Census of Antarctic Marine Life
SCAR-Marine Biodiversity Information Network

BIOGEOGRAPHIC ATLAS
OF THE SOUTHERN OCEAN

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SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH

THE BIOGEOGRAPHIC ATLAS OF THE SOUTHERN OCEAN

The "Biogeographic Atlas of the Southern Ocean" is a legacy of the International Polar Year 2007-2009 (www.ipy.org) and of the Census of Marine Life 2000-2010 (www.coml.org), contributed by the Census of Antarctic Marine Life (www.caml.aq) and the SCAR Marine Biodiversity Information Network (www.scarmarbin.be; www.biodiversity.aq).

The "Biogeographic Atlas" is a contribution to the SCAR programmes Ant-ECO (State of the Antarctic Ecosystem) and AnT-ERA (Antarctic Thresholds- Ecosystem Resilience and Adaptation) (www.scar.org/science-themes/ecosystems).

Online dynamic version :

A dynamic online version of the Biogeographic Atlas is available on the SCAR-MarBIN / AntaBIF portal : atlas.biodiversity.aq.

6.2. Phytoplankton diversity in the Southern Ocean: a satellite view

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1. Satellite observations of phytoplankton

1.1. State of the art

Microscopic studies and pigments are essential tools to define phytoplankton diversity and distribution to the best level. However, they are rather time consuming methods when often a quick assessment of potential biodiversity is required. In addition, given the sampling strategies generally used in situ for phytoplankton analyses (discrete sampling), phytoplankton datasets are often restricted to sampling sites. Hence these types of data are much localized and difficult to extrapolate to larger scales. Even if the ocean colour observation from space faces some important limitations also (information restricted to the near-surface layer of the ocean, impact of atmospheric compounds), several satellite missions have been launched in the past decade and make it possible to monitor the evolution of phytoplankton dynamics at the global scale. Thus, the remote sensing of ocean colours has been used for more than 30 years and now provides key information about this fundamental element of the aquatic food web (O'Reilly *et al.* 1998). In the past few years, the analysis of ocean colour data has moved beyond the estimation of chlorophyll a concentration to estimate new parameters. This includes the ability to determine dominant phytoplankton groups in the surface waters. Note that for remote sensed application, the term "phytoplankton group" encompasses the assemblage of phytoplankton based on their function in biogeochemical cycles, as defined in Le Quéré *et al.* (2005). Likewise, "dominant" has been defined as situations in which a given phytoplankton group is a major contributor to the total pigment pool (ie. >60%), based on biomarkers pigments, that characterised phytoplankton groups. There have been several attempts to derive biologically relevant information from remotely sensed bio-optical spectral signatures (Brewin *et al.* 2010, Ciotti and Bricaud 2006, Hirata *et al.* 2011, Kostadinov *et al.* 2009, Raitsos *et al.* 2008, Uitz *et al.* 2006) or their heterogeneity (Rocchini *et al.* 2010).

Among them, the PHYSAT algorithm (Alvain *et al.* 2005, Alvain *et al.* 2008) has been based on an empirical relationship between coincident in situ phytoplankton groups' dominance observations and remote sensing measurements anomalies. This method has been applied to the SeaWiFS sensor archive, and more recently to the MODIS one. Despite the particularities of the Southern Ocean (ice and clouds cover) it is possible to compute maps of phytoplankton groups from PHYSAT as complementary information to in situ observations.

1.2. PHYSAT principle and limitation

The PHYSAT method validity criteria concern waters with a concentration of chlorophyll a [Chl a] which has to be lower than 3 mg m-3 to exclude waters possibly contaminated by coastal material, and higher than 0.04 mg m-3 to discard ultra-oligotrophic waters where it is unlikely that a dominant group can be found using ocean-colour data.

The PHYSAT method is based on the analysis of the second order variation in water leaving measurement (nLw) after removing the effect of Chl a variation. Thus, PHYSAT is based on the radiances anomalies, Ra, a non-dimensional unit parameter in the visible part of the spectra (i.e. between 412 and 600 nm). Simultaneous in situ biomarkers pigments inventories (or literature analysis for *Phaeocystis*-like in the Southern Ocean as detailed in Alvain *et al.* (2008)) and remote sensing measurements have empirically shown that specific Ra, in magnitude and, to a lesser extent, in shape, is empirically associated with dominant phytoplankton groups. A set of criteria was defined accordingly in order to characterise each Ra spectrum which are then used to compute maps of dominant groups. Five dominant phytoplankton groups are currently identified by specific Ra, nanoeukaryotes, *Synechococcus*, *Prochlorococcus* and *Phaeocystis*-like. These groups have been detected in situ as dominant based on their biomarkers pigments contribution to the total pigment pool as detailed in Alvain *et al.* (2005). It is thus possible to define a set of criteria to characterize each group as a function of its Ra spectrum. These criteria can thus be applied to the global daily SeaWiFS archive in order to obtain global monthly maps synthesis of the most frequently detected dominant group. Note that when no group prevails over the period of one month, the pixels are associated with an 'unidentified' group. The geographical distribution and seasonal succession of major dominant phytoplankton groups have been studied and are in good agreement with previous studies at the global scale (Alvain *et al.* 2008). A recent validation exercise, including some new in situ observations in the Southern Ocean has been performed as well as a first theoretical explanation of the PHYSAT method (Alvain *et al.* 2012). However, as for all empirical ocean colour methodology, validation based on in situ measurements has to be pursued each time a suitable dataset is available.

Results of the PHYSAT validation at the global scale were satisfactory for diatoms (73% of good identification) and nanoeucaryotes (82% of successful identification), and a decrease in the percentage of successful retrieval was observed for *Prochlorococcus* and cyanobacteria: respectively 61 and 57% of successful identification explained by a confusion between these two groups since they show similar characteristics (geographical distribution, size and specific Ra). In addition to previous global scale validation exercise, data obtained within recent program (such ICO²TA (Integrated Coastal Ocean Observations in Terre Adélie) in waters of Terre Adélie since 2008 or OISO (Océan Indien Service d'Observations) campaigns have allowed the successful matchup (i.e. good agreement between PHYSAT and in situ observation) of 12 over 13 diatoms dominance situations. However, challenges remain in high latitudes areas such as the Southern Ocean especially because of rather sparse matchup available for the calibration and validation of the PHYSAT algorithm.

PHYSAT observation can however be used to compute maps of detection frequencies for each phytoplankton groups by considering, for example, the number of days associated with one groups over a period, divided by the number of days associated with one of the dominant groups. These maps have been computed for the 12 months separately over the SeaWiFS sensors archive (1997-2010) and are shown in Figure 1 (a-f).

1.3. From PHYSAT types to the detection of hotspots of planktonic diversity from satellite

Although large, cloud-free scenes in PHYSAT daily snapshots are rare, quasi-instantaneous high resolution images constructed by composing cloud-free PHYSAT pixels over a short time period (typically less than 10 days), suggest that PHYSAT dominant types are organised in homogeneous lobular patches 10-100km wide and 100-1000 km long. In analogy with similar patterns in sea surface temperature and chlorophyll images (Lehahn *et al.* 2007), PHYSAT patterns have been compared to analyses of satellite altimetry, which provides information on the surface currents. This comparison has shown that PHYSAT patches of dominant types in some cases are enclosed in transport barriers induced by horizontal transport that on timescale of days to weeks can stir together water masses of different origin in elongated filaments. For these cases, a biophysical mechanism based on "fluid dynamical niches" has been proposed in d'Ovidio *et al.* (2010). In this scenario, patches of different origin are stirred by surface transport, each patch containing water with homogeneous characteristics and typical lifetimes of days to weeks – close to the phytoplanktonic doubling times or the duration of blooming phases. During this time, inside each patch competition can lead to the emergence of a dominant type or assemblage, possibly associated to a bio-optical anomaly visible by PHYSAT. Many patches of several different origins can be stirred together, resulting in a contrasted patchwork of fluid dynamical niches, each supporting a specific community. Eventually, these patches are stirred in thinner and thinner filaments and conclude their life cycle by becoming mixed together. These observations have indicated the central structuring role of stirring on the phytoplankton community, in particular in regions of strong mesoscale activity like the Southern Ocean. In a further development, the scenario of fluid dynamical niches has also suggested that regions in which remote sensing detects several different patches of optical anomalies may be good candidates for hotspots of phytoplanktonic biodiversity (De Monte *et al.* 2013). The possibility of extracting biodiversity information from remote sensing is particularly appealing for fragile ecosystems of difficult access like those of the Southern Ocean. Although a systematic validation of this approach has still to be done, comparisons between independent observations of biodiversity and hotspots of PHYSAT heterogeneity are promising. A climatological map of this PHYSAT-derived possible phytoplanktonic diversity induced by stirring is shown in Figure 2. Several putative hotspots appear, in particular at confluence region close to the South West Atlantic zone and in the interfrontal transitions zones between oligotrophic ecosystems and regions where the prevailing iron-limited conditions of the Antarctic Circumpolar Current are relieved by iron supply from a shallow plateau (for instance South Georgia and Kerguelen islands). This approach has several limitations. In particular, it cannot identify hotspots which are not associated to patchiness and even in this case, it cannot detect patchiness that is not detected by PHYSAT as bio-optical anomalies. Nevertheless, even if the presence of these hotspots needs to be confirmed by a comparison with in situ data and possibly model data (Follows *et al.* 2007), a similar approach based on remote sensing can suggest a guiding mechanism for mapping phytoplanktonic biodiversity in the Southern Ocean.

Figure 1a

Figure 1b

Figure 1a, b Frequency of detection of signals associated to the dominance of Nanoeucaryotes (nan), Diatoms (dia), *Phaeocystis* (pha), *Prochlorococcus* (pro), *Synecochoccus* like Cyanobacteria (slc) for (a) November and (b) December (climatology over the SeaWiFS period 1998-2010).

Figure 1c

Figure 1d

Figure 1c, d Frequency of detection of signals associated to the dominance of Nanoeucaryotes (nan), Diatoms (dia), *Phaeocystis* (pha), *Prochlorococcus* (pro), *Synecochoccus* like Cyanobacteria (slc) for (c) January and (d) February (climatology over the SeaWiFS period 1998-2010).
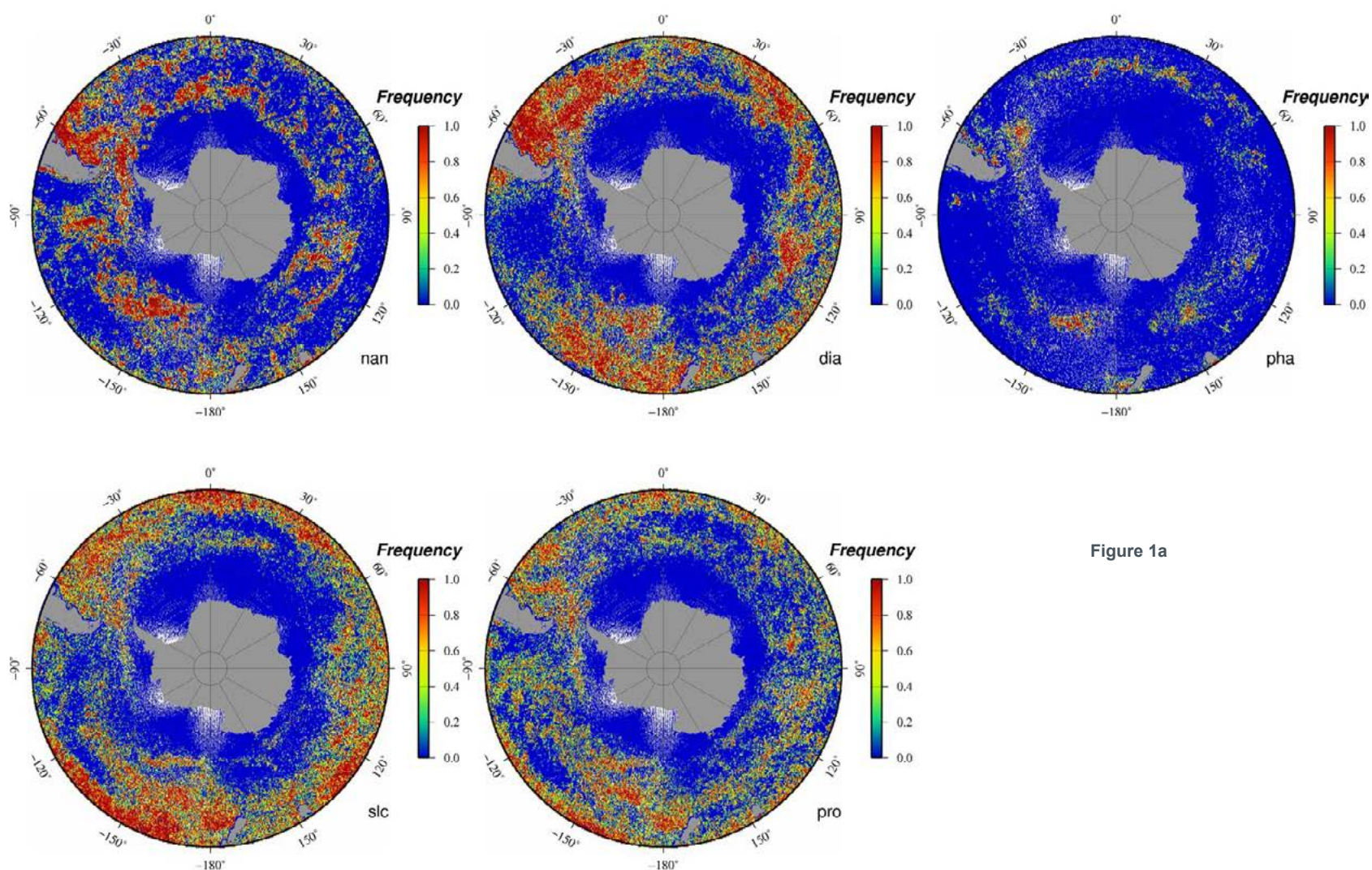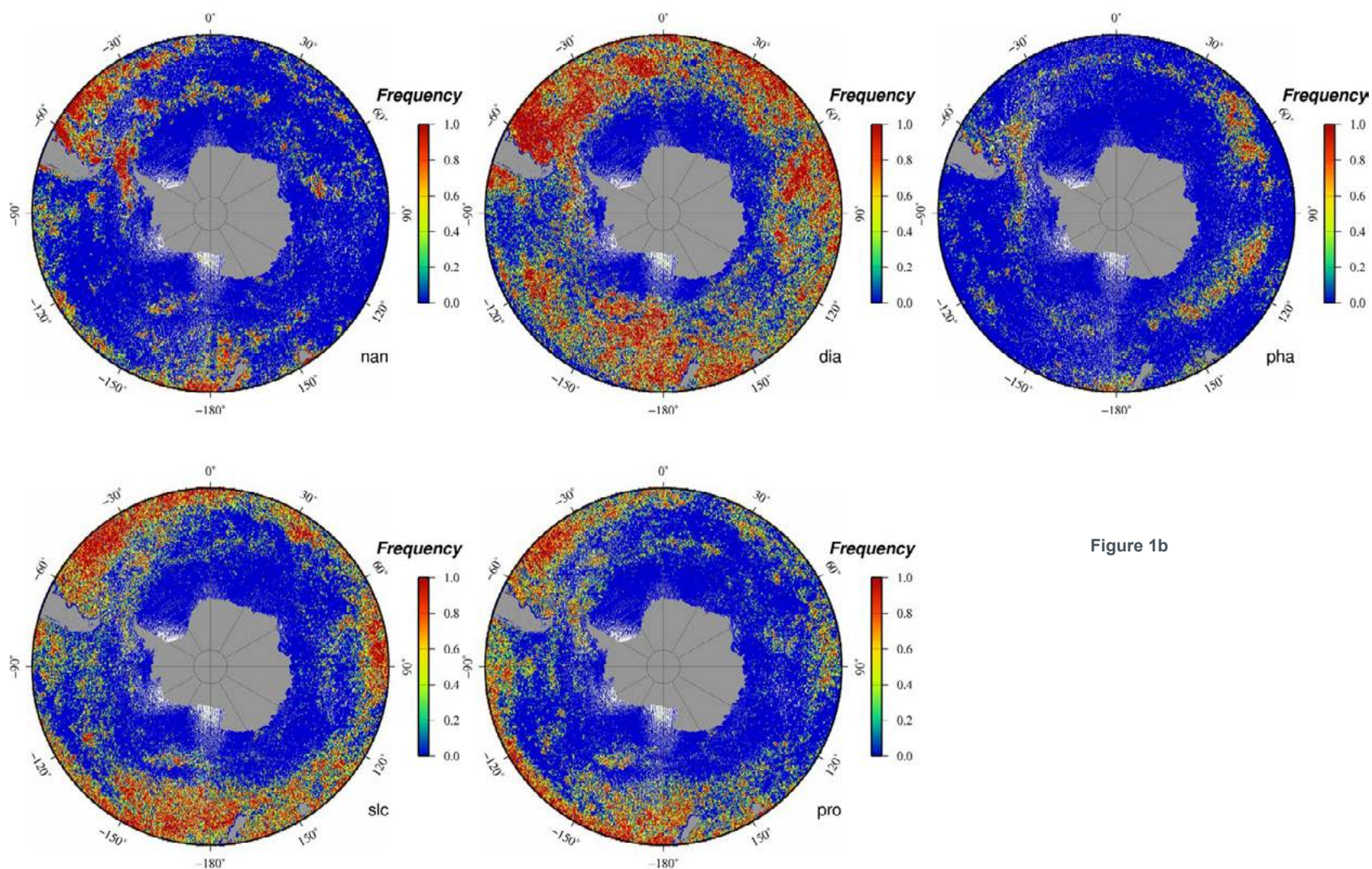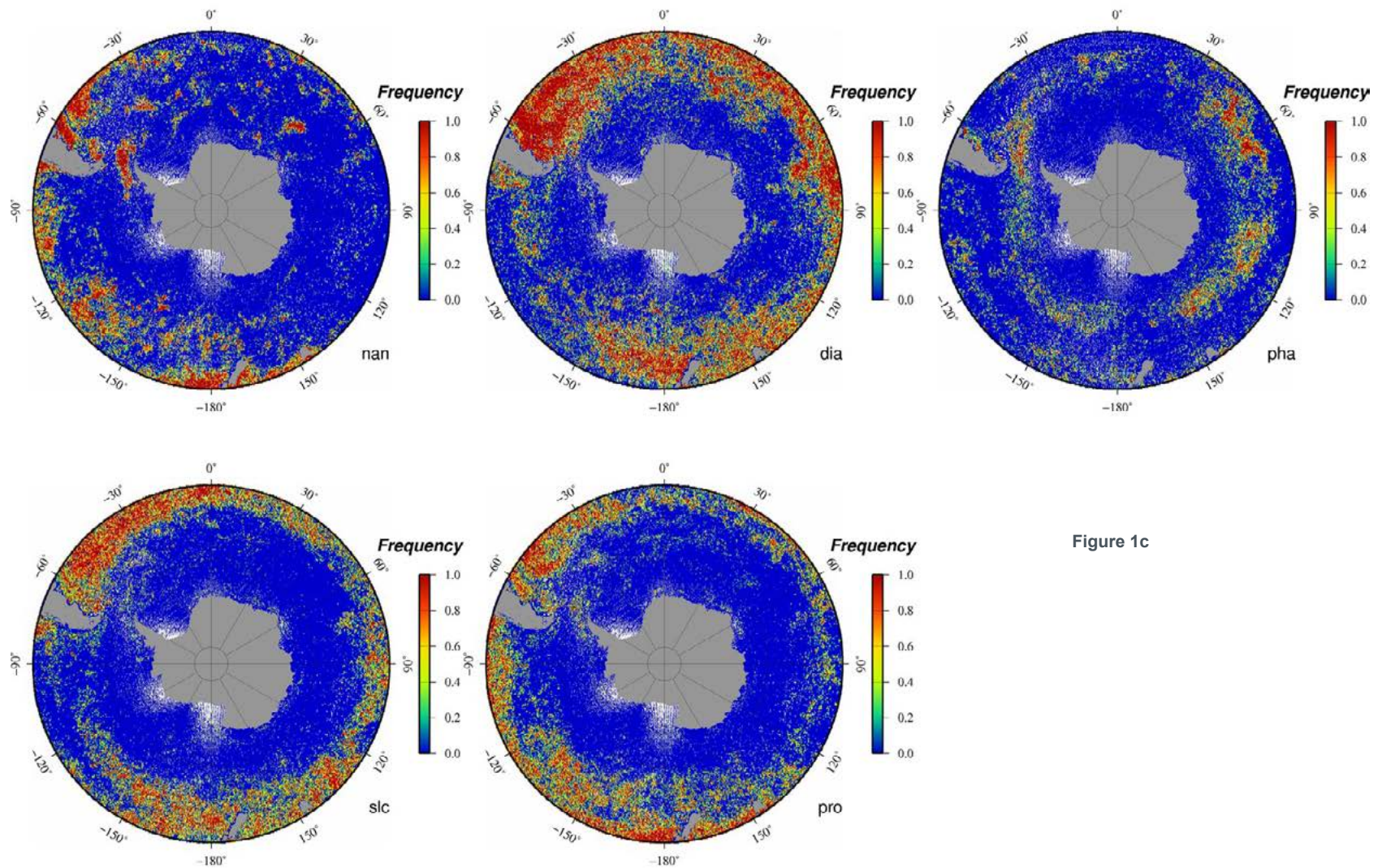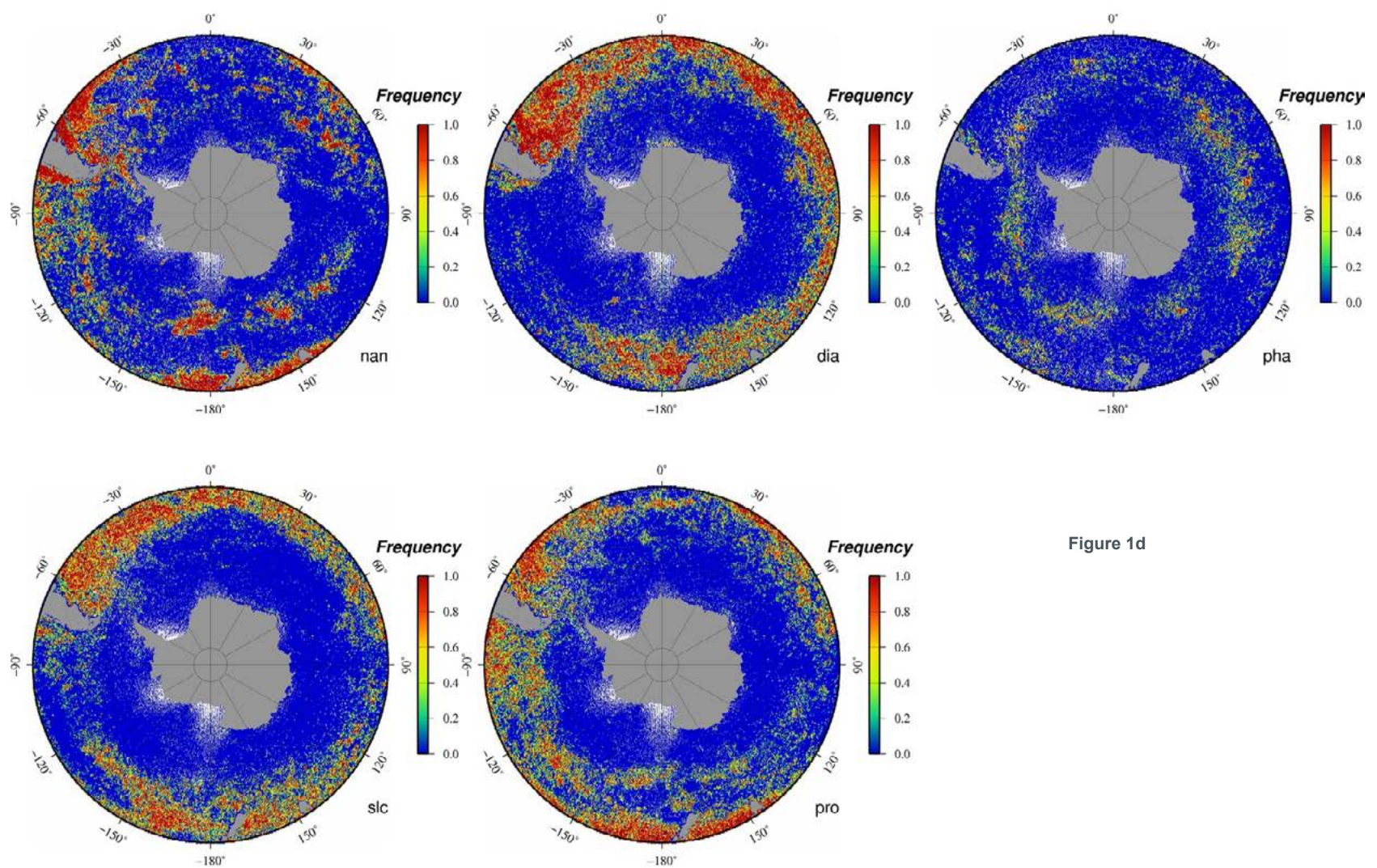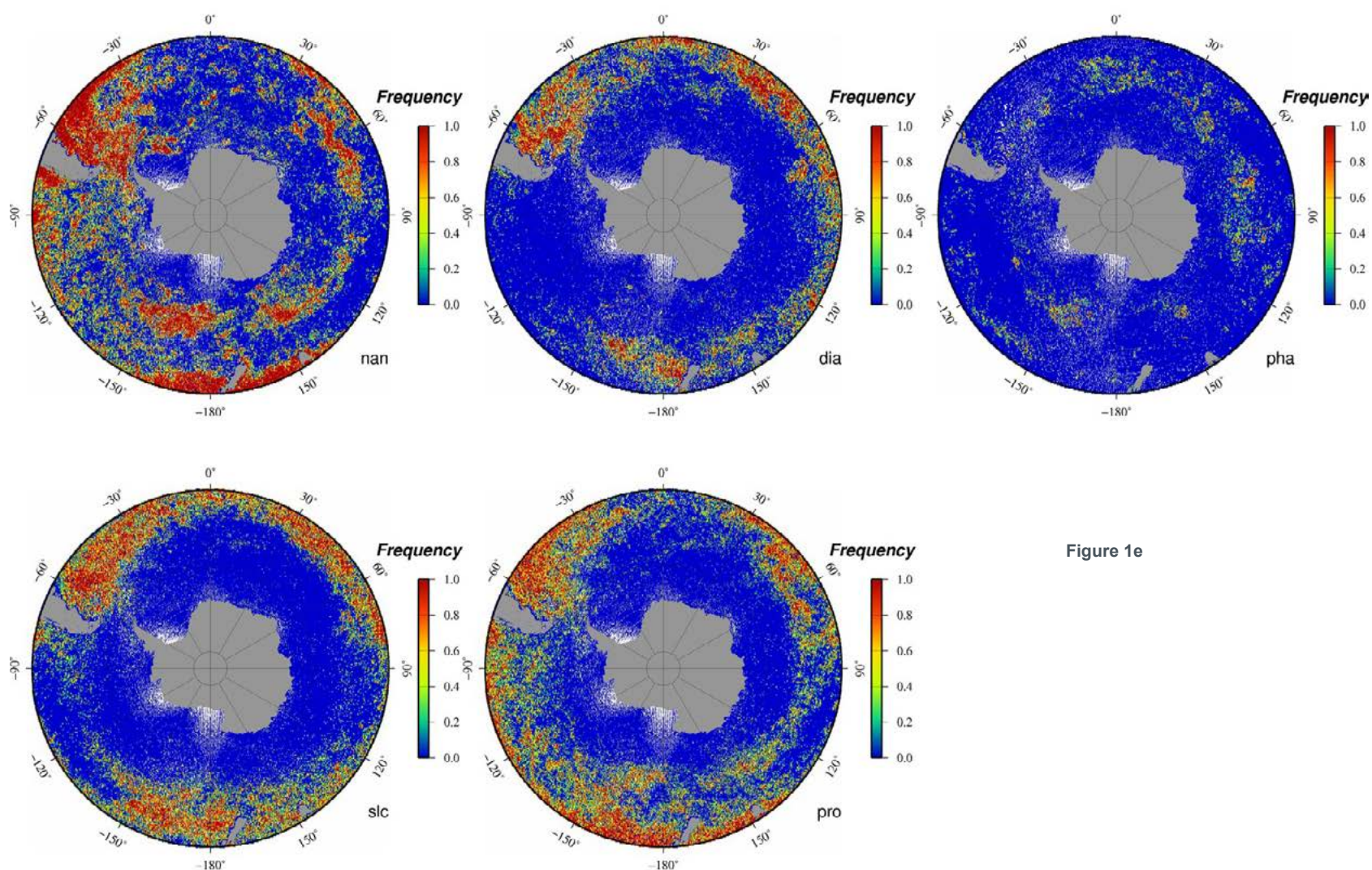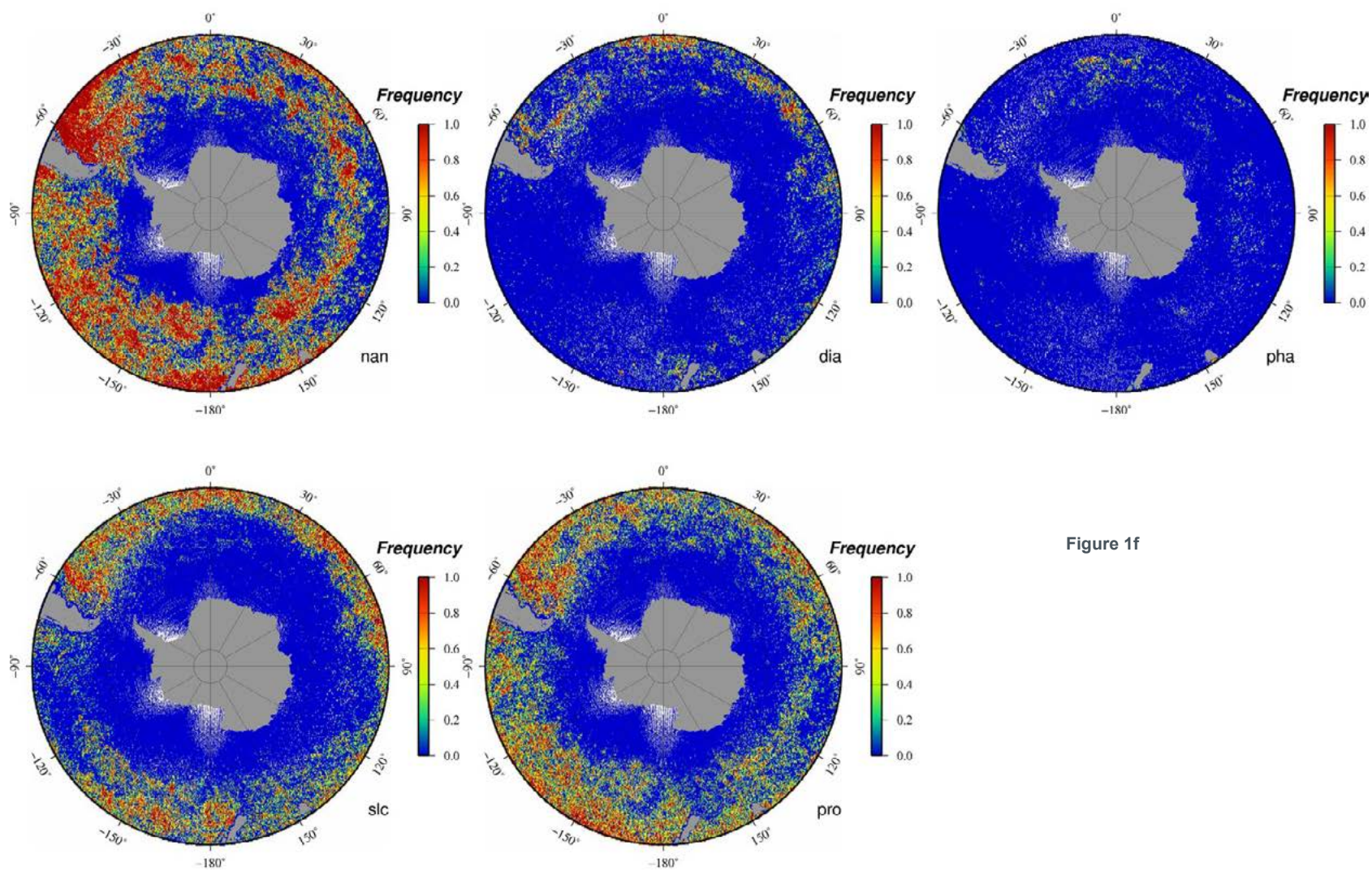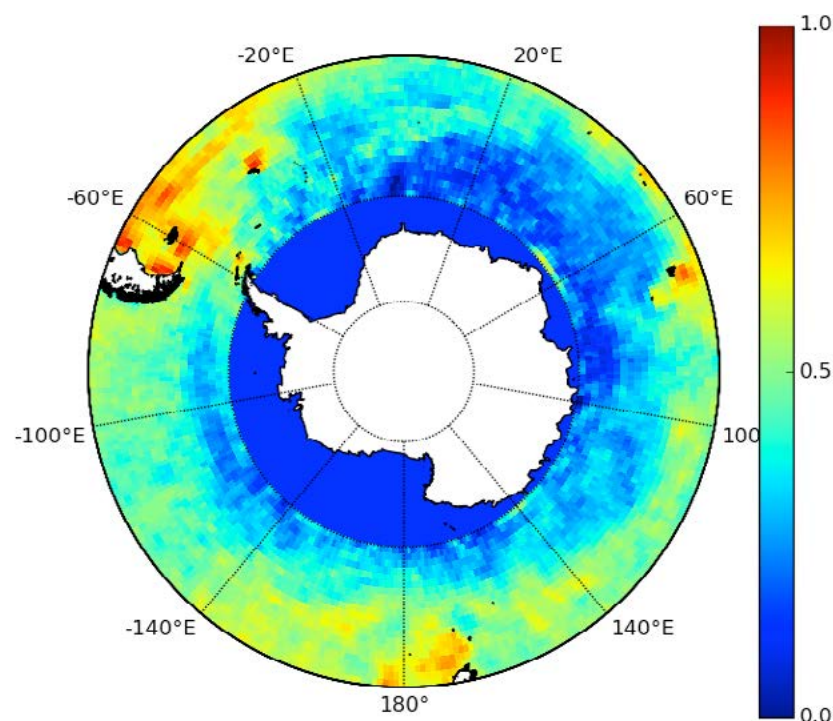
Figure 1e

Figure 1f

Figure 1e, f Frequency of detection of signals associated to the dominance of Nanoeucaryotes (nan), Diatoms (dia), *Phaeocystis* (pha), *Prochlorococcus* (pro), *Synecochoccus* like Cyanobacteria (slc) for (e) March and (f) April (climatology over the SeaWiFS period 1998-2010).

Figure 2 Putative remote-sensed phytoplanktonic diversity hotspots (Shannon index) computed by estimating the local patchiness of PHYSAT types (see De Monte *et al.* 2013 for details).

1.4. Discussion

The Southern Ocean presents the particularity of the absence of coastline and a specific topography which induce strong currents and nutrients inputs as well as large discontinuity frontal regions. These characteristics associated with strong seasonal light availability allow large phytoplankton blooms in spring and summer (Figure 3).

As shown in the Figure 1, these conditions facilitate the development of diatoms and *Phaeocystis*. In the Southern Ocean, PHYSAT (in its 2008 version) computation revealed that these large blooms of both diatoms and *Phaeocystis* were moving poleward from November to January, whereas during other period some large part of the Southern Ocean were dominated by nanoeucaryotes (Alvain *et al.* 2008). The diatoms blooms start and finish around 40°S, in the Sub-Antarctic Front zone, respectively in October and April, following the occurrence of favourable conditions, while they cover most of the region in December and January. This is in agreement with Tremblay *et al.* (2002). Diatoms were also detected in summer near the melting zone and along the stratified marginal ice zone as observed previously (Smith, *et al.* 1990, Di Tullio *et al.* 1996, Goffart *et al.* 2000, Mangoni *et al.* 2004, Smith *et al.* 2003). Additionally the use of data from past campaigns have highlighted the frequent occurrence of *Phaeocystis* blooms in the area (Goffart *et al.* 2000, Smith *et al.* 2003, Croot *et al.* 2004, Schoemann *et al.* 2005). PHYSAT maps show the widest *Phaeocystis* blooms in January and February, after the diatoms occurrences, mostly in the southern Indian Ocean and south of Patagonia, in area and latitude associated with higher Mixed Layer Depth (MLD) conditions as shown of Figure 4 (De Boyer Montégut *et al.* 2004). This observation is confirmed by previous knowledge about the *Phaeocystis* growth. Indeed, the geographical distributions of diatoms and *Phaeocystis* are strongly controlled by the thickness of the mixed layer. Diatoms are found preferentially in stratified waters (Weber and El-Sayed 1987, Jochem *et al.* 1995) whereas *Phaeocystis* prevails in areas with a deep mixed layer (Arrigo *et al.* 1999, Goffart *et al.* 2000, Mangoni *et al.* 2004).

Acknowledgements

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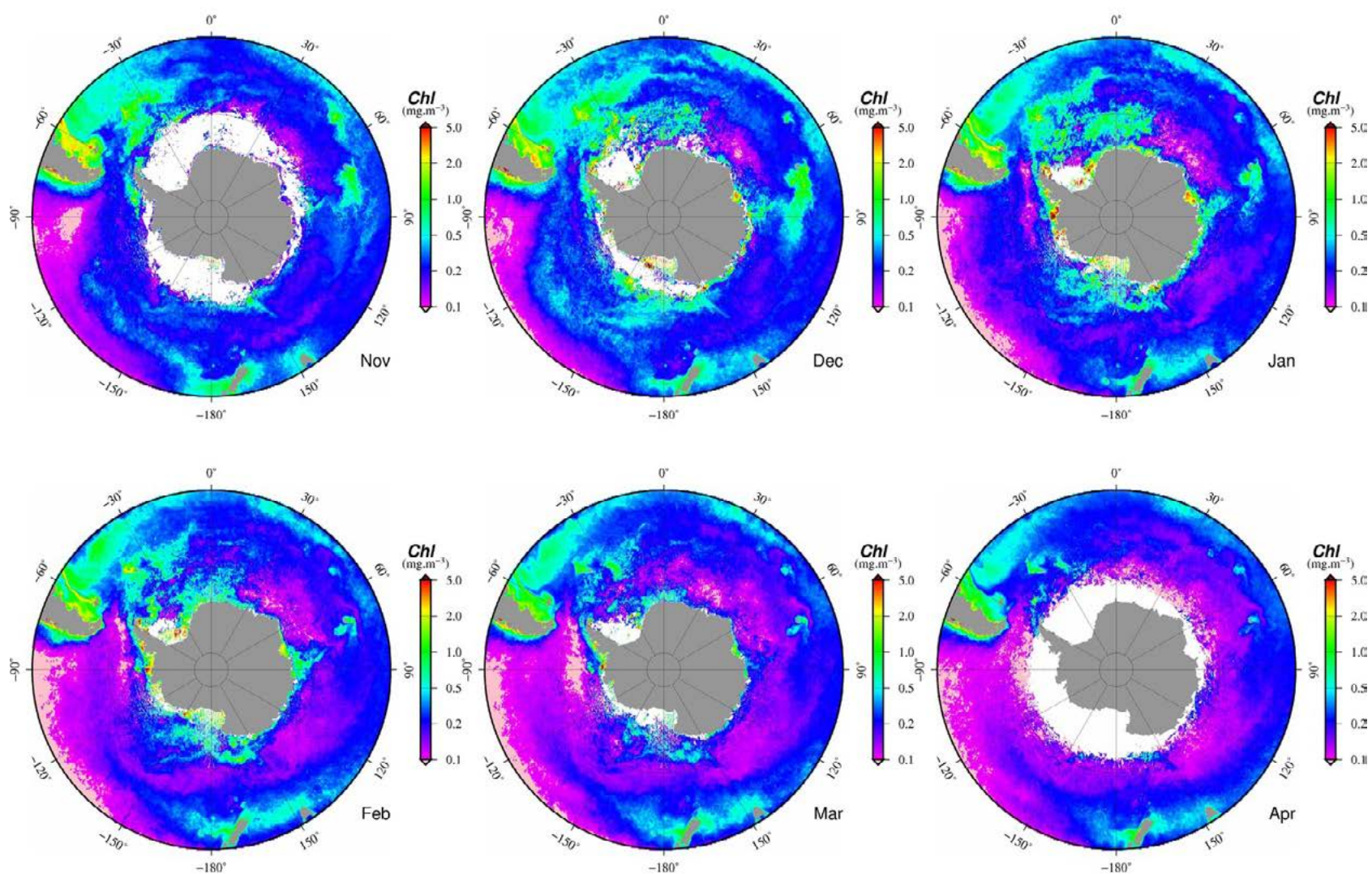
Figure 3 Monthly climatology maps of chlorophyll-a concentration from November to April (SeaWiFS 1998 – 2010, data from NASA/GSFC/DAAC).
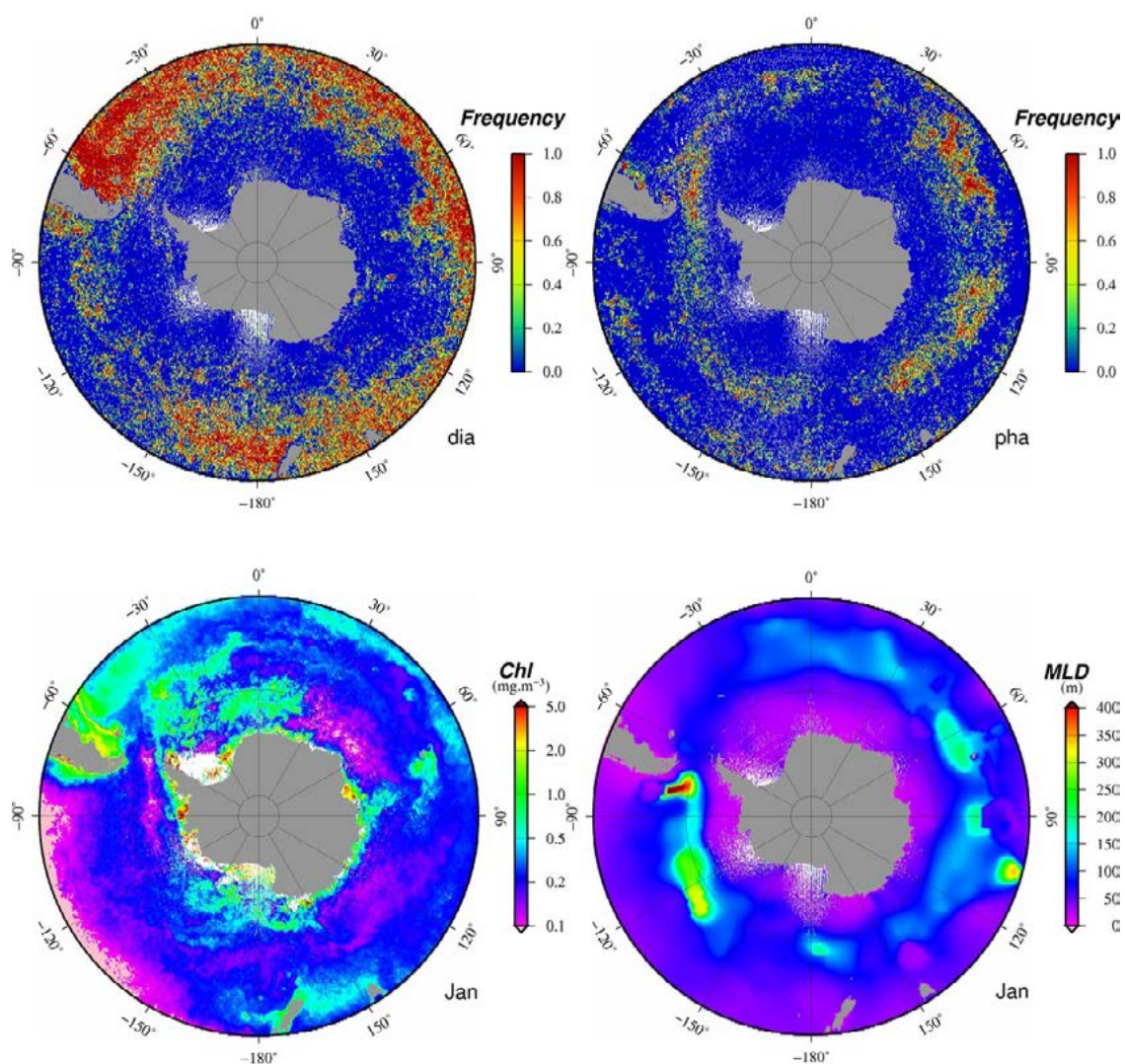
Figure 4 Comparison of diatoms and phaeocystis frequencies detection (from PHYSAT) with coincident maps of chlorophyll-a concentration (from SeaWiFS) and Mixed Layer Depth (de Boyer Montégut 2004) for January.

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.

The Editorial Team

Claude DE BROYER is a marine biologist at the Royal Belgian Institute of Natural Sciences in Brussels. His research interests cover structural and ecofunctional biodiversity and biogeography of crustaceans, and polar and deep sea benthic ecology. Active promoter of CAML and ANDEEP, he is the initiator of the SCAR Marine Biodiversity Information Network (SCAR-MarBIN). He took part to 19 polar expeditions.

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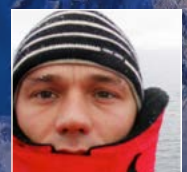
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Graham HOSIE is Principal Research Scientist in zooplankton ecology at the Australian Antarctic Division. He founded the SCAR Southern Ocean Continuous Plankton Recorder Survey and is the Chief Officer of the SCAR Life Sciences Standing Scientific Group. His research interests include the ecology and biogeography of plankton species and communities, notably their response to environmental changes. He has participated in 17 marine science voyages to Antarctica.

Alexandra POST is a marine geoscientist, with expertise in benthic habitat mapping, sedimentology and geomorphic characterisation of the seafloor. She has worked at Geoscience Australia since 2002, with a primary focus on understanding seafloor processes and habitats on the East Antarctic margin. Most recently she has led work to understand the biophysical environment beneath the Amery Ice Shelf, and to characterise the habitats on the George V Shelf and slope following the successful CAML voyages in that region.
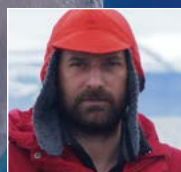
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