

# **GIS and Remote Sensing techniques for the assembly of a database characterising the spatio-temporal character of the South Australian continental shelf environments**

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## **Abstract**

Despite their comparable levels of use and importance, coastal and marine environments have long been the poor cousin of their terrestrial counterparts with regard to the availability of spatial databases suitable for GIS-based analysis. This has been a significant impediment to comprehensive and rigorous studies into the patterns, processes and management of these environments in a spatial and temporal context. In this paper we describe the development of an extensive 1km resolution raster GIS-based database characterising the spatio-temporal dynamics of the South Australian marine environment. A Digital Elevation Model of the bathymetry is constructed from RAN hydrographic survey and navigational chart data. Twelve years of monthly cloud-free composite sea-surface temperature data is acquired from CSIRO based on the NOAA AVHRR sensor. Six years of monthly chlorophyll *a* data was extracted from SeaWiFS ocean colour imagery. Eight snapshots of current speed and direction for spring and neap tides over the four seasons were also integrated into the database. The integration of these diverse data layers in a GIS environment enables the visualisation and interpretation of the complex spatio-temporal dynamics of the coastal and marine environments of the SA continental shelf. Assembly of this database forms the basis of further research into the management of this environment.

## **Introduction**

Environmental and human processes operate differentially over space and this fundamental principle makes for significant geographical heterogeneity in the environment. It is necessary to take into account this spatial variability

when managing and making decisions about the environment. Hence, spatial information is becoming increasingly important for its ability to provide a data infrastructure that can form the basis of most research and analysis of the environment and of intelligent and informed planning and policy decisions (Bryan, in press). Geographic Information Systems (GIS) can also provide an effective tool for the management and analysis of spatial information for environmental management.

Surveying, mapping, collation and digitisation of spatial information for the terrestrial environment has long been prioritised in many countries. The underlying tenet being that expenditure in a spatial data infrastructure for a region will be more than justified by the benefits in analysis and planning of both the physical and human environments in the future. As a result of this policy, extensive, detailed spatial databases are available for many terrestrial regions such that these environments have become *data rich*. Conversely, the marine environment has long been the poor cousin of its terrestrial counterpart when it comes to spatial data availability. For many important marine environments, capturing spatial information has not been a high priority for governments nor industry.

Hence, few databases exist for research and analysis for management of and planning for the marine environment. As a result, current marine research and management priorities such as the systematic design of marine protected area systems, or the analysis of the impact of harvesting commercially important species have had to proceed without the same support of extensive underlying spatial information available to their terrestrial equivalents.

However, remote sensing (Klemas 2001; Almeida-Guerra 2002; Huang and Fu 2002; Mumby and Edwards 2002; Liu *et al.* 2003; Louchard *et al.* 2003), GIS (Stanbury and Starr 1999; Bartlett 2000; Hatcher and Maher 2000; Dimov 2002) and other allied technologies enable the quantification of spatial heterogeneity of some physical environmental parameters on all scales, and the integration of these disparate data layers (Pasqualini *et al.* 2001). Clearly, broad area, deep water benthic surveys are still not feasible with current technologies but many biologically important parameters and indicators such as sea-surface temperature, ocean productivity and others are able to be quantified and analysed. Several studies have described the assembly of spatial marine databases for environmental management (West 1999; Su 2000; Wright 2000; Tsonos and Kiefer 2002; Valavanis *et al.* 2002; Wong and Eittreim 2002; Zhang and Grassle 2002; Geskou 2003).

This study aims to quantify and assemble a comprehensive spatial database of the pelagic coastal and marine environments of the South Australian continental shelf area to a depth of 200m. The database will provide insights into the spatial and temporal dimensions of the shelf environments and form a basis for a diverse array of environmental management research and policy prescription.

The objectives of this study are to create to:

- Interpolate a Digital Elevation Model of the bathymetry of the study area from hydrographic survey points in a GIS.
- Acquire, rectify, register and process remotely sensed multitemporal SeaWiFS data for derivation of chlorophyll *a* content of the water
- Acquire, rectify, register and process long term monthly cloud-free sea-surface temperature composites from the NOAA AVHRR sensor
- Resample an existing model output of current speed and direction for the study area for integration into the GIS

South Australia has over 3,700 km of coastline. The continental shelf which includes those areas of ocean less than 200m deep totals around 222,000 km<sup>2</sup> in area. This area comprises many biologically diverse and regionally significant habitats and economically important species. The region is influenced by two major biogeographic zones – a cool-temperate zone to the south-east and a transitional warm temperate zone in the west.

### **Significant Physical Environmental Variables**

The selection of biophysical parameters to be quantified was made on the basis of two criteria: (1) the assumed relevance of a parameter to patterns of marine biodiversity (i.e. the distribution of biota), (2) the potential for the parameters to be quantified in digital spatially-referenced data format and at an appropriate spatial and temporal scale. The parameters selected include bathymetry, chlorophyll *a*, sea-surface temperature (SST), current speed and direction.

Bathymetry, or specifically water depth, influences a number of physical parameters that affect plant and animal distributions, such as light intensity and pressure. In response to changes in these parameters, a distinct vertical zonation is evident in marine communities, marked by a continuous transition in floral and faunal assemblages (pelagic as well as benthic) from

the shallow coastal zone to deep offshore waters. Hence, bathymetry can be used as a surrogate for these physical environmental parameters (Kinloch, 2001).

Chlorophyll *a* concentration is a direct indicator of marine primary productivity which is the basis of oceanic food webs and occurs via the photosynthetic activity of phytoplankton. Chlorophyll *a* is the major photosynthetic pigment and is therefore regarded universally as the most appropriate measure of viable phytoplankton biomass (Aiken et al. 1995); it was hence selected as a surrogate for marine primary productivity.

Sea-surface temperature affects the biochemical reactions that take place within all living cells as these reactions are subject to metabolic constraints imposed on them by temperature. Hence the distribution of all pelagic organisms are affected by the temperature of their ocean environment. In the vertically well-mixed waters of South Australia, SST is considered representative of the depth-integrated average water column temperature (Petrusevics pers. comm.) and was therefore used to indicate the geographic distribution of relative water column temperatures.

Water currents, including both their speed and direction, have important effects on the pelagic environment as they determine the degree of stratification or vertical mixing of the water column and the presence of features such as a thermocline. Water currents also transport nutrients, in the form of inorganic and organic particulate and dissolved matter, as well as zoo- and phytoplankton, which have limited, if any, motility.

## **Methods**

The following methods describe the data and procedures used to assemble a spatial database of the physical environments of the South Australian continental shelf waters. The raster data model is used with a 1 km grid cell resolution as this was approximately the resolution of the remotely sensed data from SeaWiFS and AVHRR. Each environmental parameter exists as a raster layer in the GIS database.

### **Bathymetry**

Bathymetry data was originally acquired from the Petroleum Group of the Department of Primary Industries and Resources SA (PIRSA). Most of the

data was captured between 1970 and 1994 by the Royal Australia Navy Hydrographic Service. This data was collected as part of a national bathymetry mapping program whose aim was to characterise of the seabed topography as a base for offshore research, exploration, development and management. The data was collated from many different surveys and water depth was measured by using a variety of techniques including diving bell soundings, echo soundings, depth converted water bottom seismic two-way travel times. Complementing this, the database also includes water depth data derived by digitising marine navigation charts by Planning SA (formerly the Department for Housing and Urban Development). The data was received as a GIS point database that included 926,171 points. In its raw form the database has had minimal validation to the extent that anomalous point values have been filtered out of the original data.

Based on this irregularly spaced point data, a Digital Elevation Model was built to represent the environmental surrogate layer of water depth. The entire raw point database was initially used to interpolate a raster using the TOPOGRID module in ArcInfo with a 1km grid-cell resolution. TOPOGRID is a specialised topographic surface interpolator that combines a modified thin-plate spline interpolator with an automatic drainage enforcement process (Hutchinson, 1989). Creation of the DEM was an iterative process of building the DEM, creating an analytical hillshade, visually inspecting errors, correcting errors and rebuilding the DEM (Bryan, in press). Significant errors were prominent in the database. These included general errors in coding (many values of 1 and some large positive values that were reassigned to negative values) and what seemed to be *miscalibrated runs*, which manifested as survey sequences (lines of survey points) that were systematically higher than the underlying and nearby survey lines. These were removed from the database leaving 838,355 data points. A series of DEMs were created using a training database containing 95% of the corrected data points and tested using the withheld 5% of data points. The TOPOGRID parameters were systematically modified until a DEM was obtained that both had very low quantitative error and no visual errors. The final bathymetric DEM was built 10km larger than the study area to minimise edge effects. A maximum of 30 iterations were used and the tolerances used included a root mean square residual of 10, a drainage blocking tolerance of 2m and a saddle height limit of 25m. The 140 spurious pits were filled, cells with depths  $>0$  were reset to 0 and the continental shelf study area was defined by all cells  $<200$  in depth. The RMS error of the bathymetric DEM was 5.36m.

## Chlorophyll *a*

Analysis of ocean colour can indicate the concentration and predominant identity of living phytoplankton, inorganic sediments, detritus, and dissolved organic matter amongst other things (Zhu *et al.* 2002). The relative density of chlorophyll *a* can be estimated using remote sensing techniques through the detection of ocean colour in the euphotic (lighted) zone of the upper ocean. Very simply, oceans tend to appear blue in colour as the other parts of the visible light spectrum of sunlight are absorbed and the blue part is reflected. The more chlorophyll *a* in the water, the greener it appears.

Several sensors have been designed and/or used to analyse ocean colour including the Coastal Zone Colour Scanner (CZCS, ended 1986), the Ocean Colour and Temperature Scanner (OCTS), the Moderate Resolution Imaging Spectroradiometer (MODIS, current), and the Sea-viewing Wide Field-of-View Sensor (SeaWiFS). Data captured from SeaWiFS aboard the OrbView-2 satellite, flown by Orbimage in 1997, was originally a commercial product. Now, the full SeaWiFS data archive is freely available for non-commercial use and is distributed and managed by NASA under their Mission To Planet Earth (MTPE) Program. SeaWiFS was selected for quantification of chlorophyll *a* concentrations in this study. SeaWiFS has a temporal resolution of 2 days, a scan width of 58.3° (LAC) a scan coverage of 2,800 km (LAC), a nadir resolution of 1.13 km (LAC), and a tilt between -20 and +20°. The sensor detects 8 bands of the visible and near infrared parts of the electromagnetic spectrum.

We obtained Authorised User Status from NASA for use of the Local Area Coverage (LAC) data which is the highest resolution, level 1A (L1A) High Resolution Picture Transmission (HRPT) format stored in Hierarchical Data Format (HDF). Using the data browser, we selected 25 (almost) cloud free images from a total of 2,767 from the full data archive 1997 – 2002. L1A products contain all the raw Level-0 data (raw radiance counts from all bands plus spacecraft and instrument telemetry) with calibration and navigation data, instrument and selected spacecraft telemetry appended (Feldman 2003).

This data was downloaded and converted to L2 chlorophyll *a* product with SeaDAS (SeaWiFS Data Analysis System), purpose-built freeware for analysing SeaWiFS imagery. Initially, the conversion process, the L1A data

undergoes atmospheric correction and the radiances are converted to normalised water-leaving radiances (nLw). Next, each pixel is assessed for a number of different conditions such as discrimination between land/water, the presence of cloud, smoke, turbidity, algal blooms etc. Cells displaying any of these conditions are flagged or masked from further analysis. Finally, an the Ocean Chlorophyll 4 (OC4) algorithm is applied to the data which calculates the concentration of chlorophyll in  $\text{mg}/\text{m}^3$  of water. OC4 is a maximum band ratio algorithm where the maximum of three band ratios (2/5, 3/5, and 4/5) is used to predict chlorophyll concentration (O'Reilly et al. 2000). The OC4 algorithm is able to capture the typically 3 tiered structure of chlorophyll *a* concentration with low levels occurring in deep water, moderate levels on the continental shelf and high levels near shore.

The georegistration and projection functionality of SeaDAS failed so we registered and projected the data in a GIS. The L2 chlorophyll *a* product images were exported in ASCII format with the centroid latitude/longitude coordinate attached to each pixel. This was imported into MS Access, then into ArcMap, converted to an event theme, shapefile and then coverage format. From point coverage format the data was converted to grid format where each 1km grid cell was attributed the value of the nearest pixel centroid. Cloud and near-shore areas, masked out in the chlorophyll *a* product, were attributed the median of the chlorophyll *a* value of their nearest valid cell and its neighbours (5 x 5 neighbourhood) to minimise the influence of near-shore outliers.

In order to visualise the spatio-temporal dynamics of chlorophyll *a* in the study area, a cloud-free annual dynamics animation was created using Macromedia Flash using monthly grids averaged over the 5-year archive. For further analysis it is recommended that the mean and standard deviation of ChlA data used which provides a good indication of general conditions and variation of chlorophyll *a*.

## Sea Surface Temperature

Sea surface temperature is another physical environmental parameter that can be effectively measured using remotely sensed imagery (Sumner *et al.* 2003). Both MODIS and OCTS among other sensors have been used to measure SST. However, by far the most commonly used sensor for this purpose is the Advanced Very High Resolution Radiometer (AVHRR) aboard the US National Oceanographic and Atmospheric Administration

(NOAA) satellites. A total of 157 pre-processed cloud-free composite SST images were obtained from the CSIRO Marine Research Remote Sensing facility in Hobart.

AVHRR is a scanning radiometer with a swath nearly 3000 km wide. The current version has 5 bands with a band in the visible, the near infra-red, the reflected infra-red, and two in the thermal infra-red part of the electromagnetic spectrum. The visible and near infra-red bands are useful for cloud discrimination and the thermal infra-red bands are used for temperature estimation. Temperature is measured using a linear function of bands 4 and 5 in a split-window technique that allows the amount of atmospheric absorption to be quantified and corrected. CSIRO use the McMillin and Crosby (1984) method to derive the exact nature of the linear function by correlating satellite data with empirical data from ships, drifting buoys and other sources. This method has a bias of - 0.14°C and an RMS error of 0.55°C. The images are then rectified using the known geometry of the instrument, details of the orbit of the spacecraft, and known ground locations, each pixel in the image is attributed a theoretical ground location, then reprojected. The images were supplied in Geographic projection in decimal degrees with 226 rows, 352 columns and a spatial resolution of 1.1 km.

CSIRO processed the raw AVHRR data to create 15-day averages from the first fortnight of each month between January 1990 and December 2002 inclusive. Land pixels and most cloud pixels are masked and the average is created based only on the number of valid measurements for each pixel.

The 8-bit binary *disimp* format images were batch imported to grid format and assigned spatial coordinates using ERDAS Imagine and ArcInfo. Unusually high values within 3 km of the coastline occurred probably because of the influence of land. Hence, the 8-bit pixel values over 215 were reset to *no data* to overcome these errors. Missing values were assigned the value of the nearest valid cell. The digital numbers in the images were linearly rescaled to real temperature values, and the grids were finally resampled to 1km resolution and adjusted to match the other data. The data quality of many of the early images was not adequate which resulted in the omission of the years 1990-1993 and 7 images between 1994-96. All images between 1997-2002 are included, a total of 101 SST images. All images were animate in Flash to create a seamless SST dynamics visualisation of the study area from 1994-2002.



## Water Currents

Seasonal data on the speed and direction of water currents in SA under neap and spring tide conditions were generated by Petrushevics (1998) from a depth-integrated (vertically-averaged) numeric model developed by Bye (1976). Inputs to the model were wind stress, tidal amplitude and seabed topography and friction. Output vectors describing the speed and direction of surface water currents were modeled for the eight combinations of season (spring, summer, autumn and winter) and tidal regime (spring and neap), over an array space comprising 75 columns x 53 rows with a 15 km resolution. The model outputs ASCII files which were then imported into ESRI's ArcInfo GIS as point coverages. Each point is located at the centroid of a model array cell, hence the points are spaced 15 km apart. Surface water current velocity and direction are stored as coverage attributes. Current direction is recorded as a compass bearing between 0 and 360 degrees. Current speeds were measured in cm per second and the dataset ranged between 0 and 56 cm/s.

As the current direction data was recorded using a circular scale (degrees of azimuth), it needed to be transformed by calculating the sine and cosine values for each data point. When used together, the transformed values are amenable to numerical analysis. The sine and cosine data was converted to grids, bilinearly resampled to a 1km resolution and integrated into the GIS database.

## Results and Discussion

The bathymetry layer displays a clear and expected increase in depth with distance from the coast (Figure 1). The chlorophyll a images show marked spatio temporal dynamics including high values in the gulfs and bays with seasonal upwelling events particularly prominent in the south east (Figure 2) also displays significant spatio-temporal variation with high dynamic ranges occurring in the shallow gulf waters with little offshore variation (Figure 3). Current speed and direction data displays seasonal variation with higher speeds and more variable direction occurring in the shallower coastal waters (Figure 4).

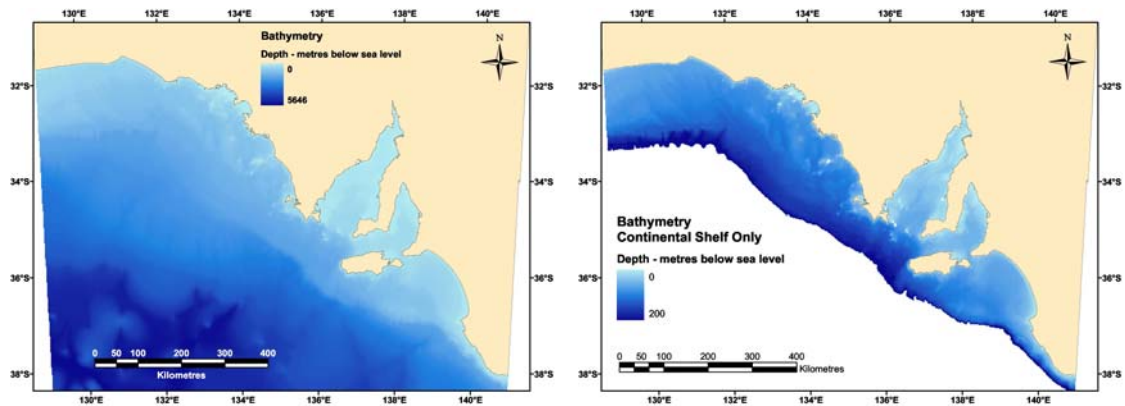


Figure 1 – Bathymetry database layers modelled for the southern Australian waters. Left includes shelf slope and abyssal bathymetry, right displays the shelf waters to 200m.

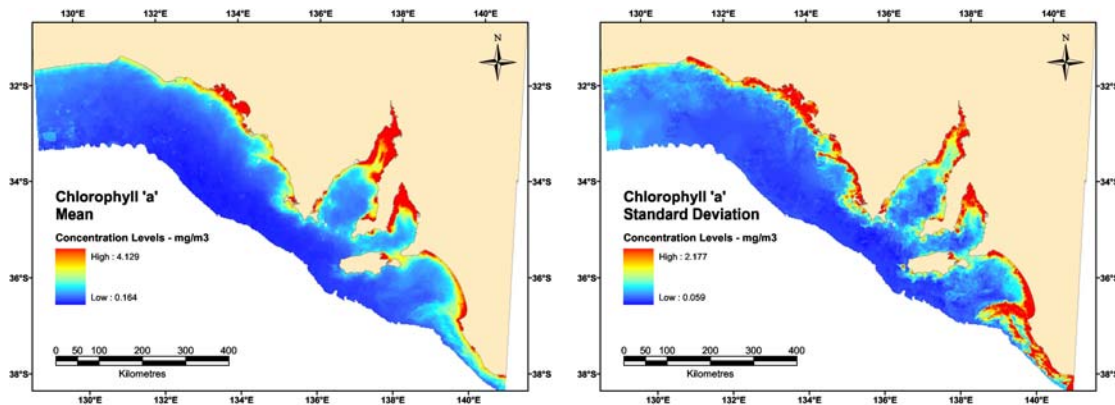


Figure 2 - Mean and standard deviation chlorophyll a of southern Australian shelf waters.

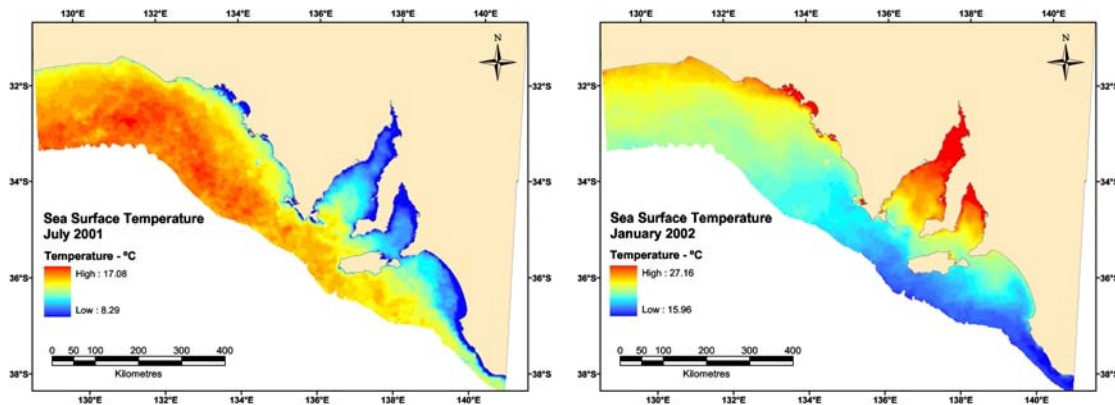
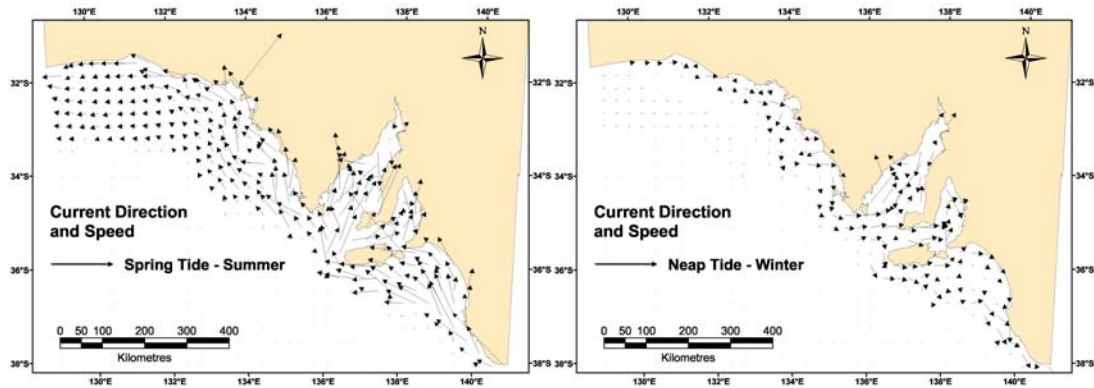


Figure 3 - Snapshot examples of the range of SST from July 2001 (left) to January 2002 (right).



*Figure 4 – Two seasonal (Spring Tide in summer & Neap Tide in winter) and tidal snapshots of water current speed and direction vectors.*

Several diverse data capture and modelling techniques have been integrated to create an extensive database of pelagic biophysical parameters influential in determining the spatio-temporal distribution of marine biota. The bathymetry surface is reasonably accurate given that the data used in its creation was an agglomeration of different datasets captured by different agencies, survey missions, vessels, all using an array of different techniques. The SST data is a database of very high quality. With its high temporal and spatial resolution sampled over more than 9 years, the database is a comprehensive representation of the spatio-temporal dynamics of SST in the study area. A small problem with the SST imagery occurs near the coast. A combination of CSIRO masking out near-shore pixels because of the effect of land and low accuracy in georegistration results in no data values near the coast. SST of these areas had to be extrapolated from nearby cells which may have caused some error in these areas. This problem typically affected a coastal buffer area of between 0 and 5 cells.

The chlorophyll a data is the best that current remote sensing technology allows. It does however, have significant problems. The main problem with the data is the effect of cloud. Images free of cloud over such a broad area are extremely rare. The presence of cloud meant that some chlorophyll a data layers exhibited patches of no data or holes, hence they did not have a continuous distribution of values over the study area. The GIS-based techniques we used to smooth over the holes by filling in the value of the nearest cell sometimes caused the holes to become filled with very high or erroneous values due to the influence of nearby cloudy, but unmasked, pixels. The influence of cloud was not completely removed from the data and this was the main reason why we prefer the use of mean and standard

deviation calculations rather than the original images themselves. The influence of cloud can be seen in the Great Australian Bight area of the standard deviation image. The mean chlorophyll *a* image seems to be free from the effects of cloud but at the same time overlooks some of the critical dynamic events in ocean productivity such as the upwelling events.

In addition, similar edge effects affect the chlorophyll *a* images as the SST images in that coastal areas tended to be masked out because of the effect of the land in erroneously elevating values. The GIS-based technique used to smooth and extrapolate values for these areas from nearby pixels may have also caused error in chlorophyll *a* values in these coastal areas. This problem was also restricted to a coastal buffer area of less than 5 cells in width.

This modelled characterisation of water current activity is broadly useful for environmental management purposes. However, the model is a simplified *snapshot* of general current activity for 8 of the most common conditions. The tidal constituents ( $S^2$ ) included are extremely simplistic. The model data become increasingly inaccurate with distance from the point of propagation of surface wind speeds (Cape Borda, Kangaroo Island) with the result that the influence of currents is limited almost entirely to the continental shelf. Much more accurate and sophisticated models (using hundreds of constituents) are now available on a much finer spatial scale. The acquisition of better current data should be prioritised. Future work may also look to model new variables such as ocean chemistry parameters (salinity, dissolved oxygen).

## **Conclusion**

This study describes the use of several remote sensing and GIS techniques for capturing and modelling four oceanographic parameters: bathymetry, sea surface temperature, water current dynamics and chlorophyll *a*. It brings together several marine pelagic biophysical datasets that comprehensively covers a broad area at a reasonably fine 1km resolution. These four data layers capture the major salient features of the pelagic environment and provide a holistic view of regional spatio-temporal oceanographic patterns. These patterns include a number of hydrographic features of the SA marine environment that are important in structuring pelagic (and possibly benthic) faunal assemblages. The results explicitly confirm the expectation of decreasing oceanographic heterogeneity with increasing distance offshore. The database created in this study provides a foundation for many diverse

environmental management applications and analyses and for more informed resource management and planning decisions such as the delineation of marine protected areas and exploitation management strategies.

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