Ocean Sci. Discuss., 6, 1173–1192, 2009
www.ocean-sci-discuss.net/6/1173/2009/

Ocean Science
Discussions

Carbon export and sequestration in the southern Benguela upwelling system: lower and upper estimates

H. N. Waldron[1], **P. M. S. Monteiro**[1,2], **and N. C. Swart**[1,*]

[1]Department of Oceanography, University of Cape Town, Rondebosch 7700, South Africa
[2]Ocean Systems & Climate Group, CSIR, P.O. Box 320, Stellenbosch 7599, South Africa
[*]now at: Earth and Ocean Science, University of British Columbia, 6339 Stores Road, Vancouver, V6T 1Z4, Canada

Received: 15 May 2009 – Accepted: 12 June 2009 – Published: 25 June 2009

Correspondence to: H. N. Waldron (howard.waldron@uct.ac.za)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Three independent studies of carbon export and sequestration in the southern Benguela upwelling system are presented. They were undertaken by Waldron (upwelling index), Monteiro (discrete upwelling centres – gate hypothesis model) and Swart (cross-shelf advection in bottom nelpheloid layers). The annual estimates were, 3.9×10^{13}, 0.72×10^{13} and 8.6×10^{11} gC respectively. The lowest estimate was derived from a consideration of low frequency lateral carbon export in the bottom nepheloid layer and was thought likely to be an under-estimate. Taking into account high frequency episodic events, intermediate nepheloid layers and along isopycnal export of DOC at surface and intermediate depths was thought likely to result in a substantial upward revision. The remaining two estimates were considered to be an upper and lower estimate of carbon export and sequestration due to factors inherent in the methodologies. The upper estimate presents a two-dimensional system, integrated alongshore; the lower estimate sums a series of upwelling centres in order to obtain a system flux. The former is therefore a uniform extrapolation along the coast while the latter omits upwelling between the upwelling centres.

1 Introduction

Approximately 93% of the world ocean can be defined as open ocean, having a nutrient-limited euphotic zone and low primary productivity and biomass. The remaining 7% are the continental margins having seasonal or sub-seasonal inputs of nutrients accompanied by high rates of primary production and biomass. The former occurs in shelf seas and the latter in upwelling systems. Eastern boundary upwelling systems cover 1% of the ocean surface area but are estimated to account for 11% of new production fluxes (Chavez and Toggweiler, 1995; Monteiro, 2009). Significant primary productivity and new production fluxes in coastal systems translate into a relatively high proportion of the CO_2 uptake by the coastal oceans ($0.36\,\mathrm{Gt\,C\,y^{-1}}$ cf global sink of 1.8±0.7 Gt C y^{-1} ~15%) (Doney et al., 2009; Chen and Borges, 2009).

Previous studies have upheld the view that the modest areal extent of the ocean margins account for a disproportionately large fraction of total ocean productivity (Walsh et al., 1981; Wollast, 1998; Chen et al., 2003; Rullkötter, 2000; Falkowski et al., 2003). Since the early 1980s there has been a combination of conjecture, experimental research and rejected hypotheses relating to the continental margin's role in the export of carbon. In respect of the NE USA, estimates of carbon export from shelf to slope have varied from 50% of unconsumed biological material (Walsh et al., 1981; Malone et al., 1983), later revised to <20% of primary production (Rowe et al., 1986) and subsequently <5% (Biscaye et al., 1994). These studies neglected to consider the substantial pool of dissolved organic carbon (DOC). Hopkinson Jr. et al. (2002) asserted that the DOC pool represented the most significant organic carbon reservoir in the ocean and that shelf export of DOC could be large. Chen et al., (2003) distinguished between recycling and export margins on the basis of shelf topography and residence time versus major coastal upwellings. It was further stated that continental shelves are net sinks for atmospheric CO_2, and that where export occurs, it is dominated by fluxes in the DOC pool. Recent re-assessments of the role of coastal systems have clarified the basis of a controversy on the magnitude of their CO_2 fluxes (Chen and Borges, 2009).

The Benguela upwelling system is an ideal system to explore this question because of its meridional contrasts in ocean-atmosphere CO_2 fluxes (Monteiro, 2009; Santana-Casiano et al., 2009). Recent syntheses have shown the southern Benguela to be a net sink of atmospheric CO_2 and this is likely to be linked to the magnitude of the carbon export across the ocean-shelf boundary (Waldron et al., 1997; Monteiro, 2009). The Benguela upwelling system, the subject of this study, has been shown to have a significant lateral carbon export in the bottom nepheloid layer (Monteiro, 2005; Inthorn et al., 2006). It is the hypothesis of this study that the contrasting CO_2 sink and source characteristics of the southern and northern Benguela are a reflection of the magnitude of the proportion of the new production fluxes that are exported across the ocean-shelf boundary. The magnitude of this flux for the southern Benguela sub-system is constrained in this study.

Three different methods of assessing carbon export in the southern Benguela upwelling system are summarized here. The first adopts an approach that is regional in space and annual in time using an upwelling index and fluxes of nitrate (converted to carbon), the second compartmentalizes the upwelling space scale into those of discrete centres and takes into account transports of dissolved inorganic carbon (DIC), and particulate and dissolved organic carbon (POC and DOC). The third models cross-shelf advection of POC in the bottom nepheloid layer and recognizes the importance of DOC flux. It is our contention that the estimates of carbon export presented here represent lower and upper boundaries.

2 Methods and results

The detail of the methods for the three different approaches have been fully described in Waldron et al. (1997), Waldron et al. (1998), Monteiro (1996) and Swart (2008) but the essence of each is described briefly below:

2.1 Waldron: upwelling index

A two-dimensional network of NO3-N (and subsequently carbon) pathways between open ocean, shelf and sediments is shown in Fig. 1.

"A" is upwelling source water (South Atlantic central Water).

"B" is shelf re-cycled nitrate.

"C" represents the southern Benguela annual potential new production (APNP).

"D" is the proportion of APNP that is advected offshore (in surface waters) and, ultimately, sequestrated below the permanent thermocline.

"E" is the proportion of APNP that sinks over the shelf.

“F” is the proportion of “E” that is sequestrated in shelf sediments. NB the remaining proportion of “E” is re-cycled (pathway “B”).

Budgetary considerations at the annual scale indicate simple algebraic linkages between these variables:

$$\text{“C”} = \text{“A”} + \text{“B”} \tag{1}$$

$$\text{“C”} = \text{“D”} + \text{“E”} \tag{2}$$

$$\text{“E”} = \text{“F”} + \text{“B”} \tag{3}$$

If estimates can be given for, say pathways “C”, “B” and “D” then pathways “A”, “E” and “F” can be solved by algebraic substitution.

“C” – southern Benguela Annual Potential New Production

Over a period of a year, upwelling occurs as a series of events. Event-scale upwelling can be identified from satellite images of sea surface temperature (SST). A relationship was established between SST and nitrate integrated over a nominal euphotic zone (30 m). Therefore from satellite imagery it was possible to estimate the quantity of nitrate per event. Upwelling events are meteorologically-forced. This triggers a response in the sea level (a coastal trapped wave). Event-scale sea level fluctuation (tide gauge data filtered of tide and atmospheric pressure) was related to event-scale nitrate (from satellite imagery) and could hence be used as an upwelling proxy to estimate annual fluxes of nitrate.

$$\text{“C”}=5.6\ (3.9\text{–}7.3)\times 10^{13}\,\text{gC year}^{-1}$$

“B” – Shelf re-cycled nitrate.

SACW has a median nitrate signature of 14 mmol m^{-3} (10–18 mmol m^{-3}) and water which upwells after nitrate enhancement has a mean nitrate signature of

20(±4) mmol m^{-3}, therefore, assuming that the nitrate concentration difference between SACW and water which upwells remains more or less fixed within their respective ranges, about 30% of "C" can be considered Local Potential New Production.

"B"=1.7 (1.2–2.2)×10^{13} gC year^{-1}

"D" – APNP advected offshore.

Satellite images of SST during upwelling events made it possible to quantify the amount of euphotic zone nitrate present seaward of the shelf edge (via the relationship between SST and integrated nitrate). It was found that on an event-scale, a maximum of 12.5% of the potential new production was occurring outside the system boundary. A mean of 3.6% was applied at the annual-scale (from an admittedly wide range of 0%–12.5%). This pathway is de-coupled from the other pathways in the system and when substituting "D" in the calculation of the range of "E", and hence "F", a conservative approach has been adopted.

"D"=0.2 (0.0–0.7)×10^{13} gC year^{-1}

These three estimates can be substituted in Eqs. (1), (2) and (3) to give calculated estimates of the remaining three variables:

"A"=3.9 (2.7–5.1)×10^{13} gC year^{-1}

"E"=5.4 (3.2–7.3)×10^{13} gC year^{-1}

"F"=3.7 (1.0 to 6.1)×10^{13} gC year^{-1}

In summary, the above estimates suggest that the southern Benguela has the potential to export (and sequestrate) 3.9×10^{13} gC year^{-1} (i.e. "F"+"D").

2.2 Monteiro: discrete upwelling centres – gate hypothesis model

This study considered the entire Benguela system and the complete picture is presented at the conceptual level with a subsequent focus on the southern Benguela in respect of carbon export estimates Monteiro, 2009; 1996). The model adopted a published typology of upwelling centres that were summed to provide system and subsystem fluxes (Lutjeharms and Meeuwis, 1987). The model was forced by event-scale resolving hourly wind-stress at each upwelling centre over two contrasting years: 1992 and 1994 (Monteiro, 1996).

The whole Benguela system is shown in Fig. 2 and the model-derived southern system carbon fluxes are depicted in Fig. 3 using the Liu et al. (2000) typology. The whole system has six upwelling centres from Cape Frio in the north to Cape Point in the south. The northern sub-system comprises the Lüderitz, Walvis Bay and Cape Frio upwelling centres, whereas the southern sub-system, which is the focus of this study, comprises the Cape Peninsula, Cape Columbine and Namaqua upwelling centres (Fig. 2), which define the aggregated fluxes in Fig. 3.

The basis for the "Gate" hypothesis was that there are preferred input points of South Atlantic Central Water (SACW) from the slope onto the shelf as opposed to generalized upwelling across the length of the shelf boundary. The basis for this has been strengthened by a recent calculation of the spatial characteristics of the regional wind stress curl that showed enhanced magnitudes at the Cape Frio, Lüderitz and Cape Columbine upwelling centres (Monteiro et al., 2005; Lass and Mohrholz, 2008). There is a subtlety regarding the inflow of SACW that precludes its inflow at Cape Columbine appearing overtly in Fig. 2. The SACW that enters the shelf in the vicinity of Cape Columbine through the Oliphants River Canyon (Dingle and Nelson, 1993) has identical characteristics to that which is advected across the ocean-shelf boundary at Lüderitz. For this reason the model was simplified to have fewer boundaries and the ocean-shelf exchange at Cape Columbine was removed. Each sector has an inflow of fresh SACW and an outflow of shelf-modified SACW. Each inflow acts as a "gate," limiting the further poleward advection of SACW from the northerly sector. Water does not outcrop at each upwelling centre directly from the slope, but as a 2-step process. Once through the "gate," SACW is entrained into a poleward flow and the part which outcrops is the inner shelf water. In terms of carbon flux, this implies that the biogeochemical characteristics of upwelled waters are governed by the distance of the upwelling centre from the "Gate" rather than pre-formed characteristics of SACW and that carbon (POC and DOC) may be exported off the shelf to the slope at preferential sites.

The fluxes shown in Fig. 3 are million tons carbon per year. The blue arrows represent dissolved inorganic carbon (DIC), the magenta arrows represent nepheloid fluxes of particulate organic carbon (POC) and the dotted green arrows represent fluxes of dissolved organic carbon. The results show that there is a substantial import of DIC but, by comparison, lesser exports of POC and DOC. The fluxes calculated from measurements and an Ekman model indicate that 1340 m Tons DIC per year are transported from the outer to inner shelf (C2 to B2) but only 117 m Tons per year are upwelled (B2 to B1). In order to compare equivalent fluxes between the Waldron and Monteiro approaches:

- Waldron's "C" (southern Benguela annual potential new production) of 5.6×10^{13} gC per year is equivalent to Monteiro's (B1 to B2)+(C1 to C2 to D2)=$(6.33+6.2)\times10^{12}=1.35\times10^{13}$ gC per year.
- Waldron's export (and sequestration) estimate of "F"+"D" (3.9×10^{13} gC year^{-1}) is equivalent to Monteiro's (B2 to B3)+(C2 to D2)=$(1.04+6.2)\times10^{12}=0.72\times10^{13}$ gC per year.
- Swart: Cross-shelf advection in bottom nelpheloid layers

This study undertook to identify where in the water column shelf-ocean carbon exchange might occur, and to quantify the magnitude of such exchanges in the southern Benguela.

The methodology combined measurements of, inter alia, POC, turbidity and dissolved organic carbon (DOC) at 12 discrete stations spaced across the shelf and slope. A five year monthly time-series of turbidity revealed bottom nepheloid layers (BNLs) to be the preferential sites of particulate matter accumulation and perennial features of the southern Benguela shelf. Measurements on three separate occasions showed these bottom nepheloid layers to also be enriched in organic carbon relative to the surrounding waters (Fig. 4). Statistically significant regressions and correlations between POC and turbidity were established in these bottom waters and it was thus possible to use routinely measured turbidity as a proxy for seldom measured POC. There was a difference between summer and winter relationships. The summer relationship (March) was $y=82x+42.7$ and the winter (obtained from two cruises (June and August) was $y=4.5x+22.9$; where x=turbidity and y=POC (μg liter^{-1}). Note that units for turbidity were relative, being the light-scattering output from the sensor mounted on the CTD. Thus the longer time series of turbidity was used to address the lateral transport of POC in the bottom nepheloid layer. A space vs. time Hoffmueller plot of turbidity 15.5 m off the bottom (Fig. 5) suggests that cross-shelf propagation of particulate material occurred in time (seasonal changes in particulate matter supply or bottom turbulence regimes cannot explain the pattern). A simple analytical model, based on the observed cross-shelf decay rate, estimated the annual off-shelf flux of POC in the BNL as 5.9×10^{10} gC yr^{-1} (see Swart, 2008 for details). The measured shelf-ocean DOC gradient was used to crudely estimate the potential DOC export in the BNL as 8×10^{11} gC yr^{-1}. Along-isopycnal export of DOC throughout the water column was recognized as a potentially important process, but was not assessed. The main conclusions from this study were that BNLs are regions of preferential organic matter accumulation and decay in the water column; DOC concentrations are often orders of magnitude greater than POC concentrations, with correspondingly greater BNL export rates, and the lateral carbon export in the BNL achieves about 25% of that required to make the southern Benguela system carbon neutral with respect to the atmosphere.

3 Discussion

3.1 The magnitude of the boundary fluxes in the southern Benguela

The carbon export results for the southern Benguela upwelling system from the approaches given above can be summarized as follows:

Waldron: 3.9×10^{13} gC year^{-1}.

Monteiro: 0.72×10^{13} gC year^{-1}.

Swart: 8.6×10^{11} gC year^{-1}; alternatively 0.86×10^{12} gC year^{-1}.

An independent assessment of the Waldron and Monteiro estimates conducted by G. B. Brundrit, University of Cape Town (personal communication, 1997) stated: "Two models are presented. The first (Waldron) is solely two-dimensional, being integrated longshore. The second (Monteiro) breaks the Benguela system into a series of upwelling centres, treating them separately and adding the results together for a system flux. The two models are complementary in that the first provides an upper bound and the second provides a lower bound for the fluxes." After conducting calculations based on water fluxes it was further stated: "Given the different approaches taken, the values are remarkably similar. Waldron's value could be expected to be on the high side given the uniform extrapolation along the coast. Monteiro's value could be expected to be on the low side given the omission of upwelling between the centres. It is therefore reasonable to use them as upper and lower bounds respectively for the southern Benguela upwelling, and then to compare with the results from (the) other regions."

At this stage it is a worthwhile exercise to examine (in the context of other studies) the estimate of southern Benguela annual potential new production (5.6×10^{13} gC year^{-1}) provided by Waldron.

- Extrapolating daily ^{15}N uptake measurements from a series of research cruises in new, mature and aged upwelling waters of the southern Benguela to the regional scale gave a mean annual new production rate of 1.4×10^{13} gC year^{-1} (Waldron et al., 1997).

- Total primary production for the southern Benguela has been estimated as 7.64×10^{13} gC year^{-1} (Brown et al., 1991). The Waldron estimate of annual potential new production from this study implies an "f"-ratio of 0.73.
- The daily rate for total primary production obtained from ^{14}C uptake studies in the Cape Columbine/St. Helena Bay region of the southern Benguela (Shannon and Field, 1985) was approximately 4.0 gC m^{-2} d^{-1}. Expressing the results of this study in the same units gave a rate of 2.87 gC m^{-2} d^{-1} implying an "f"-ratio of 0.72.

These comparisons and the associated f-ratios confirm that 5.6×10^{13} gC year^{-1} is an estimate of potential new production rather than new production per se. In addition to this assessment, the Waldron estimate of annual potential new production ("C"=5.6 $(3.9–7.3)\times10^{13}$ gC year^{-1}) is likely to be an overestimate for reasons inherent in the methodology. In the southern Benguela, upwelling is seasonal, occurring mainly in the Spring and Summer months (nominally, September to January inclusive). Upwelling favourable winds do blow during other periods but with less frequency and intensity. The upwelling index did not exclude the Winter months and an adjustment to take this into account leads to a revised estimate of 4.2 $(2.9–5.5)\times10^{13}$ gC year^{-1}. It should also be noted that the estimate assumes the complete utilization of upwelled nitrate (hence the term "potential new production"). One could argue that new production resulting from the assimilation of this nitrate can be attributed to the southern Benguela even if it occurs over longer time scales outside the system boundary.

The magnitude of the flux estimated by Swart (2008) is around 2% of the figure given by Waldron, and around 10% that of Monteiro. It should be emphasized that the estimate of Swart pertains only to lateral carbon export in the bottom nepheloid layer, the preferential site of detrital accumulation in the southern Benguela. Thus Swart's figures are useful as an indication of the importance of the BNL, rather than an estimate of the total lateral carbon flux. Further, the monthly sampling of Swart was only able to resolve low frequency off-shelf advection of organic matter. High frequency pulses of organic matter export induced by turbidity currents or rapid, episodic downwelling events were not taken into account. Therefore 0.8×10^{12} gC year^{-1} is likely an underestimate, and indicates that the true lateral export in the BNL could form a significant fraction of the total carbon export from the southern Benguela. Lateral export by intermediate nepheloid layers, as observed by Inthorn et al. (2006), and along isopycnal export of DOC at surface and intermediate depths, could likely account for the remaining discrepancy in the figures of Swart and Waldon/Monteiro.

3.2 The link between CO2 sink and ocean – shelf exchange

The importance of shelf – ocean POC and DOC carbon export fluxes lies in the role that they play in determining the magnitude of the net sink for atmospheric CO_2 on the shelf system. The southern Benguela upwelling system covers an area which is approximately 0.3% of the global shelf area and a comparable fraction of the global shelf CO_2 uptake from the atmosphere (Chen and Borges, 2009).

The box model output shows the southern Benguela to be a sink of CO_2 with an annual magnitude of 1.7 Mt C (Fig. 3), which is a small fraction of the global shelf CO_2 sink of 360 MtCy^{-1} (Chen and Borges, 2009). However, the area specific fluxes for the southern Benguela (16.3 gC m^{-2} year^{-1}) are comparable in magnitude to other upwelling and shelf systems (Chen and Borges, 2009; Santana-Casiano et al., 2009). A sensitivity analysis undertaken with the model showed that the magnitude of the CO_2 sink is sensitive to the fraction of the DOC flux that is oxidised prior to being transported by turbulent mixing or isopycnal mixing to sub-thermocline waters. The DOC flux was also the least constrained flux in the model derived from the non-Redfield anomalies in the uptake of CO_2 and NO_3 (Monteiro, 1996). However, the most recent estimate of the magnitude of CO_2 sink flux (14.4 gC m^{-2} year^{-1}) derived from direct observations of pCO_2 over the seasonal cycle of 2 years (2005–2006) (Santana-Casiano et al., 2009) is in close agreement with the comparable magnitude from the box model (16.3 gC m^{-2} year^{-1}). The agreement of the two independent estimates provides some confidence in the overall magnitudes of the fluxes, particularly the DOC export, derived by the box model.

Although the DOC concentrations were obtained more recently by direct observation (Swart, 2008), the calculated flux was based on a horizontal diffusion assumption which is likely to significantly underestimate the actual cross shelf export flux. This makes it difficult to compare the model and observation based cross shelf export fluxes of DOC which differ by an order of magnitude (model: 6×10^{12} gC year^{-1} direct observation 0.8×10^{12} gC year^{-1}). Given the model's CO_2 sink sensitivity to the magnitude of the DOC flux and its oxidation, it is likely that the data based calculation of the DOC export flux is too low.

This investigation into the links between the magnitude of CO_2 sink shelf systems and the proportion of the production which is exported across the ocean – shelf boundary highlights the gaps in the observational and modelling scales to adequately understand the dynamics of these links. Of particular interest are the spatial and temporal scales that govern rates and magnitudes of ocean – shelf exchange on the one hand and the rates of oxidation of both POC and DOC. A CO_2 sink in any upwelling system reflects a net autotrophic status of the system integrated over seasonal time scales and the sink will remain sensitive to forcing factors which alter the rate of oxidation and the rates of transport and export across the shelf boundary.

References

Biscaye, P. E., Flagg, C. N., and Falkowski, P. G.: The Shelf Edge Exchange Processes experiment, SEEP-II an introduction to hypotheses, results and conclusions, Deep-Sea Res. Pt II, 41(2/3), 231–252, 1994.

Brown, P. C., Painting, S. J., and Cochrane, K. L.: Estimates of phytoplankton and bacterial biomass and production in the northern and southern Benguela ecosystems, S. Afr. J. Marine Sci., 11, 537–564, 1991.

Chavez, F. P. and Toggweiler, J. R.: Physical Estimates of Global New Production: The Upwelling Contribution, Env. Sci. Res. Reps., 18, 313–320, 1995.

Chen, C., Liu, K., and Macdonald, J. R.: Ocean biogeochemistry: a synthesis of the Joint Global Ocean Flux Study (JGOFS), Springer-Verlag, New York, 3, 53–95, 2003.

Chen, C.-T. A. and Borges, A. V.: Reconciling opposing views on carbon cycling in the coastal ocean: Continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO_2, Deep-Sea Res. Pt II, 56(8–10), 578–590, 2009.

Dingle, R. V. and Nelson, G.: Sea-bottom temperature, salinity and dissolved oxygen on the continental margin off south-western Africa, S. Afr. J. Marine Sci., 13, 33–49, 1993.

Doney, S. C., Tilbrook, B., Roy, S., Metzl, N., Le Quéré, C., Hood, M., Feely, R. A., and Bakker, D.: Surface-ocean CO_2 variability and vulnerability, Deep-Sea Res. Pt II, 56(8–10), 640–655, 2009.

Falkowski, P., Laws, E., Barber, R., and Murray J.: Ocean biogeochemistry: a synthesis of the Joint Global Ocean Flux Study (JGOFS), Springer-Verlag, New York, 4, 99–121, 2003.

Hopkinson Jr., C. S., Vallino, J., and Nolin, A.: Decomposition of dissolved organic matter from the continental margin, Deep-Sea Res. Pt II, 49, 4461–4478, 2002.

Inthorn, M., Wagner, T., Scheeder, G., and Zabel, M.: Lateral transport controls distribution, quality, and burial of organic matter along continental slopes in high-productivity areas, Geology, 34(3), 205–208, 2006.

Lass, H. U. and Mohrholz, V.: On the interaction between the subtropical gyre and the Subtropical Cell on the shelf of the SE Atlantic, J. Marine Syst., 76, 1–43, 2008.

Liu, K. K., Iseki, K., and Chao, S. Y.: Continental margin carbon fluxes, in: Hanson, R. B., Ducklow, H. W., and Field, J. G.: The changing ocean carbon cycle, Cambridge University press, 187–239, 2000.

Lutjeharms, J. R. E. and Meeuwis, J. M.: The extent and variability of South-East Atlantic upwelling, in: The Benguela and Comparable Ecosystems, edited by: Payne, A. I. L., Gulland, J. A., and Brink, K. H., S. Afr. J. Marine Sci., 5, 51–62, 1987.

Malone, T. C., Hopkins, T. S., Falkowski, P. G., and Whitledge, T. E.: Production and transport of phytoplankton biomass over the continental shelf of the New York Bight, Cont. Shelf Res., 1, 305–337, 1983.

Monteiro, P. M. S.: The oceanography, the biogeochemistry and the fluxes of carbon dioxide in the Benguela upwelling system, Ph D thesis, University of Cape Town, South. Africa, 354 pp., 1996.

Monteiro, P. M. S., Nelson, G., van der Plas, A., Mabille, E., Bailey, G. W., and Klingelhoeffer, E.: Internal tide-shelf topography interactions as a potential forcing factor governing the large scale sedimentation and burial fluxes of particulate organic matter (POM) in the Benguela upwelling system, Cont. Shelf Res., 25, 1864–1876, 2005.

Monteiro, P. M. S.: Carbon fluxes in the Benguela Upwelling System, in: Carbon and Nutrient Fluxes in Continental Margins: A Global Synthesis, edited by: Liu, K. K., Atkinson, L., Quiòones, R., and Talaue-McManus, L., Springer, Berlin, in press, 2009.

Rowe, G., Smith, S., Falkowski, P., Whitledge, T., Theroux, R., Phoel, W., and Ducklow, H.: Do continental shelves export organic matter?, Nature, 324, 559–561, 1986.

Rullkötter, J.: Organic matter: The driving force for early diagenesis, in: Marine Geochemistry, edited by: Schulz, H. D. and Zabel, M., Springer, Berlin, 4, 129–172, 2000.

Santana-Casiano, J. M., González-Dávila, M., and Ucha, I. R.: Carbon dioxide fluxes in the Benguela upwelling system during winter and spring: A comparison between 2005 and 2006, Deep-Sea Res. Pt II, doi:10.1016/j.dsr2.2008.12.010, in press, 2009.

Shannon, L. V. and Field, J. G.: Are fish stocks food-limited in the southern Benguela pelagic ecosystem?, Mar. Ecol. Prog. Ser., 22(1), 7–19, 1985.

Swart, N. C.: Lateral carbon transport from the southern Benguela, MSc. Thesis, University of Cape Town, South. Africa. 139 pp., 2008.

Waldron, H. N., Probyn, T. A., and Brundrit, G. B.: Preliminary annual estimates of regional nitrate supply in the southern Benguela using coastal sea level fluctuations as a proxy for upwelling, S. Afr. J. Marine Sci., 18, 93–105, 1997.

Waldron, H. N., Probyn, T. A., and Brundrit, G. B.: Carbon Pathways and export associated with the southern Benguela upwelling system: a re-appraisal, S. Afr. J. Marine Sci., 19, 113–118, 1998.

Walsh, J. J., Rowe, G. T., Iverson, R. L., and McRoy, C. P.: Biological export of shelf carbon is a sink of the global CO_2 cycle, Nature, 291, 196–201, 1981.

Wollast, R.: The Global Coastal Ocean: Processes and Methods, The Sea, Vol 10, John Wiley & Sons, New York, 9, 213–252, 1998.

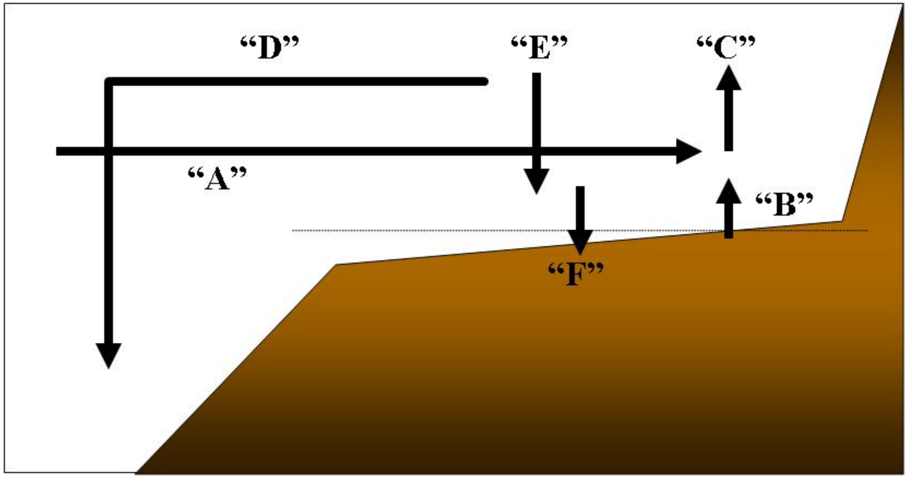
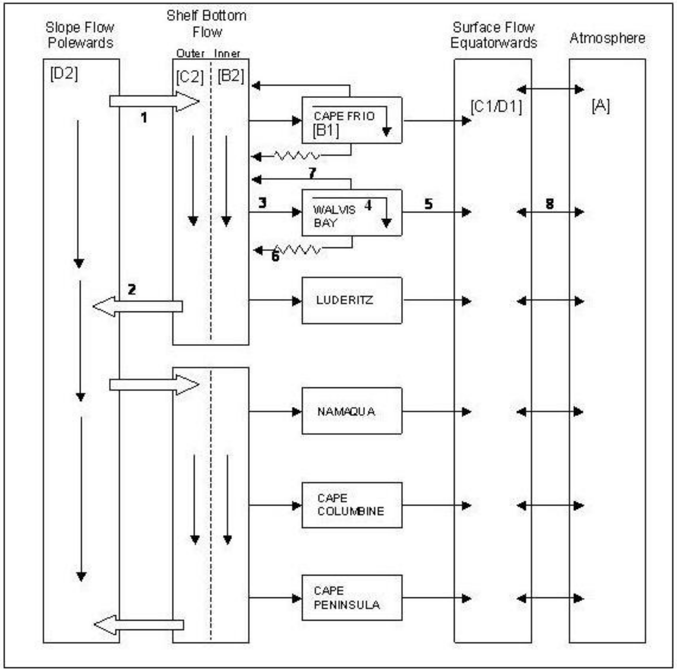


Fig. 1. Two-dimensional network of NO_3-N driven carbon pathways in the southern Benguela upwelling system.



Fluxes:
1. DIC [D2-C2/B2]
2. DIC [C2/B2-D2]
3. DIC [B2-B1]
4. DIC [B1-C1]
5. DIC [C1-D1]
6. DIC [B1-B2]
7. DIC [B1-B2/C2]
8. DIC [A-B1/C1/D1]

Fig. 2. The conceptual model of the Benguela System: "Gate Hypothesis" of advective fluxes of dissolved inorganic carbon (later quantified with a box model).

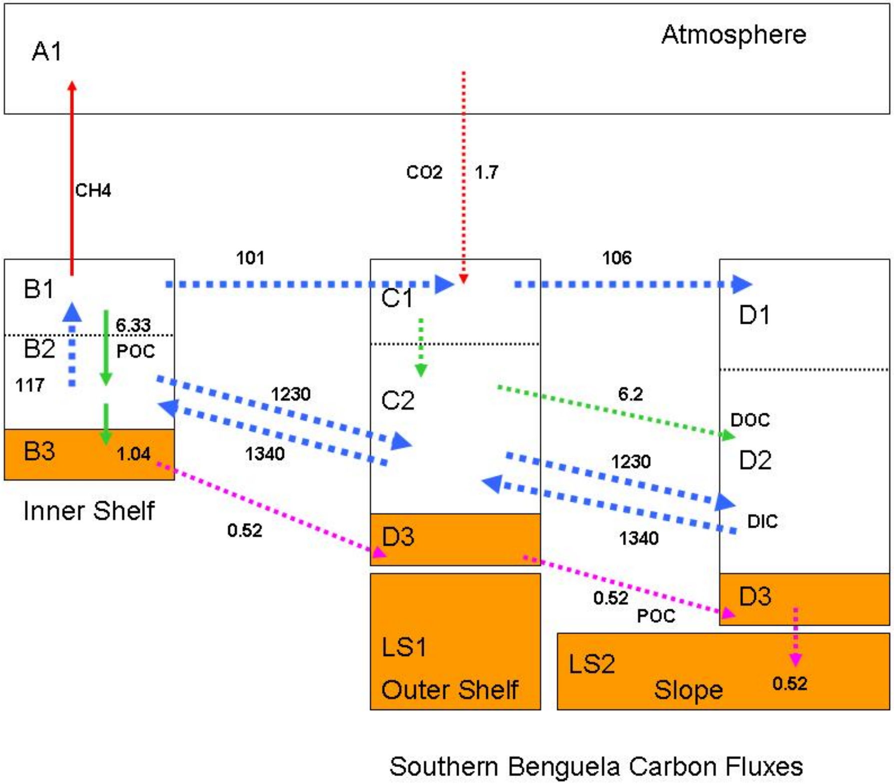


Fig. 3. Southern Benguela carbon fluxes.

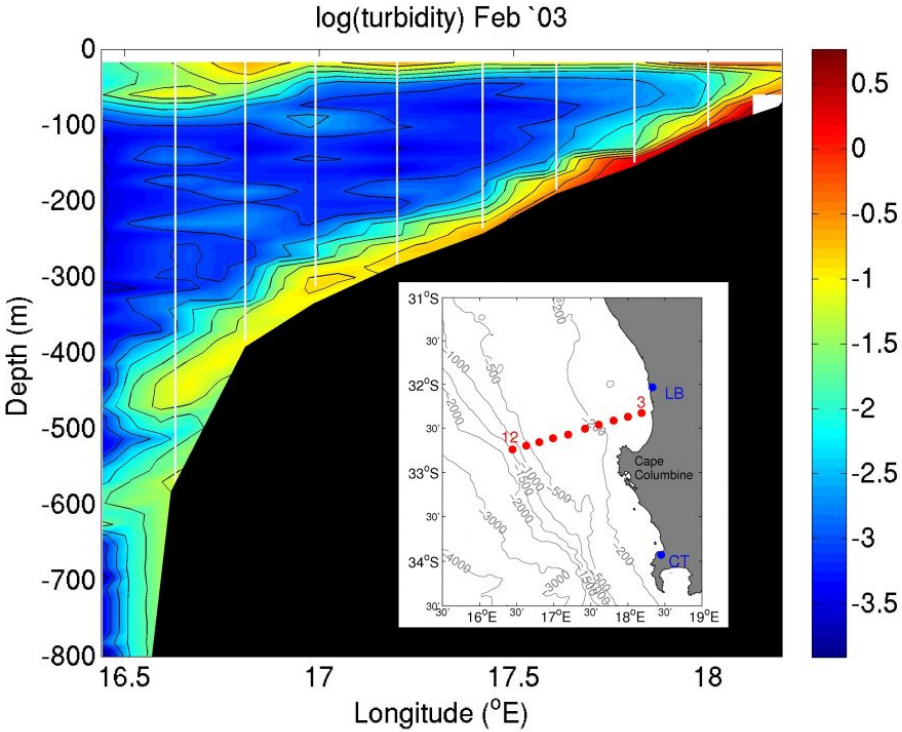


Fig. 4. Turbidity section from the southern Benguela (coastline to 16.5° E in the vicinity of St Helena bay), illustrating the presence of a bottom nepheloid layer. Note that units for turbidity are a relative measure.

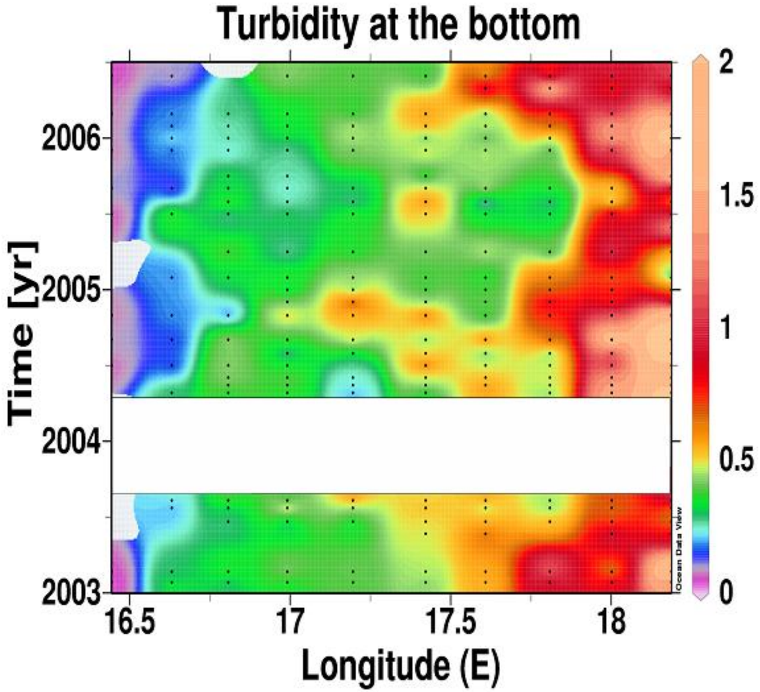


Fig. 5. Hoffmueller plot of turbidity 5 meters off the bottom. Tongues of high turbidity stretching across the shelf in time suggest a cross-shelf propagation of particulate matter The Shelf Break is at 16.75° E. Note that the colour bar is not linear and that units for turbidity are a relative measure.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮
▶▮
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion