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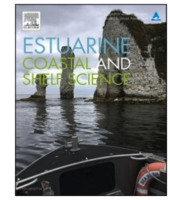

A new model-based coastal retention index (CORE) identifies bays as hotspots of retention, biological production and cumulative anthropogenic pressures

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ABSTRACT

Retention is a key driver of biological productivity near the coast since increased concentrations of planktonic particles in retention hotspots boost local primary production, availability of particulate food and larval recruitment. Known retention sites, such as bays, are also places where anthropogenic pressures accumulate in the form of pollution, harmful algal blooms, fisheries, aquaculture and port developments. In the face of these growing hazards, South African bays were recently declared 'threatened' priority sites for enhanced conservation and marine spatial planning (MSP). Multidisciplinary studies that spatially relate human impacts to physical features (such as retention patterns) and ecological processes (such as primary production) are valuable in this context. This study made use of a high resolution CROCO (Coastal and Regional Ocean Community Model) model along with the Parcels particle-tracking tool to develop a spatio-temporal coastal retention index (CORE) for the South African coastal ocean. To explore links between retention, biological productivity and anthropogenic impacts, a monthly time series of CORE (2001–2012) was evaluated in relation to satellite-derived coastal chlorophyll-a (Chl-a) and an index of cumulative human pressure. CORE showed variable temporal relationships with Chl-a among different subregions, however, when integrated over time, their spatial trends and peaks commonly aligned. This was most obvious on the south coast, where retention, Chl-a and human pressures peaked in the majority of bays that characterise this region. In the case of St Helena Bay on the west coast, CORE failed to represent a prominent retentive feature associated with upwelling, due to rapid alongshore advection of particles outside the 25-km retention radius of CORE. Despite this limitation, CORE provided profound insight into the variability of the coastal circulation around South Africa and its coupling with other socio-ecological variables. By contributing a novel data layer for MSP, CORE assists the integrated coastal management of bay ecosystems that face the hazards of multiple destructive uses.

1. Introduction

Coastal oceans support the livelihoods of a large proportion of Africa's population through fisheries and other extracted resources, tourism, shipping and various ecosystem services (Spalding, 2016). With growing Blue Economies, multiple and at times conflicting interests commonly exist for the utilisation of coastal oceans, while cumulative pressures on coastal ecosystems compromise the functioning and health of ecosystems (Lotze et al., 2006). To facilitate fair decision-making and the sustainability of resources, ecosystem-based marine spatial planning (MSP) has been increasingly promoted as an inclusive multi-stakeholder process that balances economic, social and environmental demands (Long et al., 2015; Qiu and Jones, 2013). MSP depends on reliable spatial data that capture the diverse aspects of the socio-ecological system, including the different uses and impacts, distribution of natural resources and habitats, and ecological processes. Since ecosystem

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health in the oceans is tightly linked with oceanographic processes that support biological functioning, hydrodynamic ocean models can provide useful spatially and temporally continuous information of essential ecological processes.

In South Africa, 30% of the population live within 60 km of the coast (DEA, 2015) and coastal goods and services in the form of direct economic benefits from the fishing industry, ports and harbours, coastal lifestyles, recreation and tourism contribute ca. 35% to the GDP (WWF-SA, 2016). In the National Biodiversity Assessment of 2018 (Sink et al., 2018), coastal ecosystems have been identified as hotspots of cumulative human pressures (Majiedt et al., 2018). Bays were highlighted as 'threatened' ecosystems, where a myriad of hazards that threaten ecosystem health coexist. These include various forms of fishing and harvesting, aquaculture, port and harbour developments, shipping, new introductions of invasive species, pollution and harmful algal blooms (Pfaff et al., 2019). Based on this assessment, bay ecosystems were recommended as priority areas for engaging recently legislated MSP processes (Marine Spatial Planning Bill, DEA (2017)) to prevent further degradation and eventual collapse. An initial and fundamental challenge in this process has been the objective spatial delineation of bays according to physical features that make them ecologically discrete and distinct from areas outside bays, which is particularly challenging given the great variability in the geomorphology of bays. A key physical process that characterises bay ecosystems is the retention of water and particles induced by the interaction of coastal currents with the shelf and shoreline topography (Largier, 2020). However, to date, retention on the very inner shelf has not been quantified and mapped in a format that can be used in spatial planning.

Various socio-ecological processes are facilitated by retention. By causing longer residence time of seawater and its associated planktonic life forms in the sunlit coastal zone, retention leads to warm and thermally stratified environments, which are ideal for the formation of dense phytoplankton blooms (Largier, 2020). These in turn support productive pelagic food webs (Kudela et al., 2008), as higher trophic levels, like zooplankton, fish and birds aggregate in bays to feed or reproduce. Benthic marine communities also benefit from retention and the associated stratification and surface productivity, which promote the transport of planktonic larvae and particulate food to coastal habitats inside bays (Pfaff et al., 2015). Such concentration of life, in turn, attracts fishing and other extractive activities into bays (e.g., Pfaff et al., 2019).

In terms of ocean dynamics and geomorphology South Africa has three distinctly different coastal regimes that support different ecosystems and different coastal and offshore industries, presenting different hazards to coastal communities. The west coast encompasses part of the Benguela Upwelling System (BUS), one of the world's four major eastern boundary upwelling systems, which is highly productive and supports rich marine food webs, a lucrative fishing industry and artisanal fishing communities. Upwelling on the relatively broad shelf (Fig. 1) is strongly

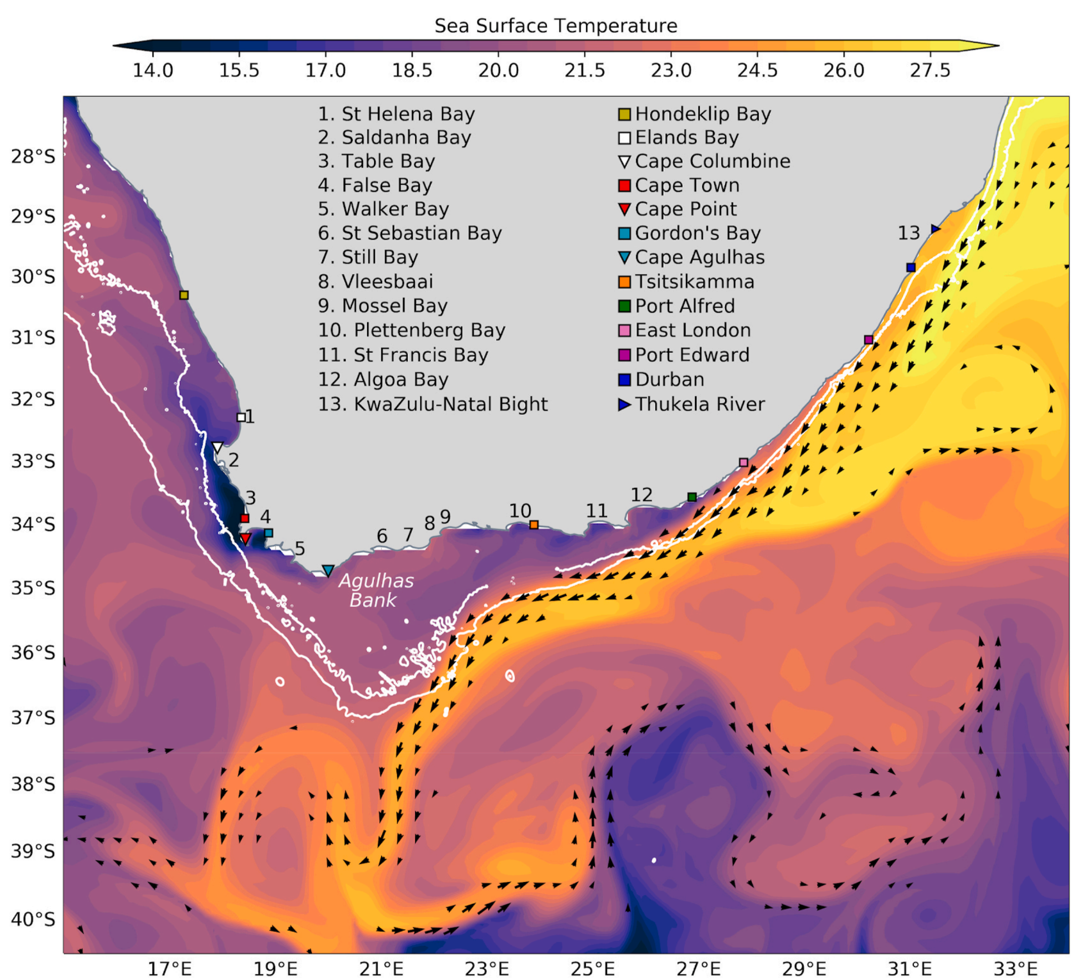

Fig. 1. Sea surface temperature of the oceans surrounding South Africa, with overlaid arrows showing current velocities that exceed 0.8 m s^{-1}; the data shown are daily means (on January 20, 2020) at 1/12° spatial resolution obtained from the CMEMS *Operational Mercator global ocean analysis and forecast* model product (global-analysis-forecast-phy-001-024). The 1000-m and 200-m isobaths, from GEBCO_2021 (https://www.gebco.net/data_and_products/gridded_bathymetry_data/), are shown as white lines. The frame of the figure corresponds with the boundaries of the CROCO domain. Numbers indicate positions of the most prominent bays and bights, and symbols mark place names mentioned in the text.

seasonal along the west coast and dominates during austral summer months.

The net flow over the inner shelf, from Cape Point to about 27°S, is perennially poleward (Nelson, 1985; Nelson and Polito, 1987) and related to a persistent northward sea surface slope (Nelson, 1985). Only during the early upwelling season (November–December) when upwelling-favourable winds are most persistent, are the coastal currents predominantly equatorward, while they revert to poleward during the late upwelling season when there are more wind relaxation events (Fawcett et al., 2008). Measurements of the mid-shelf region reveal an equatorward flow with weak directional stability and, at the shelf break, intense baroclinic equatorward jets (Nelson, 1985). This current structure is suggestive of the retentive nature of the broad shelf region northward of Cape Columbine that was investigated in a recent modelling study (Manyakanyaka, 2020). The intensification of the shelf-break jets during the upwelling season (Veitch et al., 2018) serve to intensify the retentive nature of this entire shelf region. Phytoplankton abundance on the west coast generally increases throughout spring with the start of upwelling and increased day length, with concentrations peaking in late summer. North of Cape Columbine the shelf waters are characterised by warmer, stratified water and higher phytoplankton biomass, as dinoflagellate blooms tend to form and persist on the shelf throughout summer (Pitcher et al., 2010).

The South African south coast, eastward of Cape Agulhas up to and including Algoa Bay is subject to coastal upwelling when the dominant winds are easterly during summer months (Schumann and Martin, 1991). Upwelling-favourable wind events on the south coast have been reported to be more frequent but less persistent than on the west coast (Schumann and Martin, 1991), which is suggestive of reduced periods of offshore Ekman transport losses and enhanced retention. Unlike the more topographically homogeneous west and east coasts, the south coast is characterised by a series of prominent capes and crenulated embayments. Upwelling is initiated at these capes, with the upwelling plumes moving westward with the upwelling jet (Schumann, 1999). There have been limited studies of potential retentive features within the south coast embayments, with most of them focussing on Algoa Bay. Roberts (1990) showed that upwelling-favourable northeasterly winds resulted in complex circulation patterns on the western part of Algoa Bay, while southwesterly winds caused alongshore currents directed downwind. Although the south coast typically displays the physical and biological characteristics of a temperate continental shelf environment, with thermal stratification and subsurface chlorophyll maxima, day to day variability may occur as phytoplankton respond to changes in the physical environmental and nutrient availability (Probyn et al., 1994) e.g., as introduced by intermittent wind-driven upwelling off the capes.

South Africa's east coast is characterised by a much narrower shelf than both the south and west coasts, other than the KwaZulu-Natal Bight region where the shelf broadens. The coastline is oriented toward the northeast, without any distinct embayments. The Agulhas Current influences the dynamics all along the east coast, most directly where the shelf is narrowest, between approximately Port Edward and Port Alfred where nearshore currents flow predominantly southwestward (Harris, 1978). Nearshore countercurrents are observed to occur on the narrow shelf off East London that are thought to be related to the propagation of coastal trapped waves that are not observed to penetrate further northward (Schumann, 1999). Dynamic upwelling on the inshore edge of the Agulhas Current is found at locations where the shelf broadens along the path of the current (Lutjeharms et al., 2000), most prominently at Port Alfred where wind-driven upwelling also occurs. Aside from the region between Port Alfred and East London, the only other region on the east coast that is known to support retention is the KwaZulu-Natal Bight where there is a semi-permanent cyclonic eddy, known as the Durban eddy, that is thought to be driven by the interaction of the Agulhas Current with the topographic deviations off Durban (Guastella and Roberts, 2016). Unlike the oligotrophic waters associated with the Agulhas Current, the shelf waters of the KwaZulu-Natal Bight are considered to be mesotrophic (Barlow et al., 2008; Lamont and Barlow, 2015), with chlorophyll concentrations tending to be elevated in the north and decreasing towards the south (Lutjeharms et al., 2000).

Lagrangian particle tracking has been used in a variety of oceanographic and fisheries applications in the oceans surrounding South Africa. Miller et al. (2005); Lett et al. (2006, 2015) used this modelling technique to simulate and quantify retention patterns in the southern Benguela region, however, while indicating high levels of retention in some coastal embayments, the resolution of their models (9 km) was too coarse to resolve nearshore circulation patterns. In the Greater Agulhas System, applications include the dispersion of juvenile turtles (Le Gouvello et al., 2020), plastic transport (Collins and Hermes, 2019), ocean surface product validation (Hart-Davis et al., 2018) and ocean dynamic studies (Daher et al., 2020). In this study, we apply a particle tracking model to characterise the nearshore ocean dynamics around the South African coast with respect to retention and develop a spatio-temporal coastal retention index (CORE) for the 25-km strip adjacent to the coast, based on 20 years of model output. We use this index to interrogate the following hypotheses: (1) bays are hotspots of coastal retention; (2) greater retention is associated with greater biological productivity, as indicated by coastal Chl-a concentrations; and (3) areas of greater retention coincide with areas where human pressures accumulate, such as proposed for coastal bays. By providing a novel data layer that quantifies retention, a key physical driver of coastal ecosystem dynamics and productivity, this study contributes important and thus far missing information for the sustainable management of South Africa's coastal resources, e.g., through MSP.

2. Material and methods

2.1. The CROCO numerical model

For the development of the CORE index, the realistic, regional hydrodynamic model described by Tedesco et al., (2019) was used. This configuration, based on the Coastal and Regional Ocean Community (CROCO) model captures the salient dynamics of the Indian and Atlantic sectors of Southern Africa's ocean and provides an improved representation of the shelf-scale dynamics at a high resolution. CROCO is based on the Regional Ocean Modelling System (ROMS: Shchepetkin and McWilliams (2005)) that solves the hydrostatic primitive equations for momentum and the state variables on a terrain-following grid.

The approach was to make use of the AGRIF two-way nesting capability (Debreu et al., 2008) of CROCO that not only allows features of the lower resolution 'parent' model to feed into the boundaries of the higher resolution 'child' model, but also for features of the child to feedback into the parent domain. In this case, a triply-nested (a parent-child- and grand-child domain, with two-way nesting between each) configuration with 60 terrain-following vertical levels was developed, scaling down from a 1/4° grid that encompasses most of the South Equatorial Indian Ocean and part of the Atlantic, to a 1/12° grid that captures the salient ocean features around Southern Africa and finally to a 1/36° grid that is limited to South Africa's ocean region and resolves the smaller-scale features of the shelf. The triply-nested configuration was run for 22 years, spanning 1993 to 2014, with output saved as daily averages. The 1/4° GLORYS global reanalysis product (Ferry et al., 2012) was used to force the oceanic lateral boundaries of the CROCO parent domain, while daily ERA-ECMWF atmospheric reanalysis outputs (Dee et al., 2011), with a horizontal resolution of ~80 km, were used for the surface forcing. More detailed information on the model configuration can be found in Tedesco et al. (2019). All three of the domains can be accessed at: http://dap.saeon.ac.za/thredds/catalog/SAEON.EGAGASINI/2019.Penven/catalog.html.

The highest resolution grid described above was used by Tedesco et al. (2019) as lateral boundary conditions (in an offline nested approach) for an even higher resolution simulation. They evaluated the 1/36° grid with respect to the mean Agulhas Current as well as surface turbulence, or eddy kinetic energy (EKE), compared to its satellite-derived counterparts (refer to Fig. 4 in Tedesco et al. (2019)). Key features of the Agulhas Current, including the patterns and magnitudes of EKE were found to be generally well represented by the model and the explanation to amplitude deviations was the different spatial resolutions of the datasets. Simulating coastal regions in models tends to be much more difficult to achieve accurately due to the increasing dominance of smaller-scale variability due to coast-current interactions and, in uncoupled models such as this one, the poor representation of nearshore wind patterns in the global atmospheric forcing products. A detailed model validation, based on the bias and correlation of daily model SST vs. satellite SST, is provided in Appendix 1 (Supplementary material). Despite a persistent warm model bias on the west coast, probably related to an under-representation of upwelling favourable winds in the model, the SST correlations are consistently high in this region, suggesting that the variability is well captured. SST biases tend to be smaller everywhere else along the coastline (<1 °C), except where the Agulhas Current starts to veer away from the coast in the vicinity of the Port Alfred upwelling cell, where the model underestimates SST by more than 2 °C. The correlations are lower on the east coast, suggesting that the model does not capture the full extent of the more extreme variability in this region. While a rigorous evaluation of the coastal currents is limited by a paucity of *in situ* observations, our assessment of coastal SST provides an indication that the model does sufficiently well at this scale.

2.2. Development of the CORE index from a particle tracking model

The spatio-temporal CORE index was developed for the full coastline of South Africa using a Lagrangian particle tracking framework, Parcels (Delandmeter and Sebille, 2019), which was forced by the ocean surface current data obtained from the CROCO model. Surface-confined particle tracking was applied to test hypothesis (2), that retention hotspots coincide with areas of primary production. The Chl-a data used in this study are derived from satellite ocean colour products (see 2.3) which only detect surface chlorophyll. Furthermore, various forms of coastal pollution are positively buoyant, such as those associated with riverine run-off, oil spills and nurdle spills. A surface-confined configuration therefore seemed most appropriate. Based on pilot trials, monthly retention was defined as the length of time a particle stayed within 25 km from its deployment site near the coast. This measure was chosen to account for retention in some of the larger bays in the region and to allow the particles to be influenced by a representative number of grid cells of the model.

Virtual particles of neutral buoyancy were deployed at the sea surface in each 3x3-km model grid cell along the 20-m bathymetry contour, i.e., within the first 1–2 grid cells from the shore, along the entire (>3000 km) coastline of South Africa for 12 years (2001–2012). These criteria were chosen after some pilot runs, to simulate very near-shore phytoplankton particles, but avoid that too many virtual particles 'get stuck' when colliding with the coastline, which would inflate retention estimates. In this study, when a particle hit a boundary such as the coastline, the particle was stopped, its position was recorded, and it was removed from the study. No additional boundary conditions were applied as the model used to force the virtual particle did not contain tides and waves to justify the use of boundary conditions to move the 'stuck' particles back into the model domain. While mostly successful, in regions of extremely narrow coastlines particles would occasionally recirculate within a certain region which resulted in spikes in retention (Figs. 2d and 7d). Although these events may not be realistic, they were not removed from this study as it is difficult to disentangle real from artificial trapping events. To obtain a representative monthly retention value, two virtual particles were deployed per 3x3-km grid cell for 100 consecutive days starting at the first day of each month and for all 12

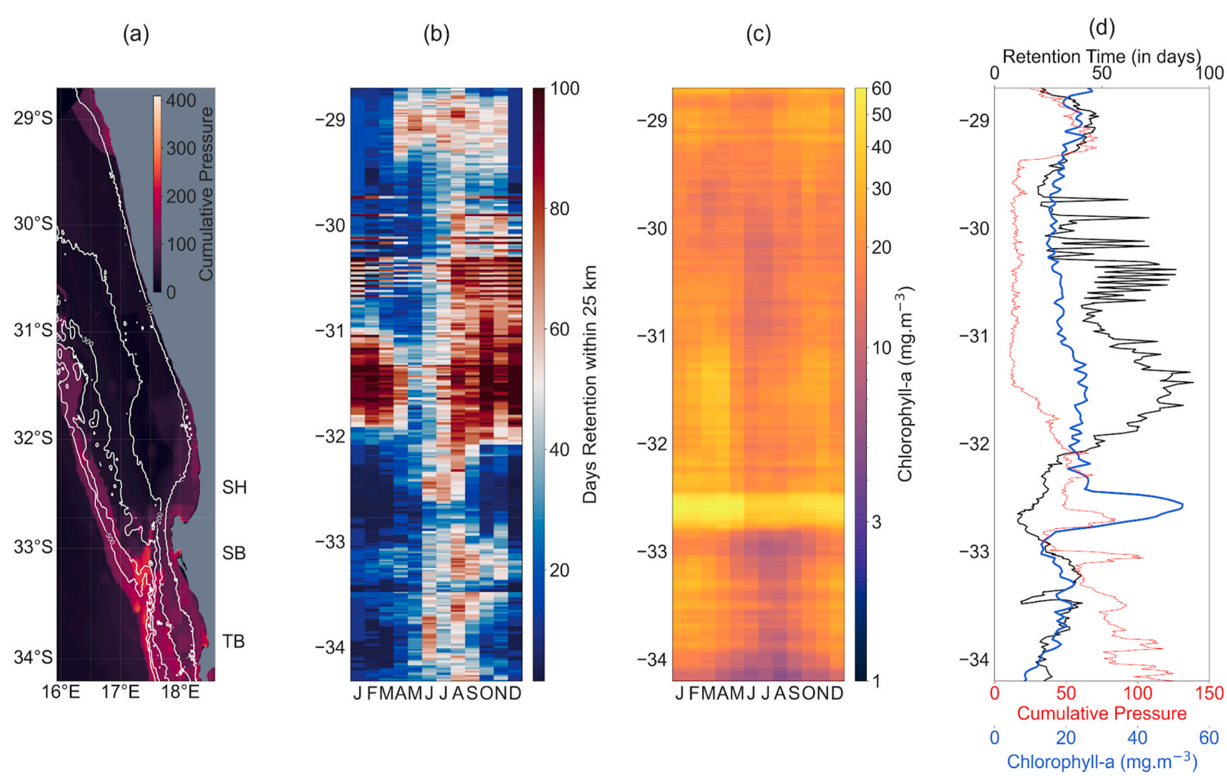

Fig. 2. The West Coast: (a) cumulative anthropogenic pressure map (shading) and bathymetry (white lines represent 100-m isobaths); (b) the spatio-temporal coastal retention index (CORE); (c) spatio-temporal coastal chlorophyll-a; (d) latitudinal variability and relationships between long-term averages of CORE (black line), chlorophyll-a (blue line) and cumulative anthropogenic pressures (red line). The abbreviations given in (a) provide a representation of the position of important coastal features: St Helena Bay (SH); Saldanha Bay (SB) and Table Bay (TB). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

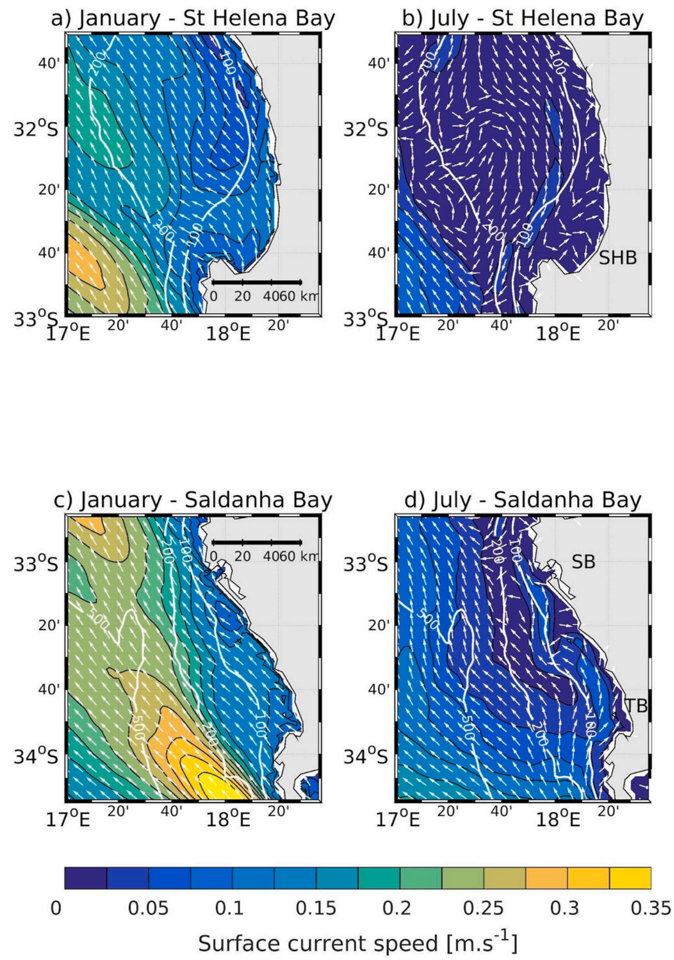

Fig. 3. West coast bays: Average surface current speed (shading; m.s^{-1}) and direction (vectors) in January (left) and July (right) for (a, b) St Helena Bay (SHB) and (c, d) Saldanha Bay (SB) and Table Bay (TB). The solid while lines show bathymetry (100-m intervals) and every third vector is plotted.

years of the simulation. For each particle that was deployed, its retention time was estimated based on the length of time it took to travel 25 km from the deployment site. The data for each monthly deployment were then binned and monthly averages calculated, accounting for differences in the numbers of days for different months.

2.3. Chlorophyll-a

We used the V4.2 monthly 4-km Chl-a product from the ESA Ocean Colour Climate Change Initiative (OC–CCI) (https://www.oceancolour.org/thredds/ncss/grid/CCI_ALL-v4.2-MONTHLY/dataset.html). This product is derived from a globally merged dataset comprising of MEdium spectral Resolution Imaging Spectrometer (MERIS), Moderate-resolution Imaging Spectroradiometer-Aqua (MODIS-Aqua), Sea-viewing Wide-Field-of-view Sensor (SeaWiFS) and Visible and Infrared Imaging Radiometer Suite (VIIRS) data, providing fewer missing data points than any single mission or other global ocean colour time series (Sathyendranath et al., 2019). The OC-CCI chlorophyll product, chlor_a, is a climate-quality product that is derived using the best performing algorithm for the appropriate optical water type, where the algorithms are blended on a per pixel basis (Jackson et al., 2017); the inclusion of the OC5 algorithm (Gohin et al., 2002) ensures improved performance in optically complex coastal waters compared to standard global ocean colour satellite products. Due to the differences in shoreline orientation, Chl-a data within the first 25 km of the coast were cumulated (i.e. pixel values were summed up) longitudinally for the west and east coasts and latitudinally for the south coast. Data covering the period from January 1, 2001–December 31, 2012 were averaged for each month to create a monthly climatology.

2.4. Anthropogenic pressure data

A cumulative anthropogenic pressure index was sourced from the South African Biodiversity Institute (Sink et al., 2018). The cumulative pressure map incorporates spatial data layers from 31 anthropogenic activities, which include pressures from 20 different fisheries sectors, the petroleum industry, mining, shipping, ports and harbours, coastal developments, mariculture, pollution and freshwater flow reduction. Each pressure was scored according to its intensity in different parts of the South African coastal and marine areas, and data standardised to a consistent format and range. All individual pressures were then summed up to provide a cumulative score (see Sink et al. (2018) for details on individual pressures and data processing). Coastal cumulative pressure scores were extracted by averaging scores within 0.25° (ca. 25 km) from the coast. For the west and east coasts, data were averaged by latitude, and for the south coast by longitude to align with retention and Chl-a datasets.

3. Results

The CORE index developed in this study was evaluated in relation to Chl-a and cumulative anthropogenic pressures (see Supplementary materials Appendix 2, showing seasonal averages of the index). Of primary focus was the very inner shelf region, and results refer to retention within ca. 25 km from the shore. To account for the differences in shoreline orientation of the South African coast and associated differences in oceanographic regimes, the coast was divided into west, south and east coast segments and results are presented and discussed separately. For the purpose of this study, the coastal stretch between Cape Point and Cape Agulhas was considered as part of the south coast to account for the angle of the shoreline and southward-facing bays, while it is commonly considered as part of the west coast upwelling region.

3.1. West coast

On the west coast, four distinct subregions emerged in terms of the coupling between coastal retention, Chl-a and cumulative anthropogenic pressures. (i) North of 30°S, where the shelf is relatively broad (Fig. 2a) and upwelling perennial, retention was high from April to November and low in the summer months (Fig. 2b), while Chl-a showed little seasonality (Fig. 2c). Long-term averages did however reveal similar spatial trends in retention, Chl-a and cumulative pressures, which were all high in northern Namaqualand (north of 29.5°S) and decreased towards the southern part of the subregion (Fig. 2d). (ii) In the central subregion (30–32°S), which is characterised by a narrow shelf (Fig. 2a), retention and Chl-a were both relatively high for most of the year except during winter (May–July) (Fig. 2 b, c). Long-term average retention showed substantial spatial variability (spikes) in the CORE index (Fig. 2d), especially in the northern section of this subregion (30–31°S), which is likely an artefact since some virtual particles inevitably get trapped in nearshore circulation features under narrow-shelf deployment, thereby generating inflated retention times. Nevertheless, coastal retention and Chl-a were also coupled in this subregion, both gradually increasing from north to south, with the broadening of the shelf in the greater St Helena Bay region (Fig. 2d). Cumulative pressures were low in most of this subregion but rose steeply in northern St Helena Bay (Fig. 2d). (iii) The St Helena Bay subregion (32–32.8°S) is characterised by a very wide shelf. Chl-a is high in summer-autumn, while CORE is inversely related, both in terms of seasonality and long-term averages, and reaches the lowest values on the west coast (Fig. 2b and c). Two distinct spikes in cumulative pressures occur in the bay. (iv) In the southern subregion (south of 32.8°S), where the shelf is relatively

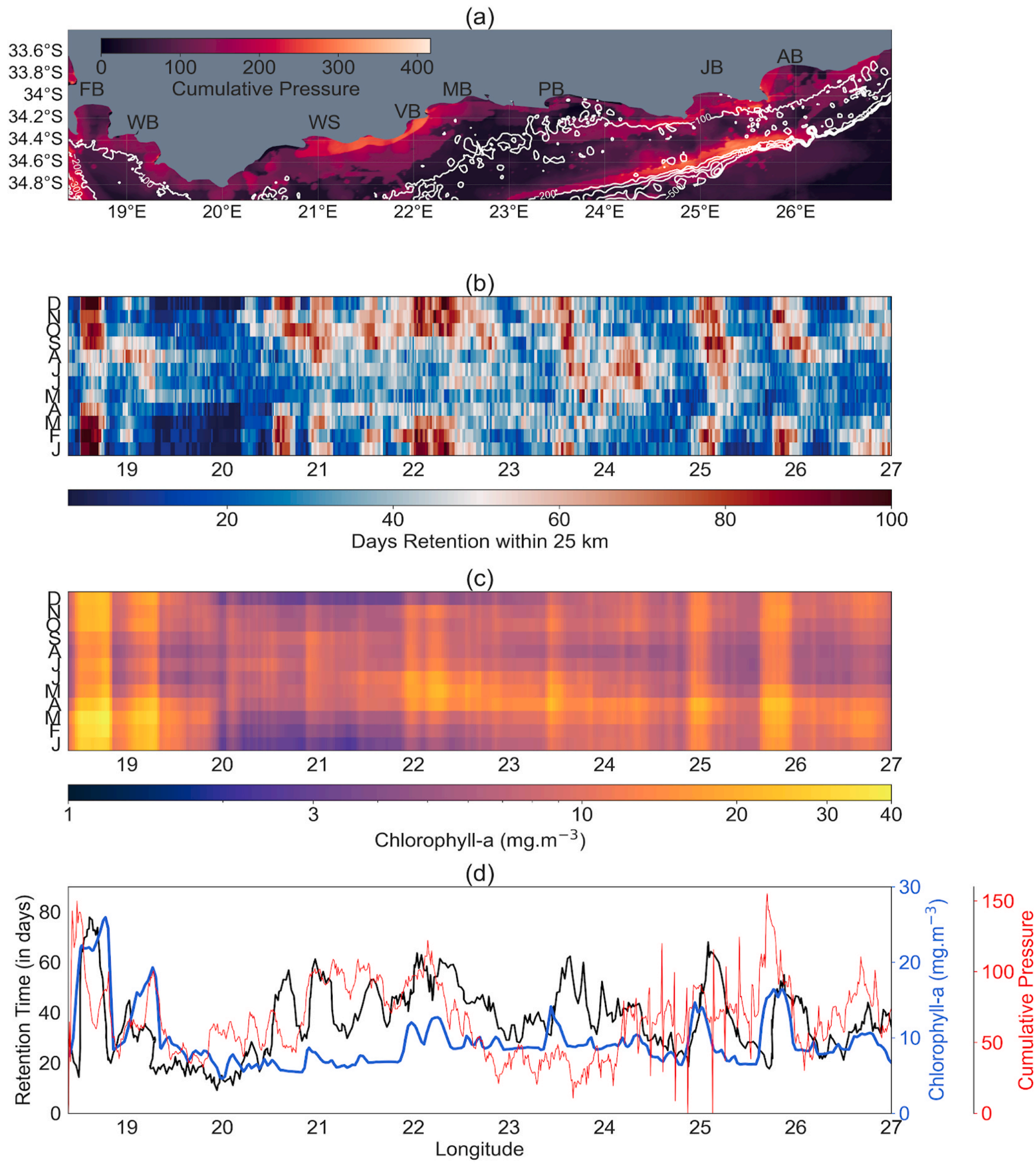

Fig. 4. The South Coast: (a) cumulative anthropogenic pressure map (shading) and bathymetry (white lines represent 100-m isobaths); (b) the spatio-temporal coastal retention index (CORE); (c) spatio-temporal coastal chlorophyll-a; (d) longitudinal variability and relationships between long-term averages of CORE (black line), chlorophyll-a (blue line) Vleesbaai-Mossel Bay and decreasing again towards the east. All three indices showed distinct peaks in St Sebastian Bay, Stillbaai (Witsands) and Vleesbaai-Mossel Bay. The exception was Plettenberg Bay, where retention and Chl-a were also elevated but cumulative and cumulative anthropogenic pressures (red line). The abbreviations given in (a) provide a representation of the position of important coastal features: False Bay (FB); Walker Bay (WB); Witsands (WS); Vleesbaai (VB); Mossel Bay (MB); Plettenberg Bay (PB); Jeffreys Bay (JB) and Algoa Bay (AB). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

broad and upwelling seasonal during austral summer, CORE and Chl-a were again inversely related, with retention peaking in winter (June–September) while Chl-a was highest during the rest of the year (Fig. 2 b, c). Long-term spatial averages of CORE and Chl-a were low and closely coupled (Fig. 2d), while anthropogenic pressure steadily increased southward of 33°S.

A closer look at average surface currents obtained from the CROCO model in January and June for three bays on the west coast shows distinct seasonal circulation patterns. In summer (January), when upwelling is most pronounced, strong equatorward currents predominate over most of the inner shelf (<200 m depth) (Fig. 3 a, c), introducing a northward alongshore current in the very nearshore, which is stronger within St Helena Bay, between 32°S and 32°40′S than further northward and around the Cape. In winter (July), surface current speeds are lower and the inshore region, particularly in bays, is characterised by complex patterns, including the recirculation in the lee of headlands (Fig. 3 b, d). During the summer upwelling season, the surface flow in the model is dominated by northwestward Ekman drift throughout this west coast region, however at greater depths a cyclonic circulation is evident (not shown) within SHB, with a distinct poleward flow that is established in the nearshore region, which is consistent with observations.

3.2. South coast

The coastal topography of the south coast is characterised by a series of bays. West of Cape Agulhas, bays are square-shaped and bounded by headlands on either side, whereas east of the cape bays tend to be crenulate-shaped and bounded by a headland on the west while open on

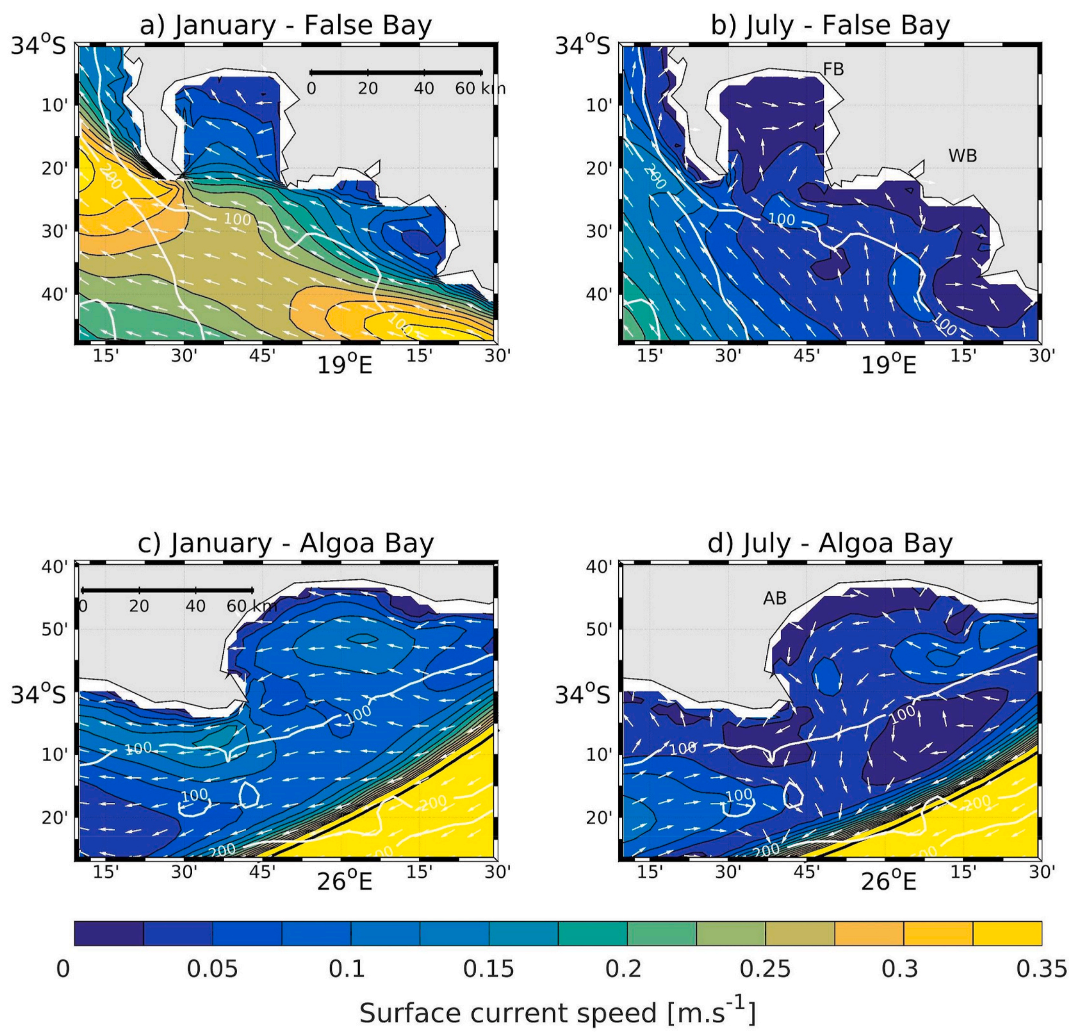

Fig. 5. South coast, western bays: Average surface current speed (shading; m.s^{-1}) and direction (vectors) in January (left) and July (right) for (a, b) False Bay, Walker Bay (FB and WB respectively) and (c, d) Algoa Bay (AB). The solid while lines show bathymetry (100-m intervals) and every third vector is plotted.

their eastern side (Fig. 4a). Maxima of the CORE index coincided with bays (and minima with stretches of straight coastline), with the most pronounced retention centres arising in False Bay, the Vleesbaai-Mossel Bay area and St Francis Bay, but clear signals of retention also present at Walker Bay, de Hoop (Bay), St Sebastian Bay (Witsands), Still Bay, Plettenberg Bay and Algoa Bay (Fig. 4b). Retention was strongly seasonal in all cases, and greatest during the summer upwelling months (September–March). With respect to the coupling between retention, Chl-a and cumulative pressures, three subregions emerged. (i) West of Cape Agulhas (20°E), retention and Chl-a were both high in summer and low in winter, most obviously in False Bay (Fig. 4b and c). Long-term averages of cumulative pressure, CORE and Chl-a all reached regional maxima in this bay and clear peaks in Walker Bay (Fig. 4 d). (ii) In the central region between Cape Agulhas and Tsitsikamma (24°E), CORE remained greatest in summer, while Chl-a peaked in autumn and winter. Long-term averages showed similar spatial trends of retention and human pressures, increasing from Cape Agulhas to Vleesbaai-Mossel Bay and decreasing again towards the east. All three indices showed distinct peaks in St Sebastian Bay, Stillbaai (Witsands) and Vleesbaai-Mossel Bay. The exception was Plettenberg Bay, where retention and Chl-a were also elevated but cumulative pressures were low. (iii) In the eastern subregion, retention and Chl-a were closely coupled and concentrated in bays from spring to autumn (September–March) (Fig. 4b and c), which was also reflected in the long-term averages (Fig. 4d). Anthropogenic pressure was highly variable but expressed a distinct maximum in Algoa Bay which coincided with peaks in Chl-a and retention (Fig. 4d).

Surface currents in all south coast bays (except for Plettenberg Bay) were stronger in summer (January) than in winter (July) (Figs. 5 and 6). In the summer upwelling season, average current speeds inside bays were markedly lower than immediately offshore and outside the bays, suggesting a recirculation of water inside bays and water retention (Fig. 5a, c, 6a, 6c). Various bays featured pockets of minimum current speed in the lee of the headlands that form their boundaries. In winter, alongshore surface currents inside bays were more similar to those outside, suggesting the regular flushing of bays and low retention (Fig. 5b, d, 6b, 6d).

3.3. East coast

There are no major bays on the east coast; the most pronounced bathymetric feature is the broadening of the shelf at the KwaZulu-Natal Bight (Fig. 7a). Four distinct subregions were evident according to retention, Chl-a and anthropogenic pressures: (i) South of 31.5°S near Port Alfred, retention and Chl-a both peaked seasonally from spring to summer (September–March) and were low in winter (Fig. 7b and c). All three indices increased from north to south but were spatially variable. (Fig. 7d). (ii) In the central subregion (30.5–31.5°S), where the shelf is extremely narrow, retention was very low year-round, and Chl-a had a minor peak in late winter/spring (July–September) (Fig. 7b and c).

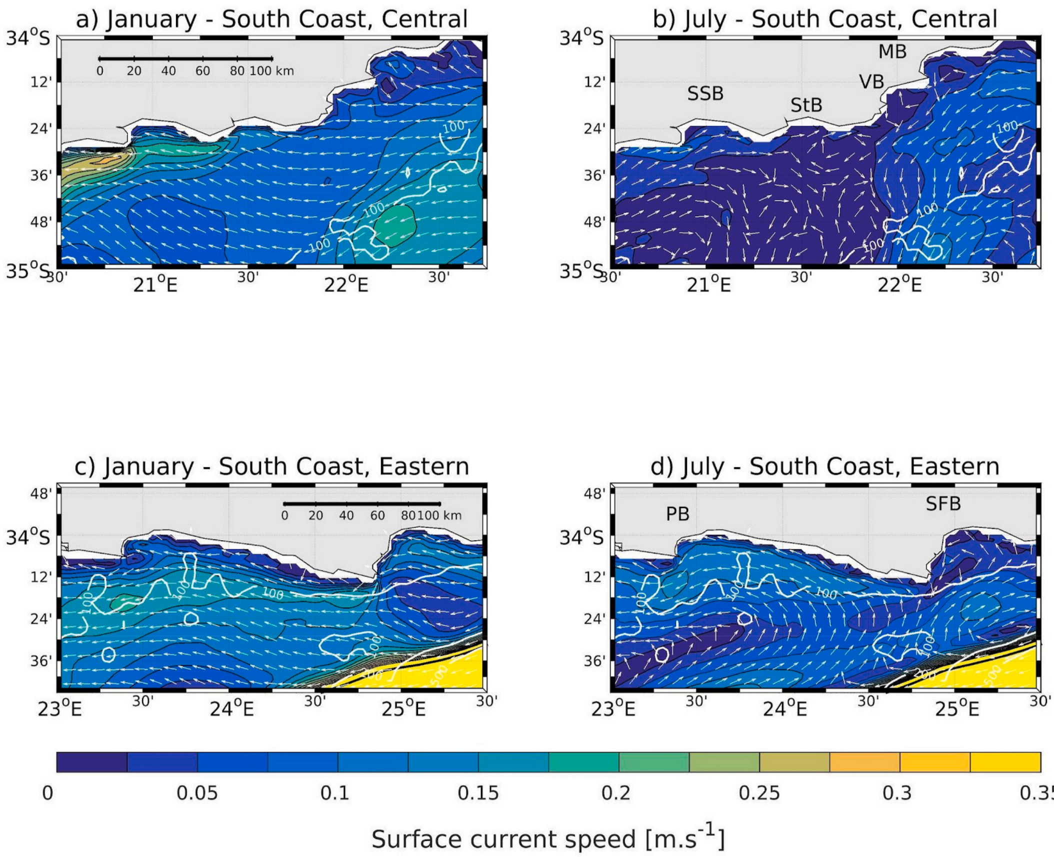

Fig. 6. South coast, central and eastern bays (top and bottom, respectively): Average surface current speed (shading; m.s^{-1}) and direction (vectors) in January (a, c) and July (b, d) for (a, b) St Sebastian Bay (SSB), Still Bay (StB), Vleesbaai (VB) and Mossel Bay (MB), and (c, d) Plettenberg Bay (PB) and St Francis Bay (SFB). The solid while lines show bathymetry (100-m intervals) and every third vector is plotted.

Long-term averaged Chl-a and retention were low (the spikes being artefacts due to particles colliding with the coast), and cumulative pressures were intermediate (Fig. 7d). (iii) The northern subregion (28.5–30.5°S) was dominated by the signal of the KwaZulu-Natal Bight, with enhanced retention and Chl-a, particularly in the winter months (June–September) (Fig. 7b). Chl-a had a pronounced perennial peak to the north of the Thukela River mouth (29.2°S) in the northern part of the KwaZulu-Natal Bight (ca. 29°S), which did however not coincide with the regional peak of retention which was further south. (Fig. 7d). While CORE was greater in the southern part of the bight, anthropogenic pressures were high throughout the subregion. (iv) In the very north, the shelf was again narrow, which coincided with very low retention. In this region CORE was confounded by particle collisions with the coast (spikes). Anthropogenic pressures and long-term averaged Chl-a gradually declined from south to north.

Mean surface current speeds were lower in the KwaZulu-Natal Bight region than adjacent of it, in both summer and winter (Fig. 8). While complex nearshore circulation features existed in both seasons, current speeds in the northern part of the bight were particularly low in July, with a cyclonic eddy recirculating water into the bight (Fig. 8b), indicating enhanced retention in this area in winter.

4. Discussion

Retention is a vital driver of coastal ecosystem dynamics, yet it has rarely been quantified for the inner shelf region. In this study, we used a particle tracking tool (Parcels by Delandmeter and Sebille (2019)) to develop the a spatio-temporal coastal retention index (CORE) based on virtual particles released on the very inner shelf (within 3 km of the shore), and presented it in relation to variables that describe biological productivity (Chl-a) and human impacts (a cumulative pressure index based on Sink et al. (2018)). This was applied in the South African context, to interrogate the notion that retentive coastal environments, such as bays, are regions of enhanced primary production supporting rich marine food webs, but also areas where anthropogenic hazards concentrate. We chose this transdisciplinary angle to evaluate the usefulness of the CORE index for Marine Spatial Planning (MSP) and postulate that hotspots of coastal retention are essential for maintaining healthy marine ecosystems. In the further discussion, the emphasis is to explain how CORE captures the coastal circulation patterns of different regions (and nested subregions) around the contrast-rich South African coast, and how it relates to Chl-a and cumulative human pressures. Emphasis is placed on understanding the circulation patterns in South African bays, particularly in the socio-ecologically important St Helena Bay, False Bay and Algoa Bay.

4.1. West coast retention and Chl-a

The current dynamics on the west coast of South Africa are primarily driven by upwelling-favourable southerly winds, which are modulated by the shape of the shoreline and shelf, which gives rise to upwelling centres associated with the less obvious bathymetric features (Kamstra, 1985; Shannon and Nelson, 1996) of headlands. This study identified four subregions on the South African west coast with distinct relationships between the CORE index and Chl-a, as well as cumulative anthropogenic pressures. The northern subregion (Namaqualand; north of 30°S) is characterised by a relatively broad shelf and more perennial upwelling. In the central subregion (30–32°S), the shelf is narrow in the north and broadens in the south, entering the northern extent of the greater St Helena Bay region. In the St Helena Bay subregion, the shelf

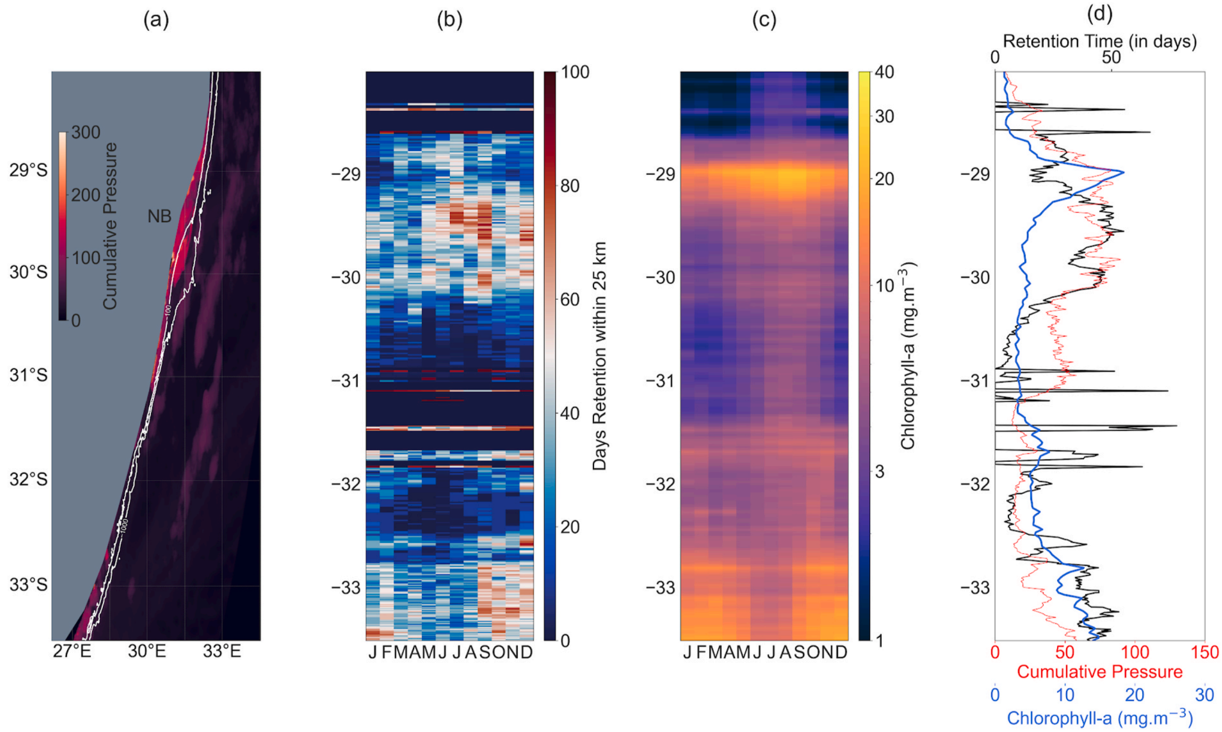

Fig. 7. The East Coast: (a) cumulative anthropogenic pressure map (shading) and bathymetry (white lines represent 100-m isobaths); (b) the spatio-temporal coastal retention index (CORE); (c) spatio-temporal coastal chlorophyll-a; (d) latitudinal variability and relationships between long-term averages of CORE (black line), chlorophyll-a (blue line) and cumulative anthropogenic pressures (red line). The abbreviation NB is shown in (a) to provide a representation of the position of the Natal Bight. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

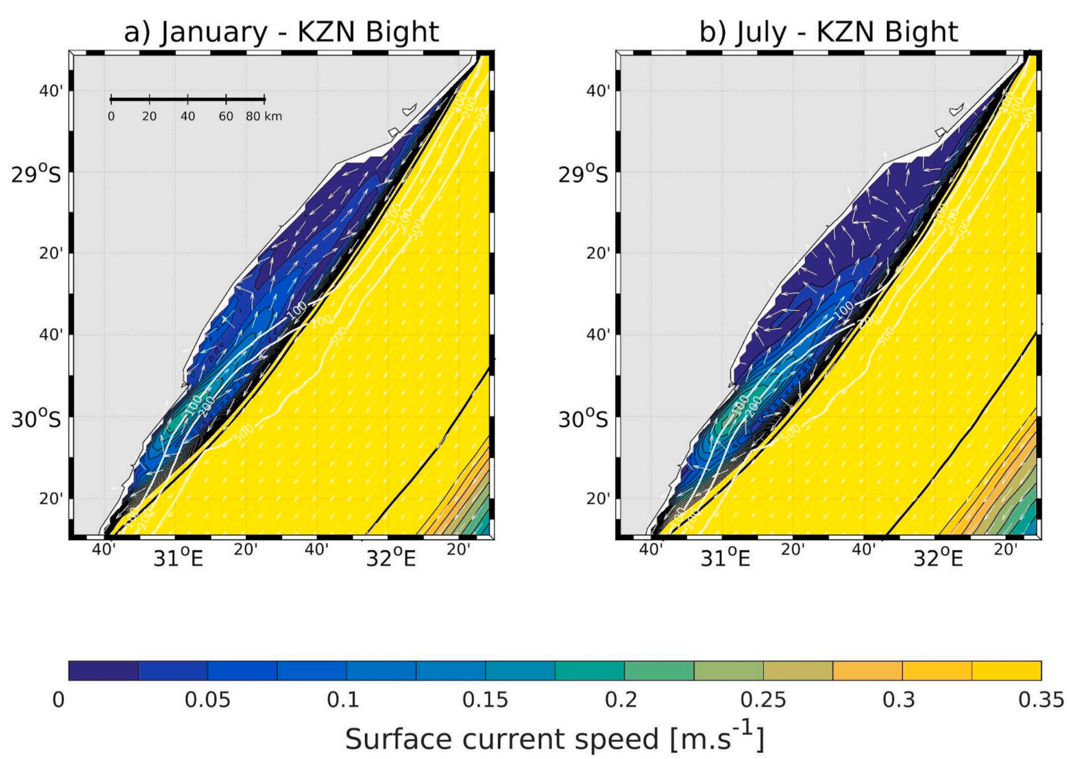

Fig. 8. East coast bight: Average surface currents speed (shading; m.s^{-1}) and direction (vectors) in January (left) and July (right) for the KwaZulu-Natal Bight region. The solid while lines show bathymetry (100-m intervals) and every third vector is plotted. The vectors associated with the strong Agulhas Current (saturated in yellow on this plot) are uniformly directed southwestward.

broadens further and upwelling is strongly seasonal, with a cyclonic circulation feature that forms to the south of Elands Bay during the summer upwelling season (Penven et al., 2000; Supplementary material, Appendix 1). Lastly, in the southern subregion the shelf continues to be broad, except near the prominent headlands of Cape Columbine and the Cape Peninsula, where distinct seasonal plumes of upwelled water form during southerly winds.

In the northern (north of 30°S) and southern (south of 33°S) subregions, seasonality of the CORE index and Chl-a were both weak and their relationship diffuse. Despite the more perennial upwelling in the north, that would suggest a shorter retention season, it was in fact longer than the retention season in the south. This can be related to the fact that the shelf is much narrower in the south, resulting in the coastal upwelling dynamics being much more impacted by the intense shelf-edge jet that is intensified during summer months (Veitch et al., 2018), effectively allowing for enhanced 'flushing' of this narrow-shelf region.

In the central shelf subregion (30–32°S), the CORE index detected the greatest particle retention (i.e., the greatest particle retention time) of the entire west coast during the spring–summer upwelling season, which coincided with elevated Chl-a concentrations; this was as expected, since retention is conventionally thought to promote primary production (Largier, 2020). This is likely related to the intensification of a strong alongshore shelf-edge jet current (Veitch et al., 2018) and its role in driving retention on the Southern Benguela shelf (Barange et al., 1992; Pitcher and Nelson, 2006). There is also a distinct offshore veering of the shelf-edge jet current at 30–31°S, which is in response to the widening bathymetry (Veitch, 2010) and is particularly strong in the summer months (Veitch et al., 2018), which explains the relatively low CORE values at this part of the coast in summer.

St Helena Bay is the most prominent bay on the west coast, and - despite its relatively remote location and sparse coastal population - a centre of cumulative pressures (Hutchings et al., 2012). It's remarkable ecological and economic importance has been highlighted in numerous studies, primarily because it is an important nursery area for pelagic fish (Hutchings et al., 2002). The distinct promontory of Cape Columbine encloses St. Helena Bay at its southern boundary. The bay is a well-known retention zone due to the interaction of an equatorward jet associated with the Cape Columbine upwelling plume (Penven et al., 2000) that is present during austral summer months and the ambient poleward flow on the inner shelf (Nelson, 1985) that forms a distinct cyclonic recirculation feature. This feature is not present during winter months when the poleward flow weakens, and the intensified equatorward jet associated with the upwelling plume also dissipates. The relevance of these features is that they have a key role in the formation of high-biomass phytoplankton blooms (Pitcher et al., 2010), as reflected in the extreme Chl-a values we reported in this study. Some of them constitute harmful algal blooms, the occurrence of which peaks in February and March in St Helena Bay (Pitcher et al., 1998). Their decay frequently leads to low-oxygen conditions that cause mass mortalities of marine life and lobster strandings, as well as a permanent reservoir of low-oxygen water in the centre of the bay (Lamont et al., 2015; Pitcher et al., 2014). What might appear puzzling is that the CORE index indicated extremely low coastal retention in southern St Helena Bay during the upwelling season. When interpreting CORE, it is however important to consider that it was deliberately developed to quantify retention of water parcels on the very inner shelf (of particles released within 3 km of the coast that are retained within a 25-km radius), and that this does not necessarily correspond with larger-scale retention processes further offshore. The presence of strong alongshore currents during the upwelling season within St Helena Bay (Fawcett et al., 2008), which can typically range between 7 and 10 km day^{-1} (Pitcher et al., 1998), explains the low particle retention in this subregion, since particles (e.g. phytoplankton blooms) may be advected out of the initial 25 -km CORE deployment grid relatively quickly, whilst still being retained near the coast.

In the southern part of west coast, where upwelling is intermittent and strongly seasonal, retention and Chl-a were inversely related. Here, intense upwelling during the summer leads to the continued advection of water parcels from the coast and low retention, while upwelled nutrients from the adjacent upwelling cells are advected into these regions, resulting in the high Chl-a values during summer months. However, when looking at long term averages, spatial trends of retention and Chl-a were closely coupled. In the context of MSP, where variables tend to be temporally integrated, our hypothesis that retention is associated with greater biological productivity still holds for spatial trends.

4.2. South coast retention and Chl-a

Coastal currents on the south coast are influenced by the fast-flowing Agulhas C urrent, its interactions with the broad shelf region of the Agulhas Bank and seasonal upwelling-favourable easterly winds during summer. In addition, this highly dynamic regime is modulated by a complex shoreline topography, which features numerous medium-sized embayments. At this scale, the CORE index consistently associated bays as areas of enhanced coastal retention, as was predicted, but the signal was strongly seasonal. Similar to the west coast, the exchange between bay waters and offshore waters is reduced during the summer upwelling season, either through the physical barrier of upwelling plumes that are associated with headlands and cut off bay circulations from the open ocean, or because of the formation of cyclonic circulation features in bays; this generally results in greater retention (Du et al., 2020). During winter, recirculation features within bays decay and stronger alongshore currents develop, which flush the bay water; retention is therefore low. Chl-a was also seasonal, but the timing of blooms varied among the western, central and eastern parts of the south coast. We identified three distinct subregions with respect to the relationship between CORE, Chl-a and cumulative human pressures.

Between Cape Point and Cape Agulhas, the coast features two large bays, False Bay and Walker Bay. Here retention was strongly coupled with Chl-a. The highest Chl-a concentrations occurred in autumn, which is the time of year when high biomass (>30 mg m^{-3}) and potentially harmful dinoflagellate blooms are known to occur in the region (Pitcher and Pillar, 2010; Pitcher et al., 2008). Pitcher and Pillar (2010) noted that both False Bay and Walker Bay are also sites of bloom accumulation through physical processes like enrichment of nutrients by upwelling and retentive circulation patterns. The extremely high retention in False Bay is likely due to its square shape, and the fact that the western (downstream) headland traps westward currents in a recirculation pattern during upwelling, when the bay is also isolated from the open ocean by an upwelling plume (Largier, 2020). Historic observations and model results (Nicholson, 2012) indicate that the circulation tends to be cyclonic in nature, particularly under upwelling favourable conditions in summer (Pitcher et al., 2010). A semi-permanent anticyclonic eddy is situated in the northeastern corner of the bay near Gordon's Bay (Grindley et al., 1964), enhancing retention and vulnerability to poor water quality and HABs (Pitcher and Pillar, 2010). Very little information is available on the more exposed Walker Bay, but model results (not shown) suggest that it offers shelter from an intense northwestward jet that crosses its mouth as well as the mouth of the adjacent False Bay during summer upwelling favourable months.

In the central subregion of the south coast, where the shelf is very broad, Chl-a appeared extremely low during the summer months, despite retention being high. Particularly during summer, when seasonal thermal stratification is at its strongest on the Agulhas Bank (Lutjeharms, 2006), Chl-a maxima form subsurface (10–30 m) near the nutricline (Probyn et al., 1994); as a result, the water column Chl-a concentrations are likely underestimated in these satellite data. Despite this complication, long-term averages still associate both greater retention and enhanced Chl-a with most of the bays along this part of the coast.

On the eastern part of the south coast, where the shelf is gradually narrowing, retention and Chl-a were once again temporally coupled, and spring-summer phytoplankton blooms coincide with peaks of retention in St Francis and Algoa Bay. Here the Agulhas Current veers away from the coast as the shelf broadens at the eastern edge of the Agulhas Bank in the vicinity of Algoa Bay. As such, the extent of its influence on south coast dynamics is limited to Algoa Bay. While there have been observations of warm Agulhas plumes associated with Agulhas meanders and Natal pulses impacting the thermal structure and circulation within Algoa Bay (Goschen and Schumann, 1994; Roberts, 2010; Schumann et al., 1988), there has been no indication of the Agulhas Current directly impacting retention within the bay.

4.3. East coast retention and Chl-a

The east coast of South Africa is characterised by the fast-flowing and dynamic Agulhas Current, which brings warm, oligotrophic waters from the tropics into this sub-tropical region. Winds are weaker than on the west and south coasts, and while dynamic upwelling exists year-round, it is generated by the inshore edge of the Agulhas current interacting with the shelf edge, instead of by wind. In sections where the shelf is extremely narrow, i.e. in the central and extreme northern regions of the east coast (30.5–32.5°S), the Agulhas current flows very close to the coast. In areas where the shelf broadens, the current interacts with the shelf and circulation features form, including counter currents and retentive eddies. This is the case in the KwaZulu-Natal Bight region, as well as on the southern extent of the east coast, near Port Alfred. These alternating current conditions have led to our delineation of four subregions, according to CORE, Chl-a and cumulative pressures.

In the extreme north and central subregions, coastal retention and Chl-a are both low as a result of the advective nature of the fast-flowing Agulhas Current. In the KwaZulu-Natal Bight and the Port Alfred subregions, substantial peaks in Chl-a form seasonally, concurrent with seasonal retention signals. However, the most pronounced peak in Chl-a on the east coast occurs in spring over the Thukela River floodplain in the northern part of the KwaZulu-Natal Bight, where retention is relatively low. This has been attributed to nutrient inputs from topographically induced upwelling (Meyer et al., 2002), wind-driven upwelling (Roberts and Nieuwenhuys 2016), and the Thukela River (Scharler et al., 2016) which synergistically promote phytoplankton blooms.

5. Conclusions

In this study, we developed the CORE index for the South African coast, with the aim to generate a novel data layer for coastal retention, which constitutes one of the most important physical processes for the sustainability of marine resources, by facilitating the formation of phytoplankton blooms that nourish entire marine food webs. When assessing CORE in context of known retention patterns and satellite-derived Chl-a, its overall performance was scale-dependent. Particularly enlightening was the case of the large embayment of St Helena Bay, where CORE, designed to quantify retention of particles that have been deployed close to shore (at the 20-m depth contour), showed minimum coastal retention during a season when a prominent retentive feature would have dominated the bay-scale dynamics (10s of km offshore). Furthermore, alongshore currents were present that rapidly advect virtual particles out of the retention radius of 25 km (while potentially still retaining them near the shore but further upstream). Despite this limitation when applied to large embayments, CORE showed distinct retention hotspots for the series of medium-sized bays on the south coast, and also reflected well-known seasonal dynamics. We thus conclude that CORE, under its current deployment scheme, is more suitable for assessing retention in medium-sized bays than in large partially open bays with strong wind-driven alongshore flow.

Regarding our initial hypotheses we conclude, firstly, that most bays can be considered hotspots of coastal retention, particularly on the South African south coast. However, the retention signal varied among bays and was in most cases strongly seasonal. Other centres of retention also exist, such as the area north of St Helena Bay on the central west coast and the KwaZulu-Natal Bight on the east coast, as well as a few other areas where the shelf broadens upstream of narrow stretches. Secondly, the relationship between retention and Chl-a is region-specific, which suggests that other factors are also at play that affect phytoplankton bloom formation. On the west coast, where upwelling winds are the strongest driver of ocean dynamics and productivity, the coupling of retention and Chl-a is surprisingly weak, but this could also be a result of the limitations of CORE pointed out above. On the south coast, long term retention peaks were closely coupled with Chl-a peaks, although their timing was not always synchronised and their spacing was not perfectly aligned. Other shelf processes here include the formation of subsurface Chl-a peaks during the summer upwelling season, which is not as intense here as on the west coast. On the east coast, retention was coupled with enhanced Chl-a in sections of the coast where the shelf was wider; however, by far the strongest Chl-a peak was associated with the Thukela River region where riverine input and upwelling supplied limiting nutrients for phytoplankton growth. Thirdly, areas of greater retention regularly coincided with areas where human pressures accumulate, but not always. On the west coast, maximum retention occurred on the remote central coast, where cumulative pressures were low. On the south and east coast, however, distinct hotspots of retention emerged that were also focal points of human impacts, such as False Bay, Walker Bay, St Sebastian Bay, the Vleesbaai-Mossel Bay area, St Francis Bay, Algoa Bay and the southern KwaZulu-Natal Bight region. These areas, where a natural process that is vital for the sustained health of marine ecosystems coincides with the hazard of cumulative human uses, are obvious candidates for engaging ecosystem-based MSP processes to manage the growing demands and ensure the sustainable utilisation of marine and coastal resources.

CRediT authorship contribution statement

Maya C. Pfaff: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Michael Hart-Davis:** Data curation, Formal analysis, Methodology, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **Marié E. Smith:** Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jennifer Veitch:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2022.107909.

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