Chapter 5 The Underwater Light Climate in Kongsfjorden and Its Ecological Implications



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Abstract Due to its Arctic location at 79°N, Kongsfjorden in Svalbard experiences strong seasonality in light climate, changing from polar night to midnight sun. Sea ice conditions and the optical properties of seawater further modify the amount and the spectral composition of solar radiation penetrating into the water column, thus defining the underwater light climate in Kongsfjorden. Light represents one of the major shaping factors for the entire marine ecosystem. A number of studies focusing on implications of the underwater light for marine organisms have been

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conducted in Kongsfjorden, generating diverse datasets on seawater optical properties, scattered over time and space. This review synthesizes the fragmentary information available from the literature as well as presenting some unpublished data, and discusses the underwater light climate and its main controlling factors in Kongsfjorden. Furthermore, we provide a short synopsis about the relevance of light for different components of an Arctic marine ecosystem, exemplified by studies carried out in Kongsfjorden. Due to its year-round accessibility and its high-Arctic location, Kongsfjorden has become a prime fjord for studying how the strong seasonal changes in light availability, ranging from polar night to midnight sun, affect marine life with respect to primary production, behavioural aspects and synchronization of growth and reproduction.

Keywords Arctic · Svalbard · PAR · UVR · Optical properties · Marine ecosystem

5.1 Introduction

Located in the Arctic at 79°N on the west coast of Svalbard Archipelago, Kongsfjorden is influenced by marine- and land-terminating glaciers (Fig. 5.1). Due to the proximity of the West Spitsbergen Current (WSC), warm and saline Atlantic Water is regularly advected into the fjord throughout the year (Cottier et al. 2007). Furthermore, little landfast sea–ice has been observed in Kongsfjorden during the past decade (Pavlova et al., Chap. 4), which is largely associated with an increase of northward heat flux in the WSC and a consequent warming of West Spitsbergen fjords (Cottier et al. 2007; Spielhagen et al. 2011; Pavlov et al. 2013). This change has affected the underwater light climate and has many biological and ecological implications, such as, increasing exposure of pelagic microalgae to high irradiances

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Fig. 5.1 Kongsfjorden, Svalbard. Location of common observation sites: Hansneset (HN), Nansen Bay (NB), Old pier (OP, which is the closest location to the Kings Bay Marine Laboratory), Brandal (BR), London (L), EPOCA mesocosm experiment (E), mooring stations M1 and M2 (2010–present) as well as oceanographic stations KB0 to KB7. Satellite image is a composite of two Landsat 8 satellite scenes taken on 19 and 30 August 2013. (Credits: Norwegian Polar Institute and USGS)

(Leu et al. 2016; Wiencke and Hop 2016) and shifts of kelps to shallower depths (Bartsch et al. 2016).

The strong seasonality of the light climate in Kongsfjorden, alternating from polar night to midnight sun, is characteristic of Arctic marine environments. In addition, the variability of cloud cover (Maturilli et al., Chap. 2) and sea ice cover with snow (Pavlova et al., Chap. 4) at different time scales are important factors defining the amount and spectral composition of light reaching the upper water column. As a water body, Kongsfjorden is also a dynamic system, characterized by an estuarine circulation, water mass exchange with the adjacent West Spitsbergen shelf, processes of sea ice formation and melting, input of local run-off and glacial meltwater introducing inorganic and organic matter into the system (Svendsen et al. 2002), and phytoplankton blooms at diverse times and locations. Together, these factors result in a complex underwater light climate with high variability in time and space (e.g. Hanelt et al. 2001, 2004; Hegseth et al., Chap. 6).

While Kongsfjorden is the site of considerable research efforts (e.g. Wiencke and Hop 2016), one challenge of particular relevance for studies of the underwater light climate is a lack of coordination and standardization of methods. Despite the wealth of multidisciplinary data from this Arctic fjord system, there is a need for

both targeted and comprehensive studies addressing the optical properties and the underwater light climate in Kongsfjorden in a systematic way. So far, most of the available optical data are by-products from biologically motivated studies (e.g. Hanelt et al. 2001, 2004; Wiencke et al. 2004, 2006; Leu 2006; Leu et al. 2006a, b, 2016; Volent et al. 2007; Sakshaug et al. 2009; Pavlov et al. 2014; Cohen et al. 2015; Berge et al. 2015a; Taskjelle et al. 2016) at various sites in this fjord (Fig. 5.1).

This review compiles the fragmentary information available (both published and unpublished) on underwater irradiance, absorption, scattering and diffuse attenuation coefficients, and identifies the most important steering factors for seasonal and long-term variability. Moreover, it provides a brief overview as to the relevance of Arctic underwater light conditions for marine organisms and the marine ecosystem in Kongsfjorden. It can serve as a source of useful background information for future studies of processes that influence or are influenced by the underwater light climate in Kongsfjorden and other similar high-latitude marine environments.

5.2 The Underwater Light Climate in Kongsfjorden

5.2.1 Incoming Irradiance

Incoming irradiance (i.e. that reaching the bottom of the atmosphere) represents the boundary condition for the underwater light climate. In addition to strong seasonality, there is a large day-to-day variability in incoming light throughout the season as seen from daily averages of incoming downwelling irradiance in the photosynthetically active radiation (PAR) range. Mean daily irradiance in the PAR range (E_d (PAR)) values during the course of 2012 (Fig. 5.2) is based on measurements of the broadband downwelling planar irradiance (measured with CM11 and CMP21 pyranometers, Kipp & Zonen) over the wavelength range 370–695 nm, which is close to conventional PAR range of 400–700 nm (Maturilli et al., Chap. 2). Monthly means of E_d (PAR) for the period 1993–2013 are presented in Maturilli et al. (Chap. 2), providing insights on inter-annual variability of incoming PAR.

Daily averaged $E_d(PAR)$ values range from <5–10 µmol m⁻² s⁻¹ in October– February, to 720–740 µmol m⁻² s⁻¹ in June (Fig. 5.2). Based on episodic measurements taken between May and July (Table 5.1), maximum $E_d(PAR)$ measured above the water surface is usually below 1300 µmol m⁻² s⁻¹. During the period of midnight sun, $E_d(PAR)$ values in air during night range from 100 to 300 µmol m⁻² s⁻¹ in May (Leu et al. 2016; Table 5.1).

Daily cycles of $E_d(PAR)$ observed at Baseline Surface Radiation Network (BSRN) at the AWIPEV station in Ny-Ålesund (for details, see Maturilli et al., Chap. 2) under clear sky and overcast conditions demonstrate a strong influ-



Fig. 5.2 Mean daily irradiance in the PAR range (E_d (PAR)) values during the course of 2012 (data from Maturilli et al., Chap. 2). E_d (PAR) values in the range 370–695 nm were observed by a Baseline Surface Radiation Network (BSRN) pyranometer at the AWIPEV station, and converted to µmol m⁻² s⁻¹ with a conversion factor 4.6. (Morel and Smith 1974; McCree 1981)

ence of clouds (Fig. 5.3a). On a cloudy day, E_d (PAR) values at noon are only about half of those on a day with clear skies. The corresponding incoming downwelling spectral irradiance ($E_d(\lambda)$) was measured with TriOS Ramses ACC-VIS radiometers (TriOS Mess- and Datentechnik GmbH, Rastede, Germany) at the Sverdrup station on the same days (Fig. 5.3b; for methodological details, see Pedersen et al. 2015). In this case, the cloud cover acts as a neutral density filter over the PAR wavelength range, not significantly changing the spectral composition of light (Fig. 5.3b). However, cloud cover does significantly reduce the fraction of incoming solar energy that is outside the PAR wavelengths.

A detailed overview over longer time series of incoming downwelling ultraviolet radiation, $E_d(UV)$ can be found in Maturilli et al. (chap. 2). Data from episodic measurements of incoming $E_d(PAR)$ and $E_d(UV)$ available in the literature are presented in Tables 5.1, 5.2 and 5.3.

5.2.2 Underwater Irradiance in the PAR Range

Numerous light measurements have been carried out in Kongsfjorden over the past decades, employing a wide variety of methods and instruments. The following sections summarize the available information, and present also hitherto unpublished material.

		References		Hanelt (1998) and Hanelt et al. (1997)	Wiencke et al. (2000)		Bischof et al. (1998)		Hanelt et al. (2001)	Bischof et al. (1999)	Leu (2006)		Leu et al. (2006a)	Wiencke et al. (2006)	Fricke et al. (2001)	Leu, unpubl.
	During night (µmol m ⁻² s ⁻¹ if not	otherwise specified)									100-300			100-200		157 at midnight
Kongsfjorden	Daily maximum (µmol m ⁻² s ⁻¹ if not	otherwise specified)	$E_{\rm d}({\rm PAR})$ in air	1100			<1300			1130-1250	1200		700-1200	1200–1400	1249	894 at noon, cloudless
sured in I	1% depth	(m)	L	20–25	7	7	6.2- 24.2	6-24	6–38	20	30–50	23-46				37–48
t,Z)) mea	10% depth	(m)) in wate			4		3-12	3–19	01	≈ 20	12–23				18–24
on $(E_d(PAR)$	$K_{\rm d}({ m PAR})$	(m ⁻¹)	E _d (PAR,Z)		0.62		0.19–0.74		0.10-0.80	0.23	0.10-0.20					0.09-0.12
osynthetic active radiati		Sensor type		LI-COR LI-192	LI-COR LI-190, 192		LI-COR LI-190, 192		LI-COR LI-190, 192	LI-COR LI-190, 192	LI-COR LI-190, 193 spherical		LI-COR LI-190, 193 spherical	LI-COR LI-190	LI-COR LI-190	LI-COR 190, 193
Irradiances of photo		Location		Nansen Bay	Old pier		Old pier		Old pier	Kongsfjorden	Kongsfjorden		Kongsfjorden	Between old and new pier	Old pier 500 m east	Station KB3
Table 5.1	Period (month/	year)		Aug-Sep 1995	May-Jul 1997		Jun–Jul 1997		Mar-Oct 1996- 1998	May–Jul 1998	May–Jun 2004		May–Jun 2004	Jun 2004	May–Jul 2006	May 2008

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Jun 2008	Brandal	LI-COR LI-190, 192	0.09-0.19	12-26	24–51			Woelfel et al. (2014)
	Nansen Bay	LI-COR LI-190, 192	0.20-0.21	11.5	22-23			Woelfel et al. (2014)
	London	LI-COR LI-190, 192	0.19-0.27	9–26	17–24			Woelfel et al. (2014)
Jun–Jul 2010	EPOCA experiment	LI-COR LI-192	0.30-0.40	6-8	12–15	700-1500	>150	Schulz et al. (2013)
Jan 2014	Nansen Bay	IMO-PAR				0.000015		Cohen et al. (2015)
Jan 2015	Nansen Bay	QE Pro				0.000013		Cohen et al. (2015)
			Ed(PAR) ii	n sea ice				
Mar 2002	Kongsfjorden	FieldSpec spectrophotometer	6.14					60 cm ice with 15 cm snow;
								Winther et al. (2004)
Apr 2010	Old pier	Ramses spectrophotometer	<i>1.01–1.74</i>					15 cm without snow; Taskjelle et al. (2016)
Data are tak Used instru Biosciences radiometers spectromete reference, th including th $K_a(PAR)$ va	en from the cited r ments: LI-COR 1 , Lincoln, Nebrasl (TriOS Mess- an r (Ocean Optics, I ne site is listed as " te northwest and s lues for sea ice are	eferences; new data wer 90 cosine corrected fit ka, USA), the meteorol d Datentechnik GmbH Dunedin, Florida, USA) Kongsfjorden". If Nanss outheast parts of the fj s also included where a	re calculated at head air logical sens (, Rastede, (), IMO-PAR en Bay has t jord close tu vailable. Ke	I from K_{d} or LI-CC ors of th- Germany) C (In-situ been men o Ny-Åle: ep in miri	(PAR) val DR 192 u e BSRN : , FieldSp Marine C tioned in sund. For	ues provided in the orig nderwater sensors, LL- station (Baseline Surfa ec spectroradiometer (pptics, Perth, Western <i>A</i> prics, Perth, Western <i>A</i> in coher locations, it is cons • other locations, see F ial differences in $K_a(PA)$	ginal references or from raw d. COR 193 spherical underwi- ce Radiation Network), TriO Analytical Spectral Devices Anaralia). If no specific local Australia). If no specific local sidered to be the closer region ig. 5.1. In addition to water (R) values estimated based or (R) values estimated based or (R) values estimated based or (R) values estimated based or (ata (shown in italics). ater sensor (LI-COR S Ramses ACC-VIS Inc., USA), QE Pro tion was given in the around Ny-Ålesund, column information,

from cosine (LI-COR LI-192) and spherical (LI-COR LI-193) sensors



Fig. 5.3 (a) Examples of incident irradiance in the PAR range (E_d (PAR)) daily cycles in Ny-Ålesund on a clear day (25 May 2010) and an overcast day (28 May 2010). Data were obtained from Baseline Surface Radiation Network (BSRN) pyranometer measurements at the AWIPEV station and converted from W m⁻² to µmol m⁻² s⁻¹ by using a conversion factor of 4.6 (Morel and Smith 1974; McCree 1981); (b) Examples of incident downwelling spectral irradiance, $E_d(\lambda)$ in the range 370–695 nm at noon on the same dates, as well as their ratio. Data were obtained with TriOS Ramses ACC-VIS radiometers (TriOS Mess- and Datentechnik GmbH, Rastede, Germany) at Sverdrup station

5.2.2.1 Point and Episodic Measurements of Underwater Irradiance in the PAR Range

During summer, attenuation coefficients in water tend to be higher than during clear water conditions in spring (Hanelt et al. 2001) due to the high concentration of optically active substances (OAS), such as inorganic particles and phytoplankton. The diffuse attenuation coefficient of downwelling irradiance in the PAR range (K_d (PAR)), estimated from irradiance measurements with cosine (flat) sensors, ranged between

	Į	, ,	References		Hanelt (1998) and Hanelt et al.	(1661)	Wiencke et al.	(2000)	Bischof et al. (1998)	Hanelt et al.	(2001)	Hanelt et al. (2001)	Hanelt et al. (2001)	Bischof et al. (1999)	Leu (2006)): Leu et al. (2006b) 1^{-2}	(continued)
	UVA (W m ⁻² if	not otherwise	specified)			9–13			19					16.8–19.0	15-30.3		Daily $E_d(UVA)$ 900–1500 kJ m	
	UV (280–400 nm) (W m ⁻² if not	otherwise	specified)	$E_{\rm d}({\rm UVA})$ in air	14					300–370 nm: 16.8	Daily averages: 5.5–6.2							
		1% depth	(m)			4.0	5.1	(320 nm) 6.0				3-4	6–12		<28	20–29		
	10%	depth	(m)	in water			3.0					1.5–2.1	2.9–5.8		<15	5-15		
)		$K_{d}(UVA)$	(m ⁻¹)	$E_d(UVA,Z)$			0.73					1.1–1.5	0.4–0.8					
		(Sensor type		BSRN-station	Gröbel UV RM21	32 channel UV spectrometer		Gröbel UV RM21/BSRN	BSRN-station		Kruse UW spectrophotometer	Kruse UW spectrophotometer	Gröbel UV RM21	Ramses spectrophotometer			
			Location		Nansen Bay		Old pier		Old pier	NDSC-	building	Nansen Bay	Hansneset	Kongsfjorden	Kongsfjorden		Kongsfjorden	
	Period	(month/	year)		Aug–Sep 1995		May-Jul	1997	Jun–Jul 1997	Mar-Oct	1996– 1998	27 May 1998	7 July 1998	May–Jul 1998	May–Jun 2004		May–Jun 2004	

Table 5.2 Irradiances of UVA radiation $(E_d(UVA,Z))$ measured in Kongstjorden

145

References	Hanelt, unpubl.	60 cm ice with 15 cm snow; Winther et al. (2004)
UVA (W m ⁻² if not otherwise specified)	5.7	
UV (280-400 nm) (W m ⁻² if not otherwise specified)		
1% depth (m)	2-5 6-10	
10% depth (m)	1–2 3–5	sea ice
$K_{\rm d}({ m UVA})$ (m ⁻¹)	0–1.5 m: 0.95–1.98 1.5–5.4 m: 0.44–0.71	<i>E</i> _d (UVA) in 7.36
Sensor type	Kruse UW spectrophotometer 320-400 nm	FieldSpec spectroradiometer (>350 nm); NILU-UV irradiance meter (<350 nm)
Location	Brandal	Kongsfjorden
Period (month/ year)	1 Jul 2001	Mar 2002

Data are taken from the cited references; new data were calculated from $K_a(UVA)$ values provided in the original references or from raw data (shown in *italics*). Bremerhaven, Germany), TriOS Ramses ACC-VIS radiometers (TriOS Mess- and Datentechnik GmbH, Rastede, Germany), and FieldSpec spectroradiometer Analytical Spectral Devices Inc., Boulder, USA). If no specific location was given in the reference, the site is listed as "Kongsfjorden". If Nansen Bay has been mentioned in the references, it is considered to be the closer region around Ny-Ålesund, including the northwest and southeast parts of the fjord close to Used instruments are: the meteorological sensors of the BSRN station (Baseline Surface Radiation Network), the RM 21-UVA sensor of Gröbel (Germany), the AWI 32 channel UV underwater-spectrometer of ISITEC (Bremerhaven, Germany), the handheld Kruse underwater spectrophotometer (Kruse, Ny-Ålesund. For other locations, see Fig. 5.1. In addition to water column information, K_d(UVA) values for sea ice are also included where available

Table 5.2 (continued)

Table	111 14010 J.Z 041 11	VI O Y D LAMAITOIL					
Period (month/			$K_{\rm d}({ m UVB})$		1% depth		
year)	Location	Sensor type	(m ⁻¹)	10% depth (m)	(m)	UVB (W m^{-2})	References
			$E_{\rm d}({\rm UVB,Z})$ in	n water		$E_{\rm d}({\rm UVB})$ in air	
Aug-Sep 1995	Nansen Bay	Gröbel UV RM21		From 0.5 m no U ^T measureable	VB	0.14	Hanelt et al. (1997)
May–Jul 1997	Old pier	32 channel UV spectroradiometer	0.9		4.5 (305 nm)		Wiencke et al. (2000)
				3	5		
Jun–Jul 1997	Old pier	32 channel UV spectroradiometer	0.51–1.34	Max. transmittance			Bischof et al. (1998)
				2-5	3–9		
Mar-Oct 1996-98		32 channel UV spectroradiometer	0.35-0.75	3-7	6–13	Max. daily $E_{\rm d}({\rm UVB})$ 24 kJ m ⁻²	Hanelt et al. (2001)
May-Aug 1998	Nansen Bay	32 channel UV spectroradiometer				Max. daily $E_d(UVB)$ 50 kJ m ⁻²	Bischof et al. (2002)
Jun–Jul 1997	Nansen Bay	32 channel UV spectroradiometer			2.5-8.5	0.8–1.2	Karsten et al. (1999)
May–Jul 1998	Kongsfjorden	32 channel UV spectroradiometer				1.0–1.2	Bischof et al. (1999)
May-Jun 2004	Kongsfjorden	Ramses spectrophotometer		<7	<14	0.9-0.98	Leu (2006)
			For 310 nm: 0.33–0.49	5-7	12–14.5		
				5-7	9–14		

Table 5.3 As in Table 5.2 but for UVB radiation

(continued)

Period (month/			$K_{\rm d}({ m UVB})$		1% depth		
year)	Location	Sensor type	(m ⁻¹)	10% depth (m)	(m)	UVB (W m ⁻²)	References
May-Jun 2004	Kongsfjorden	Ramsesspectrophotometer				Daily dose 25–48 kJ m ⁻²	Leu et al. (2006b)
Jun 2004	Between old and new pier	ELUV dosimeter	0.67-1.28		3.6–6.9	0.018–0.045 (erythemal)	Wiencke et al. (2006)
May–Jul 2006	Old pier 500 m east mooring	Ramses spectrophotometer	At 0.5 m: 0.18			0.45	Fricke et al. (2001)
12 Jun-4 Jul 2001	Nansen Bay	UV-DNA dosimeter(cyclobutane- pyrimidine dimers, CPD)		CPD 4–8 m detectable			van de Poll et al. (2002)
			$E_{\rm d}({\rm UVB})$ in s	ea ice			
Mar 2002	Kongsfjorden	NILU-UV irradiance meter	9.21				60 cm ice with 15 cm snow; Winther et al. (2004)
Used instrun	nents are: the meteo	rological sensors of the BSRN station	(Baseline Surfa	ace Radiation Netw	ork), the RN	[21-UV sensor of C	Jröbel (RM-21, Gröbel

e | counting UV spectroradiometer (Isitec, Bremerhaven, Germany), and NILU-UV Irradiance Meter (Norwegian Institute for Air Research, Kjeller, Norway). In UV-Elektronik, Germany), the ELUV electric light dosimeter (AWI, Germany), the home-made dosimeters using calf thymus DNA, 32-channel single-photon addition to water column information, $K_a(UVB)$ values for sea ice are also included where available

Table 5.3 (continued)



Fig. 5.4 Example of differential water column stratification in August 2012 at a coastal site off Hansneset influenced by freshwater run-off causing an apparent 3-layer structure (named here as Surface, Intermediate, Deep) with regards to attenuation of E_d (PAR,Z) with depth. (Source: D. Hanelt, unpubl.)

0.09 m⁻¹ for clear water conditions and 0.80 m⁻¹ in turbid waters (Table 5.1). Inflow of turbid glacier water or sediment-loaded meltwater streams can cause a stratification in water turbidity (Hanelt et al. 2001), which may result in several layers with different light attenuation, as observed in August 2012 at Hansneset (K_d (PAR) = 0.49 m⁻¹ for 0–6 m depth, K_d (PAR) = 0.29 m⁻¹ for 6–13.5 m depth, and K_d (PAR) = 0.15 m⁻¹ for 13.5–25 m depth (Fig. 5.4; D. Hanelt, unpubl.). Based on literature data, the 10% depth transmittance of E_d (PAR) ranged between 3 and 26 m and the 1% depth ranged between 6 and 51 m (Table 5.1), with highest values at >50 m depth in waters not significantly influenced by meltwater from glaciers (Woelfel et al. 2014).

5.2.2.2 Temporal Variability of Underwater Irradiance in the PAR Range

Point measurements, such as those presented in Table 5.1 and Fig. 5.4, do not include information on diurnal changes, and reflect poorly seasonal and inter-annual variability and change of the light climate. In recent years, light loggers have been deployed in Kongsfjorden as part of various coastal benthic studies. Additionally, cosine corrected PAR sensors have been mounted on moorings deployed in the pelagic zone of Kongsfjorden since autumn 2009 (M1 and M2 locations, Fig. 5.1), providing a near continuous record of underwater irradiance in the PAR range E_d (PAR,Z). There, the sensor has been deployed at various depths (Z), from a minimum depth of 27 m in 2010–2011 to a maximum of 43 m in 2012–13 (Fig. 5.5b, c; F. Cottier, unpubl.). The E_d (PAR,Z) data were part of a multi-parameter suite of measurements collected from the moorings that have been used to support



Fig. 5.5 (a) Seasonal time series of incident downwelling irradiance, E_d (PAR) at noon in 2010–2011; Data was obtained with TriOS Ramses ACC-VIS radiometers (TriOS Mess- and Datentechnik GmbH, Rastede, Germany) at Sverdrup station. (b, c) Seasonal measurements of normalized mean daily irradiance, E_d (PAR,Z) (grey) and fluorescence, F (green) at two pelagic mooring sites in 2010–11 (b) and 2012–13 (c), respectively (M1 and M2; see Fig. 5.1). Moorings were equipped with Satlantic PAR sensors and Seapoint Chlorophyll fluorometers in addition to standard temperature and salinity sensors and current meter. Due to the extended period of deployment of both sensors and the problems associated with fouling of sensors and their calibration, the data were normalized to each year's maximum value. The occurrence of sea ice (shown as white rectangle) above the mooring was detected using acoustic Doppler current profiler (ADCP) data with the method of Hyatt et al. (2008)

oceanographic and ecological studies in Kongsfjorden since 2002. In addition, an underwater $E_d(PAR,Z)$ time series has been initiated close to Ny-Ålesund, to characterize the light climate of the coastal zone, within the COSYNA measuring network with online information available since autumn 2016 (https://www.awi.de/en/expedition/observatories/water-cosyna.html).

Although in the atmosphere the highest $E_d(PAR)$ at the terrestrial BSRN station is reached in mid-summer (Sect. 5.2.1; Kupfer et al. 2006; Maturilli et al. 2015, Chap. 2), the situation appears more complex underwater. The recent near-shore (Bartsch et al. 2016) and pelagic long-term measurements (Fig. 5.5b, c), show that the highest underwater $E_d(PAR,Z)$ in the years 2011 and 2013 occurred in mid-March to mid-April (neither site was ice-covered), followed by a temporary reduction of $E_{d}(PAR,Z)$ by >50% in May, and then another maximum in June, slightly lower than in March-April. The pattern is consistent between the 2 years and the different locations (coastal and pelagic), although the second peak in June was more pronounced at the pelagic site, compared to the coastal site (Bartsch et al. 2016). Based on measurements at Sverdrup station, the reduction in underwater $E_d(PAR,Z)$ in May in 2011 is not coincident with a decrease in incoming E_d (PAR) (Fig. 5.5a; J.-C. Gallet, unpubl.). The transient decrease of underwater $E_d(PAR,Z)$ in May is linked to phytoplankton blooms indicated by elevated fluorescence values (Fig. 5.5b, c), which is a typical timing for spring phytoplankton blooms in Kongsfjorden (Hegseth et al., Chap. 6). Lower values and an increasing variability during the summer months (from July onwards) may be caused by two factors: biofouling and meltwater inflow from the marine-terminating tidewater glaciers, leading to strongly variable and rather turbid water conditions from July through September (Zajaczkowski and Legezvnska 2001). Biofouling build-up on the sensors during long-term deployment obviously leads to increasingly greater underestimates of the available light. Thus, such time series provide valuable information on seasonal dynamics, whereas absolute values have to be treated with caution.

Besides the pronounced seasonal variability of underwater $E_d(PAR,Z)$, considerable short-term (day-to-day) variation is also apparent throughout the year (Fig. 5.5), owing to changes in both cloud cover and the optical properties of seawater. Underwater diurnal cycles of $E_d(PAR,Z)$ at shallow sites in Kongsfjorden were recently described in details by Sevilgen et al. (2014) and Leu et al. (2016). The spectral composition of irradiance also changes, depending on both solar angle and cloud cover. During night, however, at the lowest solar elevations, the differences between clear sky and cloudy conditions become subtle (Leu et al. 2016). In stands of macroalgae along rocky coasts, an additional variation of irradiance is caused by the algae, as shown by diurnal $E_d(PAR,Z)$ along a depth profile, measured both above and below the kelp canopy (I. Bartsch, unpubl.). Dense kelp beds at 2.5 and 5 m depth (Bartsch et al. 2016) only allowed a low transmission of light, varying between 3% and 29% depending on time of the day, turbidity, and wave exposure and currents, mechanically moving kelp forests.

While the incoming surface radiation at noon in May was approximately 5 times higher than at midnight, irrespective of clear or overcast conditions (Fig. 5.3a), the underwater day–night variation also depends on the content and properties of OAS, mainly non-algal matter delivered along with the glacial run-off, which often experiences diurnal variations in Svalbard during summer (e.g. Hodgkins 2001). At coastal sites (Hansneset) in the beginning of July 2012, the mean underwater E_d (PAR,Z) values at noon were 10–13 times higher than at midnight, but only 5–8 times higher at the end of July. This non-linear response pattern was likely caused by an increase of turbidity due to elevated concentration of non-algal matter during times of glacial melt, as irradiances steadily declined in July 2012 (Bartsch et al. 2016). The two contrasting situations are represented in Fig. 5.6a, b. Because turbidity normally increases even more during August and September (e.g. Paar et al. 2016), the day–night variation presumably drops even further. As to absolute



Fig. 5.6 Diurnal variation of irradiance in the PAR range (E_d (PAR,Z)) (10 min intervals) measured at several depths above and below the kelp forest off Hansneset during a day (7 July) with relatively clear waters (**a**) and a day (29 July) with more turbid waters (**b**) in 2012. Two irradiance loggers (Odyssey Dataflow Systems, Christchurch, New Zealand) calibrated against a cosine corrected underwater quantum sensor (LI-192, LI-COR Biosciences, Lincoln, Nebraska, USA) were mounted on each of four vertical racks which were fixed at the seafloor at 2.5, 5, 10 and 15 m depth (Bartsch et al. 2016). One logger was installed below the kelp canopy, approx. 20 cm (±10 cm) above the seafloor representing the "below canopy" situation, and another logger was mounted 90 cm (±10 cm) above the first logger, representing the "above canopy" situation. The diurnal variations in irradiance were possibly related to variable cloud cover but also influenced by tides; correlation to these factors was not achievable. Cleaning of the sensors surface took place approximately every 10 days except for the logger "4.2 m above canopy – sensor not cleaned" (black line, lower graph), which shows the considerable reduction in irradiance through sedimentation or fouling taking place within 3 weeks. Note the scale difference of the Y-axis between (a) and (b). (I. Bartsch, unpubl.)

values, E_d (PAR,Z) values at midnight in July at coastal sites (Hansneset) do not exceed 2.5 µmol m⁻² s⁻¹ at 15 m depth (Fig. 5.6).

Time series data presented in this section reflect the strong variability of $E_d(PAR,Z)$ in a natural system, and underline the importance of these types of measurements as providers of realistic *in situ* data for estimates of primary production, ecological interpretation and for monitoring the potential "darkening" of Kongsfjorden, an increase in light attenuation observed in other Sub-Arctic and Arctic coastal waters as a consequence of increased land run-off due to melting of glaciers (Aksnes et al. 2009).

5.2.3 Underwater Irradiance in the UV Range

Measurements of UVA (320–400 nm) and UVB (280–320 nm) radiation are summarized in Tables 5.2 and 5.3. Some of the references in tables only mention the available K_d (UVA) and K_d (UVB) values, whereas others provide corresponding UV penetration depths.

UV radiation is readily attenuated by snow and ice or absorbed in the upper water layer, especially during summer when relatively high concentrations of coloured or chromophoric dissolved organic matter (CDOM) and particulate matter are present. During the main productive period in spring, however, the 1% depth for $E_d(UVA,Z)$ was between 2 and 29 m, and for $E_d(UVB,Z)$ between 10 and 15 m on sunny days (Leu 2006). Diurnal measurements of $E_d(UVB,Z)$ and $E_d(UVA,Z)$ at 0.5 and 8 m depth, obtained between 29 April and 1 May 2008 close to Ny-Ålesund, showed maximum values for E_d (UVA,Z) at these two depths of 9 and 3.5 W m⁻², respectively, and 0.27 and 0.03 W m⁻² for E_d (UVB,Z) (Fig. 5.4 in Leu et al. 2016). The $E_d(UVA)$ in air was generally in the range of 9–19 W m⁻², with values up to 30 W m⁻² reported by Leu (2006) during late spring 2004. These higher values might partly be attributed to a wider wavelength range of the sensor used (290-400 nm), as opposed to the instruments at the meteorological BSRN station (300-370 nm). Values of K_d (UVA) are higher than K_d (PAR), and range from 0.73 up to 1.5 m⁻¹ in the Nansen Bay, resulting in a 10% depth of $E_d(UVA,Z)$ at coastal locations between 2 and 6 m depth, and a 1% depth between 3 and 12 m. Diurnal measurements in May 2008 confirmed that UVB absorption was stronger than UVA absorption between 0.5 and 8 m depth (Fig. 5.4 in Leu et al. 2016).

5.2.4 Light Climate During Polar Night

Knowledge about Arctic marine biological activities during polar night is very limited (Berge et al. 2015b) and only few studies have focused on underwater light climate (Berge et al. 2015a; Cohen et al. 2015). Although light levels during the polar night are not extreme *per se* in that they do resemble night light levels at lower latitudes, they

remain constant for prolonged periods during winter. Thus, it is not the low light levels in itself that affect organisms during the polar night, but the fact that the low light levels do not change (Berge et al. 2015b). Despite almost constant low atmospheric illumination for extended periods, light during polar night might still play a role as environmental cue for zooplankton species, as demonstrated from *in situ* observations and behavioural experimental studies in Kongsfjorden (Båtnes et al. 2015; Last et al. 2016). For the end of January, Cohen et al. (2015) reported incoming E_d (PAR) levels of 1.0– $1.5 \cdot 10^{-5}$ µmol m⁻² s⁻¹ over the day–night cycle, with a spectral maximum around 455 nm at solar noon. Further, modelling of the underwater light field in Kongsfjorden demonstrated a shift in wavelength maximum of transmitted light towards longer wavelengths, e.g. 465 nm at 10 m and 485 nm at 30 m (Cohen et al. 2015).

5.2.5 Attenuation of Light by Snow and Sea Ice in Kongsfjorden

When present, snow and sea ice strongly attenuate solar radiation, limiting its transmission into Kongsfjorden waters (Hamre et al. 2004; Winther et al. 2004; Taskjelle et al. 2016). Snow is an effective scattering medium, with low absorption in the visible spectrum, giving it its bright white appearance. While the absorption properties of sea ice and water are similar, sea ice causes much more scattering of light than liquid seawater (e.g. Hamre et al. 2004; Johnsen et al. 2009) due to air and brine inclusions. Data from Kongsfjorden show that 60 cm of bare sea-ice attenuates E_{d} (PAR) by about 80% (Winther et al. 2004). Snow-covered sea-ice typically transmits less than 1% of $E_d(PAR)$, and even less $E_d(UV)$ (Winther et al. 2004). The effective attenuation coefficients for $E_d(PAR)$ and $E_d(UV)$ of 60 cm of sea ice with 15 cm of snow are nearly an order of magnitude higher than those of the water column (Tables 5.1, 5.2 and 5.3). Thus, the extent and evolution of the sea-ice cover in Kongsfjorden strongly affects the availability of light for photosynthesis, especially during early spring, and protect algae in or under the ice from harmful UV and excessive PAR values (e.g. Vincent and Roy 1993). The coverage by landfast sea-ice in the inner part of the fjord, restricted by a virtual line between Brandal and Tønsneset, has been monitored since 2003 (see Gerland and Renner 2007 for details). Less ice has been recorded in recent years, especially since 2007 (Pavlova et al., Chap. 4), and most importantly this has left most of the optical observation sites (Fig. 5.1) virtually free of landfast sea-ice in spring during the last decade.

5.2.6 Optically Active Substances

Light absorption and scattering is affected not only by seawater and sea ice, but also by optically active substances (OAS). The main subgroups of OAS are CDOM and particulate matter (defined operationally as the material that retains on a filter of nominal pore size of 0.7 μ m) including algal pigments, and non-algal particles (matter). Below we summarize the limited knowledge of OAS in fjord waters and sea ice.

5.2.6.1 Optically Active Substances in Seawater

Several studies have been published that contain data on OAS in the water of Kongsfjorden (e.g. Carlsen et al. 2007; Volent et al. 2007; Pettersen et al. 2011; Pavlov et al. 2014). Average spectral absorption coefficient for CDOM ($a_{CDOM}(\lambda)$) from the fjord in June 2010 (Location E; Pavlov et al. 2014) is shown (Fig. 5.7), along with previously unpublished data on total particulate absorption ($a_p(\lambda)$) from several stations in Kongsfjorden in April 2014 (J. Meler, unpubl.). Absorption by CDOM was measured following Stedmon and Markager (2001), and particulate absorption was measured using a filter-pad technique according to Tassan and Ferrari (2002).

CDOM absorption in Kongsfjorden follows a characteristic exponential increase towards shorter UV wavelengths (e.g. Bricaud et al. 1981). Pavlov et al. (2014) reported $a_{\text{CDOM}}(375)$ values between 0.10 and 0.18 m⁻¹ in surface waters of Kongsfjorden, which is similar or slightly higher compared to $a_{\text{CDOM}}(375)$ of



Fig. 5.7 Absorption by chromophoric dissolved organic matter (CDOM), $a_{\text{CDOM}}(\lambda)$ and total absorption by particulate matter, $a_p(\lambda)$ in Kongsfjorden for the wavelength range 380–700 nm. CDOM data are from Pavlov et al. (2014) for marine waters in the fjord (location E, Fig. 5.1) and those influenced by presence of mycosporine-like amino acids (MAA). Data on $a_p(\lambda)$ are the average of 4 samples at surface, 5, 10 and 15 m depth collected at stations KB2, KB3, KB5, KB6, KB7 in April 2014. Spectra of $a_p(\lambda)$ are obtained using the method of Tassan and Ferrari (2002). For station locations, see Fig. 5.1. For reference, the absorption by pure water $a_w(\lambda)$ is also shown (Pope and Fry 1997)

0.10 m⁻¹ on average in the core of the WSC outside Kongsfjorden (cf. Granskog et al. 2012; Pavlov et al. 2015). Given that Atlantic Water and its mixing products have been dominant water masses in Kongsfjorden over the past decade, this indicates that Atlantic Water from WSC is an important source of CDOM in the fjord. At the same time, local production of marine CDOM in Kongsfjorden has also been documented and associated with bacterial activity (Pavlov et al. 2014) and with degradation of kelp tissue, which contains CDOM substances (Hulatt et al. 2009). Additionally, phytoplankton in Kongsfjorden may produce mycosporinelike amino acids (MAA), known as photoprotective compounds that are effective absorbers in some UV bands (Karsten 2008; Ha et al. 2012; Pavlov et al. 2014). In some cases, MAA-like absorption peaks appear in CDOM spectra and can increase absorption of UV and PAR in near-surface waters substantially (Fig. 5.7). The contribution of terrestrial CDOM, which is significant in many coastal environments (e.g. Babin et al. 2003), is believed to be low in Kongsfjorden. Pavlov et al. (2014) described the dominance of marine CDOM in surface waters of Kongsfjorden (in June–July 2010), as well as reported relatively low concentrations of dissolved organic carbon (DOC) below 90 µmol L⁻¹, which is low compared to other Arctic coastal waters with prominent terrestrial input of dissolved organic matter (Stedmon et al. 2011; Pavlov et al. 2016). This is most likely caused by sparse terrestrial vegetation and dominance of glacial melt with low fraction of dissolved organic matter.

The contribution of particulate matter to total attenuation is typically significant in glacial environments (Volent et al. 2007; Johnsen et al. 2009; Lund-Hansen et al. 2010; Murray et al. 2015; Holinde and Zielinski 2016). Particulate absorption is then dominated by non-algal particles (Fig. 5.7), while the main algal (phytoplankton) absorption peaks (at 440 and 675 nm) are not pronounced, as these measurements were made early in the season before phytoplankton biomass had developed. For the reference, the timing and magnitude of phytoplankton blooms in Kongsfjorden have been rather variable (for a summary, see Hegseth et al., Chap. 6). These observations are similar to other fjords influenced by glaciers (e.g. Lund-Hansen et al. 2010). Overall, particulate absorption coefficients are quite low in the outer parts of the fjord (stations KB2 and KB3 in Fig. 5.7), and increase towards the inner fjord (stations KB5 and KB6), where the contribution of non-algal matter (most likely coming from glacial meltwater) is significant (Fig. 5.1). Later in the season, large amounts of glacial run-off likely cause the absorption by non-algal material to be even higher (by order of magnitude), with effects on underwater light conditions.

Particulate matter in the water column is known to cause more scattering than absorption (Mobley 1994). Here we present vertical profiles of scattering coefficient at 555 nm, b(555), from a synoptic survey along the main fjord axis (Fig. 5.8; S. Sagan, unpubl.), measured with an ac-9 absorption and attenuation meter (WET Labs, Philomath, OR, USA; for details on methods and data processing, see Granskog et al. 2015). The gradient in b(555) along the fjord is pronounced with



Fig. 5.8 (a) Vertical profiles of total scattering coefficient at 555 nm, b(555) at 5 stations in Kongsfjorden, measured in July 2010; (b) Spectra of total absorption coefficient, $a(\lambda)$ averaged over top 10 m at the same stations; (c) Spectra of total scattering coefficient, $b(\lambda)$ averaged over top 10 m at the same stations. (S. Sagan, unpubl.)

highest scattering observed in the inner part of the fjord at station Kb5 (Fig. 5.8a). Corresponding spectra of both absorption and scattering coefficients, averaged over the top 10 m, show that scattering coefficients are 5–6 times higher than absorption coefficients across visible wavebands (Fig. 5.8b, c). For comparison, a higher ratio of scattering to absorption (ca. 12) across PAR wavelengths was reported for Kangerlussuaq fjord in Greenland (Lund-Hansen et al. 2010).

5.2.6.2 Optically Active Substances in Sea Ice

In sea ice, algae that can be found throughout the ice layer are particularly important. These algae quickly colonize new ice (thinner than 15 cm) in spring (Taskjelle et al. 2016) and continue to accumulate, increasing particulate absorption. In snowfree new ice in Kongsfjorden (Taskjelle et al. 2016), the presence of MAA compounds is apparent from absorption spectra with peaks at typical MAA absorption bands around 330–360 nm (cf. Pavlov et al. 2014), and MAA also make a significant contribution to the attenuation of UV radiation in sea ice. In the new ice described in Taskjelle et al. (2016), the absorption by particulate matter is slightly higher than that by CDOM, except at UV wavelengths when MAAs are produced. In thicker ice with snow cover, no indications of MAA absorption peaks have been found (M.A. Granskog and B. Hamre, unpubl.), which is most likely an effect of less E_d (UV) exposure due to high attenuation of UV radiation by snow and ice (Winther et al. 2004).

5.3 Underwater Light: Implications for Organisms and the Marine Ecosystem of Kongsfjorden

Underwater light is critical in many different ecological contexts, from phototrophic primary production of algae to visual orientation in predators. These topics have been a research topic in many studies performed in Kongsfjorden – and the major results are summarized in the following sections.

5.3.1 Light as Energy Source for Arctic Primary Producers: Challenges of Strong Seasonality and Consequences of Ongoing Changes

The pronounced seasonal changes in irradiance in Arctic waters and the generally low incoming radiation have strong implications for primary production and seasonal growth of marine phototrophs, consisting of phytoplankton, microphytobenthos and macroalgae (very sparse data only available on sea ice algae and phototrophic bacteria in Kongsfjorden).

In the pelagic realm, the bulk of annual new primary production takes place during a short time window in spring, with a strong peak in algal biomass concentrations providing the basis for the pelagic food web. Grazers that depend on phytoplankton as food supply for successful reproduction have adjusted their annual cycles to match this timing (Søreide et al. 2010; Varpe 2012). Light availability is the single most important factor controlling the timing of phytoplankton blooms, although other factors might play important roles as well (for details about the situation in Kongsfjorden, see Hegseth et al., Chap. 6). In Kongsfjorden, the phytoplankton bloom usually declines in late spring because of nutrient depletion (Hodal et al. 2012; Piquet et al. 2014; Hegseth et al., Chap. 6), in combination with grazing. The bloom as such may already cause some shading (see Fig. 5.5), but most importantly, light availability drops sharply in late spring/early summer caused by the onset of runoff from land and glacier melt, bringing large amount of particulate matter into the fjord. In the innermost part of the fjord, reduced light availability due to glacier meltwater run-off (Figs. 5.1 and 5.8) and sea ice affects the phytoplankton development already in early spring, resulting in lower biomass development and smaller size composition of the phytoplankton community (Piquet et al. 2014). During summer, pelagic primary production can continue, but is generally lower than in the spring, due to reduced availability of nutrients and light. The few published studies presenting data on phytoplankton in Kongsfjorden indicate primary production rates ranging between 27 and 180 g C m⁻² yr⁻¹ (e.g. Hop et al. 2002; Hodal et al. 2012). These values are within the range of those reported from the Barents Sea and Fram Strait region (see Hodal et al. 2012, and references therein), but higher than annual primary production reported from Young Sound, Greenland $(6-10 \text{ g C y}^{-1}; \text{Rysgaard and Nielsen 2006}).$

Even during wintertime, living vegetative phytoplankton cells have been found in Svalbard surface waters (Berge et al. 2015a; Vader et al. 2015; Kvernvik et al. 2018), although ambient radiation in Kongsfjorden during the polar night is too low to allow primary production (Kvernvik et al. 2018). Whereas details of their overwintering strategies are still to be resolved, it has been documented that Arctic benthic diatoms and perennial kelps utilize storage compounds (lipids, polysaccharides) to cope with polar winter conditions (Dunton 1990; Karsten et al. this volume).

Microphytobenthic communities in shallow waters are physiologically well adapted to fluctuating light conditions as well as to hydrological gradients and sediment characteristics (Karsten et al. 2009). Benthic diatoms dominate the shallow water sediments in Kongsfjorden, as reflected in high chlorophyll *a* (chl *a*) values of up to 317 mg m⁻², but the spatial heterogeneity is large (Woelfel et al. 2010). Daily microphytobenthic gross primary production in Kongsfjorden was estimated to range between 2 and 48 mmol $O_2 m^{-2} d^{-1}$ depending on site and applied model (Woelfel et al. 2010; Sevilgen et al. 2014), resulting in a gross production of 17–554 mg C m⁻² d⁻¹ (Woelfel et al. 2010).

For seaweeds in Kongsfjorden, the majority of annual biomass is probably also formed prior to mid-summer, and the bulk of it is composed of large brown algae of the order Laminariales (kelps), while bushy red algae (Rhodophyta) constitute the understory seaweeds (Bartsch et al. 2016, Hop et al. 2012, 2016; Karsten et al., Chap. 8). There are four biomass dominant species, which occur between 0 and ca. 20 m depths: *Laminara digitata, Saccharina latissima, Alaria esculenta* and *Saccorhiza dermatodea* (Hop et al. 2016). These kelps form new blades every spring and constituted a maximum of 9.5 m² of blade area per m² seabed at a depth of 2.5 m at the onset of summer in 2012. The maximum standing stock of seaweeds was 14.1 kg m⁻² fresh weight at 2.5 m, decreasing to 0.6 kg m⁻² fresh weight at 15 m depth in 2012–13 (Bartsch et al. 2016). This is the highest seaweed biomass recorded at an Arctic site and normally more characteristic for sub-Arctic to cold–temperate communities (e.g. Sharp et al. 2008).

Physiological studies of algae in Kongsfjorden have furthermore revealed low light compensation points (= irradiance at which gross photosynthesis equals respiration) of about 2–7 μ mol m⁻² s⁻¹. Photosynthesis in kelps was saturated at low light levels of 20–40 μ mol m⁻² s⁻¹, and microphytobenthic photosynthesis was half-saturated at 33 μ mol m⁻² s⁻¹ (Latala 1990; Karsten et al. 2006; Roleda et al. 2006; Sevilgen et al. 2014; Krüger 2016). These features constitute adaptations to the highly variable and often low light environment, which are a general characteristic of polar phototrophs (Glud et al. 2002; Gómez et al. 2009).

Climate warming causes changes in the light conditions in Arctic aquatic ecosystems (see Sect. 5.2): decrease in sea ice cover results in increased E_d (PAR,Z) in the water column; glacial melting processes and riverine run-off increase turbidity and reduce the light available for photosynthetic primary production later in the year. The strong decrease in sea–ice cover in Kongsfjorden is probably also one of the major factors behind the increase of seaweed biomass off Hansneset between 1996– 98 and 2012–13 (Bartsch et al. 2016). At the outer part of Kongsfjorden, where the community was dominated by crustose coralline algae in 1980, filamentous brown algae had become dominant by 1995, pointing to increased benthic primary productivity as a consequence of an overall more favourable light climate (Kortsch et al. 2012).

5.3.2 Light as Stress Factor: Adverse Effects of High Irradiance in the PAR ($E_d(PAR,Z)$) and UV Range ($E_d(UV,Z)$) on Arctic Primary Producers

Although light is necessary as an energy source for primary production, excessive levels of irradiance can also become detrimental to organisms. Primary producers, with their ability to efficiently collect PAR by means of their pigments, are particularly threatened. Of the incoming radiation, UV radiation has the greatest potential to affect organisms negatively due to both its high energy content, and the fact that these wavelengths are absorbed specifically by several important biomolecules, such as proteins and deoxyribonucleic acid (DNA). Due to the relatively high transparency of the water column in Kongsfjorden (except for the inner basin close to glaciers) during the peak production period in spring, irradiances might even become detrimental for organisms residing close to the sea surface. The considerable body of research on the impact of $E_d(UV,Z)$ especially on seaweeds of Kongsfjorden has been reviewed (see Bischof et al. 2006, and references therein), and will not be described in detail here. For over a decade, the effects of UV radiation on macroalgal ecology, physiology, biochemistry, cell biology and molecular biology have been studied in Kongsfjorden. Major insights include a reduced reproductive success because of the pronounced UV-susceptibility of early life history stages such as spores, gametes, gametophytes and juvenile seaweed stages (e.g. Wiencke et al. 2004, and references therein). The UV-susceptibility of kelp spores often determines the upper depth distribution of kelp species (e.g. Wiencke et al. 2006).

Ambient levels of E_d (PAR,Z) in the uppermost part of the water column in Kongsfjorden have been shown to decrease growth rates and affect the biochemical composition of phytoplankton communities (Leu et al. 2006a), decreasing their content of polyunsaturated fatty acids (PUFAs), and inducing the production of photoprotective pigments. Similar results were found in a controlled exposure of diatom cultures at two different depths *in situ* (Leu et al. 2016), however, no negative effects that could be attributed to UV radiation alone were reported. Similarly, a mesocosm study with a natural phytoplankton community, performed in summer 2001, showed no distinct negative effects of UVB (Wängberg et al. 2008). Benthic diatoms in Kongsfjorden are generally not affected by UV radiation, because most taxa avoid this waveband by physiological, biochemical and behavioural mechanisms, which include, for example, the synthesis and accumulation of MAAs or the capability of vertical migration into the upper sediments (Karsten et al. 2012).

5.3.3 Photoperiod as Environmental Signal for Seasonal Growth Patterns in Arctic Kelp Species

Besides the significance of daylength for providing light energy for growth and carbon allocation, photoperiod (daylength) is also a primary trigger for the regulation of seasonal growth and reproduction (Lüning 1989). For the Arctic, little information is available on the impact of photoperiod for the regulation of phytoplankton, microphytobenthos or seaweed growth and reproduction. One exception is the endemic Arctic kelp Laminaria solidungula, also present in Kongsfjorden (Hop et al. 2012; Fredriksen et al. 2014), which grows predominantly in winter (Chapman and Lindley 1980). The onset of growth is presumably regulated by an endogenous circannual growth rhythm and short photoperiods. This has been verified for temperate kelp species with a similar growth strategy (Lüning 1991; tom Dieck 1991). The onset of reproduction of L. solidungula and another Arctic brown algae, Saccorhiza dermatodea, is induced by short daylengths (Hooper 1984; Keats and South 1985; Henry 1987; tom Dieck 1989; Roleda 2016). Two other Arctic kelp species from Kongsfjorden (Saccharina latissima and Saccharina nigripes) are fully fertile only in autumn (I. Bartsch, pers. comm.), potentially indicating that their fertility is induced by short daylengths.

5.3.4 Visual Predation During Polar Night: Foraging at the Light Limit

For many animals, light is vital for visual predation (Kaartvedt et al. 1996; Torgersen 2001; Abrahamsen et al. 2010; Varpe et al. 2015). In Kongsfjorden, many organisms, including fish, seabirds, euphausiids (krill), amphipods, and copepods that are active and feeding throughout the year adapt their behavioural pattern according to the annual course of fluctuating light levels (Kraft et al. 2013; Båtnes et al. 2015; Berge et al. 2015a). Recent work from Kongsfjorden suggests that even low levels of atmospheric light (diffuse sunlight, moon, Aurora Borealis), during periods when a photoperiod of about 5 h is present (Cohen et al. 2015), may indeed play a role in predator-prey dynamics (Cronin et al. 2016; Last et al. 2016). For example, approximately half of the fish (Polar cod [Boreogadus saida], Atlantic cod [Gadus morhua], and haddock [Melanogrammus aeglefinus]) collected in trawls from Kongsfjorden in winter had stomachs at least half full, with mainly pelagic euphausiids prey, and for polar cod both euphausiids and calanoid copepods (Berge et al. 2015a). Likewise, the gut content of seabirds collected from Kongsfjorden in winter (Little auk [Alle alle], Brünnich's guillemot [Uria lomvia], and Black guillemot [Cepphus grylle]) showed evidence that the birds fed on euphausiids and amphipods (Berge et al. 2015a). Interestingly, lenses in the eyes of polar cod show adaptations for maintaining a focused visual image at low light levels, which is not the case for lenses of boreal Atlantic cod (Jönsson et al. 2014). Collectively, this

suggests that ambient light may play a variable role in winter feeding among fish (and perhaps seabird) species in Kongsfjorden, with Arctic species being better adapted to winter light levels and more recently established boreal species relying on other sensory modalities (Varpe et al. 2015).

The pelagic zooplankton in Kongsfjorden, preyed upon by fishes and seabirds, can likewise use available light even at the darkest times of the year. While conventional light meters are not sensitive enough to measure underwater light in the polar night (e.g. Table 5.1), Cohen et al. (2015) used measurements of diffuse skylight irradiances near Ny-Ålesund and measurements of inherent optical properties of seawater (such as spectral absorption and attenuation) from Kongsfjorden to model the underwater light field during the polar night. After weighting the spectrally-resolved light field by the spectral sensitivity of zooplankton visual systems, they determined that Arctic zooplankton (*Thysanoessa inermis* euphausiids and *Calanus* spp. copepods) could detect and utilize ambient light down to 20–30 m depth at midday.

5.3.5 Diel Vertical Migration of Zooplankton During Midnight Sun and Polar Night

Diurnal changes of incoming irradiance are known to cause synchronized diel vertical migration (DVM) in zooplankton. Zooplankton DVM occurs in all oceans of the world and in lakes, and involves a trade-off between increased foraging opportunities in surface layers and a reduced risk of predation at depth (Hays 2003). The phenomenon is generally found to be light-mediated (for reviews, see Hays 2003; Cohen and Forward 2009; Ringelberg 2009). The extreme variability in diurnal light-dark cycles in Polar Regions also has been shown to cause seasonal patterns in DVM (Wallace et al. 2010; Berge et al. 2014). Diel changes in irradiance are most pronounced during the intervening autumn and spring seasons. One would therefore anticipate little or no DVM during the summer and winter, whereas DVM in spring and autumn is likely to offer the greatest benefits (see e.g. Fischer and Visbeck 1993; Berge et al. 2014). One study from Kongsfjorden reported complete absence of synchronized migrations of zooplankton during midnight sun (Blachowiak-Samolyk et al. 2006). In contrast, Cottier et al. (2006) described - also based on data collected in Kongsfjorden - a conceptual model of asynchronous DVM during the Arctic summer, where each individual migrates according to its own needs rather than as part of a population, with the more typical synchronized mode of DVM reestablished as soon as the diel cycle of irradiation returns to a more distinct daynight cycle. Findings about DVM during the polar night are similarly diverse: whereas several studies have reported a complete lack of synchronized migrations of zooplankton during the polar night (e.g. Kosobokova 1978; Fischer and Visbeck 1993 from the Arctic; Cisewski et al. 2010 from Antarctica), Berge et al. (2009) presented the first evidence of synchronized migration pattern during the polar night in two Svalbard fjords, Kongsfjorden and Rijpfjorden (northern Svalbard). Wallace et al. (2010) provided further evidence of this by examining migration patterns from a continuous acoustic data series covering two annual cycles in Kongsfjorden and Rijpfjorden, addressing as well the impact of sea ice cover on this behaviour. Last et al. (2016) determined that the lunar cycle serves as a proximate cue for zooplankton DVM during polar night.

5.4 Future Directions for Studies of the Underwater Light Climate

The review work has pinpointed some essential knowledge gaps that can be of interest to study in the future. Geographically, waters near marine-terminating glaciers in Kongsfjorden have recently been described as biological hotspots (Lydersen et al. 2014; Urbanski et al. 2017); however, optical observations from these areas are rare and might be an important focus of future studies. Temporally, evidence for high levels of biological activity during polar night has recently been presented (Berge et al. 2015a, b); additional and more thorough optical observations during this time of year would be important to better understand how low light conditions influence the marine ecosystem in Kongsfjorden during winter.

Another knowledge gap relates to a lack of longer time series of optical observations, covering different areas of Kongsfjorden and different ranges of depths, and that are also coordinated with land-based observations of incoming solar radiation (broadband and spectral). Additionally, there is clearly a need for direct observations of inherent optical properties, such as spectral absorption and attenuation coefficients in the water column, which can be further assimilated into radiative transfer and coupled physical-biological models to get a better understanding of the underwater light climate during different seasons and locations in the fjord (cf., Cohen et al. 2015).

To overcome many observational challenges, new technological advances in both instrumentation (e.g. new hyperspectral sensors, setups to prevent biofouling of instruments) and observation platforms (e.g. underwater observatories in the coastal domain, gliders and remotely operated vehicles) will be helpful to better comprehend the variability of underwater light climate, and thus, its ecological implications. In turn, this might create even more challenges when it comes to comparison of different optical datasets. Thus, standardization and intercalibration of optical measurements and subsequent processing and sharing of the data should be prioritized.

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