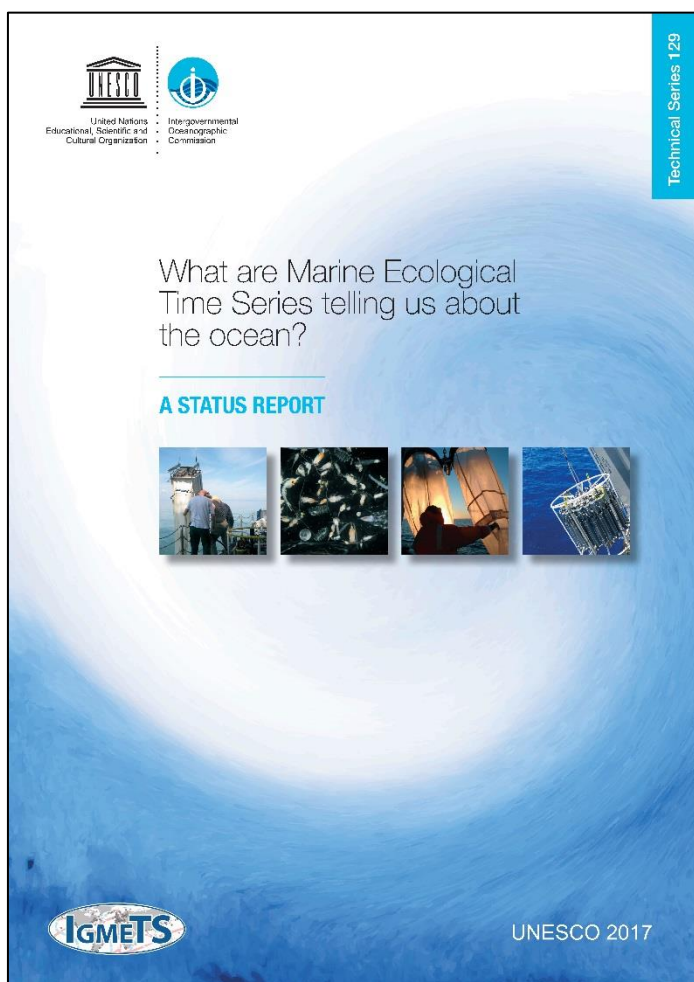


What are Marine Ecological Time Series telling us about the ocean? A status report

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Chapter 01: New light for ship-based time series (Introduction)

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Annex: Directory of Time-series Programmes

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3 Arctic Ocean

Nicholas R. Bates, Todd D. O'Brien, and Laura Lorenzoni

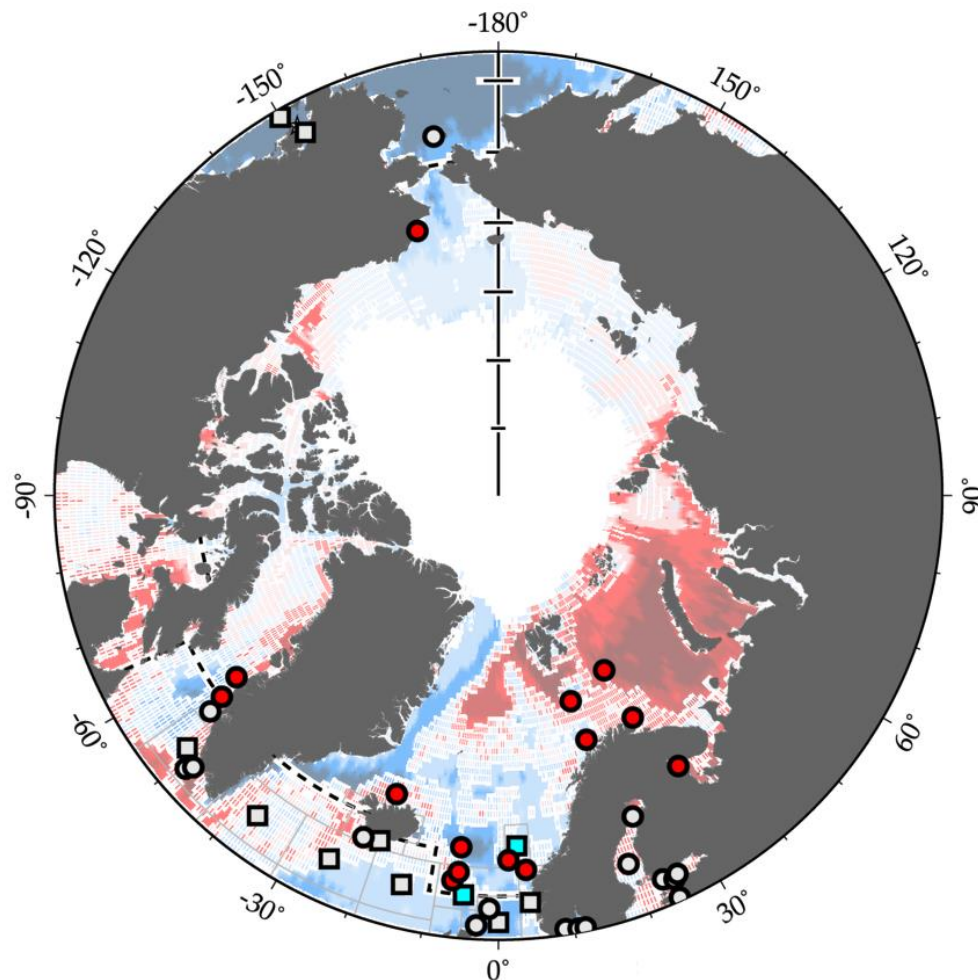


Figure 3.1. Map of IGMETS-participating Arctic Ocean time series on a background of 10-year time-window (2003–2012) sea surface temperature trends (see also Figure 3.3). At the time of this report, the Arctic Ocean collection consisted of 16 time series (coloured symbols of any type), of which two were from Continuous Plankton Recorder subareas (blue boxes). Un-coloured (gray) symbols indicate time series being addressed in a different regional chapter (e.g. North Atlantic, North Pacific). Dashed lines indicate boundaries between IGMETS regions. See Table 3.3 for a listing of this region’s participating sites. Additional information on the sites in this study is presented in the Annex.

Participating time-series investigators

Alexey Babkov, Cecilie Broms, Claudia Castellani, Padmini Dalpadado, Martin Edwards, Lisa Eisner, Ed Farley, Eilif Gaard, Astthor Gislason, Hafsteinn Gudfinnsson, Kristinn Gudmundsson, Solva Jacobsen, Inna Kutcheva, Priscilla Licandro, Daria Martynova, Webjørn Melle, Jeffrey Napp, S.A. Pedersen, Igor Primakov, Regina Prygunkova, Rowena Stern, and Nikolay Usov

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3.1 Introduction

The Arctic Ocean has experienced rapid and complex environmental changes over the last few decades in response to changes in climate and physical forcing that influence Arctic atmospheric properties, air–cryosphere–ocean interaction and exchanges, and terrestrial inputs. Atmospheric warming (Overland *et al.*, 2014) and changes in the terrestrial hydrological cycle of the region, combined with physical circulation and gateway exchange of the Arctic have contributed to well-documented summertime sea ice loss (Serreze *et al.*, 2000; Polyakov *et al.*, 2002, 2012; Maslanik *et al.*, 2007; Markus *et al.*, 2009; Perovich *et al.*, 2007, 2014; Stroeve *et al.*, 2007, 2014; Perovich and Richter-Menge, 2009; Wang

and Overland, 2009; Screen *et al.*, 2013; Overland and Wang, 2013; Simmonds and Goverkar, 2014; Frey *et al.*, 2014a,b, 2015). The rapid loss of sea ice is the most recognizable phenomena associated with the emerging “new Arctic” climate (Carmack *et al.*, 2015).

These physical changes have resulted in changes in the biology and biogeochemistry of the shallow and deep areas of the Arctic Ocean (Grebmeier *et al.*, 2010; Wassmann *et al.*, 2011). Increased ice-free waters and warmer temperatures appear to have caused changes in rates of primary production in the deep Arctic (Pabi *et al.*, 2008; Arrigo *et al.*, 2008, 2012, 2014; Arrigo and van Dijken, 2011) and associated shelves (Ardyna *et al.*, 2014). They have affected the seasonal timing of the annual phytoplankton bloom (Kahru *et al.*, 2010), the

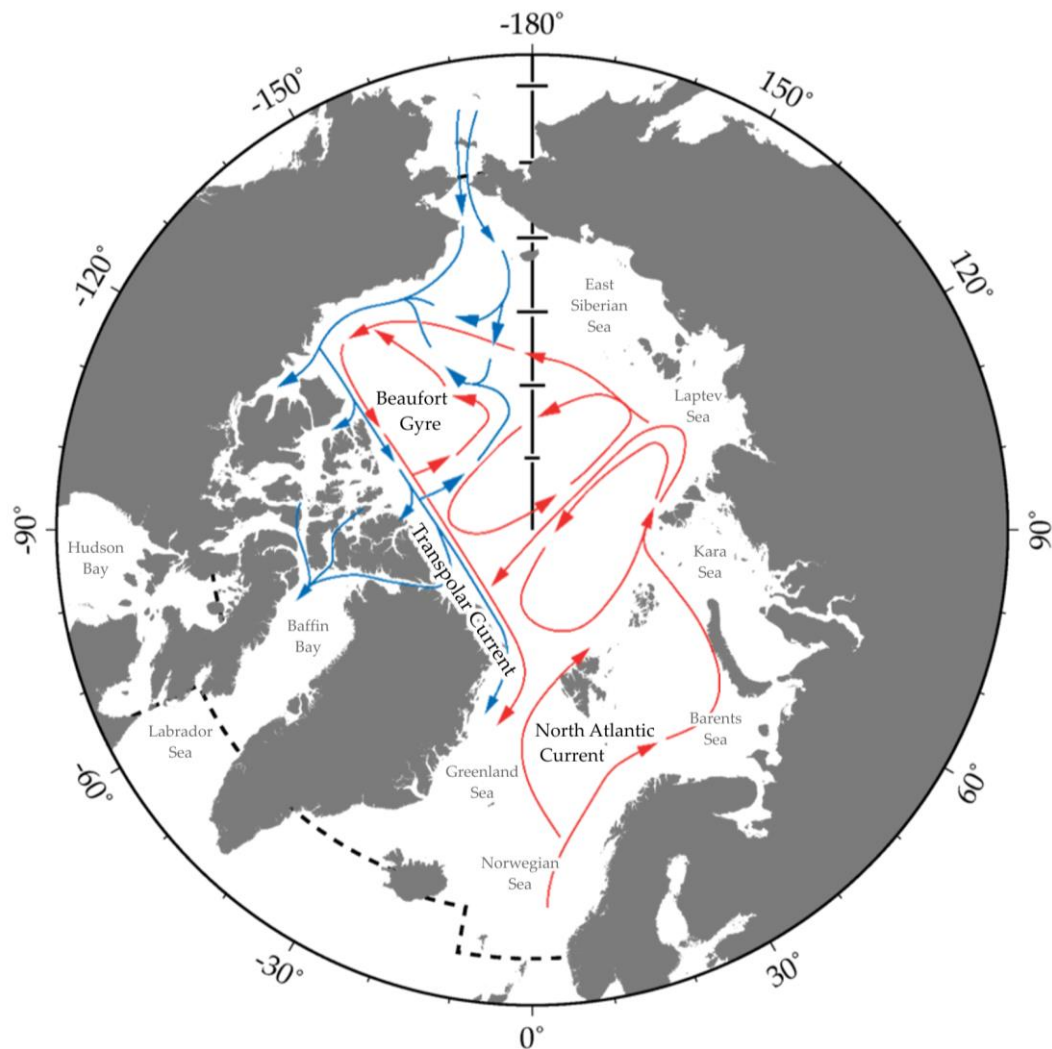


Figure 3.2. Schematic of major current systems, bays, and seas in the IGMETS-defined Arctic Ocean region. Red arrows indicate generally warmer water currents; blue arrows indicate generally cooler water currents. In this and subsequent figures, the Arctic Ocean region includes the Barents Sea, Siberian Shelf seas, Chukchi Sea, Beaufort Sea, Canadian Archipelago, and the central Arctic basins, but does not include the marginal seas (i.e. Greenland–Iceland–Norwegian Sea, Labrador Sea, Hudson Bay, Bering Sea). See “Methods” chapter for a complete description and methodology used.

composition of the phytoplankton (Li *et al.*, 2009), and have shifted higher trophic-level pelagic and benthic communities (Grebmeier *et al.*, 2015). The biogeochemical dynamics of carbon and nutrients have also been altered (McGuire *et al.*, 2006; Macdonald *et al.*, 2008), with an acceleration in the biological pump of carbon leading to enhanced export of carbon to the deep ocean (Lalande *et al.*, 2009, 2014a; Nishino *et al.*, 2011), and ultimately ocean carbon dioxide (CO₂) uptake and ocean acidification (OA) impacts in the region (Orr *et al.*, 2005; Bates *et al.*, 2006; Bates and Mathis, 2009; Steinacher *et al.*, 2009; Takahashi *et al.*, 2009; Manizza *et al.*, 2013; Schuster *et al.*, 2013; Bates, 2015). Loss of sea ice appears to be increasing momentum transfer to the ocean, increasing gateway inflows and outflows (Woodgate *et al.*, 2015), and increasing circulation and mixing (Rippeth *et al.*, 2014). This may have additional unknown implications for the biological communities and biogeochemical cycling of carbon and nutrients in the region.

The harsh polar climate and difficulties in sampling the Arctic Ocean have resulted in few sustained observations of ocean physics, biology, and biogeochemistry. As such, there remains much uncertainty about the present ocean function and understanding about the future response of the Arctic Ocean to rapid environmental change. However, the few existing time series that occupy Arctic waters have provided invaluable information that has enabled the understanding we now have of the dramatic changes the region has undergone (Figure 3.1).

3.2 Physical setting of the Arctic Ocean

The relatively small Arctic Ocean (ca. 10.7×10^6 km²) is almost completely landlocked except for the gateways at the Bering Strait and Canadian Archipelago and the Fram Strait and Barents Sea that allow exchanges with the Pacific and Atlantic oceans, respectively (Figure 3.2). The Arctic Ocean is dominated by interocean exchanges between the Pacific and Atlantic oceans (Macdonald *et al.*, 2008) and subsequent physical and biogeochemical modifications and transformations of water. This includes river inputs of freshwater and materials (McGuire *et al.*, 2006; Cooper *et al.*, 2008), sea ice production and melting (Peterson *et al.*, 2002; Carmack and Chapman, 2003), and atmosphere–ocean interaction (Rigor *et al.*, 2002; Overland and Wang, 2005; Wang *et al.*, 2005) and exchanges, which combined, act to dictate

water column stratification (Aagaard *et al.*, 1981; Rudels *et al.*, 1996) and circulation and residence time in the Arctic. The inputs to the Arctic in descending order include: Atlantic inflow through Fram Strait and via the Barents Sea of ca. 5–6 Sv (Sv = sverdrup = 10^6 m³ s⁻¹); Pacific inflow (through Bering Strait) of ca. 1 Sv (Woodgate *et al.*, 2005; 2015); and freshwater inputs of ca. 0.10–0.14 (Aagaard and Carmack, 1989; Wijffels *et al.*, 1992; Fahrbach *et al.*, 2001; Macdonald *et al.*, 2008), with outflow through the Canadian Archipelago, across the Barents Sea, and through Fram Strait.

The relatively broad, generally shallow (<200 m deep) continental shelves surrounding the central basin comprise about 53% of the area of the Arctic Ocean (Macdonald *et al.*, 2008). Each of the Arctic continental shelves is unique and thus difficult to characterize generically. As a simplification, the Chukchi and Barents seas can be characterized as “inflow” shelves (Carmack and Wassmann, 2006), with inflow of warm, nutrient-rich waters from the Pacific and Atlantic, respectively (Müller-Karger *et al.*, 1987; Nihoul *et al.*, 1993; Hopcroft and Day, 2013; Cai *et al.*, 2014; Grebmeier *et al.*, 2015). The Siberian shelves (i.e. Kara, Laptev, and East Siberian Sea) and the Beaufort Sea (Mackenzie Shelf) constitute “interior shelves” and are highly influenced by exchanges with other shelves and freshwater inputs. The Canadian Archipelago represents an “outflow shelf” where Arctic water is exported via Hudson Bay and Baffin Bay to the Atlantic Ocean. In the deep central basin of the Arctic Ocean, waters of the Canada Basin or Beaufort Gyre are separated from the Eurasian Basin by the surface transpolar drift. Strong seasonal atmosphere–ocean interaction (e.g. changes in Arctic Dipole Anomaly; Ogi and Wallace, 2012; Overland *et al.*, 2012), sea ice production and melting (e.g. associated with Arctic Sea Ice Oscillation; Frey *et al.*, 2014a, 2015), lateral transports of water (Coachman, 1993; Danielson *et al.*, 2014), and freshwater inputs dictate the physical setting of the Arctic and its biological and biogeochemical characteristics.

The geographic scope of this review encompasses the Arctic Ocean shelves (i.e. Barents, Kara, Laptev, East Siberian, Chukchi, Beaufort, and Canadian Archipelago seas) and central basin (i.e. Canada and Eurasian Basin), but does not extend past the gateways of the Arctic Ocean to the Greenland, Iceland, Norwegian, and Bering seas, and Hudson and Baffin bays.

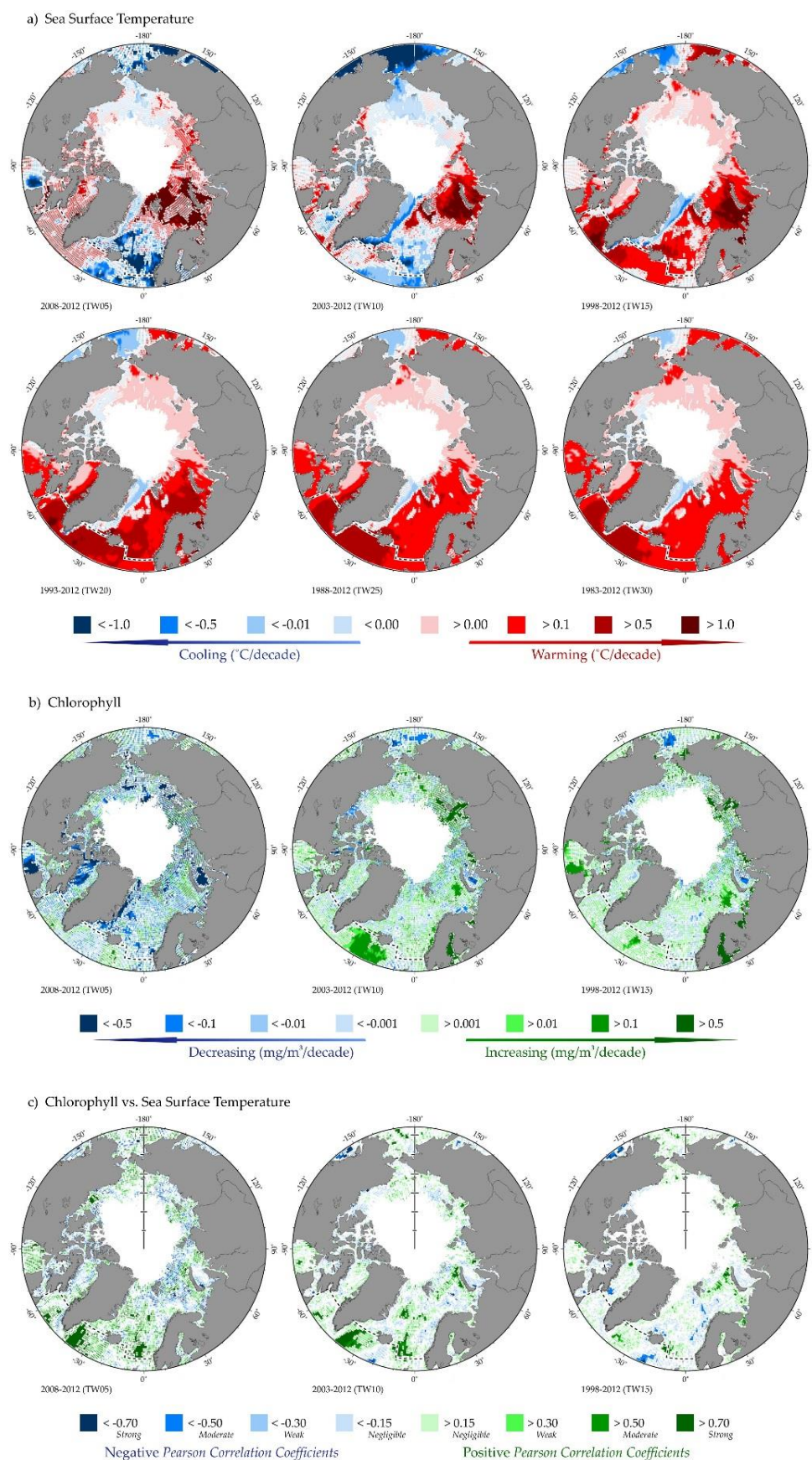


Figure 3.3. Annual trends in the Arctic Ocean region sea surface temperature and chlorophyll for each of the standard IGMETS time-windows. See “Methods” chapter for a complete description and methodology used.

3.3 Trends in the Arctic Ocean

3.3.1 Pan-Arctic Ocean sea ice and hydrological changes

The synergistic interactions among atmospheric warming, pressure changes associated with the Arctic Dipole Anomaly, air–sea interaction, and Arctic amplification (e.g. the drivers of pan-Arctic change; Holland and Bitz, 2003; IPCC, 2007, 2014; Serreze *et al.*, 2007; Serreze and Stroeve, 2009; Stroeve *et al.*, 2014) have brought about an Arctic-wide reduction in sea ice extent and thickness, especially during the last decade (Polyakov *et al.*, 2012; Lindsay and Schweiger, 2015). The loss of multiyear ice and summer sea ice has been accompanied by earlier melt onset in spring and later freeze-up in autumn (Stroeve *et al.*, 2012; Parkinson, 2014; Frey *et al.*, 2015; Wood *et al.*, 2015). Summer sea ice concentrations have declined in most Arctic marginal seas (Stroeve *et al.*, 2014), particularly in areas where multiyear sea ice used to prevail. In the central Arctic, annual mean sea ice thickness has decreased by 65% from 3.59 to 1.25 m since 1975 (Lindsay and Schweiger, 2015). As noted by Wood *et al.* (2015), the primary regulation of the upper ocean environment has shifted from a once stable sea ice-dominated system (Kwok and Unstersteiner, 2011) toward a system more sensitive to variable meteorological forces, especially wind and waves, and to cloud-cover-mediated radiation (Kay *et al.*, 2008; Perovich and Polashenski, 2012; Jeffries *et al.*, 2013; Timmermans, 2015; Wang *et al.*, 2015).

Analysis of sea surface temperature from available gridded satellite data indicates that over 85% (79% at $p < 0.05$) of the Arctic Ocean has warmed over the past 30 years (Table 3.1, Figure 3.2). This warming trend has been sustained in the Chukchi, Barents, and Kara seas, and in Baffin Bay and Davis Strait (Figure 3.3a). Of the limited number of sustained field observations in the Arctic, several time-series sites in the Barents Sea (i.e. Fugløya-Bjørnøya North, Fugløya-Bjørnøya South, Vardø-Nord North, and Vardø-Nord South) exhibit similar trends over the past 15–30 years. Across much of the central basins and several of the marginal seas of the Arctic, there are insufficient data to establish trends due primarily to cloud cover and sea ice extent. At the periphery of the Arctic Ocean, warming has been observed in the Greenland–Iceland–Norwegian (GIN) seas, whilst modest regional cooling has been observed in the Bering

Strait and in the Fram Strait in the region of the outflow from the central Arctic Basin.

Over shorter time-scales, regional variability of the coupled atmosphere–ocean system does not show ubiquitous warming trends within the Arctic Ocean. In the Chukchi Sea, modest cooling is observed over the past ten years or so (Wood *et al.*, 2015) (Figure 3.3a). However, this appears to relate to a shift in the Arctic Dipole (and its related wind field) in 2012 that allowed sea ice to persist in the Chukchi Sea longer during summer despite a record-low sea ice extent for the pan-Arctic. Fluctuations in regional wind fields also contribute to gateway flows through the Bering Strait (Coachman, 1993; Danielson *et al.*, 2014) that, in turn, impact the upwelling and transport of nutrient-rich Pacific water into the Arctic (Coachman and Shigaev, 1992; Nihoul *et al.*, 1993; Hopcroft and Day, 2013). In the Barents Sea, two out of the four longer-term time series show modest cooling. These examples illustrate the complex short-term and longer-term feedbacks operating in the Arctic Ocean.

The warming is also likely to have been accompanied by salinity changes, with a freshening of the polar mixed layer associated with increased sea ice melt and freshwater inputs. While significant freshening has been observed over the past 30 years in the periphery of the Arctic (e.g. Baltic Sea and near Iceland), lack of sustained observations precludes any summary of salinity changes in the Arctic Ocean itself. In the Barents Sea, four time-series sites (i.e. Fugløya-Bjørnøya North, Fugløya-Bjørnøya South, Vardø-Nord North, and Vardø-Nord South) show increased salinity over the past 15–30 years, presumably reflecting the influence of increased Atlantic water in the surface ocean (Table 3.1, Figure 3.4). This mixture of trends underscores the regional complexities in surface stratification, dictated by a balance of buoyancy input, freshwater inflow, and mixing processes (Tremblay and Gagnon, 2009; Carmack and McLaughlin, 2011; Popova *et al.*, 2012).

3.3.2 Sea surface chlorophyll and primary production in the Arctic Ocean

Observations of chlorophyll biomass derived from MODIS and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) in the Arctic Ocean during 1998–2012 are limited by the presence of clouds and sea ice cover in the region. During 1998–2010, cloudiness has increased,

Table 3.1. Relative spatial areas (% of the total region) and rates of change within the Arctic Ocean region that are showing increasing or decreasing trends in sea surface temperature (SST) for each of the standard IGMETS time-windows. Numbers in brackets indicate the % area with significant ($p < 0.05$) trends. See “Methods” chapter for a complete description and methodology used.

Latitude-adjusted SST data field surface area = 10.6 million km ²	5-year (2008–2012)	10-year (2003–2012)	15-year (1998–2012)	20-year (1993–2012)	25-year (1988–2012)	30-year (1983–2012)
Area (%) w/ increasing SST trends ($p < 0.05$)	59.9% (22.1%)	46.0% (26.6%)	83.0% (66.2%)	83.8% (74.3%)	86.5% (75.0%)	85.3% (79.2%)
Area (%) w/ decreasing SST trends ($p < 0.05$)	40.1% (13.6%)	54.0% (27.2%)	17.0% (7.7%)	16.2% (6.8%)	13.5% (5.5%)	14.7% (7.4%)
> 1.0°C decade ⁻¹ warming ($p < 0.05$)	17.6% (12.9%)	5.4% (5.4%)	4.9% (4.9%)	0.8% (0.8%)	0.2% (0.2%)	0.1% (0.1%)
0.5 to 1.0°C decade ⁻¹ warming ($p < 0.05$)	9.3% (3.9%)	8.3% (8.0%)	9.8% (9.8%)	17.2% (17.2%)	4.4% (4.4%)	1.8% (1.8%)
0.1 to 0.5°C decade ⁻¹ warming ($p < 0.05$)	20.5% (4.7%)	15.7% (8.9%)	29.4% (25.4%)	24.9% (24.3%)	37.0% (36.7%)	38.6% (38.5%)
0.0 to 0.1°C decade ⁻¹ warming ($p < 0.05$)	12.7% (0.5%)	16.6% (4.3%)	39.0% (26.2%)	40.9% (32.1%)	44.9% (33.6%)	44.8% (38.8%)
0.0 to -0.1°C decade ⁻¹ cooling ($p < 0.05$)	15.6% (1.8%)	28.4% (8.8%)	11.0% (2.6%)	12.9% (4.0%)	11.8% (4.0%)	12.9% (5.9%)
-0.1 to -0.5°C decade ⁻¹ cooling ($p < 0.05$)	11.4% (3.0%)	19.7% (12.8%)	4.9% (3.9%)	3.3% (2.7%)	1.7% (1.4%)	1.7% (1.4%)
-0.5 to -1.0°C decade ⁻¹ cooling ($p < 0.05$)	6.7% (3.4%)	4.8% (4.5%)	1.1% (1.1%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)
> -1.0°C decade ⁻¹ cooling ($p < 0.05$)	6.3% (5.4%)	1.1% (1.1%)	0.1% (0.1%)	0.0% (0.0%)	0.0% (0.0%)	0.0% (0.0%)

Table 3.2. Relative spatial areas (% of the total region) and rates of change within the Arctic Ocean that are showing increasing or decreasing trends in phytoplankton biomass (CHL) for each of the standard IGMETS time-windows. Numbers in brackets indicate the % area with significant ($p < 0.05$) trends. See “Methods” chapter for a complete description and methodology used.

Latitude-adjusted CHL data field surface area = 10.7 million km ²	5-year (2008–2012)	10-year (2003–2012)	15-year (1998–2012)
Area (%) w/ increasing CHL trends ($p < 0.05$)	25.7% (1.8%)	56.5% (14.3%)	60.8% (21.7%)
Area (%) w/ decreasing CHL trends ($p < 0.05$)	74.3% (30.2%)	43.5% (9.0%)	39.2% (8.3%)
> 0.50 mg m ⁻³ decade ⁻¹ increasing ($p < 0.05$)	7.1% (1.0%)	10.1% (5.8%)	9.7% (7.2%)
0.10 to 0.50 mg m ⁻³ decade ⁻¹ increasing ($p < 0.05$)	11.0% (0.7%)	20.9% (6.8%)	20.3% (9.8%)
0.01 to 0.10 mg m ⁻³ decade ⁻¹ increasing ($p < 0.05$)	6.7% (0.1%)	22.6% (1.6%)	26.0% (4.5%)
0.00 to 0.01mg m ⁻³ decade ⁻¹ increasing ($p < 0.05$)	0.9% (0.1%)	3.0% (0.0%)	4.8% (0.2%)
0.00 to -0.01mg m ⁻³ decade ⁻¹ decreasing ($p < 0.05$)	0.9% (0.0%)	2.9% (0.1%)	4.2% (0.1%)
-0.01 to -0.10 mg m ⁻³ decade ⁻¹ decreasing ($p < 0.05$)	9.6% (0.5%)	20.7% (1.9%)	23.1% (3.8%)
-0.10 to -0.50 mg m ⁻³ decade ⁻¹ decreasing ($p < 0.05$)	31.0% (10.7%)	15.4% (4.9%)	9.9% (3.4%)
> -0.50 mg m ⁻³ decade ⁻¹ decreasing ($p < 0.05$)	32.8% (19.0%)	4.4% (2.1%)	2.0% (1.0%)

leading to reduced incoming solar radiation across the pan-Arctic region (Belanger *et al.*, 2013). In addition, satellite retrieval algorithms of chlorophyll are confounded by the signals of river turbidity in coastal regions (Demidov *et al.*, 2014), chlorophyll maxima deeper than the optical depth of satellite sensor capabilities (Ardyna *et al.*, 2013), and the contribution of coloured dissolved organic material (CDOM) to assessment of chlorophyll *a* biomass (Siegel *et al.*, 2005). This latter confounding signal is of particular importance to Arctic marginal seas where substantial riverine CDOM or coloured detrital materials are supplied from the Arctic watersheds.

Given the above caveats, chlorophyll biomass has increased during 1998–2012 in over 60% (22% at $p < 0.05$) of the Arctic Ocean, and especially over continental margins (Table 3.2, Figure 3.3b). This finding is consistent with other studies showing increases in Arctic Ocean chlorophyll biomass (Arrigo *et al.*, 2008, 2012, 2014; Pabi *et al.*, 2008; Arrigo and van Dijken, 2011; Ardyna *et al.*, 2014). More recently, Frey *et al.* (2014b) report higher chlorophyll biomass in 2014 relative to mean values in 2003–2013. As we show in Figures 3.3b, 3.4b, and 4.4c, the largest increases in chlorophyll biomass occurred in the Laptev, Kara, and Barents seas, with this finding similar to studies of Petrenko *et al.* (2013) and Frey *et al.* (2014). These longer-term trends in chlorophyll biomass appear consistent with global ocean increases over the past 20–50 years shown by McQuatters-Gollop *et al.* (2011) (in contrast to declines in marine phytoplankton reported by Boyce *et al.*, 2010 using Secchi disk and other data). The seasonal timing of the annual phytoplankton bloom has become earlier (Kahru *et al.*, 2010), and there is evidence for an autumn bloom now occurring in the Arctic marginal seas (Ardyna *et al.*, 2014). Early satellite studies of the Bering Sea also showed evidence of an autumn bloom (Müller-Karger *et al.*, 1990), with either the Arctic now experiencing similar phenomena to the Bering Sea or increased observations in the Arctic have simply revealed the occurrence of a pre-existing seasonal phenomenon.

Over the past five years (2008–2012), chlorophyll biomass in the marginal seas decreased over 74% (30% at

$p < 0.05$) of the Arctic Ocean (Figures 3.3b, 3.4b, and 3.4c; Table 3.2). The causes for this decline in marine phytoplankton are uncertain. It may be related to reduced solar radiation due to increased cloudiness (Belanger *et al.*, 2013), or deepening of the chlorophyll maximum (Monier *et al.*, 2014). For example, Bergaron and Tremblay (2014) have shown a deepening of the nitracline and subsurface chlorophyll maximum, with diatoms consuming nutrients over a greater water depth. Light and nutrient availability in the Arctic Ocean appears to be one of the primary drivers of marine phytoplankton biomass and primary production (Popova *et al.*, 2010).

Challenges remain in establishing trends in marine phytoplankton abundance, depth-integrated chlorophyll concentration, and rates such as primary production in the Arctic Ocean. For example, Petrenko *et al.* (2013) suggest that the Barents and Greenland seas are the most productive in the Arctic, with the East Siberian and Chukchi seas the least productive. This satellite-derived finding contrasts markedly with evidence that the highest rates of *in situ* primary production (Müller-Karger *et al.*, 1987; Walsh *et al.*, 1989; Cota *et al.*, 2004; Arrigo *et al.*, 2012) and net community production (from inorganic nutrient and dissolved inorganic carbon changes; Bates and Mathis, 2009; Codispoti *et al.*, 2013) in the Arctic are found in the Chukchi Sea, with the Barents Sea a close second (Dalpadado *et al.*, 2014). What remains consistent is that the Arctic marginal seas are productive (Müller-Karger and Alexander, 1987; Müller-Karger *et al.*, 1987, 1990; Walsh *et al.*, 1989; Hill and Cota, 2005; Arrigo *et al.*, 2014; Ulfsbo *et al.*, 2014) compared to the highly oligotrophic central basins (English, 1961; Moran *et al.*, 1997; Wheeler *et al.*, 1996; Lalande *et al.*, 2014b).

The loss of sea ice will also affect the standing stocks of sea ice algae, their rates of primary production, and their importance to the marine biochemical cycles of the Arctic (Legendre *et al.*, 1992). Dupont (2012) estimates that sea ice biology contributes about 7.5% of the total primary production for the entire Arctic Ocean, with declining sea ice extent presumably reducing the contribution to carbon and nutrient cycling in the Arctic (Boetius *et al.*, 2014).

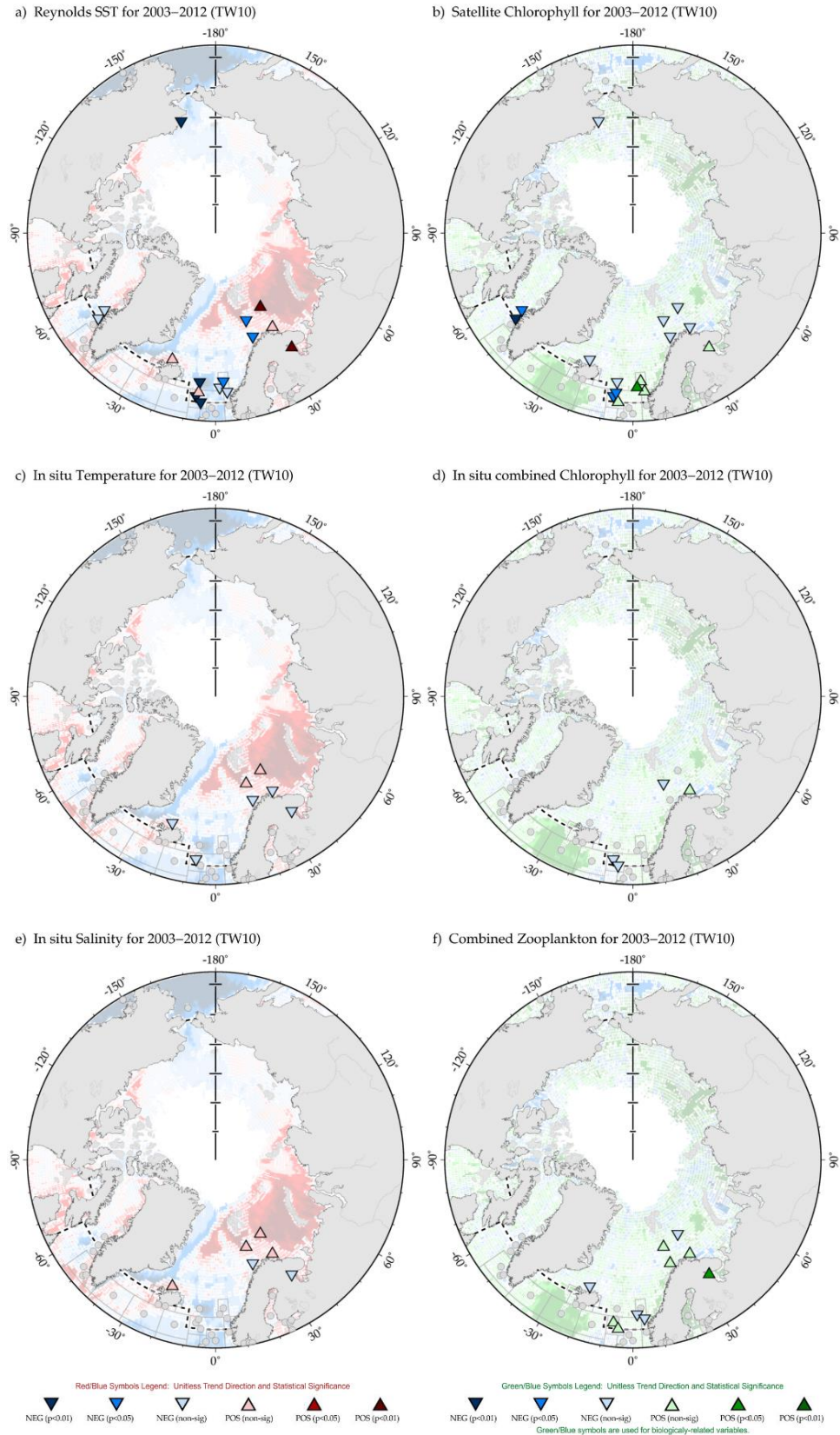


Figure 3.4. Map of Arctic Ocean region time-series locations and trends for select variables and IGMETS time-windows. The Arctic Ocean region is defined in the Figure 3.2 caption. Upward-pointing triangles indicate positive trends; downward triangles indicate negative trends. Gray circles indicate time-series site that fell outside of the current study region or time-window. Additional variables and time-windows are available through the IGMETS Explorer (<http://IGMETS.net/explorer>). See “Methods” chapter for a complete description and methodology used.

3.4 Zooplankton changes

The response of zooplankton to the physical and biological changes occurring in the Arctic is mixed and difficult to assess due to limited time-series observations. Over the past ten years, zooplankton appear to have increased in the White Sea (Usov *et al.*, 2013) and in the Barents Sea, the latter often concomitant with surface warming, increased chlorophyll biomass, and primary production (Dalpadado *et al.*, 2014). Such increases in primary production are also observed in the Fram Strait adjacent to the Barents Sea (Cherkasheva *et al.*, 2014). Over longer time-scales (15+ years), zooplankton appear to have declined at three of the four Barents Sea time-series sites and at the White Sea site. Unfortunately, other concomitant ecological data (e.g. diatom, dinoflagellate, and nutrient concentrations) were lacking from these sites.

Elsewhere on the Siberian shelves and central basins of the Arctic, ecological data are scarce, making it difficult to assess trends. However, in the Chukchi Sea, Ershova *et al.* (2015) report a significant increase in large copepod biomass (primarily *Calanus glacialis* and other calanid taxa) between 1946 and 2012, concomitant with longer-term warming. Of note is a more recent decline in copepod biomass (2004–2012) that accompanies the modest cooling of the region and a decline in primary production (Lee *et al.*, 2013).

3.5 Conclusions

In general, the surface Arctic Ocean has been steadily warming over the past 30 years. Chlorophyll biomass, as determined by satellite observations, has increased slightly over the past 15 years. The complexity of the Arctic marginal seas and the central basin settings coupled with a scarcity of *in situ* data only allows us to superficially assess biogeochemical and biological community changes across the pan-Arctic.

Table 3.3. Time-series sites located in the IGMETS Arctic Ocean subarea. Participating countries: Denmark (dk), Faroe Islands (fo), Iceland (is), Norway (no), Russia (ru), United Kingdom (uk), and United States (us). Year-spans in red text indicate time series of unknown or discontinued status. IGMETS-IDs in red text indicate time series without a description entry in the Annex A1.

No.	IGMETS-ID	Site or programme name	Year-span	T	S	Oxy	Ntr	Chl	Mic	Phy	Zoo
1	dk-10101	Hellefiske Bank – S1 (West Greenland)	1950–1984 (?)	X	-	-	-	-	-	-	X
2	dk-10102	Sukkertop Bank – S2 (West Greenland)	1950–1984 (?)	X	-	-	-	-	-	-	X
3	fo-30101	Faroe Islands Shelf (Faroe Islands) <i>see North Atlantic Annex (A2)</i>	1991– present	X	-	-	X	X	-	-	X
4	fo-30102	Norwegian Sea Transect – North (North Faroe Islands)	1990– present	X	-	-	-	X	-	-	X
5	fo-30103	Norwegian Sea Transect – South (North Faroe Islands)	1990– present	X	-	-	-	X	-	-	X
6	is-30101	Siglunes Transect (North Iceland)	1952– present	X	X	-	-	X	-	-	X
7	no-50101	Svinøy Transect – East (Norwegian Sea)	1994– present	-	-	-	-	X	-	-	X
8	no-50102	Svinøy Transect – West (Norwegian Sea)	1994– present	-	-	-	-	X	-	-	X
9	no-50201	Fugløy-Bjørnøya Transect – North (Western Barents Sea)	1990– present	X	X	-	-	X	-	-	X
10	no-50202	Fugløy-Bjørnøya Transect – South (Western Barents Sea)	1990– present	X	X	-	-	X	-	-	X
11	no-50301	Vardø-Nord Transect – North (Central Barents Sea)	1990– present	X	X	-	-	X	-	-	X
12	no-50302	Vardø-Nord Transect – South (Central Barents Sea)	1990– present	X	X	-	-	X	-	-	X
13	ru-10101	Kartesh D1 (White Sea)	1961– present	X	X	-	-	-	-	-	X
14	uk-40101	SAHFOS-CPR A01 (Norwegian Sea)	1958– present	-	-	-	-	X	-	X	X
15	uk-40114	SAHFOS-CPR B04 (Southern Norwegian Sea)	1958– present	-	-	-	-	X	-	X	X
16	us-50604	EMA-4: Chukchi Sea (Chukchi Sea)	2003– present	X	X	-	X	X	-	-	-

3.6 References

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