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ORIGINAL RESEARCH ARTICLE

Kongsfjorden and Hornsund hydrography — comparative study based on a multiyear survey in fjords of west Spitsbergen

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Summary A recent study has shown increased warming in the fjords of west Spitsbergen. Their location is critical, as they are situated along the main northward pathway of Atlantic Water (AW) which is a great source of heat to the Arctic Ocean and the fjords. In the light of ongoing warming, we aim to discuss differences between the fjords under northward transformation of oceanic waters. We compared summer hydrographic conditions in two fjords located in two opposite ends of west Spistbergen: Hornsund in the south and Kongsfjorden in the north. The study is based on high resolution CTD measurements collected during Arctic cruises between 2001 and 2015. The emphasis was put not only on differences in water temperature, salinity and water masses but also the freshwater content (*FWC*), AW transport and heat delivery to the fjords. In general, the water in Kongsfjorden is on average 1°C warmer and its salinity is higher by 0.5 compared to Hornsund. It is also characterized by two times greater transport of AW and heat delivery to the fjord. On the other hand, Hornsund reveals two times higher *FWC*. Both fjords undergo a gradual warming due to an increased presence of Atlantic origin waters. The ongoing warming is accompanied by an increase in variability of temperature and salinity dependent on the domination of the Sørkapp Current (SC) or the West Spitsbergen Current (WSC) on the West Spitsbergen Shelf (WSS). Nonetheless, Hornsund remains more Arctic-type fjord compared to Kongsfjorden, due to stronger blocking by SC.

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1. Introduction

Fjords of the west coast of Spitsbergen are located in a critical area — along the main pathway of the Atlantic Water (AW) toward the Arctic Ocean. AW, carried by the West Spitsbergen Current (WSC) with its core following the continental slope, brings a huge amount of heat to the Arctic Ocean through the deep Fram Strait (Schauer et al., 2004). WSC is separated from the fjords by the Sørkapp Current (SC) which transports cold and fresher Arctic Water (ArW) from the Barents Sea along the West Spitsbergen Shelf (WSS) toward the north. Both currents meet and mix along the Polar front (Swerpel, 1985; Walczowski, 2013) which is also called the Arctic Front (Saloranta and Svendsen, 2001). On its way to the north, WSC undergoes significant transformation, cooling and freshening (Nilsen et al., 2006; Saloranta and Haugan, 2004). This is mostly due to heat loss to the atmosphere or ice melting and heat transfer to coastal waters (Saloranta and Haugan, 2004; Tverberg et al., 2014), which is why WSC plays a significant role as a source of heat to the fjords as well. The terrestrial boundary of the Arctic fjords is characterized by numerous tidewater glaciers which constitute the main source of freshwater in the fjords (Weslawski et al., 1995), thus leading to strong stratification in summer (Cottier et al., 2010).

A long-term analysis show the warming of the west Spitsbergen fjords, which is manifested by an increase in water temperature (Pavlov et al., 2013), acceleration of tidewater glaciers (Blaszczyk et al., 2013) as well as changes in the sea ice cover in the fjords (Muckenhuber et al., 2016). The increase in maximum water temperature in autumn of approximately 2°C over the last century is mainly explained by the changes observed in WSC and the wind pattern in the Arctic and the Fram Strait (Pavlov et al., 2013). Blaszczyk et al. (2013) show significant acceleration of tidewater glaciers in Hornsund in the last decade due to changes in air temperature and increased water temperature in the fjord. Observations from the last 14 years clearly show that the area of sea ice cover that usually formed in winter in the Svalbard fjords (Hornsund and Isfjorden) reduced in response to increased winter air temperature and AW inflows (Muckenhuber et al., 2016). In all the cases AW is mentioned as an important factor leading to the observed changes.

AW enters the fjords in an annual cycle during the shift from winter to summer conditions (Cottier et al., 2010; Nilsen et al., 2008). However, AW inflow is also observed during winter time (Cottier et al., 2007; Promińska et al., unpublished data), which is linked with a growing number of winter cyclones passing through the Fram Strait (Nilsen et al., 2016).

In this study, we aim to compare the summer hydrography of two Arctic fjords, Hornsund and Kongsfjorden, as the southernmost and the northernmost component of the west Spitsbergen fjords' network. So far, a comparison of hydrographic conditions was done in Isfjorden and Grønfjorden (a small fjord being a part of the Isfjorden system), and it was based on long time series (Pavlov et al., 2013). The major part of the comparative study regarding Kongsfjorden and Hornsund has been dedicated to biology and usually been based on a short time period (Gluchowska et al., 2016; Węsławski et al., 1995, 2006). Here, we provide two comparable hydrographic data sets collected by the Institute of Oceanology PAN during Arctic cruises that took place in the years 2001—2015. The purpose of the paper is to answer the question: what is the difference between the west Spitsbergen fjords in the light of the warming that they experience? More, what is the difference between the fjords located in the south and those up north, taking into consideration the northward transformation of oceanic waters? Many important aspects of the study are related to the content of Promińska et al. (unpublished data) devoted to interannual changes in temperature, salinity and water masses in Hornsund. In this paper we extend the analysis to discuss the differences between Kongsfjorden and Hornsund not only in water temperature, salinity and water masses distribution but also water column stability, freshwater content and transport of AW toward the fjords. Moreover, we test the hypothesis that the ongoing warming is accompanied by an increase in water temperature and salinity in the studied fjords.

2. Fjords description

Two glaciated fjords, Hornsund and Kongsfjorden, are the southernmost and one of the northernmost fjords on the west coast of Spitsbergen, the largest island of Svalbard Archipelago (Fig. 1). Hornsund is about 35 km long with a width ranging between 2 and 12 km. The hypsometric curve and volume calculated for both fjords are presented in Fig. 2a and b. Bathymetry is based on electronic charts developed by Primar and distributed by NavSim Polska sp. z o.o. The data from NavSim are interpolated on a regular grid matrix of 1000 $\times$ 1000 elements. A grid cell resolution is 32.1 m and 22.6 m in latitudinal and longitudinal direction for Hornsund and 26.6 m and 23 m for Kongsfjorden. The surface area and corresponding volume is 284.48 km^2 and 22.63 km^3 for Hornsund (Fig. 2a) and 267.81 km^2 and 27.98 km^3 for Kongsfjorden (Fig. 2b).

There is a significant difference in bathymetry between the studied fjords. Fig. 3 shows cross-fjord (a) and along-fjord (b) sections bathymetry in Hornsund (solid line) and Kongsfjorden (dash-dotted line), which location is shown in Fig. 1. Both fjords have no pronounced entrance sill, which facilitates the inflow of waters from the outside. However, the entrance to Hornsund is rather flat and shallow with maximum depth slightly exceeding 150 m (Fig. 3a, solid line). In Kongsfjorden the maximum depth along the cross section is almost 400 m on the southern side (Fig. 3a, dash-dotted line). The along-fjord sections reveal clear division into Main part (green) and Inner part (blue) in both fjords. Here the area of Brepollen (the Inner part of Hornsund) is larger and locally deeper than the Inner part of Kongsfjorden. Additional geometrical aspect, which makes the fjords different, is that Hornsund has more complex coastline including several bays (e.g. Burgerbukta, Samarinvågen), which cannot be found in Kongsfjorden.

The ubiquitous tidewater glaciers in Svalbard shape the landscape of the fjords and are the main source of freshwater (Weslawski et al., 1995 and references herein). The annual freshwater discharge into Hornsund has been estimated to 1.8 km^3 (Weslawski et al., 1995 and references herein), while in Kongsfjorden it is 1.4 km^3 (Svendsen et al., 2002). Calculations based on momentary hydrographic measurements gave also higher values of 0.7 km^3 (for July 1987) for Hornsund

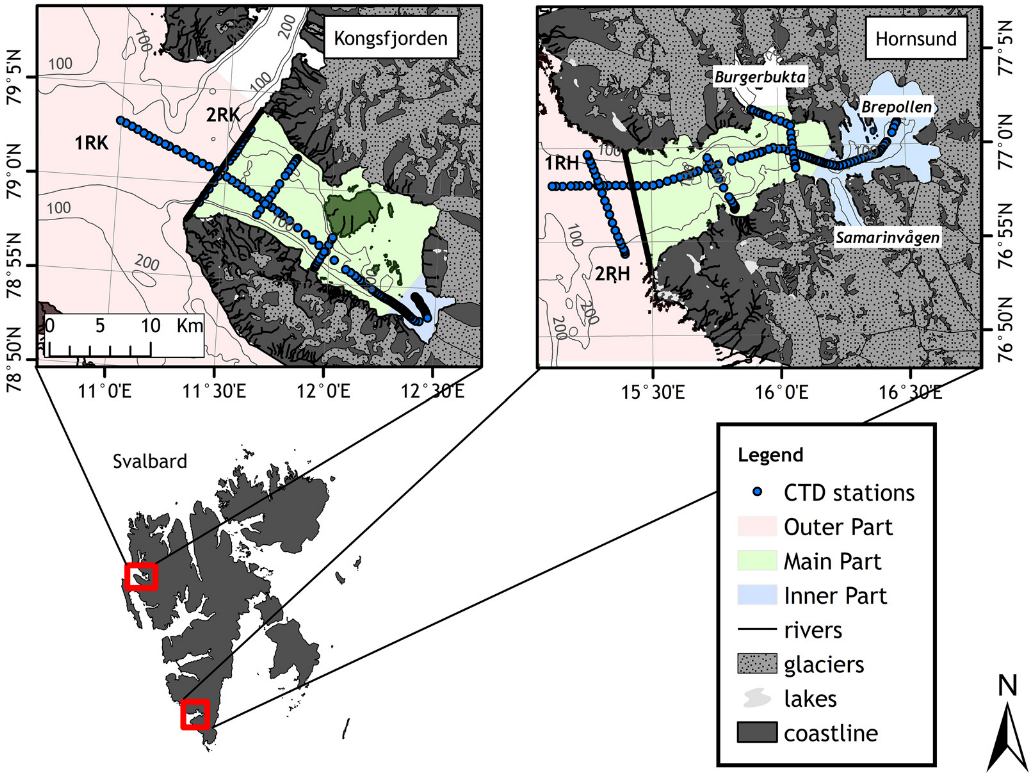

Figure 1 Study area. Location of CTD stations in Kongsfjorden and Hornsund. Black lines indicate geographical boundaries of the fjords. Different colors represent different parts of the fjords: Outer part (light coral), Main part (light green), Inner part (light blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

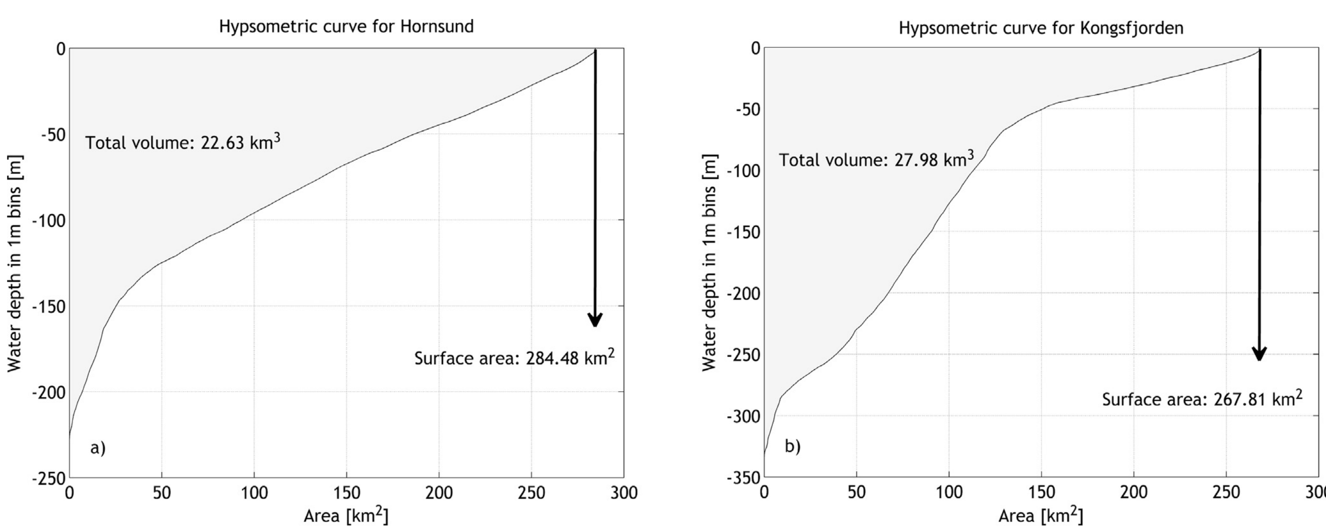

Figure 2 Hypsometric curve for Hornsund (a) and Kongsfjorden (b) based on area calculations for every 1 m depth interval. Bathymetric data based on electronic charts developed by Primar and distributed by NavSim Polska sp. z o.o.

compared to 0.3 km^3 (for July 1988) for Kongsfjorden (Węsławski et al., 1991).

3. Material and methods

3.1. Hydrographic measurements

The study is based on high resolution CTD measurements along monitoring sections, which locations are shown in Fig. 1. Measurements along longitudinal sections are carried out almost every year and only the number of cross sections differs in some years. The towed CTD system were used, which means that the measurements are taken continuously from the surface to the bottom, while the ship is moving with more or less constant speed of 3—3.5 knots. Data on water temperature and salinity were collected during summer cruises onboard r/v *Oceania*, under the long-term monitoring program AREX between 2001 and 2015. The average time

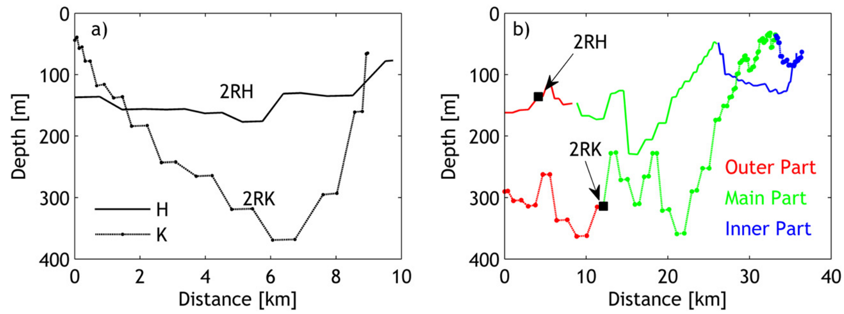

Figure 3 Bathymetry of cross sections 2RH and 2RK (a) and along-fjord sections 1RH and 1RK (b) in Hornsund (solid line) and Kongsfjorden (dash-dotted line). Different colors represent different parts of the fjords: Outer part (red), Main part (green), Inner part (blue). Black squares indicate intersection with section 2RH and 2RK. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

difference between the measurements in both fjords was about 7 days. All the data were filtered and vertically averaged every 1db. Further the data were interpolated into a regular grid of 1 m in vertical and 0.5 km bins in horizontal using kriging method.

Mean values of potential temperature (hereafter temperature) and practical salinity (hereafter salinity) were calculated using weighted average, where the weight was a cube with a dimensions 0.5 km × 1 m × 1 m (defined as a unit volume). Each value in each profile was multiplied by the unit volume and then the sum of it was divided by the volume of the section (the volume of a 1 m wide section along the Main part of section 1RK and 1RH). Mean values of temperature and salinity presented in the paper are calculated for the Main part (light green in Fig. 1) of the longitudinal sections, defined by the black lines (boundaries of the fjords in Fig. 1) and longitude 16.14 E for Hornsund and 12.35 E for Kongsfjorden (location of a shallow sill). Detailed device specification and characteristics of hydrographic measurements can be found in Table S1 of supplementary material.

3.2. Freshwater calculation

Freshwater calculations were based on the methodology described in Beszczynska-Möller et al. (1997 and references herein) as well as recent study of freshwater in Hornsund (Dølven, 2015). Freshwater content (*FWC*) was calculated by the integration of measured salinity relative to a reference salinity over water column:

$$FWC = \int_z^0 \frac{S_{ref} - S}{S_{ref}} dz,$$

where *FWC* is the height of the freshwater portion of the water column [m], S_{ref} is the reference salinity, S is the measured salinity, z is the depth [m].

For the salinity data with vertical resolution of 1 m the expression above is discretized to:

$$FWC = \sum_{z=z_0}^{n} \frac{S_{ref} - S}{S_{ref}}.$$

Each value of measured salinity in each CTD profile was subtracted from the reference salinity and then divided by reference value and the sum of it gave the *FWC* — the height of the freshwater portion in each CTD profile. To avoid negative values of *FWC*, all the data where measured salinity is higher than the reference salinity were excluded from the calculation. The total volume of freshwater (FWC_{total}) was calculated by multiplying the average of all calculated *FWC* values in the fjord by its surface area. The percentage of the total volume of a given fjord is presented as well. *FWC* calculations in this study were based on the data covering the Main parts of the fjords (light green in Fig. 1).

Reference salinity of 34.2 was taken from Dølven (2015) based on measurements taken in Hornsund in April 2012 and May 2011 and 2013 and the assumption that all the freshwater was flushed out before winter (Dølven, 2015).

3.3. Stability of water column

Stability of water column is represented by the square of the Brunt—Väisälä frequency (a measure of stratification):

$$N^2 = -\frac{g}{\rho}\frac{d\rho}{dz},$$

where g is the acceleration of gravity, ρ is the potential density.

For stability calculations data are averaged every 5 db to eliminate noise.

3.4. Transports

For sections located at the mouth of the fjords (sections 2RK and 2RH in Fig. 1) transport of volume and heat was calculated. Geostrophic currents were calculated with use of dynamic height method, with reference to the no-motion layer (*NML*). Here, the bottom was adopted as the *NML*. Transports of properties were calculated using gridded velocity and property fields.

4. Results

4.1. Water mass distribution

The general overview of water masses is contained in supplementary material. Ranges of temperature and salinity are defined in Table S2. Fig. 4 shows distribution of water masses along the longitudinal sections in Hornsund and Kongsfjorden for summers 2001—2015 according to ranges of temperature and salinity defined in Table S2 of the supplementary material. The black lines separate the Outer part, Main part and the Inner part of the fjords (starting from the left side of each figure). The Surface Water (SW, light orange) was found along Kongsfjorden in all years. In most years a layer of SW was very thin (~10 m) but in some years it extended to ~50 m (2003, 2004, 2010, 2011, 2015). Below SW there is an Intermediate Water (IW, green). Only in 2004 it was covered by the Local Water (LW, blue), which typically was observed in deeper parts. The thickness of IW was typically ~50 m but in 2002,

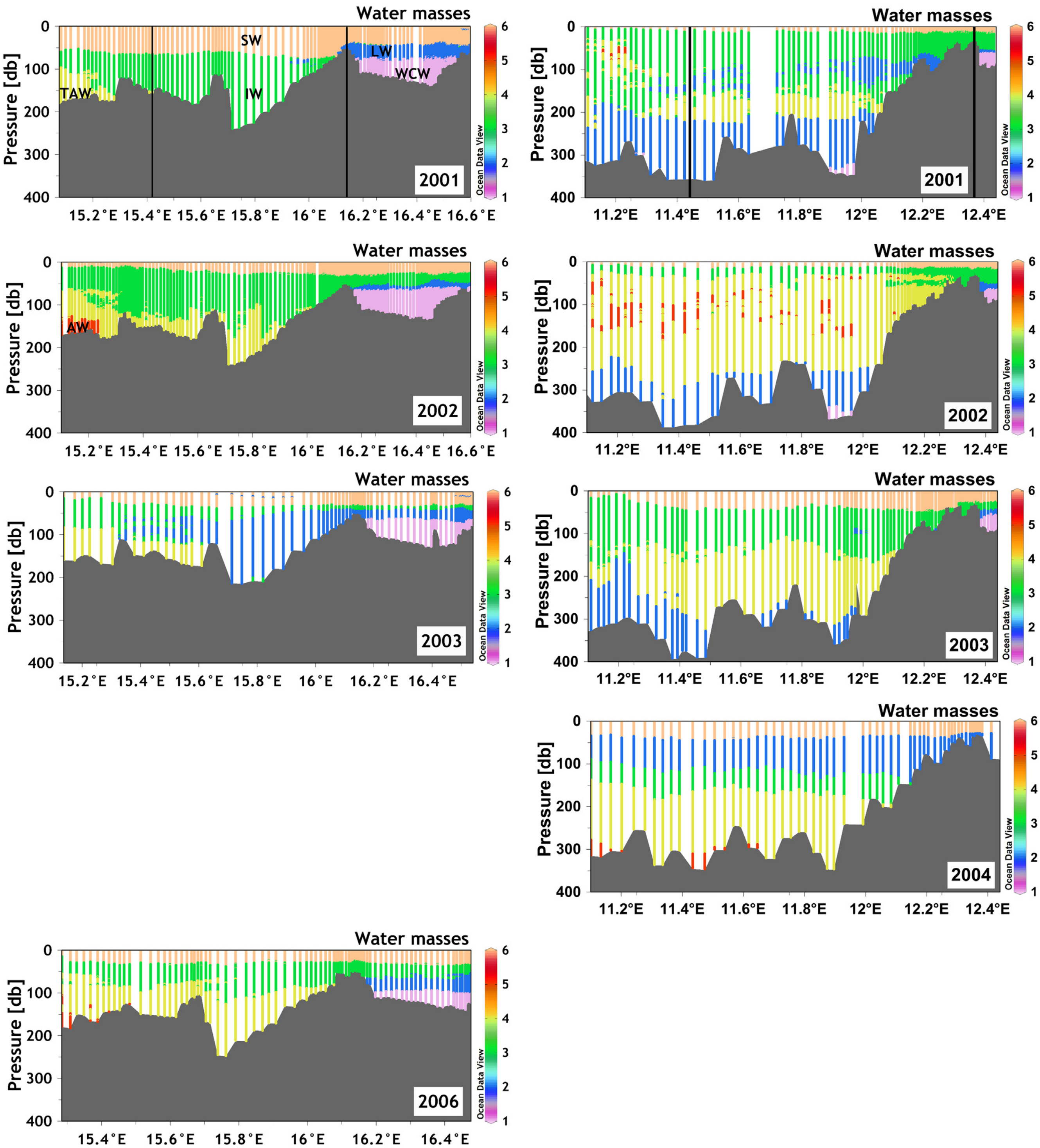

Figure 4 Distribution of particular water masses along fjord axis in Hornsund Fjord (left column) and Kongsfjorden (right column) for years 2001—2015. The left side of figures is the seaward site and on the right side are the innermost fjords parts. The following numbers are assigned to particular water masses (see Table S2 in supplementary material): 1 — Winter Cooled Water (WCW, pink); 2 — Local Water (LW, blue); 3 — Intermediate Water (IW, green); 4 — Transformed Atlantic Water (TAW, yellow); 5 — Atlantic Water (AW, red); 6 — Surface Water (SW, orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2010 and especially in 2014 there was almost no IW at all. Transformed Atlantic Water (TAW, yellow) is a typical water of Atlantic origin found in Kongsfjorden. It usually spreads below IW and extends to the bottom. The exceptional years are 2001, 2002, 2003 when TAW was observed at the intermediate depths with LW below. In 2004 and 2010 LW was much lighter than TAW and filled the upper 50—100 m below the SW. Pure Atlantic Water (AW, red) defined by $\theta > 3°C$ and $S > 34.9$ was found in the Main Basin at the bottom (2004) or as patches at intermediate depths in 2002, 2007, 2013 and 2015. In 2014 AW filled the fjord from 20 m up to 250 m. It also reached the Inner part for the first time in study period.

The extent of Atlantic origin waters differs significantly in both fjords. In Hornsund AW typically occurred at the entrance to the fjord and TAW was the only water of Atlantic origin that reached the Main Basin. In Kongsfjorden TAW filled

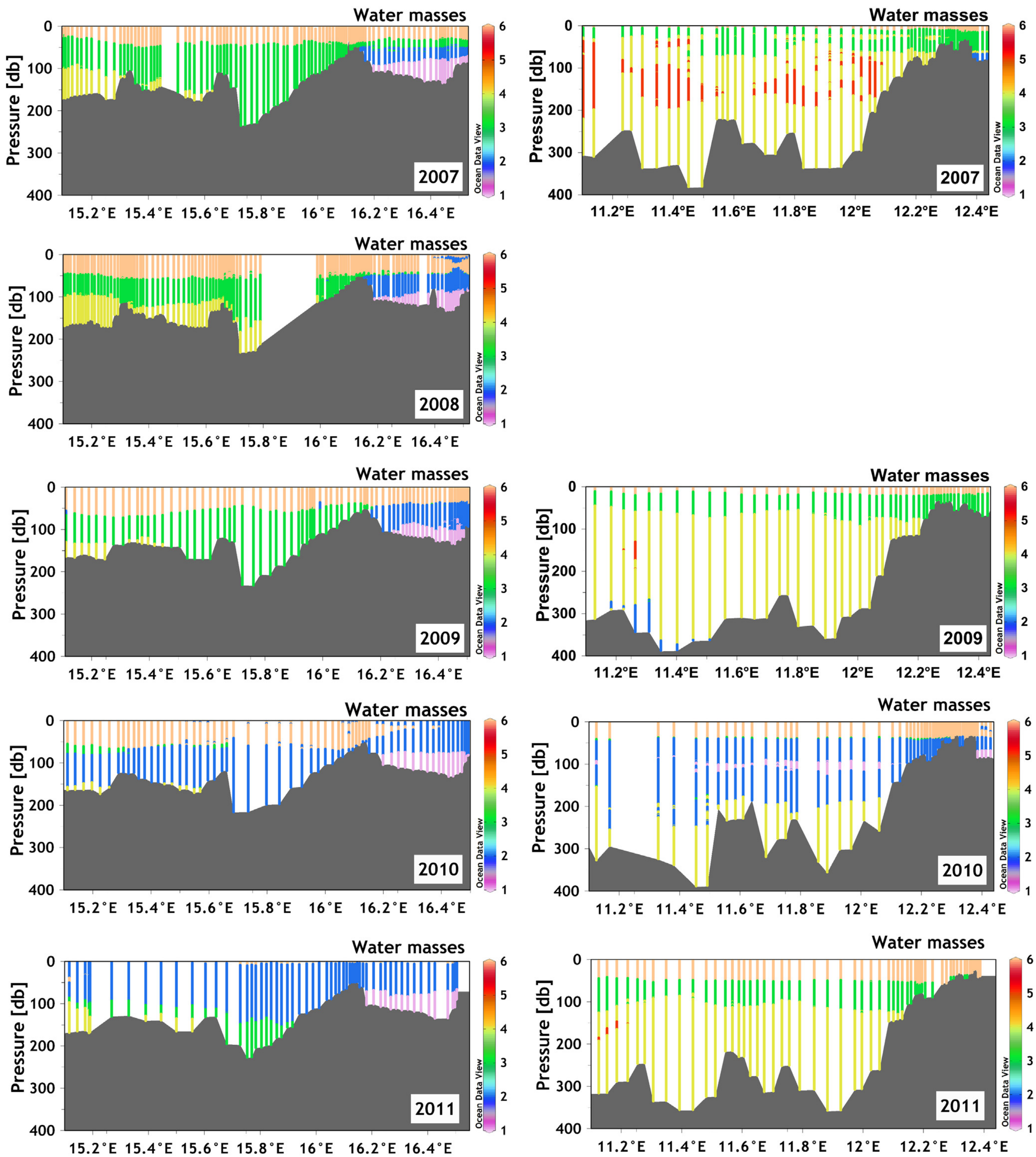

Figure 4 (*Continued*)

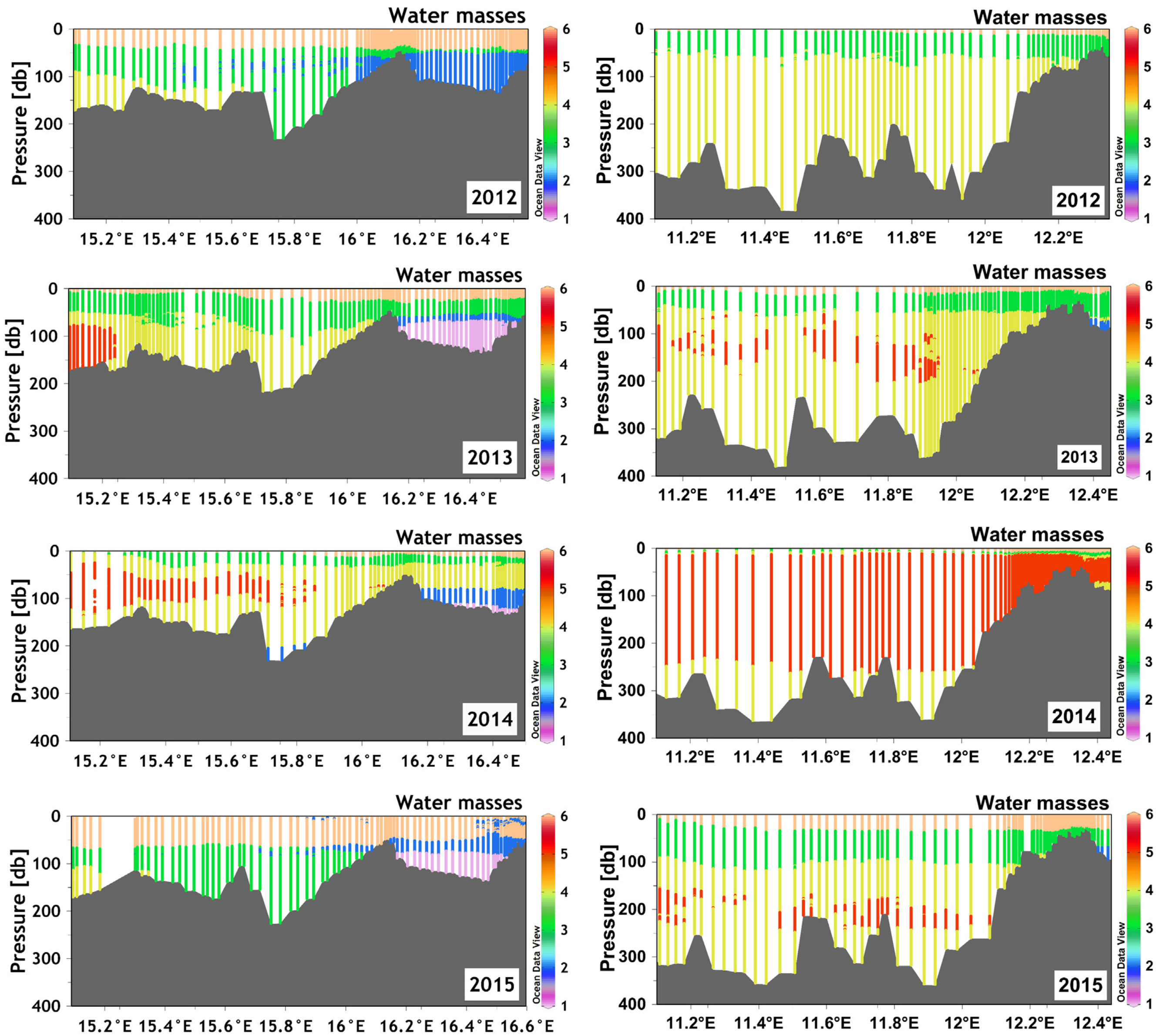

Figure 4 (*Continued*).

the large part of the fjord almost in all years and AW was observed also in the fjord's Main Basin. However, summer 2014 was extreme for both fjords. AW covered the largest extent in the fjords and TAW reached their Inner parts.

4.2. Interannual variability in hydrography

Table 1 shows mean values of temperature and salinity calculated for along-fjord sections 1RH and 1RK, only for the Main part of the sections. Differences in both variables between Hornsund and Kongsfjorden are shown as well. Graphical representation can be found in Fig. 5. Mean water temperature in Hornsund ranges between 0.45°C (2011) and 3.63°C (2014) and is on average 0.92°C lower than in Kongsfjorden, where it ranges between 1.06°C (2010) and 4.54°C (2014). Mean water salinity in Hornsund ranges between 33.33 (2011) and 34.67 (2014) and is on average 0.46 lower than in Kongsfjorden, where it reaches values between 34.00 (2004) and 35.00 (2014). Fig. 5 shows that changes in temperature and salinity correspond very well in Hornsund ($r = 0.88$). In Kongsfjorden the situation is more complex, resulting in lower correlation of temperature and salinity ($r = 0.67$).

The long-term (2001—2015) summer mean temperature and salinity is equal to 2.17°C and 34.06 for Hornsund and 2.90°C and 34.46 for Kongsfjorden. Temperature and salinity anomalies clearly show periods of warming and salinification, as well as periods of cooling and freshening of waters in both fjords (Fig. 6). The strongest negative anomalies were observed in 2010 (in Kongsfjorden) and 2011 (in Hornsund). Generally, after 2011, positive temperature and salinity anomalies were observed with the strongest in 2014 for both fjords, when water temperature was ca. 1.5°C higher than the long-term mean values.

Changes in water temperature and salinity can be seen in the entire water column, which is evident in Figs. 7 and 8. Fig. 7a and b shows longitudinal changes in water

Table 1 Mean water temperature, salinity, temperature and salinity difference for Hornsund and Kongsfjorden for summers 2001—2015.

Year	Mean *T*		Mean *S*		Δ*T*	Δ*S*
	Hornsund	Kongsfjorden	Hornsund	Kongsfjorden		
2001	1.92	1.80	33.79	34.43	0.13	0.64
2002	2.78	3.20	34.29	34.65	0.42	0.35
2003	1.46	2.86	34.13	34.23	1.40	0.10
2004	—	1.63	—	34.00	—	—
2005	—	—	—	—	—	—
2006	2.85	—	34.25	—	—	—
2007	2.71	2.89	34.14	34.71	0.18	0.57
2008	2.09	—	34.02	—	—	—
2009	1.80	3.11	33.87	34.56	1.32	0.70
2010	1.07	1.06	33.90	34.11	0.01	0.21
2011	0.45	3.30	33.33	34.21	2.85	0.87
2012	1.98	3.09	34.10	34.63	1.11	0.53
2013	3.20	3.31	34.34	34.62	0.12	0.28
2014	3.63	4.54	34.67	35.00	0.91	0.33
2015	2.27	3.96	33.90	34.35	1.69	0.45
Mean	2.17	2.90	34.06	34.46	0.92	0.46

temperature and salinity at the depth of 25 m in Hornsund between 2001 and 2015. Black lines divide the section into Outer part (west of the black line in Fig. 1), Main part and Brepollen, the innermost part of Hornsund. The years 2001—2009 are characterized by a small variability in both temperature and salinity. Temperature ranges between 2.5°C in colder years (2001, 2003, 2008 and 2009) and 3.5—4°C in warm years (2002, 2006 and 2007). Salinity ranges between 33.1 and 33.5 (2001, 2008, 2009 and 2010) and 33.9 and 34.1 (years 2002—2003 and 2006—2007). Typically salinity at 25 m did not exceed 34, except for 2002 in the Outer part of Hornsund. Years 2010—2015 are characterized by much larger variability in both temperature and salinity. Minimum temperature (~0°C) was noted in the coldest year (2011) in all parts of Hornsund with a corresponding minimum salinity of 31.9. The strongest warming and even the most pronounced increase in salinity was observed in 2014 in all parts of Hornsund. That year the temperature exceeded 4.5°C, also in Brepollen, and salinity reached values above 34.5 in the Main part and Brepollen and 34.7 in the Outer part.

Fig. 7c and d presents longitudinal changes in water temperature and salinity at 25 m depth in Kongsfjorden between 2001 and 2015. The black line divides the section into Outer part (west of the black line in Fig. 1) and Main part.

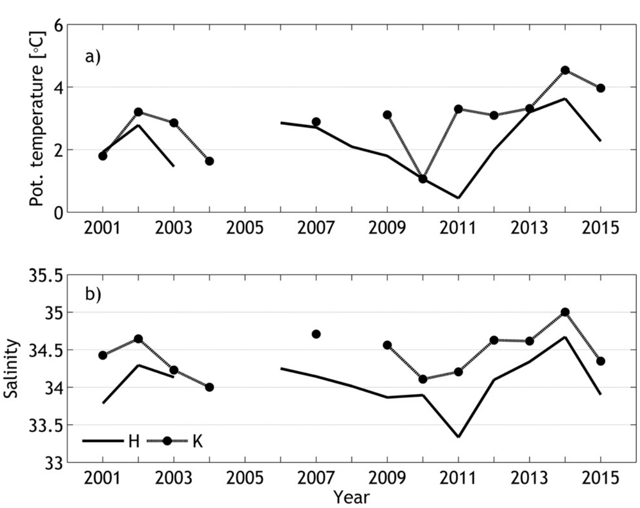

Figure 5 Time series of water temperature and salinity for Hornsund (solid line) and Kongsfjorden (dashed-dotted) in summers 2001—2015.

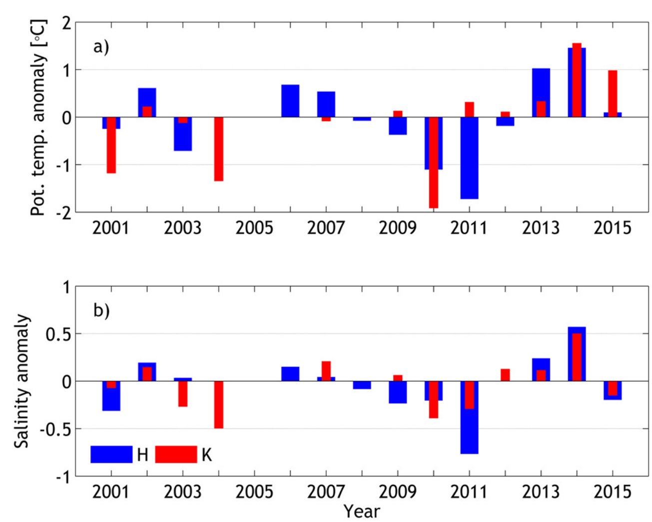

Figure 6 Time series of temperature (a) and salinity (b) anomalies in Hornsund (blue bars) and Kongsfjorden (red bars). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

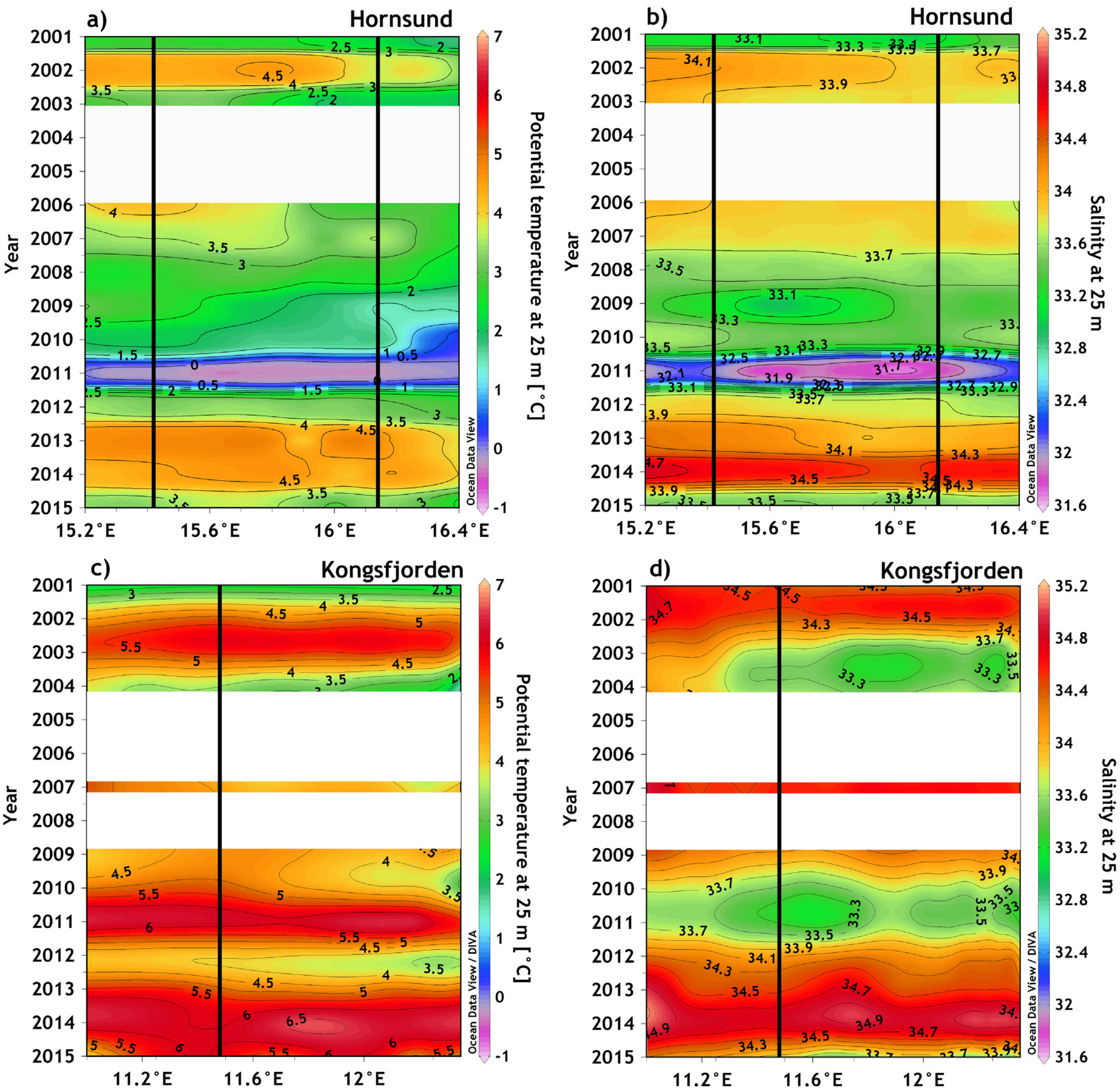

Figure 7 Longitudinal water temperature and salinity distribution at 25 m in Hornsund (a and b) and Kongsfjorden (c and d). Black lines indicate boundaries between Outer part, Main basin and Inner part of the fjords.

There are not sufficient data to show the Inner part of the fjord. Temperature ranges from 3.5°C to 4.5°C in years 2001, 2007, 2009 and 2012 to more than 5°C in the years 2002, 2010—2011 and 2013—2015. Salinity ranges from 33.1 to 33.7 in the years 2003—2004, 2010—2011. In the other years studied, salinity typically exceeded 34 with a significant increase between 2002 and 2003, and the highest value was recorded in 2014 (above 34.9).

Fig. 8a and b presents longitudinal changes in water temperature and salinity at 100 m depth in Hornsund. There is a clear difference between Brepollen and the remaining part of the section. One can clearly see significantly low values of water temperature (~−1.5°C) in Brepollen between 2001 and 2003, while after that period the recorded values were remarkably higher, with the highest temperatures observed in 2012 and 2014 (below −0.5°C). In the period 2001—2009, the strongest warm signal was observed in the Outer part of Hornsund in the years 2001—2003, 2006—2008 and 2012—2015. In 2006 and 2007 that warm signal was observed partly in the Main Basin and in 2014 it was observed all over the Main part almost throughout its entire depth. 2014 was also a year with the highest salinity on record in the study period in all parts of the section. The lowest salinity (less than 34.4) was observed in Brepollen in 2012. Relatively low values were also recorded in Brepollen in 2009 and almost in the entire section in 2010.

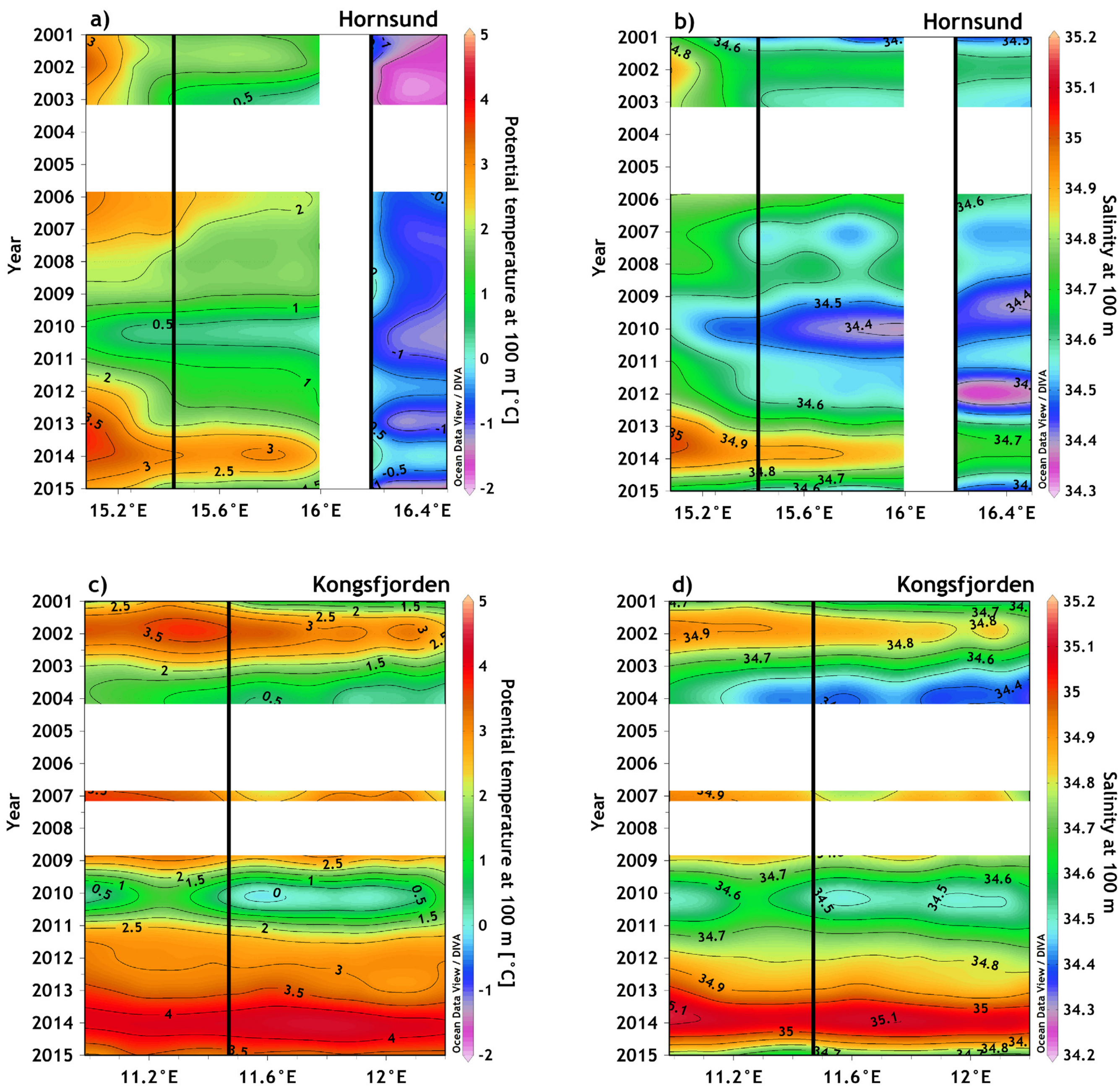

Figure 8 Longitudinal water temperature and salinity distribution at 100 m in Hornsund (a and b) and Kongsfjorden (c and d). Black lines indicate boundaries between Outer part, Main basin and Inner part of the fjords.

In Kongsfjorden, strong warming at the depth of 100 m was observed in the years 2002, 2007 and 2012—2015, when temperature exceeded 3°C (Fig. 8c). The corresponding high salinity was observed in the years 2002 and 2013—2014 (Fig. 8d). In the other years of the study (2007, 2012 and 2015), despite the warming shown in Fig. 8c, salinity was relatively low (Fig. 8d). 2014 is the year when the highest temperature (above 4°C) and salinity (above 35) was recorded in the study period in Kongsfjorden. A significant cooling and freshening was observed in 2003—2004 and 2010.

To look closer to the differences between the fjords, we chose years 2010, 2011 and 2014 in a case study of different hydrographic conditions. In summer 2010 both fjords experienced cooling and freshening (Fig. 9). In Hornsund, below the 70 m fresh surface layer, cold water filled the fjord almost down to the bottom in the Outer and Main part. In Brepollen the entire water column was cold, its temperature centered around 0°C in the upper 50 m and it was colder below the sill. Water mass distribution shows LW (blue) in large part of the fjord. In the Outer part, at the bottom, there are some patches of TAW (yellow). In Kongsfjorden, very cold water temperature was observed from 50 m down to 150—200 m and water mass distribution shows LW (with patches of WCW characteristics, pink) in this area. Below 200 m water had properties typical for TAW ($\theta > 1$°C, $S > 34.7$).

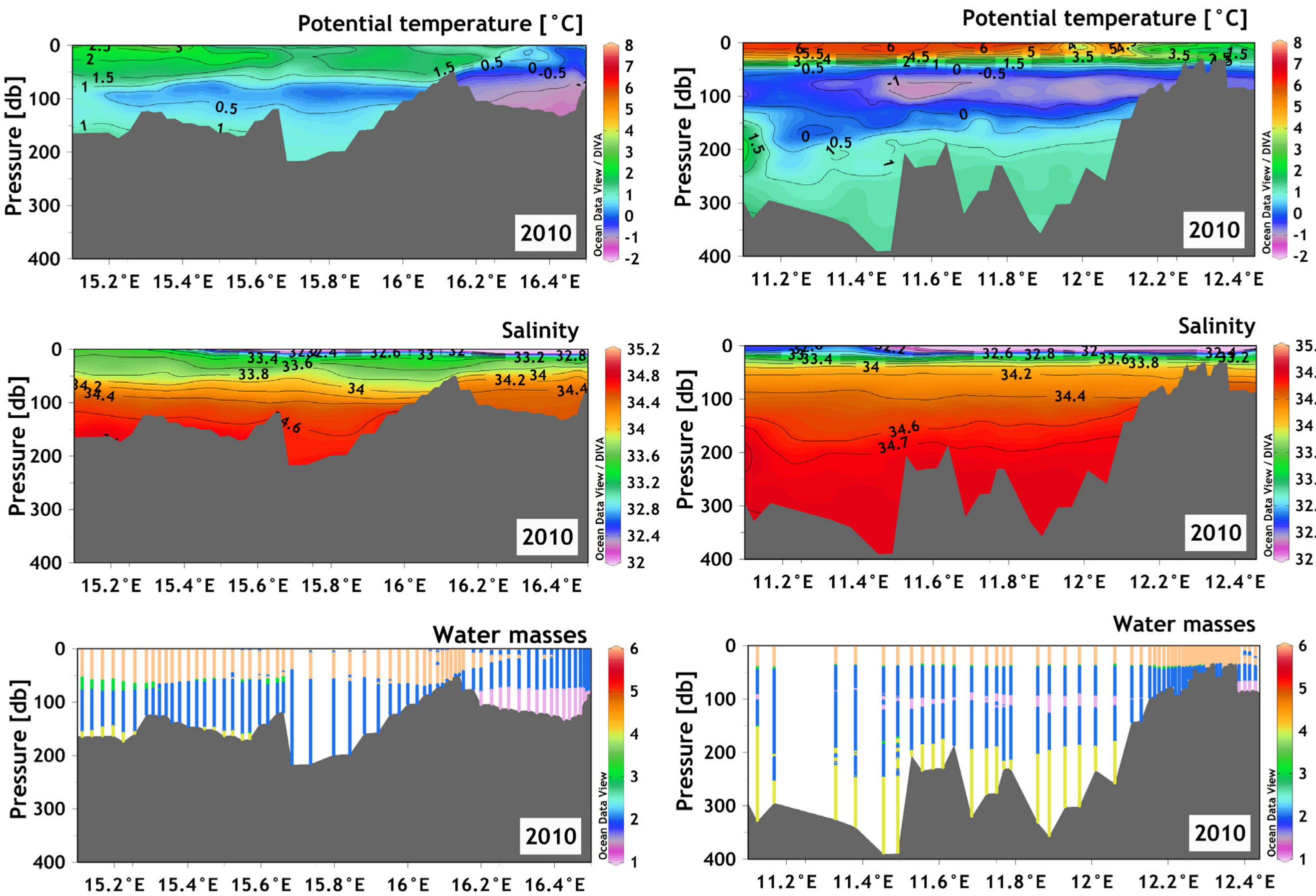

Figure 9 Longitudinal distribution of temperature, salinity and water masses in summer 2010 in Hornsund (left column) and Kongsfjorden (right column). The left side of each figure is the seaward site and on the right side are the innermost fjords parts. The following numbers are assigned to particular water masses (see Table S2 in supplementary material): 1 — Winter Cooled Water (WCW, pink); 2 — Local Water (LW, blue); 3 — Intermediate Water (IW, green); 4 — Transformed Atlantic Water (TAW, yellow); 5 — Atlantic Water (AW, red); 6 — Surface Water (SW, orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In 2011 hydrographic conditions differed between the fjords (Fig. 10). In Hornsund the upper 75 m was filled with cold and very fresh water all over the fjord, resulting in the lack of layer that could be classified as the SW (light orange). In the Outer and Main part patches of TAW (yellow) and IW (green) could be observed. In Kongsfjorden there was a completely different distribution. There was no cold and fresh signal at all, unlike the situation observed in Hornsund. The upper 50 m was very warm and relatively fresh, representing SW. Below that level, a ~50 m thick layer of IW could be observed, and from 100 m down to the bottom the fjord was filled with warm and saline TAW. In the Outer part patches of pure AW (red) occurred.

In summer 2014 the highest values of temperature and salinity in the fjords during the study period (Fig. 11) were recorded. For the first time the isohaline of 34.9 (a threshold salinity value for the pure AW) occurred in the Main part of Hornsund, resulting in the greatest extent of AW in the fjord. In Brepollen TAW was observed for the first time. The thickness of AW in Hornsund ranged between ~100 m in the Outer part and ~50 m in the Main part. In Kongsfjorden that warming was even greater. The fjord was filled in large extent with AW (25–250 m), reaching far into the fjord. Deeper parts of the fjord were filled with TAW. In both fjords there was hardly any SW. LW was observed only in Hornsund, in the deepest area of the Main part and in Brepollen. WCW (pink) reached the lowest thickness in Hornsund compared to 2010 and 2011, and it disappeared completely in the Inner part of Kongsfjorden.

4.3. Stability of water column

Different hydrographic conditions described above also indicate a different stability of water column. Fig. 12 shows vertical profiles of temperature, salinity and corresponding stratification (Brunt — Väisälä frequency squared). For all the presented years Hornsund (blue) is characterized by higher values of stratification than Kongsfjorden (red). In 2010 the range of temperature (Fig. 12a) and salinity (Fig. 12b) was similar in both fjords. Only upper 50 m was significantly warmer in Kongsfjorden. The highest values of water column stability were observed at 5 m in Hornsund and decreased down to 150 m where the value centered around 0 (Fig. 12c). In Kongsfjorden the maximum of water column stability was observed at 23 m and below 150 m it was close to 0.

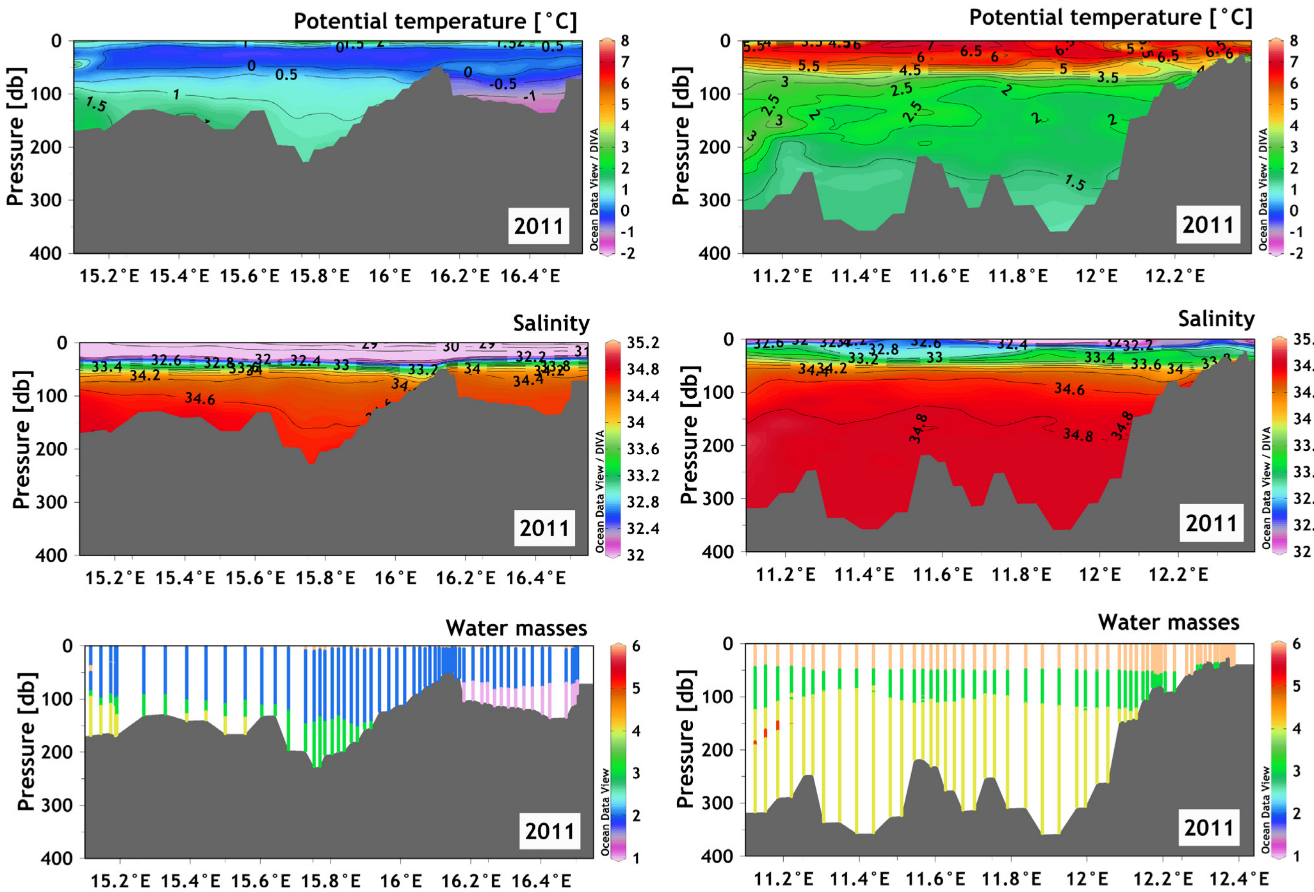

Figure 10 Longitudinal distribution of temperature, salinity and water masses in summer 2011 in Hornsund (left column) and Kongsfjorden (right column). The left side of each figure is the seaward site and on the right side are the innermost fjords parts. The following numbers are assigned to particular water masses (see Table S2 in supplementary material): 1 — Winter Cooled Water (WCW, pink); 2 — Local Water (LW, blue); 3 — Intermediate Water (IW, green); 4 — Transformed Atlantic Water (TAW, yellow); 5 — Atlantic Water (AW, red); 6 — Surface Water (SW, orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Very different conditions were observed in 2011 (Fig. 12d—f). A great difference was noted in the upper 50 m, where the fjords are in the opposite phase. In Hornsund (blue) temperature decreased from ~4°C in the surface layer to ~0°C at 15 m with a relatively low salinity. In Kongsfjorden (red) very warm water occurred, of temperature reaching almost 7°C and salinity was remarkably higher than in Hornsund. However, there was a similar pattern in water column stability. In the upper 100 m of both fjords, high values occurred with two-fold maxima, at 5 m and 40 m in both fjords.

In 2014 very warm and saline water occurred in both fjords (Fig. 12g—i), yet in the case of Hornsund it was less saline and shifted toward colder waters (a shift of about 2°C). Water column stability was highest at 4—5 m in both fjords. Moreover, in Kongsfjorden high values could be observed at 70 m and 260 m.

4.4. Freshwater content

Calculations of the total *FWC* in Hornsund provide values ranging from 0.06 km^3 to 0.81 km^3 (Fig. 13a, blue bars), which represents 0.27—3.58% of the fjord volume (Fig. 13b, blue bars). The minimum of total *FWC* occurred in 2014. Summer 2011 was the most outstanding year with the highest total *FWC*. The years 2001, 2009 and 2015 are characterized by significantly lower values of total *FWC* (less than 2% of Hornsund volume) relative to summer 2011. However, compared to the other years, the summers of 2001, 2009 and 2015 can be considered as years with high total *FWC*.

Total *FWC* in Kongsfjorden ranges between 0.03 km^3 and 0.42 km^3 (Fig. 13a, red bars), which represents 0.12—1.5% of the fjord's volume (Fig. 13b, red bars). Similar to Hornsund, summer of 2014 was the year with the lowest total *FWC*. Similar values are showed for the years 2004 and 2011.

4.5. Transports

To compare both fjords, the baroclinic currents were calculated for the years 2001—2003 and 2010—2015, when sections across the Hornsund (2RH) and Kongsfjorden (2RK) mouths were performed. Mean baroclinic inflow to Hornsund equals approximately 20 mSv (10^3 m^3 s^{-1}) with 238 MW of heat delivered to the fjord (Table 2). On average 1.4 mSv of AW delivers 24.7 MW of heat to Hornsund. Mean baroclinic inflow to Kongsfjorden is about 40 mSv (10^3 m^3 s^{-1}) with 525 MW of

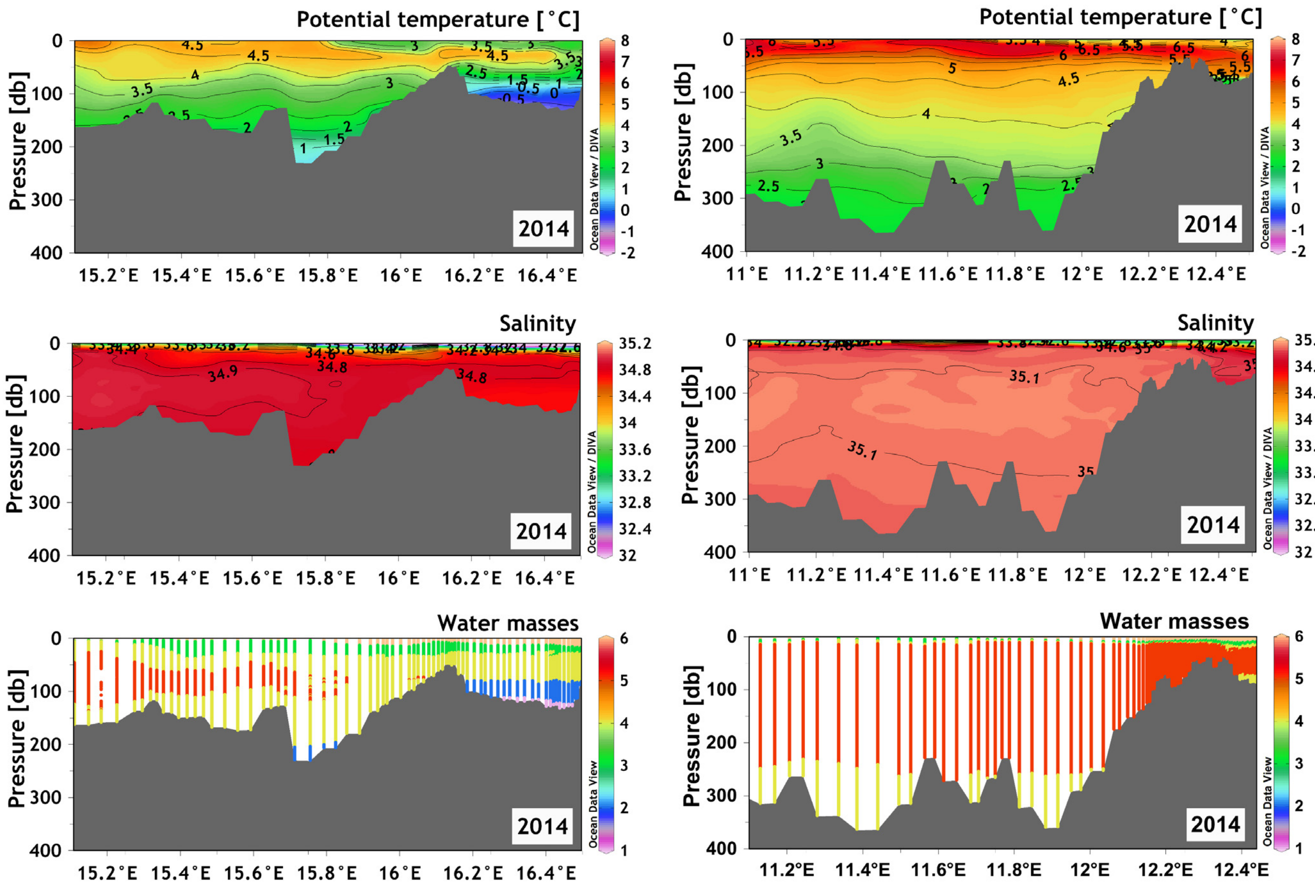

Figure 11 Longitudinal distribution of temperature, salinity and water masses in summer 2014 in Hornsund (left column) and Kongsfjorden (right column). The left side of each figure is the seaward site and on the right side are the innermost fjords parts. The following numbers are assigned to particular water masses (see Table S2 in supplementary material): 1 — Winter Cooled Water (WCW, pink); 2 — Local Water (LW, blue); 3 — Intermediate Water (IW, green); 4 — Transformed Atlantic Water (TAW, yellow); 5 — Atlantic Water (AW, red); 6 — Surface Water (SW, orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 2 Mean characteristics of water temperature and salinity, transport of volume and heat through the cross sections in Hornsund (2RH) and Kongsfjorden (2RK).

	Vol [mSv]	Vol+ [mSv]	Vol− [mSv]	Temp [°C]	Sal	Heat [MW]	Heat+ [MW]	Heat− [MW]	AW_Vol [mSv]	AW heat [MW]
2RH mean	−2.7	20.9	−23.6	2.55	34.27	−43.9	238	−282	1.4	24.7
2RK mean	3.1	36.3	−33.1	2.86	34.61	37	525	−488	3.4	46

heat delivered to the fjord. On average 3.4 mSv of AW delivers 46 mW of heat to Kongsfjorden.

5. Discussion

Our comparable hydrographic data set shows that under the continuing warming in Svalbard fjords, both Hornsund and Kongsfjorden significantly differ in water temperature, salinity, freshwater content and AW presence. Our main finding is that Hornsund is approximately 1°C colder and its salinity is on average lower by 0.5 compared to Kongsfjorden. More waters of the Atlantic origin are found in Kongsfjorden. The fjord is characterized by approximately 2 times higher inflow of AW and the corresponding heat delivery, but 2 times lower total *FWC* in comparison to Hornsund. As the fjords are located on the main pathway of AW into the Arctic Ocean, one can assume that the fjords experience more (less) inflow of AW within a similar time period. Even so, the present study shows that in some years the fjords may demonstrate very different conditions. Moreover, we observed increased variability of water temperature and salinity during summer in Hornsund and Kongsfjorden with the exceptional and unprecedented warming and increase in salinity in the summer of 2014 in the period 2001—2015 for both fjords.

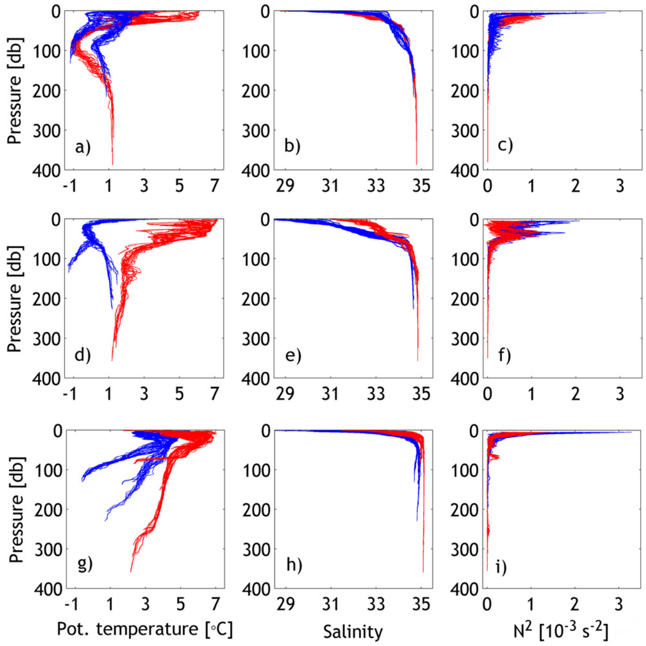

Figure 12 Potential temperature, salinity and stratification profiles for data collected along fjords' axis for Kongsfjorden (red) and Hornsund (blue) in 2010 (a–c), 2011 (d–f) and 2014 (g–i). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

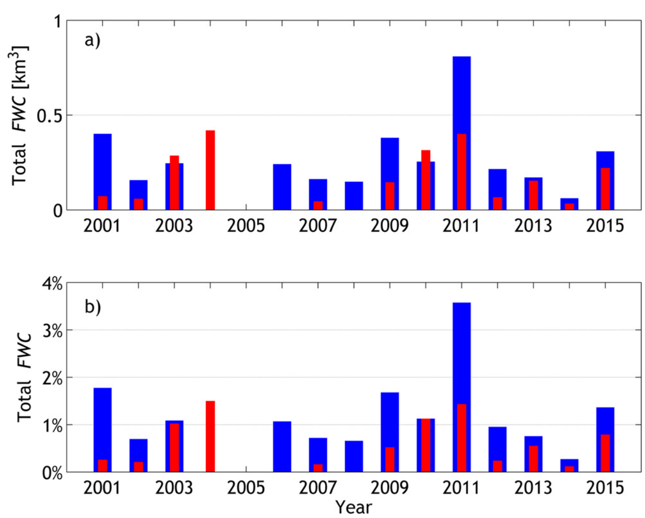

Figure 13 Total freshwater volume (a) and percentage of the fjord volume (b) in Hornsund (blue) and Kongsfjorden (red) in summers 2001–2015. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In most years both fjords experienced warming or cooling at the same time (Fig. 6). Since the fjords on the west coast of Spitsbergen have no entrance sill there is a direct influence of waters from the outside. The Inner parts of the fjords are of more Arctic character due to remnants of water from the previous winter. However, Fig. 4 shows clearly that the fjords undergo a transition toward more Atlantic type. It is particularly evident after 2006, when deeper parts of the fjords have been replaced by TAW instead of LW or IW, and in summer 2014 when large areas of the fjords were filled with pure Atlantic Water. That was an exceptional year of the analyzed period. Moreover, in Inner parts, where typically WCW was found, there were years with no WCW at all (Fig. 4). The warming may be a result of an increased inflow of AW into the fjords due to changes in the atmosphere (Cottier et al., 2005, 2007; Nilsen et al., 2016).

A previous study of Hornsund hydrography showed a weak occupation by the AW explained with stronger blocking by SC compared to other fjords west of Spitsbergen (Promińska et al., unpublished data). They presented yearly mean Sea Ice Concentration (SIC) as a proxy for SC and showed high correlation with water temperature and salinity in Hornsund. The extremely low temperature and salinity in summer 2011 in Hornsund was explained by the sea ice inflow brought by the SC from the Barents Sea, which was also documented by Kruszewski (2012). The sea ice events in July occurred several times between 2001 and 2015, with the highest sea ice concentration in July 2004 and 2011 but they were also present in July 2001, 2005 and 2008 (Promińska et al., unpublished data). Fig. 4 shows that the cold signal is not observed in Kongsfjorden (summer 2011), since the sea ice can melt completely on its way north due to heat gain from the atmosphere and mixing of cold water with surrounding warm water from WSC (Saloranta and Haugan, 2004; Tverberg et al., 2014). On the other hand, the presence of LW in the upper layer (Fig. 4) and negative temperature and salinity anomalies in summer 2004 (Fig. 6) may be linked to a sea ice event in July 2004. This shows that despite a great number of papers concentrated on the variability of WSC and processes governing the inflow of AW into the fjords, variability in SC and relation with WSC is still poorly documented and understood.

Kongsfjorden is characterized by on average 1°C higher water temperature and 0.5 higher salinity compare to Hornsund. That difference results from a combination of geographical and environmental settings. First of all, Węsławski et al. (unpublished data) showed essential difference between frontal zone demarcating the WSC from the SC, which is much more pronounced at Hornsund foreground. Despite the northward cooling of the WSC (Saloranta and Haugan, 2004) AW is more available for Kongsfjorden than for Hornsund. Another limiting factor are deep troughs across the WSS, playing an important role in supplying water from the outside (Nilsen et al., 2016). The trough leading to Hornsund is very narrow and shallower than in case of Kongsfjorden. The geometry of Hornsund (numerous inner bays), as well as higher freshwater content (Fig. 13), leads to higher water mass transformation in the fjord toward more Arctic characteristics, resulting in lower temperature and salinity.

Approximately twice higher total *FWC* in Hornsund compared to Kongsfjorden may result from landscape diversity as one source of freshwater comprising glacial water (ablation and melting of a glacier, melting of icebergs), river runoff, precipitation. At first sight, there are more tidewater glaciers distributed along the fjord coastline in Hornsund (97% of glacierized area, Blaszczyk et al., 2013). In Kongsfjorden, there are only 5 tidewater glaciers with the ice front positions distributed mainly along the coastline of the Inner fjord basin (Fig. 1). On the other hand, the southern coast of Kongsfjorden is rich in branched river network. However, assuming that rivers are a minor source of freshwater in the fjords (Węsławski et al., 1991 and references herein) and considering the fact that among all tidewater glaciers on Svalbard those in Hornsund retreat fastest (Blaszczyk et al., 2013), the landscape contrast of both fjords could serve as a sufficient explanation of higher total *FWC* in Hornsund. Our result shows that the seaward boundary is an additional factor influencing the total *FWC* in the fjord. The strongest manifestation of the seaward influence in Kongsfjorden and Hornsund is summer 2004 and 2011, respectively (Fig. 4), where the evident contributor to the total *FWC* was SC.

It is worth recalling that our calculations of the total *FWC* are based on momentary observations representing hydrographic conditions at the specific time. Another limitation of the method is that it gives overall *FWC* without specifying contribution of particular freshwater source. Moreover, the choice of the reference salinity may also influence the results. A previous study of freshwater in Hornsund and Kongsfjorden was based on the reference salinity taken for the summer measurements outside the fjords (S_{ref} = 35.23 for Hornsund and S_{ref} = 34.56 for Kongsfjorden, Węsławski et al., 1991), which, besides the fact that those values do not represent the fjords' waters, can significantly overestimate the FWC calculations.

Our results show that despite the continuing warming, both Kongsfjorden and Hornsund experience increased variability in temperature and salinity (Fig. 6) dependent on the domination of SC (Figs. 9 and 10) or WSC (Fig. 11). This increase is likely to be more pronounced in the future as a result of growing number of extreme weather events. Increased inflow of AW into the fjords is possible due to increased frequency of winter cyclones passing through the Fram Strait, which drives the mostly barotropic Spitsbergen Trough Current — transformed Atlantic Water circulating along the WSS troughs (Nilsen et al., 2016). More unmodified AW during winter may influence the local climate (Walczowski and Piechura, 2011) and sea ice cover (Muckenhuber et al., 2016). Warmer winters and lack of sea ice cover lead to an increased occurrence of years with no Winter Cooled Water (Promińska et al., unpublished data), which in turn is one of the factors controlling the AW inflow (Nilsen et al., 2008).

The baroclinic calculations usually underestimate total flow, but on the other hand it allows to assess the average flows and fluxes. Calculations give reasonable results, in case of both fjords maximal currents velocities are up to 30 cm s^{-1}. The inflow is usually situated at the deeper layer along the southern coast of the fjord and the outflow along the northern coast of the fjord. However, there is also the inflow of warm water into the fjord observed in the middle or close to the northern coast of the fjord. Results show that during the summer the intensity of exchange processes in Kongsfjorden is almost two times higher than in the case of Hornsund (Table 2). Greater inflow and higher water temperature result in much higher heat transport into Kongsfjorden than into Hornsund (525 MW vs 238 MW). The Atlantic Water plays important role in this transport. The water exchange in the Outer parts of the fjords is more intensive and residence time in this region is even shorter. The Inner parts of the fjords exchange water much slower. It is visible especially in the case of Hornsund, where WCW in Brepollen is observed in most summer observations. Nevertheless, even in Brepollen the upper layer of the water column has exchanged.

To conclude, both fjords located at two opposite ends of west Spitsbergen experience the ongoing warming accompanied by an increased variability in water temperature and salinity. Nonetheless, weaker occupation by AW, less heat transport to Hornsund as well as higher freshwater content in the fjord lead to lower values of water temperature and salinity in Hornsund compared to Kongsfjorden resulting in a more Arctic character of Hornsund.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.oceano.2017.07.003.

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