

# Late Holocene paleoceanographic changes off south-western Africa as inferred from coccolithophore assemblages

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**Abstract** Coccolith occurrences in sediment core GeoB 8323-2, from the Benguela Upwelling System off south-western Africa, were analysed to reconstruct the temporal changes in surface water conditions, upwelling intensity and associated productivity during the late Holocene (last 2.25ka BP). Absolute numbers of total coccolithophores are low throughout the core, reaching a maximum of  $320 \times 10^6$  coccoliths/gram sediment around 770 years BP. Despite the low abundance of coccoliths, coherent patterns of a changing assemblage composition can be identified. These suggest a consistent paleoceanographic development of highly variable Late Holocene environmental change during the last three millennia. Phases of decreased upwelling in the Benguela Upwelling System are indicated by elevated abundances of *Florisphaera profunda* alongside reduced occurrence of *Coccolithus pelagicus* and *C. braarudii* from 2.25–2.00ka BP, ~ 1.00ka BP and during the last 200 years, also accompanied by a reduced species diversity. Sea surface temperatures estimated with a *Gephyrocapsa*-based transfer function are in the order of 18–20°C. These phases are intersected by periods of colder sea surface temperatures of 16–17°C and increased productivity, as indicated by an opposing trend for the aforementioned species. Given the climatological and oceanographical complexity of the area, deciphering a single driving mechanism for these changes proves difficult. Synchronous changes in the Antarctic sea ice extent, however, give credit to the conceptual model of latitudinal migration of the westerly wind belt and its interaction with the south-easterly trade winds as an important driver for oceanographic changes in the area.

**Keywords** calcareous nannoplankton, Holocene, nearshore environment, Benguela, paleoceanography, upwelling, sea-surface temperatures

## 1. Introduction

Paleoecological investigations largely contribute to our understanding of spatial and temporal variability of (marine) environments as a whole and their linkage with variations in the climatic systems.

The southern African paleoclimate, the South Atlantic and the adjacent BUS (Benguela Upwelling System) have been studied with increasing attention as they are key parameters for local and global climatic and oceanographical evolution, water mass transfer and the regional rainfall patterns (e.g. Summerhayes *et al.* 1995; Wefer *et al.* 1996; Kirst *et al.* 1999; Rouault *et al.* 2003; Farmer *et al.* 2005). The BUS is one of the most productive regions in the world's oceans and one of the five major upwelling areas worldwide (Summerhayes *et al.* 1995). Here, a linkage of glacial-scale and millennial variability with orbital parameters has been well established, with the majority of data suggesting SSTs (sea surface temperatures) and less intense upwelling during interglacials as well as continental rainfall varying in phase with summer insolation (e.g. Partridge *et al.* 1997; Flores *et al.* 1999; Shi *et al.* 2000; Baumann & Freitag 2004).

Reconstructions for the Holocene are less conclusive, partially due to the scarcity of adequate climate records and

to the apparently highly variable climatic evolution of this period. While a continuous aridification trend in the winter rainfall zone from 9–5.5ka BP, paralleled by decreasing upwelling intensities in the southern Benguela, was suggested by Weldeab *et al.* (2013), decreasing Mg/Ca-SST estimates point to the opposite trend (Kirst *et al.* 1999). The latter data indicates a pronounced period of enhanced upwelling from 8.5–5.5ka BP, with highest SSTs at around 6ka BP. Despite reporting an ongoing aridification trend, Chase *et al.* (2009) also named a humid period in the late Holocene from 4.2 to 3.5ka BP, followed by pronounced aridity until 0.3ka BP, that coincides with a decreasing number of sunspots as reported by Solanki *et al.* (2004). Based on speleothem data, Sletten *et al.* (2013) proposed relatively humid conditions from 4.6–3.3ka BP and from 1.8ka BP to present.

The potential of coccolithophores as a paleoproxy for surface water conditions such as water temperature and nutrient availability has been well established in the study area (Giraudeau 1992; Giraudeau & Rogers 1994; Boeckel & Baumann 2004), partially with emphasis on upwelling and eddy formation (Winter & Martin 1990) or Agulhas retroflexion (Flores *et al.* 1999). Moreover, studies from different core sites show a good applicability of

coccolithophores as environmental indicators in nearshore settings (Green *et al.* 2008; Silva *et al.* 2008; Guerreiro *et al.* 2013; Guerreiro *et al.* 2013, 2014; Bonomo *et al.* 2014). Thus, aiming to contribute to the attempts made to explain the discrepancies in late Holocene oceanographical and climatic reconstructions of the area, we present high resolution data from the coccolithophore assemblage composition alongside the absolute and relative abundance of individual species, as well as absolute values for reconstructed SSTs.

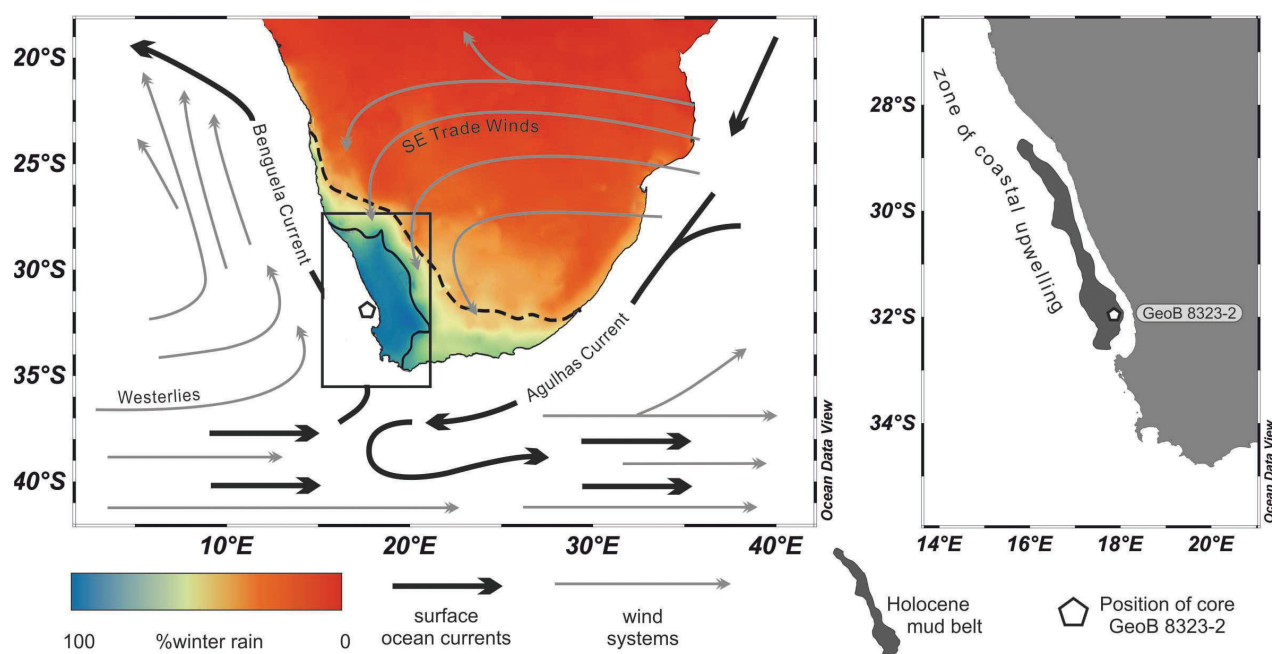
## 2. Modern oceanography of the study area

Southern Africa is an area of close juxtaposition of several major climate components (Figure 1). Encircled by the warm Indian Ocean and its AC (Agulhas Current) in the East and the colder South Atlantic with the BC (Benguela Current) in the West, it is one of the most climatically convoluted regions on Earth. In addition, two opposing wind regimes dominate atmospheric circulation in the area: the south-easterly trade winds and the westerly wind belt or westerlies (Chase & Meadows 2007), with the SE-trades not only being the main driver for upwelling in the southern BUS, but also the main pathway for moisture advection to the large parts of the continent (see Figure 1).

The Agulhas Current is responsible for intense heat and moisture transport from the Indian Ocean into the Atlantic Ocean and, therefore, directly influences the climate, especially at the eastern coast of South Africa (Figure 1). It has repeatedly been identified as one of the key components of global ocean circulation (Gordon *et al.* 1992; De Ruijter *et al.* 1999; Lutjeharms 2006).

At the southernmost tip of the African continent these waters interact with the Benguela Current and Antarctic Circumpolar Current in a feature known as the Agulhas Retroflexion. This retroflexion shortcuts every few months, spawning a large column of warm and salty Indian Ocean water that drifts into the Atlantic, a phenomenon known as Agulhas leakage, creating large scale eddies called the Agulhas Rings (De Ruijter *et al.* 1999). These have an important impact on the inter-ocean exchange and, therefore, the Atlantic Meridional Overturning Circulation. As pointed out by Biastoch *et al.* (2009) this leakage is directly linked to the position and intensity of the Westerlies and can have a significant effect on the Benguela Current and the Benguela Upwelling area, where the warm waters from the Indian Ocean effectively caps the water column, weakening the upwelling intensity.

The cool Benguela Current is the eastern boundary current in the South Atlantic, flowing equatorward along the South African and Namibian coast. It is most known for its immediate relation to the BUS off northern South Africa and Namibia, which is one of the most productive regions in the world's oceans, reaching from Cape Point (34.58°S) in the south to Cape Frio (18.066°S) at the border between Namibia and Angola (Nelson & Hutchings 1983). The BC is often divided into the BOC (Benguela Ocean Current) and a smaller coastal branch, the BCC (Benguela Coastal Current), which shows a weaker mean northward flow and is more strongly influenced by local winds, even leading to reversals in the mean flow direction (Fawcett *et al.* 2008).



**Figure 1:** Overview illustrating the main components of the oceanic and atmospheric circulation over southern Africa and the core position of core GeoB 8323-2 in the Namaqualand mudbelt. Modified after Truc *et al.* (2013) and Chase & Meadows (2007). Colour shading indicates primary rainfall season and amount (red/white/right: Summer Rainfall Zone [SRZ], blue/black/left: Winter Rainfall Zone [WRZ])

In the Benguela upwelling region (Figure 1), the equatorward component of the south east trade winds is the driving force for offshore Ekman pumping that maintains the upwelling up to several hundred kilometres offshore. Upwelling prevails throughout the year and is also a common feature on the inner shelf. It is, however, enhanced during the austral summer (Lutjeharms & Stockton 1987; Summerhayes *et al.* 1995). Interannual and interdecadal fluctuations of the upwelling intensity have been linked to latitudinal shifts in the zone of the austral westerlies. Not only do they have a direct influence on the Ekman effect, also but govern the amount of Agulhas intrusions that may significantly alter the structure of the water column (Hardman-Mountford *et al.* 2003; Biastoch *et al.* 2009). Rouault *et al.* (2003) emphasized the importance of anomalies in SST, especially off south western Africa, for governing rainfall at coastal as well as more inland regions.

At the southern tip of the BUS, a coast parallel Holocene mud belt has formed due to the high input of terrigenous material through the Orange River and, to a limited extend, smaller, local rivers in eastern South Africa (Figure 1). Its inner margin lies 1km to 10km offshore, where water depth in the area varies between 80m and 140m. Given the rapid accumulation of sediments, it provides a paleoclimatic archive of exceptionally high resolution (Meadows *et al.* 2002). While the coarse grained fraction of the Orange River sediment load is mainly transported north due to wave-induced longshore drift at the river mouth, the presence of a poleward undercurrent facilitates the accumulation of very fine material in the southern part of the mudbelt (Mabote *et al.* 1997; Rogers & Rau 2006; Hahn *et al.* 2016). Despite the fact that the mudbelt sediments are primarily of terrigenous origin, a significant amount of biogenic sediment is added due to the presence of a particularly productive upwelling cell in close vicinity to the core site (e.g. Monteiro & Roychoudhury 2005).

### 3. Material and methods

Gravity core GeoB 8323-2 was retrieved during Meteor-cruise M57/1 from a water depth of 92m at the shelf off the Olifants River, South Africa (32.0283°S, 18.2035°E). Its overall length is 285cm and it is composed of homogeneous, dark greenish-grey sandy mud (Schneider & cruise participants 2003). A hiatus between the sandy base of GeoB 8323-2 and the overlaying fine-grained sediments was observed at 227cm (2.25ka). The age model is based on linear interpolations of five AMS-<sup>14</sup>C determinations on marine gastropods calibrated using the OXCAL software (Hahn *et al.* 2016). Thus, the undisturbed upper sequence of core GeoB 8323-2 records at least the last 2.25ka, with the core top considered to be of recent age (0ka BP i.e. 1950 A.D.). Mean sedimentation rate was calculated as 1mm per year for the uppermost 227cm of the sediment core.

Sample preparation for coccolith counts followed Andrleit (1996): Between 95mg and 125mg dried bulk

sediment were weighed and brought into suspension with buffered water without further chemical treatment or filtering. Slightly alkaline water was used to prevent coccolith dissolution. The chosen amount of sediment has proven useful to ensure representativeness of the sample and, at the same time, minimised the weighing error. Since small particles, such as coccoliths, tend to form aggregates, ultrasonic treatment for 15–45 seconds was necessary in order to suspend remaining clumps. The suspension was then diluted using a rotary splitter so that 1/100 of the original sample material was recovered in a glass beaker. This amount has proven to be adequate for creating a monolayer of particles. The suspension was vacuum filtered onto a polycarbonate filter with a pore width of 0.45µm. After drying, about 1cm<sup>2</sup> of the filter was cut out and glued onto SEM stubs and finally sputter-coated with a gold-palladium alloy.

The prepared samples were examined using a ZEISS DSM 940A scanning electron microscope at 2000x magnification, and coccoliths were counted in a known representative area of the sample. Counts range from 80–230 coccoliths per sample. Iterative counting showed, however, that this low abundance is still sufficient for an adequate representation of the assemblage composition. Coccolith fragments smaller than 50% of the original size were not counted. The calculation of numbers of coccoliths per gram sediment followed Andrleit (1996):

$$\text{Coccoliths} \left[ \frac{\text{No.}}{\text{g. sed.}} \right] = \frac{F * C * S}{A * W}$$

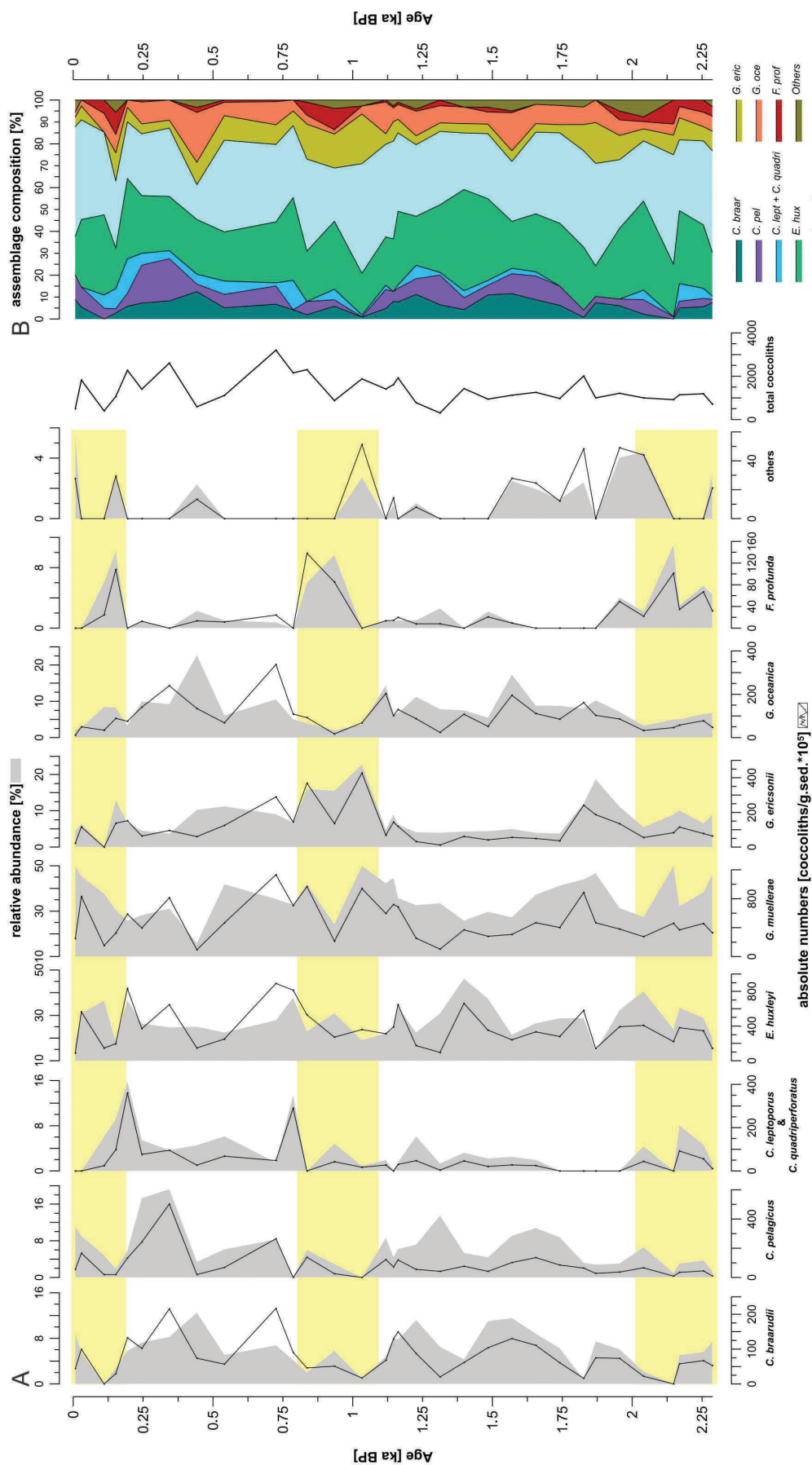
Where:

- F = filter area [mm<sup>2</sup>]
- C = number of counted coccoliths
- A = investigated area [mm<sup>2</sup>]
- S = split factor (100)
- W = weight of sample (g)

For the calculation of SST, a transfer function based on six morphotypes of *Gephyrocapsa* was used (Bollmann *et al.*, 2002; Henderiks & Bollmann, 2004). Therefore, at least 33 coccoliths per sample were counted extra according to the informal terminology given in Bollmann *et al.* (1997). Special emphasis was put on the identification of the three temperature-sensitive morphotypes GE, GC and GO (*Gephyrocapsa* equatorial, cold, and oligotrophic, respectively). The relative abundances of the six different morphotypes were calculated without any further measurement of the coccoliths, and mean SST was calculated using the formula of Bollmann *et al.* (2002):

$$\text{MeanSST [}^{\circ}\text{C]} = 19.4336 + (0.1161 * \% \text{GE}) \\ + (-0.0560 * \% \text{GC}) + (0.0806 * \% \text{GO}).$$

Species identification is based on the taxonomic guide published by the International Nannoplankton Association



**Figure 2:** a) Relative abundances (top) and absolute numbers (bottom) of the coccolithophore species identified in the core. Black line gives absolute numbers, the grey-shaded areas indicate percentage relative abundance; b) overview of the assemblage composition



(Young *et al.* 2003) and the electronic guide to the biodiversity and taxonomy of coccolithophores, Nannotax 3 ([ina.tmsoc.org/Nannotax3/index.html](http://ina.tmsoc.org/Nannotax3/index.html)). Differentiation between *Coccolithus pelagicus* and *Coccolithus braarudii* is predominantly based on a 10µm criterion.

#### 4. Results

Absolute numbers of coccoliths are low throughout the core, reaching a maximum of  $320 \times 10^6$  coccoliths/gram sediment (coc/g sed.) around 770yrs. BP, with an average of  $140 \times 10^6$  coc/g sed (see Figure 2). Preservation can be described as average at best, possibly due to elevated content of TOC (total organic carbon) in the sediment. Numbers are especially low in the period from 2.25ka BP to 1.40ka BP and only show minor variation in that interval. Higher, albeit strongly variable, values characterize the period after 1.40ka BP to present. Figure 2a shows absolute values and relative abundances of the most dominant species, with an overview of the assemblage composition is given in Figure 2b.

The abundances of *Gephyrocapsa muelleri* and *Emiliania huxleyi* show a similar pattern to that of the total numbers. These two species dominate the assemblage, accounting for ~30% and 25%, respectively. Their abundances and absolute numbers vary significantly (from <10 to >80  $\times 10^6$  coc/g sed.) but do not seem to follow a clear trend.

Similarities can moreover be found between *Coccolithus braarudii*, *C. pelagicus* and *Gephyrocapsa oceanica*. Three intervals of low abundances can be distinguished (2.25–2.00ka BP, around 1.00ka BP and during the last 250 years.) In between, namely between 2.00 and 1.10ka BP and between 0.80 and 0.25ka BP, these species are more abundant. This trend seems to be less prominent in the record of *G. oceanica* than for the other two species. These three aforementioned species seem to be anti-correlated to *Gephyrocapsa ericsonii* and *F. profunda*, which show maxima from 2.25–2.00ka BP, around 1.00ka BP and during the last 200 years. The maximum around 1.00ka BP is especially pronounced for both species. *Florisphaera profunda* also shows a distinct increase during the last 250 years, which can only be observed for *G. ericsonii* to a minor extent. *Calcidiscus leptoporus* and *C. quadriperforatus* do not seem to follow any of these trends. They are fairly rare until 0.80ka BP, followed by a period of higher abundances with a distinct maximum at 0.20ka BP, and decrease again after that. Species grouped as ‘others’ are mainly composed of *Syracosphaera* spp. and only account for up to 6% of the assemblage.

Ecological diversity within the coccolithophore assemblage was determined by calculating Shannon-Index H' (see Figure 3d). This reveals two distinct minima around 1.00 and 0.10ka BP. Diversity appears to be elevated in the lowermost part of the core, but is also characterized by a pronounced minimum at 2.15ka BP. The period from 2.00ka BP to 1.25ka BP shows slightly elevated values, just as the time span between 0.80ka BP and 0.20ka BP.

Notably, the last 200 years are marked by a distinct drop from the overall highest value to the pronounced minimum mentioned above.

#### 5. Discussion

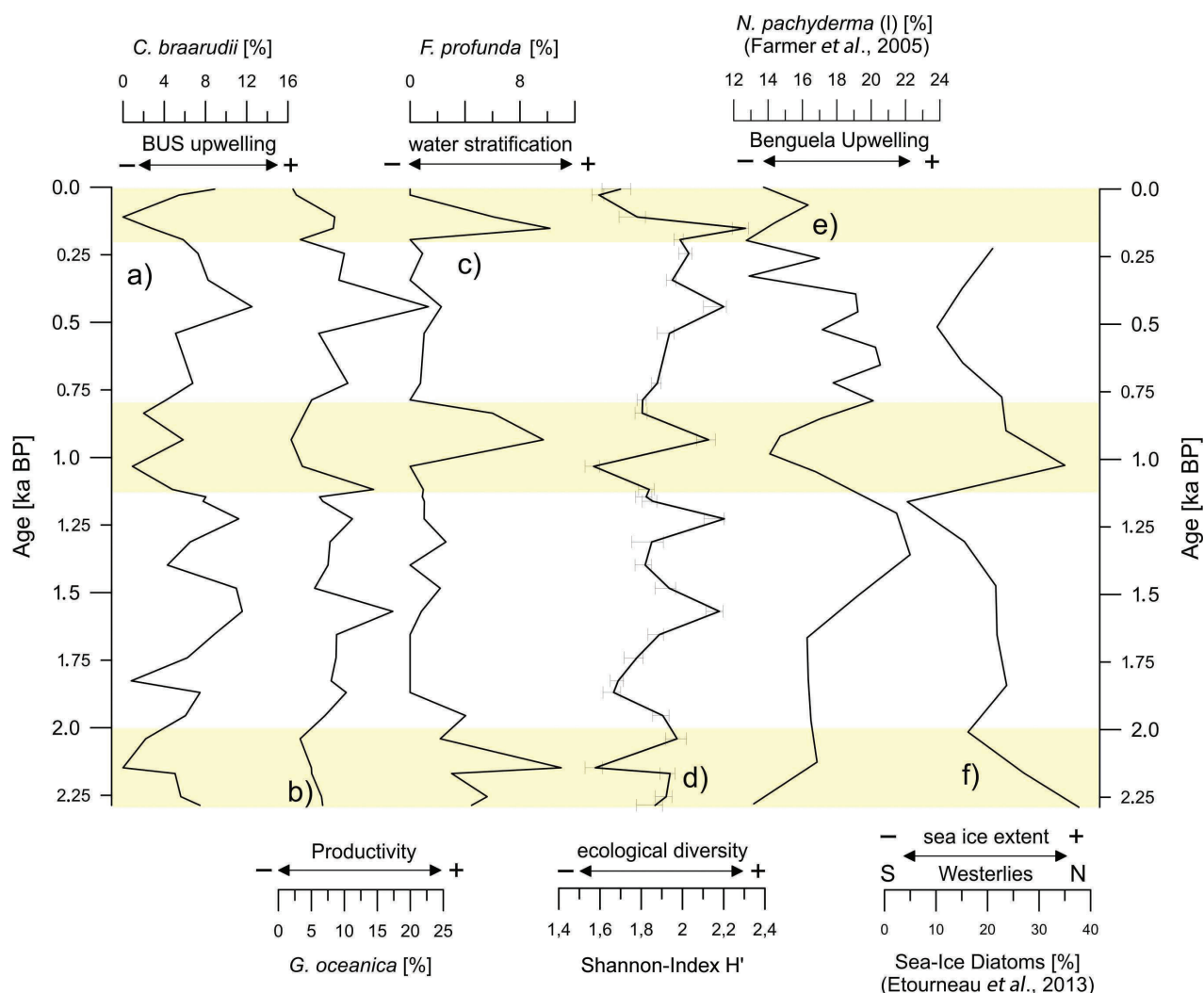
##### 5.1 SST-variability based on the coccolithophore assemblage

Absolute values for past SSTs estimated with the *Gephyrocapsa*-based transfer function point towards a pattern of three warm intervals (18–20°C), intersected by two colder phases (16–17°C, see Figure 4). Absolute values are however, slightly higher than the modern annual mean SSTs (15–17°C). This might be due to the distinct seasonality in coccolithophore growth in the area as reported by Giraudeau *et al.* (2000) and Romero *et al.* (2002). The *Gephyrocapsa*-genus that the transfer function is based on especially thrives in austral spring/summer, which might explain why the estimated absolute temperatures exceed modern day annual averages.

Relative changes in SSTs can furthermore be inferred from the abundances of the cold water adapted *C. pelagicus* (Okada *et al.* 1979; Samtleben & Bickert 1990; Samtleben *et al.* 1995; Silva *et al.* 2008) and the warm-water adapted *G. ericsonii* (McIntyre & Bé 1967; Cortés *et al.* 2001; Baumann & Freitag 2004). These indicate low SSTs from 2.00–1.10ka BP and from 0.80–0.25ka BP, while warmer waters can be inferred from high abundances of *G. ericsonii* in between those phases, especially around 1.00ka BP (Figure 4). The ratio of *G. ericsonii* over *C. pelagicus* moreover reveals a pronounced warm phase towards the core top, nicely mirroring the result of the SST estimates. As the core position is well within the Benguela upwelling region, the lower temperatures can potentially be assigned to increased upwelling.

##### 5.2 Coccolithophore paleo-productivity

Three of the identified species (*C. braarudii*, *F. profunda* and *G. oceanica*) are especially useful for the reconstruction of past productivity changes and stratification at the core site. *Coccolithus braarudii* and *G. oceanica* are indicators of high-productivity, with *C. braarudii* often associated with upwelling conditions (Cachão & Moita 2000; Parente *et al.* 2004), while *G. oceanica* has been found to change in phase with sedimentary TOC and mirror general surface water productivity (Kinkel *et al.* 2000; Silva *et al.* 2008). Elevated occurrences of *F. profunda* have been reported as indicators of low productivity and well-stratified waters (Okada *et al.* 1979; Beaufort 1997; Marino *et al.* 2008). Jointly, their absolute numbers and relative abundances suggest a consistent development regarding the coccolithophore paleo-productivity similar to the five phases of varying SSTs before. Until ~2.00ka BP upwelling, water mixing and coccolithophore productivity was low, as indicated by low abundances of *C. braarudii* and *G. oceanica* and high abundances of *F. profunda* (Figure 3). The following period until 1.10ka BP shows an opposing



**Figure 3:** Compilation of the datasets used for estimating productivity and diversity alongside reference datasets: **a)** abundance of *C. braarudii*, as a putative indicator of upwelling intensity; **b)** *G. oceanica*, as a general productivity-indicator; **c)** abundance of *F. profunda*, mirroring water column stratification; **d)** ecological diversity of the coccolithophore assemblages, as expressed by the Shannon-Index H'; **e)** abundance of *N. pachyderma* (l) from the central BUS, as indicator of upwelling intensity (Farmer et al. 2005); **f)** abundance of sea-ice diatoms in core JPC-10 from the Antarctic Peninsula, as an indicator of latitudinal shifts in the westerly wind belt (Etourneau et al. 2013)

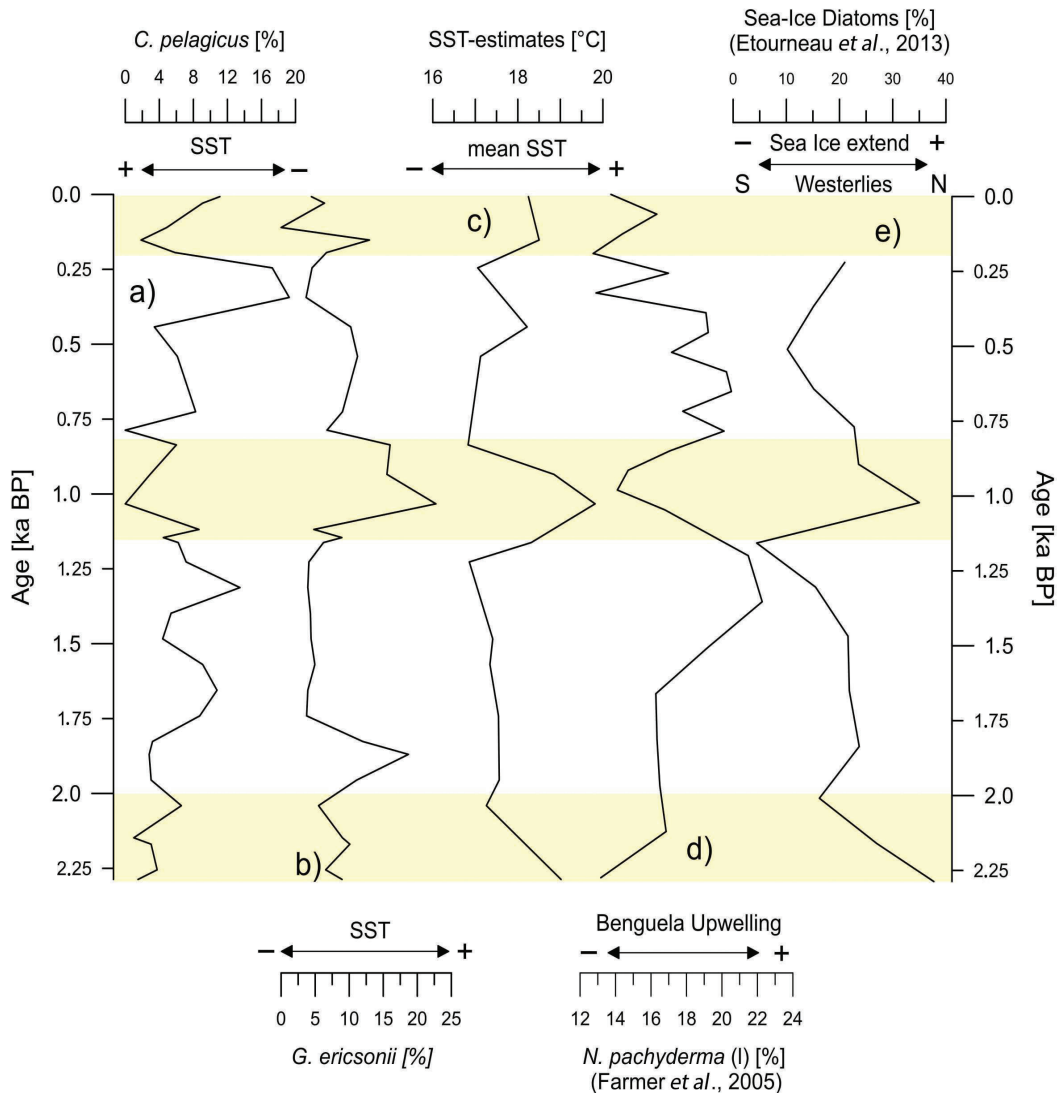
pattern for all three species, which indicates increased mixing and productivity.

For the period between 1.10ka BP and 0.80ka BP a pronounced change towards more stratified waters can be inferred from the strong increase in abundance of *F. profunda*, alongside very low numbers of *C. braarudii* and *G. oceanica*. Productivity increased again between 0.80 and 0.25ka BP, while conditions similar to the period around 1.00ka BP prevailed during the last 250 years.

Although increasing total coccolith numbers generally suggest rising primary productivity in the upper water column, they may not necessarily always indicate increases in upwelling intensity. Coccolithophores are known to also be adapted to less nutrient-rich areas of the open ocean (e.g. Townsend et al. 1994; Van der Wal et al. 1995; Baumann et al. 2005) and are often outcompeted by siliceous

organisms in high-production regimes. This might explain why the highest overall counts are registered during a phase of apparent stagnation of the water column (1.1–0.8ka BP). Bearing this in mind, a significant change in the productivity can still be identified at around 1.50ka BP, from which point total absolute numbers show constantly higher values than in the lower part of the sediment core (Figure 2).

The uncertainty regarding the influence of changing upwelling conditions, and its imprint on the nannofossil assemblage, might also explain the slightly ambiguous results of the Shannon-Index H' diversity assessment (Figure 3). The phases of low inferred coccolithophore productivity show the most monotonous species assemblages; however, a few samples with arguably more diverse assemblages fall within these timeframes as well (e.g. 2.10ka BP and 0.40ka BP).



**Figure 4:** Compilation of the datasets used for SST-reconstruction, alongside reference datasets: **a)** *C. pelagicus* as a cold water indicator; **b)** *G. ericsonii* as a warm water indicator; **c)** results from the *Gephyrocapsa*-based SST-transfer function as developed by Bollmann *et al.* (2002); **d)** abundance of *N. pachyderma* (l) from the central BUS as indicator of upwelling intensity (Farmer *et al.* 2005); **e)** abundance of sea-ice diatoms in core JPC-10 from the Antarctic Peninsula, as an indicator of latitudinal shifts in the westerly wind belt (Etourneau *et al.* 2013)

### 5.3 Link to continental climate variability and possible driving mechanisms

As mentioned above, there are two principal mechanisms that can alter upwelling intensity in the southern BUS. The first one being the Ekman pumping induced by the equatorward component of the South East trade winds; the second being the variability in the strength of the Agulhas leakage, where a reduced leakage of warm saline water is thought to facilitate the upwelling (Cohen & Tyson 1995; Schumann *et al.* 1995; Lund & Curry 2006; Biastoch *et al.* 2009). As the amount of leakage is linked to the position and intensity of the westerly wind belt, both the SE-trades and the Westerlies have to be considered when assessing the driver behind the observed changes.

Relating the coccolithophore data with other paleo-oceanographical and paleoclimatological datasets from

the area is limited by the scarcity of comparable records that cover this short period of time at a similar resolution. The data reported by Farmer *et al.* (2005) on the abundances of *N. pachyderma* (l) from IODP-site 1084 (central BUS, 25.51°S, 13.03°E) reveal a good agreement to the observed changes in upwelling intensity (Figure 3). This coherence over a relatively large distance and between different oceanographical settings (inner shelf vs. lower continental slope) implies a common driving mechanism where, generally, upwelling intensifies in phase with a strengthening of the SE-trade winds.

As mentioned before, the trade winds are the main source of moisture in the SRZ (Summer Rainfall Zone) (see Figure 1) of southern Africa (Tyson *et al.* 2000; Chase & Meadows 2007; Truc *et al.* 2013). Building on this understanding, Chase *et al.* (2009) recently published work

on the nitrogen isotopic composition of rock hyrax mid-dens from the SRZ, establishing this as an approximation for SE-trade wind intensity. This record does not reveal any major changes in the investigated interval, except for the last 250 years. The nitrogen isotopic composition indicates wetter conditions and therefore a strengthening of the SE-trades in the same period where more stratified and warmer waters are indicated by the coccolithophore assemblage. This mismatch either points to a decoupling of trade wind strength and upwelling intensity for the late Holocene or the presence of another localized driving mechanism in the southern BUS.

As an alternative, data on the abundance of sea-ice diatoms from the Palmer Deep, western Antarctic Peninsula (64.88°S, 64.20°W), presented by Etourneau *et al.* (2013), can be used as an indicator for the extent of the Antarctic sea ice and, therefore, the latitudinal position of the Westerlies in the late Holocene. Here, a better correlation with the changing composition of the coccolithophore assemblage can be found. Higher abundances of sea ice diatoms (indicative of a northward shift in the westerly wind belt) generally coincide with phases of reduced upwelling intensity and warmer SSTs as inferred from the coccolithophore assemblages here (see Figure 3, 4). On the one hand, this contradicts the proposed hypothesis that the Agulhas leakage, as governed by the Westerlies, controls upwelling intensity in the southern BUS. On the other hand, a clearer pattern emerges when taking into account that the Southern Hemisphere Westerlies and the South East Trade Winds are counteracting atmospheric systems. Weakening of the one usually results in a greater influence of the other. Therefore, the aforementioned phases of increased sea ice presence mean a more northerly position of the westerly wind belt which, in turn, reduces the influence on the upwelling in the southern BUS. It does not seem to affect the general trade wind intensity, as the nitrogen isotopic composition does not follow this trend, but does appear to have a localized effect on the water column structure in the vicinity of the core site.

## 6. Conclusion

Changes in the nannofossil assemblage of sediment core GeoB 8323-2 from the Namaqualand mudbelt allow for a detailed reconstruction of late Holocene oceanographic changes in the southern Benguela upwelling system. Throughout the last three millennia, five phases of characteristic environmental conditions can be identified:

1. 2.25 to 2.00ka BP: Upwelling and productivity indicate species are low in abundance, while a high percentage of *F. profunda* and results from the SST-transfer function indicate warm, stratified waters. This coincides with a more northerly inferred position of the Westerlies.
2. 2.00 to 1.10ka BP: The coccolithophore assemblage shows a distinctly different composition, indicating

cooler, more productive waters. This interpretation is backed by similar results from the northern BUS, as well as reduced influence of the Westerlies.

3. 1.10 to 0.70ka BP: A brief episode of warmer, more stratified waters is indicated, coinciding with peak northward expansion of the Antarctic Sea Ice and, therefore, the westerly wind belt.
4. 0.70 to 0.25ka BP: A second phase of cooler waters is indicated by distinct increases in *C. pelagicus* and *C. braarudii*. Increased coccolithophore productivity is implied by higher amounts of *G. oceanica*. Moreover, *F. profunda* is nearly absent from the samples of this period, pointing towards more turbulent waters.
5. 0.25ka BP to present: The coccolithophore assemblage implies another period of warmer, more stratified water at the core site. This stands in contrast to trade wind related data from the continent, as well as results from the nearby cores as shown by Weldeab *et al.* (2013), who presented geochemical and sedimentological indications for cooler SST and stronger upwelling.

Deciphering a single driving mechanism proves difficult, as no direct correlation with either of the proposed mechanism can be identified. Bearing in mind the counteracting nature of the two main wind systems, the Westerlies and SE-trades, the latitudinal changes of the Antarctic sea ice extent gives credit to the conceptual model of a modulation of upwelling in the southern BUS driven by the position of the westerly wind belt. As these changes are, however, not necessarily mirrored in reconstructions of the trade wind intensity, this appears to be a localized effect.

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Raw data can be accessed as digital appendix through the information system PANGAEA ([www.pangaea.de](http://www.pangaea.de)).

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