Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Biogeochemical climatology for the Southern Benguela Upwelling System, constructed from *in situ* monitoring data

Stephanie de Villiers

Centre for Coastal Paleoscience, Nelson Mandela University, Port Elizabeth, South Africa

Correspondence to: Stephanie de Villiers (steph.devilliers@gmail.com)

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Abstract. An annual and a seasonal biogeochemical climatology had been constructed for the Southern Benguela Upwelling System, from *in situ* data collected along a 12 station monitoring line, sampled at monthly intervals from 2001 to 2012. The monitoring line reaches a maximum offshore distance of almost 190 km, with monitoring station depths ranging from 27 to 1 465 m. In addition to temperature, salinity and oxygen CTD profile data, archived monitoring data for the macro-nutrients (phosphate, nitrate + nitrite, silicate) and chlorophyll-a was evaluated. The climatologies exhibit clear spatial and seasonal variability patterns for all parameters, that yield important insight into the SBUS upwelling cycle. These data sets comprise valuable additions to our knowledge base, and will aid both future modelling efforts and studies of biogeochemical processes in upwelling systems. Data for the constructed climatologies has been made available via the PANGAEA Data Archiving and Publication database at http://doi.pangaea.de/10.1594/PANGAEA.882218.

Keywords: Upwelling; Benguela; climatology; biogeochemistry; oxygen; nutrients; chlorophyll-a.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

1 Introduction

The world's four Eastern Boundary Upwelling Systems (EBUSs), the California, Humboldt, Canary/Iberian and the Benguela, are regions of intense biological production and ocean-atmosphere exchange of CO_2. Together they account for more than 10% of new oceanic primary production and provide more than 20% of the world's commercial fish catches (Chavez and Toggweiler, 1995; Fennel, 1999; Pauly and Christensen, 1995). In addition, they serve as important sources of nutrients to adjacent oligotrophic subtropical gyres. The strength of the biological pump in these large coastal upwelling systems depends on the availability of nutrients in the photic zone. Nutrient supply and export, in turn, are controlled by complex and climate-sensitive physical forcing factors, such as thermal stratification, coastal wind fields and upwelling intensity (Bakun, 1990; McGowan et al., 1998; Wang et al., 2005; Barross et al., 2014; Bakun et al., 2015; Rykaczewski et al., 2015). Increased stratification (e.g. in response to warmer surface ocean temperatures) will result in decreased nutrient transport into the photic zone, whereas enhanced upwelling intensity (e.g. in response to increased atmospheric temperature gradients) will increase nutrient transport into the photic zone. The latter may also potentially increase offshore transport of nutrients.

In order to understand variability in the productivity of EBUSs, and to predict the potential impact of climate and global change, the relationship between nutrient availability and coastal upwelling processes need to be much better understood than it is at present (Cury and Roy, 1989; Bakun et al., 2010; 2015; Botsford et al., 2006). Coupled physical-biogeochemical models have played a vital role in advancing our understanding of these systems (Skogen, 1999; Qian, 2012; Gutknecht et al., 2013). Such modelling efforts benefit greatly from the availability of climatological data. Data for parameters such as surface ocean temperature and chlorophyll-a levels are relatively easily measured and monitored with remote sensing techniques (Fiúza et al., 1982; Chen et al., 2012; Tim et al., 2015*)*. Construction of comparative climatologies for key biogeochemical parameters such as dissolved oxygen and nutrients, however, require systematic *in situ* sampling. The scarcity of data sets that are appropriate for the construction of biogeochemical climatologies, is problematic. This data gap limits our understanding of upwelling system dynamics (Palacio et al., 2004; Garcia-Reyes e al 2015).

The Benguela Upwelling System (BUS) is located along the south-west coast of Africa (Figure 1). It consists of two parts that differ in their mean seasonality, atmospheric drivers and large-scale climate modes (Agenbag and Shannon, 1988; Tim et al., 2015), the Northern Benguela Upwelling Systems (NBUS) and the SBUS. At least eight discrete upwelling cells have been identified within the BUS (Figure 1; Lutjeharms and Meeuwis, 1987). The Lüderitz cell, in the NBUS, is the major upwelling cell and displays the highest frequency of occurrence and strength (Lutjeharm and Meeuwis, 1987; Gutknecht et al., 2013). The NBUS and the Lüderitz cell have been the subject of numerous, but irregular, biogeochemical research cruises and studies (Dittmar and Birkicht, 2001; Emeis et al., 2004; Kuypers et al., 2005; van der Plas et al., 2007; Mohrholz et al., 2008; Sohm et al., 2011; Noble et al., 2012; Nagel et al., 2013; Flohr et al., 2014;). The SBUS had been monitored for longer and in a more systematic manner than the NBUS, including along the St. Helena Bay Monitoring Line (SHBML) across the Columbine upwelling cell (Figure 1). The monitoring data for the SBUS, however, had been available to a limited extent (Hutchings et al., 2009; Lamont et al., 2015) and most of the bottle data had not been quality controlled or compiled into a distinct long-term monitoring data set. The latter issue had recently been addressed. This biogeochemical monitoring data have now been used to construct both an annual and a seasonal climatology for the SBUS, accompanied by analogous climatologies for temperature, salinity and oxygen, from CTD data.

2 Data processing

2.1 Sampling location, frequency and data availability

The location, bottom depth and sampling depths for the 12 monitoring stations along the SHBML are given in Table 1 and illustrated in Figure 1. The sampling frequency was approximately monthly, with the actual cruise occurrences summarized in Table 2. The months of March and September were sampled every year from 2001 to 2012. The other months were sampled at least 9 times during the 12 year monitoring period, with the exception of November, which was sampled only 4 times. The bottle sampling depths used to construct a climatology for dissolved phosphate (PO_4^{3-} or P), nitrate + nitrite ($NO_3^- + NO_2^-$, or TN), silicate (SiO_2 or Si) and chlorophyll-a (Chl-a) are listed in Table 1. These depths were sampled routinely; depths that were sparsely sampled were not included in the construction of the climatology, to avoid possible bias. CTD data (T, S and O_2) was condensed to 1 m sampling intervals, for the surface-to-bottom depth ranges indicated in

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Table 1. The following data was not used in the construction of the climatologies: (i) CTD data from 2009 to 2012, because of concerns about infrequent sensor calibrations since 2009, (ii) Bottle data for 2001 to 2003, because of concerns about nutrient data quality prior to 2004. The total number of discrete data points used to construct a climatology for each of the parameters are given in Table 3.

CTD data and bottle samples were collected according to published protocols and analytical methods (Lamont et al., 2015; Ismail et al., 2015). CTD measurements were carried out using three different vessels and multiple Sea-Bird Electronics SBE 911 systems according to international standards, including Winkler titrations to calibrate dissolved oxygen profiles (Lamont et al., 2015). Bottle samples for nutrient analysis were collected using the same protocols, and analysed with the same equipment and analytical methods (Astoria Analyzer Series 300; Ismail et al., 2015), over the monitoring period. It is difficult to definitively establish long-term data uncertainty and accuracy over such an extended period of time, for any of the parameters, not least of all because of intrinsic spatial and temporal variability. The most practical method with which to evaluate data uncertainty, for the purpose of constructing this climatology, is crossover analysis of measurements made at the furthest offshore station (Station 12), at depth (1 350 m), where temporal and spatial variability is expected to be small. Since temporal variability cannot be ruled out, this provides an upper estimate of the uncertainty associated with analytical methodologies. The signal-to-noise ratios (calculated as the average/standard deviation, using all measurements at this depth, over the monitoring period) are as follows: ~ 65 for T, ~ 1634 for S, ~ 24 for O_2, ~ 6.5 for P, ~ 15.6 for TN and 17.3 for Si. These values suggest that long-term analytical data uncertainty is appropriate for the construction of a climatology.

2.2 Data reduction and construction of seasonal and annual climatologies

The monthly monitoring data was first reduced to a seasonal climatology for each parameter (X), by calculating average monthly values for each parameter at each of the 12 stations, at each of the depths provided in Table 1 (results illustrated in Figure 2 and 3). The seasonal climatologies were then used to construct annual climatologies for each parameter (results illustrated in Figure 4, 5 and 6), as described below.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

At each of the 12 monitoring stations, every parameter is represented by a set of calculated average monthly values, $X_M[S_i, D_Z]$, at each of the discrete sampling depths listed in Table 1:

$X =$ T = Temperature (°C), S = Salinity (psu), O_2 = Dissolved oxygen (ml O_2 dm^{-3}), P = Dissolved phosphate (µmol P dm^{-3}), TN = Dissolved nitrate + nitrite (µmol N dm^{-3}), Si = Dissolved silicate (µmol Si dm^{-3}), or Chl = Chlorophyll-a (µg dm^{-3})

$S_i =$ Station number (S_1 to S_{12})

$Y_j =$ Year (Y_{first} to Y_{last}; 2001 to 2008 for CTD data, 2004 to 2013 for bottle data)

$M =$ Month (1 to 12, or January to December)

$D_Z =$ Depth (5 m etc. as listed in Table 1, 1 m increments for CTD data)

For Station S_i at discrete sampling depth D_l, the seasonal climatology for parameter X consists of the following 12 monthly average values (for January to December):

$X_{JAN}[S_i, D_Z]$ $X_{FEB}[S_i, D_Z]$ $X_{MAR}[S_i, D_Z]$ $X_{APR}[S_i, D_Z]$ $X_{MAY}[S_i, D_Z]$ $X_{JUN}[S_i, D_Z]$
$X_{JUL}[S_i, D_Z]$ $X_{AUG}[S_i, D_Z]$ $X_{SEP}[S_i, D_Z]$ $X_{OCT}[S_i, D_Z]$ $X_{NOV}[S_i, D_Z]$ $X_{DEC}[S_i, D_Z]$

with $X_M[S_i, D_Z] = \text{AVERAGE}\{X_M[S_i, Y_{first}, D_Z]\ldots\ldots X_M[S_i, Y_{last}, D_Z]\}$

The seasonal climatology is then reduced to an annual climatology for each parameter (X_{ANN}), by calculating the average of the twelve monthly $X_M[S_i, D_Z]$ values (at discrete sampling depths, for each of the 12 stations):

$$X_{ANN}[S_i,D_Z] = \text{AVERAGE}\{X_{JAN}[S_i, D_Z]; X_{FEB}[S_i, D_Z]\ldots X_{DEC}[S_i, D_Z]\}$$

The standard deviation ($X_{sd}[S_i,D_Z]$) associated with the calculated annual averages represents the intra-annual variability in each parameter, i.e. the magnitude and location of variability:

$$X_{sd}[S_i,D_Z] = \text{STANDARD DEVIATION}\{X_{JAN}[S_i, D_Z]; X_{FEB}[S_i, D_Z]\ldots X_{DEC}[S_i, D_Z]\}$$

For each parameter X the annual climatology, as a function of depth along the monitoring transect, is represented by a matrix of values:

$X_{ANN}[S_1, 5]$ $X_{ANN}[S_1, 10]$ $X_{ANN}[S_1, 23]$
$X_{ANN}[S_2, 5]$ $X_{ANN}[S_2, 10]$ $X_{ANN}[S_2, 21]$ $X_{ANN}[S_2, 30]$
$X_{ANN}[S_3, 5]$ $X_{ANN}[S_3, 10]$ $X_{ANN}[S_3, 20]$ $X_{ANN}[S_3, 30]$ $X_{ANN}[S_3, 55]$ $X_{ANN}[S_3, 70]$
$X_{ANN}[S_4, 5]$ $X_{ANN}[S_4, 10]$ $X_{ANN}[S_4, 20]$ $X_{ANN}[S_4, 30]$ $X_{ANN}[S_4, 55]$ $X_{ANN}[S_4, 79]$

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

etc.

The calculated seasonal climatologies for each of the parameters are available as a text file on the PANGAEA database (http://doi.pangaea.de/10.1594/PANGAEA.882218).

3 Description of the climatologies

3.1 Annual climatologies

The annual average and intra-annual variability patterns (i.e. standard deviation) for T, S, O_2 and the dissolved nutrients are illustrated with cross shelf vertical transects, for the upper 600 m, in Figure 4 and 5. The data for chlorophyll-a is plotted to a 40 m depth only (Figure 6). At the surface (5 m depth), temperature ranges from 13.1 to 18.2°C along the 190 km long transect from Station 1 (inshore) to Station 12 (offshore), and salinity from 34.77 to 35.40 (Figure 4). Along the bottom, temperature ranges from 11.3 to 3.0°C, and salinity from 34.77 to 34.65, in an offshore direction. Surface water nutrient concentrations vary from high inshore to much lower levels offshore: 1.55 to 0.36 µmol dm^{-3} for P, 10.6 to 1.4 µmol dm^{-3} for TN and 16.2 to 2.6 µmol dm^{-3} for Si (Figure 4). Surface water chlorophyll-a ranges from values > 8 µg dm^{-3} inshore to < 1 µg dm^{-3} offshore (Figure 6). High chlorophyll-a values (> 3 µg dm^{-3}) are also restricted to the upper ~ 25 m depth interval at the inshore stations. The highest nutrient values, and lowest oxygen levels, are observed in the bottom waters underlying Stations 2 to 5 (Figure 4). The calculated annual climatology for Stations 1 to 5 yield bottom water ranges of 2.0 to 2.5 µmol dm^{-3} for P, 20 to 25 µmol dm^{-3} for TN, and 28 to 33 µmol dm^{-3} for Si. Calculated values for the annual dissolved oxygen climatology in these bottom waters fall within the 1 to 2 ml dm^{-3} range.

Water is known to upwell from a depth of 200 to 300 m in the BUS (Nelson and Hutchings, 1983). The 10°C isotherm shallows from a depth of 293 m at Station 12, to 46 m at Station 4 (Figure 4). If this isotherm is used to trace the flow path of upwelling water, it suggests the following "pre-formed" values (for 10°C water): salinity ~ 34.8, O_2 ~ 4.1 ml dm^{-3}, P ~ 1.3 µmol dm^{-3}, TN ~ 16 µmol dm^{-3}and Si ~ 12 µmol dm^{-3}. At Station 1, the shallowest station, the average nutrient content is 1.68 µmol dm^{-3} for P, 13.1 µmol dm^{-3} for TN and 19.0 µmol dm^{-3} for Si. This is much higher than the values for warm offshore surface water (P = 0.40 µmol dm^{-3}, TN = 1.80 µmol dm^{-3} and Si = 2.88 µmol dm^{-3} for the upper 30 m

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

at Station 12). The average nutrient content of water at Station 1 is also higher, for P and Si, than the "pre-formed" values at a depth of 293 m at Station 12 detailed above. This indicates enrichment of shallow coastal water in P and Si relative to upwelled water, from either land-based sources or from entrainment of the nutrient-enriched bottom water that is present at Stations 1 to 6.

There are considerable spatial differences in intra-annual variability for all the parameters, expressed as the standard deviation associated with calculated annual average values (Figure 5 and 6). However, physical and biogeochemical parameters exhibit distinctly different patterns. Intra-annual variability in temperature and salinity is highest within the upper 100 m of the water column at the offshore stations, while oxygen and the nutrients are more variable at the inshore stations and at sub-surface to bottom water depths. Chlorophyll-a is most variable at shallow depths close to the coast (Figure 6). A detailed evaluation of these zones of high variability, and discussion of the factors responsible, is not the focus of this data discussion. Suffice it to say that areas of high intra-annual variability in temperature and salinity are most likely associated with seasonal changes in the depth of the thermoocline and intrusion of mesoscale features, such as warm, salty Agulhas rings. High variability in the biogeochemical parameters are most likely the result of the seasonal cycle of organic matter production and regeneration.

3.2 Seasonal climatologies

The January to December seasonal climatologies exhibit temporal and spatial variability, for all of the parameters, that are typical of coastal upwelling systems (Figure 2, 3 and 8). The seasonal upwelling cycle is most pronounced at Stations 2, 3 and 4 (Figure 7). The 10^{o}C isotherm in the temperature climatology again serves as a useful indicator of the evolution of the seasonal upwelling cycle. At Stations 4 to 12 the 10^{o}C isotherm is present throughout the water column all year round (Figure 2). At Station 4, the 10^{o}C isotherm reaches its maximum depth (~ 60 m) mid-winter (July), starts to shoal in August and reaches it shallowest depth (~ 30 m) mid-summer (January) (Figure 7). At Station 3, the 10^{o}C isotherm makes it appearance in the bottom waters in August, in September at Station 2, and in October at Station 1. This suggests the timing and evolution of the seasonal upwelling cycle. The deeper 9^{o}C isotherm starts to shoal towards shallower depths even earlier, during the months of May and June, according to the seasonal climatology at Station 4 (Figure 7).

Another pronounced seasonal change evident in the physical water mass parameters, is the movement of an upper ocean warm and salty (S > 34.9) water mass, that migrates closer to shore during the winter months and that is located further offshore in summer (Figure 2).

The mixing of warm, oxygen-rich and nutrient-depleted surface water to deeper depth during winter is a prominent feature in the seasonal climatologies at Stations 2 to 4 (Figure 7). This is followed by the upwelling of nutrient-rich, oxygen-depleted, bottom water, from September onwards. Surface water chlorophyll-a values start to increase with the spring upwelling cycle and is reduced during the winter months (Figure 8). The depth of the chlorophyll-a rich surface layer reaches its deepest depth in early summer, November to December. This period of peak summer productivity evident in the chorophyll-a climatology is followed by a further reduction of oxygen, and enrichment of nutrients, in the bottom waters at the inshore stations in later summer/early autumn (Figure 7), resulting from the respiration of organic matter.

4 Conclusions

Annual and seasonal climatologies constructed from long-term monitoring data exhibit well-resolved spatial and temporal changes. This demonstrates the importance of long-term monitoring efforts, and illustrates what is achievable with systematic sampling and measurement strategies, even for biogeochemical parameters such as dissolved nutrients. This data set can be used to optimize future and ongoing monitoring efforts. It contains a wealth of information for the study of biogeochemical cycles and processes in this and analogous upwelling systems, and it should prove invaluable to coupled physical-biogeochemical modelling efforts.

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Data availability

Data for the constructed climatologies have been made available via the PANGAEA Data Archiving and Publication database at http://doi.pangaea.de/10.1594/PANGAEA.882218.

Author contribution

The author identified the value of the unused archived data sets used in this study, retrieved the data, performed all data rescue tasks such as quality control and data reduction, and conceived of and wrote this manuscript.

Acknowledgements

Numerous present and past employees of the Department of Environmental Affairs and Marine and Coastal Management were involved in sample collection, analysis and data archiving; most notable have been the long-term efforts of Christien Illert, Gavin Tutt and Marcel van der Bergh.

References

Agenbag JJ, Shannon LV. A suggested physical explanation for the existence of a biological boundary at 24°30'S in the Benguela system. S.A.J. Mar. Sci. 6: 119-132 (1988).

Bakun A. Global climate change and intensification of coastal ocean upwelling. Science 247: 198-201 (1990).

Bakun A, Black BA, Bograd SJ, García-Reyes M, Miller AJ, Rykaczewski RR et al. Anticipated effects of climate change on coastal upwelling ecosystems. Curr. Clim. Change Rep. 1: 85-93 (2015).

Bakun A, Field DB, Redondo-Rodriquez A and Weeks SJ. Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. Glob. Change Biol. 16: 1213-1228 (2010).

Barros VR, Field DB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE et al. (eds). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, New York, NY: Cambridge University Press. 688pp. (2014).

Botsford LW, Lawrence CA, Dreyer EP, Hastings A and Largier J. Effects of variable winds on biological productivity on continental shelves in coastal upwelling systems. Deep-Sea Res. Pt. II 53: 3116-3140 (2006).

Chavez FP, Toggweiler JR. Physical estimates of global new production: The upwelling contribution. In Dahlem Workshop on Upwellling in the Ocean: Modern Processes and Ancient Records, Chichester, UK, John Wiley Sons, 313-320 (1995).

Chen Z, Yan X-H, Jo Y-H, Jiang L, Jiang Y. A study of Benguela upwelling system using different upwelling indices derived from remotely sensed data. Cont. Shelf Res. 45: 27-33 (2012).

Cury P, Roy C. Optimal environmental window and pelagic fish recruitment success in upwelling areas. Can. J. Fish. Aquat. Sci. 46: 670-680 (1989).

Dittmar T, Birkicht M. Regeneration of nutrients in the northern Benguela Upwelling and the Angola-Benguela Front Areas. S. Afr. J. Sci. 97: 239-246 (2001).

Emeiss K-C, Brüchert V, Curriec B, Endler R, Ferdelman T, Kiessling A, Leipe T, Noli-Peard K, Struck U, Vogt T. Shallow gas in shelf sediments of the Namibian coastal upwelling ecosystem. Cont. Shelf Res. 24: 627-642 (2004).

Fennel W. Theory of the Benguela upwelling system. J. Phys. Ocean. 29: 177-190 (1999).

Fiúza AF de G, de Macedo ME, Guerreiro MR. Climatological space and time variation of the Portuguese coastal upwelling. Oceanologica Acta 5(1): 31-40 (1982).

Flohr A, van der Plas AK, Emeis K-C, Mohrholz V, Rixen T. Spatio-temporal patterns of C:N:P ratios in the northern Benguela upwelling system. Biogeosciences 11: 885-897 (2014).

Garcia-Reyes M, Sydeman WJ, Schoeman DS, Rykaczewski R, Black BA, Smit AJ, Bograd SJ. Under pressure: climate change, upwelling, and Eastern Boundary upwelling ecosystems. Front. Mar. Sci. 2: 109. Doi: 10.3389/fmars.2015.00109 (2015).

Gutknecht E, Dadou I, Le Vu B, Cambon G, Sudre J, Garçon V, Machu E, Rixen T, Kock A, Flohr A, Paulmier A, Lavik G. Coupled physical/biogeochemical modelling including O_2-dependent processes in the Eastern Boundary Upwelling System: application in the Benguela. Biogeosciences 10: 3559-3591 (2013).

Hutchings L, Van der Lingen CD, Shannon LJ, Crawford RJ, Verheye HMS, Bartholomae CH, van der Plas AK, et al. The Benguala Current: an ecosystem of four components. Prog. Oceanogr. 83: 15-32 (2009).

Ismail HE, Agenbag JJ, de Villiers S, Ximba BJ. Relation between upwelling intensity and the variability of physical and chemical parameters in the Southern Benguel Upwelling System. Int. J. Ocean. Dx.doi.org/10.1155/2015/510713 (2015).

Kuypers MMM, Lavik G, Woebken D, Schmid M, Fuchs BM, Amann R, Jørgensen BB, Jetten MSM. Massive nitrogen loss from the Benguela upwelling system through anaerobic ammonium oxidation. PNAS 102: 6478-6483 (2005).

Lamont T, Hutchings L, van den Berg MA, Goschen WS, Barlow RG. Hydrographic variability in the St Helena Bay region of the southern Benguela ecosystem. J. Geophys. Res: Oceans 120: 2920-2944, doi:10.1002/2014JC010619 (2015).

Lutjeharms JRE and Meeuwis JM. The extent and variability of South-East Atlantic upwelling. S.Afr. J. Mar. Sci. 5: 51-62, doi:10.2989/025776187784522621 (1987).

Mohrholz V, Bartholomaeb CH, van der Plas AK, HU Lass HU. The seasonal variability of the northern Benguela undercurrent and its relation to the oxygen budget on the shelf. Cont. Shelf Res. 28: 424-441 (2008).

Nagel B, Emeis K-C, Flohr A, Rixen T, Schlarbaum T, Mohrholz V, van der Plas A. N-cycling and balancing of the N-deficit generated in the oxygen minimum zone over the Namibian shelf – an isotope-based approach. J. Geophys. Res: Biogeosci. 118: 361-371 (2013).

Nelson G, Hutchings L. The Benguela Upwelling Area. Prog. Oceanog. 12: 333-356 (1983).

Noble AE, Lamborg CH, Ohnemus DC, Lam PJ, Goepfert TJ, Measures CI, Frame CH, Casciotti KL, DiTullio GR, Jennings J, Saito MA. Basin-scale inputs of cobalt, iron, and manganese from the Benguela-Angola front to the South Atlantic Ocean. Limnol. Oceanogr. 57: 989-1010 (2012).

Qian S. Construction of a high resolution biogeochemical climatology for Eastern Boundary Upwelling System: Case Study in Canary Upwelling System. Masters Thesis, ETH Zurich (2012).

Palacios DM, Bograd SJ, Mendelssohn R, Schwing FB. Long term and seasonal trends in stratification in the California Current, 1950-1993. J. Geophys. Res. 109: C10016, doi:10.1029/2004JC002380 (2004).

Rykaczewski RR, Dunne JP. Enhanced nutrient supply to the California Currrent Ecosystem with global warming and increased stratification in an earth system model. Geophys. Res. Lett. 37: L21606. doi:10.1029/2010GL045019 (2010).

Sohm JA, Hilton JA, Noble AE, Zehr JP, Saito MA, Webb EA. Nitrogen fixation in the South Atlantic Gyre and the Benguela Upwelling System. Geophys. Res. Lett. 38: 1-6, doi:10.1029/2011GL048315 (2011).

Tim N, Zorita E, Hünicke B. Decadal variability and trends of the Benguela upwelling system as simulated in a high-resolution ocean simulation. Ocean Sci. 11: 483-502 (2015).

Van der Plas AK, Monteiro PMS, Pascall A. Cross-shelf biogeochemical characteristics of sediments in the central Benguela and their relationship to overlying water column hypoxia. Afr. J. Marine Sci. 29: 37-47 (2007).

Wang D, Gouhier TC, Menge BA, Ganguly AR. Intensification and spatial homogenization of coastal upwelling under climate change. Nature 518: 390-394 (2015).

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Figure 1: The Benguela Upwelling System (shaded green area), off the west coast of southern Africa. The upwelling cells identified by Lutjeharms and Meeuwis (1987) are indicated by the stippled yellow lines. The St Helena Bay Monitoring Line (SHBML) is indicated by the line of green circles, representing the 12 monitoring stations; the shelf bathymetry along this line and the sample bottle depths used to construct climatologies for nutrients and chlorophyll-a, are shown in the inset.

Figure 2: Monthly climatologies for temperature, salinity and oxygen.

Figure 3: Monthly climatologies for P, N and Si.

Figure 4: Cross-shelf transects for the annual climatology of the parameters temperature, salinity, dissolved oxygen and the three dissolved nutrients, constructed as outlined in the text. Data is plotted for the upper 600 m only, to accentuate the upper ocean gradients.

Figure 5: Cross-shelf transects for intra-annual variability, or the standard deviation associated with the annual averages for temperature, salinity, dissolved oxygen and the three dissolved nutrients.

Figure 6: Annual climatology and intra-annual variability, expressed as the standard deviation, for chlorophyll-a along the SHBML, shown for the upper 40 m of the water column only.

Figure 7: Seasonal changes, as a function of depth, in temperature, dissolved oxygen, phosphate and nitrate + nitrite, for Stations 2, 3 and 4, constructed as discussed in the text.

Figure 8: Average chlorophyll-a profiles along the SHBML, illustrated for each month and the upper 50 m of the water column

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Table 1: Monitoring station locations, bottom depth, standard bottle sampling depths and CTD depth ranges used to construct the climatology

Station	LAT (°S)	LONG (°E)	Bottom (m)	Offshore distance (km)	Standard bottle depths (m)	CTD depth range (m)
1	32.300	18.311	27	3	5 - 10 - 23	5 - 23
2	32.310	18.273	32	7	5 - 10 - 21 - 30	5 - 30
3	32.332	18.178	77	16	5 - 10 - 20 - 30 - 50 - 70	5 - 70
4	32.374	17.991	107	35	5 - 10 - 20 - 30 - 50 - 79	5 - 100
5	32.416	17.809	152	53	5 - 10 - 20 - 30 - 50 - 73 - 100	5 - 145
6	32.464	17.611	192	73	5 - 10 - 20 - 30 - 50 - 75 - 100 - 150 - 180	5 - 180
7	32.502	17.422	244	92	5 - 10 - 20 - 30 - 50 - 100 - 235	5 - 235
8	32.573	17.194	285	115	5 - 10 - 20 - 30 - 50 - 100 - 200 - 275	5 - 275
9	32.618	16.991	310	134	5 - 10 - 20 - 30 - 50 - 100 - 200 - 305	5 - 305
10	32.661	16.804	392	153	5 - 10 - 20 - 30 - 100 - 370	5 - 370
11	32.706	16.622	560	172	5 - 10 - 20 - 30 - 100 - 540	5 - 540
12	32.745	16.434	1 465	190	5 - 10 - 20 - 30 - 100 - 1 350	5 - 1 350

Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Table 2 SHBML monitoring cruises occurrences, from 2001 to 2012

YEAR	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
2001	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
2002	yes	no	yes	yes	yes	yes	no	no	yes	yes	yes	yes
2003	yes	yes	yes	no	yes	yes	yes	yes	yes	yes	no	yes
2004	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes	yes
2005	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
2006	yes	yes	yes	yes	yes	yes	no	yes	yes	yes	no	yes
2007	yes	yes	yes	yes	yes	no	yes	yes	yes	yes	no	yes
2008	yes	yes	yes	no	yes	yes	no	yes	yes	yes	yes	no
2009	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
2010	yes	yes	yes	yes	no	yes	yes	yes	yes	yes	no	no
2011	no	yes	yes	no	yes	yes	yes	yes	yes	no	no	yes
2012	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	no

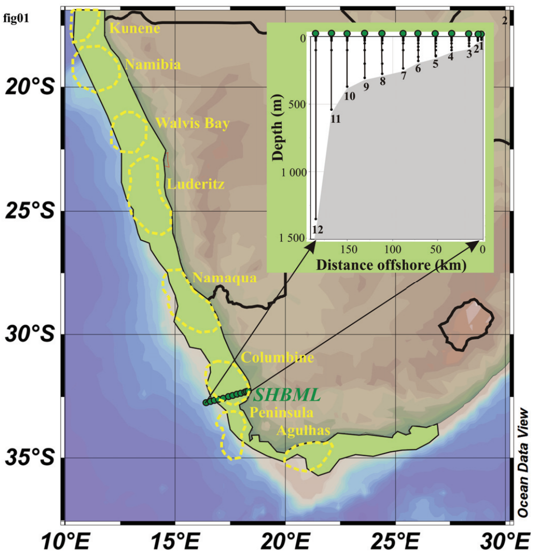
Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Table 3 Number of discrete measurements used to construct a climatology for each of the parameters (as discussed in the text, data from 2004 to 2012 for nutrients and chl-a; and CTD data from 2001 to 2008).

Station	**PO_4^{3-}**	**$NO_3^- + NO_2^-$**	**SiO_2**	**Chl-a**	**CTD** (T, S and O_2)
1	231	231	231	216	1 536
2	293	293	293	261	2 016
3	406	409	409	287	6 336
4	413	414	414	279	9 216
5	460	460	460	276	13 536
6	483	483	483	284	16 896
7	509	509	509	282	22 176
8	519	519	519	279	26 016
9	516	513	517	276	28 896
10	546	537	550	274	35 136
11	540	535	540	231	51 456
12	543	539	543	237	129 216
TOTAL	**5 459**	**5 442**	**5 468**	**3 182**	**342 432**

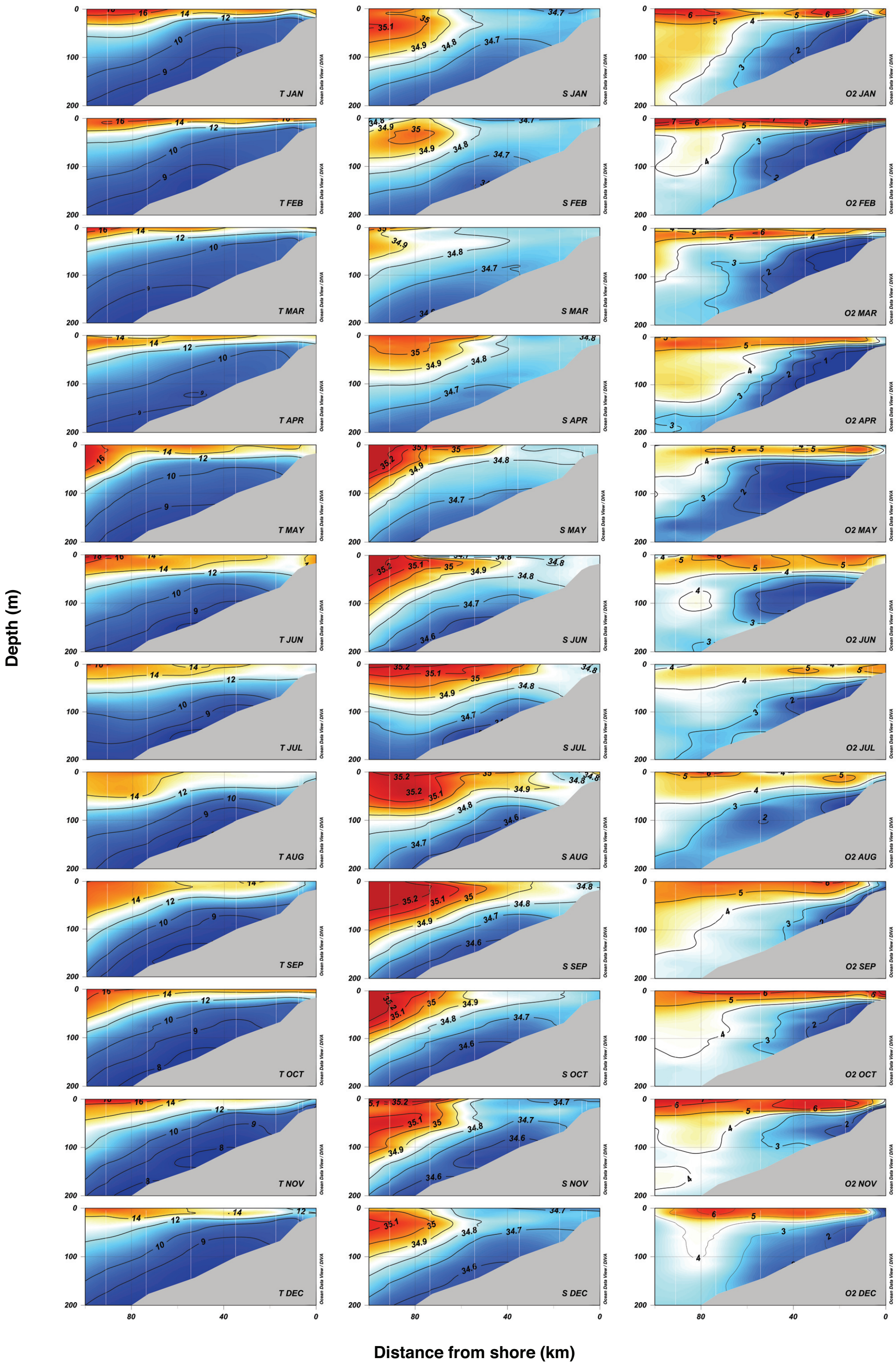
Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

fig01



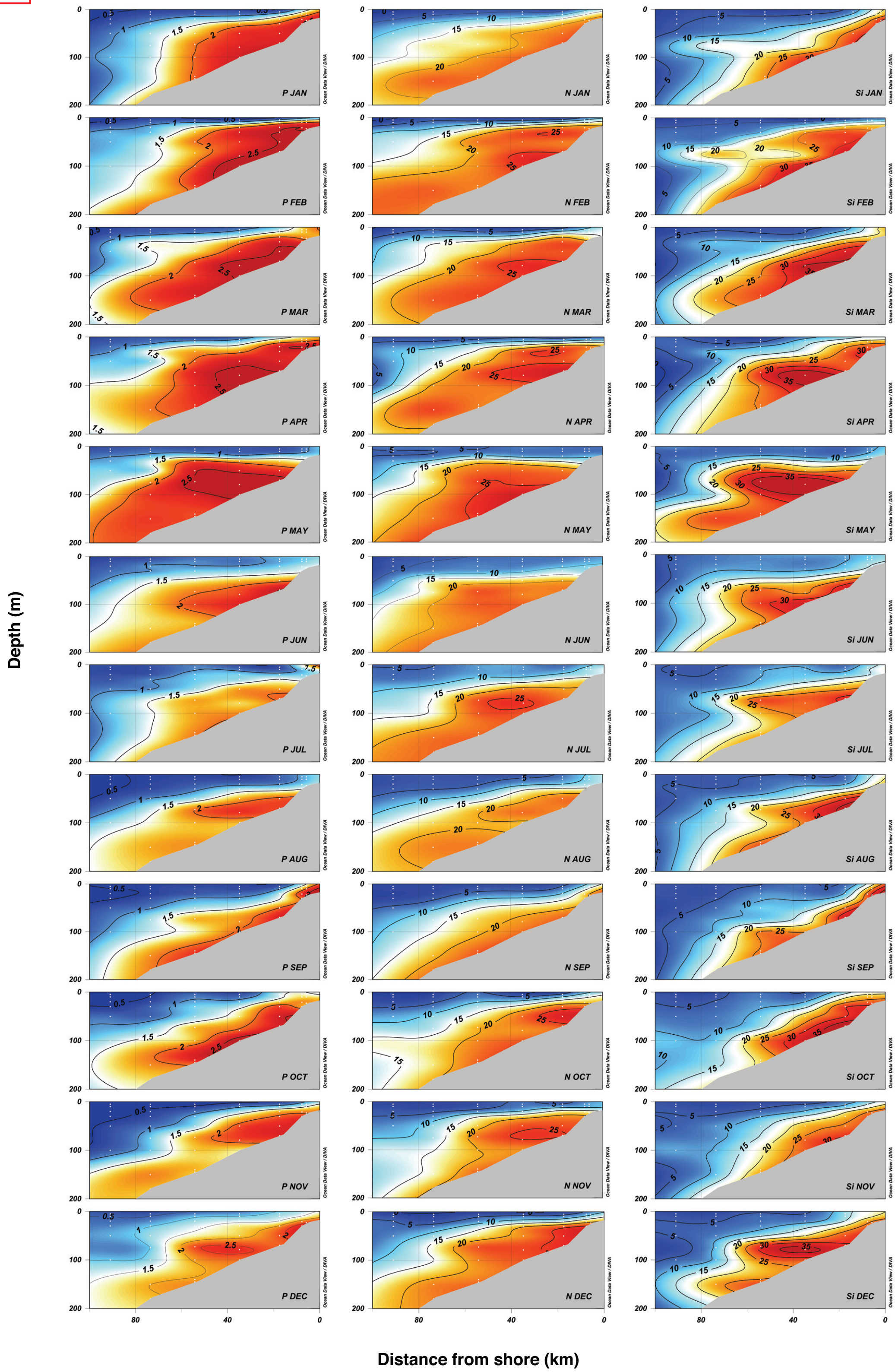
Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

fig02



Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

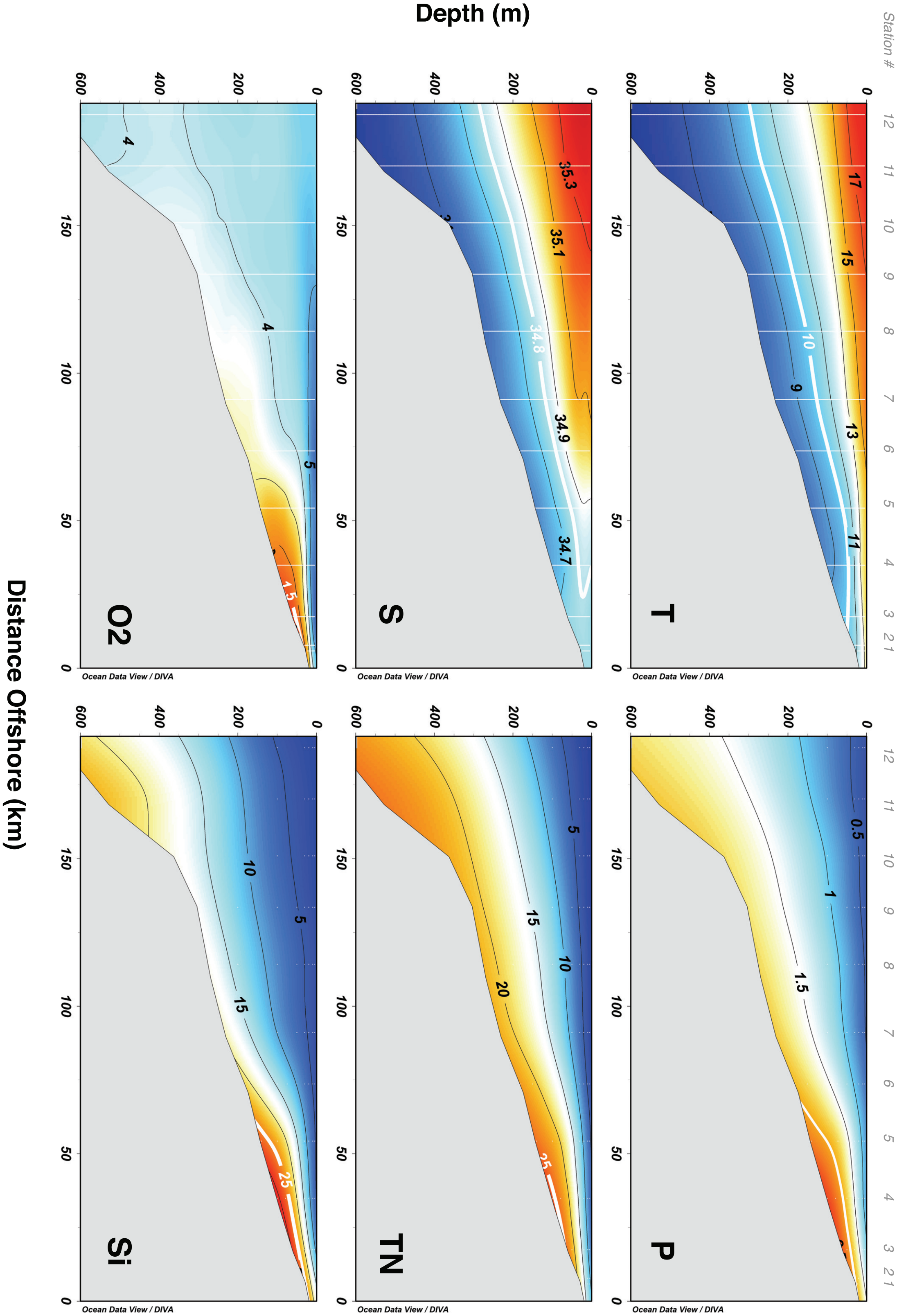
fig03



Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Open Access Earth System Science Data Discussions

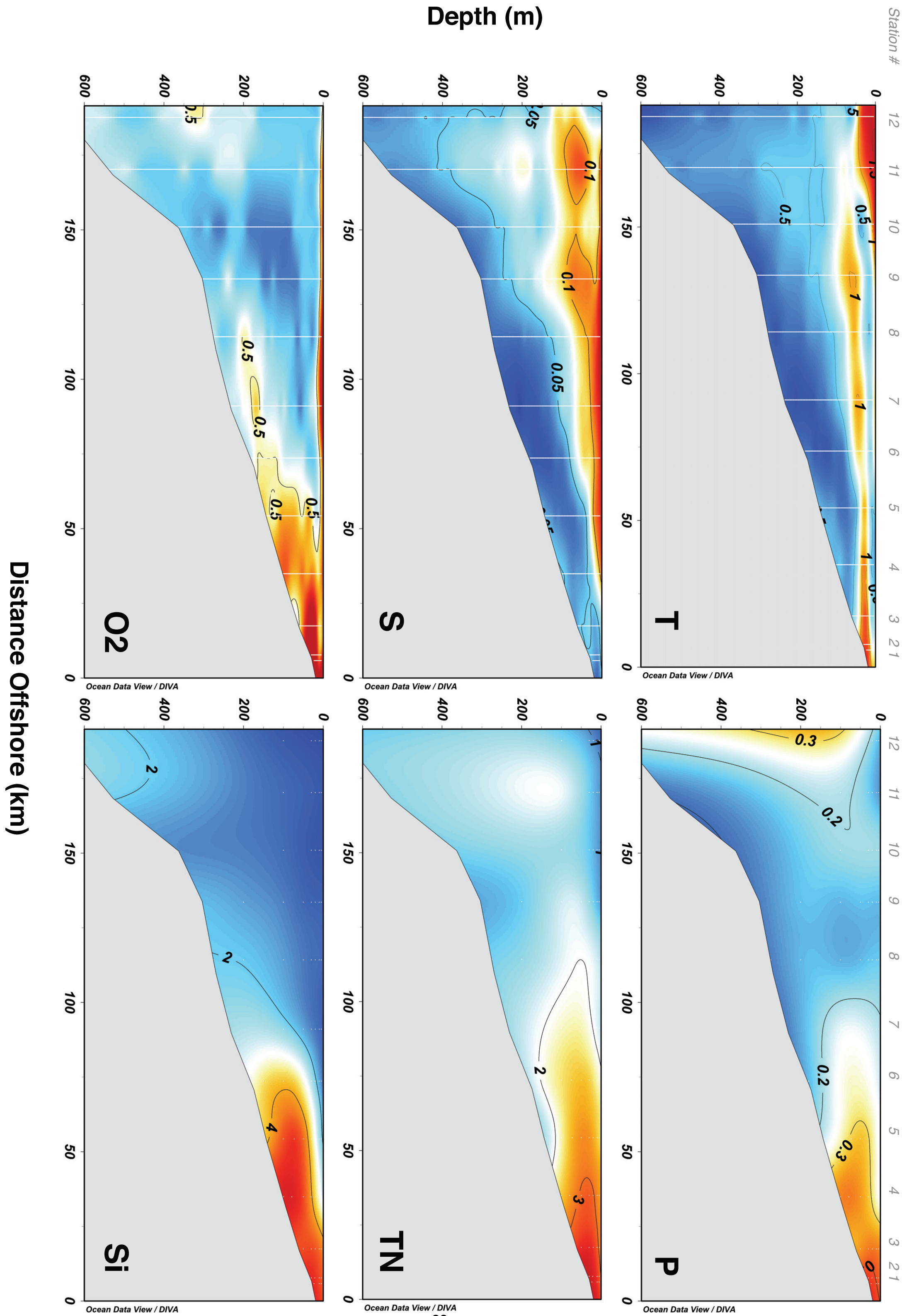
fig04



Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

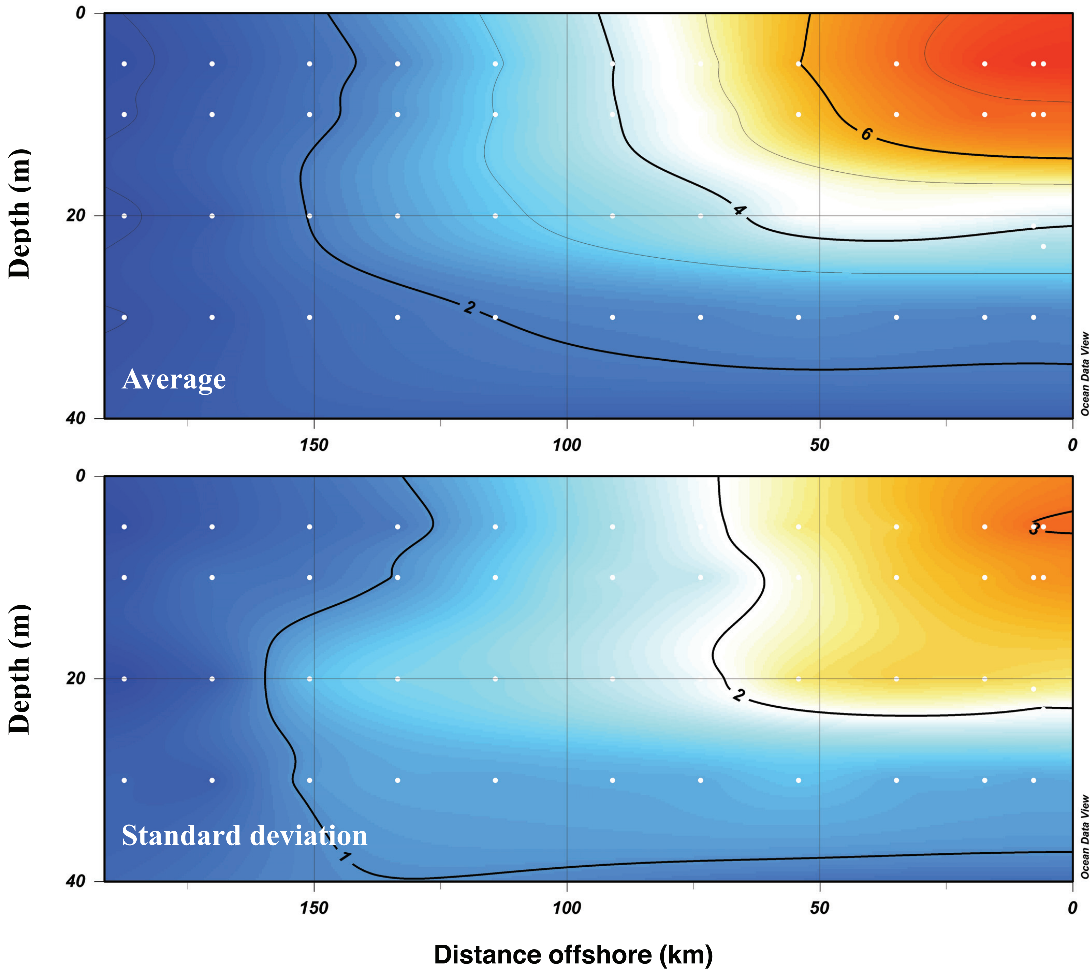
Open Access Earth System Science Data Discussions

fig05



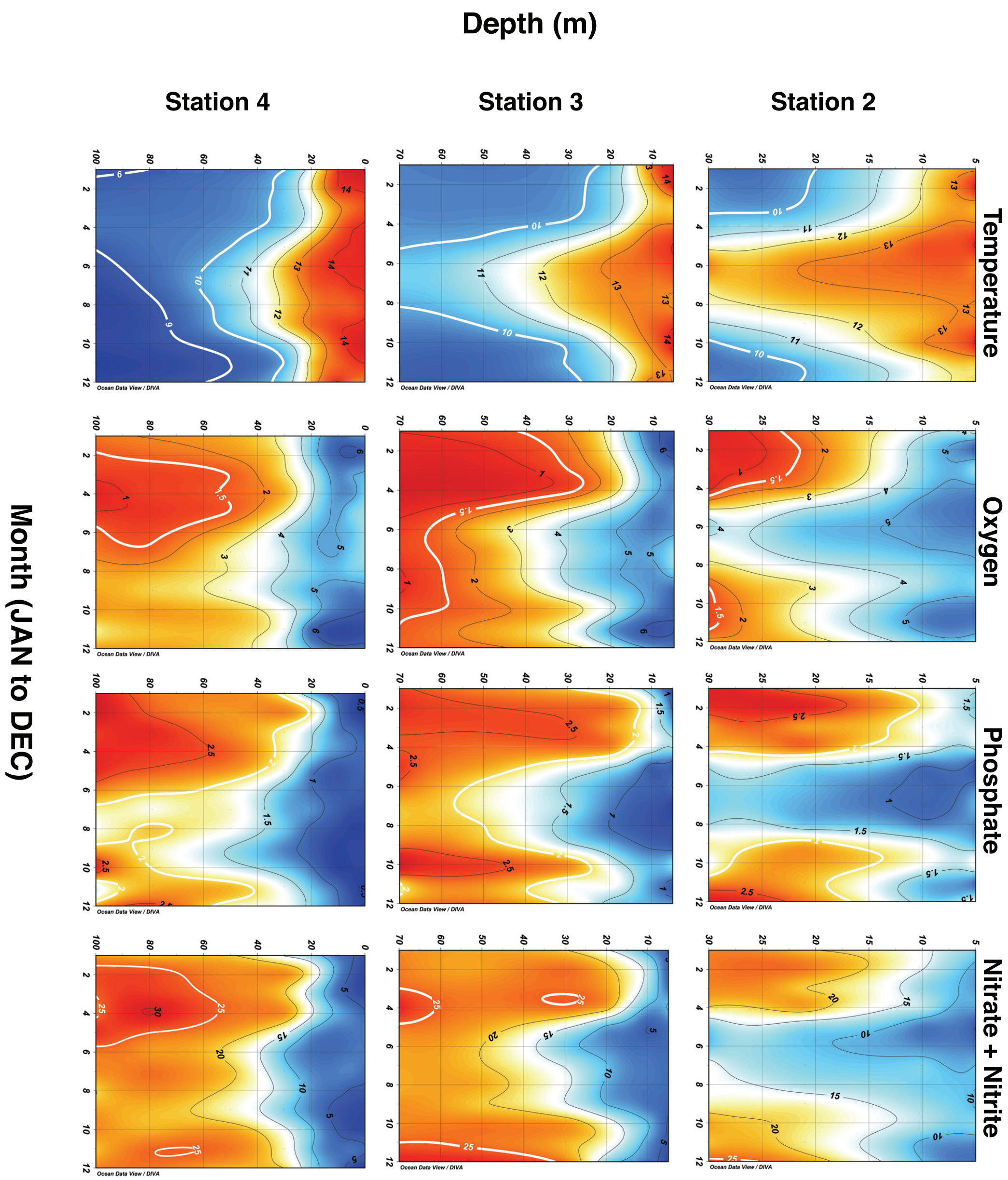
Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

fig06



Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

fig07



Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-60
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 18 May 2018

Open Access Earth System Science Data Discussions

fig08