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

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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

The continental margins account for 7% of the world ocean surface area. They are however, subject to seasonal or sub-seasonal inputs of nutrients accompanied by high rates of primary production and biomass. The former (seasonal) occurs in shelf seas and the latter (sub-seasonal) 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 $\mathrm{Gt\,C\,y^{-1}}\sim15\%$ (Doney et al., 2009; Chen and Borges, 2009).

Previous studies have supported 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; Rullktter, 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 north east 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 re-cycling and export margins on the basis of shelf topography and residence time versus major coastal upwelling. Their paper 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 coastal systems as CO_2 sinks have helped to resolve the controversy on the magnitude of the coastal CO_2 sink by assigning a reduced role to terrestrial POC fluxes in coastal remineralization (Chen and Borges, 2009). The

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conclusions were that coastal systems are net sinks of atmospheric CO_2 ($\sim$0.36 Gt C y^{-1}) because a much larger fraction of terrestrial POC is trapped by estuarine systems (Chen and Borges, 2009). The southern Benguela upwelling system is a good system to explore this question because the terrestrial POC and nutrient input to the shelf system is insignificant and the CO_2 sink will therefore depend mostly on ocean – shelf exchange of the different carbon fractions (Monteiro, 2009; Santana-Casiano et al., 2009). The role of shelf bathymetry and dynamics has been recognised as being important to the export of remineralised TCO_2 (Ianson et al., 2009). Here we expand this to show the link between the magnitude of the CO_2 sink and the export of POC and DOC. We hypothesize that this atmospheric CO_2 sink is linked to the magnitude of the carbon export across the ocean-shelf boundary (Waldron et al., 1997; Monteiro, 2009).

Three different methods of quantifying carbon [POC & DOC] export in the southern Benguela upwelling system are examined 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 NO_3-N (and subsequently carbon) pathways between open ocean, shelf and sediments is shown in Fig. 1.

- "A" is upwelling source water nitrate (South Atlantic Central Water).
- "B" is shelf re-cycled nitrate.
- "C" represents the southern Benguela annual potential production due to nitrate. It consists of the nitrate-based production due to the sum of source "A" (referred to as C(a)) and source "B" (referred to as C(b)). C(a) is the annual potential new production (APNP) since the nitrate sustaining this production is "new" to the system. C(b) is sustained by a shelf-recycling loop of nitrate and cannot be considered as new production *per se*. This follows Roemmich (1989) who applied the same distinction referring to "imported new" production (C(a) in this study) and "local new" production (C(b) in this study).

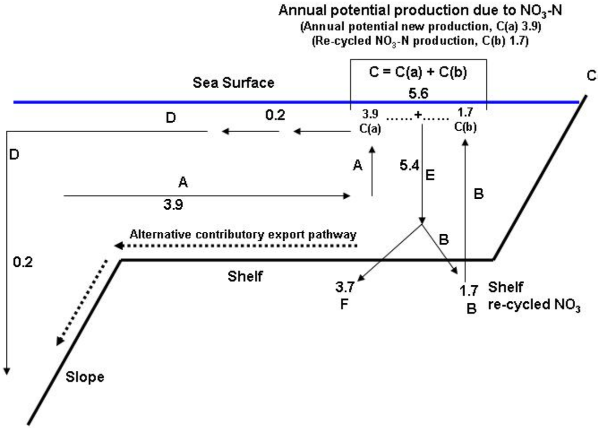


Fig. 1. Two-dimensional network of NO_3-N driven carbon pathways in the southern Benguela upwelling system.

- "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 annual potential nitrate production (C) that sinks over the shelf.
- "F" is the proportion of "E" that is sequestrated in shelf sediments. NB the remaining proportion of "E" re-enters the shelf re-cycling 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 Production due to nitrate

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 image records of SST it was possible to identify upwelling events of varying intensity and estimate the quantity of nitrate per event that was available to the euphotic zone. These upwelling events (and their associated nitrate content) were positively related to the coastal sea level fluctuation evident in the tide gauge record resulting from coastal trapped wave activity. Upwelling events and coastal trapped waves are meteorologically-forced. The event-scale sea level fluctuations caused by the propagation of coastal trapped waves (tide gauge data filtered of tide and atmospheric pressure) were related to coincident upwelling events and their nitrate content and were hence used as an upwelling proxy to estimate annual fluxes of nitrate.

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

(numbers in parentheses refer to the range in the 1980s dataset).

“B” – Shelf re-cycled nitrate.

South Atlantic Central Water (SACW) has a median nitrate signature of 14 mmol m^{-3} (10–18 mmol m^{-3}) and water which actually upwells after nitrate enhancement has a mean nitrate signature of 20 (±4) mmol m^{-3}. The enhancement results from interaction between SACW and nutrient-rich shelf waters (which have been subject to NO_3-N inputs due to shelf re-mineralisation). Assuming that the nitrate concentration difference between SACW and water which upwells remains more or less fixed within their respective ranges, 30% of “C” can be considered locally re-cycled production due to nitrate: (20–14)/20 expressed as a percentage.

$$\text{“B”} = 1.7(1.2 - 2.2) \times 10^{13}\,\text{gC year}^{-1}$$

“D” – Annual potential production due to nitrate advected offshore.

Pathway “D” accounts for the amount of potential production due to nitrate that is advected offshore and was obtained from integrated nitrate values occurring seaward of the shelf edge. It is assumed that once a short-lived bloom finds itself outside the system boundary it will die or be consumed by secondary producers. In either case it will sink (either as dead material or faecal pellets) and enter the “twighlight zone” where it is assumed to be exported (and sequestrated) carbon. Note that the remaining fraction of potential new production due to nitrate that sinks over the shelf is divided between “F” (incorporated in shelf sediments) and “B” (the shelf re-cycling nitrate loop). It is suggested that a proportion of “F” may be transported off-shelf and sequestrated in continental slope sediments. This is analogous to the bottom nepheloid layer described by Swart and is shown as a dashed arrow in figure 1. The algebraic relationship between the network of nitrate pathways balances the various sources and sinks.

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.

$$\text{“D”} = 0.2(0.0 - 0.7) \times 10^{13}\,\text{gC year}^{-1}$$

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

$$\text{“A”} = 3.9(2.7 - 5.1) \times 10^{13}\,\text{gC year}^{-1}$$

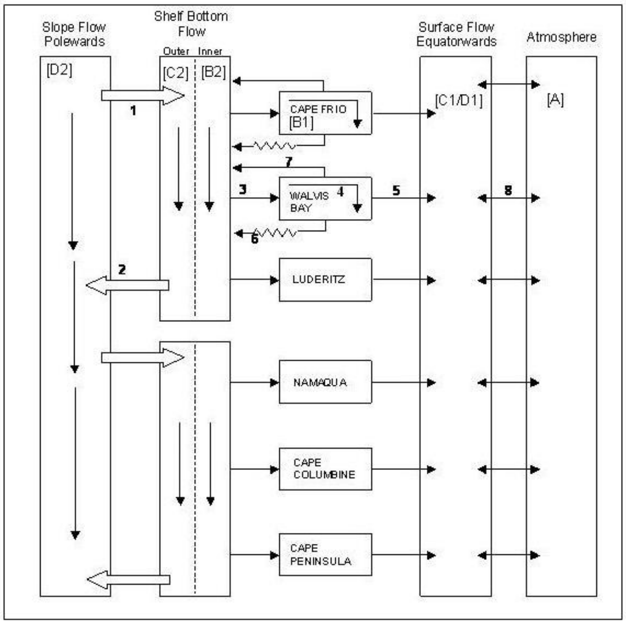
$$\text{“E”} = 5.4(3.2 - 7.3) \times 10^{13}\,\text{gC year}^{-1}$$

$$\text{“F”} = 3.7(1.0 \text{to} 6.1) \times 10^{13}\,\text{gC year}^{-1}$$

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”). It should be noted that “F” may not be sequestrated in shelf sediments in its entirety. It is suggested that a proportion of “F” may be transported off-shelf and sequestrated in continental slope sediments (Fig. 1).

2.2 Monteiro: discrete upwelling centres – Gate Hypothesis Model

The Gate Hypothesis, proposed that ocean – shelf exchange of thermocline waters occurred preferentially at a few specific sites characterized by shelf narrowing and maxima in the wind stress curl (Monteiro and van der Plas, 2006). These preferential exchange sites dominated by zonal flow (Cape Frio, Luderitz and Cape Columbine) act as barriers (Gates) to meridional flow thus creating shelf sectors with unique physical and biogeochemical properties (Monteiro, 2009). This has been shown to affect the variability of physical properties such as salinity and biogeochemical characteristics such as CO_2 and hypoxia (Duncombe Rae, 2005; Monteiro, 2009). 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”,



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).

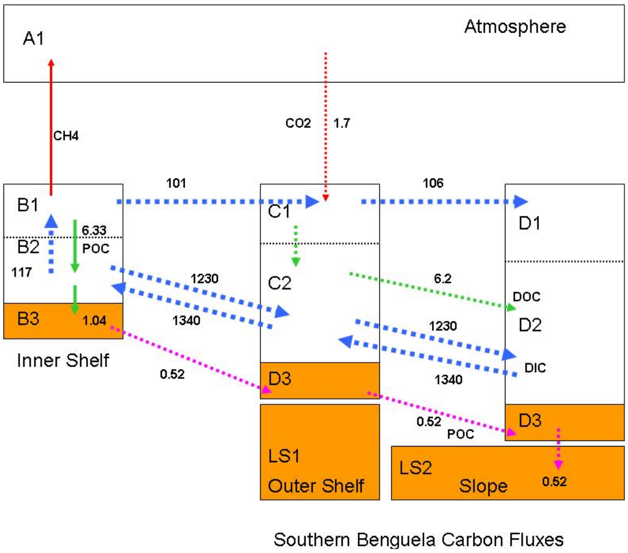


Fig. 3. Southern Benguela carbon fluxes.

SACW is entrained into a meridional shelf 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.

This is schematically depicted by Monteiro (2009). The model adopted a published typology of upwelling centres that were summed to provide system and sub-system fluxes (Lutjeharms and Meeuwis, 1987). Upwelling in the model was forced by hourly wind-stress observations from each upwelling centre over two contrasting years: 1992 and 1994 (Monteiro, 1996). The model was a simple Ekman flux calculation forced by equatorward wind stress that persisted for periods longer than the inertial oscillation period (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 biogeochemical fluxes were calculated based on the total annual Ekman-based upwelling rates at each upwelling centre and the concentrations of the biogeochemical constituents at each stage of the upwelling cycle (Monteiro, 1996, 2009). 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 fluxes shown in Fig. 3 are million tons carbon per year (=TgCy^{-1}). 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 mTons DIC per year are transported from the outer to inner shelf (C2 to B2) but only 117 mTons 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 production due to nitrate) 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)=$(1.04+6.2)\times10^{12}$ = 0.72×10^{13} gC per year.

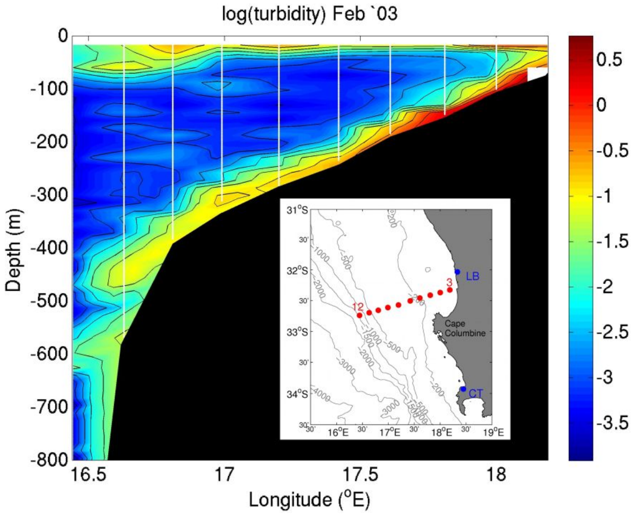


Fig. 4. Turbidity section from the southern Benguela (coastline to 16.5° E in the vicinity of St. Helena bay), illustrating the presence of a bottom nepheloid layer. Note that units for turbidity are a relative measure.

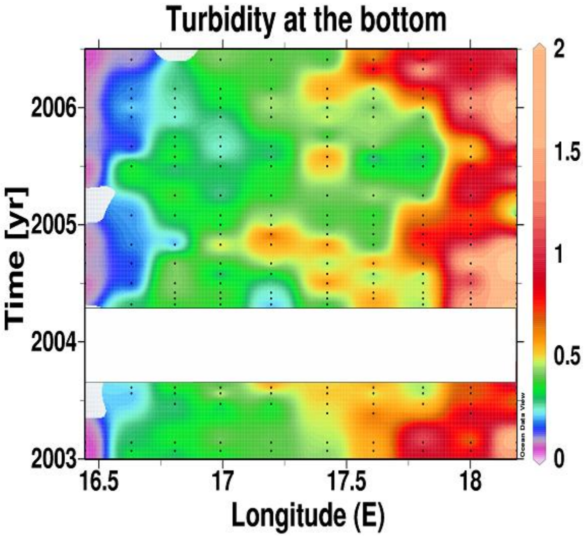


Fig. 5. Hoffmöeller plot of turbidity 5 m off the bottom. Tongues of high turbidity stretching across the shelf in time suggest a cross-shelf propagation of particulate matter The Shelf Break is at 16.75° E. Note that the colour bar is not linear and that units for turbidity are a relative measure.

2.3 Swart: cross-shelf advection in bottom nelpheloid layers

Swart's 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 $y=82x+42.7$ ($r^2=0.16$, $p=0.03$) and the winter, an average obtained from two cruises (June: $y=3.3x+5.5$, $\mathrm{r}^2=0.73$, $p=<0.01$; and August: $y=5.8x+21.4$, $r^2=0.33$, $p=<0.01$) where x=turbidity and y=POC (μg litre^{-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 Hoffmöeller plot of turbidity 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 of organic material, 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 Swart's 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 Prof. 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 production due to nitrate (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 production due to a parameterised upwelled nitrate flux rather than production due to nitrate uptake *per se*. It is important to note that potential production assumes the complete assimilation of all available nitrate. All the nitrate is unlikely to be used at the event scale, however, over longer time (and wider space) scales it is likely to be utilized, unless there is a means of transporting the nitrate below the euphotic zone. Also note that the Waldron estimate of annual potential production due to nitrate ("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}. The magnitude of the f-ratio based on direct observations of ^{15}N uptake rates was found to be in the range of 0.2–0.3 (Probyn, 1992). This magnitude is 30–50% of the calculated f-ratio from potential new production so the estimate of PNP can be further revised downwards to 0.5–2×10^{13} gC year^{-1} which is now very close to the box model estimate of 0.72×10^{13} gC year^{-1}.

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 of POC by intermediate nepheloid layers sustained by sea bed turbulence (Monteiro et al., 2005), 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 Waldron/Monteiro. This is an area of further investigation.

3.2 The link between CO_2 sink and ocean – shelf exchange of POC and DOC

The importance of shelf – ocean POC and DOC carbon export fluxes lies is the role that they play in determining the magnitude of the net sink for atmospheric CO_2 on the shelf system (Chen and Borges, 2009; Monteiro 2009). 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 Mt C y^{-1} (Chen and Borges, 2009). However, the area specific fluxes for the southern Benguela (16.3 g Cm^{-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 Benguela box model showed that the magnitude of the CO_2 sink is sensitive to both the POC export flux and 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 as a mass balance closure term 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 ($14.4\,\mathrm{g\,C\,m^{-2}\,year^{-1}}$) derived from direct observations of $p\mathrm{CO_2}$ 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 ($16.3\,\mathrm{g\,C\,m^{-2}\,year^{-1}}$). The agreement of the two independent estimates provides some confidence in the overall magnitudes of the POC export fluxes and particularly the DOC export, derived by the box model.

Although the DOC concentration observations were obtained more recently by in situ 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: $6\times10^{12}\,\mathrm{gC\,year^{-1}}$; direct observation $0.8\times10^{12}\,\mathrm{gC\,year^{-1}}$). 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 and emphasises that the link between CO_2 sink and POC and DOC export across the ocean shelf boundary remains an important area of investigation.

This investigation into the links between the magnitude of CO_2 sink in 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 necessary to adequately understand the dynamics of these links. Of particular interest are the spatial and temporal scales of the physical processes (internal tide driven turbulence, Ekman and non-Ekman advection, sedimentation) that govern rates and magnitudes of ocean – shelf exchange on the one hand and the biogeochemical 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.

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