academicJournals

Vol. 5(7), pp. 55-63, November, 2014
DOI : 10.5897/JOMS2014.0114
Article Number: 7008B6F48536
ISSN 2141-2294

http://www.academicjournals.org/JOMS

Journal of Oceanography and Marine Science

Full Length Research Paper

On the influence of interseasonal sea surface temperature on surface water *p*CO_2 at 49.0°N/16.5°W and 56.5°N/52.6°W in the North Atlantic Ocean

Nsikak U. Benson[1]*, Oladele O. Osibanjo[2], Francis E. Asuquo[3] and Winifred U. Anake[1]

[1]Department of Chemistry, School of Natural and Applied Sciences, Covenant University, Ota, Ogun State, Nigeria.
[2]Department of Chemistry, University of Ibadan, Ibadan, Oyo State, Nigeria.
[3]Institute of Oceanography, University of Calabar, P. M. B. 1115, Calabar, Cross River State, Nigeria.

Received 19 July, 2014; Accepted 29 October, 2014

The sea surface temperature (SST) and partial pressure of carbon dioxide (*p*CO_2) derived from hourly *in situ* measurements at Northwest (56.5°N, 52.6°W) and Northeast (49.0°N, 16.5°W) subpolar sites of the Atlantic Ocean from 2003 – 2005 were employed to investigate the seasonal *p*CO_2–SST relationship. The results indicate weak to moderately strong significant negative relationships (r = -0.04 to -0.89, p<0.0001) and (r = -0.56 to -0.97, p<0.0001) between SST and *p*CO_2 for the Northeast and Northwest observed data respectively. At the Northwestern site, the variation in surface water *p*CO_2 might be partly controlled by the seasonal change in SST as well as biological activities and other physical processes. The variability in *p*CO_2 distribution at the Northeastern oceanographic site were attributed principally to mixing and stratification processes during the autumn and spring seasons, while the *p*CO_2–SST interrelationship obtained during summertime suggested that *p*CO_2 variability could have been induced mainly by thermodynamic effects.

Key words: Sea surface temperature, *p*CO_2, temperature effects, temperature anomalies, North Atlantic Ocean.

INTRODUCTION

Carbon dioxide (CO_2) dominance in the atmosphere (mainly from anthropogenic sources) over other greenhouse gases has resulted in increasing *p*CO_2 in the surface ocean leading to measurably decreased pH (ocean acidification) (Canadell et al., 2007; Hopkins et al., 2010; Keeling and Whorf, 2005; Levine et al., 2008; Sabine and Feely, 2007). The world oceans are major natural sinks of atmospheric CO_2. However, the North Atlantic Ocean is generally regarded as a primary gate for CO_2 entering the global ocean due to its subpolar climate.

In the open ocean, it has been established that significant correlation exists between surface water *p*CO_2 and sea surface temperature (SST). However, the sea surface *p*CO_2–SST relationships are primarily governed by a combination of processes, such as biological activity, physical transport-upwelling of nutrients, and thermodynamics (e.g. temperature effects on CO_2 dissociation and solubility) (Körtzinger et al., 2008a, b; Chen et al., 2007). Takahashi et al. (2002, 2009) have elucidated the mechanism and the role of thermodynamic effects on the uptake of CO_2 by the global oceans. Recently, several studies have reported the low uptake of *p*CO_2 in the North Atlantic Ocean suggesting a gradual weakening of an active carbon storehouse (Corbière et

*Corresponding author. E-mail: nbenson@covenantuniversity.edu.ng

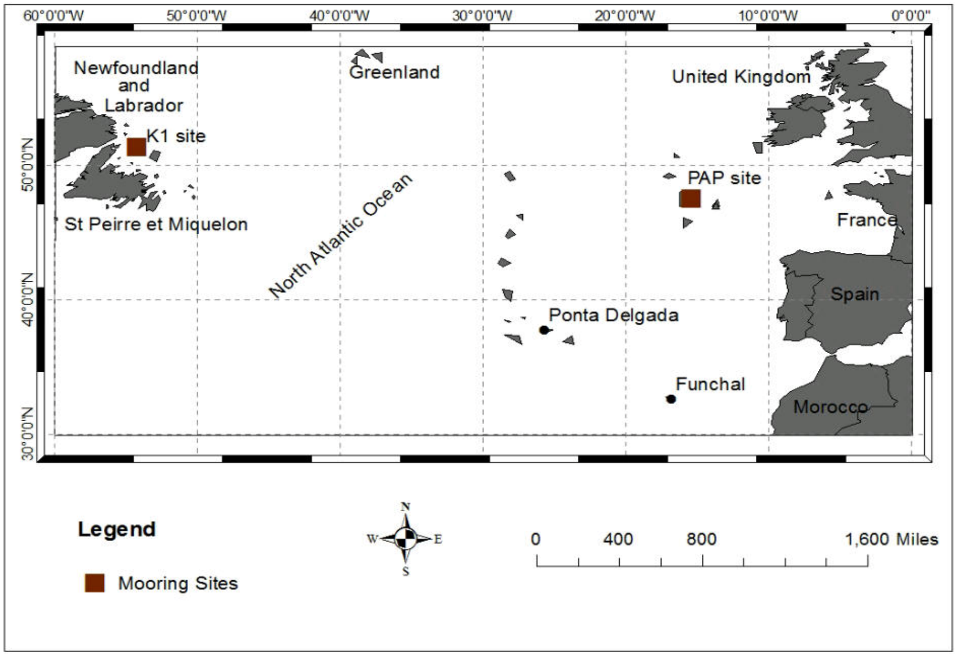

Figure 1. Map of the North Atlantic Ocean showing the Porcupine Abyssal Plain (49.0^{o}N, 16.5^{o}W) and Labrador Sea (56.5°N, 52.5°W) mooring sites.

al., 2007; Omar and Olsen, 2006; Schuster and Watson, 2007; Schuster et al., 2009; Ullman et al., 2009). The phenomenal CO_2 low uptake is due to several factors including rising sea surface temperatures (Corbière et al., 2007), deep convection and re-stratification periods (Körtzinger et al., 2008a, b; Straneo, 2006) and variations in biological productivity (Behrenfeld et al., 2006; Lefèvre et al., 2004).

The role of temperature-controlled and biological processes in regulating ocean pCO_2 have been intensively investigated and reported (Feely et al., 2002; Friederich et al., 2008; Körtzinger et al., 2008a; Takahashi et al., 1993; 2002; Watson et al., 1991). According to Shim et al. (2007), the temporal change in surface water temperature could be a major factor that drives a seasonal variation in surface pCO_2. However, thermodynamic effect is caused by the dependence of CO_2 solubility and dissociation constants on temperature (Rangama et al., 2005). Many global biogeochemical cycles (notably CO_2 and CH_4 cycles), mediated by biological processes are highly dependent on temperature. The solubility of CO_2 and the dissociation of carbonic acid in seawater are moderated by temperature. It has been established that as temperature decreases the solubility of gases increases; this infers greater gas solubility for seawater in high latitudes. In this paper, observed data from two North Atlantic time series sites are employed in an attempt to assess the interseasonal sea surface temperature variations and anomalies at the eastern and western basins of the North Atlantic Ocean, and examine its effect on seasonal pCO_2 distribution at these sites.

Description of mooring stations

The Porcupine Abyssal Plain (PAP) observatory (Figure 1), located in the Northeast Atlantic oceanographic region is a major long-term ocean observatory operated since 1989 for international and interdisciplinary scientific research and monitoring, which are focused on physical-biogeochemical observations. It is approximately 4800 m deep and is geographically positioned between the North Atlantic Current (NAC) and Azores Current (AC), and lies south of the main stream of the NAC, where it is subject to return flows from the West and Northwest. It is also characterized by significant presence of mesoscale eddies and deep winter mixing with strong interannual variability between 300 and 800 m (Longhurst, 2007). On the other hand, the K1 Central Labrador Sea (K1 CELAS) mooring site (Figure 1) is a deep-water formation oceanographic site of research importance that examines complex oceanic processes from surface waters to the seafloor by recording biological, chemical and physical parameters, as well as investigations of trends and variability in deep convection activity (Avsic et al., 2006).

METHODS AND DATA ANALYSIS

Detailed sampling and analytical procedures for SST and pCO_2 data generation at the KI CELAS and PAP observatories have been

Table 1. SST and pCO_2 measurements, depths and time intervals at PAP and K1 CELAS stations.

Parameter	Depths measured (m)	Sensor employed	Sampling interval
Dissolved carbon dioxide	30, 40, 60, 75, 90, 110, 130, 150	Sunburst SAMI	1 h (PAP2 and K1), 2 h (PAP3, PAP4)
Temperature	0, 250, 300, 1000	MicroCat	15 min (PAP2, PAP3, PAP4), 12 h (K1)

Table 2. Geographical coordinates of PAP and K1 CELAS observatory mooring stations.

Mooring identifier	Mooring coordinates	Deployment cruise / date	Recovery cruise / date	Duration (days)	Total number of measurements
PAP-2	49.0°N 16.5°W	RV Poseidon 300 / 13-Jul-2003	RV Poseidon 306 / 03-Nov-2003	113	2679
PAP-3	49.0°N 16.5°W	Poseidon 306 / 18-Nov-2003	RSS-Charles Darwin 158 / 20-Jun-2004	213	2519
PAP-4	49.0°N 16.5°W	RSS Charles Darwin 158 / 23-Jun-2004	RSS Discovery 295 / 18-March-2005	267	6353
K1 CELAS	56.5°N, 52.5°W	15-Sept -2004	21-July-2005	310	7404

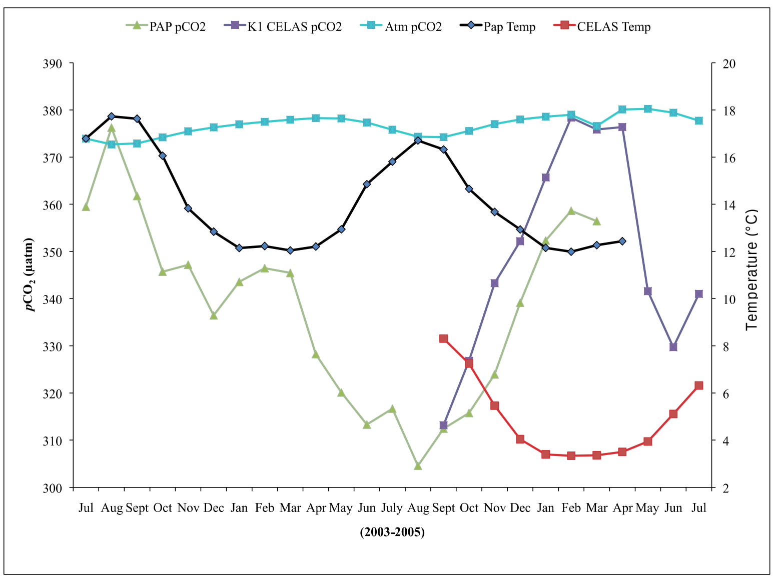

Figure 2. Monthly variation pCO_2 and SST at PAP and K1 CELAS observatories Atmospheric CO_2 (cyan) is obtained from Mauna, Loa.

reported previously (Körtzinger et al., 2008a, b). These involved measurements of pCO_2 with an autonomous sensor (SAMI-CO_2, Sunburst Sensors LLC, Missoula, Montana, United States), while temperature measurements were carried out with an SBE-37 MicroCAT recorder (Sea-Bird Electronics Inc., Bellevue, Washington, United States). The data used in this study were obtained during three consecutive deployments between July 2003 and July 2005 for the PAP and K1 CELAS mooring stations. Details of mooring coordinates, nominal depth of deployment of sensors used, sampling interval, deployment and recovery dates, parameters measured and the total number of observational data successfully recovered are presented in Tables 1 and 2.

RESULTS AND DISCUSSION

Distribution of surface water pCO_2 and SST

The distributions of sea surface temperature and pCO_2 for the PAP-2 to PAP-4 deployments at the PAP and K1 CELAS time series observatories together with the atmospheric CO_2 are shown in Figure 2. The pCO_2 distribution across the spatial gradients at both the eastern (PAP) and western (K1 CELAS) sites of the

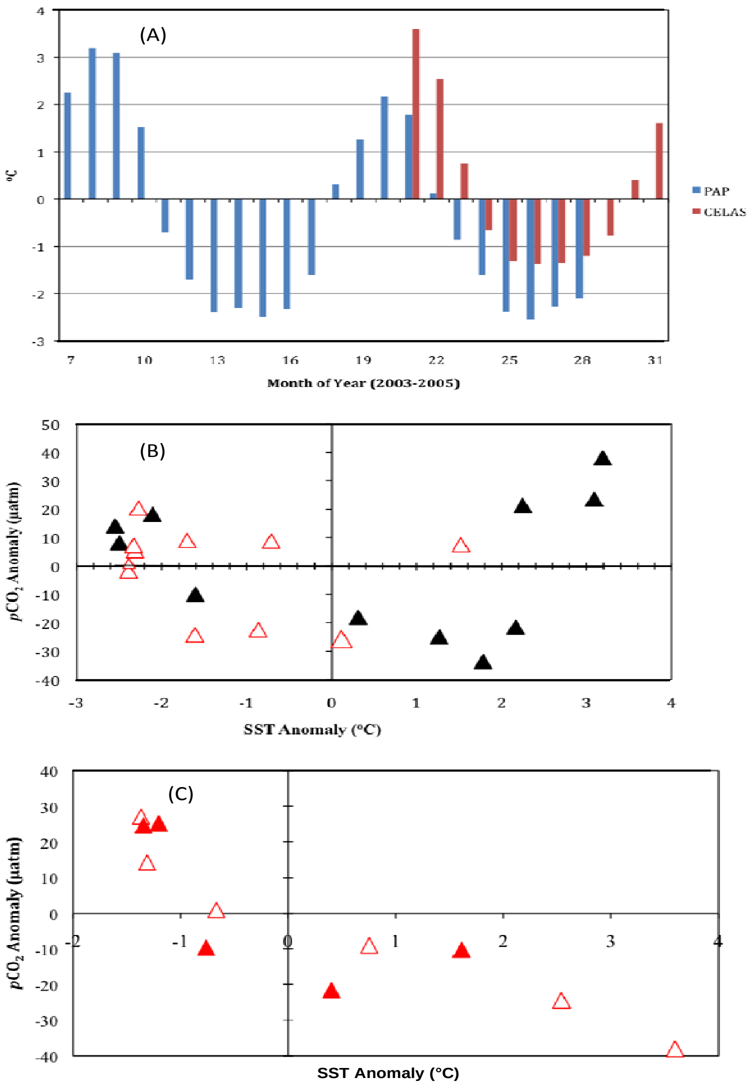

Figure 3. (a) Monthly SST anomalies (°C) at the K1 Central Labrador Sea (CELAS) and Porcupine Abyssal Plain (PAP) sites between July 2003 – July 2005, (b) Monthly anomalies of pCO_2 against SST monthly anomalies at the PAP site for fall/winter period (transparent red triangles) and the spring/summer period (black triangles), (c) Monthly anomalies of pCO_2 against SST at the K1 CELAS site for the fall/winter period (transparent red triangles) and spring/summer period (red riangles).

subpolar North Atlantic Ocean showed distinct and consistent seasonal variability. The surface water pCO_2 cycle is characteristically marked by a minimum and maximum pCO_2 distribution pattern for the summertime and wintertime, respectively. It is also well depicted in Figure 2 that the pCO_2 distribution patterns at both oceanographic sites are in antiphase to the temperature signal.

SST anomalies

The PAP and K1 CELAS monthly anomalies of SST derived as a difference between monthly averages and the long-term mean temperatures of each oceanographic station are presented here. Negative SST anomalies (>2.5°C) were generally observed during late fall through the wintertime into springtime, whereas positive SST anomalies (<3.2°C) characterized the summertime at all the PAP sites (Figure 3a). A similar trend was observed for the K1 Central Labrador Sea data although with a relatively smaller but significant negative SST anomaly of approximately 1.36°C and high SST positive anomaly of 3.6°C (Figure 3a).

A comparison of the monthly anomalies of observed pCO_2 with respect to SST anomalies at both sites are shown in Figure 3b and c. For pCO_2 anomalies calculated based on average monthly observations at the PAP and K1 CELAS sites indicate positive anomalies of approximately 38 and 25 µatm respectively. These positive deviations coincided with the highest SST positive anomaly obtained for the PAP observations during spring/summer period (black triangles) Figure 3b, while it corresponded with the lowest SST negative anomaly for the K1 CELAS observed data during fall/winter period (transparent red triangles) Figure 3c. This implies that a positive pCO_2–SST relationship exists for the observed data obtained from the PAP time series site, while an inverse correlation may be established for K1 CELAS site. However, it should be noted that the pCO_2–SST anomalies comparison did not suggest a clear and consistent relationship especially for the PAP location. For instance, positive pCO_2 deviations derived for summer and early fall of 2003 (July – October) coincided with positive SST anomalies, whereas the SST anomalies indicated an opposite behavior with marked negative pCO_2 anomalies during the same period in 2004 (corresponding to 3rd PAP deployment) (Figure 3b). This variation might be attributed to thermodynamic effect or other physical processes such as mixing and stratification that might have resulted in negative pCO_2 anomalies with corresponding positive SST anomalies. Moreover, for the winter / springtime, positive pCO_2 anomalies at the PAP site are generally associated with significant negative SST anomalies which suggest biologically driven pCO_2 variability. Negative SST anomalies are usually associated with enhanced nutrient and dissolved inorganic carbon (DIC) inputs, which could invariably lead to increase in primary productivity (Borges et al., 2007; Boyd et al., 2001).

Dependence of surface water pCO_2 on temperature

Correlation between pCO_2 and SST

The Pearson correlation analysis were carried out to establish the inter-annual / inter-seasonal relationships between observed pCO_2 and SST data obtained from the PAP and K1 CELAS sites. More so, given the large number of data, the interseasonal test of linear fits between pCO_2 and SST were evaluated based on average monthly data collated from hourly measurements. The derived linear fits generally indicated strong but negative correlations between pCO_2 and SST.

Correlation between pCO_2 and SST at PAP site

Figures 4a, b and c show the results of fitting linear model to describe the relationship of observed PAP site pCO_2 as a function of sea surface temperature for the second (PAP2), third (PAP3), and forth (PAP4) deployments on an annual timescale.

A better mechanistic understanding of how changes in SST and other processes may have influenced sea surface pCO_2 was evaluated using seasonal observed data during each deployment. Sea surface pCO_2–SST correlations generally showed negative correlations between these two variables (r^2 = 25.85, 74.13, 5.75, p < 0.0001) (Figures 4a to c) at the PAP site suggesting that SST had a non-dominance influence on pCO_2 variability. This also suggests that a large part of the observed variation may be attributed to non thermal processes such as the enhanced biological activity associated with physical transport – upwelling of nutrient enriched water into the euphotic zone, mixing or stratification. This argument is supported by the derived pCO_2–SST correlations for summer – fall 2003 observed data that characteristically indicated a strong influence of SST on pCO_2 variability (Table 3). It should be noted however, that changes in sea surface temperature principally influenced the surface water pCO_2 cycle at the PAP site during deployments in 2004 to 2005, with insignificant biological effect except during wintertime. In general, the correlations between temperature and pCO_2 based on observed data suggest that pCO_2 seawater patterns in the Northeast subpolar Atlantic Ocean is due to the counteracting effects of temperature, mixing and strong to moderate biological production. This observation is consistent with earlier reports by Körtzinger et al. (2008a) and Takahashi et al. (2002, 2009).

Inter-relationship between pCO_2 and SST at Labrador sea site

Figure 5a and b illustrate the relationships of pCO_2 as a function of SST during the period. A closer inspection of the derived linear fits reveal that the sea surface pCO_2–SST correlations were characteristically more variable and generally depicted the irrefutable effect of temperature and biology on pCO_2, although it is clear that the pCO_2 cycle is strongly governed by thermodynamic forcing than biological effect. The pCO_2–SST correlation obtained for observed data during the deployment in 2004 indicated that there is a good linear relationship between sea surface pCO_2 and in-situ SST (Table 3).

A similar relationship was found for sea surface pCO_2–SST correlations obtained for 2005 K1 deployment, but with a moderately strong relationship (r^2 = 0.53, p<0.0000) (Figure 5b). On an annual to seasonal timescale, the distribution pattern in surface seawater pCO_2 might not be controlled by a seasonal change in temperature only but also by biology as well as mixing within the subsurface and stratification of the epipelagic zone of the K1 CELAS site (Körtzinger et al., 2008b).

However, it is obvious that the thermodynamic effects and other physical processes are the dominating variability driver compared to weak biology signature at

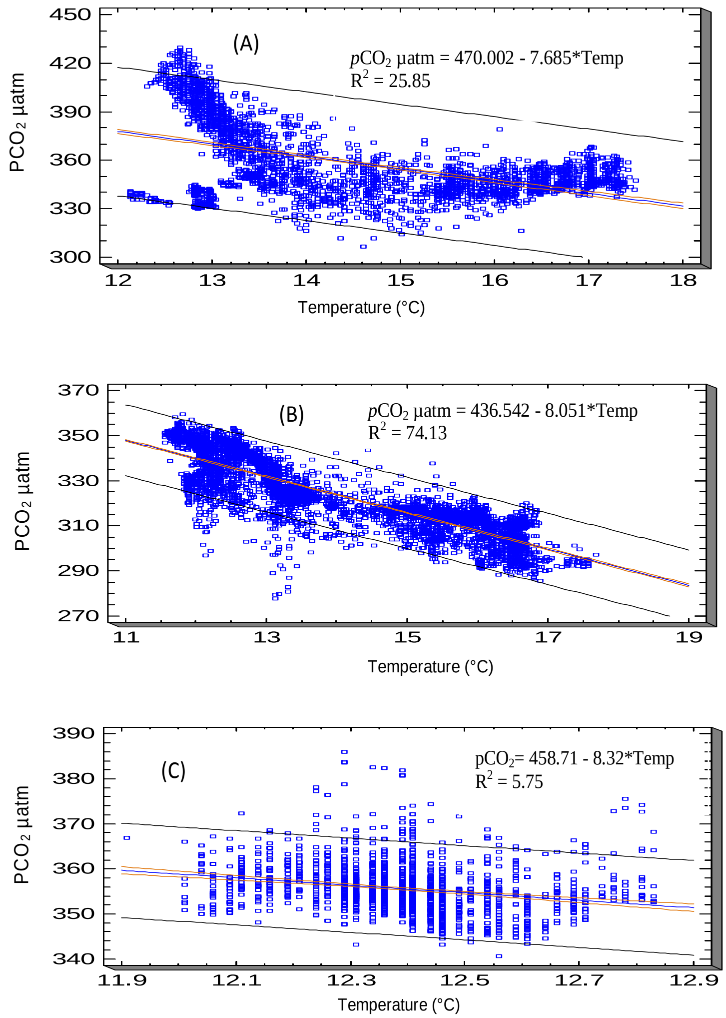

Figure 4. Distributions of pCO_2 as a function of SST during PAP2 (a), PAP3, (b) and PAP4 (c) deployments.

Table 3. PAP and K1 CELAS seasonal pCO_2 distributions as a function of SST.

Time series location	Season	Correlation equation for pCO_2 (µatm)/SST (ºC)	Correlation Coefficient (r)	Coefficient of determination (R^2) %
PAP	Summer (July-August) 2003	$pCO_2 = -23.49 \times SST + 645.54$	-0.80	64.28
	Fall 2003	$pCO_2 = -7.09 \times SST + 427.26$	-0.66	43.48
	Winter 2004	$pCO_2 = -11.88 \times SST + 469.58$	-0.72	51.29
	Spring 2004	$pCO_2 = -24.97 \times SST + 615.49$	-0.60	35.45
	Summer 2004	$pCO_2 = -12.30 \times SST + 430.95$	-0.87	75.37
	Fall 2004	$pCO_2 = -8.52 \times SST + 374.36$	-0.89	79.49
	Winter 2005	$pCO_2 = -26.65 \times SST + 616.52$	-0.85	71.69
	March (Early Spring) 2005	$pCO_2 = -1.65 \times SST + 308.19$	-0.04	0.16
K1 CELAS	Fall 2004	$pCO_2 = -9.65 \times SST + 395.45$	-0.97	93.87
	Winter 2005	$pCO_2 = -27.00 \times SST + 462.18$	-0.81	65.27
	Spring 2005	$pCO_2 = -49.69 \times SST + 543.54$	-0.87	75.74
	Summer (July-August) 2005	$pCO_2 = -11.54 \times SST + 399.29$	-0.56	31.18

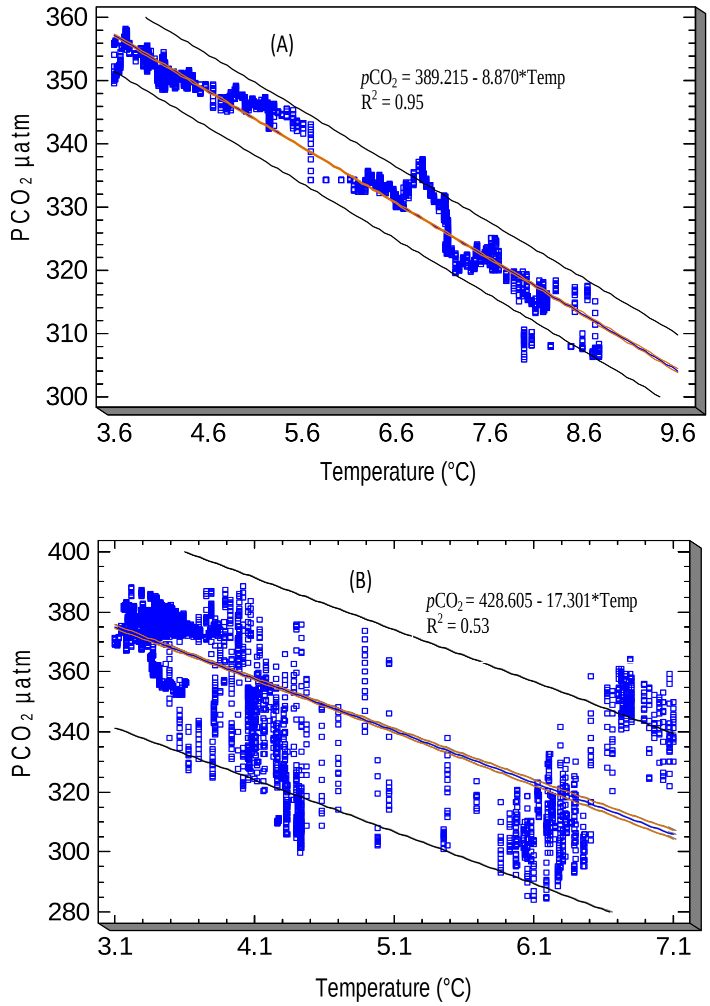

Figure 5. Distributions of pCO_2 as a function of SST at the Northwest Labrador Sea in 2004 (a), and 2005 (b) K1 deployments.

this subpolar NW Atlantic site. A comparison of the seasonal sea surface pCO_2–SST correlations at the K1 CELAS site also reveal significant but negative correlations between these two parameters during autumn 2004 and spring 2005. This implies that other physical processes such as turbulence, mixing and stratification primarily govern the variability in pCO_2 distribution. On the other hand, the pCO_2–SST correlation obtained for summer 2005 indicates a positively significant correlation implying that mainly thermodynamic effects induce pCO_2 variability. A summary of pCO_2–SST relationships at both the Northeast and Northwest sites of the Atlantic Ocean is presented in Table 3.

CONCLUDING REMARKS

This study has demonstrated that the surface water pCO_2 distribution across the spatial gradients over a seasonal timescale at both the eastern (PAP) and western (K1 CELAS) basins of the subpolar North Atlantic Ocean is relatively consistent, however with distinct seasonal large variability. At the PAP site, consistent undersaturation of oceanic surface water was observed relative to the atmospheric CO_2, while a similar trend occurred over the western area at the K1 CELAS location but with some degree of supersaturation between February and March 2005. On a seasonal timescale, the surface water pCO_2 cycle is characteristically marked by minimum and maximum pCO_2 distribution pattern for the summertime and wintertime respectively. It is obvious that the pCO_2 distribution pattern in the NE PAP and NW CELAS sites of the subpolar North Atlantic were in antiphase to the temperature signal. Investigation of sea surface pCO_2–SST correlations generally indicated moderate to strong but negative correlations between pCO_2 and SST. Thus we conclude that the variation in surface ocean pCO_2

may not be controlled by change in sea surface temperature only, but by biological activities and other physical processes. In the Northeastern basin, the variability in pCO_2 distribution is primarily governed by other physical processes such as mixing and stratification during the autumn and springtime, while the pCO_2–SST relationship obtained for summertime indicates that pCO_2 variability is induced mainly by thermodynamic effects.

Conflict of Interest

The authors have not declared any conflict of interest.

ACKNOWLEDGEMENTS

The EuroSITES Project data was used for this research, contributions of the principal investigator and other scientists involved in the PAP project are acknowledged. The first author is particularly thankful to Professors G. A. McKinley and Arne Körtzinger for technical guidance. The fellowship opportunity provided by the Fulbright Scholarship Program to the Department of Atmospheric, Space and Ocean Sciences, University of Wisconsin, Madison is acknowledged. The authors would like to thank anonymous reviewers for their comments and suggestions made to improve the original manuscript.

REFERENCES

Avsic T, Karstensen J, Send U, Fischer J (2006). Interannual variability of newly formed Labrador Sea Water from 1994 to 2005. Geophys. Res. Lett. 33:L21S02. doi:10.1029/2006GL026913. http://dx.doi.org/10.1029/2006GL026913

Behrenfeld MJ, O'Malley RT, Siegel DA, McClain CR, Sarmiento JL, Feldman GC, Milligan AJ, Falkowski PG, Letelier RM, Boss ES (2006). Climate-driven trends in contemporary ocean productivity. Nature 444:752-755.

Borges AV, Tilbrook B, Metzl N, Lenton A, Delille B (2007). Inter-annual variability of the carbon dioxide oceanic sink south of Tasmania. Biogeosciences Discuss. 4:3639-3671.

Boyd PW, Crossley AC, DiTullio GR, Griffiths FB, Hutchins DA, Queguiner B, Sedwick PN, Trull TW (2001). Control of phytoplankton growth by iron supply and irradiance in the subantarctic Southern Ocean: Experimental results from the SAZ Project. J. Geophys. Res. 106(C12)31:573-583.

Canadell JG, Le Que´re´ C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G (2007). Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc. Natl. Acad. Sci. 104(47):18866-18870, doi:10.1073/pnas.0702737104, http://dx.doi.org/10.1073/pnas.0702737104

Corbière A, Metzl N, Reverdin G, Brunet C, Takahashi T (2007). Interannual and decadal variability of the oceanic carbon sink in the North Atlantic subpolar gyre. Tellus 59B(2):168-178.

Chen F, Cai W-J, Benitez-Nelson C, Wang Y (2007). Sea surface pCO2-SST relationships across a cold-core cyclonic eddy: Implications for understanding regional variability and air-sea gas exchange. Geophys. Res. Lett. 34:L10603, doi:10.1029/2006GL028058. http://dx.doi.org/10.1029/2006GL028058

Feely RA, Boutin J, Cosca CE, Dandonneau Y, Etcheto J, Inoue HY, Ishii M, Le Quéré C, Mackey DJ, McPhaden M, Metzl N, Poisson A, Wanninkhof R (2002). Seasonal and interannual variability of CO_2 in the equatorial Pacific. Deep Sea Res. Part II: Top. Stud. Oceanogr. 49(13-14):2443-2469.

Friederich GE, Ledesma J, Ulloa O, Chavez FP (2008). Air-sea carbon dioxide fluxes in the coastal southeastern tropical Pacific. Prog. Oceanogr. 79:156-166, doi.10.1016/j.pocean.2008.10.001

Hopkins FE, Turner SM, Nightingale PD, Steinke M, Bakker D, Liss PS (2010). Ocean acidification and marine trace gas emissions. Proc. Natl. Acad. Sci. 107(2):760-765, doi:10.1073/pnas.0907163107, http://dx.doi.org/10.1073/pnas.0907163107

Keeling CD, Whorf TP (2005). Atmospheric CO_2 records from sites in the SIO air sampling network. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Körtzinger A, Send U, Lampitt RS, Hartman S, Wallace DWR, Karstensen J, Villagarcia MG, Llinas O, DeGrandpre MD (2008a). Seasonal pCO_2 cycle at 49°N / 16.5°W in the northeast Atlantic Ocean and what it tells us about biological productivity. J. Geophys. Res.113, C04020, doi:10.1029/2007JC004347. http://dx.doi.org/10.1029/2007JC004347

Körtzinger A, Send U, Wallace DWR, Kartensen J, DeGrandpre M (2008b). Seasonal cycle of O_2 and pCO_2 in the central Labrador Sea: Atmospheric, biological, and physical implications. Global Biogeochem. Cycles 22, GB1014, doi:10.1029/2007 GB003029.

Lefèvre N, Watson AJ, Olsen A, Ríos AF, Pérez FF, Johannessen T (2004). A decrease in the sink for atmospheric CO_2 in the North Atlantic. Geophys. Res. Lett. 31:L07306, doi:10.1029/2003GL018957. http://dx.doi.org/10.1029/2003GL018957

Levine NM, Doney SC, Wanninkhof R, Lindsay K, Fung IY (2008). Impact of ocean carbon system variability on the detection of temporal increases in anthropogenic CO_2. J. Geophys. Res. 113:C03019, doi:10.1029/2007JC004153. http://dx.doi.org/10.1029/2007JC004153

Longhurst AR (2007). Ecological Geography of the Sea, 2nd ed., 542 pp. Academic, Boston, Mass.

Omar AM, Olsen A (2006). Reconstructing the time history of the air-sea CO_2 disequilibrium and its rate of change in the eastern subpolar North Atlantic, 1972-1989. Geophys. Res. Lett. 33:L04602, doi:10.1029/2005GL025425, http://dx.doi.org/10.1029/2005GL025425

Rangama Y, Boutin J, Etcheto J, Merlivat L, Takahashi T, Delille B, Frankignoulle M, Bakker DCE (2005). Variability of the net air-sea CO_2 flux inferred from shipboard and satellite measurements in the Southern Ocean of Tasmania and New Zealand. J. Geophys. Res. 110, C09005, doi:10.1029/2004JC002619, http://dx.doi.org/10.1029/2004JC002619

Sabine CL, Feely RA (2007). The Oceanic Sink for Carbon Dioxide, in: Reay, D.S., Hewitt, C.N., Smith, K.A., Grace, J. (Eds), Greenhouse Gas Sinks. Athenaeum Press Ltd, Gateshead, UK.

Schuster U, Watson AJ (2007). A variable and decreasing sink for atmospheric CO_2 in the North Atlantic. J. Geophys. Res. 112:C11006, doi:10.1029/2006JC003941, http://dx.doi.org/10.1029/2006JC003941

Schuster U, Watson AJ, Bates NR, Corbiere A, Gonzalez-Davila M, Metzl N, Pierrot D, Santana-Casiano M (2009). Trends in North Atlantic sea-surface fCO_2 from 1990 to 2006. Deep-Sea Res. II, doi:10.1016/j.dsr2.2008.12.011, http://dx.doi.org/10.1016/j.dsr2.2008.12.011

Shim J, Kim D, Kang YC, Lee JH, Jang S-T, Kim C-H (2007). Seasonal variations in pCO_2 and its controlling factors in surface seawater of the northern East China Sea. Cont. Shelf Res. 27:2623-2636, doi:10.1016/j.csr.2007.07.005, http://dx.doi.org/10.1016/j.csr.2007.07.005

Straneo F (2006). Heat and Freshwater Transport through the Central Labrador Sea. J. Phys. Oceanogr. 36(4):606-628. doi: 10.1175/JPO2875.1, http://dx.doi.org/10.1175/JPO2875.1

Takahashi T, Olafsson J, Goddard J, Chipman DW, Sutherland SC (1993). Seasonal variation of CO_2 and nutrients in the high-latitude surface oceans: A comparative study. Global Biogeochem. Cycles 7: 843-878.

Takahashi T, Sutherland SC, Sweeney C, Poisson A, Metzl N, Tilbrook B, Bates N, Wanninkhof R, Feely RA, Sabine C, Olafsson J, Nojiri Y (2002). Global sea to air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. Deep Sea Res. Part II: Top. Stud. Oceanogr. 49:1601-1622. http://dx.doi.org/10.1016/j.dsr2.2008.12.009

Takahashi T, Sutherland SC, Wanninkhof R, Sweeney C, Feely RA, Chipman DW, Hales B, Friederich G, Chavez F, Sabine C, Watson A, Bakker DCE, Schuster U, Metzl N, Inoue HY, Ishii M, Midorikawa T, Nojiri Y, Körtzinger A, Steinhoff T, Hoppema M, Olafsson J, Arnarson TS, Tilbrook B, Johannessen T, Olsen A, Bellerby R, Wong CS, Delille B, Bates NR, de Baar HJW (2009). Climatological mean and decadal change in surface ocean pCO_2, and net sea–air CO_2 flux over the global oceans. Deep-Sea Research II, doi:10.1016/j.dsr2.2008.12.009.

Ullman D, McKinley GA, Bennington V, Dutkiewicz S (2009). Trends in the North Atlantic carbon sink: 1992-2006. Global Biogeochem. Cycles 23, GB4011, doi:10.1029/2008GB003383, http://dx.doi.org/10.1029/2008GB003383

Watson AJ, Robinson C, Robinson JE, Williams PJL, Fasham MJR (1991). Spatial variability in the sink for atmospheric carbon dioxide in the North Atlantic. Nature 350:50-53.