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Arctic Marine Productivity from Plankton to Fish: Tools and First Estimates

J.-N. Druon, E. Jardim, F. Mélin

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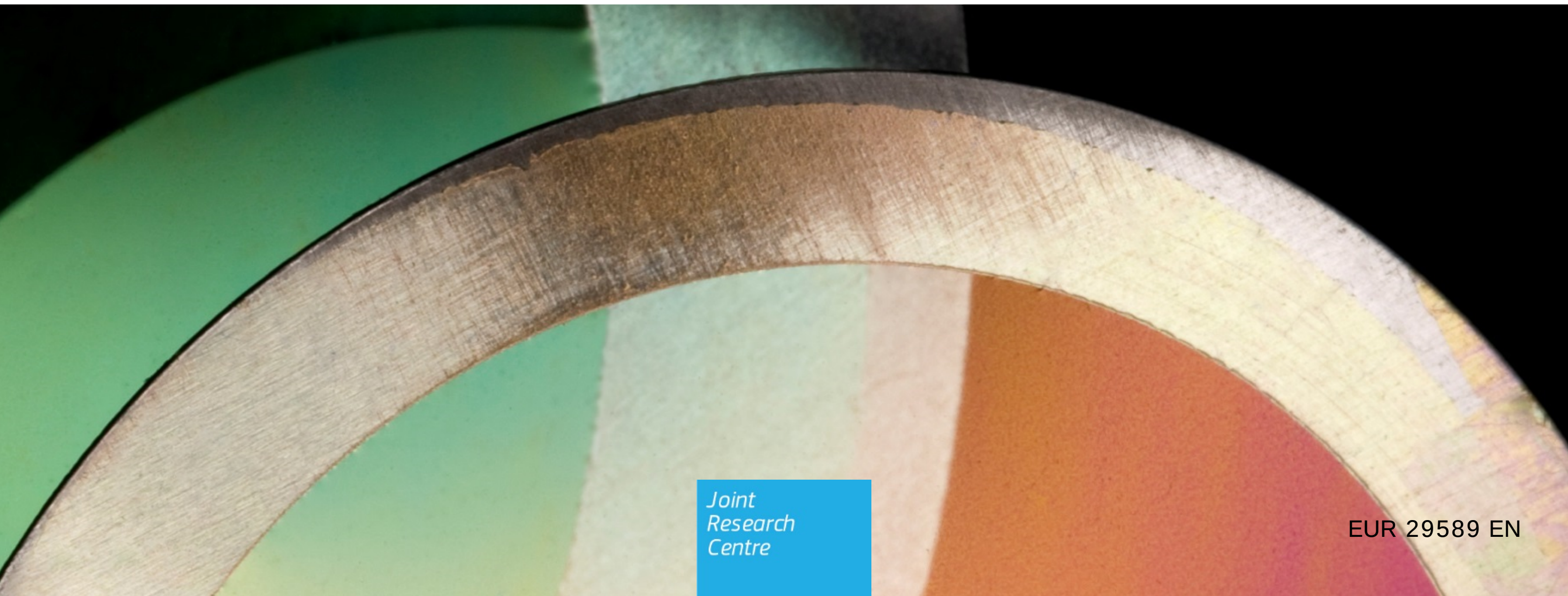

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Foreword

This report is a contribution to the Work Package 6304 ECO-ARCTIC (deliverable #2) of the JRC ARCTIC project (2018), about “Climate impacts and sustainable provision of ecosystem services in the Arctic” supporting the orientation of “advancing our understanding of how climate change interacts with other parts of the Earths system, in particular the vulnerability of the Arctic region to climate change, and translating the findings into specific strategies for mitigation, adaptation and sustainable developments”.

Acknowledgements

The Ocean Biology Processing Group (OBPG) from the U.S. National Aeronautics and Space Administration (NASA) is duly acknowledged for the distribution of ocean color satellite data from the SeaWiFS, MODIS-Aqua and VIIRS missions.

Authors

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Abstract

The Arctic region undergoes major pressures from climate variability. Its major manifestations are the increase in temperature and decrease in sea ice coverage and volume, with associated variability in ocean and atmosphere circulation. Warming and ice melting might also open up economic opportunities in the region that might in turn lead to more pressure on this fragile ecosystem. The ECO-ARCTIC activity of the JRC addresses “climate impacts and sustainable provision of ecosystem services in the Arctic”. ECO-ARCTIC focuses jointly on the priority areas "Climate Change and Safeguarding the Arctic Environment" and "Sustainable development in and around the Arctic" of the joint communication “An integrated European Union policy for the Arctic". This report describes on-going efforts at studying and documenting Arctic marine productivity across trophic levels, including primary production by phytoplankton, secondary production by zooplankton, and fisheries management.

1 Introduction

The Arctic region undergoes major pressures from climate variability. Its major manifestations are the increase in temperature and decrease in sea ice coverage and volume (IPCC 2007, Overland and Wang, 2013) with associated variability in ocean and atmosphere circulation. The region is also receiving atmospheric inputs from lower latitudes, including black carbon aerosols (Quinn et al. 2008). Warming and ice melting might also open up economic opportunities in the region that might in turn lead to more pressure on this fragile ecosystem.

The ECO-ARCTIC activity of the JRC addresses “climate impacts and sustainable provision of ecosystem services in the Arctic”. ECO-ARCTIC focuses jointly on the priority areas "Climate Change and Safeguarding the Arctic Environment" and "Sustainable development in and around the Arctic" of the joint communication “An integrated European Union policy for the Arctic" (JOIN 2016). On one side the work package investigates the impacts of climate change on fragile and temperature sensitive elements of the Arctic, like the biosphere and the permafrost. In parallel, ECO-ARCTIC investigates the ongoing and future challenges for the sustainable provision of ecosystem services in the Arctic and boreal regions exposed to accelerated warming. In this context the activity will provide an assessment of the climate risks and related vulnerability of natural resources and primary productivity in both terrestrial and marine biomes under alternative climate scenarios. Moreover, under the remit of the panel Scientific Experts on Fish Stocks in the Central Arctic Ocean (FISCAO), and in line with the joint communication “An integrated European Union policy for the Arctic" (JOIN 2016), the JRC will, as EU-Delegate, contribute to the setting of a scientific framework for the management of future fisheries in the Central Arctic Ocean and advise DG MARE on that matter.

In that context, a specific item focuses on the Arctic marine productivity, with three trophic levels taken into consideration, primary production by phytoplankton, secondary production by zooplankton, and fisheries. These 3 points are covered by different methods but they are here summarized in a common report.

2 Towards Satellite-based Primary Production by Phytoplankton

Changes affecting the Arctic Ocean are likely to have profound effects on marine life, including phytoplankton. The Arctic Ocean is a complex and diverse environment but among possible changes predicted to affect the region overall are i) earlier spring blooms in the seasonal ice zone, ii) more intense blooms at high latitudes, iii) a decrease in primary productivity at lower latitudes because of increased stratification, and iv) increased occurrence of fall blooms (Wassmann and Reigstad 2011). Some of these predictions are getting preliminary confirmations already (e.g., Ardyna et al. 2014) and the Arctic might be the marine ecosystem that will encounter the fastest and most profound changes in the global ocean.

In that context, extended time series of ocean color data are essential to monitor the evolution of the Arctic Ocean. These time series will have to rely on a suite of successive and partly overlapping satellite missions. Even though data from different missions generally agree, the construction of a consistent multi-mission data record from ocean color has proved to be a challenging task since inter-mission differences associated with ocean color products are significant and vary as a function of wavelength, season and location (Djavidnia et al. 2010, Mélin et al. 2009, Mélin 2010, 2011). Seemingly small differences can actually introduce artefacts in temporal analyses if they are not taken into account and be a serious impediment to assess the existence of trends in a specific region (Mélin 2016, Mélin et al. 2017). This is further compounded in the Arctic Ocean as this region is characterized by specific challenges for optical remote sensing. Cloud and ice cover and winter darkness mean a sparser data record with respect to other regions. The solar zenith angle are usually low and longer optical paths tend to increase the uncertainty of the derived products. The presence of sea ice with various states of overlying snow can impact the ocean color signal within the pixel or through adjacency effects when the pixel is close to an extended bright surface (Bélanger et al. 2007). A significant part of the Arctic Ocean is influenced by an increasing flow of large rivers laden with sediments and/or dissolved organic matter (e.g., Shiklomanov and Lammers 2009) and therefore qualifies as optically complex waters, conditions that are known to affect the uncertainties of the products derived from ocean color remote sensing. All these elements are likely conducive to fairly large uncertainties but these are not always easy to quantify in a comprehensive manner as field observations in the Arctic Ocean are sparse. Considering a higher level product, namely primary productivity, an exercise of model assessment (Lee et al. 2015) has shown large differences between model outputs from 32 participant models and field data, stressing the need for improved satellite data and models.

Taking these elements into account, the aim of this activity is to collect and process Earth Observation (EO) data sets relevant to the assessment of marine biology in the Arctic Ocean and to develop the tools appropriate to derive primary productivity estimates for the basin. Below are described modelling aspects, data sources, elements of processing and an illustration of the data sets.

2.1 Primary Production Modelling

The primary production model managed by JRC is driven by satellite observations (mostly from ocean color remote sensing) following the equations:

$$P(z,t) = \frac{\Pi(z,t).Chl(z)}{\sqrt{1+\left(\frac{\Pi(z,t)}{P_m^B}\right)^2}}$$

$$\Pi(z,t) = \int_{400}^{700} \alpha^B(\lambda).\bar{E}(z,t,\lambda)d\lambda$$

where *P*(z,t) is the rate of carbon fixation at depth z and time t. *P* depends on the photosynthetic parameters that define the shape of the light-to-photosynthesis relationship (Platt and Sathyendranath 1988), the photosynthetic rate at light saturation P_m^B, and the initial slope of the light-to-photosynthesis curve α^B (also known as photosynthetic action spectrum). Both parameters are normalized to chlorophyll-a concentration *Chl* (thus the superscript B, for biomass). *P* also depends on light at (z,t) represented here by the scalar irradiance $\bar{E}(z,t,\lambda)$. *P* is obtained by spectral integration for visible wavelengths, from 400 to 700 nm.

Finally, daily primary production *PP* can be computed by integration over depth (from surface to euphotic depth, where irradiance has become 0.1% of the surface value) and time (over the dawn to dusk):

$$PP = \int_{ti}^{tf} \int_{0}^{Zeu} P(z,t)dzdt$$

This wavelength-resolved, depth-resolved (and potentially time-resolved) formalism is the most complete for primary production modelling. Some other models are wavelength-integrated and/or depth-integrated (Behrenfeld and Falkowski 1997) with imbedded simplifying assumptions.

In order to compute *PP* with satellite data using that formalism, a minimum set of elements are required:

- The distribution of incident light at the water surface: Daily Photosynthetically Available Radiation (PAR) is a standard satellite product associated with the satellite ocean color data record (as illustrated in Sections 2.2 and 2.3). Additional information about atmospheric conditions are required if a distinction between direct and diffuse components and/or a spectral resolution are needed (see Section 2.4).
- Chlorophyll-a concentration at surface and depth *Chl*(z): the value at surface can be provided by satellite data (see Sections 2.2 and 2.3) and be extended down the water column if the shape of the vertical profile is known. This can be computed as a function of the surface *Chl* value (e.g., Morel and Berthon 1989) or imposed by region and season following a partition of the ocean into biogeographic provinces where certain parameters are kept constant as suggested by field data (Longhurst et al. 1995, Mélin and Hoepffner 2004).
- A model propagating light from the surface down the water column to a depth where it has been fully absorbed (taken as the 0.1% light level, where light is 0.1% of the surface value).This can be done by linking *Chl*(z) to optical properties of absorption and scattering coupled with a radiative transfer model. Additional independent ocean color products such as absorption by dissolved organic matter are part of available satellite data (even though not illustrated here) and can also be used to drive the vertical propagation of light.
- When light and *Chl* are available at any depth z, *P* can be computed using appropriate values of the photosynthetic parameters. The current formalism assumes that these parameters are known by region and season (Longhurst et al. 1995, Mélin and Hoepffner 2004).

The following sections introduce and illustrate the satellite ocean color archive with emphasis on *Chl* and PAR.

2.2 Data Archive

2.2.1 Data Source

The main sensors considered for the activity are the Sea-viewing Wide Field-of-view Sensor (SeaWiFS, Hooker et al., 1992) onboard a Geoeye spacecraft, the Moderate Resolution Imaging Spectroradiometer (MODIS, Esaias et al., 1998) onboard the Aqua platform (MODISA), the Moderate Resolution Imaging Spectrometer (MERIS, Rast et al., 1999) and the Visible/Infrared Imager/Radiometer Suite (VIIRS, Schueler et al., 2002) onboard the Suomi National Polar-orbiting Partnership (NPP). The satellite data from SeaWiFS, MODIS and VIIRS are acquired from the Goddard Space Flight Center of the U.S. National Aeronautics and Space Administration (GSFC-NASA) through https://oceancolor.gsfc.nasa.gov/. The MERIS data have been acquired from the same source even though the raw data are initially produced by the European Space Agency (ESA). MODIST data (MODIS on-board Terra) is also a potential source of data for the archive but this sensor suffers from various issues mostly related to calibration (Franz et al. 2008).

- SeaWiFS: The SeaWiFS mission provided data from September 1997 to December 2010 with some interruptions in the last years.
- MODISA: The MODIS mission on Aqua started providing data in June 2002, with a global coverage at full resolution up to present.
- MERIS: The MERIS mission was launched in March 2002, and collected measurements up to April 2012. As this missions still awaits a full reprocessing by NASA to bring the corresponding data set in line with the other sensors, its inclusion into the Arctic archive is postponed.
- MODIST: The Terra platform was launched in December 1999 and data have been distributed since February 2000. For the reason stated, it is not considered for the Arctic data set as yet.
- VIIRS: The NPP platform was launched in October 2011, and VIIRS has been collecting useful data starting in 2012.

Global mapped data, so-called Level-3 data, are distributed in 2 forms: Level-3 "binned" data (L3BIN, code L3b) are stored onto sinusoidal grids in a format well studied to spare memory space (a long vector of data only at locations of valid data) and Level-3 "standard mapped images" (L3SMI, code L3m) regridded onto regular latitude/longitude files (equidistant cylindrical projection). Both formats are distributed as netCDF (4) files.

The chlorophyll-a product is obtained from the same software (SeaDAS, Fu et al. 1998) with the same bio-optical algorithm operating a combination of the maximum-band-ratio OC4 (O'Reilly et al. 2000) and the 3-band algorithm OCI by Hu et al. (2012). The PAR product is produced according to Frouin et al. (2003). All data shown here are associated with NASA reprocessing 2018.0.

2.2.2 Data Sets and Domain of Analysis

The data introduced above are remapped onto a geographical projection more suitable for polar studies, using an equidistant azimuthal projection. The resolution is ~9.2 km ($1/12^{th}$ degree along the meridians) and the domain is the interval between 50ºN and 90ºN, leading to a size of 960 points (see Figure 2.1). The remapping software is an ad-hoc program created at JRC as the remapping tool from NASA l3mapgen appears to produce unclear results for this region. Output files are in netCDF-4 format.

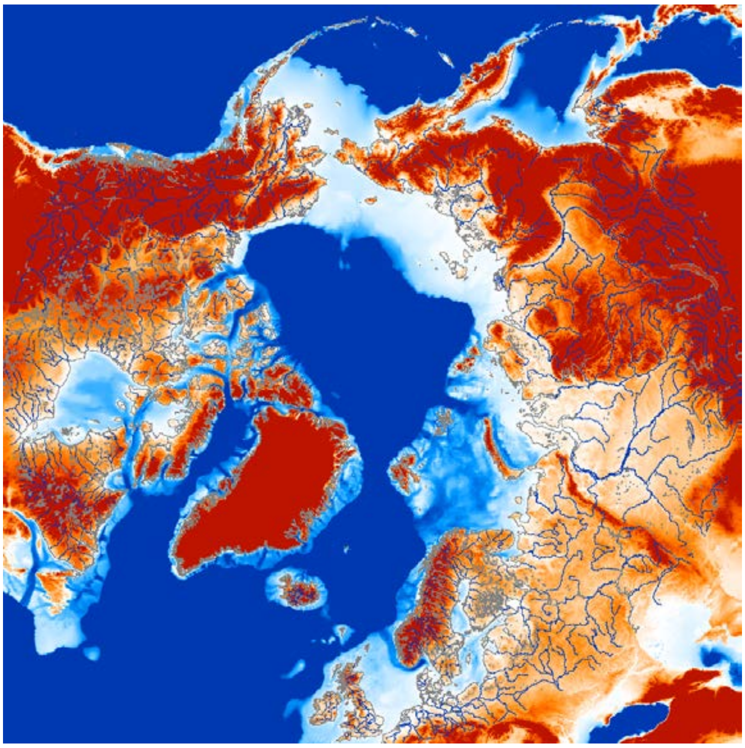

Figure 2.1 Extent of the domain, with latitude interval 50°N - 90°N, nx=ny=960

For temporal and budget analysis, the domain has been partitioned into specific regions (Figure 2.2) for which average values are computed for each monthly file.

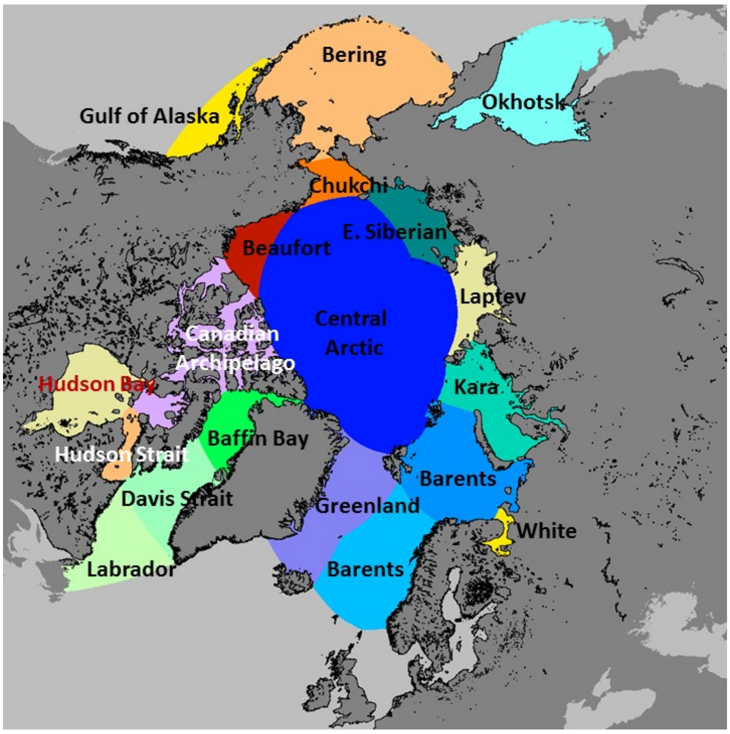

Figure 2.2: Domain partitioned into separate regions for temporal analysis

The data sets for the Arctic basin contain the concentration of chlorophyll-a *Chl* (in mg m^{-3}) and Photosynthetically Available Radiation PAR (in E m^{-2} d^{-1}) onto an equidistant azimuthal projection (Figure 2.1) for the 3 missions SeaWiFS, MODIS-Aqua and VIIRS.

Each file starts with a letter specific to the mission:

- **A**: MODIS Aqua
- **S**: SeaWiFS
- **V**: VIIRS

Being remapped data onto a geographic projection, the code for Level-3 data is:

- **L3m**: L3SMI, or Level-3 standard mapped image data, in standard projection (equidistant azimuthal for the Arctic)

Extensions for the time interval of the data files are:

- **DAY**: daily composites,
- **8D**: 8-day composites,
- **MO**: monthly composites.

For now, only monthly files for SeaWiFS, MODIS-Aqua and VIIRS have been created but other time resolutions as well as MERIS and MODIS-Terra products could follow.

The storage points (including monthly data and png illustration) associated with each mission are:

- /netsea1/vol04/data/archive/SeaWiFS/ARCT
- /netsea1/vol04/data/archive/MODISA/ARCT
- /netsea1/vol04/data/archive/VIIRS/ARCT

The storage points are in practice "read-only" and the only action that can be taken is to copy the data set needed to the local user's working environment for analysis. The files can also be read directly (being in uncompressed form).

2.3 Climatology and Time Series

In this section are illustrated the concentration of chlorophyll-a *Chl* and Photosynthetically Available Radiation PAR for the Arctic domain. The *Chl* data are updates of the results shown for the 2017 activity (longer time series and reprocessed data).

2.3.1 Chlorophyll-a Concentration

The monthly climatology for the chlorophyll-a concentration is illustrated below for the example of SeaWiFS, where climatology is computed over the period 1998-2010. A major feature is the seasonal excursion of the data coverage whereby most of the Arctic Ocean is void of data in winter, a period when ocean color remote sensing is not operating because of the little amount of light. Already in April and more prominently in May, large *Chl* concentrations can be seen in the Bering and Barents Seas. As open water extends, large concentrations are also detected along the Siberian coasts from June onwards.

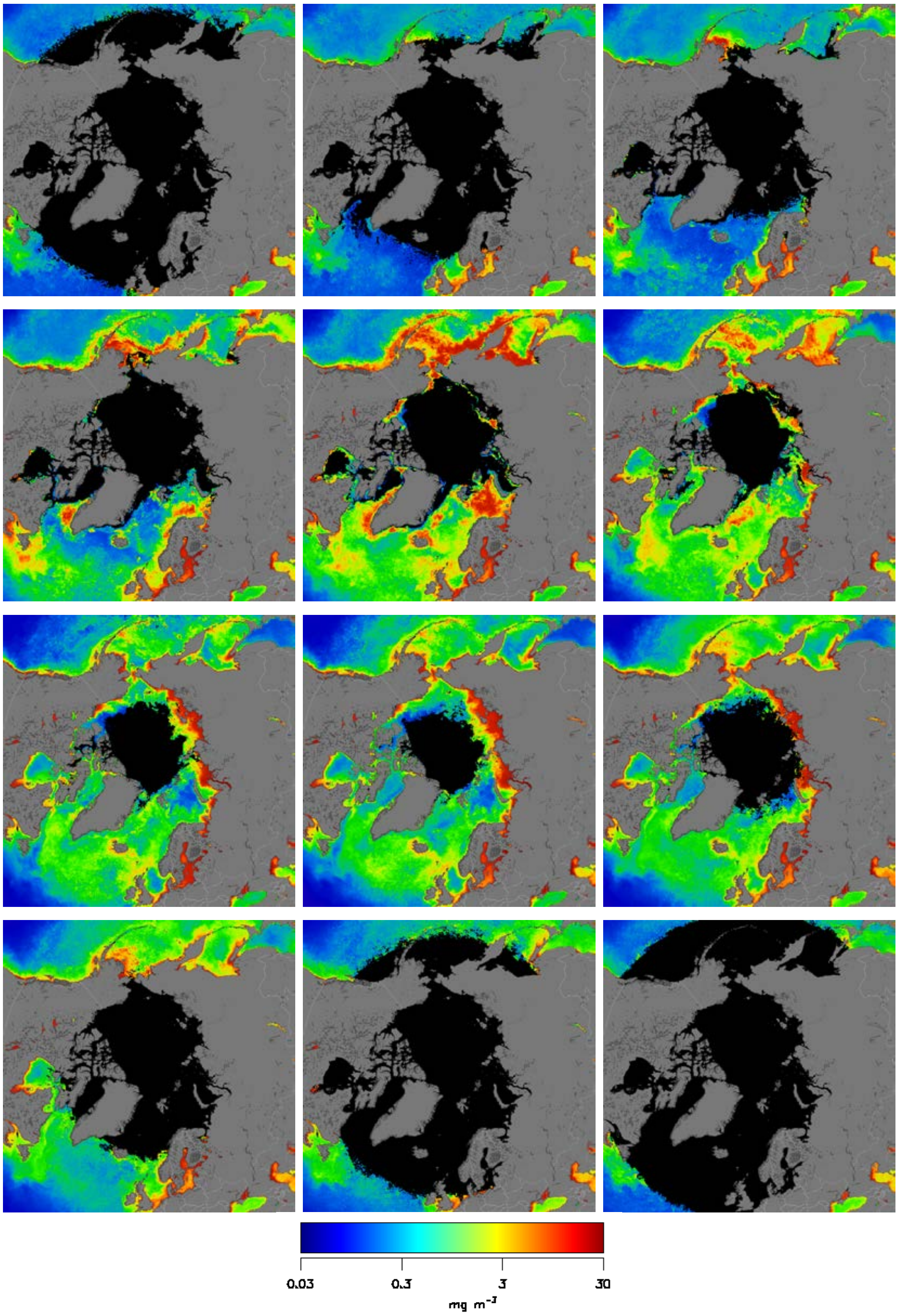

Figure 2.3: SeaWiFS monthly climatology (1998-2010) of chlorophyll-a concentration, January to December from left to right and top to bottom.

The variations of *Chl* can be further illustrated by time series over 20 years as provided by the missions SeaWiFS, MODIS-Aqua and VIIRS averaged over specific regions (see Figure 2.2 for their definition), the Norwegian, Barents, Greenland and Bering Seas (Figures 2.4 to 2.7). These regions are chosen for illustration as they offer the largest data coverage. The time series of the different missions show a good agreement when they overlap but also some differences that should be further explored and reduced. For all missions and regions, *Chl* maxima are observed in late spring-summer.

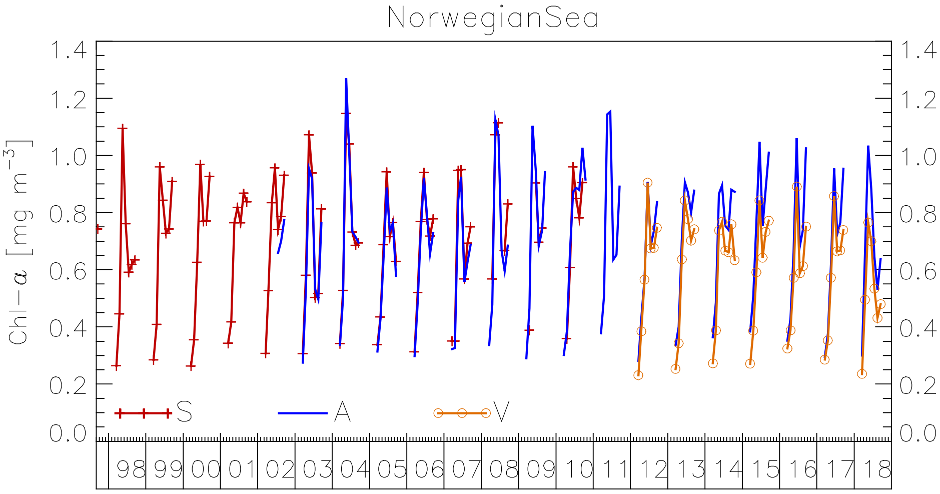

Figure 2.4: Monthly time series of averaged chlorophyll-a concentration from SeaWiFS (S), MODIS-Aqua (A) and VIIRS (V) over the Norwegian Sea. Data records are plotted if the coverage for the domain is at least 25%.

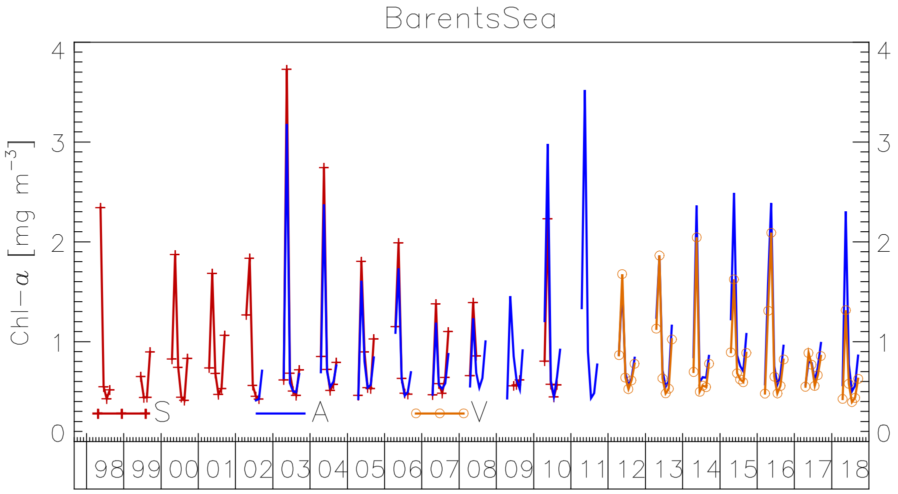

Figure 2.5: Monthly time series of averaged chlorophyll-a concentration from SeaWiFS (S), MODIS-Aqua (A) and VIIRS (V) over the Barents Sea. Data records are plotted if the coverage for the domain is at least 25%.

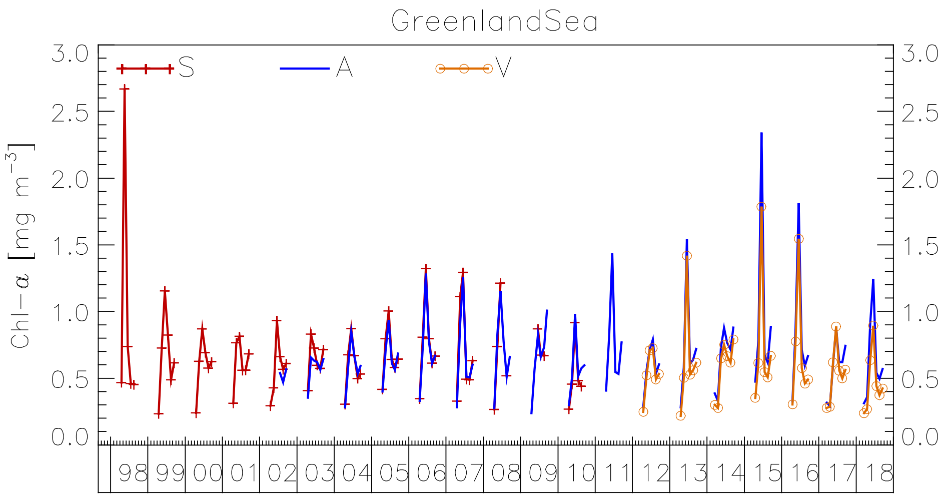

Figure 2.6: Monthly time series of averaged chlorophyll-a concentration from SeaWiFS (S), MODIS-Aqua (A) and VIIRS (V) over the Greenland Sea. Data records are plotted if the coverage for the domain is at least 25%.

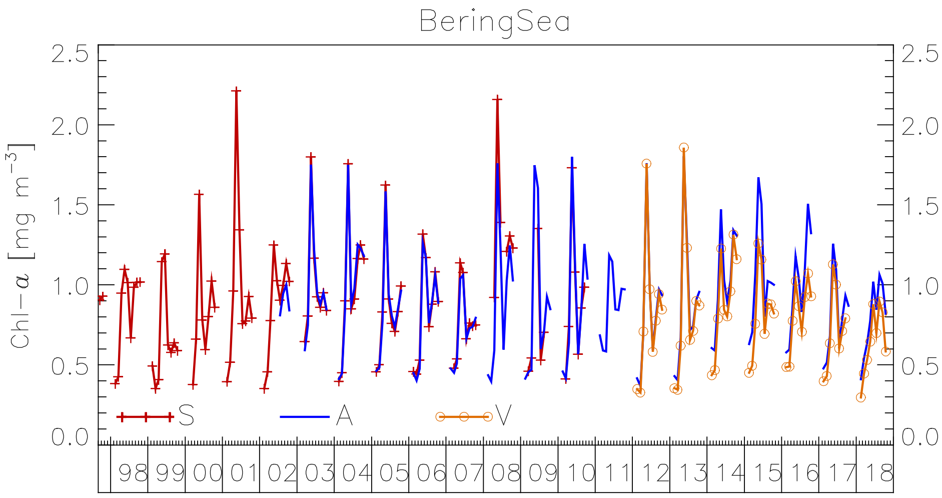

Figure 2.7: Monthly time series of averaged chlorophyll-a concentration from SeaWiFS (S), MODIS-Aqua (A) and VIIRS (V) over the Bering Sea. Data records are plotted if the coverage for the domain is at least 25%.

2.3.2 Photosynthetically Available Radiation

The monthly climatology for PAR is also illustrated by the SeaWiFS record for the years 1998-2010. The patterns associated with PAR are smoother than those observed for *Chl* as PAR is primarily driven by the solar elevation (and thus strongly seasonal) and secondarily by cloud cover that tends to be rather homogeneous as far as a multi-annual monthly climatology is concerned.

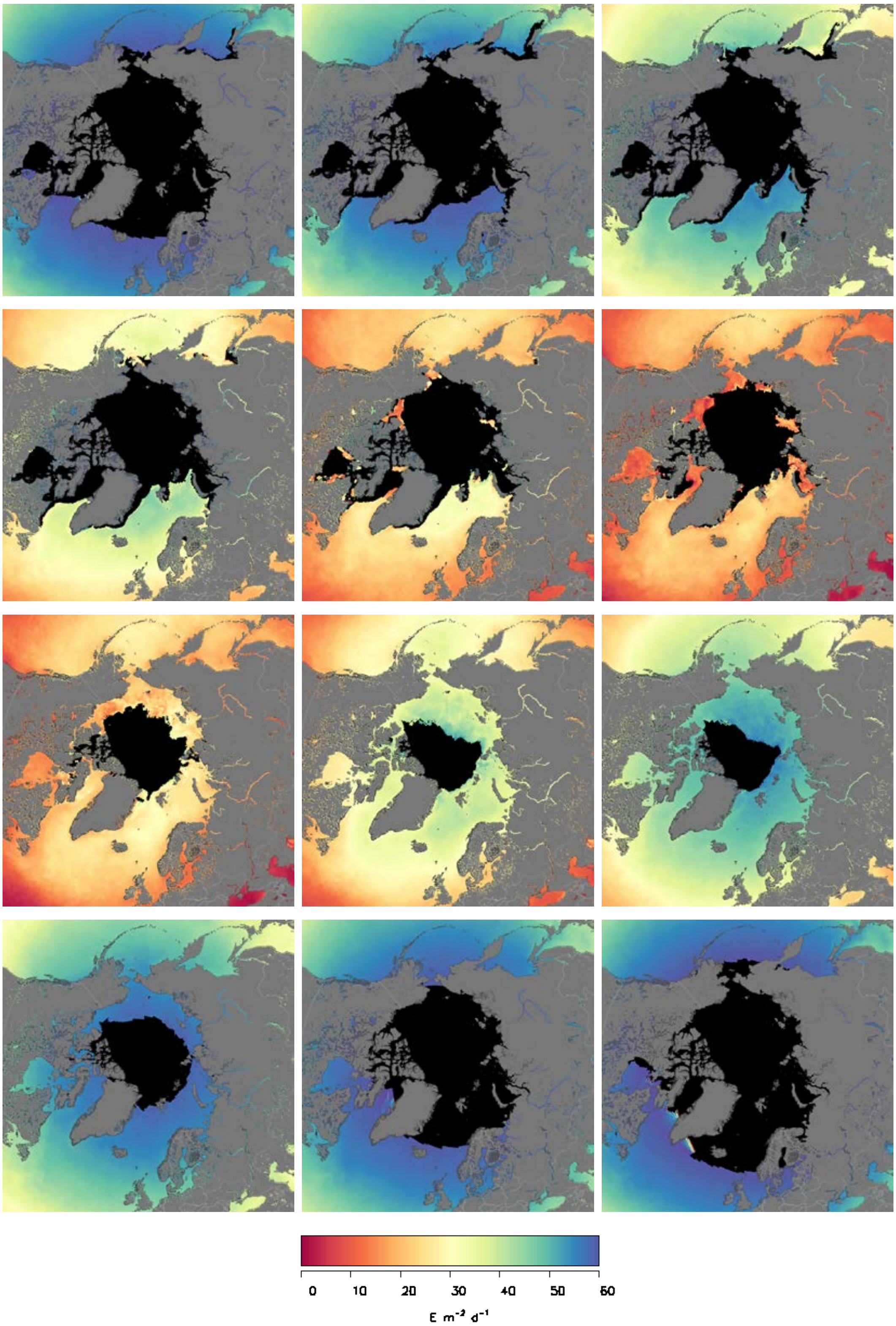

Figure 2.8: SeaWiFS monthly climatology (1998-2010) of PAR, January to December from left to right and top to bottom.

As for *Chl*, 20-year multi-mission monthly averages are shown for the Norwegian, Barents, Greenland and Bering Seas (Figures 2.9 to 2.12). As anticipated above, a clear annual cycle is visible as driven by solar elevation. As mentioned for *Chl*, the time series from different missions agree well with some exceptions. Particularly, SeaWiFS maxima appear higher than MODIS data, whereas MODIS and VIIRS show great consistency.

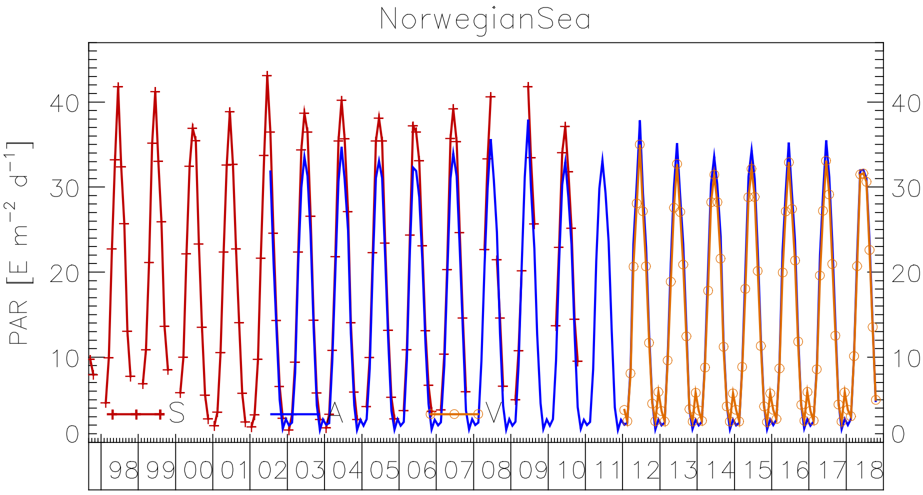

Figure 2.9: Monthly time series of averaged PAR from SeaWiFS (S), MODIS-Aqua (A) and VIIRS (V) over the Bering Sea. Data records are plotted if the coverage for the domain is at least 25%.

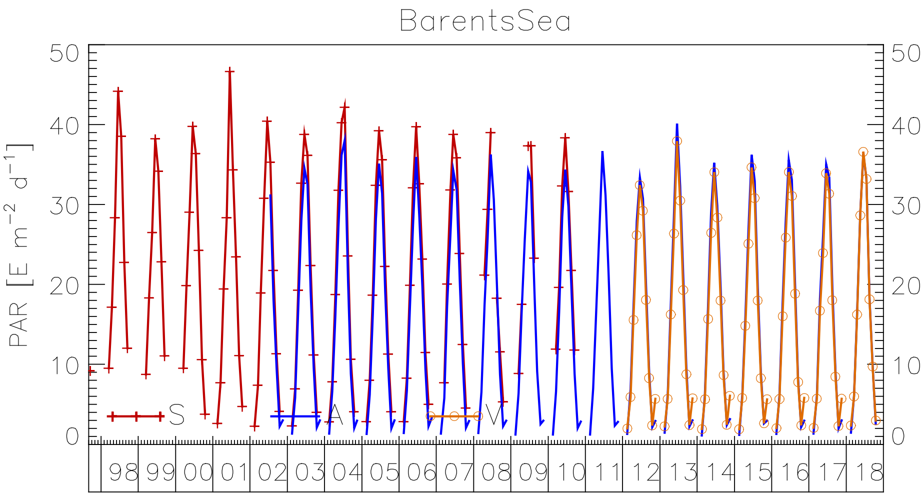

Figure 2.10: Monthly time series of averaged PAR from SeaWiFS (S), MODIS-Aqua (A) and VIIRS (V) over the Barents Sea. Data records are plotted if the coverage for the domain is at least 25%.

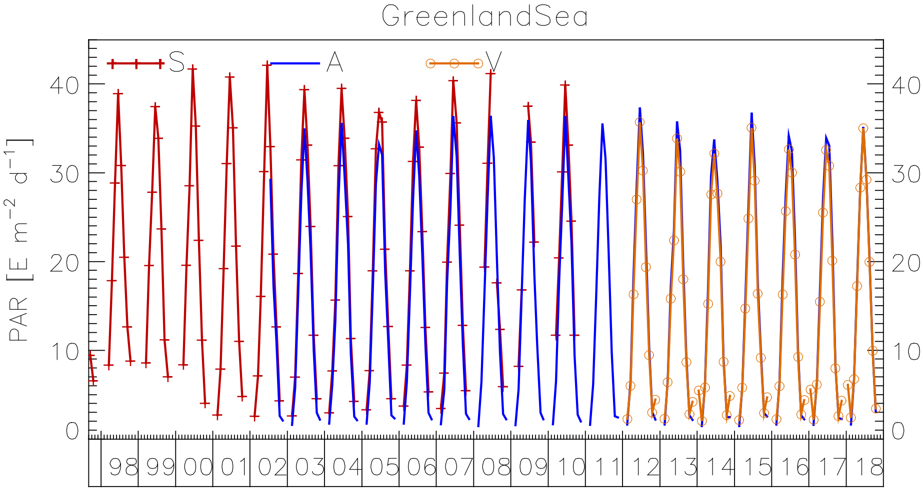

Figure 2.11: Monthly time series of averaged PAR from SeaWiFS (S), MODIS-Aqua (A) and VIIRS (V) over the Greenland Sea. Data records are plotted if the coverage for the domain is at least 25%.

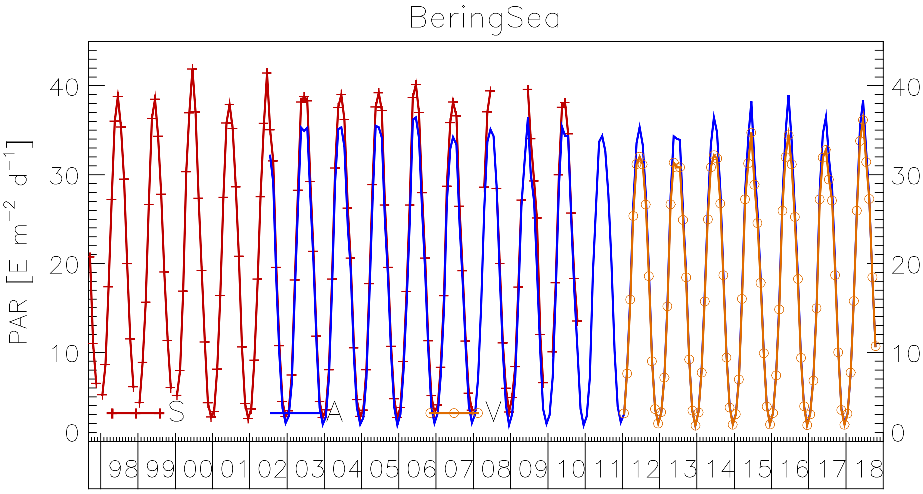

Figure 2.12: Monthly time series of averaged PAR from SeaWiFS (S), MODIS-Aqua (A) and VIIRS (V) over the Bering Sea. Data records are plotted if the coverage for the domain is at least 25%.

2.4 Developments

The previous sections illustrate the ocean color data required to drive the primary production model (Section 2.1). However, additional information is needed. On-going developments address two specific issues.

2.4.1 Photosynthetic Parameters

The JRC primary production model has regularly been tested against in-situ data (comparison with field measurements of primary production) in the framework of international assessment exercises (Primary Production Algorithms Round Robins). The JRC model usually compared favourably with respect to other participating models (Carr et al. 2006, Friedrichs et al. 2009, Saba et al 2010, 2011). These exercises were based on field measurements collected in open ocean waters as well as coastal regions and marginal seas. A typical root-mean-square (RMS) difference between modelled *PP* and field data for the best models is approximately 0.3 (in log-scale).

More recently, a similar exercise was conducted for the Arctic Ocean (Lee et al. 2015). Even though that particular analysis suffers from methodological weaknesses, it appears that model results (from 32 participants) are much worse than in other regions (with RMS differences of 0.5 in log-scale). Several factors can contribute to these discrepancies, notably the modelling of light propagation through the water column. Another source of differences might be the use of photosynthetic parameters not fully appropriate for the Arctic Ocean. Some additional knowledge about these parameters is now available from the work of the University of Oxford and the Plymouth Marine Laboratory (with a collaboration from JRC) who have compiled an updated data base of field measurements of photosynthetic parameters for the global ocean, where sub-arctic and arctic waters contribute significantly (Bouman et al. 2018). It is expected that similar data bases could lead to improvements in the photosynthetic model for Arctic waters.

2.4.2 Spectral irradiance

The satellite distributions of PAR are a great resource for driving primary production but wavelength-resolved models need irradiance fields with a spectral resolution and a distinction between diffuse and direct components. This is all the more true for the Arctic region characterized by low solar elevation (and long atmospheric path lengths), long duration of illumination in summer, and intense cloud cover.

An effort is on-going to derive these characteristics from the value of PAR itself together with ancillary information on latitude, date and atmospheric data (such as ozone concentration). This work requires the capacity to represent the effect of different types of clouds and aerosols on the surface downwelling light field (Mélin and Clerici 2010) with the use (among other things) of a radiative transfer model (Mayer and Kylling 2005).

First results are illustrated here. Fig. 2.13 shows the PAR direct-to-diffuse ratio as a function of PAR for different types and optical thicknesses of cloud and aerosols for conditions typical of May at 60° latitude North. As soon as cloud optical thickness exceeds that typical for very thin clouds (such as cirrus), the direct component is negligible. The direct component in presence of aerosols also becomes small but for an aerosol optical thickness reaching 1. The ratio varies little as a function of aerosol type for a given optical thickness.

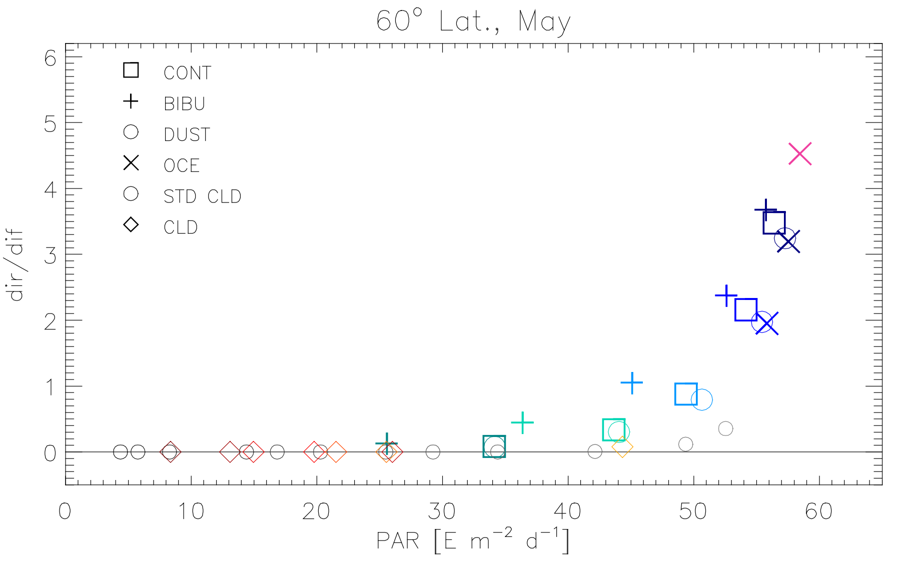

Figure 2.13: Direct-to-diffuse ratio versus daily PAR for various types and optical thicknesses of clouds, as well as different types and optical thicknesses of aerosols (continental, biomass burning, dust and marine aerosols). Conditions are in May at latitude 60°N.

Fig. 2.14 shows the relative spectral shapes of PAR for conditions in April at latitude 60°N for a fixed PAR. Various aerosol types and various cloud droplet size radii are considered. Conditions with aerosols show irradiance spectra with depressed values in the blue with respect to cloudy conditions, particularly for dust and biomass burning aerosols. On the other hand, the cloud droplet radius has little effect on the irradiance spectral shape.

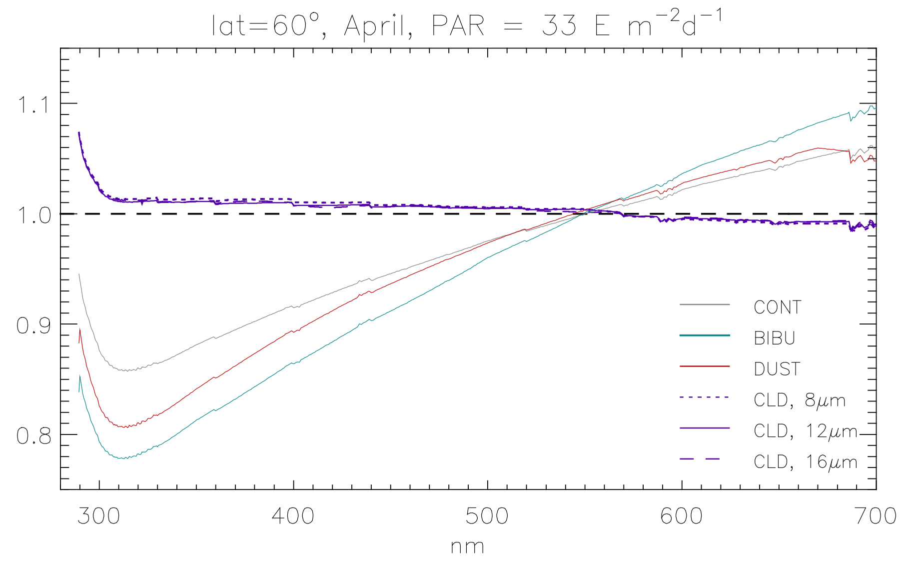

Figure 2.14: Relative spectral shapes of daily PAR for conditions in April at latitude 60°N and a PAR value of 33 E m^{-2} d^{-1}. Continental, biomass burning and dust aerosols are considered as well as clouds (CLD) of different droplet sizes (from 8 to 16 µm).

3 Satellite-based Estimate of Secondary Production by Zooplankton

This section is an update on advances done in 2018 based on the 2017 report: *Ocean Productivity index for Fish in the Arctic Ocean: Initial assessment of satellite-derived plankton-to-fish productive habitats*

(http://publications.jrc.ec.europa.eu/repository/bitstream/JRC109947/ocean_productivity_index_for_fish_in_the_artic.pdf)

This first report (Druon, 2017) described for the first time a satellite-derived approach of secondary production in relative levels based on productive frontal features (chlorophyll-a fronts, CHL fronts). Productive fronts that result from the resurgence of subsurface nutrient-rich waters such as on the edge of eddies or gyres were shown to attract fish and top predators (Druon et al. 2017, 2016, 2015, 2012, Panigada et al. 2017). These productive features are active long enough (from weeks to months) to allow the development of zooplankton populations ensuring a high transfer rate of energy from primary to secondary production. These productive fronts, which are daily detected by ocean colour satellite sensors, are used as a spatial proxy of food availability to fish populations. The satellite-derived Ocean Productivity index for Fish (OPFish) represents the potential production of high tropic level communities (fish) which results of the analysis of feeding preferences of various trophic levels such as meso-zooplankton, small pelagic fish, hake recruits, tuna species, fin whale and blue shark.

A major step forward towards the validation of the approach was done in 2018 through the analysis and finding of the tight link between the size of the chlorophyll-a front (horizontal gradient value of chlorophyll-a, gradCHL) and the biomass of meso-zooplankton (Druon et al. submitted). This habitat analysis for meso-zooplankton was performed using a comprehensive data base of 54,282 samples from the Continuous Plankton Recorder (Colebrook, 1991) covering all seasons and areas of the North Atlantic from 2002 to 2016. The large random sampling in the North Atlantic allowed to highlight four groups (clusters) of meso-zooplankton biomass that details the relationship with chlorophyll-a fronts:

- One cluster corresponds to the lowest level of meso-zooplankton biomass, mostly located in the warm-temperate and subtropical Atlantic or subpolar latitudes in winter. This cluster is characterised by low CHL and gradCHL levels, indicating relatively small productive fronts and low productivity levels.

- The other three clusters are sequential describing the main maturity phases of productive fronts in the northern part of the North Atlantic. The first cluster of this series is characterized by the highest levels of CHL and gradCHL (i.e. relatively high phytoplankton productivity) and by medium-high levels of meso-zooplankton biomass with higher frequencies in spring. This cluster describes the start of the spring bloom at different latitudes during the spring months.

- The second cluster in the sequence corresponds to medium levels of CHL and gradCHL and to exceptionally high levels of meso-zooplankton biomass in temperate and subpolar latitudes. This second cluster is interpreted as representing fully developed meso-zooplankton populations in relatively mature fronts which likely graze heavily on phytoplankton, but where there is little predation by high trophic levels (HTLs).

- The third cluster of the series has medium levels of CHL and gradCHL and medium-high levels of meso-zooplankton biomass. This cluster occurs in almost all latitudes, with a higher frequency in autumn. This last cluster is interpreted as corresponding to the oldest productive fronts which can be associated with fully developed food web where HTL predation controls the meso-zooplankton biomass.

The tight links between zooplankton biomass and chlorophyll-a fronts explains why most fish species in the upper ocean are attracted by these productive features. Furthermore, productive fronts are revealed to be the keystone for marine food web feeding as they sustain zooplankton production from weeks to months, continuously upwelling nutrient into surface waters and, on the opposite to subsurface waters, where light is not limiting phytoplankton productivity.

The Ocean Productivity index for Fish (OPFish, Druon 2017) was built from the aggregation of the information on the niches from meso-zooplankton to top predators as regards to the suitable productive fronts. The step from a combination of habitats to a notion of productivity of the OPFish is done through the inclusion of the day duration. The favourable habitat to feeding describes the daily distribution of productive fronts but it does not inform on the time per day these fronts are active. The inclusion of day length, which is highly variable depending on latitude and day-of-the-year, accounts for the daily duration of frontal activity.

The figures below i) describe the main seasonal variability of meso-zooplankton habitat for feeding in the Arctic to be compared to OPFish (Druon 2017) and ii) the effect of the additional 2017 and 2018 years in the time series and trend of OPFish.

The main difference between the meso-zooplankton favourable habitat and OPFish relates to latitudinal and seasonal differences in day duration. This explains the lower values of OPFish in lower latitudes in spring-summer months (Druon, 2017, Figure 6) compared to the more homogeneous distribution of meso-zooplankton habitat (Figure 3.1). Similarly, a zero value was attributed to OPFish in most Arctic areas in autumn and winter due to continuous night while no CHL data and therefore meso-zooplankton habitat was available, but was presumed to be extremely low during these months in the absence of light and primary production. Consequently, the multiannual mean of meso-zooplankton habitat (Figure 3.2) is biased towards the summer months due to the lack of data during the winter months. Figure 3.2 therefore represents mostly the mean and trend of meso-zooplankton habitat from April to September. Instead, the mean and trends of OPFish (Figure 3.3 and in Druon, 2017, Figure 8, 9, 10) cover the four seasons.

The addition of the years 2017 and 2018 on the OPFish time series (Figure 3.3) lower panel) shows another periodic cycle of 4 to 5 years of increase and decrease rate but also confirming the overall positive trend in the last 16 years of about 2.7% per decade in absolute values. The most striking difference compared to Druon (2017) is the increase poleward of free-ice areas in the last two years.

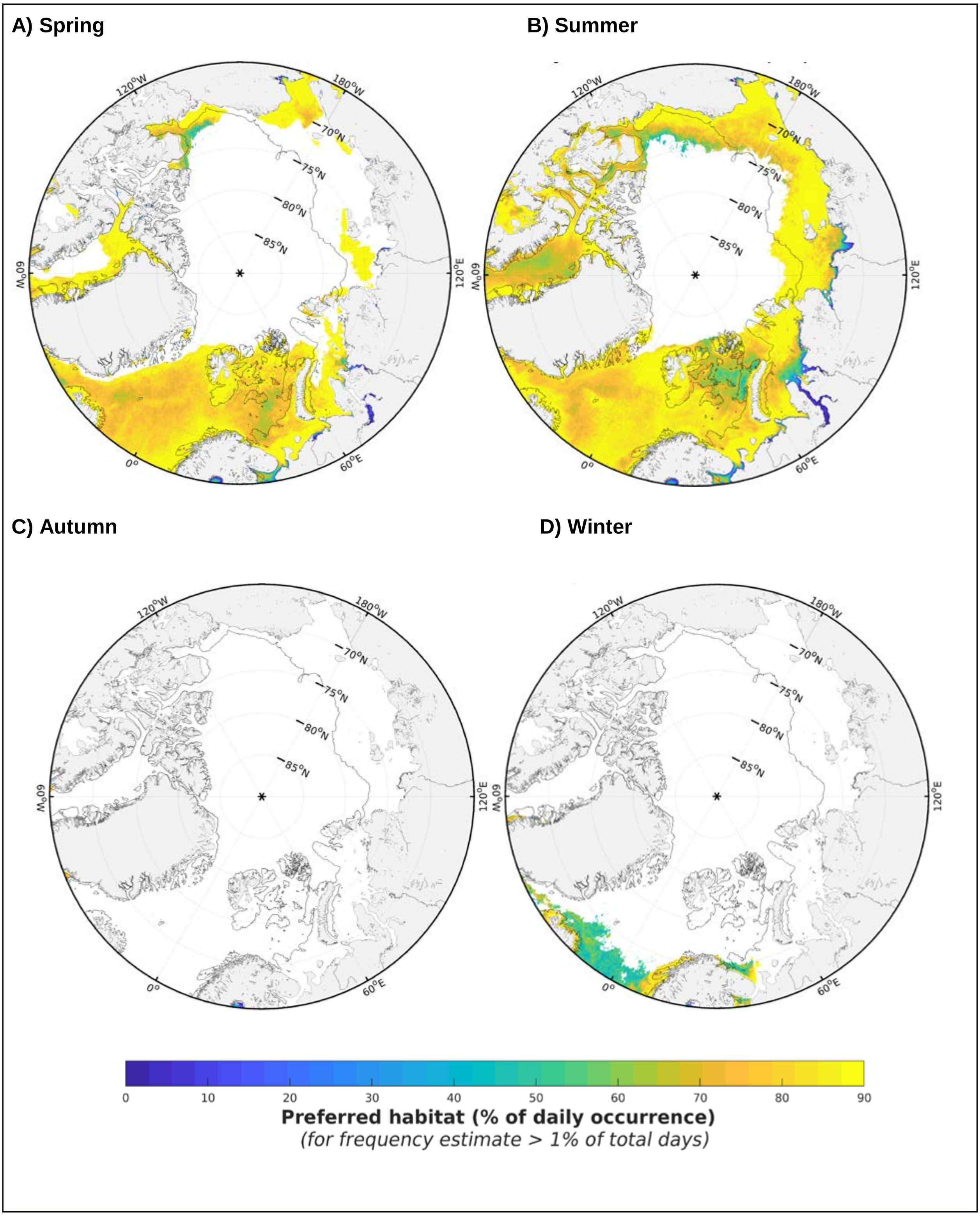

Figure 3.1 Seasonal meso-zooplankton favourable habitat for the 2003-2018 period (A) from April to June, (B) from July to September, (C) from October to December and (D) from January to March (in frequency of favourable occurrence). High habitat values represent a high frequency of occurrence of large productive fronts. The blank areas correspond to sea ice cover or index occurrence below 1% of the total number of days in the considered time period. The 200 m-isodepth contour is shown.

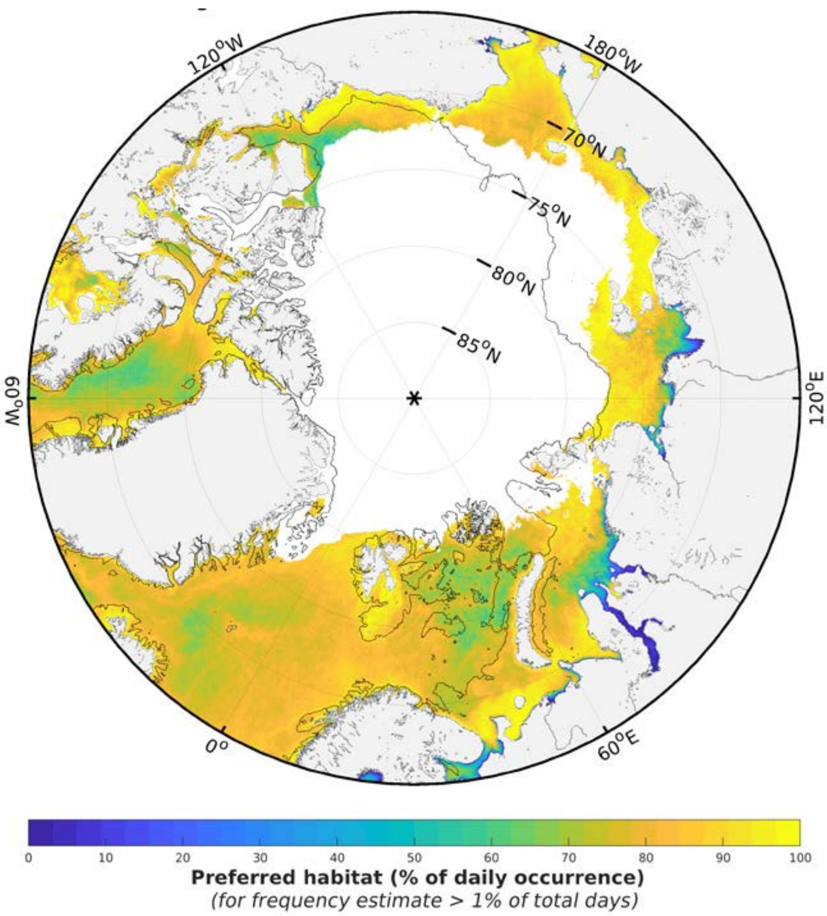

Figure 3.2 Mean meso-zooplankton favourable habitat for the 2003-2018 period computed from monthly means. High habitat values represent a high frequency of occurrence of large productive fronts. The blank areas correspond to sea ice cover, or to index or chlorophyll-a concentrations (CHL) occurrence below 1% of the total number of days in the considered time period. The 200 m-isodepth contour is shown.

We conclude that the association of meso-zooplankton activity with chlorophyll-a fronts is a major finding that substantially increases the robustness of top predators' habitat and OPFish approach. The OPFish provides a common proxy of secondary productivity across the oceans, including the Arctic, to trace in relative values the flow of energy that is available to high trophic levels. The OPFish subsequently represents most of the 10% of energy which is commonly assumed to be transferred from phytoplankton to zooplankton.

The OPFish is in the process of being confronted to fisheries data, namely i) fishing effort and landings from the Data Collection Framework by ICES-rectangles and quarters in the North-East Atlantic shelf and ii) bottom trawling catch per unit effort from scientific surveys in the North-East Atlantic shelf (DATRAS) and in the Mediterranean Sea (MEDITS). The result of these analysis will be compiled in the 2019 report.

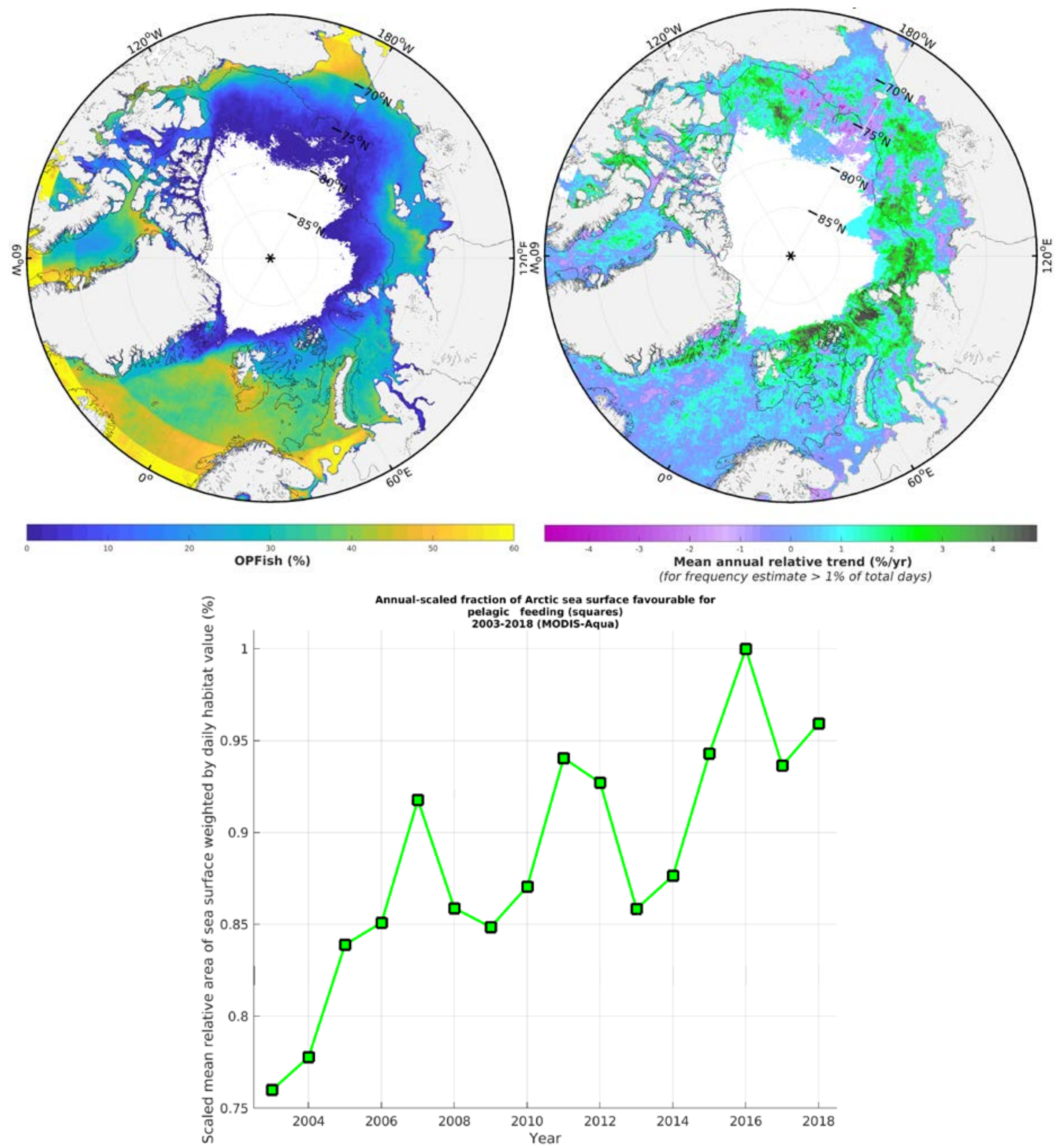

Figure 3.3 Mean (upper left panel)**, local trend** (upper right panel) **and annual size** (lower panel) **of Ocean Productivity index for Fish (OPFish) for the 2003-2018 period scaled to the maximum values** in the time-series. Note the recent retreat of sea ice and subsequent increase poleward of open sea waters compared to Druon (2017). The 200 m-isodepth contour is shown on maps.

4 Fisheries in the Arctic Ocean

The JRC continued its participation as EU-delegate in the meetings of Scientific Experts on Fish Stocks in the Central Arctic Ocean (FiSCAO) and advise DGMARE on the setting of a scientific framework for management of future fisheries in the Central Arctic Ocean. The latest FiSCAO meeting was in 2017, hosted by Canada.

The outcomes of the meeting were used to shape the “Agreement to prevent unregulated high seas Fisheries in the Central Arctic Ocean” (COM(2018) 453 final), signed during 2018 by all parties.

FiSCAO discussed:

1) The design of a 1-3 year long mapping program. Wich refers to the process of establishing a baseline for the CAO fisheries. It was agreed, as before, that the process will have to be coordinated across the different parties, making use of surveys already planned, may be complemented by additional surveys to cover potential gaps. Germany is currently preparing the MOSAiC survey (http://www.mosaicobservatory.org/), which is the most complete survey foreseen at the moment. The EU will have a good possibility of contributing to the mapping process by having fisheries scientists on board.

2) The design a monitoring programc for changes in the CAO and adjacent seas that may indicate changes in productivity or migration of stocks into the area. Such monitoring will be carried out by computing a set of indicators every year. For each indicator there should exist a threshold. If an indicator, or a group of indicators, reaches the threshold it will trigger a new mapping process to evaluate how the conditions to start a fishery evolved. The indicators and thresholds are still to be developed.

3) Identify human, financial, vessel/equipment resources needed for mapping and monitoring. An exercise about the needs and approximate costs to carry out the research required was developed. The values obtained are only indicative and to a large extent depend on the effort the parties want to allocate. It’s obviously very different in terms of costs to use ships of opportunity or set up a dedicated survey.

4) Develop data collection, sharing, and hosting protocols that outline the details of what and how data shall be collected, shared, and hosted for consideration by the Parties. The group discussed (i) a policy document, which will be included in the report, (ii) the integration with other activities already on the ground, e.g. the Arctic Data Committee, and (iii) the need to clarify data sharing formalities, since the different parties have different legal backgrounds regarding sharing of data, its re-utilization and property.

The EC/JRC proposed to host the 6th FiSCAO, which was welcome. The decision to organize a new FiSCAO will have to be taken by the parties.

5 Conclusion

Considering the pressures faced by the Arctic Ocean, developing instruments to understand and monitor the Arctic marine ecosystems is required. The ECO-ARCTIC work package is particularly relevant in that context as its components, covering trophic levels from primary producers to fish, are well complementary and results obtained so far are encouraging. Conversely, the Arctic Ocean is characterized by specific conditions that make progress acutely challenging with respect to other marine ecosystems. While it is a complex system with interactions between atmosphere, ocean, land and cryosphere, field data are often sparse because of isolation and harsh conditions. Moreover, optical remote sensing faces an atmosphere with frequent cloudiness, optically complex waters and very little light for a large part of the year, resulting in a restricted data coverage. So, the activities developed in ECO-ARCTIC need to be seen as integrated into a long-term endeavour.

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