AUTHORS:
Gregor T. Feig[1]
Warren R. Joubert[1,2]
Azwitamisi E. Mudau[1]
Pedro M.S. Monteiro[1]

AFFILIATIONS:
[1]Natural Resources and the Environment, Council for Scientific and Industrial Research, Pretoria, South Africa

[2]Cape Point GAW Station, Climate and Environmental Research and Monitoring, South African Weather Service, Stellenbosch, South Africa

CORRESPONDENCE TO:
Gregor Feig

EMAIL:
gfeig@csir.co.za

South African carbon observations: CO$_2$ measurements for land, atmosphere and ocean

Carbon dioxide plays a central role in earth's atmospheric, ocean and terrestrial systems.[1,2] About 40% of the total anthropogenic emissions since 1750 have remained in the atmosphere, with the balance being removed by the ocean and vegetation sinks.[3] Increasing atmospheric CO$_2$ concentrations have been well documented,[3] as have widespread impacts on human and natural systems, such as warmer surface temperatures, ocean warming and decreasing pH, loss of ice mass over the cryosphere, increasing global mean sea level, and alterations in the global hydrological cycle.[3,4] The impact of increased atmospheric concentrations of CO$_2$ on the biosphere includes shifting species extent, seasonal activities, migration patterns and abundances, as well as changes in species interactions.

Monitoring of atmospheric CO$_2$ and other greenhouse gases (GHGs) has been identified as a priority by international agencies, such as the United Nations Framework Convention on Climate Change and government departments that are interested in mitigating the effects of climate change. South Africa has made a commitment to a low carbon future as part of its role in global climate policy instruments through a national low carbon development strategy.[5,6] At the Conference of the Parties in November 2015 (COP21), high level of agreement by developed and developing countries encouraged stakeholders to urgent action to address climate change. The agreement emphasises the urgent mitigation pledges with respect to GHG emissions by 2020. As South Africa implements its White Paper on Climate Change, to stimulate a shift towards a low carbon economy, it faces a monitoring and evaluation challenge. Currently, the South African GHG emission inventory is based on fossil fuel emissions, as part of the National Atmospheric Emissions Inventory System, under the *National Air Quality Act, 2004* (*Act No. 39 of 2004*). Briefly, emissions are rarely measured directly, but rather based on proxy estimates of activity, extrapolated by an emission factor for the specific activity. There is therefore a need to independently assess the effectiveness of emissions reductions within the context of natural CO$_2$ fluxes. Understanding the changing driving forces of climate change and evaluation of the carbon emission reduction activities requires long-term and high-precision measurements of CO$_2$ gas emissions and sinks as well as their evolution.

Land can act as both a source and a sink for GHGs.[7] Currently the baseline GHG emissions from land and agriculture are thought to amount to 3.03x10^{10} kg CO$_2$ eq per year in South Africa. The land sector is responsible for an uptake of 2.1x10^{10} kg CO$_2$ eq per year while agriculture is responsible for a release of 5.06x10^{10} kg CO$_2$ eq per year.[7] The GHG emissions for South African industry amounted to ~5.45x10^{11} kg CO$_2$ eq in 2010[8,9], with approximately 79% from the energy sector – an order of magnitude larger than the emissions from agriculture[7].

Under the proposed White Paper policy, South Africa's GHG peak, plateau and decline trajectory anticipates emissions to peak at 6.1x10^{11} kg CO$_2$ eq between 2020 and 2025, plateau at this range for about 10 years and decline to ~4.3x10^{11} kg CO$_2$ eq by 2050.[6] Determining these fluxes accurately will facilitate assessment of the proposed commitments to mitigation and adaptation strategies adopted by South Africa. At present there is infrastructure deployed in South Africa for the measurement of the concentrations and fluxes of CO$_2$, which include observations in the atmosphere, on land and in the ocean.

Carbon dioxide observations in South Africa

Terrestrial observations

A number of sites for terrestrial CO$_2$ observations are in place (Figure 1). These include:

- A network of cavity ring-down spectroscopy analysers for measurement of CO$_2$, CH$_4$ and H$_2$O concentrations. The placement of these instruments was guided by the inverse modelling work of Nickless et al.[10] These instruments have been used by the City of Cape Town for estimation of the CO$_2$ flux from the city.[11,12] The instrumentation has been set up around the country at the following locations:

  - The Cape Point Global Atmospheric Watch station: -34.35°, 18.48°; 172 metres above sea level (masl); operational since 1991; operated by the South African Weather Service.[13-16]

  - The Elandsfontein Air Quality Monitoring Station: -26.24°, 29.41°; 1747 masl; operational since April 2016; Eskom ambient air quality monitoring station.[17,18]

  - The Medupi Ambient Air Quality Monitoring Station: -23.74°, 27.54°; 900 masl; operational since January 2016.

- A network of eddy covariance flux towers with instruments located at the following sites:

  - Skukuza: -25.02°, 31.49°; 365 masl; savanna site in conservation area; operational since 2000; operated by the Council for Scientific and Industrial Research (CSIR).[19-21]

  - Malopeni: -23.83°, 31.21°; 385 masl; savanna site in conservation area; operational since 2008; operated by the CSIR.

  - Agincourt: -24.82°, 31.21°; 534 masl; savanna in communal area; operational since 2016; operated by the CSIR.

  - Vuwani: -23.14°, 30.43°; 629 masl; savanna site in communal area; operational since 2016; operated by the University of Venda.

- Middelburg: -31.52°, 25.01°; Karoo site in heavily grazed and lightly grazed agricultural area; operational since 2015; operated by Grootfontein Agricultural College and Stellenbosch University.

- Cathedral Peak: -28.9755°, 29.2359°; 1860 masl; operational since 2012; operated by the South African Environmental Observation Network (SAEON) Grasslands–Forests–Wetlands node.

- Welgegund: -26.56°, 26.93°; 1477 masl; grassland site under commercial agriculture; operational since 2010; operated by the North-West University.[22]

Marine observations

A number of different approaches has been adopted to address the needs of understanding and resolving the trends in Southern Ocean CO_2. One of the key gaps is observational-based estimates because of the geographical extent and remoteness of the Southern Ocean.[23] This gap is being addressed in two main ways. Firstly, by increasing the coverage and quality of global data sets through international coordinated efforts such as Surface Ocean CO_2 Atlas (SOCAT)[24] and supplementing these data with linear and non-linear empirical models and proxy variables. Secondly, by expanding the ship-based approaches with autonomous platforms such as floats[25] and gliders[23,26].

The ongoing data coverage in the Southern Ocean since 1995 has a seasonal bias for summer (Figure 2). The Southern Ocean Carbon and Climate Observatory's annual partial pressure CO_2 (pCO_2) observations programme on board the MV SA *Agulhas II* currently operates in the Southern Ocean basin annually. These pCO_2 observations seasonally characterise the drivers and variability of CO_2 fluxes in the Southern Ocean south of Africa. Moreover, these observations reduce the uncertainty of the mean annual flux of CO_2 in the Southern Ocean.[27] Reducing the uncertainty to less than 10% (or 0.1 Pg C/year) of the mean net uptake of CO_2 is critical to resolving interannual variability and trends of CO_2 flux in the Southern Ocean.[25,28]

An integrated carbon observation network which combines the current ongoing initiatives of ocean, atmosphere and terrestrial observations would provide essential information to decision-makers involved in mitigation targets and policy. In South Africa, quantitative measurement and monitoring of high-quality (climate-focused) carbon concentrations in the terrestrial, ocean and atmosphere domains already exist. Integrating these flux measurements across spatial scales and between the marine and terrestrial systems is essential.

Empirical modelling methodologies provide a method to utilise high-precision measurements of CO_2 to estimate CO_2 fluxes or to improve prior estimates of CO_2 fluxes. These methods have been successfully used in terrestrial systems including the City of Cape Town[11,12], and regional and global CO_2 emissions inventories[29,30]. This method relies on high accuracy measurements of atmospheric CO_2 (or other) concentrations to constrain a priori estimates of CO_2 fluxes derived from activity and emission factor estimates.[11,30]

Similarly, within the marine domain, empirical modelling provides an interim solution to estimate CO_2 fluxes accurately enough to estimate inter-annual and seasonal changes, as deterministic ocean models do not yet accurately depict the seasonality of CO_2. Empirical modelling utilises the relationship between in-situ CO_2 measurements and remotely sensed parameters (temperature, salinity, chlorophyll, etc.). The relationship is then applied to remotely sensed data for which there are no CO_2 measurements, to improve CO_2 data coverage. This approach has shown some promising potential in the North Atlantic where data coverage is more extensive[31,32], and has also been extended to the Southern Ocean[33]. Furthermore, the approach has more recently been refined by using artificial neural networks to highlight the importance of input parameters and self-organising maps, to illustrate the usefulness of empirical models as tools to reduce uncertainty of CO_2 estimates.[34]

The currently available CO_2 observation platforms allow the opportunity for spatial integration to provide national and metro policy management with an independent assessment capability of the effectiveness of emissions mitigation measures at local and regional (southern Africa) scales. It is necessary to maintain and expand the CO_2 observation network across ocean, terrestrial and atmospheric platforms in Southern Africa, to link the observations and modelling platforms in order to establish an observation-based CO_2 inventory for South Africa and to develop temporally relevant indicators of the state of the terrestrial, atmospheric and ocean carbon systems that are relevant and accessible to policymakers and the general public.
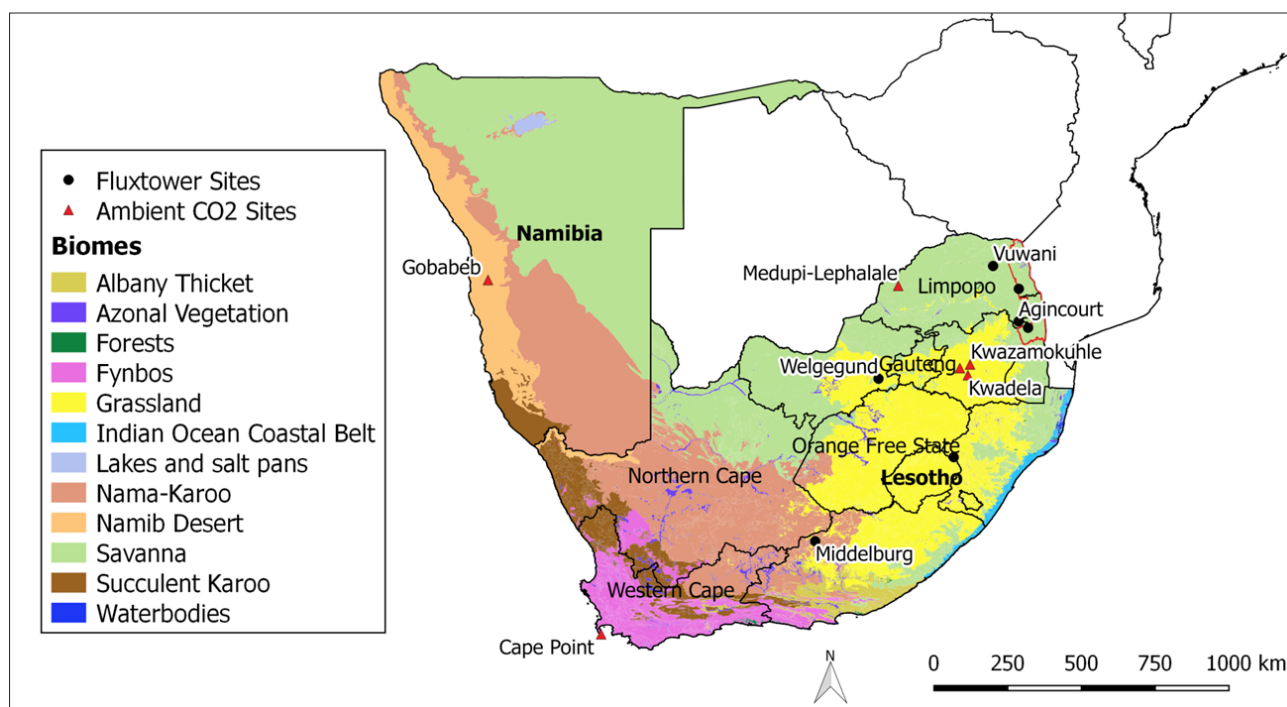

Figure 1: Sites of terrestrial CO_2 measurements in South Africa including both the flux tower locations and the CO_2 measurement sites.
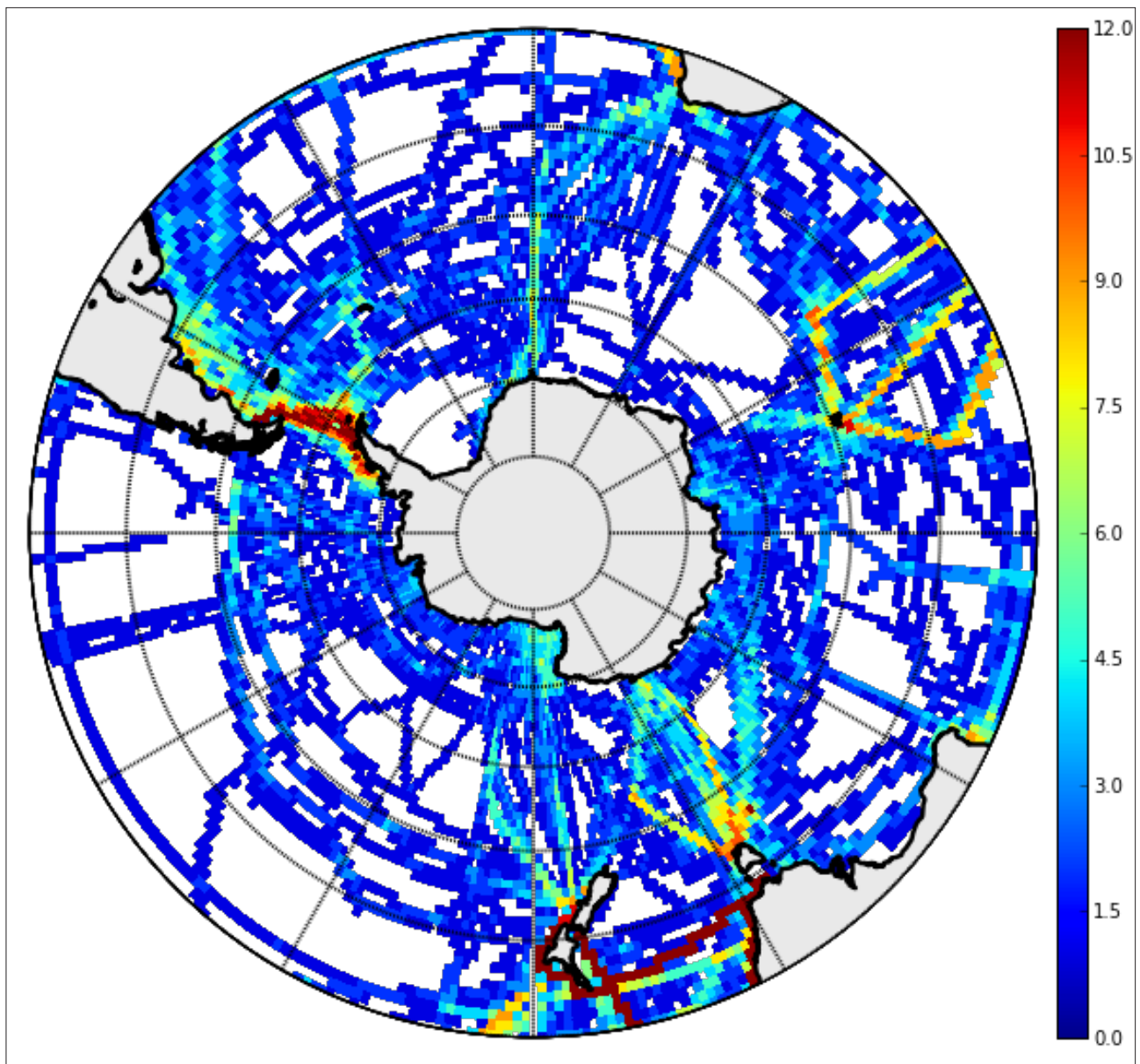
Figure 2. Gridded CO_2 observations in the Southern Ocean between 1995 and 2013 from the Surface Ocean CO_2 Atlas (SOCAT v3). The annual occupation of the seasonal cycle (in months) is shown; white space indicates no data.

References

1. Houghton RA. Balancing the global carbon budget. Annu Rev Earth Planet Sci. 2007;35:313–347. https://doi.org/10.1146/annurev.earth.35.031306.140057

2. Denman KL. Climate change, ocean processes and ocean iron fertilization. Mar Ecol Prog Ser. 2008;364:219–225. https://doi.org/10.3354/meps07542

3. Intergovernmental Panel on Climate Change (IPCC). Climate change 2014: Synthesis report: Summary for policymakers [document on the Internet]. c2014 [cited 2017 Nov 06]. Available from: http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf

4. Le Quéré C, Peters GP, Andres RJ, Andrew RM, Boden TA, Ciais P, et al. Global carbon budget 2013. Earth Syst Sci Data. 2014;6(1):235–263. https://doi.org/10.5194/essd-6-235-2014

5. South African National Planning Commission. National development plan (2030). Pretoria: The Presidency; 2010.

6. South African Department of Environmental Affairs (DEA). National Climate Change Response White Paper. Pretoria: DEA; 2012. p. 56.

7. Stevens L, Henri A, Van Nierop M, Van Staden E, Lodder J, Piketh SJ. Towards the deveolpment of a GHG emissions baseline for the agriculture, forestry and other land use (AFOLU) sector in South Africa. Clean Air J. 2016;26(2):34–39. http://dx.doi.org/10.17159/2410-972X/2016/v26n2a11

8. Thambiran T, Diab RD. Air quality and climate change co-benefits for the industrial sector in Durban, South Africa. Energy Policy. 2011;39(10):6658–666. http://dx.doi.org/10.1016/j.enpol.2011.08.027

9. South African Department of Environmental Affairs (DEA). GHG Inventory for South Africa. Pretoria: DEA; 2014.

10. Nickless A, Ziehn T, Rayner PJ, Scholes RJ, Engelbrecht F. Greenhouse gas network design using backward Lagrangian particle dispersion modelling – Part 2: Sensitivity analyses and South African test case. Atmos Chem Phys. 2015;15(4):2051–2069. https://doi.org/10.5194/acp-15-2051-2015

11. Nickless A, Scholes RJ, Filby E. Spatial and temporal disaggregation of anthropogenic CO_2 emissions from the City of Cape Town. S Afr J Sci. 2015;111(11–12), Art. 2014-0387, 8 pages. https://doi.org/10.17159/sajs.2015/20140387

12. Nickless A, Rayner PJ, Engelbrecht F, Brunke E, Erni B, Scholes RJ. Estimates of CO_2 fluxes over the City of Cape Town, South Africa, through Bayesian inverse modelling. Atmos Chem Phys Discuss. Preprint 2017 July. https://doi.org/10.5194/acp-2017-604

13. Nzotungicimpaye CM, Abiodun BJ, Steyn DG. Tropospheric ozone and its regional transport over Cape Town. Atmos Environ. 2014;87:228–238. Available from: http://dx.doi.org/10.1016/j.atmosenv.2014.01.063

14. Venter AD, Beukes JP, Van Zyl PG, Brunke EG, Labuschagne C, Slemr F, et al. Statistical exploration of gaseous elemental mercury (GEM) measured at Cape Point from 2007 to 2011. Atmos Chem Phys. 2015;15(18):10271–10280. https://doi.org/10.5194/acp-15-10271-2015

15. Brunke EG, Labuschagne C, Parker B, Scheel HE, Whittlestone S. Baseline air mass selection at Cape Point, South Africa: Application of 222Rn and other filter criteria to CO_2. Atmos Environ. 2004;38(33):5693–5702. https://doi.org/10.1016/j.atmosenv.2004.04.024

16. Brunke EG, Labuschagne C, Scheel HE. Trace gas variations at Cape Point, South Africa, during May 1997 following a regional biomass burning episode. Atmos Environ. 2001;35(4):777–786. https://doi.org/10.1016/S1352-2310(00)00260-0

17. Giannakaki E, Van Zyl PG, Müller D, Balis D, Komppula M. Optical and microphysical characterization of aerosol layers over South Africa by means of multi-wavelength depolarization and Raman lidar measurements. Atmos Chem Phys Discuss. 2015;15(23):35237–35276. https://doi.org/10.5194/acpd-15-35237-2015

18. Collett KS, Piketh SJ, Ross KE. An assessment of the atmospheric nitrogen budget on the South African highveld. S Afr J Sci. 2010;106(5–6), Art. #220, 9 pages. https://doi.org/10.4102/sajs.v106i5/6.220

19. Archibald SA, Kirton A, Van der Merwe MR, Scholes RJ, Williams CA, Hanan N. Drivers of inter-annual variability in net ecosystem exchange in a semi-arid savanna ecosystem, South Africa. Biogeosciences. 2009;6(2):251–266. https://doi.org/10.5194/bg-6-251-2009

20. Scholes R, Gureja N, Giannecchinni M, Dovie D, Wilson B, Davidson N, et al. The environment and vegetation of the flux measurement site near Skukuza, Kruger National Park. Koedoe. 2001;44(1):73–83. https://doi.org/10.4102/koedoe.v44i1.187

21. Feig GT, Mamtimin B, Meixner FX. Soil biogenic emissions of nitric oxide from a semi-arid savanna in South Africa. Biogeosciences. 2008;5(6):1723–1738. https://doi.org/10.5194/bgd-5-2795-2008

22. Räsänen M, Aurela M, Vakkari V, Beukes JP, Van Zyl PG, Josipovic M, et al. Carbon balance of a grazed savanna grassland ecosystem in South Africa. Biogeosciences Discuss. Preprint 2016 July. https://doi.org/10.5194/bg-2016-268

23. Waldron HN, Monteiro PMS, Swart NC. Carbon export and sequestration in the southern Benguela upwelling system: Lower and upper estimates. Ocean Sci Discuss. 2009;6(2):1173–1192. https://doi.org/10.5194/os-5-711-2009

24. Pfeil B, Olsen A, Bakker DCE, Hankin S, Koyuk H, Kozyr A, et al. A uniform, quality controlled Surface Ocean CO_2 Atlas (SOCAT). Earth Syst Sci Data. 2013;5(1):125–143. https://doi.org/10.5194/essd-5-125-2013

25. Majkut JD, Carter BR, Frölicher TL, Dufour CO, Rodgers KB, Sarmiento JL. An observing system simulation for Southern Ocean carbon dioxide uptake. Philos Trans R Soc A. 2014;372, Art. #2013-0046, 17 pages. https://doi.org/10.1098/rsta.2013.0046

26. Swart S, Chang N, Fauchereau N, Joubert W, Lucas M, Mtshali T, et al. Southern Ocean Seasonal Cycle Experiment 2012: Seasonal scale climate and carbon cycle links. S Afr J Sci. 2012;108(3–4):3–5. https://doi.org/10.4102/sajs.v108i3/4.1089

27. Thomalla SJ, Racault M-F, Swart S, Monteiro PMS. High-resolution view of the spring bloom initiation and net community production in the Subantarctic Southern Ocean using glider data. ICES J Mar Sci. 2015;72(6):1999–2020. https://doi.org/10.1093/icesjms/fsv105

28. Landschützer P, Gruber N, Bakker DCE, Schuster U, Nakaoka S, Payne MR, et al. A neural network-based estimate of the seasonal to inter-annual variability of the Atlantic Ocean carbon sink. Biogeosciences Discuss. 2013;10(5):8799–8849. https://doi.org/10.5194/bg-10-7793-2013

29. Carouge C, Peylin P, Rayner PJ, Bousquet P, Chevallier F, Ciais P. What can we learn from European continuous atmospheric CO_2 measurements to quantify regional fluxes – Part 2: Sensitivity of flux accuracy to inverse setup. Atmos Chem Phys. 2010;8(5):3119–3129. https://doi.org/10.5194/acp-10-3119-2010

30. Ogle SM, Davis K, Lauvaux T, Schuh A, Cooley D, West TO, et al. An approach for verifying biogenic greenhouse gas emissions inventories with atmospheric CO_2 concentration data. Environ Res Lett. 2015;10(3):34012. https://doi.org/10.1088/1748-9326/10/3/034012

31. Levevre N, Watson AJ, Olsen A, Rios AF, Perez FF, Johannessen T. A decrease in the sink for atmospheric CO_2 in the North Atlantic. Geophys Res Lett. 2004;31(7):2–5.

32. Chierici M, Olsen A, Johannessen T, Trinañes J, Wanninkhof R. Algorithms to estimate the carbon dioxide uptake in the northern North Atlantic using shipboard observations, satellite and ocean analysis data. Deep Res Part II Top Stud Oceanogr. 2009;56(8–10):630–639. https://doi.org/10.1016/j.dsr2.2008.12.014

33. Landschützer P, Gruber N, Bakker DCE, Schuster U. Recent variability of the global ocean carbon sink. Global Biogeochem Cycles. 2014;28(9):927–949. https://doi.org/10.1002/2014GB004853

34. Jamet C, Moulin C, Lefèvre N. Estimation of the oceanic pCO_2 in the North Atlantic from VOS lines in-situ measurements: Parameters needed to generate seasonally mean maps. Ann Geophys. 2007;25(11):2247–2257. https://doi.org/10.5194/angeo-25-2247-2007