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Inter-annual variability of the carbon dioxide oceanic sink south of Tasmania*

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Abstract

We compiled a large data-set from 22 cruises spanning from 1991 to 2003, of the partial pressure of CO_2 (pCO_2) in surface waters over the continental shelf (CS) and adjacent open ocean (43° to 46° S; 145° to 150° E), south of Tasmania. Sea surface temperature (SST) anomalies (as intense as 2°C) are apparent in the subtropical zone (STZ) and subAntarctic zone (SAZ). These SST anomalies also occur on the CS, and seem to be related to large-scale coupled atmosphere-ocean oscillations. Anomalies of pCO_2 normalized to a constant temperature are negatively related to SST anomalies. A depressed winter-time vertical input of dissolved inorganic carbon (DIC) during phases of positive SST anomalies, related to a poleward shift of westerly winds, and a concomitant local decrease in wind stress are the likely cause of the negative relationship between pCO_2 and SST anomalies. The observed trend is an increase of the sink for atmospheric CO_2 associated with positive SST anomalies, although strongly modulated by inter-annual variability of wind speed. Assuming that phases of positive SST anomalies are indicative of the future evolution of regional ocean biogeochemistry under global warming, we show using a purely observational based approach that some provinces of the Southern Ocean could provide a potential negative feedback on increasing atmospheric CO_2.

1 Introduction

The ocean is a major and dynamic sink for anthropogenic CO_2 (e.g. Sabine et al. 2004) playing an important role in the mitigation of climate change. The inclusion in climate models of potential feedbacks of air-sea CO_2 fluxes on the increase of atmospheric CO_2 is required to improve the reliability of the predictions of the future evolution of the global carbon cycle and climate change. The collection of partial pressure of CO_2 (pCO_2) data for surface waters during the last 30 years has allowed the investigation and characterisation of changes in air-sea CO_2 fluxes on decadal scales in some regions of the open ocean (e.g., North Atlantic Ocean (Lefèvre et al., 2004; Corbière et al., 2007), Pacific Ocean (Feely et al., 2006; Midorikawa et al., 2006; Takahashi et al., 2006), and Southern Ocean, Inoue and Ishii, 2005). These studies have aided in our understanding of how pCO_2 in surface waters and the associated air-sea CO_2 fluxes are responding to climate changes, and provide data to constrain and understand feedbacks in the carbon cycle related to changes in oceanic physical and biogeochemical processes.

The investigation of long term trends in surface water CO_2 requires the description of the inter-annual variability of pCO_2. The main drivers of the inter-annual variability of surface pCO_2 described to date are large-scale atmosphere-ocean coupled climate oscillations including the El Niño Southern Oscillation (ENSO) for the equatorial and subtropical Pacific Ocean (Feely et al., 2002; Dore et al., 2003; Brix et al., 2005), and the North Atlantic Oscillation for the North Atlantic Ocean (Gruber et al., 2002). In the Southern Ocean, atmosphere-ocean coupled climate oscillations such as the Southern Annular Mode (SAM) (Wetzel et al. 2005; Le Quéré et al., 2007; Lenton and Matear, 2007; Lovenduski et al., 2007) and ENSO (Verdy et al., 2007) have been identified using biogeochemical ocean general circulation models as major drivers of inter-annual variability of pCO_2. These atmosphere-ocean coupled-climate oscillations can alter mixed layer dynamics with an effect on biogeochemical cycles (Le Quéré et al., 2000, 2002, 2003; Lovenduski and Gruber, 2005). The detection of changes in biogeochemical cycling in response to inter-annual changes in mixed layer properties can provide insights into the marine biogeochemical response to future climate changes, namely increases in sea surface temperature (SST) and stratification that are predicted by coupled climate models (e.g. Le Quéré et al., 2000, 2002, 2003). This has been addressed through modelling (e.g. Le Quéré et al., 2000, 2003, 2007; Lenton and Matear, 2007; Lovenduski et al., 2007; Verdy et al., 2007), and through correlation analysis of remote sensed chlorophyll a and SST (e.g. Le Quéré et al., 2002), but seldom through the analysis of field data. One of the few field data analysis by Park et al. (2006) used relationships between monthly pCO_2 and SST data from the Takahashi et al. (2002) cli-

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matology to study inter-annual variations of air-sea CO_2 fluxes for the different oceanic basins. This study suggested that inter-annual variations of air-sea CO_2 fluxes are low in most oceanic basins including the Southern Ocean, as also suggested by large-scale ocean biogeochemical models. However, the Park et al. (2006) study used data smoothed over large spatial scales (4°×5°) and excluded data from El Niño years.

Due to the relative scarcity of pCO_2 field data in the Southern Ocean, the inter-annual variability of air-sea CO_2 fluxes has seldom been investigated from a purely observational based approach. The impact of warm anomalies on air-sea CO_2 fluxes in the Southern Ocean has to some extent been investigated using cruise-to-cruise comparisons (Jabaud-Jan et al., 2005; Brévière et al., 2006). These two studies show warm anomalies lead to significant, but opposing, effects on air-sea CO_2 fluxes in different regions of the high latitude Southern Ocean. This could be due to the spatially heterogeneous control of export production through either light or nutrient limitation in the Southern Ocean (Le Quéré et al., 2000, 2002, 2003), with some modulation by thermodynamic effects of SST change on pCO_2.

The aim of the present work is to investigate inter-annual variations of pCO_2 in the surface waters of the continental shelf (CS) and adjacent open ocean (43° to 46° S; 145° to 150° E) south of Tasmania, based on a compilation and synthesis of 40 transects obtained during 22 cruises by the Université of Liège (ULg), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Laboratoire d'Océanographie et du Climat: Expérimentations et Approches Numériques/Institut Paul Simon Laplace (LOCEAN/IPSL) (Fig. 1, Table 1). We analyzed how surface pCO_2 and air-sea CO_2 exchange varied in response to warm and cool anomalies, and discuss how this might be indicative of the future feedback of surface water warming on air-sea CO_2 exchange in the sub-polar region of the Southern Ocean.

2 Methods

Measurements of pCO_2 were obtained with the equilibration technique as described by Frankignoulle et al. (2001) for ULg, by Lenton et al. (2006) for CSIRO, and by Poisson et al. (1993) for LOCEAN/IPSL. CSIRO and LOCEAN/IPSL systems were inter-calibrated during the *R. V. Meteor* international at-sea intercomparison (6 June–19 June 1996) in the North Atlantic (Körtzinger et al., 2000), and the results showed that the pCO_2 data were consistent within ±1 μatm. ULg and LOCEAN/IPSL systems were inter-calibrated during the OISO3 cruise (21 December–28 December 1998) in the central Indian sector of the Southern Ocean, and the results showed that the pCO_2 data were consistent within ±6 μatm. ULg and CSIRO systems were inter-calibrated during the AA0301 cruise (11 October–27 October 2003) in eastern Indian sector of the Southern Ocean, and the results showed that the pCO_2 data were consistent within ±5 μatm. Since 82% of the data were obtained by one single group (CSIRO; Table 1), we assume the uncertainty of the whole data-set to be better than ±3 μatm. All data were converted to pCO_2 in wet air at 1 atm. During the time-span of the data-set (from 1991 to 2003), atmospheric pCO_2 increased by 20 μatm (1.7 μatm yr^{-1}), so data were referenced to 1997, the middle of the time series, according to:

$$pCO_{2sea1997} = pCO_{2sea199i} + (pCO_{2air1997} - pCO_{2air199i}) \quad (1)$$

where $pCO_{2sea1997}$ is the pCO_2 in seawater referenced to 1997, $pCO_{2sea199i}$ is the pCO_2 in seawater from a given year, $pCO_{2air1997}$ is the atmospheric pCO_2 in 1997, and $pCO_{2air199i}$ is the atmospheric pCO_2 for the same given year.

Atmospheric pCO_2 data from the Cape Grim station (40.7° S, 144.7° E; Tasmania) were obtained from the Cooperative Air Sampling Network of the National Oceanic and Atmospheric Administration/Earth System Research Laboratory/Global Monitoring Division (http://www.cmdl.noaa.gov/). Hereafter, pCO_2 refers to $pCO_{2sea1997}$.

Data were collocated with bathymetry based on the Smith and Sandwell (1997) global seafloor topography (http://topex.ucsd.edu/). Data over the CS were gathered

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and averaged by sorting for depths <300 m, and data at depths >1000 m were considered as open ocean. The sub-Tropical Front (STF) was identified from gradients of sea surface salinity (SSS) and SST (e.g. Belkin and Gordon 1996). The STF separates warmer and saltier sub-tropical zone (STZ) waters from cooler and fresher sub-Antarctic zone (SAZ) waters.

3 Results and discussion

3.1 Climatological SST and pCO_2 seasonal cycles

Climatological seasonal cycles of SST, pCO_2 and pCO_2 normalized to a temperature of 14°C (pCO_2@14°C, using the algorithms of Copin-Montégut, 1988, 1989) were obtained by fitting monthly averages with a wave function in the form of:

$$y = a + b\sin\left(\left(\frac{x}{c} + d\right)\right) \quad (2)$$

where y is either SST, pCO_2 or pCO_2@14using the algorithms ofC, x is time (julian days) and a, b, c, and d are fitted constants.

In the CS, STZ and SAZ, under-saturation of CO_2 is observed throughout the year (Figs. 2, 3, 4), showing these regions are perennial sinks for atmospheric CO_2. In the 3 regions, similar climatological pCO_2 and pCO_2@14°C seasonal trends are observed in timing and amplitude: values decrease from late September to late February (austral spring-summer) as net biological uptake removes dissolved inorganic carbon (DIC) from surface waters. From March to September (austral fall-winter), pCO_2 and pCO_2@14°C values increase in relation to destratification and mixing of surface waters with DIC rich deeper waters (Goyet et al., 1991; Poisson et al., 1993; Metzl et al., 1991, 1995, 1998, 1999). The amplitude of the seasonal cycle of pCO_2 was lower than the one of pCO_2@14°C because warming of surface waters during spring and summer leads to a thermodynamic increase of pCO_2, that opposes a decrease due to net biological carbon uptake. The thermodynamic effect of SST change on the seasonal amplitude of pCO_2 is similar in the CS (51 μatm), the STZ (50 μatm), and the SAZ (47 μatm), because SST amplitude is similar in the 3 regions (3.7°C, 3.6°C and 3.3°C, respectively).

The SSS values for all three water masses do not show a distinct seasonal signal like SST, which is strongly influenced by seasonal heating and cooling of surface waters. The water mass on the Tasmanian CS is a mixture of STZ and SAZ waters (Harris et al., 1987, 1991). This is apparent in our data-set, as the average SSS value in the CS (35.02±0.17) lies between those of the STZ (35.19±0.15) and the SAZ (34.73±0.15). The SSS values in the CS show more scatter than in the other two regions (Figs. 2, 3, 4), suggesting a variable degree of mixing between the STZ and SAZ water masses. For a two end-member mixing model, the water mass on the CS is on average composed of 64% STZ water, consistent the annual average of SST in the CS (13.8±1.3°C) being similar to the STZ (13.4±1.3°C) and distinctly different from the SAZ (11.5±1.2°C) annual averages.

3.2 Inter-annual SST and pCO_2 variations

Monthly anomalies of SST, pCO_2, and pCO_2@14°C were computed as the difference between observations and averaged monthly values for all the cruise data. SST anomalies of up to 2°C are observed in the CS, STZ and SAZ, and similar trends of pCO_2@14°C are observed in the three regions (Figs. 2, 3, 4). SST values that are below the climatology tend to coincide with less saline waters suggesting a greater contribution of SAZ waters. Warm anomalies are typically associated with saltier waters implying a greater contribution of subtropical waters and consistent with observations of increases in warming and salinity for the region (Rintoul and Sokolov, 2001; Rintoul and Trull, 2001; Morrow et al., 2007[1]).

A comparison of the monthly SST anomalies with anomalies for pCO_2 and

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pCO_2@14°C show consistent trends. Values of pCO_2@14°C associated with positive SST anomalies (>0.5°C) generally lie below the climatological pCO_2@14°C cycle. Values associated with significant negative SST anomalies (<0.5°C) generally lie above the climatological pCO_2@14°C cycle (Figs. 2, 3, 4). The trends for pCO_2 anomalies are not as clear. In the STZ, positive pCO_2 and pCO_2@14°C anomalies correspond to negative SST anomalies during spring (October–December). However, during the summer (January-March) the pCO_2 anomalies in the STZ show the opposite behavior of pCO_2@14°C. For summer, the pCO_2 values associated with positive SST anomalies generally occur above the climatological pCO_2 cycle, and values associated with significant negative SST anomalies tend to lie below the climatological pCO_2 cycle.

The SST anomalies in the STZ, SAZ and CS are roughly consistent in timing and amplitude (Fig. 5), suggesting a similar driver of these anomalies in the three water masses. Large-scale coupled atmosphere-ocean oscillations likely to drive such large SST anomalies simultaneously in the mid-latitude band of the Southern Ocean are ENSO through atmospheric bridges (Li, 2000; Verdy et al., 2006; Morrow et al., 2007[1]), the subtropical dipole pattern (Behera and Yamagata, 2001), or SAM (Hall and Visbeck, 2002; Lovenduski and Gruber, 2005; Morrow et al., 2007[1]).

SAM is the principal mode of atmospheric forcing and climate variability in the Southern Ocean with potential to significantly impact on biogeochemical carbon cycling and air-sea CO_2 fluxes (Le Quéré et al., 2007; Lenton and Matear, 2007; Lovenduski et al., 2007; Verdy et al., 2007). An increase in the SAM index leads to synchronous SST anomalies in the STZ and SAZ (Lovenduski and Gruber 2005; Lovenduski et al. 2007), as we observed in our dataset (Fig. 5). The increased SAM index is associated with a poleward shift of westerly winds with a local decrease in wind stress (Hartmann and Lo, 1998; Thompson and Wallace, 2000). This causes an increase in Ekman convergence in the SAZ, with deepening isopycnals, surface warming in the mid-latitudes, and a southward expansion of subtropical waters (Cai et al., 2005; Roemmich et al., 2007). Near Tasmania, surface warming and an increased outflow of warm and salty subtropical waters from the South Tasman Sea have been observed and linked to a polewards

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shift in the wind stress over the Southern Ocean (Rintoul and Sokolov, 2001; Morrow et al., 2007[1]; Ridgway, 2007).

A reduction in available nutrients and reduced DIC input through either the expansion of subtropical waters or less vertical mixing, could explain the observed relationship between pCO_2@14°C and SST anomalies for all 3 regions (Figs. 6, 7). Surface waters of the Tasman Sea have relatively low macronutrient concentrations (Condie and Dunn 2006) and low pCO_2 values (Takahashi et al. 2002), compared to subAntarctic waters to the south of the STF. The surface warming and decreased wind stress associated with a positive SAM index will also produce a deepening of isopycnal surfaces (Roemmich et al., 2007) and result in more stratified surface mixed layers (Chaigneau et al., 2004), thus reducing the potential to entrain subsurface waters with high nutrient and DIC concentrations into the surface mixed layer over winter (Le Quéré et al., 2000, 2002, 2003). The net effect of altered vertical mixing and the southerly expansion of the subtropical waters should be to produce warm SST anomalies and low pCO_2@14°C values in the mid-latitude waters. Conversely, during periods when the SAM index is reduced, there is likely to be a greater supply of nutrients and DIC to the surface layer through vertical mixing and a retreat of subtropical waters to the north. Under these conditions the surface waters are expected to contain a greater component of relatively high nutrient and DIC waters of the SAZ, producing cool SST anomalies and high pCO_2@14°C anomalies.

The response of the region to the SAM could also explain different slopes between pCO_2@14°C anomalies and SST anomalies observed during spring-summer and fall-winter periods (Figs. 6, 7). Negative SST anomalies would be associated with enhanced nutrient and DIC inputs. Primary production in the region is partly limited by nutrient availability (Boyd et al., 2001). The greater nutrient availability associated with negative SST anomalies would lead to enhanced primary production during spring and summer, and a decrease of the slope (becomes less negative) between pCO_2@14°C and SST anomalies for the fall-winter to spring-summer periods (Fig. 7). The overall negative relationship between pCO_2@14°C anomalies and SST anomalies (Fig. 6) shows that the enhanced primary production associated with negative SST anomalies does not overcome the enhanced winter inputs of DIC.

The pCO_2 anomalies in the 3 regions show more scatter than pCO_2@14°C anomalies versus SST anomalies (Fig. 6). This is due to the thermodynamic effect of temperature change that leads to a decrease of the positive pCO_2 anomalies associated with negative SST anomalies, and conversely to an increase of negative pCO_2 anomalies associated with positive SST anomalies (Fig. 7). In some extreme cases there is a reversal of the direction of the pCO_2 anomalies, particularly in the STZ (Fig. 6).

3.3 Inter-annual air-sea CO_2 flux variations

Air-sea CO_2 fluxes were computed according to:

$$F = k\alpha\Delta pCO_2 \quad (3)$$

where F is the air-sea CO_2 flux, k is the gas transfer velocity, α is the CO_2 solubility coefficient, and ΔpCO_2 is the air-sea pCO_2 gradient. We used the k-wind parameterization of Wanninkhof (1992), and the Weiss (1974) formulation of α as a function of SSS and SST. Atmospheric pCO_2 data from 1997 were expressed in wet air using the water vapour pressure formulation of Weiss and Price (1980) as a function of SSS and SST.

The relationship of SST anomalies to inter-annual variations of air-sea CO_2 fluxes was examined using the longest possible consistent time series of SST and wind speed (u_{10}), from 1982 to 2005. The SST data were taken from the Reynolds et al. (2002) monthly SST climatology (Reyn_SmithOIv2, http://iridl.ldeo.columbia.edu/). Wind speed data were obtained from the Kalnay et al. (1996) National Centers for Environmental Prediction (NCEP) daily u_{10} (http://www.cdc.noaa.gov/), with the data from the two NCEP grid nodes in the study region (Fig. 1) averaged and assumed representative of u_{10} over the CS, STZ and SAZ. The Reyn_SmithOIv2 SST grid node n°1 (Fig. 1) was used to compute monthly SST anomalies for the CS. The remaining

Reyn_SmithOIv2 SST grid nodes (n°2 to n°11, Fig. 1) were averaged, and used to compute monthly SST anomalies for the STZ and SAZ. This assumes that SST anomalies in the STZ and SAZ are synchronous and similar in amplitude and direction as shown in Fig. 5. Also, the position of the STF is highly variable in time (Sokolov and Rintoul, 2002) and it is not possible to arbitrarily associate the Reyn_SmithOIv2 SST grid nodes to either STZ or SAZ water masses.

The pCO_2@14°C anomalies were computed from the Reyn_SmithOIv2 monthly SST anomalies using the linear relationships shown in Fig. 6. These pCO_2@14°C anomalies were added to the climatological pCO_2@14°C cycles shown in Figs. 2, 3 and 4. The Reyn_SmithOIv2 monthly SST anomalies were added to the climatological SST cycles shown in Figs. 2, 3 and 4. The pCO_2 values were then computed from pCO_2@14°C and SST (both including the respective anomalies), using the algorithms of Copin-Montégut (1988; 1989). The daily air-sea CO_2 fluxes were calculated using Eq. (3), and the NCEP u_{10} data.

For the whole 1982-2005 period, the CS, STZ and SAZ act annually as sinks for atmospheric CO_2 at the rate of, respectively, −6.4±0.7, −6.8±0.5, and −5.7±0.5 mmol m^{-2} d^{-1}. Significant potential inter-annual variability of annual *F* is apparent in the 3 regions (Fig. 8). Consistent with pCO_2, negative annual *F* anomalies (stronger sink for atmospheric CO_2) are associated with positive annual SST anomalies, and conversely positive annual *F* anomalies (weaker sink for atmospheric CO_2) are associated with negative annual SST anomalies for the 3 regions. For positive annual SST anomalies, the strongest *F* anomalies (Table 2) lead to an increase of the 1982–2005 average annual sink for atmospheric CO_2 of 26, 21, and 59%, in the CS, STZ and SAZ, respectively. For negative annual SST anomalies, the strongest *F* anomalies (Table 2) lead to a decrease of the 1982–2005 average annual sink for atmospheric CO_2 of 15, 11, and 51%, in the CS, STZ and SAZ, respectively. For positive annual SST anomalies, the average *F* anomalies (Table 2) cause an increase of the 1982–2005 average annual sink for atmospheric CO_2 of 5, 3, and 21%, in the CS, STZ and SAZ, respectively. For negative annual SST anomalies, the average *F* anomalies

(Table 2) lead to a decrease of the 1982–2005 average annual sink for atmospheric CO_2 of 4, 3, and 18%, for the CS, STZ and SAZ, respectively.

The annual *F* anomalies computed from the 1982-2005 mean of daily u_{10} data show a consistent negative relationship with the annual SST anomalies for all three regions (Fig. 8). This suggests the scatter in the annual *F* anomalies computed from daily u_{10} data versus the annual SST anomalies is to a large extent related to inter-annual variability in u_{10}. In particular, the annual *F* anomalies in 1985, 1989, 1999 and 2001 are larger compared to other years for the 3 regions, leading to positive annual *F* anomalies in the CS and the STZ during 1985, 1989 and 1999, and to virtually neutral annual *F* anomalies in the SAZ during 1985 and 1989.

The *F* anomalies computed for the fall-winter and spring-summer periods using the 1982–2005 mean of daily u_{10} (Fig. 9) show that the annual *F* anomalies (Fig. 8) are mainly driven by the fluxes during the fall-winter period. This is related to the thermodynamic effect of temperature change that tends reduce the magnitude of pCO_2 anomalies (Fig. 7), and due to SST anomalies being more marked during the periods of stratification (spring-summer, Figs. 2, 3, 4). Higher wind speeds during the fall-winter period (not shown) are also responsible for the larger contribution of *F* anomalies during this period. These trends are reflected in the *F* anomalies computed for the fall-winter and spring-summer periods using the daily u_{10}, but with more scatter due to inter-annual variability of u_{10} (Fig. 9). The small annual *F* anomalies in 1985, 1989, 1999 and 2001 (Fig. 8) are due to the spring-summer *F* anomalies (Fig. 9). Figure 10 shows that average u_{10} during the spring-summer period of 1985, 1989, 1999 and 2001 were lower than other years. This is most likely related to a poleward shift of westerly winds related to changes in the SAM which causes a local decrease in wind stress and positive SST anomalies (Hartmann and Lo, 1998) and reduced air-sea fluxes of CO_2.

3.4 Future change and potential feedback on increasing atmospheric CO_2?

The comparison of CO_2 and SST anomalies provides insights of biogeochemical responses to projected changes in SST and stratification of the Southern Ocean (Le

Quéré et al., 2002, 2003). Based on correlations of remotely sensed chlorophyll-a and SST, Le Quéré et al. (2002) suggested that an increase of SST would lead to an overall increase in primary production in the Southern Ocean. This was attributed to stronger light limitation compared to nutrient limitation for most regions of the Southern Ocean and supported by the simulation of propagating warm anomalies using a biogeochemical ocean general circulation model (Le Quéré et al., 2003). Bopp et al. (2001) have also suggested that export production in the Southern Ocean will increase with projected warming of surface waters. The comparison of pCO_2@14°C and SST anomalies during fall-winter and spring-summer periods (Fig. 6) suggests that in our study region an increase of SST leads to a decrease of export production (Fig. 7). This is in agreement with evidence for nutrient rather than of light limitation of primary production for the sub-polar waters near Tasmania (Boyd et al., 2001).

Besides modifying export production, climate changes associated with warming of surface waters will also change air-sea CO_2 fluxes due to changes of the input of CO_2 from deeper layers. Indeed, numerical models of CO_2 dynamics and air-sea CO_2 exchange in the Southern Ocean highlight the very significant role of vertical mixing at seasonal (Louanchi et al., 1996; Metzl et al., 1999, 2006) and inter-annual (Louanchi and Hoppema, 2000; Verdy et al., 2007) time scales. Changes in vertical mixing in the Southern Ocean can have an impact on the intensity of the air-sea CO_2 fluxes and can potentially modulate the atmospheric CO_2 content by changing the natural biogeochemical CO_2 cycle. Indeed, to explain the decrease of atmospheric CO_2 during the last glacial period, some hypothesis are based on a decrease in the ventilation of deep DIC rich water in relation to an increase of stratification (Toggweiler, 1999; Sigman and Boyle, 2000), due to a northward shift of the westerly winds (Toggweiler et al., 2006) or due to an increase of salinity in deeper waters (Watson and Naveira Garabato, 2006). The decrease of vertical inputs of DIC combined with constant or enhanced export production could have increased the biological pump (in regions of light limitation for primary production) and enhanced the atmospheric CO_2 sink (Toggweiler, 1999; Sigman and Boyle, 2000; Toggweiler et al., 2006; Watson and Naveira Garabato, 2006).

This clearly illustrates that a modification of the natural biogeochemical cycle of CO_2 in the Southern Ocean can lead to strong feedbacks on the atmospheric CO_2 content.

Our study region is small but includes a portion of two important waters masses: the STZ and SAZ. The results do indicate that a decrease of vertical input of DIC during winter associated to climate changes associated with positive SST anomalies could lead to an increase of the sink for atmospheric CO_2, although strongly modulated by inter-annual variability in wind speed. This suggests that climate change associated to warming of surface waters of some regions of the Southern Ocean, would lead to a negative feedback on increasing atmospheric CO_2.

4 Conclusions

We compiled data obtained along 40 transects during 22 cruises carried out between 1991 and 2003, on the CS and adjacent open oceanic waters south of Tasmania. This allowed us to analyze how surface pCO_2 and air-sea CO_2 exchange vary in relation to warm and cool anomalies. Strong SST anomalies up to 2°C were observed in the STZ and the SAZ. As the waters on the CS are a mixture of STZ and SAZ, these SST anomalies also propagate onto the CS. The consistency in timing and amplitude of SST anomalies in the STZ and SAZ can only be attributed to a large scale coupled atmosphere-ocean oscillation.

Overall, positive SST anomalies are associated with negative pCO_2@14°C anomalies, and negative SST anomalies with positive pCO_2@14°C anomalies, in the CS, STZ and SAZ. This seems to be related to a depressed input of DIC during the fall-winter period, during the phases of positive SST anomalies, in relation to a poleward shift of the westerly winds, and a local decrease in wind stress.

The potential effect of SST anomalies on air-sea CO_2 exchange were investigated using a 23 years consistent time series of SST and wind speed. The general trend is an increase in the sink for atmospheric CO_2 associated with positive SST anomalies. This increase in the sink for atmospheric CO_2 is mainly due to the fluxes during the fall-winter period. However, this general trend is strongly modulated by inter-annual variations of wind speed that affects the gas transfer velocity and the intensity of the air-sea CO_2 flux. Assuming that phases of positive SST anomalies are indicative of the future evolution of ocean biogeochemistry under global warming, we show based on a spatially restricted observational data-set, that some provinces of the Southern Ocean could provide a potential negative feedback on increasing atmospheric CO_2 and associated climate change. The observations from our region are in agreement with recent modelling studies that show during positive phases of SAM a decrease of the CO_2 sink in high latitude areas of the Southern Ocean due to enhanced upwelling and an increase of the CO_2 sink in the low latitude areas of the Southern Ocean (Wetzel et al., 2005; Le Quéré et al., 2007; Lenton and Matear, 2007; Lovenduski et al., 2007). A larger scale investigation in the Southern Ocean is required to quantify more rigorously potential feedbacks on the increase atmospheric CO_2 due to warming of surface waters.

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Table 1. Cruises, ships, data originators, dates (dd/mm/yyyy) of transects in the continental shelf (CS), the subtropical zone (STZ) and the subAntarctic zone (SAZ) south of Tasmania.

Cruise	ship	data originator	date	CS	STZ	SAZ
V191	*R.S.V. Aurora Australis*	CSIRO	05/10/1991	+	+	+
			25/10/1991	+	+	+
V192	*R.S.V. Aurora Australis*	CSIRO	21/11/1992	+		
V792	*R.S.V. Aurora Australis*	CSIRO	05/01/1993	+	+	
			07/03/1993	+	+	+
V993	*R.S.V. Aurora Australis*	CSIRO	12/03/1993	+	+	+
			08/05/1993	+	+	+
V193	*R.S.V. Aurora Australis*	CSIRO	07/08/1993	+	+	+
			08/10/1993	+	+	+
V493	*R.S.V. Aurora Australis*	CSIRO	19/11/1993	+		+
			27/12/1993	+		+
AA9407	*R.S.V. Aurora Australis*	CSIRO	02/01/1994	+	+	+
			28/02/1994	+	+	+
AA9401	*R.S.V. Aurora Australis*	CSIRO	31/08/1994	+	+	+
AA9404	*R.S.V. Aurora Australis*	CSIRO	13/12/1994	+	+	+
			31/01/1995	+	+	+
AA9501	*R.S.V. Aurora Australis*	CSIRO	18/07/1995	+	+	+
			07/09/1995	+		+
SS9511	*R.V. Southern Surveyor*	CSIRO	23/11/1995	+		+
AA9604	*R.S.V. Aurora Australis*	CSIRO	19/01/1996	+		+
			30/03/1996	+	+	+
AA9601	*R.S.V. Aurora Australis*	CSIRO	22/08/1996	+	+	+
			20/09/1996	+	+	+
MINERVE38	*S.V. Astrolabe*	LOCEAN/IPSL	21/10/1996	+	+	+
			23/11/1996	+	+	+
MINERVE39	*S.V. Astrolabe*	LOCEAN/IPSL	02/02/1997	+	+	+
			17/02/1997		+	
AA9703	*R.S.V. Aurora Australis*	CSIRO	14/11/1997		+	+
			26/11/1997	+	+	+
AA9706	*R.S.V. Aurora Australis*	CSIRO/ULg	28/02/1998	+	+	
			31/03/1998	+	+	
SS9902	*R.V. Southern Surveyor*	CSIRO	05/02/1999	+		
			16/02/1999	+	+	+
AA9901	*R.S.V. Aurora Australis*	CSIRO	16/07/1999	+	+	+
			05/09/1999	+	+	+
99R0	*S.V. Astrolabe*	ULg	22/10/1999	+	+	
99R1	*S.V. Astrolabe*	ULg	26/12/1999	+	+	+
OISO10	*R.V. Marion Dufresne*	LOCEAN/IPSL	29/01/2003		+	
AA0301	*R.S.V. Aurora Australis*	CSIRO/Ulg	11/09/2003	+	+	
			29/10/2003	+	+	+

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Table 2. The strongest and average annual anomalies of air-sea CO_2 fluxes (F) for positive and negative sea surface temperature (SST) annual anomalies in the continental shelf (CS), the subtropical zone (STZ) and subAntarctic zone (SAZ) south of Tasmania, from 1982 to 2005. Annual anomalies were computed as the difference between the annual mean value and the average of annual mean values of the whole data-set.

	CS	STZ	SAZ
Strongest annual F anomaly (mmol m^{-2} d^{-1})			
Positive SST anomalies	−1.7	−1.4	−3.4
Negative SST anomalies	1.0	0.8	2.9
Average annual F anomaly (mmol m^{-2} d^{-1})			
Positive SST anomalies	−0.3	−0.2	−1.2
Negative SST anomalies	0.3	0.2	1.0

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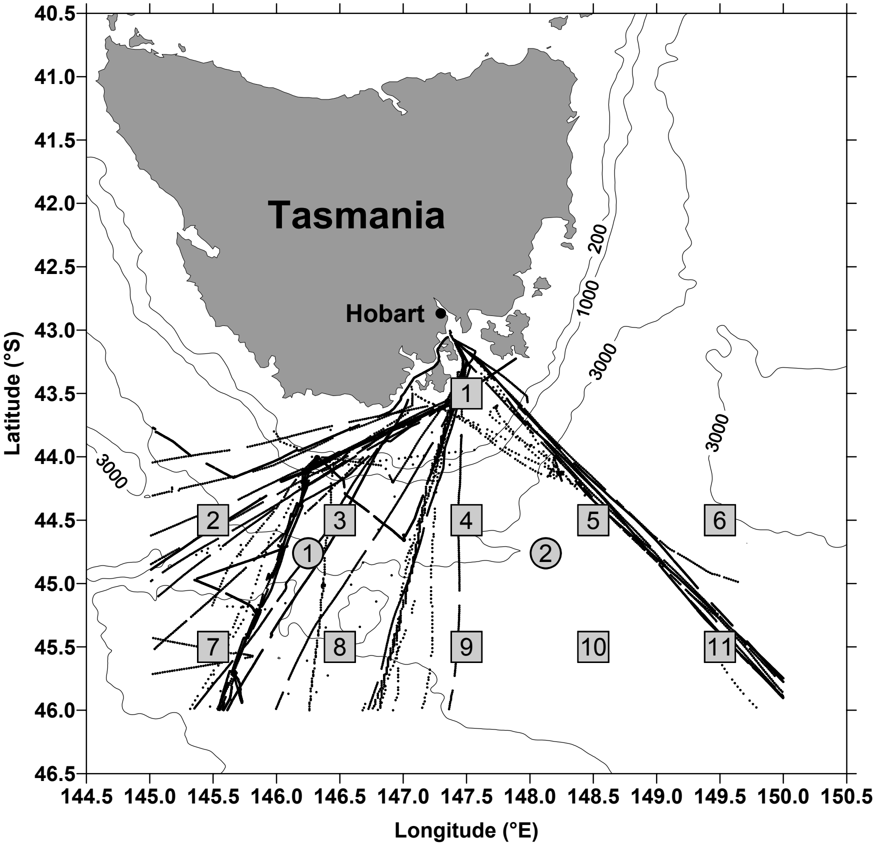

Fig. 1. Map showing ship tracks, bathymetry based on the Smith and Sandwell (1997) global seafloor topography, grid nodes from the Reynolds et al. (2002) sea surface temperature monthly climatology (squares), and the grid nodes of the Kalnay et al. (1996) National Centers for Environmental Prediction daily wind speeds (circles).

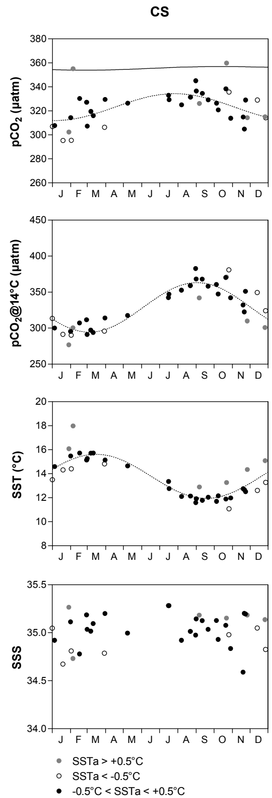

Fig. 2. Seasonal cycles of the partial pressure of CO_2 (pCO_2), the pCO_2 normalized to a temperature of 14˚C (pCO_2@14˚C), sea surface temperature (SST) and sea surface salinity (SSS) over the continental shelf (CS) south of Tasmania. Solid line shows atmospheric pCO_2 for 1997. Dotted lines show the climatological cycles based on a wave function curve fitted to the monthly averages. Data were sorted for significant positive SST anomalies (SSTa>0.5˚C, grey circles), significant negative SST anomalies (SSTa<−0.5˚C, open circles), and no significant SST anomalies (−0.5˚C<SSTa<0.5˚C, black circles).

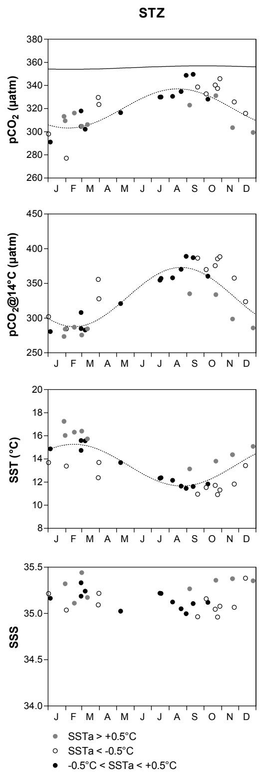

Fig. 3. Seasonal cycles of the partial pressure of CO_2 (pCO_2), the pCO_2 normalized to a temperature of 14°C (pCO_2@14°C), sea surface temperature (SST) and sea surface salinity (SSS) in the subtropical zone (STZ) south of Tasmania. Solid line shows atmospheric pCO_2 for 1997. Dotted lines show the climatological cycles based on a wave function curve fitted to the monthly averages. Data were sorted for significant positive SST anomalies (SSTa>0.5°C, grey circles), significant negative SST anomalies (SSTa<−0.5°C, open circles), and no significant SST anomalies (−0.5°C<SSTa<0.5°C, black circles).

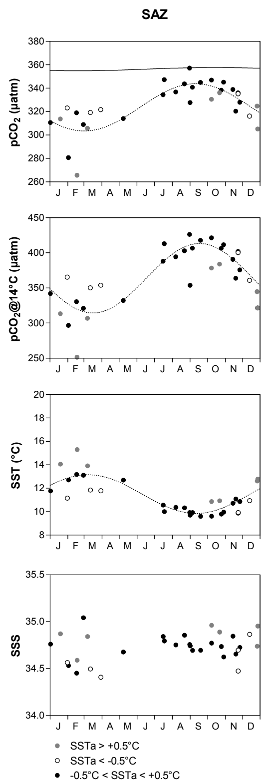

Fig. 4. Seasonal cycles of the partial pressure of CO_2 (pCO_2), the pCO_2 normalized to a temperature of 14°C (pCO_2@14°C), sea surface temperature (SST) and sea surface salinity (SSS) in the subAntarctic zone (SAZ) south of Tasmania. Solid line shows atmospheric pCO_2 for 1997. Dotted lines show the climatological cycles based on a wave function curve fitted to the monthly averages. Data were sorted for significant positive SST anomalies (SSTa>0.5°C, grey circles), significant negative SST anomalies (SSTa<−0.5°C, open circles), and no significant SST anomalies (−0.5°C<SSTa<0.5°C, black circles).

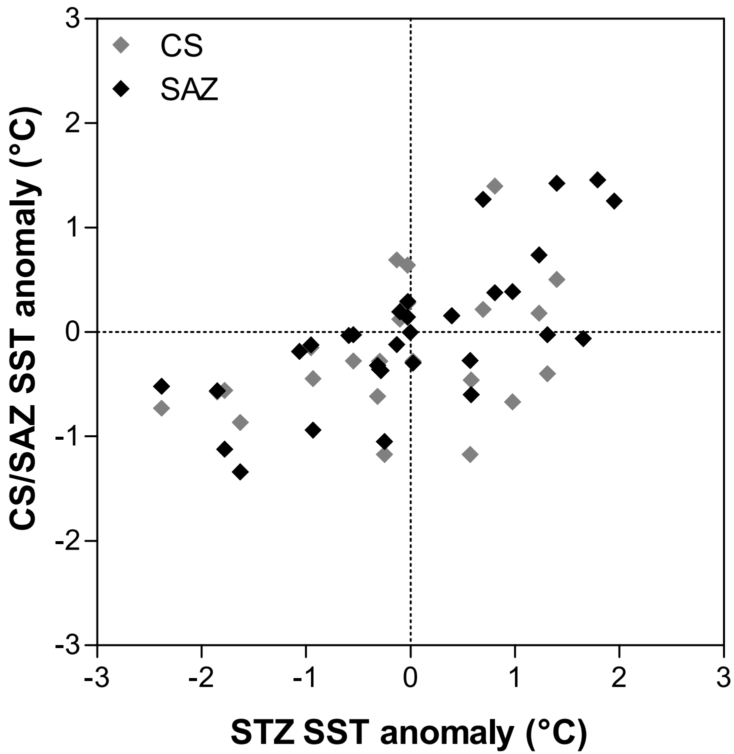

Fig. 5. Sea surface temperature (SST) monthly anomalies in the continental shelf (CS) and subAntarctic zone (SAZ) plotted against the SST monthly anomalies in the subtropical zone (STZ), south of Tasmania.

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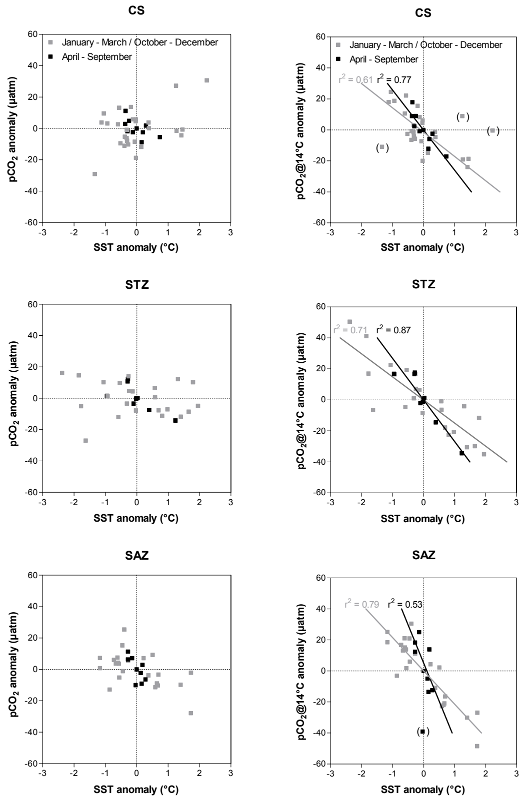

Fig. 6. Monthly anomalies of the partial pressure of CO_2 (pCO_2) and of the pCO_2 normalized to a temperature of 14°C (pCO_2@14°C) plotted against the sea surface temperature (SST) monthly anomalies in the continental shelf (CS), the subtropical zone (STZ) and subAntarctic zone (SAZ) south of Tasmania, for the spring-summer period (grey squares) and the fall-winter period (black squares). Solid lines correspond to linear regression functions, and r^2 to the corresponding coefficient of determination. Symbols in brackets were excluded from the linear regressions.

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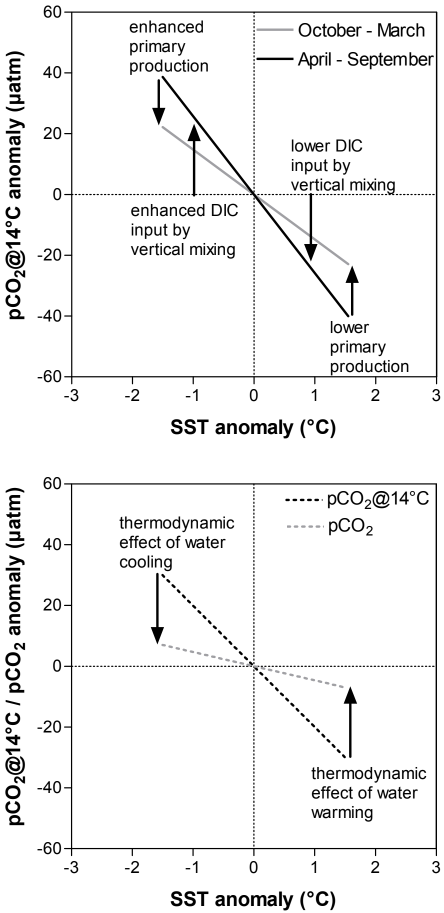

Fig. 7. Conceptual frame relating the partial pressure of CO_2 (pCO_2) normalized to a temperature of 14°C (pCO_2@14°C), and pCO_2 anomalies to sea surface temperature (SST) anomalies.

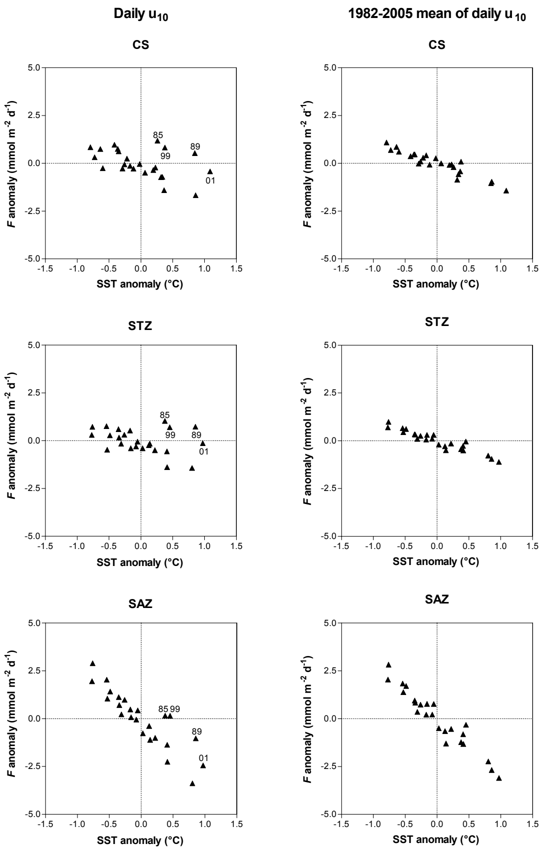

Fig. 8. Annual anomalies of air-sea CO_2 fluxes (F) computed with daily wind speeds (u_{10}) and 1982–2005 mean of u_{10} daily, plotted against the sea surface temperature (SST) annual anomalies in the continental shelf (CS), the subtropical zone (STZ) and subAntarctic zone (SAZ) south of Tasmania, from 1982 to 2005. Annual anomalies were computed as the difference between the annual mean value and the average of annual mean values of the whole data-set.

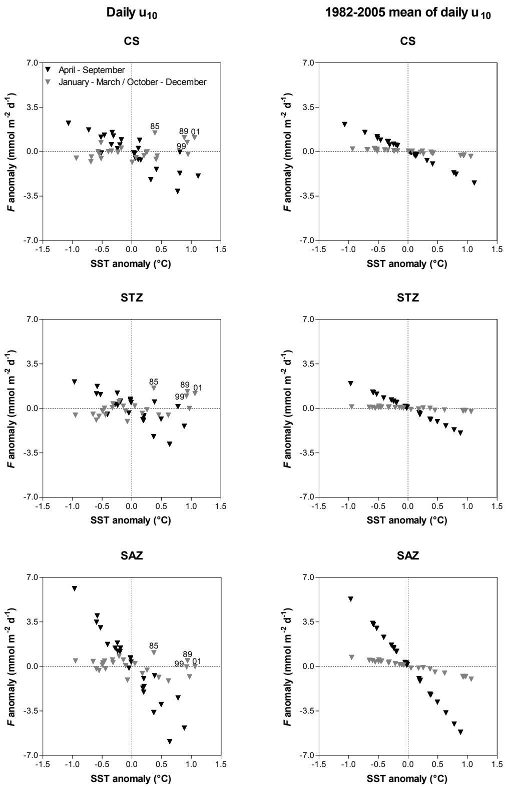

Fig. 9. Anomalies of air-sea CO_2 fluxes (F) computed with daily wind speeds (u_{10}) and 1982–2005 mean of u_{10} daily, plotted against the sea surface temperature (SST) anomalies in the continental shelf (CS), the subtropical zone (STZ) and subAntarctic zone (SAZ) south of Tasmania, for the spring-summer period (grey triangles) and the fall-winter period (black triangles), from 1982 to 2005. Spring-summer (fall-winter) period anomalies were computed as the difference between the spring-summer (fall-winter) period mean value and the average of spring-summer (fall-winter) period mean values of the whole data-set.

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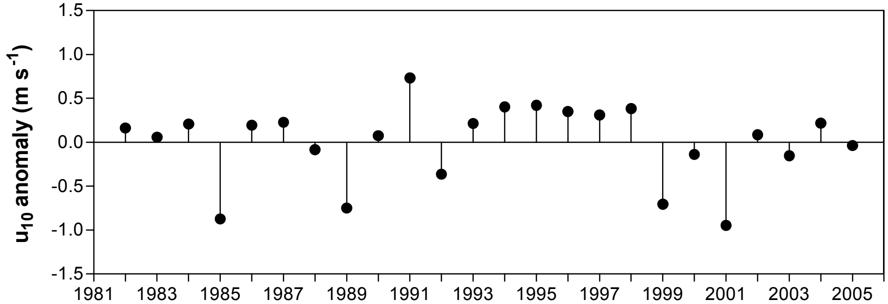

Fig. 10. Wind speed (u_{10}) anomalies for the spring-summer period, from 1982 to 2005. Spring-summer period anomalies were computed as the difference between the spring-summer period mean value and the average of spring-summer period mean values of the whole data-set.

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