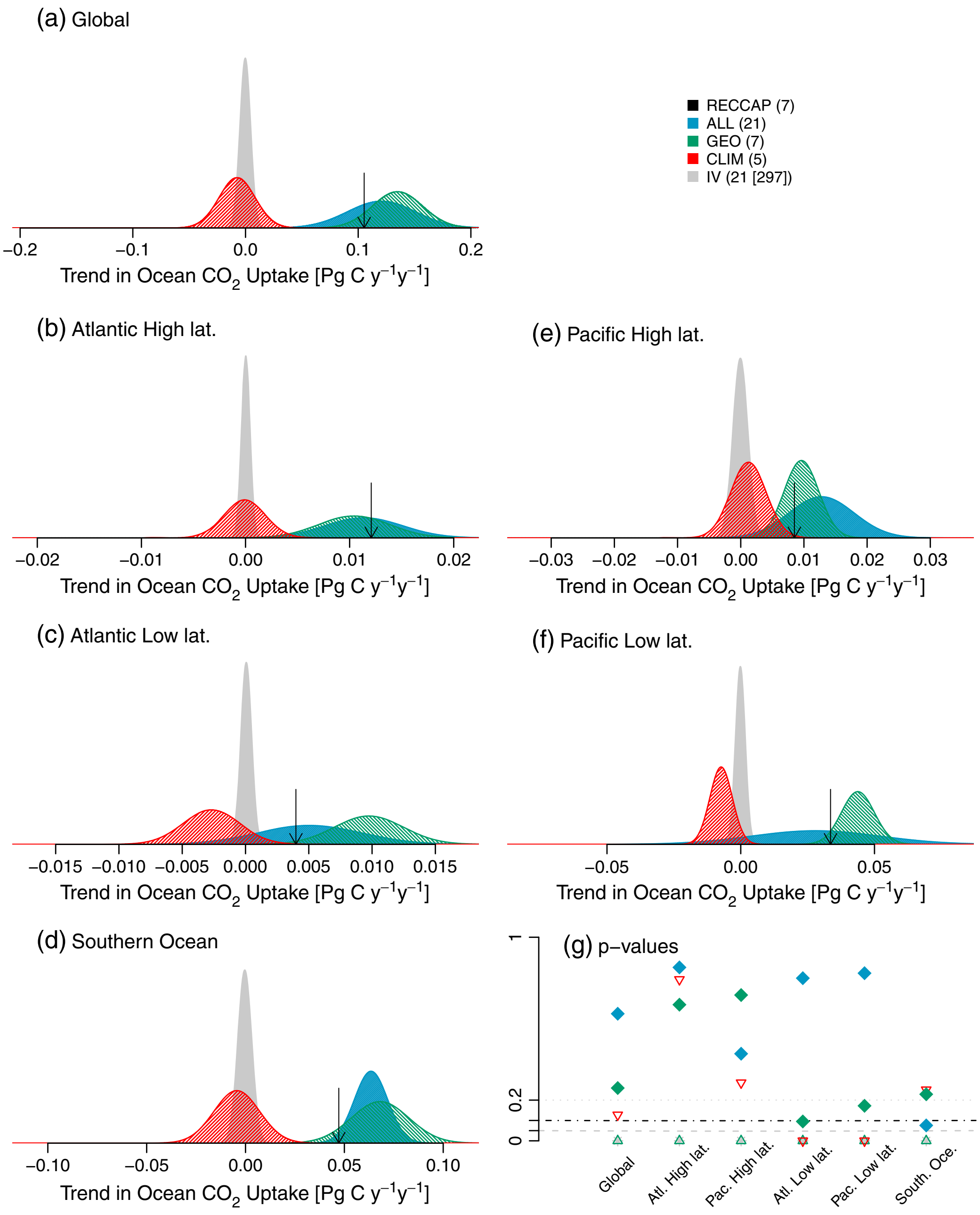

Figure 3. Probability density function (pdf) of ocean CO_2 uptake 1960–2005 long-term trends at global and regional scale. Multi-decadal trends of ocean CO_2 uptake including all external forcings are estimated from the ALL ensemble (in blue pdfs), while those representing the individual influence of the geochemical and the climate forcings are estimated from the GEO and CLIM ensembles (in green and red pdfs, respectively). Black arrows give the long-term evolution of the RECCAP multi-model mean. The p-values testing the different hypotheses are given in (g). Grey stars (respectively, green and red filled squares) illustrate, respectively, the *p*-values obtained from testing whether the RECCAP (respectively, GEO and ALL) multi-model mean is consistent with the distribution of the internal variability (IV, in grey pdfs). The *p*-values testing whether the GEO and CLIM multi-model mean are consistent with the IV distribution are given with green and red triangles. *P*-values thresholds at 5% and 10% significance levels are given in black and grey dashed lines. The size of each ensemble used is bracketed.

range between 0.4–0.8 and 0.6–1.0, respectively. Exceptions are found for CCSM-BOGCM and MICOM-HAMOCC5.1 at both the global scale and in the high-latitude Pacific, for ETHk15 in the low-latitude Pacific and for NEMO-PlankTOM5 in the Southern Ocean. Better reconstructions-data agreement is found in the low-latitude Pacific; moderate agreement is found in the high-latitude oceans, low-latitude Atlantic and at global scale;

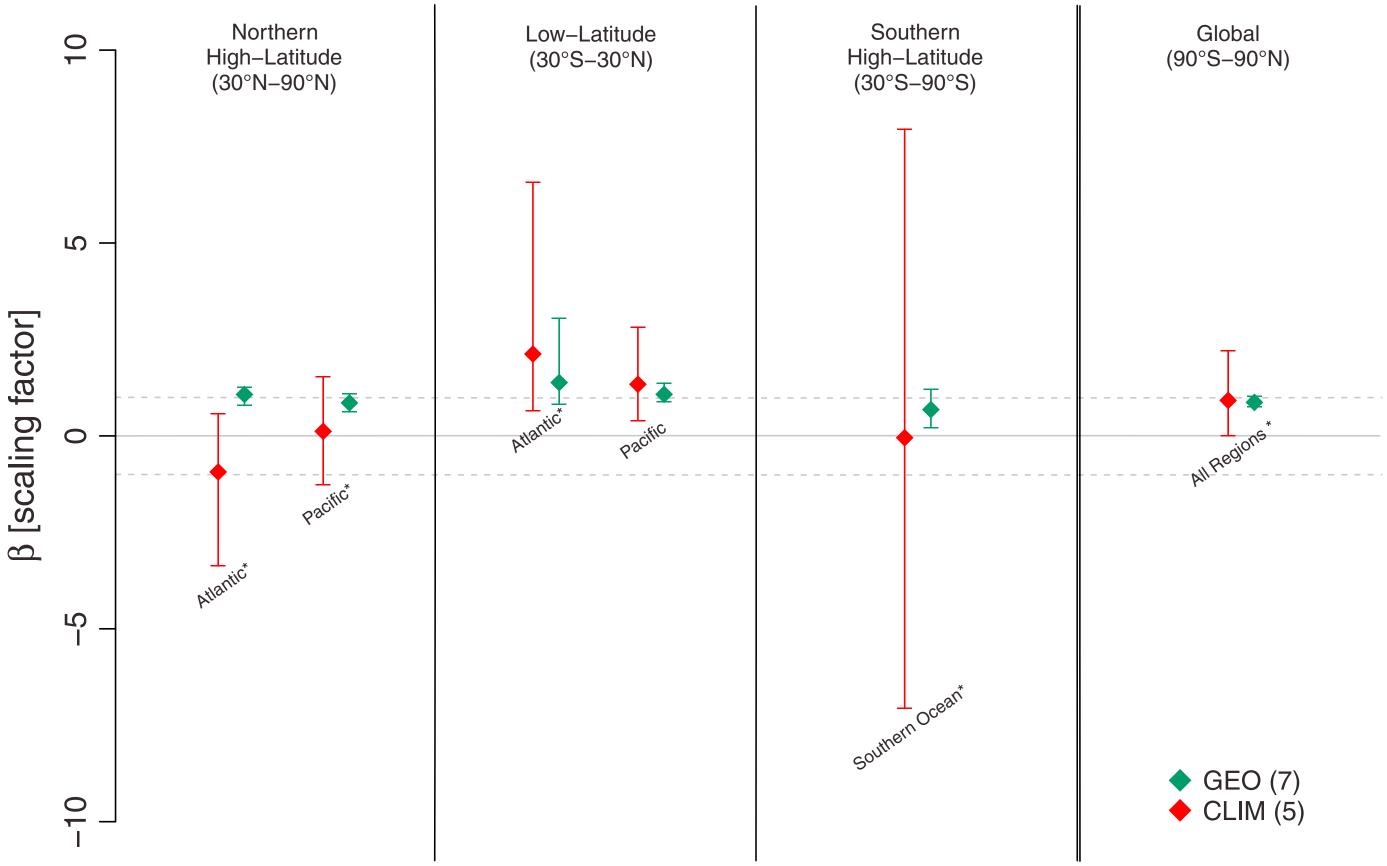

Figure 4. Scaling factors (β) best estimates and their 5%–95% confidence intervals as computed from the optimal fingerprints analysis applied to the RECCAP data sets. Regional scaling factors are estimated from time series of ocean carbon uptake anomalies, while global scaling factor integrates spatiotemporal information by performing all of the regional time series at once in the optimal fingerprints analysis (* indicates a passed residual consistency test). Optimal fingerprints analyses were based on the 1960–2005 ensemble mean time series. The size of each ensemble used is bracketed.

while the poorest reconstructions-data agreement is found in the Southern Ocean. The RECCAP reconstructions underestimate the spatiotemporal variability at both regional and global scales; that is, the normalized standard deviations are lower than 1.

Despite these discrepancies, anomalies of regionally and globally averaged pCO_2 estimated from the RECCAP reconstructions are in good agreement with those estimated from SOCATv2 (Figure 1, see also [*Tjiputra et al.*, 2014]). Given that the correlation between the RECCAP ensemble mean and SOCATv2 pCO_2 are higher than 0.8, the RECCAP ensemble mean should be a reasonable surrogate for air-sea CO_2 exchange observations.

5. Results and Discussions

The multi-decadal evolution of ocean carbon uptake estimated by the RECCAP reconstructions and the one simulated by the CMIP5 models in the ALL ensemble indicate a reinforcement of the oceanic carbon sink over the last 5 decades (Figure 2). Considering influences of each forcing, the individual influence of rising atmospheric CO_2 alone (GEO on Figure 2) leads to a progressive reinforcement of the carbon uptake in the various oceanic domains, whereas the influence of the climate change alone (CLIM on Figure 2) leads to a progressive but smaller reduction (Figure 2).

With our first simple approach, we have compared long-term trends of the RECCAP's multi-model mean to the distribution of the expected trends from CMIP5 models under different combinations of forcings (Figure 3). Our analysis demonstrates that substantial changes in ocean carbon uptake are detected over all regions (inconsistency with the internal variability, p-value $< 10^{-5}$) and are well captured by the combination of external forcings (consistency with ALL, p-value > 0.1). The attribution is completed by comparing the influence of each forcing individually. While the influence of rising atmospheric CO_2 (GEO on Figure 3) is clear in the high-latitude oceans and at global scale, a significant influence of climate forcing (CLIM on Figure 3) can only be attributed in the low-latitude oceans (p-value $< 10^{-5}$, Figure 3). In the other oceanic domains, influence of climate forcing drives changes, which are confounded with internal variability (IV). This result demonstrates that, even at multi-decadal time scales, the lower signal-to-noise ratio of the climate forcing long-term trend is difficult to distinguish from the internal variability for a high confidence level (90%).

The relative contribution of each external forcing to the multi-decadal evolution of the ocean carbon uptake has been assessed using a state-of-the-art fingerprints analysis. Outcomes of the fingerprints analysis, namely scaling factors (β, Figure 4), correspond to the amplitude coefficients that one should apply onto the simulated response given by the geochemical forcing (GEO) or the climate forcing (CLIM) to best fit the pseudo-observations (RECCAP). Goodness of this fit is assessed in turn by checking consistency of the distribution of residuals against that of the internal variability estimated from the ~13,000 years of control simulations (IV ensemble, see supporting information).

The fingerprints analysis demonstrates that geochemical forcing predominantly contributes to the evolution of the ocean carbon uptake since the best estimates of the scaling factors, β, for GEO are close to 1 at both regional and global scales. Also, the small corresponding confidence intervals indicate a clear observational constraint. Conversely, the influence of climate forcing varies regionally. Influence of climate forcing is generally confounded with the natural variability (β is consistent with 0 for CLIM ensemble), except within the low-latitude oceans where the scaling factors for CLIM are close to 1. This implies that the recent variations of carbon uptake in the low-latitude oceans cannot be explained without invoking changes due to climate forcing and confirms that ocean carbon uptake has been reduced by climate impacts in the late twentieth century. Several plausible process combinations could explain the reduction in ocean carbon uptake. Among these, recent detection and attribution studies indicate that sea surface temperature and the hydrological cycle in the Tropics have been impacted by climate change over the last decades [*Durack et al.*, 2012; *Terray et al.*, 2012]. Thus, it seems likely that the reduction in ocean carbon uptake across the low-latitude oceans was driven by changes in solubility and stratification. In other oceanic regions, no effect of climate change could be detected at the 90% significance level, potentially due to the larger internal variability of the ocean carbon fluxes. Considering the sum of all the regional influences of both the geochemical and the climate forcings, our analysis suggests that the global ocean carbon uptake has not been weakened by climate impacts over the last decades.

Despite the high statistical significance of our results, they are potentially limited by the use of model reconstructions (defined as pseudo-observations) instead of direct observations. For example, the horizontal resolution of the models used in this study is too low to account for the influence of mesoscale eddies on ocean carbon fluxes [*Ito et al.*, 2010]. Eddies may modulate the amplitude of the internal variability of the ocean carbon fluxes as well as the response of carbon uptake to climate change [*Dufour et al.*, 2013]. Yet, both the driving mechanisms and the magnitudes of the responses of the ocean carbon fluxes to eddies over different time scales are still uncertain [*Lévy et al.*, 2013; *Lovenduski et al.*, 2013]. On the other hand, the fact that preindustrial simulations were used as a surrogate for the natural variability of ocean carbon fluxes might also bias our results. Indeed, climate change can modulate the phasing and the amplitude of the natural variability of ocean carbon fluxes [*Frölicher et al.*, 2009]. A multi-model ensemble could be used to constrain this kind of uncertainty [*Deser et al.*, 2010]. However, very few ensemble simulations of Earth system models have been performed in CMIP5 and currently preclude the use of this kind of methodology. That said, even observational-based analyses may be subject to large uncertainties. Of concern, [*Tjiputra et al.*, 2014] recently showed that the scarcity of data can strongly bias the estimation of pCO_2 trends and hence demonstrates the importance of sufficient spatiotemporal coverage for trends analysis. In our case, we took advantage of the reconstructions provided by the RECCAP initiative to assess the relative influence of external forcings and internal variability on the ocean carbon fluxes at both global and regional scales.

Considering the model caveats, our study could be understood, at worst, as parallel information for the planning of future *in situ* studies. As a matter of fact, most studies of long-term changes in the ocean carbon cycle focus on the high-latitude oceans because they are the major contemporary regions of ocean carbon uptake [*Takahashi*, 2009; *Bakker et al.*, 2014]. Unfortunately, in the high-latitude oceans, the strong low-frequency variability [*Séférian et al.*, 2013] and a small response to climate change prevent the detection of multi-decadal changes in ocean carbon uptake. On the contrary, in the low-latitude oceans, the strong signal-to-noise ratio at multi-decadal time scales [*Friedrich et al.*, 2012; *Séférian et al.*, 2013] allows the detection and the attribution of anthropogenically mediated climate forcing in all oceanic basins over the recent decades. However, in the low-latitude regions the data coverage is sparse [*Takahashi*, 2009; *Bakker et al.*, 2012]. Our findings highlight the need to maintaining the current observational networks over decades and to enhance observational coverage over the low-latitude oceans to evaluate the risk of the amplification of climate change through climate-carbon feedback loops.

Acknowledgments
We sincerely thank Tilla Roy, Marion Gehlen, James Orr, and the two anonymous reviewers for their useful comments on that paper. This work was supported by the EU FP7 project CARBOCHANGE "Changes in carbon uptake and missions by oceans in a changing climate" which received funding from the European community's Seventh Framework Program under grant agreement 264879.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Allen, M. R., and P. A. Stott (2003), Estimating signal amplitudes in optimal fingerprinting, Part I: Theory, *Clim. Dyn.*, *21*(5–6), 477–491, doi:10.1007/s00382-003-0313-9.

Allen, M., and S. Tett (1999), Checking for model consistency in optimal fingerprinting, *Clim. Dyn.*, *15*(6), 419–434.

Assmann, K. M., M. Bentsen, J. Segschneider, and C. Heinze (2010), An isopycnic ocean carbon cycle model, *Geosci. Model Dev.*, *3*(1), 143–167, doi:10.5194/gmd-3-143-2010.

Atlas, R., R. N. Hoffman, J. Ardizzone, S. M. Leidner, J. C. Jusem, D. K. Smith, and D. Gombos (2011), A cross-calibrated, multiplatform ocean surface wind velocity product for meteorological and oceanographic applications, *Bull. Am. Meteorol. Soc.*, *92*(2), 157–174, doi:10.1175/2010BAMS2946.2.

Aumont, O., and L. Bopp (2006), Globalizing results from ocean in situ iron fertilization studies, *Global Biogeochem. Cycles*, *20*, GB2017, doi:10.1029/2005GB002591.

Bakker, D. C. E., et al. (2012), Global data products help assess changes to ocean carbon sink, *Eos Trans. AGU*, *93*(12), doi:10.1029/2012EO120001.

Bakker, D. C. E., et al. (2014), An update to the Surface Ocean CO_2 Atlas (SOCAT version 2), *Earth Syst. Sci. Data*, *6*(1), 69–90, doi:10.5194/essd-6-69-2014.

Bates, N. R. (2012), Multi-decadal uptake of carbon dioxide into subtropical mode water of the North Atlantic Ocean, *Biogeosciences*, *9*(7), 2649–2659.

Bopp, L., et al. (2013), Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models, *Biogeosciences*, *10*(10), 6225–6245, doi:10.5194/bg-10-6225-2013.

Buitenhuis, E. T., R. B. Rivkin, S. Sailley, and C. Le Quéré (2010), Biogeochemical fluxes through microzooplankton, *Global Biogeochem. Cycles*, *24*, Gb4015, doi:10.1029/2009GB003601.

Cadule, P., L. Bopp, and P. Friedlingstein (2009), A revised estimate of the processes contributing to global warming due to climate-carbon feedback, *Geophys. Res. Lett.*, *36*, L14705, doi:10.1029/2009GL038681.

Canadell, J. G., P. Ciais, K. Gurney, C. Le Quéré, S. Piao, M. R. Raupach, and C. L. Sabine (2011), An International Effort to Quantify Regional Carbon Fluxes, *Eos Trans. AGU*, *92*(10), 81, doi:10.1029/2011EO100001.

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, *137*(656), 553–597.

Deser, C., A. Phillips, V. Bourdette, and H. Teng (2010), Uncertainty in climate change projections: The role of internal variability, *Clim. Dyn.*, *38*(3–4), 527–546, doi:10.1007/s00382-010-0977-x.

Doney, S. C., I. Lima, R. A. Feely, D. M. Glover, K. Lindsay, N. Mahowald, J. K. Moore, and R. Wanninkhof (2009), Mechanisms governing interannual variability in upper-ocean inorganic carbon system and air–sea CO_2 fluxes: Physical climate and atmospheric dust, *Deep Sea Res., Part II*, *56*(8–10), 640–655, doi:10.1016/j.dsr2.2008.12.006.

Dufour, C. O., J. L. Sommer, M. Gehlen, J. C. Orr, J.-M. Molines, J. Simeon, and B. Barnier (2013), Eddy compensation and controls of the enhanced sea-to-air CO_2 flux during positive phases of the Southern Annular Mode, *Global Biogeochem. Cycles*, *27*, 950–961, doi:10.1002/gbc.20090.

Durack, P. J., S. E. Wijffels, and R. J. Matear (2012), Ocean salinities reveal strong global water cycle intensification during 1950 to 2000, *Science*, *336*(6080), 455–458.

Egleston, E. S., C. L. Sabine, and F. M. M. Morel (2010), Revelle revisited: Buffer factors that quantify the response of ocean chemistry to changes in DIC and alkalinity, *Global Biogeochem. Cycles*, *24*, GB1002, doi:10.1029/2008GB003407.

Fay, A. R., and G. A. McKinley (2013), Global trends in surface ocean pCO_2 from in situ data, *Global Biogeochem. Cycles*, *27*, 541–557, doi:10.1002/gbc.20051.

Friedlingstein, P., et al. (2006), Climate–carbon cycle feedback analysis: Results from the C 4MIP model intercomparison, *J. Clim.*, *10*(14), 3337–3353, doi:10.1175/JCLI3800.1.

Friedrich, T., et al. (2012), Detecting regional anthropogenic trends in ocean acidification against natural variability, *Nat. Clim. Change*, *2*(3), 167–171, doi:10.1038/nclimate1372.

Frölicher, T. L., F. Joos, G. K. Plattner, M. Steinacher, and S. C. Doney (2009), Natural variability and anthropogenic trends in oceanic oxygen in a coupled carbon cycle–climate model ensemble, *Global Biogeochem. Cycles*, *23*, GB1003, doi:10.1029/2008GB003316.

Graven, H. D., N. Gruber, R. Key, S. Khatiwala, and X. Giraud (2012), Changing controls on oceanic radiocarbon: New insights on shallow-to-deep ocean exchange and anthropogenic CO_2 uptake, *J. Geophys. Res.*, *117*, C10005, doi:10.1029/2012JC008074.

IPCC (2013), *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stoker et al., 1535 pp., Cambridge Univ. Press, Cambridge, U. K., and New York.

Ito, T., M. Woloszyn, and M. Mazloff (2010), Anthropogenic carbon dioxide transport in the Southern Ocean driven by Ekman flow, *Nature*, *463*(7277), 80–83, doi:10.1038/nature08687.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*(3), 437–472.

Le Quéré, C., et al. (2007), Saturation of the Southern Ocean CO_2 sink due to recent climate change, *Science*, *316*(5832), 1735–1738, doi:10.1126/science.1136188.

Le Quéré, C., et al. (2013), The global carbon budget 1959–2011, *Earth Syst. Sci. Data*, *5*(1), 165–185.

Lévy, M., L. Bopp, P. Karleskind, L. Resplandy, C. Ethe, and F. Pinsard (2013), Physical pathways for carbon transfers between the surface mixed layer and the ocean interior, *Global Biogeochem. Cycles*, *27*, 1001–1012, doi:10.1002/gbc.20092.

Lovenduski, N. S., N. Gruber, and S. C. Doney (2008), Toward a mechanistic understanding of the decadal trends in the Southern Ocean carbon sink, *Global Biogeochem. Cycles*, *22*, GB3016, doi:10.1029/2007GB003139.

Lovenduski, N. S., M. C. Long, P. R. Gent, and K. Lindsay (2013), Multi-decadal trends in the advection and mixing of natural carbon in the Southern Ocean, *Geophys. Res. Lett.*, *40*, 139–142, doi:10.1029/2012GL054483.

Matear, R. J., and A. Lenton (2008), Impact of historical climate change on the Southern Ocean carbon cycle, *J. Clim.*, *21*(22), 5820–5834, doi:10.1175/2008JCLI2194.1.

McKinley, G. A., A. R. Fay, T. Takahashi, and N. Metzl (2011), Convergence of atmospheric and North Atlantic carbon dioxide trends on multidecadal timescales, *Nat. Geosci.*, *4*(7), 1–5, doi:10.1038/ngeo1193.

Metzl, N., et al. (2010), Recent acceleration of the sea surface fCO_2 growth rate in the North Atlantic subpolar gyre (1993–2008) revealed by winter observations, *Global Biogeochem. Cycles*, *24*, GB4004, doi:10.1029/2009GB003658.

Plattner, G., F. Joos, T. Stocker, and O. Marchal (2001), Feedback mechanisms and sensitivities of ocean carbon uptake under global warming, *Tellus B*, *5*(53B), 564–592.

Ribes, A., S. Planton, and L. Terray (2013), Application of regularised optimal fingerprinting to attribution. Part I: method, properties and idealised analysis, *Clim. Dyn.*, *41*(11-12), 2817–2836, doi:10.1007/s00382-013-1735-7.

Roy, T., L. Bopp, M. Gehlen, B. Schneider, P. Cadule, T. L. Frölicher, J. Segschneider, J. Tjiputra, C. Heinze, and F. Joos (2011), Regional impacts of climate change and atmospheric CO_2 on future ocean carbon uptake: A multimodel linear feedback analysis, *J. Clim.*, *24*(9), 2300–2318, doi:10.1175/2010JCLI3787.1.

Sabine, C., et al. (2004), The oceanic sink for anthropogenic CO(2), *Science*, *305*(5682), 367–371, doi:10.1126/science.1097403.

Sarmiento, J., T. Hughes, R. Stouffer, and S. Manabe (1998), Simulated response of the ocean carbon cycle to anthropogenic climate warming, *Nature*, *393*(6682), 245–249.

Schuster, U., and A. J. Watson (2007), A variable and decreasing sink for atmospheric CO_2 in the North Atlantic, *J. Geophys. Res.*, *112*, 1–10, doi:10.1029/2006JC003941.

Schuster, U., A. J. Watson, N. R. Bates, A. Corbiere, M. González-Dávila, N. Metzl, D. Pierrot, and M. Santana-Casiano (2009), Trends in North Atlantic sea-surface fCO_2 from 1990 to 2006, *Deep Sea Res., Part II*, *56*(8–10), 620–629, doi:10.1016/j.dsr2.2008.12.011.

Schwinger, J., et al. (2014), Non-linearity of ocean carbon cycle feedbacks in CMIP5 earth system models, *J. Clim.*, *27*(11), 3869–3888.

Séférian, R., D. Iudicone, L. Bopp, T. Roy, and G. Madec (2012), Water mass analysis of effect of climate change on air–sea CO_2 fluxes: The Southern Ocean, *J. Clim.*, *25*(11), 3894–3908, doi:10.1175/JCLI-D-11-00291.1.

Séférian, R., L. Bopp, D. Swingedouw, and J. Servonnat (2013), Dynamical and biogeochemical control on the decadal variability of ocean carbon fluxes, *Earth Syst. Dyn.*, *4*(1), 109–127, doi:10.5194/esd-4-109-2013.

Takahashi, T. (2009), Climatological mean and decadal change in surface ocean pCO_2, and net sea–air CO_2 flux over the global oceans, *Deep Sea Res., Part II*, *56*(8–10), 554–577, doi:10.1016/j.dsr2.2008.12.009.

Terray, L., L. Corre, S. Cravatte, T. Delcroix, G. Reverdin, and A. Ribes (2012), Near-surface salinity as nature's rain gauge to detect human influence on the tropical water cycle, *J. Clim.*, *25*(3), 958–977, doi:10.1175/JCLI-D-10-05025.1.

Thomas, H., A. E. Friederike Prowe, I. D. Lima, S. C. Doney, R. Wanninkhof, R. J. Greatbatch, U. Schuster, and A. Corbière (2008), Changes in the North Atlantic Oscillation influence CO_2 uptake in the North Atlantic over the past 2 decades, *Global Biogeochem. Cycles*, *22*, GB4027, doi:10.1029/2007GB003167.

Tjiputra, J. F., A. Olsen, L. Bopp, A. Lenton, B. Pfeil, T. Roy, J. Segschneider, I. Totterdell, and C. Heinze (2014), Long-term surface pCO 2 trends from observations and models, *Tellus B*, *66*(2–3), 151–168, doi:10.1007/s00382-007-0342-x.

Wanninkhof, R., et al. (2013), Global ocean carbon uptake: magnitude, variability and trends, *Biogeosciences*, *10*(3), 1983–2000, doi:10.5194/bgd-9-10961-2012.

Watson, A. J., N. Metzl, and U. Schuster (2011), Monitoring and interpreting the ocean uptake of atmospheric CO_2, *Philos. Trans. R. Soc. London, Ser. A*, *369*(1943), 1997–2008, doi:10.1098/rsta.2011.0060.