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Predicting fishing ground accessibility in the Antarctic Weddell Sea

H. Pehlke, K. Teschke and T. Brey

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Predicting fishing ground accessibility in the Antarctic Weddell Sea

Hendrik Pehlke[1,2], Katharina Teschke[1,2] and Thomas Brey[1,2]

[1] Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany

[2] Helmholtz Institute for Functional Marine Biodiversity (HIFMB) at the University Oldenburg, Germany

Abstract

Sea ice is a major constraint of fishery performance in the Southern Ocean seasonal sea ice zone. We use sea ice concentration data from 2002-2017 that cover the wider Weddell Sea to establish statistical models of (i) accessibility, i.e. the probability that a particular area is navigable by fishery vessels at a given time, and of (ii) repeated accessibility, i.e. the probability that a particular area is navigable by fishery vessels at a given time and again within the following two years, as requested by CCAMLR research fishery regulations. Our findings indicate that under the actual sea ice conditions almost 50 % of the entire WSMPA Planning Area is not suitable for fishery vessels at any time of the year, while there are high spatio-temporal variability in repeated accessibility in particular areas such as along the ice shelf of the eastern and south-eastern Weddell Sea. We consider our models to constitute valuable, risk-reducing planning tools in the further development of fishery research as well as of ship-bound tourism in the wider Weddell Sea area.

Introduction

Fishing is one of the main human activities in the Southern Ocean, besides science and tourism (Deininger et al. 2016, Grant et al. 2013). Antarctic krill (*Euphausia superba*) is the main target of Southern Ocean licensed fisheries, but there is also commercial harvesting of various fish species, among which the highly prized Antarctic toothfish (*Dissostichus mawsoni*) and Patagonian toothfish (*Dissostichus eleginoides*) are of increasing interest (see catch history at https://www.ccamlr.org/en/fisheries/toothfish-fisheries). The fisheries in the Antarctic Treaty area are supervised and regulated by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) to ensure a sustainable development and management of such activities. The regulatory framework is laid down in CCAMLR Conservation Measures (CM) of which CM 21-01 (Anonymous 2016a) and CM 21-02 (Anonymous 2016b) are the most relevant ones.

Sea ice is, on the one hand, a core determinant of ecosystem dynamics, primarily as it controls primary production (see e.g. Smith and Comiso 2008) and the distribution of mammal and bird predators. On the other hand, sea ice constitutes a major constraint of fishery operations in the

Southern Ocean seasonal sea ice zone, as ice conditions restrict navigability, particularly for vessels with low ice class. Fenaughty and Parker (2015) evaluate the constraining effect of sea ice on longline fisheries in the Ross Sea and conclude that sea ice may restrict or deny access to preferred fishing grounds in the first instance, but will also hamper fishing operations directly. The need for sea ice prediction for fishing access has already been addressed by Parker et al. (2014). The authors propose the automated generation of spatially and temporally summaries of the sea ice situation from satellite data.

So far, our insufficient understanding of the complex ice-air-sea interaction processes as well as the distinct short term variability of meteorological conditions in the Antarctic seasonal sea ice zone renders impossible attempts to forecast sea ice conditions with the spatial resolution and the forecast length required by low ice class vessels in general and by fishing operations in particular (see e.g. Chen and Yuan 2004). Turner and Comiso (2017) call for an international joint effort towards improved models. For the time being, however, the statistical analysis of accumulated data appears to be the most suitable approach to identify “persistent” ice condition patterns that can serve as a first base for forward-looking expedition planning.

Here, we introduce a statistical model that provides two measures: (i) accessibility, i.e. the probability that a particular area is navigable by fishery vessels at a given time and (ii) repeated accessibility, i.e. the probability that a particular area is navigable by fishery vessels at a given time and again at least once within a defined time span (here the subsequent two years). A repeated investigation within two years after the first research activity is stipulated by the Working Group SAM (Anonymous 2016c, paragraph 3.26) for exploratory fishery as defined under Conservation Measure 21-02 (Anonymous 2016b) and logically requires a navigability respectively an accessibility within this time span.

Material & Methods

Study area

We apply this model to the planning area of a prospective Weddell Sea Marine Protected Area (WSMPA) (see Fig. 1) that includes areas of potential fishing and tourism activities (Teschke et al. 2016). The WSMPA Planning Area is defined by CCAMLR's MPA Planning Domains, and by taking into account a bio-geographically homogeneous region, particularly on the Antarctic shelf. The WSMPA Planning Area is limited north at 64°S and south at the continental margin and the ice shelf margin, respectively. The eastern border is at 20°E and the Antarctic Peninsula forms the western border of the planning area. Thus, the area covers approximately 4.2 million km² of which about 660 000 km² are currently covered by ice shelf.

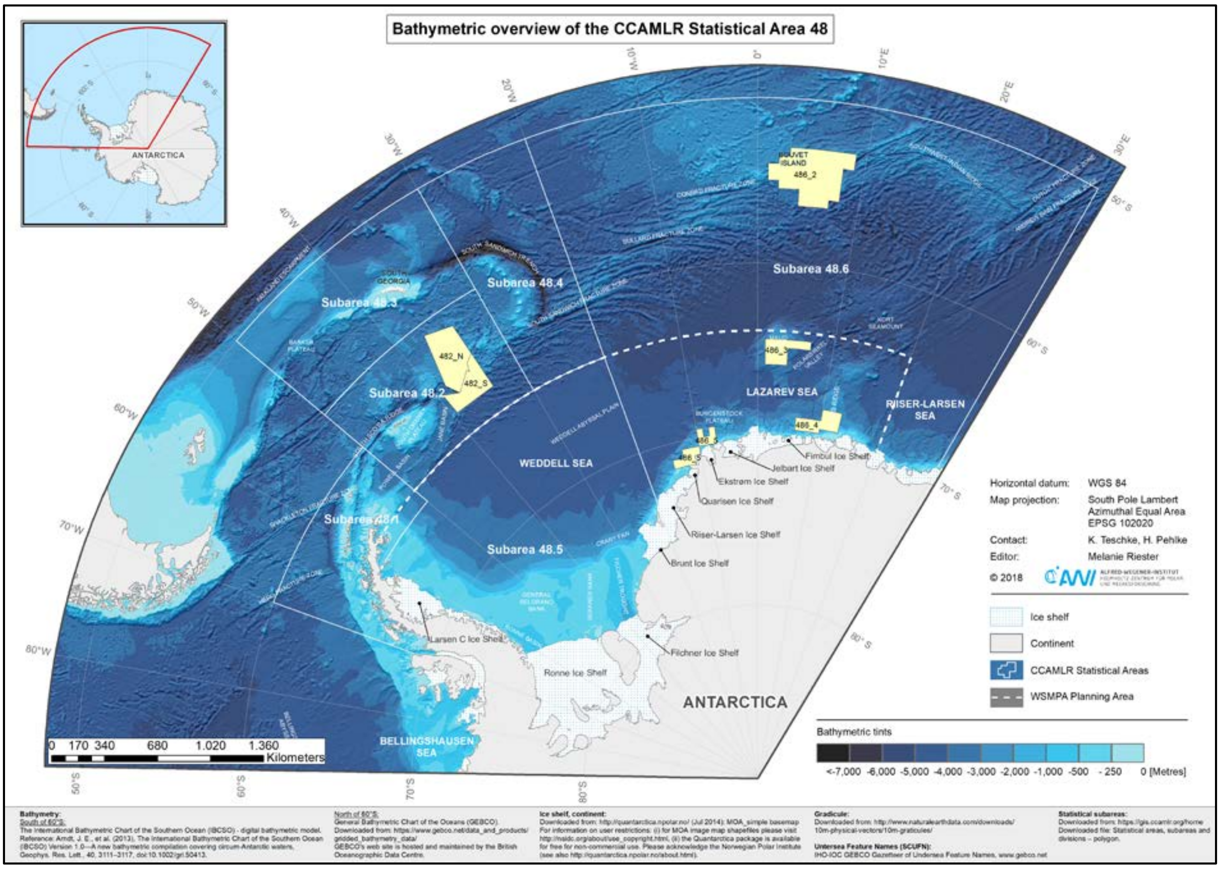

Figure 1: Weddell Sea MPA (WSMPA) Planning Area (dashed white line) in CCAMLR Statistical Area 48 with subareas (solid thin white lines) and research blocks (light yellow boxes).

Data

Daily high resolution sea ice charts of the Antarctic Ocean are provided by the PHAROS group (PHysical Analysis of RemOte Sensing images) at the Institute of Environmental Physics (IUP), the University of Bremen, Germany. These sea ice raster maps are derived from satellite observations of daily sea ice concentration from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-EOS) instrument on board the AQUA satellite and from AMSR2 (the successor of AMSR-E) on board the "Shizuku" (GCOM-W1) satellite, respectively. Daily AMSR-E sea ice concentration data (Jun 2002 – Oct 2011) and daily sea ice maps from the AMSR2 data (since Jul 2012) were downloaded from IUP at the University of Bremen:
AMSR-E: http://www.iup.uni-bremen.de/seaice/amsredata/asi_daygrid_swath/l1a/s6250/ and
AMSR2: http://www.iup.uni-bremen.de:8084/amsr2data/asi_daygrid_swath/s6250/.

The ARTIST Sea Ice (ASI) concentration algorithm is used with a spatial resolution of 6.25 km x 6.25 km (Kaleschke et al. 2001, Spreen et al. 2008). The grid cell values range from 0 to 250. Values between 0 and 200 represent the sea ice concentration (0 % <= SIC <= 100 %) in 0.5 % steps, while values >= 201 refer to country or missing data.

Data processing and analysis

We downloaded daily sea ice raster maps as GeoTIFFs (using R package *RCurl*; Temple and Lang 2016), imported them into R (R Development Core Team 2016; R package *raster*; Hijmans 2015) and re-projected the data from EPSG 3976 into EPSG 102021 (see Appendix Table 1).

Our statistical models are applied to the data of the austral summer (Dec 1st - Mar 31st) from 2002 to 2017.

Accessibility

For the daily SIC data sets, we created a raster stack with the days of the austral summer (Dec 1st - Mar 31st) as raster layer objects. The raster stack shows the accessibility (***A***) of each grid cell throughout our study area in each year (2002 - 2017) at each day. Table 1 provides an overview of the variables used for calculating accessibility.

Accessibility ***A*** of grid cell ***i*** in year ***j*** at day ***x*** is given by

$$A[i,j,x] \in \{0, 1\} \quad (1)$$

where SIC > 60 % is defined as 0 (inaccessible for fishery vessels) and SIC <= 60 % is defined as 1 (accessible) according to Parker et al. (2014). The authors stated that "*a threshold range of 40 - 60 % sea ice concentration is a useful proxy to describe an area as fishable*".

Within the data set there are some single days or periods of days where no sea ice data are available (see Appendix Table 2). For example, there are missing data for 2011 (Dec) and 2012 (Jan - Mar) due to the transition from AMSR-E to AMSR2. We substituted missing SIC data for a particular cell at a particular day of a particular year by the mean SIC for this cell and day-of-the year across all years (2002 – 2017). In case of mean SIC <= 0.5 we assigned a value of zero to the grid cell, and in case of mean SIC > 0.5 a value of one, respectively. February 29th was excluded from the dataset. Accordingly, our SIC data set covers 1692 days in total (see Appendix, Table 2).

Accessibility ***AA*** of a specific area that consists of ***n*** grid cells in year ***j*** at day ***x*** is given by

$$AA_{j,x} = \sum_{i=1}^{i=n} \frac{A_{i,j,x}}{n} \quad (2)$$

Accessibility to grid cell ***i*** in year ***j*** during a specific time window ranging from day ***t1*** to day ***t2*** is given by

$$A_{i,j,t1\rightarrow t2} = \sum_{x=t1}^{x=t2} \frac{A_{i,j,x}}{t2 - t1}$$

$1 <= t1 <= nd$; $1 <= t2 <= nd$; $t1 <= t2$ (3)

where ***nd*** is the maximum number of days (here 121, see Table 1). Accessibility to a specific area of ***n*** grid cells in year ***j*** during a specific time window ranging from day ***t1*** to day ***t2*** is computed accordingly:

$$AA_{j,t1\rightarrow t2} = \sum_{x=t1}^{x=t2} \frac{AA_{j,x}}{t2 - t1}$$

$1 <= t1 <= nd$; $1 <= t2 <= nd$; $t1 <= t2$ (4)

Table 1: Overview of the variables used in calculations.

Variable	Description	Range	Comment
i	Grid cell	1 <= *i* <= nc	WSMPA planning area: nc = 239907 cell size (X,Y): 6250m, 6250m
j	Year	n1 <= *j* <= ny	WSMPA planning area: n1 = (2002-2001), ny = (2017-2001) Note that for computation of RA, n1 < *j* < ny-1
x	Day	1 <= *x* <= nd	WSMPA planning area: nd = 121; days from Dec 1st to March 31st, Exclusion of 29 February (leap years)
A *AA*	Accessibility A: 1 cell, AA: > 1 cells	A □ {0, 1} 0 <= AA <= 1	WSMPA planning area: Values of A are defined as 0 = ice concentration > 60%, 1 = ice concentration ≤ 60%
RA *RAA*	Repeated accessibility RA: 1 cell, RAA: > 1 cells	0 <= *RA* <= 1 0 <= *RAA* <= 1	see equations 2,3,4,5

Repeated accessibility

We consider the case that the initial research fishery took place in cell ***i*** in year ***j*** at day ***x***. CCAMLR regulations require that this research fishery should be repeated within the next two years following the year ***j*** (WG-SAM-16, paragraph 3.26), i.e. the same cell ***i*** should be accessible again in year ***j***+1or ***j***+2. The probability of repeated accessibility to cell ***i*** that was visited initially in year ***j*** at day ***x*** is calculated by

$$RA_{i,j,x} = A_{i,j,x} * \frac{(A_{i,j+1,x} + A_{i,j+2,x})}{2} \tag{5}$$

$RA_{i,j,x}$ will be positive only if $A_{i,j,x} = 1$. Since navigability is required to occur only once in the specified time period to meet the requirements (see above), the value of $RA_{i,j,x}$ is set to 1 as soon as $RA_{i,j,x} > 0$.

Expanding this to the general case of a specific time window ranging from day ***t1*** to day ***t2*** during which the visit takes place leads to:

$$RA_{i,j,x} = A_{i,j,t1 \rightarrow t2} * \frac{(A_{i,j+1,t1 \rightarrow t2} + A_{i,j+2,t1 \rightarrow t2})}{2} \tag{6}$$

Please note that this could be generalized further by allowing for different time windows in each year, but we will not elaborate on this case here.

For the whole observation series of ***ny*** years (16 years) the mean repeated accessibility ***RAM*** to grid cell ***i*** visited at day ***x*** in the 1st year amounts to

$$RAM_{i,x} = \sum_{j=1}^{j=ny-2} \frac{RA_{i,j,x}}{ny-2} \tag{7}$$

Mean repeated accessibility ***RAM*** for an area of ***n*** grid cells regarding a specific year ***j*** is computed accordingly by

$$RAA_{j,x} = \sum_{i=1}^{i=n} \frac{RA_{i,j,x}}{n} \tag{8}$$

and mean probability of repeated accessibility ***RAM*** for an area of ***n*** grid cells over the whole observation period is computed by

$$RAM_{x} = \sum_{i=1}^{i=nc} \frac{RA_{i,x}}{n} \tag{9}$$

Results

Large scale distribution patterns of accessibility and of repeated accessibility

The probability that a particular area is navigable by fishery vessels during the austral summer is very high (> 80%) in the northeast of the WSMPA Planning Area between approx. 5°E and 10°W, and along the ice shelf between the prime meridian and approx. 30°W. A low probability of mean accessibility occurs at Astrid Ridge and in the entire CCAMLR Subarea 48.5 (i.e. the area west of 20°W), except of relatively small areas along the ice shelf where polynyas predominate.

The probability that the offshore area in the northeast of the WSMPA Planning Area is navigable repeatedly by fishery vessels during the austral summer within a three years' period is very high (> 80 %) (Fig. 4). Repeated accessibility decreases in direction of the ice shelf and the western part of the WSMPA Planning Area, until a repeated accessibility is no longer possible, such as in areas directly on the ice shelf east of the prime meridian and in the entire central Weddell Sea. On the shelf west of the prime meridian to approx. 30°W, however, there is a high probability of repeated accessibility in most areas.

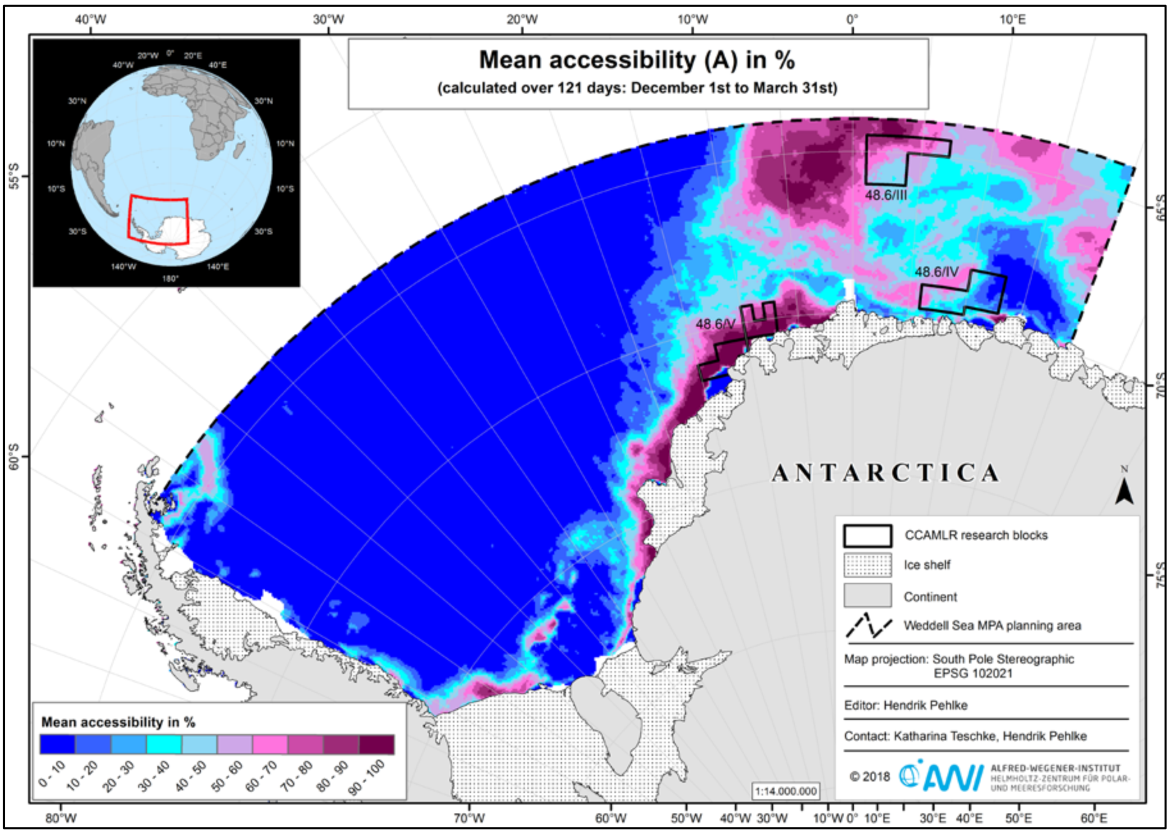

Figure 2: Mean accessibility (in %) in the Weddell Sea MPA (WSMPA) Planning Area calculated for the austral summer months (Dec - Mar) across all years (2002 – 2017).

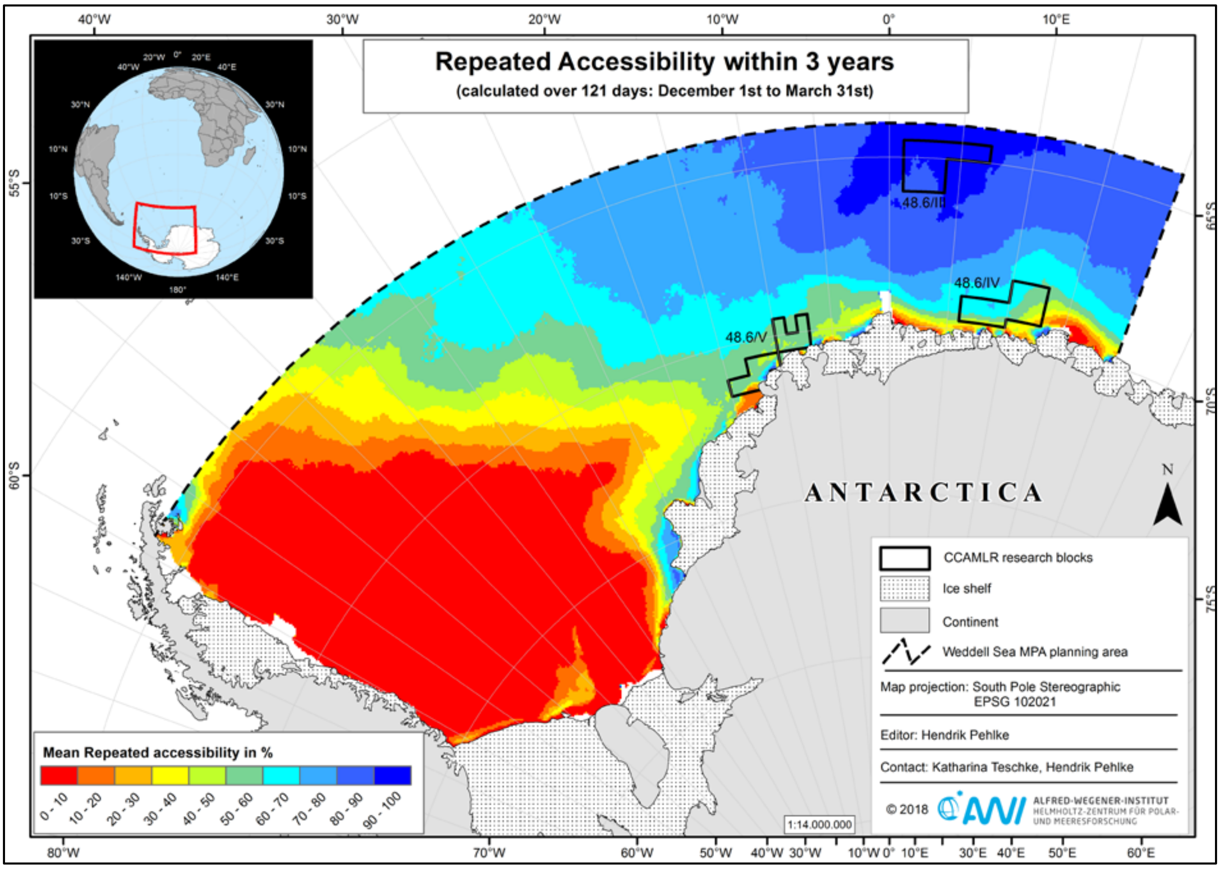

Figure 4: Mean repeated accessibility (in %) within a three years' period in the Weddell Sea MPA (WSMPA) Planning Area calculated for the austral summer months (Dec - Mar) across all years (2002 - 2017).

Example calculations of repeated accessibility

CCAMLR Research Block (RB) 48.6_3 shows a high mean repeated accessibility over the austral summer of 92 %. From the end of December to the end of March the probability is at > 90 % that RB 48.6_3 is navigable by fishery vessels repeatedly within a three years' period (Fig. 5A). RB 48.6_4 shows a mean repeated accessibility over the austral summer of almost 60 %. The time window where the probability of repeated accessibility is >= 70 % is approx. 1.5 months (end of Jan - mid of Mar) (Fig. 5B). In CCAMLR Research Block 48.6_5 a probability of repeated accessibility of >= 70 % occurs from the end of January to the beginning of March, i.e. the navigable time window shrinks again (Fig. 5C).

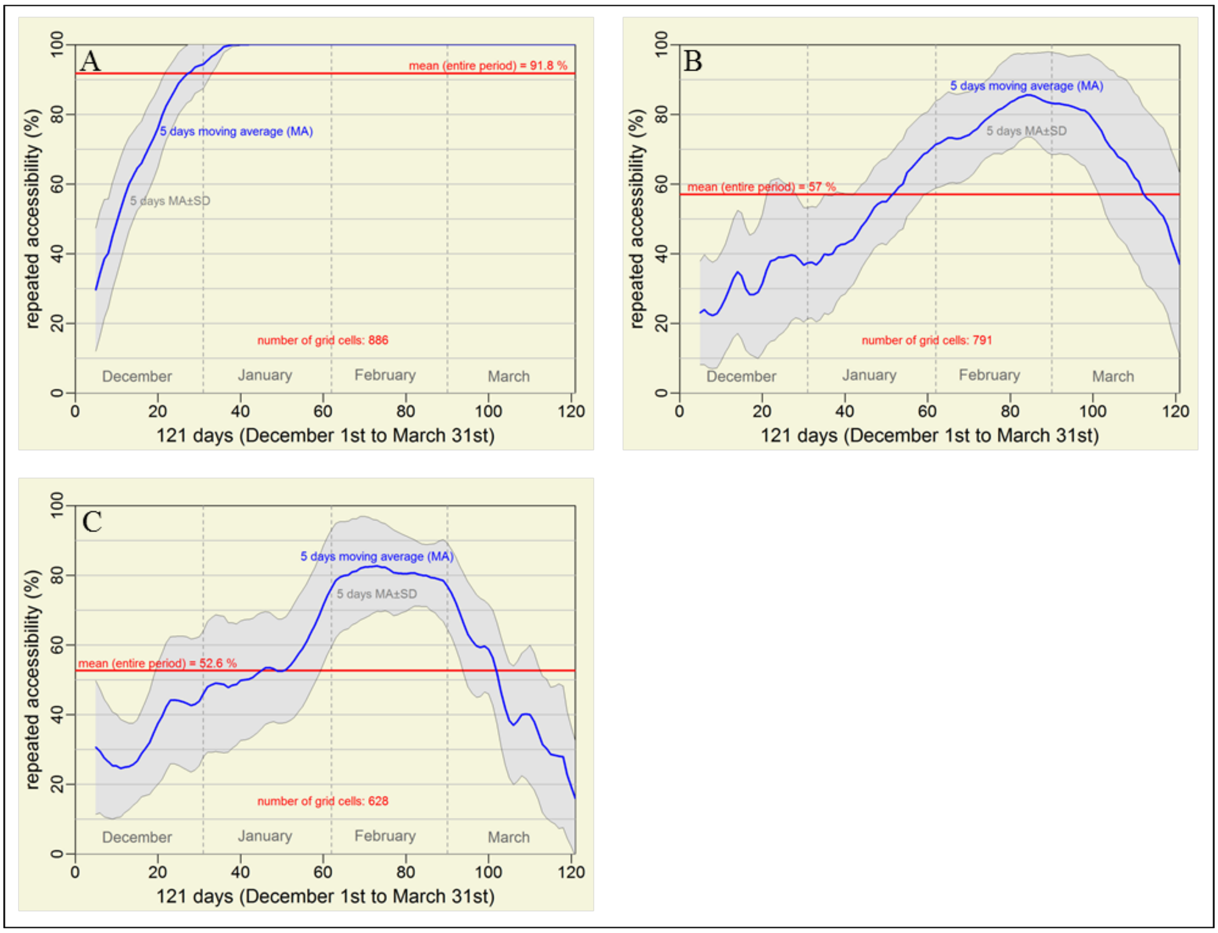

Figure 5: Mean repeated accessibility (in %), i.e. probability that a specific area is navigable by fishery vessels at a given time and again within the following two years, calculated exemplarily for the CCAMLR Research Blocks in the WSMPA Planning Area across the austral summer months of all years (2002 - 2017); CCAMLR Research Block 48.6_3 (A), 48.6_4 (B) and 48.6_5 (C).

Regarding the intra-annual variability in mean repeated accessibility an expansion of areas where a navigation by fishery vessels is highly probable is shown from December over January to February (Fig. 6). In March areas with highest probability of repeated accessibility again occur north of 70°S only, except of relatively small areas directly along the ice shelf. A general pattern that occurs every month shows a continuous increase in the probability of repeated accessibility west to east and south to north. An exception are relatively small areas along the ice shelf of the eastern and south-eastern Weddell Sea and the Antarctic Peninsula.

Values of highest standard deviation (sd) occur in an area approx. between 20°W and 40°W that is shown a steep gradient of the probability of repeated accessibility (Fig. 6). Additionally, high sd values are shown along the ice shelf of the eastern and south-eastern Weddell Sea where the probability of repeated accessibility varies at smaller spatial scales. This pattern is most clearly in February and March.

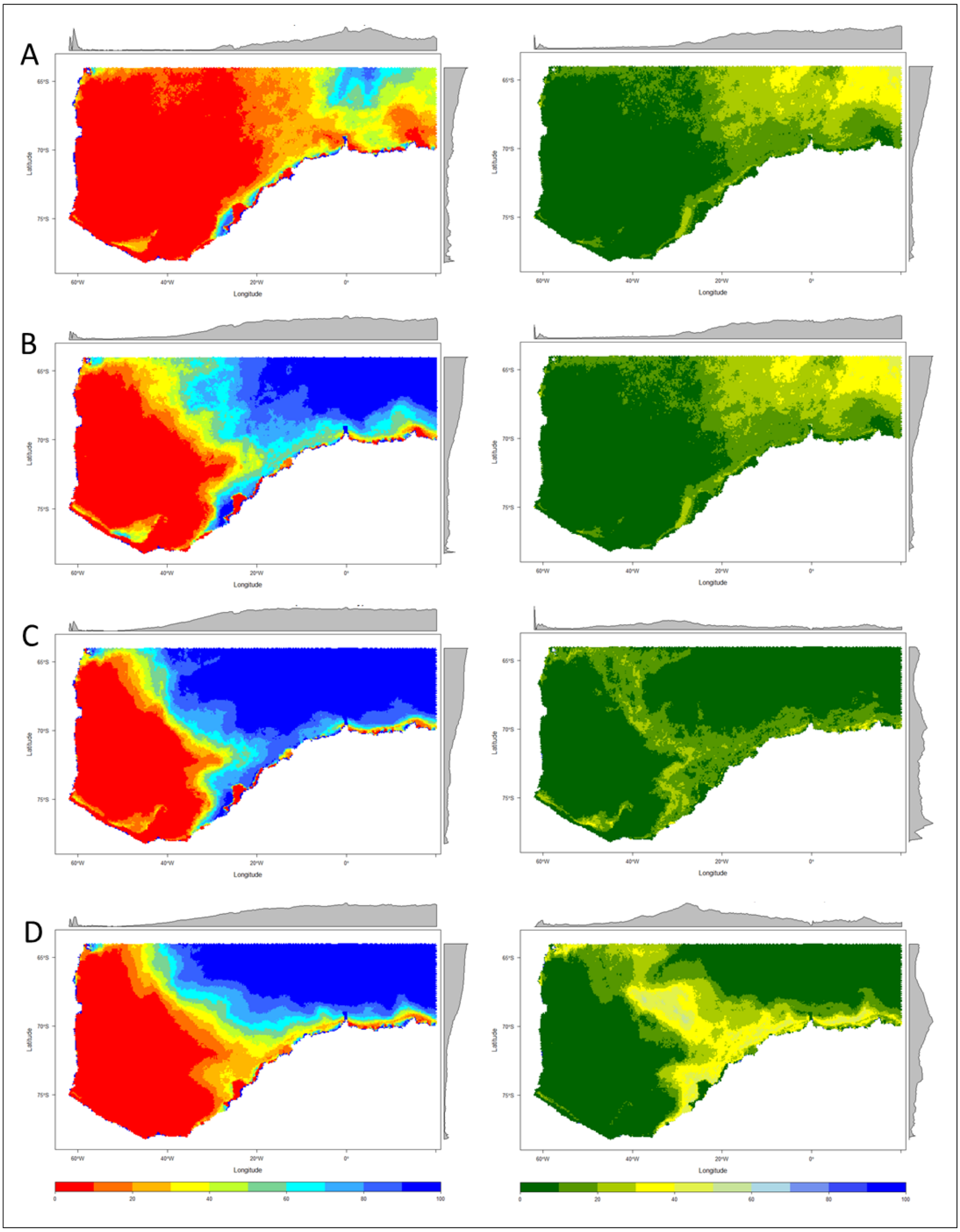

Figure 6: Mean repeated accessibility (left) +/- standard deviation (right) (in %) within a three years' period in the Weddell Sea MPA (WSMPA) Planning Area calculated for Dec (A), Jan (B), Feb (C) and Mar (D) across all years (2002 - 2017).

Perspectives

Future work on this topic will particularly concentrate on the spatio-temporal variation in repeated accessibility. For example, we would like to analyse if there is a trend in accessibility of the Weddell Sea Planning Area over the years. We are also thinking about whether we should extend our model approach to include the opportunity of calculating the accessibility for shipping passages.

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Appendix

Table 1: Characteristics of WGS 84 / NSIDC Sea Ice Polar Stereographic South projection (EPSG 3976) and South Pole Stereographic projection (EPSG 102021).

Map projections	
EPSG 3976	EPSG 102021
WGS 1984 / NSIDC Sea Ice Polar Stereographic South Projection: Stereographic South Pole False Easting: 0.0 False Northing: 0.0 Central Meridian: 0.0 Scale Factor: 1.0 Latitude Of Origin: -70.0° Linear Unit: Meter (1.0) Geographic Coordinate System: GCS WGS 1984 Angular Unit: Degree (0.0174532925199433) Prime Meridian: Greenwich (0.0) Datum: D WGS 1984 Spheroid: WGS 1984 Semimajor Axis: 6378137.0 Semiminor Axis: 6356752.314245179 Inverse Flattening: 298.257223563	South Pole Stereographic Projection: Stereographic False Easting: 0.0 False Northing: 0.0 Central Meridian: 0.0 Scale Factor: 1.0 Latitude Of Origin: -90.0° Linear Unit: Meter (1.0) Geographic Coordinate System: GCS WGS 1984 Angular Unit: Degree (0.0174532925199433) Prime Meridian: Greenwich (0.0) Datum: D WGS 1984 Spheroid: WGS 1984 Semimajor Axis: 6378137.0 Semiminor Axis: 6356752.314245179 Inverse Flattening: 298.257223563

Table 2: Overview of the availability of AMSR-E and AMSR2 daily (http://www.iup.uni-bremen.de:8084/amsr2); 1 = data is available, NA = no data available and 0 (red background) = data available, but not used for the models.

		days																														
year	month	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	sum
2002	01	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0
	02	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0
	03	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0
	12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	31
2003	01	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	31
	02	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	NA	NA	NA	28
	03	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	31
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2004	01	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	31
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