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BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

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THE BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

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9.2. Past, present and future state of the pelagic habitats in the Antarctic Ocean

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1. Introduction

The ecological geography of the oceans is not as developed as that of the continents, but it still may be approached in the same manner. Terrestrial ecosystems may be categorised as a small number of characteristic climatic zones or biomes (i.e. with a specific environmental range) such as boreal coniferous forest, dry savannah, tropical deciduous forest, and arctic/alpine tundra. Seen from a macro scale, the global ocean is similarly composed of different characteristic climatic regimes (*i.e.* Biotopes) caused by the effects of basins and regional physical and biogeochemical features that force environmental marine conditions. In the last century, several partitions of the ocean were proposed to identify these several types of climatic oceanic zones. This was done either by studying the spatial distribution of ecthothermal species (Beklemishev 1961, McGowan 1971, Reid *et al.* 1978) or by identifying the unique abiotic conditions (Cushing 1989, Emery & Meincke 1986).

Presently, the scientific community has largely accepted at least 3 global partitions for the oceans: the Biogeochemical Provinces (BGCP) (Longhurst 2007), the Marine Ecoregions of the World (MEOWS) (Spalding *et al.* 2007) and the Large Marine Ecosystems (LME) (Sherman 2005). These partitions aim to delineate the main oceanographical, ecological and economical patterns respectively to provide a valid geographical framework of marine ecosystems for ecological studies and management purposes. However, due to the growing availability of marine observations with a global or basin-scale coverage, and when combined with the application of multidimensional or exploratory analyses in ecology, several novel approaches have been developed to partition the ocean at a global (i.e. biotopes) (Hardman-Mountford *et al.* 2008, Moore *et al.* 2002, Oliver & Irwin 2008, D'Ortenzio & D'Alcalà 2009, Demarcq *et al.* 2012, Reygondeau *et al.* 2013) and regional scale (i.e. habitats) (Reygondeau *et al.* 2012, Forget *et al.* 2010, Devred *et al.* 2007, Huettmann 2000*)*. In a context of developing ecosystemic approaches for biodiversity and fisheries management and conservation, such modern partitions may be used as a spatial template to monitor, study and forecast the pelagic habitats spatial distribution, composition and dynamics. They enable a quantitative snapshot in space and time of large spatial regions that otherwise are difficult to describe, such as the Southern Ocean.

The Southern Ocean is a unique region for biogeographical studies in many aspects. First, this area has no continental barriers (e.g. except the Drake Passage), consequently the Southern Oceanic circulation can flow 'around the globe' without any interruption. Thus, the Southern Ocean has unlimited communication with virtually all other oceans, and its hydrological dynamic influences the biogeochemical and oceanographic features of each oceanic basin. Second, this region is subject to sea ice cover with a maximal extent during the austral winter when solar irradiance is highly restricted. This climate specificity influences the overall hydrological conditions of the area, starting with the stratification for instance. Environmental conditions (e.g. temperature, salinity, oxygen, current speed) are thus highly seasonal depending on the intensity of the incoming irradiance. These particular hydrological/environmental conditions combined with a highly variable topography (seafloor and land mass distribution) offer an incredible number of pelagic habitats. Nonetheless, ecological studies have shown that the Southern Ocean exhibits 'the lowest' biodiversity at a global scale (Beaugrand *et al.* 2012, Cheung *et al.* 2010, Rombouts *et al.* 2010). This is mainly attributed to the drastic conditions that force species to be specially adapted both physiologically and behaviourally.

Since the industrial revolution, human societies have exponentially emitted massive concentrations of greenhouse gases by burning fossil energies (IPCC 2007). This progressive increase of greenhouse gases in the atmosphere has for instance altered the thermodynamic properties of the troposphere, the radiative equilibrium of the atmosphere and the exchange of energy with the oceanic realm (Karl *et al.* 2003, Karl & Trenberth 2003). Recent studies have shown that the increase of the atmospheric heat content has been mainly absorbed in the past decades by the oceanic domain (Barnett *et al.* 2005) resulting in a global warming of the oceans (Parmesan & Yohe 2003, Rosenzweig *et al.* 2008). Most of the Southern Ocean appeared as one of the hot spots already altered by anthropogenic climate change (Levitus *et al.* 2005) and exhibited temperature anomalies from 0.5 to 3°C. In recent decades, an increasing number of observations show a progressive alteration of both continental and open-seas areas of the Southern Ocean affecting the associated marine habitats and species (see Resendizet *et al.* 2012 for a large-scale assessment). These modifications of the environmental conditions, characterised by a speed and magnitude never experienced by the biosphere since the last massive species extinction are expected to increase in the near future with dramatic impacts on biodiversity (Brander 2009).

In this chapter, two conceptually different biogeographical approaches (objective and non-objective, see Reygondeau *et al.* 2013) are used to identify the spatial distribution of the pelagic habitats of the Southern Ocean. Than, using the outputs of a coupled atmosphere-ocean-biogeochemistry model, the spatial distribution of each habitat is retrieved for the period 1860-2000 and projected according to the Representative Concentration Pathways scenario (RPC) 8.5 for the decades 2050 and 2090. A comparison between results from both numerical approaches is made to discuss to highlight the common trends observed in the biogeochemical delineation of the Southern Ocean and identify future hot spot of environmental change.

2. Materials & Methods

Two numerical approaches are used in this study to identify and monitor the main biogeographical delineation in the Southern Ocean. These two numerical approaches are selected, as they are conceptually different. The Macro Ecological Approach (Reygondeau *et al.* 2013) uses a geographical framework (Longhurst 2007) to identify the oceanic delineations whereas the bioregionalisation approach partition objectively the Southern Ocean according to environmental parameters based on Raymond (2011).

2.1. Macroecological approach: Dynamic biogeochemical provinces (BGCPs) of the Southern Ocean

2.1.1. Data

The selection of the variables used for this numerical approach is based on the biogeochemical literature of the global Ocean (Devred *et al.* 2007, Reygondeau *et al.* 2013). Four environmental factors are selected to identify the biogeochemical features and spatial discontinuities in the Southern Ocean: bathymetry, Sea Surface Temperature, Sea Surface Salinity and total phytoplankton biomass. Apart from bathymetry environmental factors are outputted from the IPSL-CM5 earth system model (http://icmc.ipsl.fr/model-and-data/ipsl-climate-models/ipsl-cm5) at a monthly long-term resolution between January 1850 and December 2006 at a depth of 5 meter (Aumont & Bopp 2006) and cover the global ocean from 189.5°W to 179.5°E and from 89.5°N to 89.5°N. They are interpolated at a 1°x1° spatial resolution. The projection of the selected environmental variables according to the RCP scenario 8.5 are gathered from the outputs of the same model run for three average decadal periods: 2006-2015, 2046-2055 and 2086-2095 (i.e. period available during the study). Bathymetry is used to divide the global ocean into continental shelf (<200 m) and open ocean, which correspond to different types of biogeochemical and circulation processes (Ryther 1969). The bathymetry data used are selected and downloaded from the General Bathymetric Chart of the Oceans (GEBCO) on a 1°x1° grid (Smith & Sandwell 1997).

2.1.2. Methods

Based on the prior knowledge of the BGCPs established by Longhurst (2007) and the selected four environmental parameters, we have applied the methodology implemented by Reygondeau *et al.* (2013) to examine how distributions of BGCPs in the Southern Ocean (SSTC, ANTA, SANT, APLR provinces, Table 1) fluctuate in space and time during the period from 1850 to 2100. The full methodology can be retrieved in Reygondeau *et al.* (2013). However, the major steps of the methodology are summarised in Figure 1.

Step 1: identification of the environmental conditions within each reference province

Biogeochemical provinces	code	biome
South Sub-Tropical Convergence	**SSTC**	Westerlies wind
Sub-Antarctic water ring	**SANT**	Westerlies wind
Antarctic	**ANTA**	Polar
Austral Polar	**APLR**	Polar

Table 1 Characteristics of each biogeochemical provinces used in this study.

To allocate appropriate environmental values to each biogeochemical province of the Southern Ocean, the spatial coordinates of each BGCP (SSTC, ANTA, SANT, APLR) are first retrieved from the latest version of the partition of Longhurst (2007) (Figure 1). We subsequently attributed to each geographical cell a value for SST, SSS and total phytoplankton biomass for each month of the period ranging from September 1997 to December 2006 (112 months) and a single value for bathymetry. The period from September 1997 to December 2006 is chosen to gather data used by Longhurst (2007) to implement the original biogeochemical partition. We thus obtained our 4 reference matrices (one for each province) named $X_{n,p}$ (*n* = 112 months x the number of geographical cells, *p* = 4 environmental variables).

Step 2: characterisation of the environmental envelope

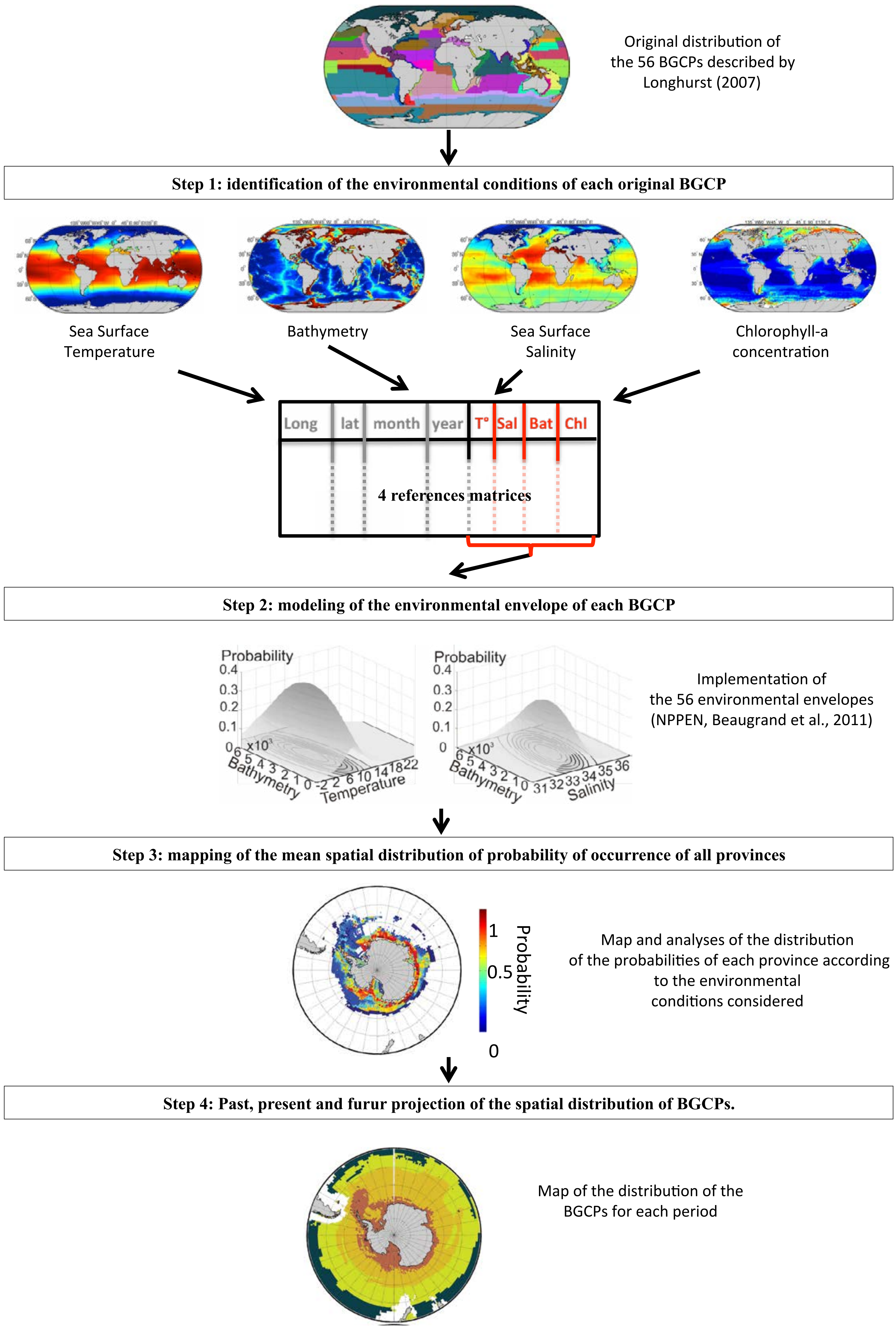


Figure 1 Sketch diagram of one macro ecological method used to derive future scenarios.

The method applied to define the environmental envelope of each BGCP is based on the Non-Parametric Probabilistic Ecological Niche Model (NPPEN; Beaugrand *et al.* 2011). This statistical method tests the probability that random observation x characterised by 4 environmental parameters belongs to a reference matrix, $X_{n,p}$. The procedure is based on a simplified version of the Multiple Response Permutation Procedure (Mielke *et al.* 1981), which was described in Beaugrand & Helaouët (2008), in Lenoir *et al.* (2011) and in Reygondeau *et al.* (2011). To summarise, the NPPEN uses the generalised Mahalanobis distance (Mahalanobis 1936) that enables the correlation between variables to be taken into account. The calculation of the Mahalanobis generalised distance and its probability was repeated m times, with m the number of observations x to be tested. The NPPEN produces the probability to find the environmental envelope of a province as a function of our four parameters (SST, SSS, total phytoplankton biomass and bathymetry (Figure 1). Further information on the methodology of NPPEN can be found in Beaugrand *et al.* (2011).

Step 3 and 4: Mean spatial distribution of probability of occurrence to BGCPs, general distribution and spatial indices.

To predict the past and present spatial distributions of each BGCP, the average SST, SSS and TPB are calculated using the NEMO-PISCES outputs in every geographical cell of the global ocean for several decades: from 1850 to 1859, from 1900 to 1909, from 1950 to 1959 and from 1990 to 1999. Then, to predict the potential spatial distribution of each BGCP in the near future according to the RPC scenario 8.5, average environmental conditions from the same AOGCM outputs are calculated for the period from 2006 to 2015, from 2046 to 2055 and from 2086 to 2095.

For each environmental climatology value calculated previously, the spatial distributions of the probability of the 4 BGCPs are first retrieved using the environmental envelopes implemented by the NPPEN. The spatial distributions of the 4 BGCPs are filtered (see Reygondeau *et al.* 2013) and mapped for the period: 1850–1859 (1850's), 1900–1909 (1900's), 1950–1959 (1950's), 1990–1999 (1990's), 2006–2015, 2046–2055 and 2086–2095 (Map 1) To obtain the general distribution of BGCP, for each averaged time period and geographic cell of the global ocean, only the provinces with the maximal probability are kept (Map 2). To summarise the long-term spatial variability of each BGCP in the Southern Ocean, the mean latitude and area are computed. These two parameters are calculated for BGCPs derived from environmental conditions yearly averaged. The mean latitude and area of each BGCP are calculated using the geographic statistics of the Matlab® mapping toolbox.

2.2. Bioregionalisation Model approach

2.2.1. Data

For this approach, we used the 20 bioregionalisation clusters from Raymond (2011; see also Grant *et al.* 2006, Sharp *et al.* 2010). These bioregions from Raymond (2011) were obtained through the useof hierarchical cluster algorithms (i.e. PAM) from essential oceanographic predictors (here sea surface temperature, depth and sea ice coverage was used). These layers exist as an ASCII as well as ArcGIS grid format and carry a decimal degrees latitude longitude coordinate system.

For environmental data, we used the IPCC RCP 85 (CanESM2) layers (Van Vuren *et al.* 2011) and their predictors (Table 2). While we did do not use an extensive predictor set yet, they still allow for a consistent framework to model the current and the assumed future state within the IPCC scenario (Schmid 2012 for overview, description and an Arctic application).

Predictor Name	Content	Units
SST	Surface Temperature	°K
SOS	Surface Salinity	PSU
CHla	Total Chlorophyll Mass Concentration at Surface	Kg m^{-3}
NO3	Dissolved Nitrate Concentration at Surface	Mol m^{-3}
MRRO	Total Run-Off (Monthly River Run-Off)	Kgm^{-2} s^{-1}

Table 2 Details on the predictors used from the rcp85 (CanESM2) model for obtaining 2010 and 2100 predictions of biogeography cluster; for more information see http://www.cccma.ec.gc.ca/data/cgcm4/CanESM2/rcp85/mon/index.shtml, as well as Van Vuren 2011 & Schmid 2012).

2.2.2. Methods

To identify the bioregionalisation clusters in time and space we followed a tree-based (Huettmann 2000, Huettmann & Diamond 2001) ecological niche model approach, as described in Elith *et al.* (2006), and Hegel *et al.* (2010), Huettmann *et al.* (2011) (Figure 2). While the clusters are following Raymond (2011) and are described therein, it should be kept in mind that these are primarily mathematical clusters, and here we use them as convenient biological groups ("containers") to assess which trends these habitats are evolving in. For each species we linked the cluster membership with 10,000 random points. We then built automated tree models (randomForest algorithm; Huettmann *et al.* 2011, Wei *et al.* 2011) in R and with Salford Systems, employing the Geospatial Modeling Environment (GME; www.spatialecology.com/gme/) for overlays and processing. Relevant layers were imported and exported as CSV files into ArcGIS10. The stereographic southpolar projection was used in ArcGIS10 for visualisation; latitude and longitude data were re-projected accordingly. Our models allowed us to create diagnostics and statistical analyses; some of the relevant metrics are presented here. We then employed the obtained randomForest model file (groove) to a 'lattice' of 8,967 equally spaced points all over the Antarctic pelagic study area (this number is based on 10,000 random points from an encompassing square which then got clipped to the Antarctic circle). The 'lattice' was overlaid in GME over the same set of environmental predictors as the bioregionalisation layer. This allowed us to obtain the randomForest predictions for each of the lattice points and for the year 2010 (~current conditions). We used the averaged 2010 data as a proxy for this time period.

For forecasting, we followed methods presented in Booms *et al.* (2011): the randomForest model for bioregional cluster membership vs. environmental data layers from the IPCC (CanESM2) was developed for the year 2010. This model was applied to the data lattice with environmental layers from the IPCC models for the year 2100. Summarised diagnostic metrics of the 2100 models (when compared to 2010) were obtained.

3. Results

3.1. Environmental envelopes of the biogeochemical provinces

The Macro ecological procedure selected (Reygondeau *et al.* 2013) allows us to infer for each oceanic geographical cell the probability to belong to one of the BGCPs (or Province suitability index; PSI) according to their environmental conditions exhibited. For each BGCP, all PSIs have been gathered for all environmental conditions possible in the Southern Ocean during the period 1860–2000. This computation offers us to infer the full environmental envelope in each of the four dimensions considered here (Figure 3) for the four selected provinces. Environmental envelopes are distributed between -2 and 23°C of SST, from 0 to 1.5 log_{10} gC of phytoplankton biomass, from 0 to 6000 m of depth and from 33 to 36 PSU of salinity.

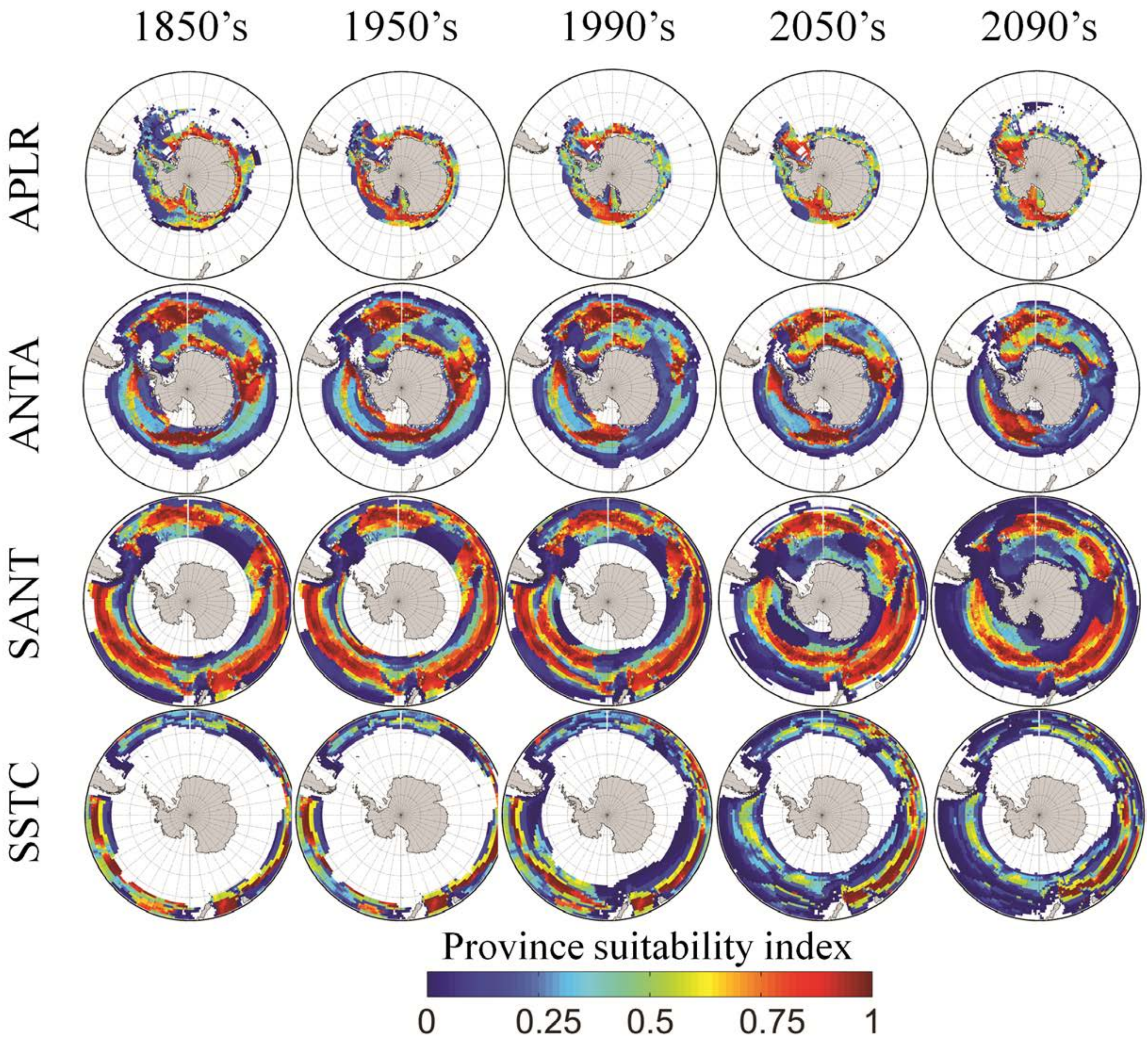
Results provided in Figure 3 show that each BGCP represents a characteristic range of environmental conditions that depict the physical and biogeochemical features of the areas, the oceanic basin and the biome in which the BGCP belong (Longhurst 2007). Results revealed that two adjacent provinces do not fully occupy similar environmental ranges (e.g. ANTA, APLR). These differences in the environmental distributions are larger between two provinces that do not belong to the same biome (here, westerly wind and polar biomes) (e.g. SSTC, ANTA).

3.2. Changes in the spatial distribution of macro ecological provinces in the Southern Ocean

Each BGCP originally delineated by Longhurst (2007) represents specific oceanographic areas delimited by invisible frontiers such as water mass convergence or divergence areas. For instance, BGCP of the polar biome are located between the Antarctic coasts, the Antarctic Convergence (APLR) and the Antarctic Polar Front (ANTA) respectively. Provinces of the westerly biome are distributed along the Antarctic Polar Front and the Sub-Antarctic Front (SANT) and beside the Sub-Tropical Convergence (SSTC). The numerical approach used here allows us to retrieve the spatial distribution of each BGCP. This is according to its environmental envelope (Figure 3) and to the environmental conditions encountered in the Southern Ocean at a given time period (Figure 1, step 3). The obtained spatial distribution for the period 1850-1990 of the PSI (Map 1) as well as the general distribution of the BGCP (Map 2) fits with the general knowledge of the Southern Ocean biogeochemical features and oceanographic partitions (Tomczak & Godfrey 2003).

From 1850 to 2000, three main climatic periods are described in the literature (Stott *et al.* 2000, Alley *et al.* 2003) and can be identified in the results (Figure 3 and Map 1). The first period starting from 1850's and ending in the 1950's can be depicted as biogeographically stable (see Map 2 and Figure 4). Only natural oscillations (i.e. change in the environmental conditions non attributes to anthropogenic activities) of the biosphere affect the PSI of the BGCP (Alley *et al.* 2003) with some variation of the PSI. The second period from 1950's to 1990's is marked by important inter-decadal environmental oscillations such as the ENSO effect and the Northern Hemisphere desalinisation (Fromentin *et al.* 1997). These strong oceanic–atmospheric oscillations affected the environmental condition of the global ocean via the ecosystem/atmospheric/oceanic teleconnection. Furthermore, according to Stott *et al.* (2000) this period characterised the first observations of anthropogenic climate change with a significant increase of the air temperature. Thus, a sensible modification of the PSI of the province SSTC can be observed on Map 1. This results mark a significant change in the latitude (Figure 4) of the province and hence on the general biogeography of the Southern Ocean (Map 2). The third period from 1990's to 2010's shows a significant change in the environmental conditions in the ocean at a global scale (Levitus *et al.* 2001, Hugues *et al.* 2005, Parmesan & Yohe 2003) attributed to anthropogenic forcing. As a consequence, SSTC, ANTA and SANT provinces show a modification of the spatial distribution of their PSI resulting in a global poleward shift (Figure 4). The spatial distribution of the province APLR is stable during this period (Figure 4a) but shows a decrease of its area due to the poleward shifting of its adjacent provinces (Figure 4b). In addition, the mean PSI of the APLR province decreases during this period, particularly near its upper boundaries.

Projections of the Southern Ocean biogeography (decades 2050's and 2090's) are performed using the IPSL-CM5 outputs (Bopp & Aumont 2006) under the RCP 8.5 scenario. Results obtained (Figures 4 and Maps 1 and 2)



Map 1 Spatial distribution of the province suitability index for the 4 biogeochemical provinces during 1850's, 1950's, 1990's and projected 2050's and 2090's decades. Information on BGCPs selected can be found on Table 1.

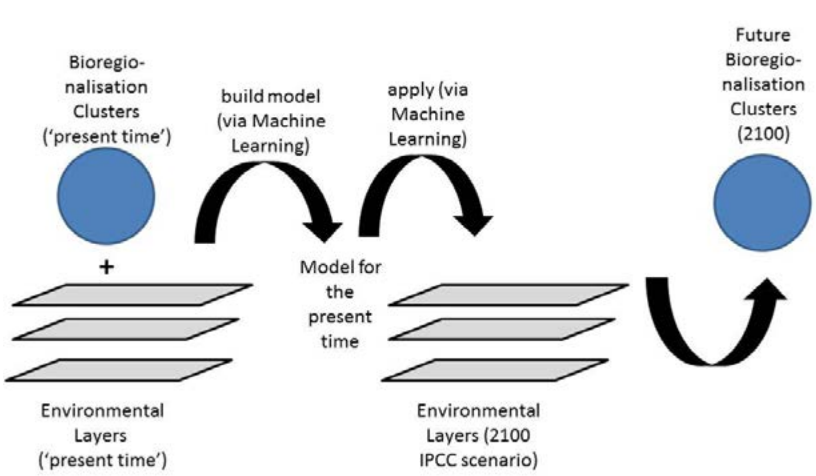


Figure 2 Sketch diagram of the bioregionalisation method used.

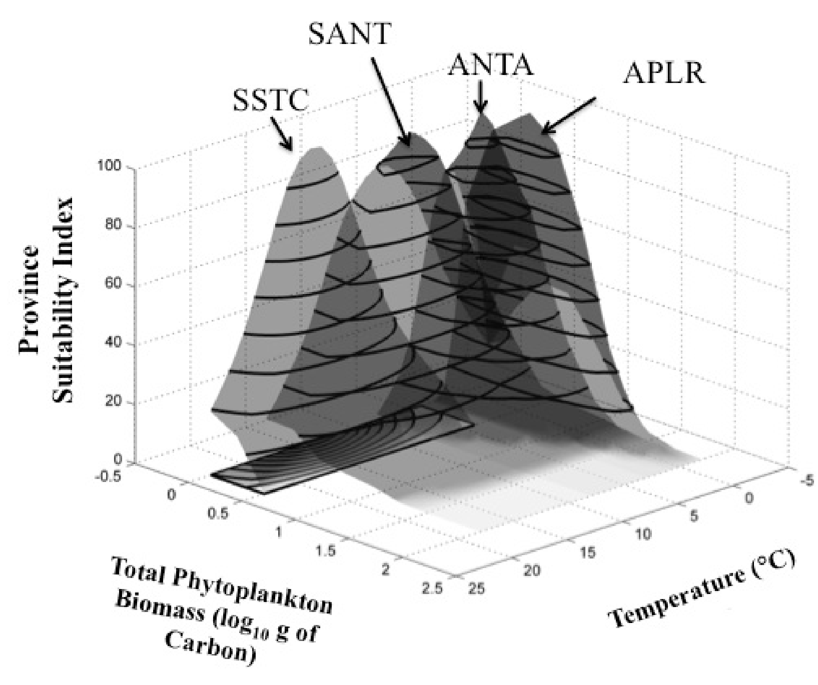
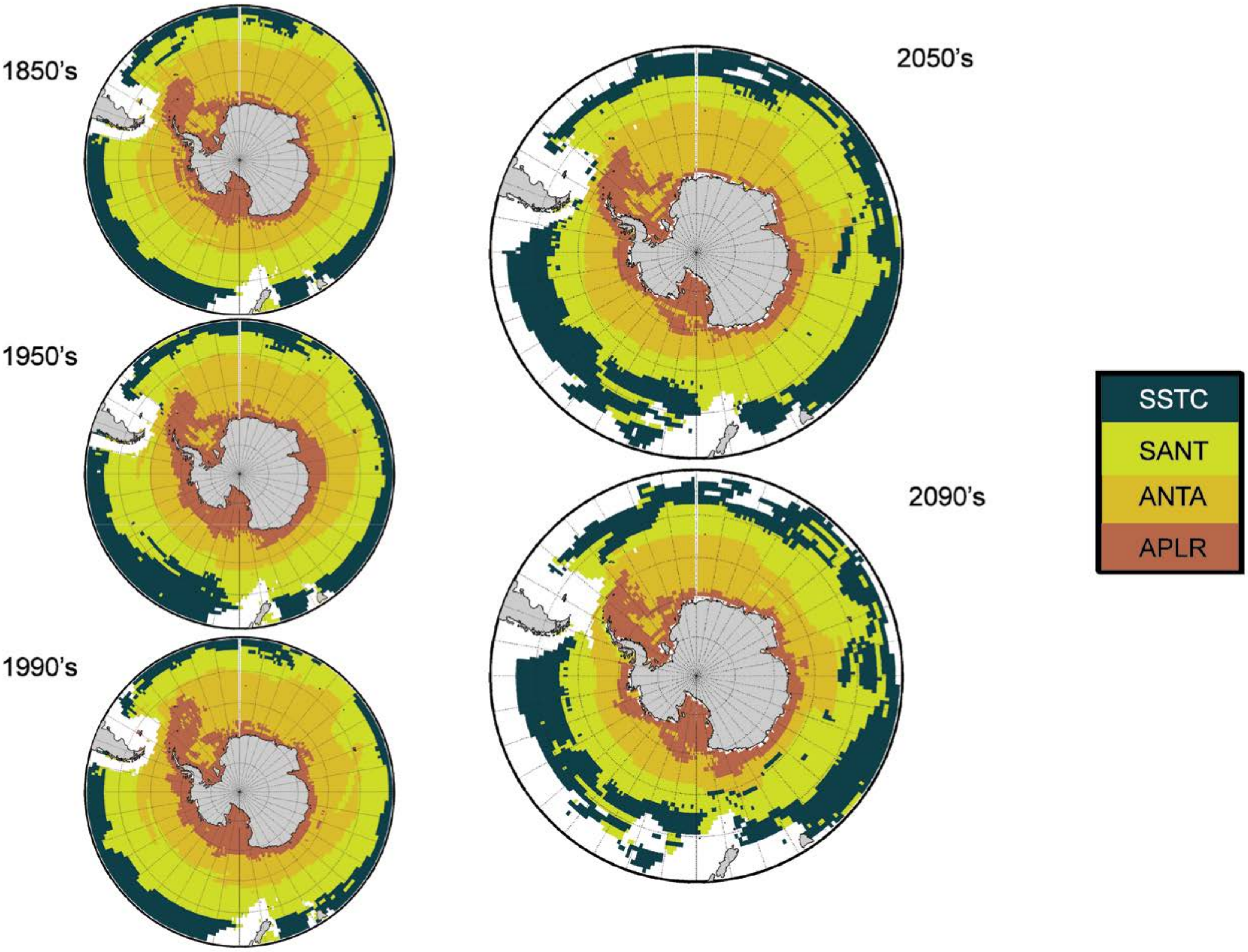


Figure 3 Environmental envelope visualisation of each BGCP in the Southern Ocean according to total phytoplankton biomass and temperature.



Map 2 General distribution of the biogeochemical province (provinces descriptions can be found in Table 1) in the Southern Ocean during 1850's, 1950's, 1990's and projected 2050's and 2090's decades.

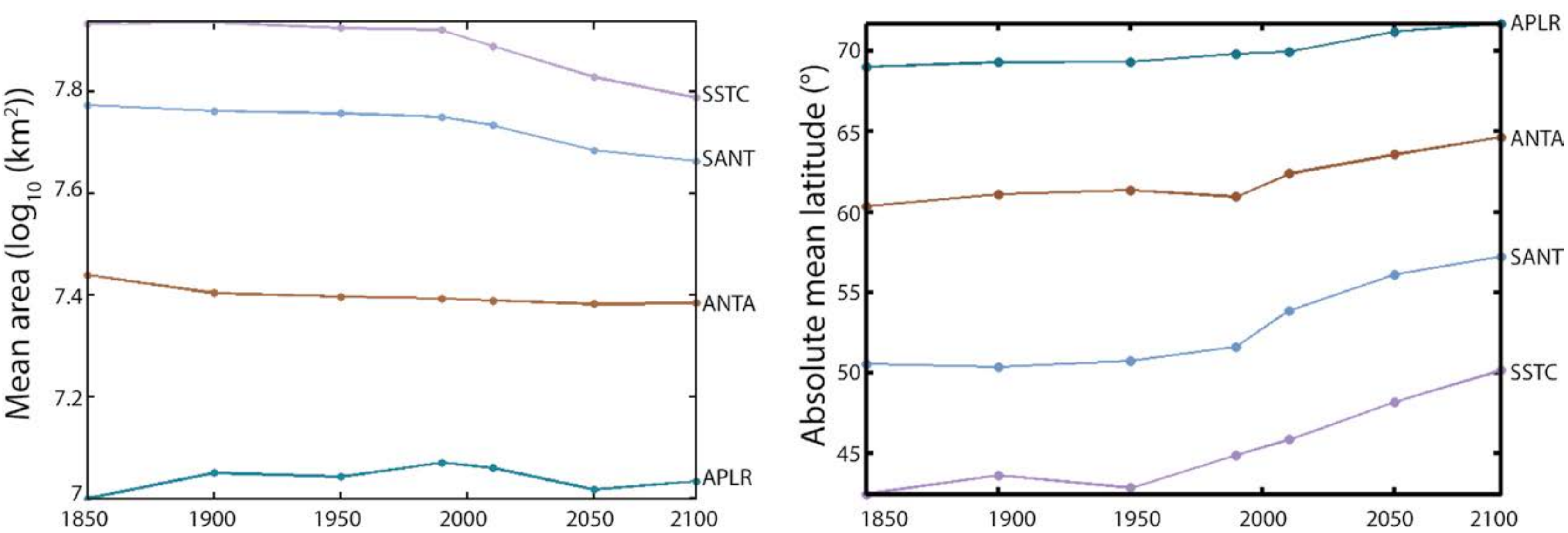
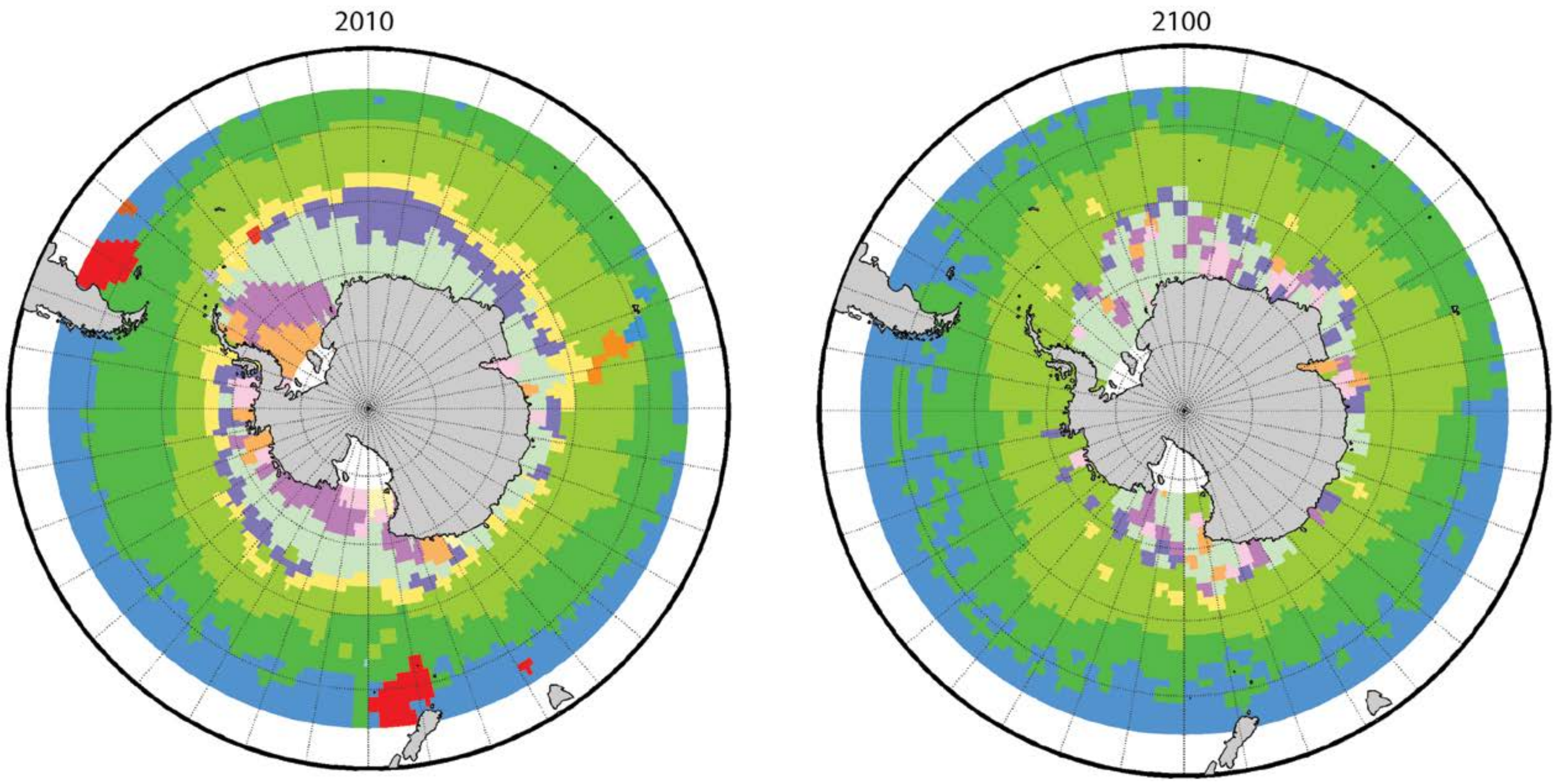


Figure 4 Evolution of the mean absolute latitude and area (in log10 km2) of four BGCPs.

show an acceleration of the biogeographical trends previously observed. An important poleward shift of all provinces is observed during 2050's and 2090's decades. However, the acceleration of the poleward shift appears higher for westerly provinces (SSTC, SANT) than polar provinces (ANTA, APLR). The area of each province tends to decrease drastically in the 21st century (e.g. half of the original SSTC provinces will disappear in the next 70 years). While the areas of polar provinces tend to decrease at a lower level due to the persistency of oceanographic features caused by global and permanent physical forcing (Antarctic convergence and polar front), it appears that the mean PSIs decrease drastically. These results indicate a severe habitat modification.

3.3. Biogeographical modifications at a regional scale

The bioregionalisation layers show strong and concentric bands around the Antarctic continent (Map 3). During 2100 this pattern moves and changes. Noteworthy are the changes of the transition zones and the extent of specific bioregions. Specific patterns are found at the two extreme ends: the warmer boundary regions are getting influenced from the 'warmer' outside, and they move more into the cooler regions poleward. The actual ice-covered areas somewhat remain, but they change their shape, extent and form (presumably the volume too). While these ice-zones get much more narrow, some other places get wider and float out. Some people might interpret that perhaps as good news for ice cover in the future, in reality though such changes of distri-



Map 3 Map of model predicted 20 bioregionalisation clusters using IPCC RCP85 predictors. (a) for the year 2010.(b) for the year 2100.

bution, shape and presumably volume will likely result in wholesale changes of the associated biodiversity community set up, and which so far has been stable and slow to adjust for thousands of years (likely longer). Areas associated with the Antarctic Peninsula such as the Bellingshausen Sea and the Weddell Sea are regions that show bigger changes in these models (as indicated in many spatial changes of cluster memberships). They feature large ice shelves, too. The intermediate transition zone between the boundary of the study area (beyond the frontal systems) and coastal Antarctica will shift the most and shows the biggest large-scale variation across years. Warmer waters will usually affect it, and the ice-related features in these zones are predicted to shrink, with local variations (a few marginal areas appear to maintain their cluster memberships, e.g. near the wider Crozet Island regions).

4. Discussion

4.1. Benefits and caveats of modeled environmental data

All environmental data used in this chapter are gathered from Atmospheric-ocean coupled models outputs approved by the 5th assessment report of the IPCC. These are 'the' global standard and will remain so for years to come. While these models offer a faithful picture of the global distributions and long-term trends of environmental parameters considered in this chapter, they can show some specific shortcomings at a more regional scale. IPCC outputs have been criticised for performing poorly on the Antarctic frontal systems at several levels: (1) The amplitude value of modeled parameters usually do not cover the same range as observed data; (2) despite a good representation of the shallower depth (i.e. 0–100m) of the water column, the vertical dimension is usually not fully achieved in AOGCM models when compared with sampled profiles due to a lack of observations to calibrate biogeochemical processes; (3) modeled inter-annual and decadal oscillations of environmental parameters (i.e. ENSO, NAO, etc.) are generally retrieved at a basin scale but they reveal a temporal shift relative to observations. Also, projected changes in ocean partition detected in the chapter are mainly derived from environmental trends extracted from past observations (IPCC 2007). Consequently, the present parsimonious methodology and the AOGCM model used cannot take into account stochastic events as well as all positive or negative retroactive loops (e.g. Change in current circulation, change in stratification) that might buffer the environmental perturbations in some areas in the coming next decades. These sums of partial errors need to be taken into account in the interpretation of the spatial distribution and trends provided for the pelagic habitats in this chapter (Huettmann & Gottschalk 2011). Arguably, any of the output relies on the provided IPCC models. However, the spatial distribution of well-known epipelagic oceanographic structures has been retrieved and their long-term dynamics during hindcast period (i.e. from 1850 to now) are mainly in accordance with literature. We see that as a rather encouraging macroecological trend, and wish that the models presented here are interpreted accordingly, and when judged over time.

4.2. Pros and cons of biogeographical approach used

Macroecological models of partitioning have been increasingly used over the last decades to summarise the global oceanic environmental complexity and dynamics. These statistical procedures allow the presentation of coarse summaries of the spatial oceanographic or ecological features at different scales, and assess trends for vast ocean areas that are widely under-sampled and for more detailed follow-up studies. At minimum, such models can summarise existing data and knowledge, and help to formulate new and improved hypotheses; knowledge is gained. Furthermore, these methods aim at implementing a powerful geographical and quantitative framework for several types of studies: ecological studies (e.g. comparison between systems), model calibration, implementation of marine protected areas or management of biodiversity and/or fisheries.

The macroecological approach proposed here (see 2.1.) was originally designed to identify and follow the main biogeochemical envelopes of each oceanic basin in the global Ocean (Longhurst 2007). This numerical approach is highly synoptic and does not take into account some mesoscale features and regional specificities and as it needs to be applicable globally with relevant values. Therefore, a first parsimonious model using only four parameters is selected to focus on macro biogeochemical processes and global spatial environmental discontinuities. The method and its outputs are directly meant for macroecological studies and approaches but not really for regional efforts such as the implementation of MPAs or identification of marine species habitats. This is because the solution depends on the context of the other oceans and within each province there is a high spatial environmental heterogeneity at a finer scale. While hierarchical scaling has been proposed in ecosystems (Townsend *et al.* 2002, Forman 2006) their utility still await to be confirmed and explained. These last types of ecologic questions are more supported by the regional approach proposed in section 2.3. Indeed, the clustering methodology used aims at detecting all spatio/environmental characteristics in a given area. Therefore, all types of habitats can be retrieved but are not linked. Furthermore, models predicting multi-categorical clusters over time have been criticised for missing clusters in the actual outcome. This can be due to new ecological arrangements and cluster set-ups in the future resulting in additional invasive clusters entering the study area that were not part of the initial model training set, or when the starting cluster set is not complete and with clusters entering from the outside. We acknowledge all of these issues, find it informative and working in favor of the argument we present (= larger changes coming due to climate change). We still emphasize that the existing set of clusters allows us to show general trends now and into the future. It is our hope that these models, data and methods will be improved over time and in a more pro-active manner (sensu Drew *et al.* 2011).

4.3. Global trends of pelagic habitats in the Southern Ocean

The use of two different numerical approaches allows to more objectively identifying (common trends between methodology) areas impacted by environmental modifications driven by global climate change.

Both models agree on a drastic change occurring throughout the entire Southern Ocean over the next 100 years. The common pattern predicted is a poleward shift of each division detected in the 2000's decade (Map 2 and Map 3). These spatial migrations underline a major restructuration of marine biotope distributions mainly driven by the warming of the Ocean. However, the rate of the poleward shift is not homogenous around the Southern Ocean. Results reveal that the sub-tropical and sub-polar areas will suffer from a more important migration than Polar Regions. This migration will be enhanced in the Indian and Pacific basins where there is little continental buffer effect. However, the migration of the westerly wind biome should stop at the edge of the Antarctic Polar Front. The spatial position of this frontal system appears not to be affected much by the change in the environmental conditions. This spatial persistence can be attributed to its high dependency on constant geostrophic properties of the earth system rather than on changes in abiotic properties of the water mass. Below the Polar Front, a major restructuration of the shape of the Polar zone is expected. Further, both models are in agreement showing changes in the wider Antarctic Peninsula region (and where much shelf ice is located affecting regional patterns). While the macroecological approach only presents a significant decrease of the PSIs, especially in the Indian Ocean basin, the regional procedures reveal a spatial reorganisation of the pelagic habitats and associated communities.

Over time, better models and understandings will be developed, here we present a first macroecological view and consensus from different model approaches; they confirm massive changes based on a wide-spread warming in the Southern Ocean. Consequences are presumably very large, with global repercussions on southern marine ecosystems.

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THE BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

Scope

Biogeographic information is of fundamental importance for discovering marine biodiversity hotspots, detecting and understanding impacts of environmental changes, predicting future distributions, monitoring biodiversity, or supporting conservation and sustainable management strategies.

The recent extensive exploration and assessment of biodiversity by the Census of Antarctic Marine Life (CAML), and the intense compilation and validation efforts of Southern Ocean biogeographic data by the SCAR Marine Biodiversity Information Network (SCAR-MarBIN / OBIS) provided a unique opportunity to assess and synthesise the current knowledge on Southern Ocean biogeography.

The scope of the Biogeographic Atlas of the Southern Ocean is to present a concise synopsis of the present state of knowledge of the distributional patterns of the major benthic and pelagic taxa and of the key communities, in the light of biotic and abiotic factors operating within an evolutionary framework. Each chapter has been written by the most pertinent experts in their field, relying on vastly improved occurrence datasets from recent decades, as well as on new insights provided by molecular and phylogeographic approaches, and new methods of analysis, visualisation, modelling and prediction of biogeographic distributions.

A dynamic online version of the Biogeographic Atlas will be hosted on www.biodiversity.aq.

The Census of Antarctic Marine Life (CAML)

CAML (www.caml.aq) was a 5-year project that aimed at assessing the nature, distribution and abundance of all living organisms of the Southern Ocean. In this time of environmental change, CAML provided a comprehensive baseline information on the Antarctic marine biodiversity as a sound benchmark against which future change can reliably be assessed. CAML was initiated in 2005 as the regional Antarctic project of the worldwide programme Census of Marine Life (2000-2010) and was the most important biology project of the International Polar Year 2007-2009.

The SCAR Marine Biodiversity Information Network (SCAR-MarBIN)

In close connection with CAML, SCAR-MarBIN (www.scarmarbin.be, integrated into www.biodiversity.aq) compiled and managed the historic, current and new information (i.a. generated by CAML) on Antarctic marine biodiversity by establishing and supporting a distributed system of interoperable databases, forming the Antarctic regional node of the Ocean Biogeographic Information System (OBIS, www.iobis.org), under the aegis of SCAR (Scientific Committee on Antarctic Research, www.scar.org). SCAR-MarBIN established a comprehensive register of Antarctic marine species and, with biodiversity.aq provided free access to more than 2.9 million Antarctic georeferenced biodiversity data, which allowed more than 60 million downloads.

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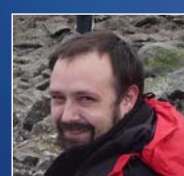

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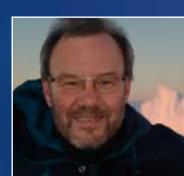

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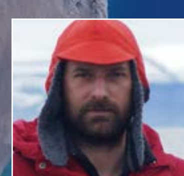

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SCAR — The International Council for Science — Scientific Committee on Antarctic Research

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