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Global ocean biomes: mean and temporal variability

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Abstract

Large-scale studies of ocean biogeochemistry and carbon cycling have often partitioned the ocean into regions along lines of latitude and longitude despite the fact that spatially more complex boundaries would be closer to the true biogeography of the ocean. Herein, we define 17 open-ocean biomes defined by environmental envelopes incorporating 4 criteria: sea surface temperature (SST), spring/summer chlorophyll *a* concentrations (Chl), ice fraction, and maximum mixed layer depth (maxMLD) on a one-by-one degree grid (doi:10.1594/PANGAEA.828650). By considering interannual variability for each input, we create dynamic ocean biome boundaries that shift annually between 1998 and 2010. Additionally we create a core biome map, which includes only the gridcells that do not change biome assignment across the 13 years of the time-varying biomes. These ocean biomes can be used in future studies to distinguish large-scale ocean regions based on biogeochemical function.

1 Introduction

In recent decades, many studies have partitioned the pelagic environment into gyre-scale regions in order to investigate biogeochemical processes at the large-scale (Longhurst, 1995; Sarmiento et al., 2004; Gurney et al., 2008; Reygondeau et al., 2013). Recent studies of the terrestrial carbon cycle have moved beyond the division of the landmasses into latitudinally defined regions (Gurney et al., 2008). Despite the clear limitation of this latitudinal-defined approach in the oceans, recent studies have generally used such definitions (Gruber et al., 2009; Schuster et al., 2013). This is, at least in part, due to the lack of an alternative biome map available from the peer-reviewed literature.

Limited sampling means that our knowledge of the detailed biogeography of the global oceans is more elementary than that of the terrestrial biosphere, though satellite-based estimates of surface ocean chlorophyll has helped to remedy this since the late

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1990s. Additionally, ocean biogeochemistry is organized, to first order, by the large-scale ocean circulation. In this study, we take advantage of satellite chlorophyll and variables associated with the large-scale circulation to define 17 surface ocean biomes that capture patterns of large-scale biogeochemical function at the basin scale. This work builds upon previous biome definitions (McKinley et al., 2011; Fay and McKinley, 2013), with the addition of biome boundaries that shift annually due to variability in physical state and surface chlorophyll.

In contrast to previous work by Reygondeau et al. (2013) and Longhurst (1995), which consider sub-basin scale ocean provinces, the biomes presented here are for only open ocean regions and do not include coastal regions. These biomes are substantially larger than the provinces proposed initially by Longhurst (1995) in order to address the first-order differences in biogeochemical function at the scale of the ocean gyres. These ocean biomes are of a similar scale to those used in TransCom (the Atmosphere Tracer Transport Model Intercomparison Project), a global intercomparison of atmospheric inversion for surface-air CO_2 fluxes (e.g. Gurney et al., 2008) (available at transcom.project.asu.edu), which have become a standard for global ocean carbon research (Jacobson et al., 2007; Mikaloff-Fletcher et al., 2007; Gruber et al., 2009; Canadell et al., 2011; Lenton et al., 2013; Schuster et al., 2013). There is substantial similarity between these biomes and the TransCom partitions. We argue that these biomes are preferable because they are defined by relevant environmental parameters instead of by lines of latitude. Going forward, these biomes could be used as a new basis for a wide range of analyses and intercomparison studies in ocean biogeochemistry and carbon cycling.

Herein, we present time varying biomes for the global ocean, spanning 1998 through 2010 (limited by chlorophyll *a* data availability). We also present a mean biome map and a core biome map, which assigns a biome classification only for those ocean gridcells that retain the same biome classification for all 13 years of the time-varying biomes.

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2 Methodology

We create physical, biologically defined regions or "biomes" delineated based on four climatological criteria: maximum mixed layer depth (maxMLD), spring/summer chlorophyll *a* (Chl), sea surface temperature (SST), and sea ice coverage (Table 1).

2.1 Biome descriptions

Using the four criteria discussed in detail in Sects. 2.2–2.5, the ocean is divided into biomes. Each biome is characterized by a range of values from the observational fields (Table 1) and, if multiple criteria define a biome, all must be met for the gridcell to be assigned to that biome.

Cooler, polar waters that have at least 50 % ice cover during some part of the year are grouped into the marginal sea ice (ICE) biome.

Subpolar seasonally stratified (SPSS) biomes have divergent surface flow driven by the positive wind stress curl and thus upwelling from below, allowing for higher summer chlorophyll concentrations due to continual nutrient resupply. The Pacific and Atlantic oceans have different constraints, with the Pacific allowing warmer, lower chlorophyll waters, while in the North Atlantic, cooler water with higher chlorophyll levels is required. The Pacific is a warmer and less productive high nutrient, low chlorophyll (HNLC) region (Table 1).

The subtropical seasonally stratified (STSS) biome is an area of downwelling due to negative wind stress curl, but intermediate chlorophyll concentrations due to deep winter maxMLDs. The subtropical permanently stratified (STPS) biome experiences negative wind stress curl, leading to convergence and year-round stratification, such that maxMLDs are shallow and chlorophyll is low.

Equatorial biomes (EQU) are defined by latitude (5° S to 5° N) as is consistent with previous studies in this region (Sarmiento et al., 2004; Gierach et al., 2012). While other studies have allowed the equatorial region to extend farther north and south (Feely et al., 2004; Lenton et al., 2012), we opted for the conservative definition (5° S to 5° N)

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due to previous work (Fay and McKinley, 2013) that shows that this restrictive definition is able to capture ENSO signals in surface ocean partial pressure of CO_2 (pCO_2) in this area. The Pacific Equatorial biome is also separated into an east and west sub-biome, divided at 160° W. In the Indian Ocean, the equatorial region is grouped in with the STPS biome due to seasonally varying physical ocean circulation patterns linked to the monsoon.

Ocean areas not defined by any of these biomes are largely coastal or influenced by coastal upwelling. A few open ocean points also cannot be grouped into biomes by our criteria. These anomalous regions are omitted.

For calculation of the mean biomes, 1998–2010 mean chlorophyll, SST and ice fraction are used with the climatological maxMLD.

2.2 Monthly ice fraction and sea surface temperature

The Hadley Centre Meteorological Office provides monthly mean gridded, global fractional sea ice coverage and sea surface temperature (SST) for years 1870 to present (HADISST) (Rayner et al., 2003).

HADISST sea ice coverage is reported as a fraction of each $1^\circ \times 1^\circ$ degree cell. A minimum threshold of 0.5 fractional coverage in any month of the year designates the ICE biome. This contrasts to Sarmiento et al. (2004) who define their ICE region as having any sea ice coverage in any part of the year.

For annual mean SST and ice fraction climatology, monthly means for years 1998–2010 are averaged. SST criteria for each biome are presented in Table 1.

2.3 Monthly chlorophyll *a*

Chlorophyll is as a proxy for the abundance of marine phytoplankton and offers a first-order quantification of rates of biogeochemical cycling in the surface ocean. Global ocean chlorophyll *a* estimates provided by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project are used to estimate chlorophyll *a* concentrations using NASAs

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OC4 algorithm (O'Reilly et al., 1998) (available at: http://oceandata.sci.gsfc.nasa.gov/). Monthly-binned climatology products at 9 km × 9 km resolution are provided by NASA beginning in September 1997 and ending in December 2010. SMIGEN (available at: http://seadas.gsfc.nasa.gov/doc/smigen/smigen.html) was used to map monthly chlorophyll *a* to 1° × 1° resolution.

In order to avoid bias due to high cloud coverage in winter, all biome selection is based on mean spring/summer chlorophyll rather than an annual climatology. April through September are used in the Northern Hemisphere, and December through March in the Southern Hemisphere. SeaWiFS data is not available for January through March 2008, which would impact Southern Hemisphere biomes in 2008 because December 2007 would be the only month with data. To avoid this potential bias, climatological summer chlorophyll is used for the Southern Hemisphere biome classification for 2008. Southern Hemisphere summer chlorophyll is used as criteria for the Indian Ocean STPS biome despite its extension into the Northern Hemisphere at its northern limits.

2.4 Climatological maximum Mixed Layer Depth

Climatological maximum MLD (maxMLD) indicates the amplitude of seasonality in biogeochemical processing, particularly in the transition regions between the subpolar and subtropical gyres (Table 1). maxMLDs do not vary annually for biome selection because data is insufficient for global coverage at monthly timescales.

Criteria for definition of the mixed layer and methods for finding its depth are numerous. We use the ARGO mixed layer depth climatology (Holte et al., 2010) calculated with the density algorithm (Holte and Talley, 2009). Other threshold methods (de Boyer Montegut et al., 2004; Sarmiento et al., 2004) were also considered. The selected algorithm builds on traditional threshold and gradient methods by drawing its estimate of the MLD from physical features in the profile and by considering a pool of various MLDs from which the algorithm selects the final MLD estimate (Holte and Talley, 2009). The ARGO climatology is based on data from years 2002–2008 that overlap reasonably well

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with the satellite chlorophyll record (1998–2010). The deBoyer-Montegut et al. (2004) climatology is based on earlier data (1941–2002) that has less overlap.

In some regions, most notably in the Southern and Arctic Oceans, MLD for some gridcells are not defined in the ARGO climatology. These missing pixels are filled with a latitudinal mean from the same ocean basin. This filling occurs mostly in the higher latitudes and near continental shelves, where the maxMLD criterion is actually not applied for biome selection (Table 1). The maxMLD criterion is applied only to divide the STPS and STSS biomes, which are generally quite well covered prior to filling.

2.5 Smoothing

After initial processing, each biome is smoothed to limit the number of gridcells that do not conform to the biome definition characteristic of a particular region. An iterative smoothing process is used, cycling through the map numerous times, changing any gridcell that is bordered on at least three sides by another biome classification.

Each of the 13 years has between 300 and 400 total gridcells changed in their biome classification by the smoothing. For the 13 years of time-varying biomes, the maximum number of $1^{\circ} \times 1^{\circ}$ gridcells smoothed is 400 in the year 2000, which is 1 % of the total gridcells in the global ocean. No more than 15 % of the gridcells in any one biome change due to smoothing. Smoothing of the mean biomes changes 263 gridcells (0.71 % of total ocean gridcells and no more than 14 % of any one biome). These smoothed areas occur predominantly in the intergyre regions, the hardest region to define due to strong interannual variability. Core biomes are created from the time-varying biomes after smoothing is performed.

2.6 Data format and availability

The biome maps are provided in netCDF-4 format (with an accompanying README file) and can be found at PANGAEA web page http://doi.pangaea.de/10.1594/PANGAEA.828650 (or doi:10.1594/PANGAEA.828650). It contains files for the Mean

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and Core biome map boundaries as well as maps for each year of the Time-varying biomes. Animation of the 13 time-varying biome maps is available at http://oceancarbon.aos.wisc.edu/biomes-2014/.

3 Biomes

Seventeen global biomes are represented on our biome maps using the criteria outlined in Table 1.

3.1 Mean biomes

Mean biomes are created using the climatological SST, Chl, and ice fraction criteria for years 1998–2010, and climatological maxMLD with the criteria in Table 1. These biomes are presented in Fig. 1 with their areas listed in Table 2. From the 5° S northward in both the Atlantic and Pacific, the resulting biomes delineate the equatorial regions (EQU) and then the subtropical gyres, or permanently stratified subtropical biome (STPS). Next come the intergyre regions between the subtropics and subpolar gyres, or seasonally stratified subtropical biomes (STSS). Then are the subpolar gyres, or seasonally stratified subpolar biomes (SPSS), and finally the marginal sea ice biome (ICE) in the far north. The Indian Ocean is entirely a permanently stratified subtropical biome (STPS). Going southward from 5° S in the Atlantic and Pacific, we find the subtropical gyres (STPS), and then the Southern Ocean regions that we define as STSS, SPSS and ICE biomes. Respectively, these three Southern Ocean biomes are directly comparable to the Subantarctic Zone (SAZ), the Polar Frontal Zone (PFZ) and Antarctic Zone (AZ) (Lovenduski et al., 2007).

3.2 Time-varying biomes

In Supplement Figs. S1–S13, biome maps spanning years 1998–2010 are presented. Chlorophyll *a* products are the limitation on the years of analysis. In each year, the

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criteria as listed in Table 1 are used. Changes between these 13 maps are due to the combined impacts of changes in Chl, SST, and ice fraction from year to year. maxMLD remains a climatological variable.

3.3 Core biomes

Core biomes are defined by the gridcells that maintain the same biome assignment for all 13 years (Fig. 2). Gridcells that shift from one biome to another in any of the 13 years of the time-varying biomes are not assigned in the core biome map. With respect to analysis of variability or trends in biogeochemical variables, core biomes would be a conservative region for analysis because there is a strict consistency with the biome definition for each individual year between 1998 and 2010. Core biome areas are included in Table 2.

Undefined regions in the core biome map are caused by variability of the time-varying biomes. Comparing the area of core biomes to time-varying biomes indicates the percent of area lost with use of core biomes. Only in the high-latitude biomes do core biomes cause a substantial percentage of area to be excluded (> 15 %, Fig. 3).

Figure 4 shows the anomaly in biome area each year, separated by ocean basin, based on a residual from the area of the corresponding biome area of the mean biomes. Between the North Pacific SPSS and ICE biome, the Bering Sea region shifts biomes year to year due to changing annual temperatures. Low productivity in some years also contributes to the northward recession of the core North Pacific SPSS biome. This is reflected by the relatively high variability of the Pacific SPSS biome area in Fig. 4a and substantial area lost with the core biomes (Fig. 3a).

In the North Atlantic ICE biome, variation in ice fraction causes changing designation between ICE and SPSS, and thus a greater area lost with the core biomes (Fig. 3b). A significant inverse correlation ($r = -0.83$) between NA ICE and NA SPSS biome area further demonstrates this exchange of biome area (Fig. 4b). Biome area changes are also large where the boundary between the North Atlantic STSS and STPS biomes shifts annually due to changes in chlorophyll concentration along the Gulf Stream and

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North Atlantic Current (Fig. 4b), but there is not a statistically significant correlation in the anomalies of these areas.

Decreasing chlorophyll in the Arabian Sea allows the expansion of the IND STPS biome over time (Fig. 4c). Interannual change in Southern Ocean circulation impacts temperature and productivity causing biome areas to have substantial variability, particularly for SO STSS (Fig. 4c). This also results in a loss of area for the core biomes (Fig. 3c).

4 Discussion

As first discussed by Longhurst (1995), ocean biogeography does not organize itself along lines of latitude and longitude. For example, in the surface ocean $p\mathrm{CO_2}$ climatology of Takahashi et al. (2009), it is clear in the North Atlantic and North Pacific that the subtropical-subpolar boundary follows the major ocean currents. Going forward, it will be advantageous to use biogeochemically-relevant biomes in studies of large-scale ocean biogeochemistry and carbon cycling so as to avoid the limitations of square regions (Takahashi et al., 2006; Canadell et al., 2011). Schuster et al. (2013) note that the limited agreement in the seasonal cycle of North Atlantic air–sea CO_2 fluxes from a range of methodologies is partially driven by the use of boundaries defined by latitude.

Previous studies have proposed that the subtropical ocean regions are expanding and that warming ocean temperatures are exhibiting reduced productivity in these important ocean gyres (Polovina et al., 2008; Behrenfeld et al., 2006). In these biomes, there are not significant trends in the area of any Northern Hemisphere subtropical biomes (STPS) over the years 1998–2010. In the Southern Hemisphere, there is a negative trend in the South Pacific STPS biome (Fig. 4a, $-2.31 \pm 1.07 \times 10^5\,\mathrm{km\,yr^{-1}}$). This negative trend is due to higher chlorophyll values in the South Pacific/Southern Ocean boundary for years 2002–2010. This allows SO STSS to extend further equatorward (Fig. 4c, Supplement figures) resulting in an expanding area between 1998–

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2010 ($2.22 \pm 1.58 \times 10^5$ km yr^{-1}). Decreasing chlorophyll levels in the Arabian Sea allow the expansion of the IND STPS biome and thus an increasing biome area trend ($1.13 \pm 1.08 \times 10^5$ km yr^{-1}) for 1998–2010 (Fig. 4c).

A negative trend in the area of the North Pacific ICE biome appears for all trends longer than 10 years if the final year is prior to 2010 (Fig. 4a). When the area timeseries is extended to include 2010, this signal of declining area of the Pacific ICE biome disappears.

In the Northern Hemisphere, the only significant biome area trend for 1998–2010 is a negative one in the North Atlantic ICE biome ($-4.84 \pm 2.90 \times 10^4$ km yr^{-1}) and a corresponding positive trend in the North Atlantic SPSS biome ($3.75 \pm 1.80 \times 10^4$ km yr^{-1}) (Fig. 4b). The statistical significance of these trends persists for any 10 year or longer timeseries considered (i.e. 1998–2008, 1999–2009, 2000–2010, 1998–2009, etc.). As mentioned above, the 1998–2010 trends in NA ICE and SPSS biome areas are highly correlated ($r = -0.83$). As more data becomes available, the time-varying biome boundaries can continue to be analyzed and may elucidate trends in the biome area extent over time.

The global biomes previously used by these authors in study of surface ocean $p\mathrm{CO_2}$ trends (McKinley et al., 2011; Fay and McKinley, 2013) varied slightly from those presented here. Time-varying biomes were not used in these previous analyses. For the products presented here, biome criteria have been updated with the most current and complete datasets and products available. This results in some noticeable differences between the mean biome map presented here and that used in previous work by Fay and McKinley. Changes in the North Atlantic biomes are primarily due to an improved mixed layer depth climatology used in this analysis. Changes in the extent of the ICE biomes here are due to the inclusion of ice fraction as a criterion with this study.

The data used as biome criteria have limitations, some of which could be improved in the future. The main constraint on the time-varying biomes is the availability of surface ocean chlorophyll estimates and complete coverage of mixed layer depth measurements. The mixed layer depth measurements should improve in the coming decade

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with expanding ARGO coverage and may elucidate temporal changes. The global chlorophyll *a* product used here is from the now-decommissioned SeaWiFS satellite. To extend the years of the time-varying biomes, a new chlorophyll product will need to be identified. Ideally, this will be a merged product extending back to the beginning of the SeaWiFS record.

5 Conclusions

We offer three versions of environmentally-defined biomes to be used as an alternative to the current standard of latitudinally-defined ocean regions for biogeochemical and carbon cycle studies. The 17 mean biomes offer full coverage of the open ocean and are based on mean data for 1998–2010. Also presented are time-varying ocean biomes for each year from 1998–2010 that should be of use to studies focused in this period. Finally, core biomes can be utilized in analyses that wish to be most conservative in their definition by avoiding any points where the biome to which that point is assigned is not the same in all years from 1998 to 2010.

Opportunities for use of these biomes in future studies are likely to be numerous. Clear distinction between biogeochemically different regions should improve the fidelity of analyses of both large datasets and numerical models. Atmospheric and ocean inversion studies could use the mean biomes for their regional discretization (Gurney et al., 2008; Gruber et al., 2009). If as widely adopted as the TransCom latitudinally-defined regions have been, this will facilitate future intercomparison studies such as RECCAP (Canadell et al., 2011).

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Supplementary information

Supplement Figs. S1–S13: time-varying biomes for years 1998–2010. Dark blue: ICE; cyan: SPSS; green: STSS; yellow: STPS; orange: EQU.

Supplementary material related to this article is available online at http://www.earth-syst-sci-data-discuss.net/7/107/2014/essdd-7-107-2014-supplement.zip.

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Table 1. Characteristics for the environmental envelopes defined for each biome.

Biome	Sea-ice fraction	SST (°C)	Chl ($mg\,m^{-3}$)	maxMLD (m)	Notes
NH ICE	$x \geq 0.5$				
N Pacific SPSS		$x < 19$	$x \geq 0.25$		
N Atlantic SPSS		$x < 14$	$x \geq 0.4$		
NH STSS		$11 \leq x < 25$		$x > 125$	
NH STPS		$x \geq 11$	$x < 0.25$	$x \leq 125$	
IND STPS		$x \geq 11$	$x < 0.25$		
Equatorial					Latitude 5° S to 5° N
SH STPS		$x \geq 8$		$x \leq 150$	
SH STSS		$x \geq 8$	$x \geq 0.15$	$x > 150$	Need **EITHER** Chl **OR** maxMLD
SH SPSS		$x < 8$			
SH ICE	$x \geq 0.5$				

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Table 2. Size (in 10^6 km^2) of the Mean biomes and Core biomes.

Biome	Mean biome area (10^6 km^2)	Core biome area (10^6 km^2)
NP ICE	4.5912	3.9112
NP SPSS	15.451	10.194
NP STSS	2.7473	2.4006
NP STPS	48.214	45.400
Pac EQU W	9.6109	9.6109
Pac EQU E	9.8813	9.8813
SP STPS	61.798	57.872
NA ICE	5.4472	4.6123
NA SPSS	10.092	7.8110
NA STSS	4.7235	4.2817
NA STPS	19.613	17.549
Atl EQU	6.8913	6.8913
SA STPS	20.134	19.625
IND STPS	36.199	33.450
SO STSS	30.414	24.783
SO SPSS	30.648	25.875
SO ICE	18.658	16.169

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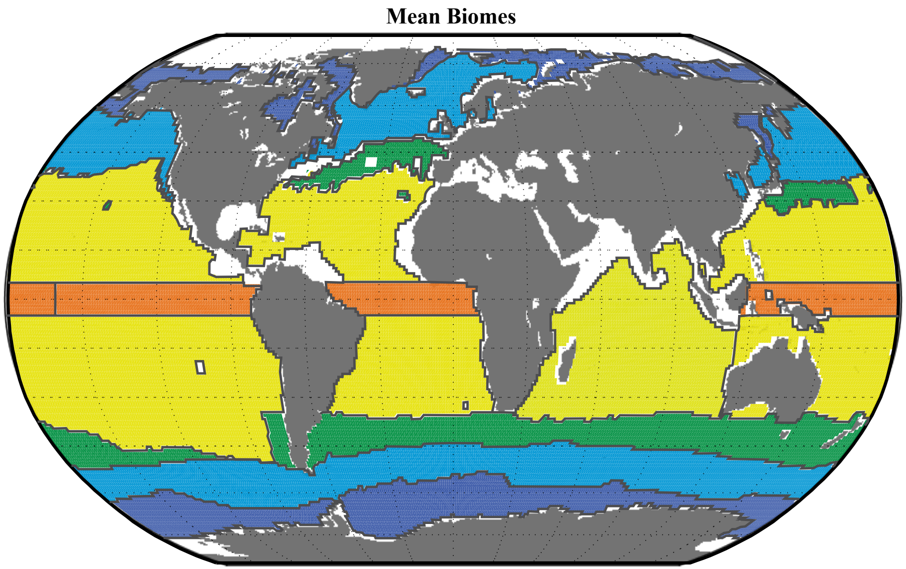

Fig. 1. Mean biome map. Dark blue: ICE; cyan: SPSS; green: STSS; yellow: STPS; orange: EQU.

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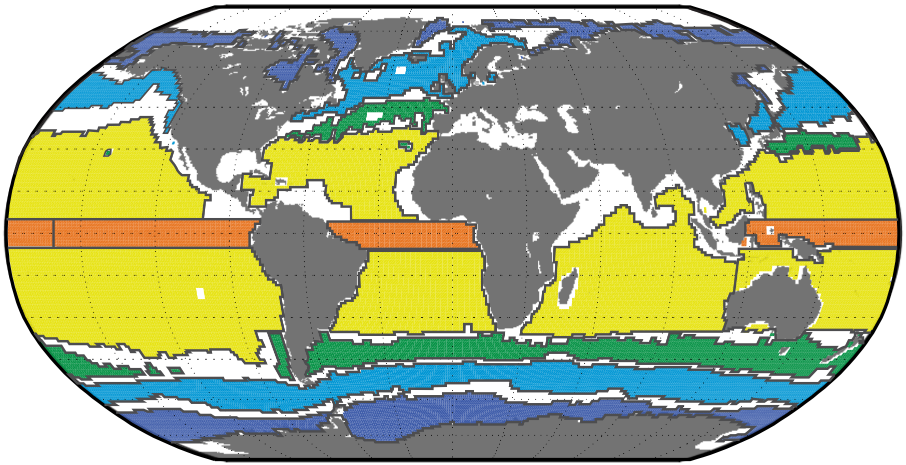

Fig. 2. Core biome map. Dark blue: ICE; cyan: SPSS; green: STSS; yellow: STPS; orange: EQU.

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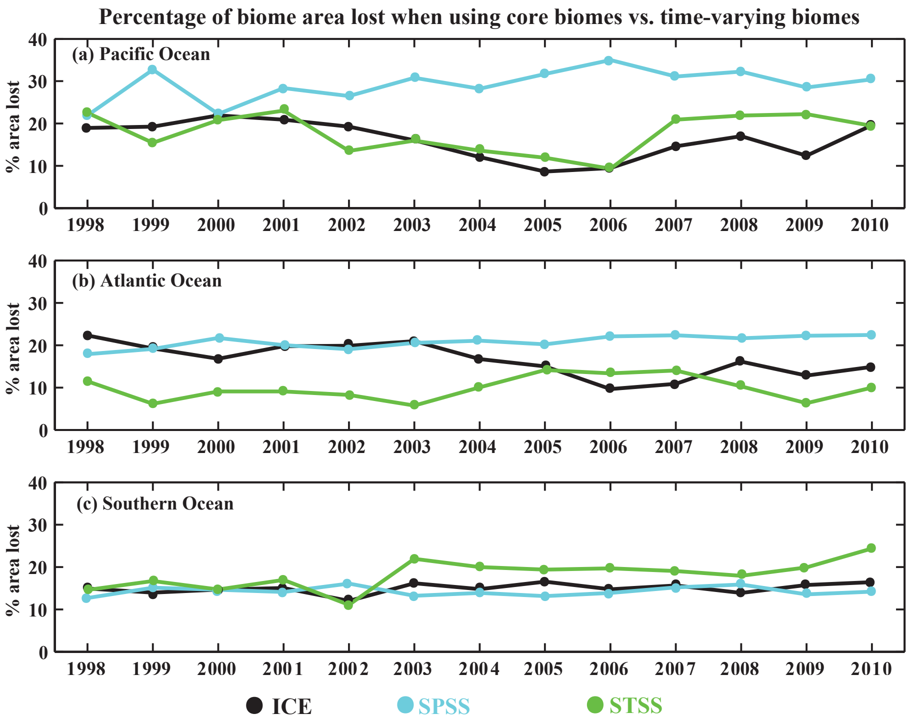

Fig. 3. Percentage of biome area lost each year if using core biomes as compared to time-varying biomes for **(a)** Pacific Ocean, **(b)** Atlantic Ocean, and **(c)** Southern ocean. Black: ICE biomes; cyan: SPSS biomes; green: STSS biomes. Biomes not included on figure are under 25 % for all years.

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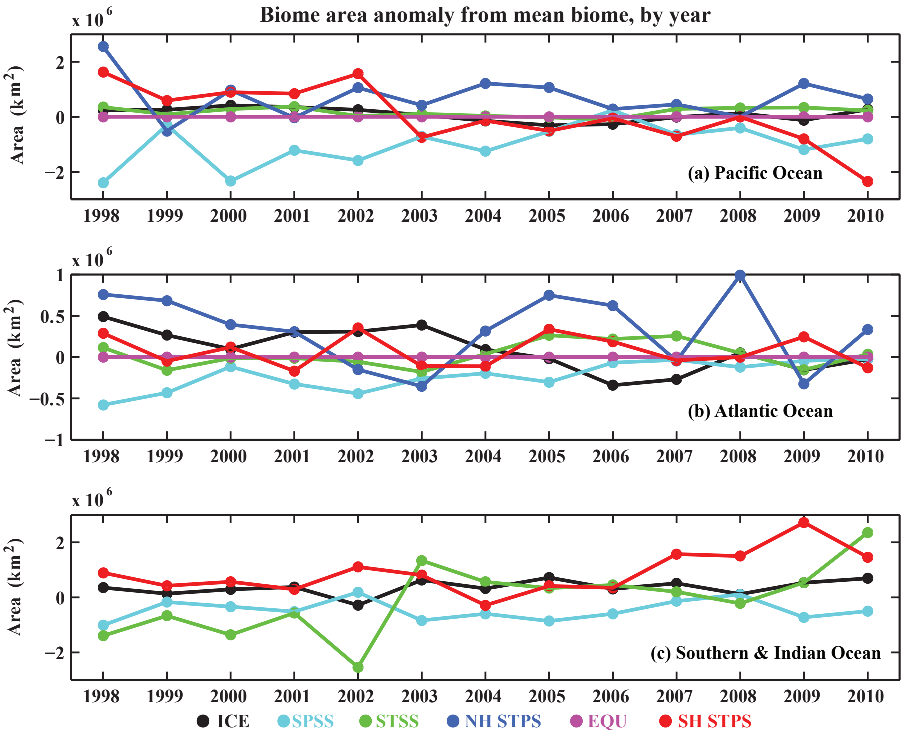

Fig. 4. Biome area anomaly from the area of the corresponding Mean biome area for years 1998–2010 in **(a)** Pacific Ocean; **(b)** Atlantic Ocean; **(c)** Southern and Indian Oceans. Black: ICE; cyan: SPSS; green: STSS; navy: Northern Hemisphere STPS; magenta: EQU; red: Southern Hemisphere STPS.

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