Trends and variability in environmental conditions and zooplankton communities in the Northwest Atlantic 1960-2013

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Sir Alister Hardy Foundation for Ocean Science team in Plymouth, UK
Atlantic Zone Monitoring Program teams in Maritimes, Newfoundland and Quebec regions

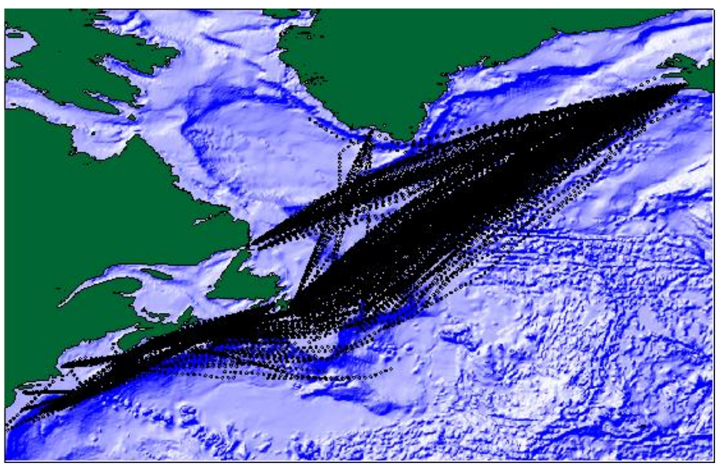
Zooplankton monitoring in the Northwest Atlantic

- the CPR[1] Survey run by SAHFOS[2] - monthly sampling, along commercial routes between Iceland and New England since 1957
- the Canadian AZMP[3] run by DFO[4] - bi-annual sampling along sections (black lines), more frequent sampling at fixed stations (red dots) since 1999

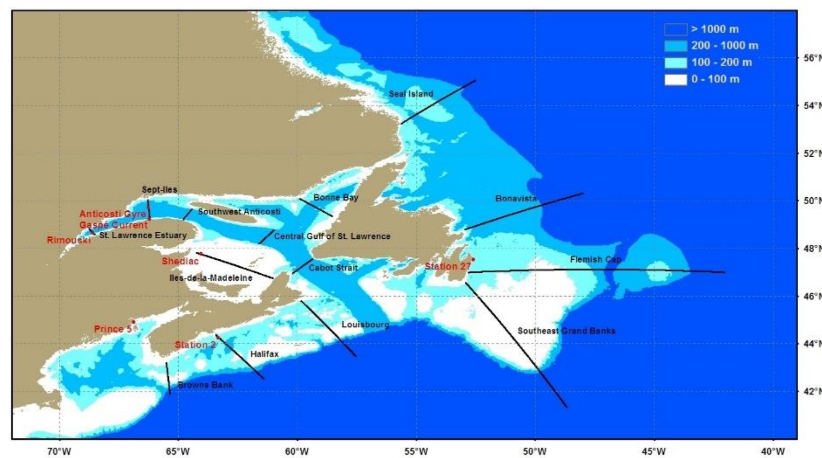
Here, abundance data are examined for some dominant and subdominant zooplankton taxa

- looking at short-term trends (1999-2013) and comparing results between programmes
- looking at long-term trends (since the 1960s) using CPR Survey data

CPR sampling stations 1957-2013



AZMP sections and fixed sampling stations

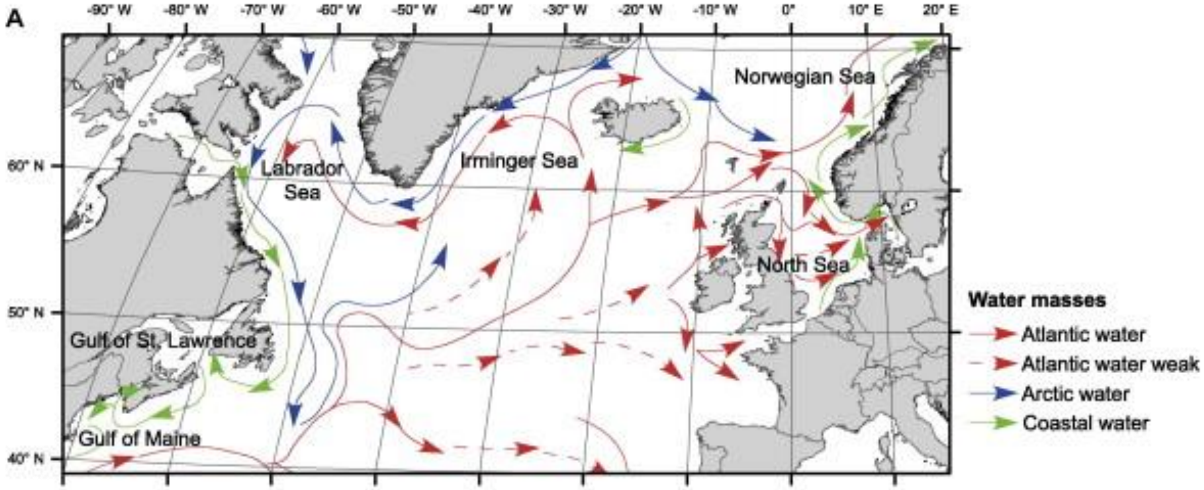


[1] Continuous Plankton Recorder, [2] Sir Alister Hardy Foundation for Ocean Science, [3] Atlantic Zone Monitoring Programme, [4] Department of Fisheries and Oceans

The Northwest Atlantic Ocean

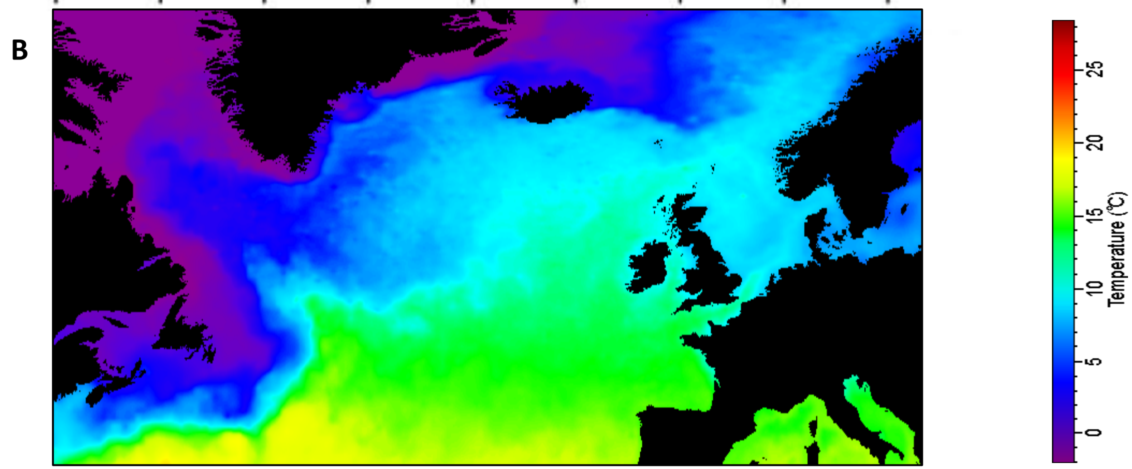
A. Major warm and cold water currents in the North Atlantic Ocean

(From Melle, W. + 19 others (2014) The North Atlantic Ocean as habitat for *Calanus finmarchicus*: environmental factors and life history traits. Prog. Oceanogr. 129, 244-284)



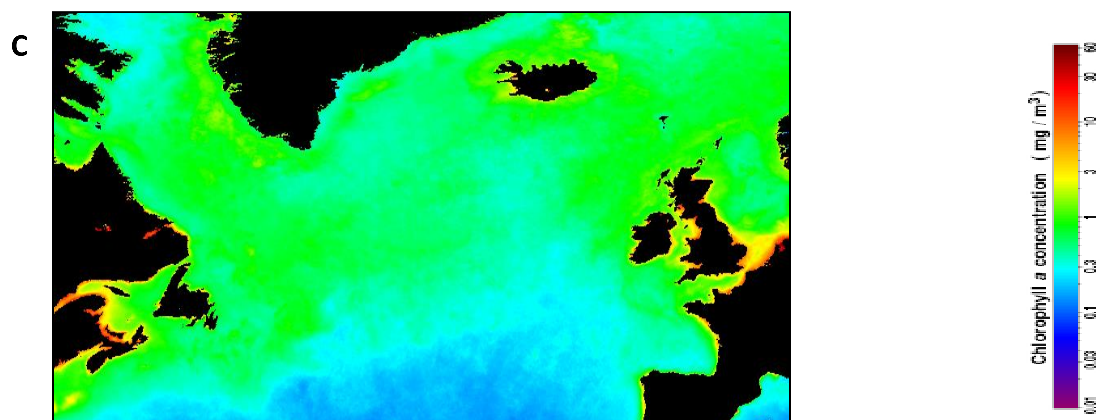
B. Average sea-surface temperature (SST) in January 2008

(From http://www.seos-project.eu/modules/oceancurrents/images/c02_north_atlantic_jan07.png)



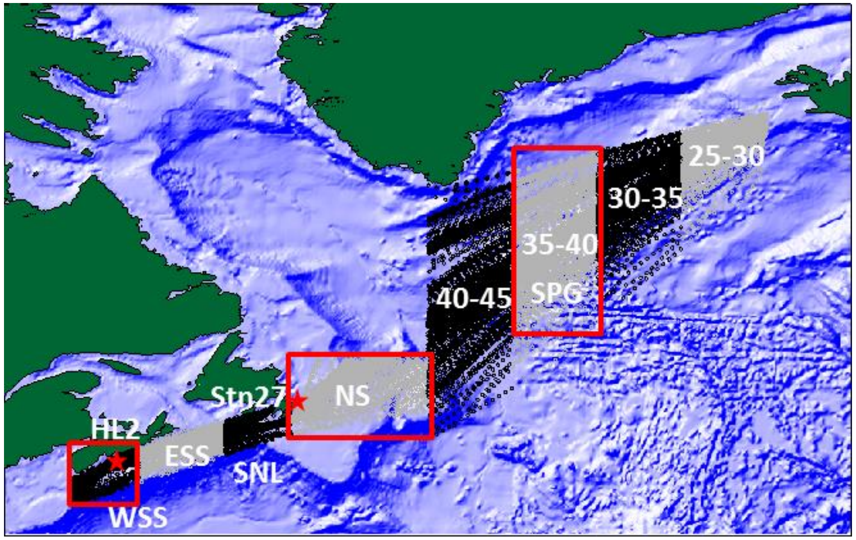
C. Average sea-surface chlorophyll concentration (SSChl) Jan 1, 2002 to Jan 31, 2008 (MODIS).

(From http://oceanworld.tamu.edu/resources/oceanography-book/phytoplanktondistribution.htm)



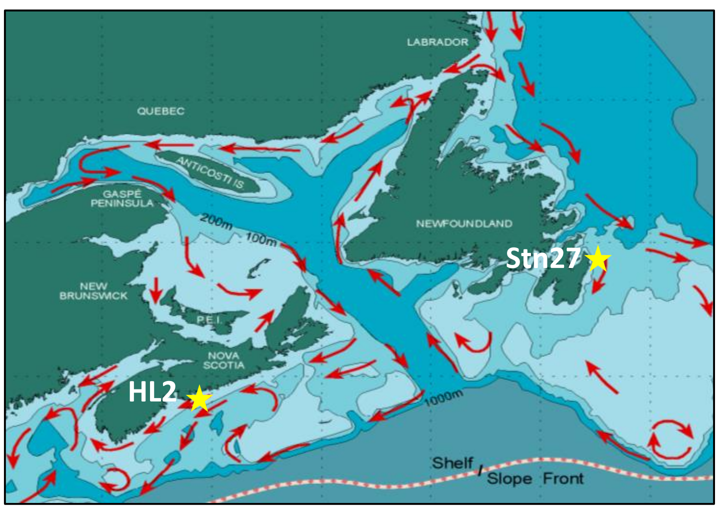
CPR and AZMP study regions and sampling methods

1) Western Scotian Shelf (WSS) and HL2 – inflows via the Nova Scotia Current and from offshore
2) Newfoundland Shelf (NS) and Stn27 – in the inshore branch of the Labrador Current
3) Sub-Polar Gyre, 35-40 (SPG) – inflows from northern (cold) and southern (warm) water regions



WSS, NS, SPG – CPR sampling, since 1957

- at ~ 7 m depth, silk mesh towed horizontally
- ~ 3 m^3 of water is filtered per sample, collected over ~ 10 km.
- Counts are semi-quantitative and data were $Log_{10}(N+1)$ transformed, where N is the number per sample.
- Transformed data were spatially averaged for each month and year sampled.



HL2, Stn27 – AZMP sampling, since 1999

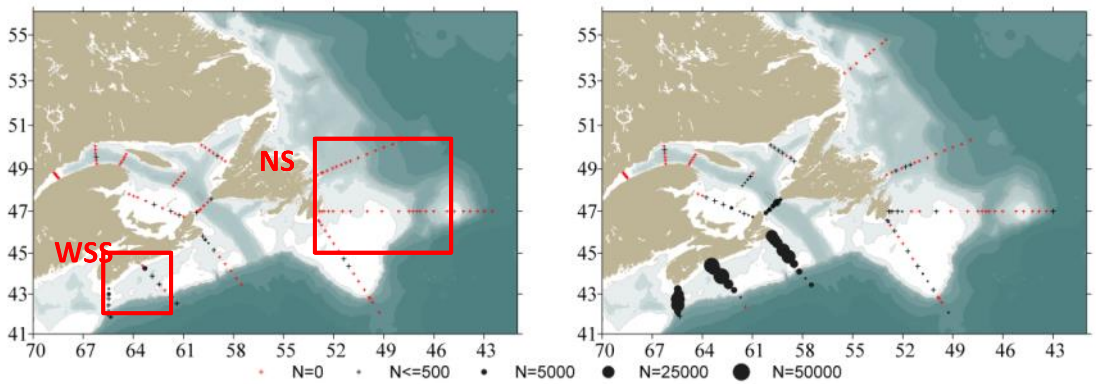
- 0.75 m diameter ring nets (200 µm mesh) towed vertically from near bottom to surface.
- Bottom depths are 150 m (HL2) and 175 m (Stn27) ~ 66 m^3 (HL2) or 77 m^3 (Stn27) of water is filtered.
- Counts were according to AZMP protocols and data were $Log_{10}(N+1)$ transformed for comparison with CPR data, where N is the number per cubic metre.
- Mostly one sample per month and year.

Spring and autumn distributions (AZMP) for two *Centropages* spp., surface-dwelling short-lived copepods

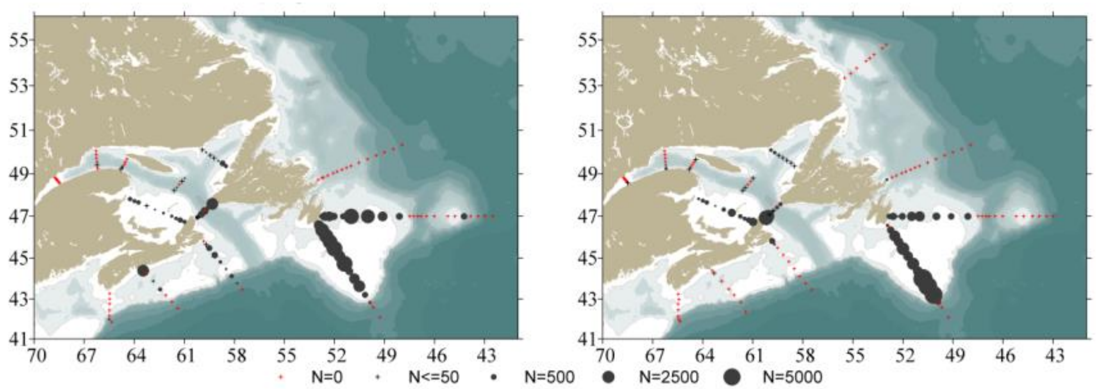
Spring

Autumn

Centropages typicus (Adults)



Centropages hamatus (Adults)



Spatial distribution maps from: Johnson, C.L, Casault, B., Pepin, P., Harvey, M. Zooplankton atlas for the Canadian northwest Atlantic continental shelf system

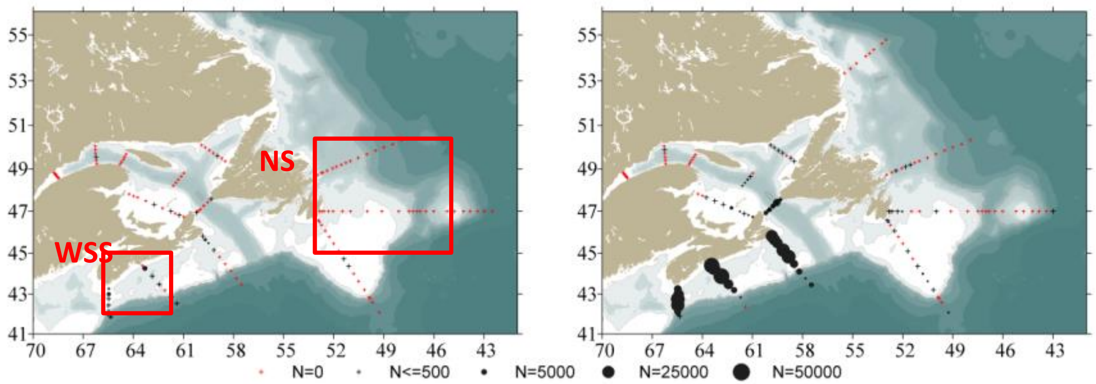
Spring and autumn distributions (AZMP) for two *Centropages* spp., surface-dwelling short-lived copepods and seasonal cycles of abundance (CPR and AZMP)

Spring

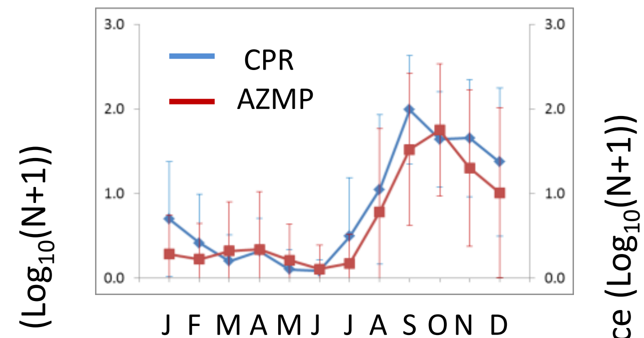
Autumn

Monthly average abundances 1999-2013

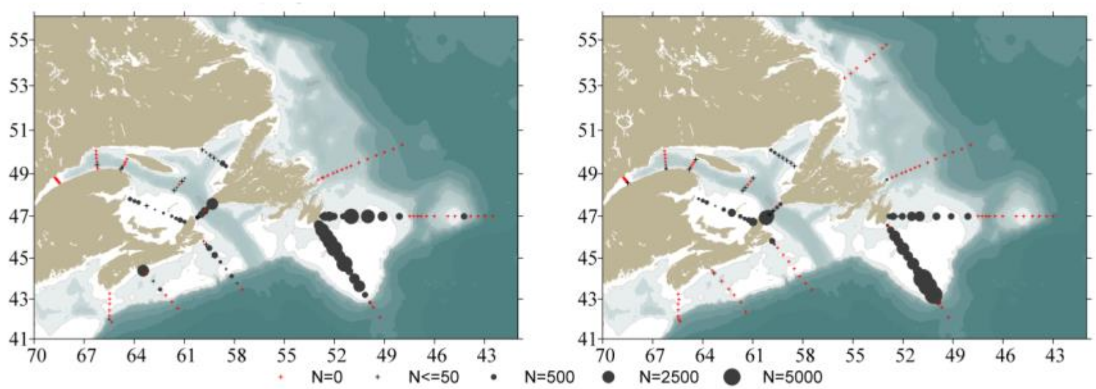
Centropages typicus (Adults)



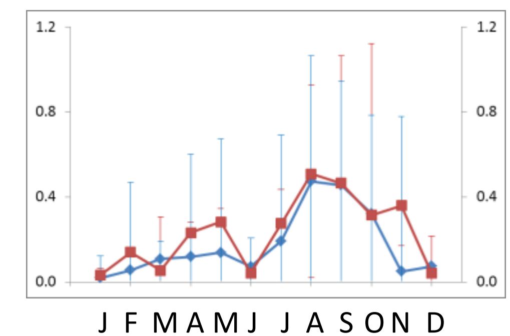
C. typicus, WSS/HL2



Centropages hamatus (Adults)



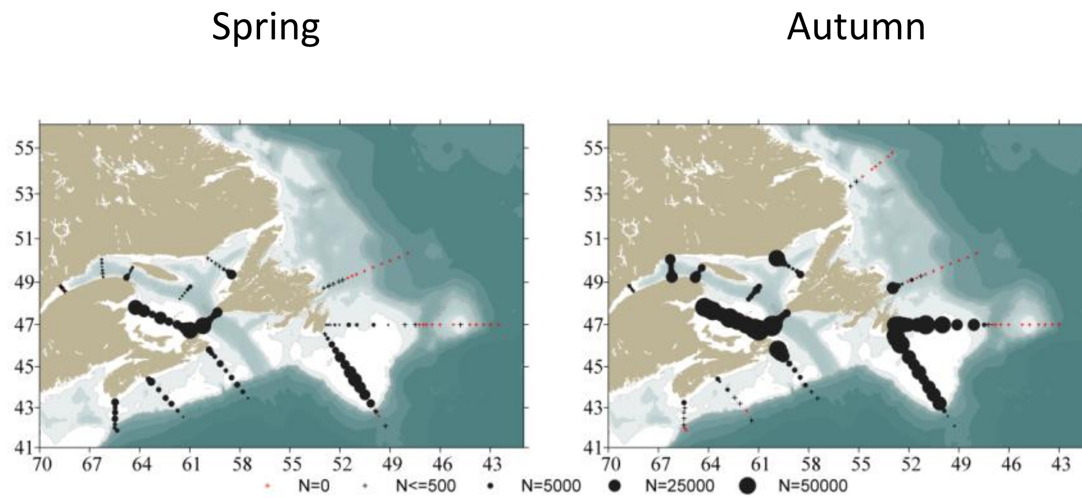
C. hamatus, NS/Stn27



Spatial distribution maps from: Johnson, C.L, Casault, B., Pepin, P., Harvey, M. Zooplankton atlas for the Canadian northwest Atlantic continental shelf system

Spring and autumn distributions (AZMP) and seasonal cycles of abundance (CPR and AZMP) for *Temora* spp., a surface-dwelling short-lived copepod species (or not?)

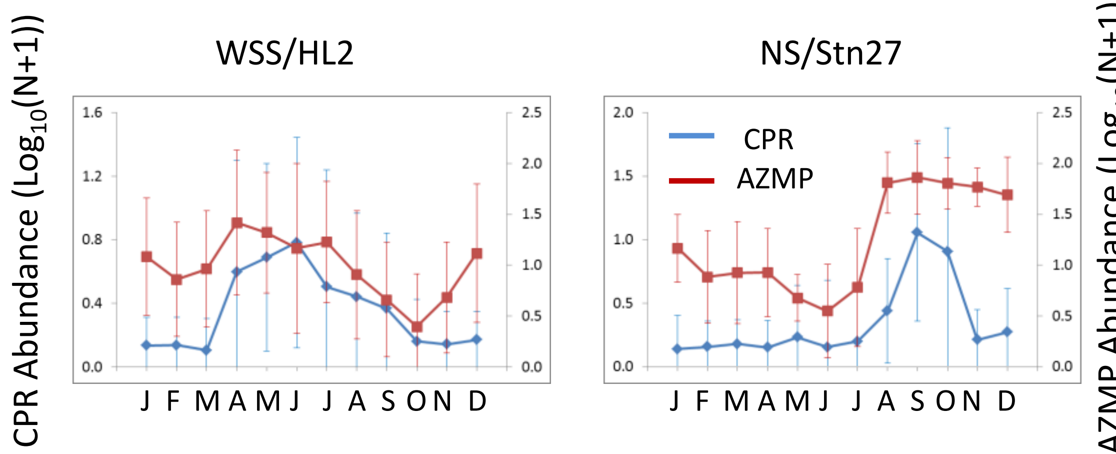
Temora spp. (All stages, mostly *T. longicornis*)



T. longicornis (Adults/CVs)

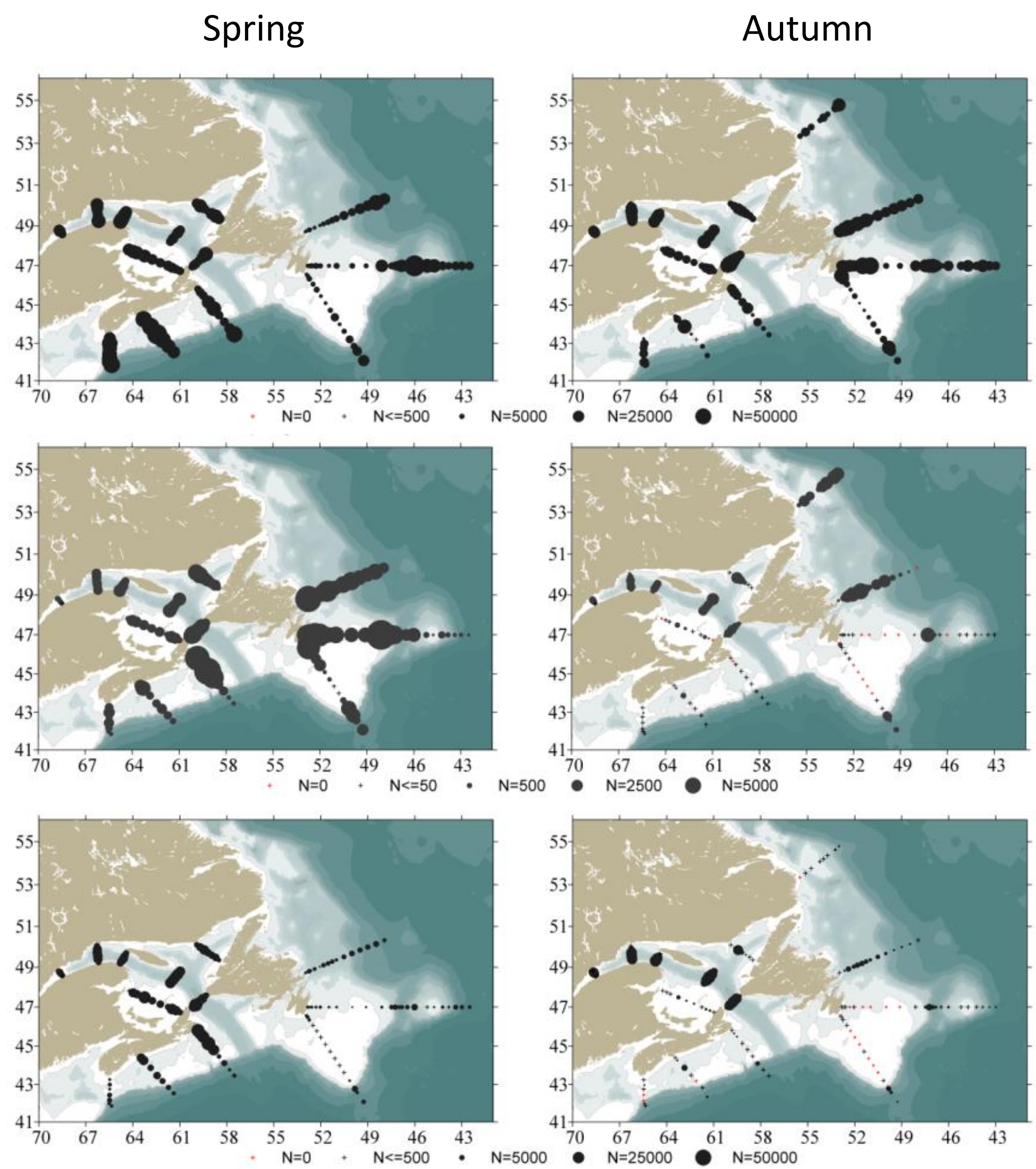
CPR abundance peaks are in spring/summer on the WSS and in autumn on the NS.

CPR data show greater differences between high and low numbers than AZMP data, suggesting some *T. longicornis* are sometimes at depths >10 m.



Spring and autumn distributions (AZMP) for three *Calanus* spp., seasonal (ontogenetic) vertical migrants

Note the differences in scale



Calanus finmarchicus (All stages)
- ubiquitous

Calanus glacialis (All stages)
- more abundant in spring than in autumn
- only abundant in the NE in autumn

Calanus hyperboreus (All stages)
- more abundant in spring than in autumn
- more abundant on the SS than on the NS, in the outflow from the GSL[1]

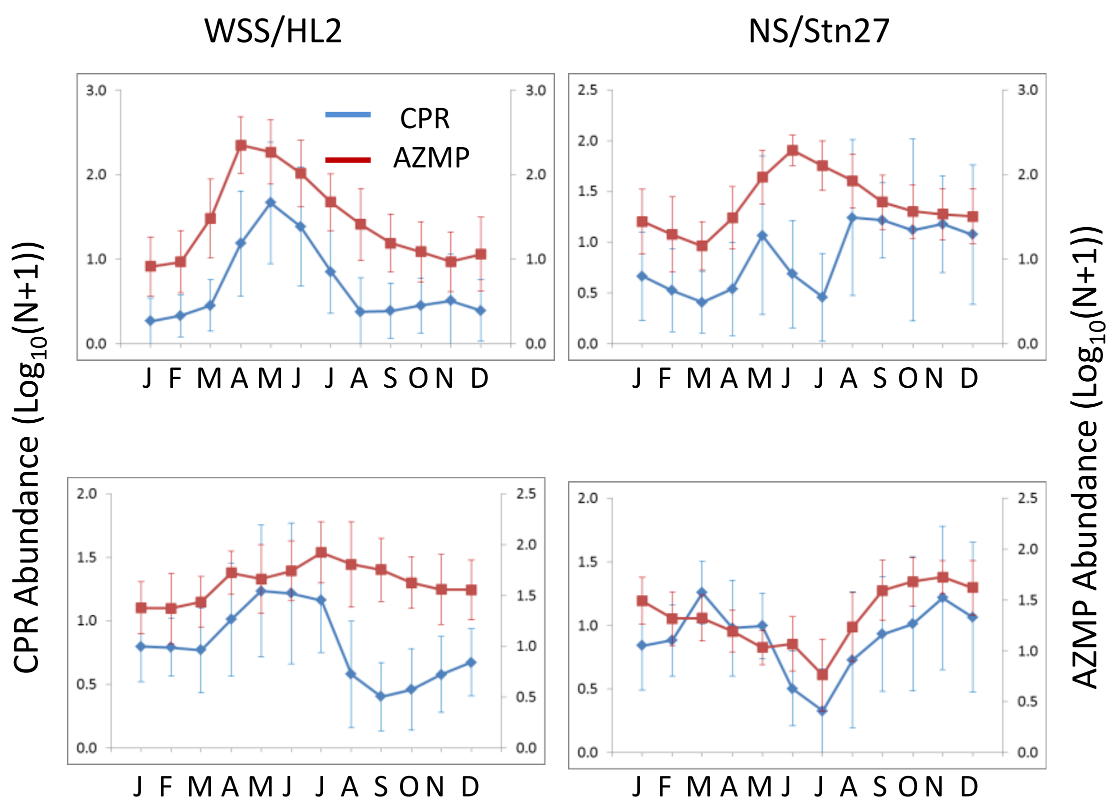
[1]Gulf of St Lawrence

Seasonal cycles of abundance (CPR and AZMP) for *Calanus* I-IV and *C. finmarchicus* V-VI, seasonal (ontogenetic) vertical migrants

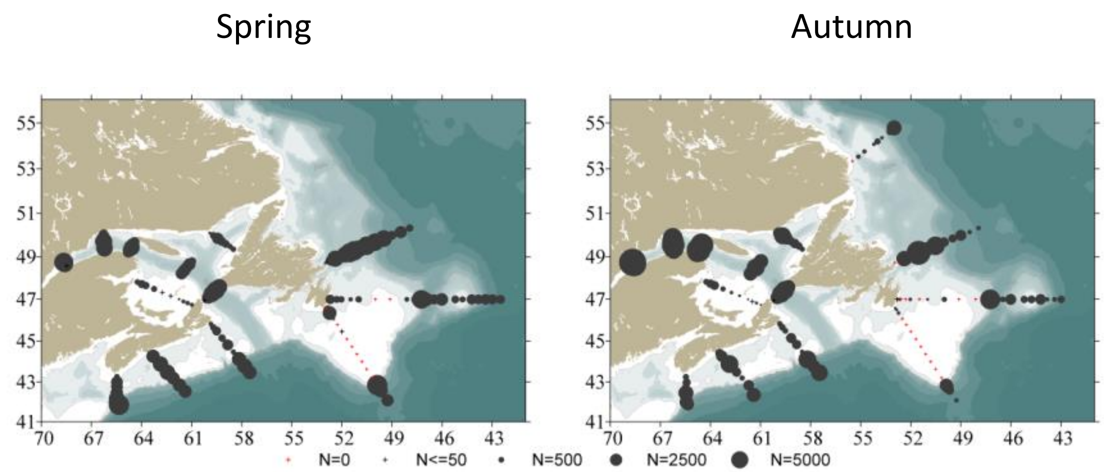
CPR sample analysis groups *Calanus* young stages: AZMP *Calanus* young stage abundances were grouped in the same way.

Calanus I-IV (*C. finmarchicus* I-IV (mostly) + *C. glacialis* I-IV + *C. hyperboreus* I-II)
WSS/HL2 - Seasonal cycles are similar.
NS/Stn27 - AZMP shows the expected pattern, but CPR shows a dip in Jun-Jul.

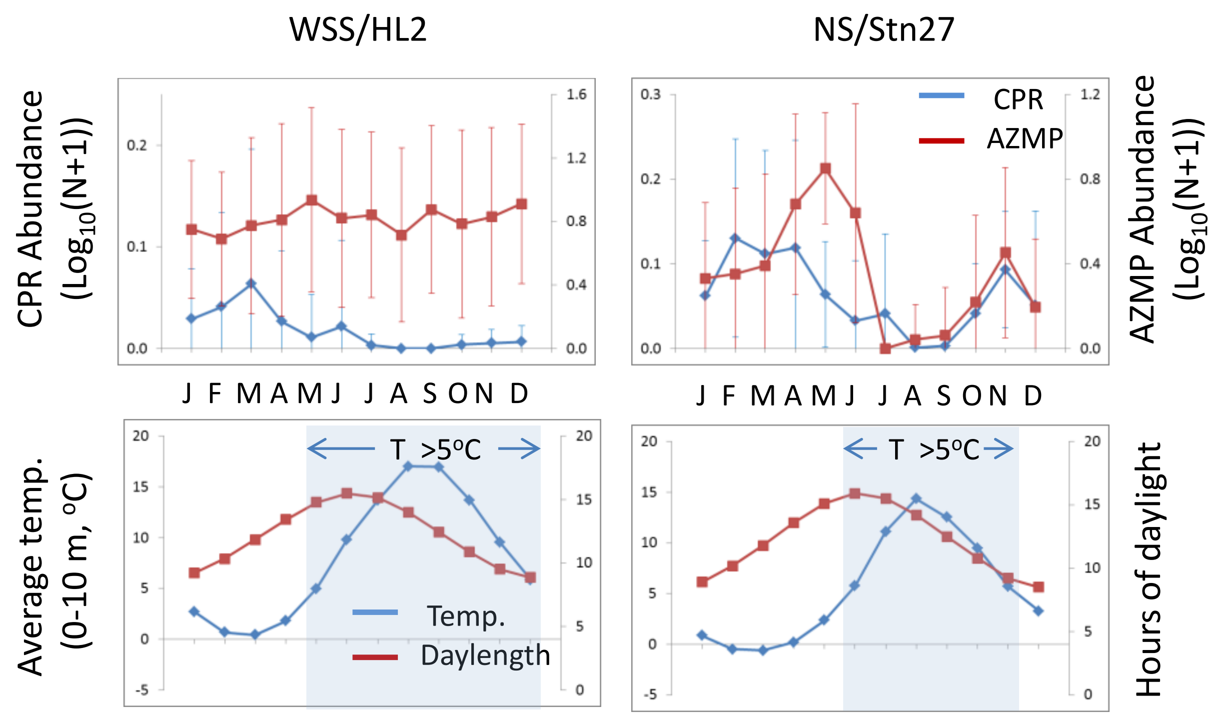
C. finmarchicus V-VI
WSS/HL2 - AZMP numbers include CVs/adults at depth: CPR numbers show when they are at the surface.
NS/Stn27 - Seasonal cycles are quite similar and both show a mid-summer dip.



Spring and autumn distributions (AZMP) and seasonal cycles of abundance (CPR and AZMP) for *Metridia longa*, a diel vertical migrant



Metridia longa (Adults)
- more abundant in deep areas
- similar abundances in spring and autumn



WSS/HL2 - AZMP, no seasonal signal: CPR numbers, low relative to AZMP numbers, and highest in winter.

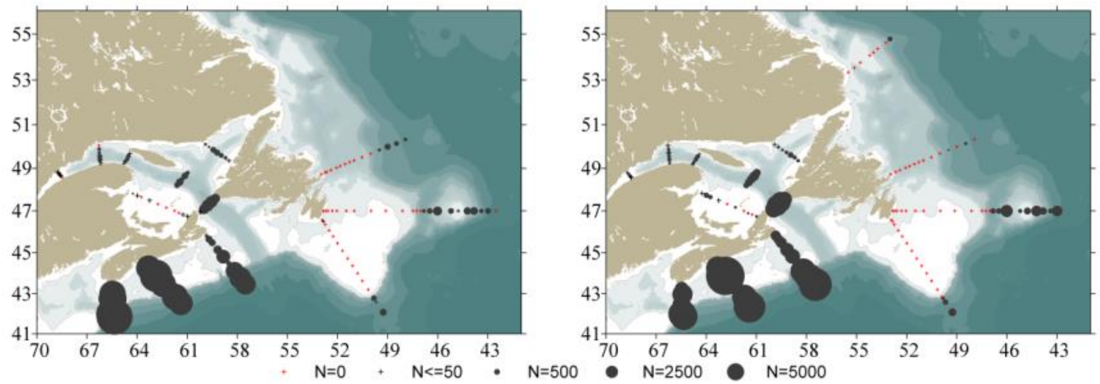
NS/Stn27 - Peak abundances in spring are offset for CPR *vs.* AZMP. Both datasets show low levels in summer.

In both regions *M. longa* seem to avoid the surface layer when near surface temperatures are >5°C.

Spring and autumn distributions (AZMP) and seasonal cycles of abundance (CPR and AZMP) for *Metridia lucens*, a diel vertical migrant

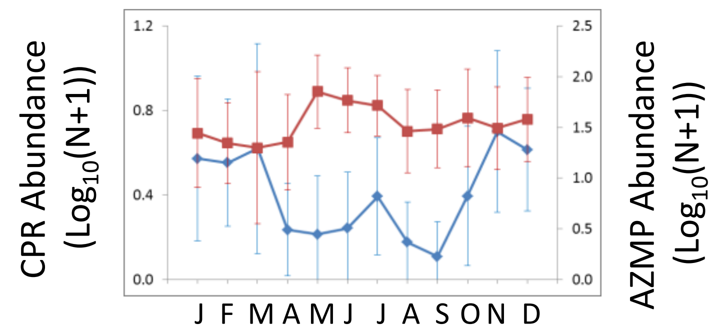
Spring

Autumn



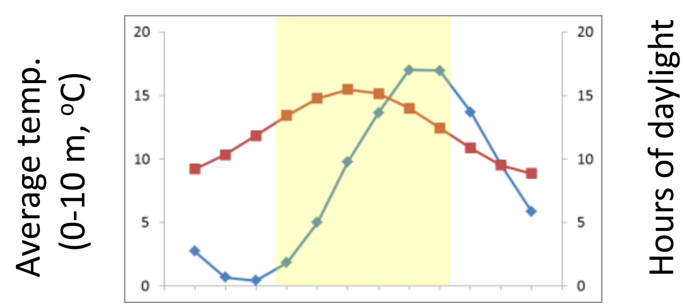
Metridia lucens (Adults)

- similar abundances on the WSS in spring and autumn
- absent from the NS



WSS/HL2 - AZMP numbers: no strong seasonal signal

CPR numbers: high Nov-Mar and low (mostly) Apr-Sep.



The decrease in CPR abundance over the summer months may be a response to high light intensities, rather than high temperatures.

Conclusions from observations of seasonal cycles of zooplankton abundance

The results of CPR and AZMP sampling are complementary and taken together

1) show differences in catchability associated with taxa that are surface-dwelling or exhibit vertical migrations linked to

- life history strategy
- temperature
- light intensity

or some combination of these

Conclusions from observations of seasonal cycles of zooplankton abundance

The results of CPR and AZMP sampling are complementary and taken together

1) show differences in catchability associated with taxa that are surface-dwelling or exhibit vertical migrations linked to

- life history strategy
- temperature
- light intensity

or some combination of these

2) suggest that trends in annual abundances

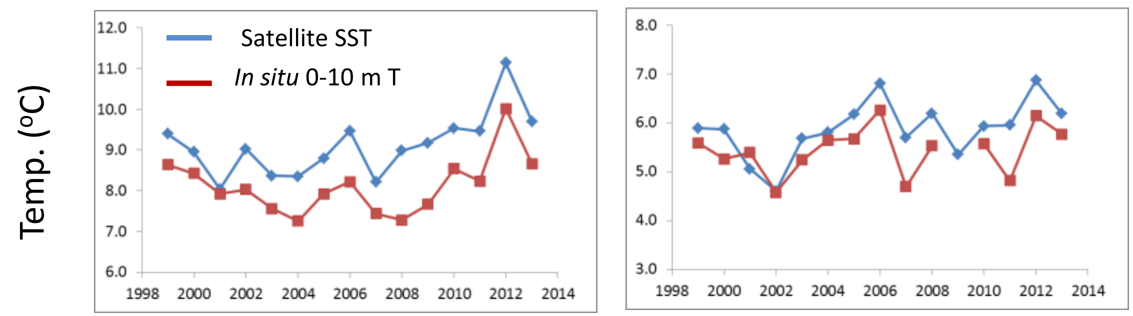
- should be similar for surface-living taxa but
- may differ for taxa that respond to environmental change by changing their vertical distributions/migration behaviour

Short-term trends and variability in environmental conditions (1999-2013)

Annual average temperatures
- satellite *vs. in situ* data

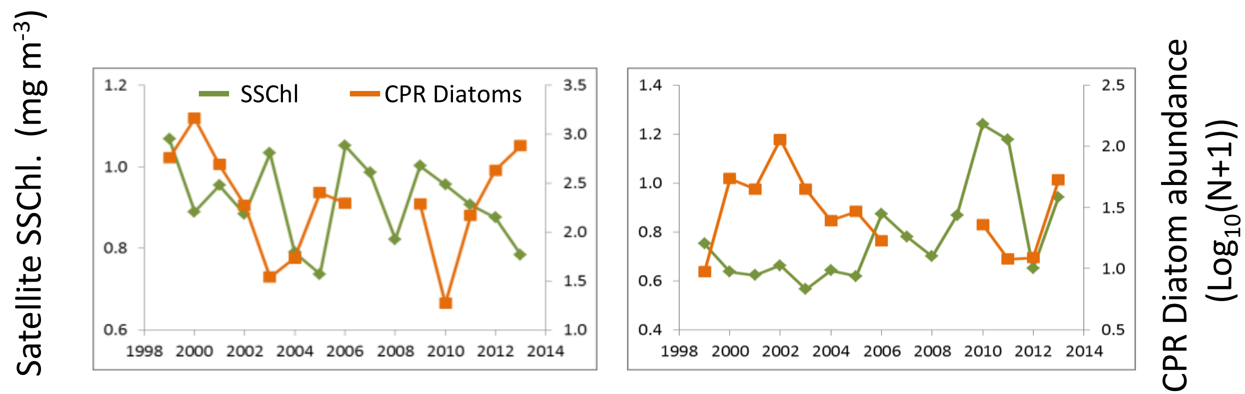
No significant trends
WSS, HL2 – record high in 2012.
NS/Stn27 – peaks in 2006 and 2012.

WSS/HL2 NS/Stn27



Annual average phytoplankton levels
- satellite *vs.* CPR diatom abundance

WSS/HL2 – no significant trends
NS/Stn27 – significant upward trend for SSChl, no trend for diatom abundance



Temperature and phytoplankton indices were not related.

Short-term trends and variability in annual average abundances for four zooplankton taxa as determined by CPR and AZMP sampling, 1999-2013

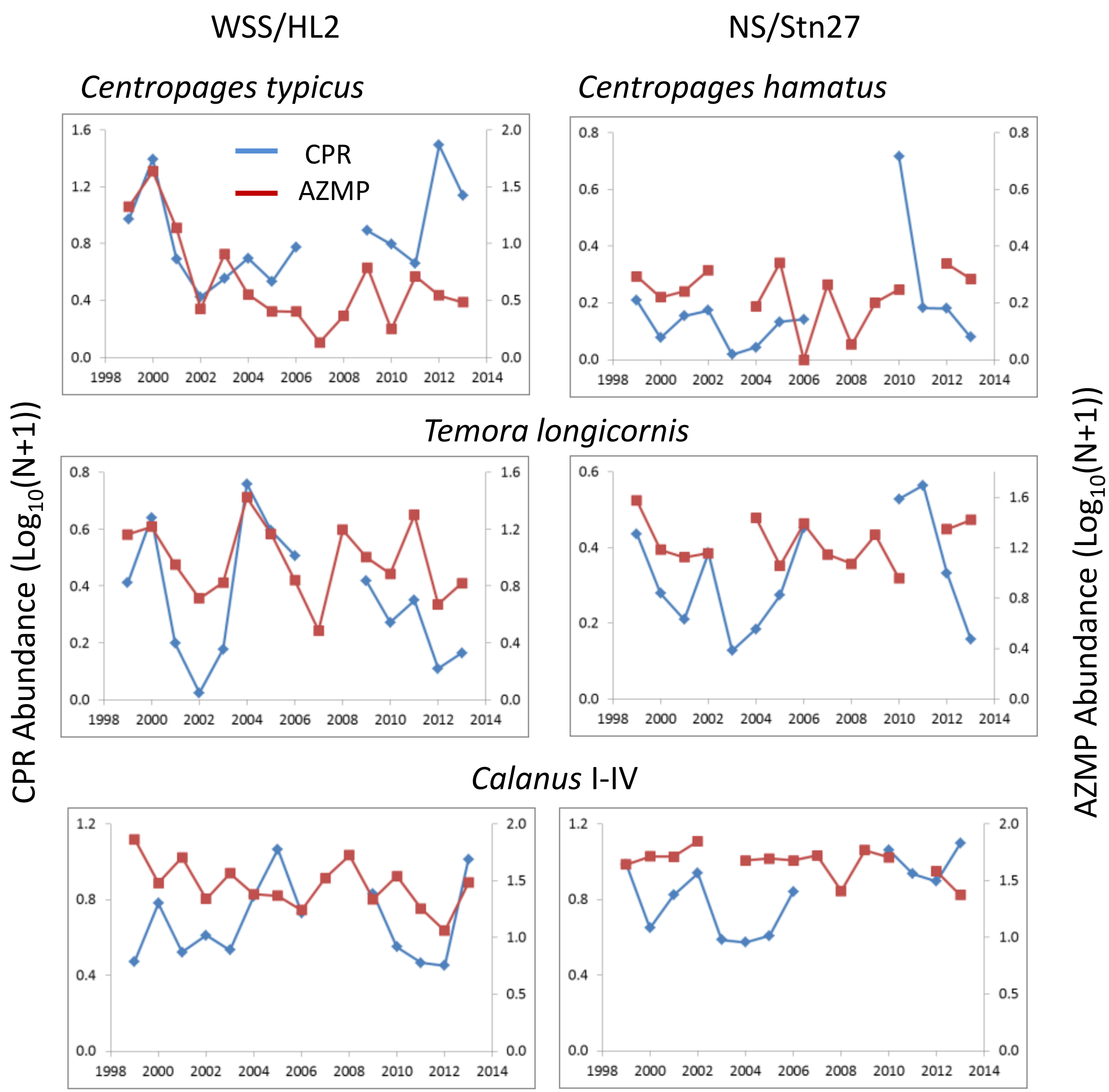
C. typicus – CPR and AZMP trends are similar until the really warm year, 2012.

C. hamatus – CPR has one real outlier in 2010.

T. longicornis – CPR and AZMP abundances are correlated for WSS/HL2 (r^2 = 0.66, P<0.001), but not for NS/Stn27.

Calanus I-IV – CPR trends are not significant: AZMP trends are slightly downward.

CPR and AZMP numbers were both low on the WSS in the very warm year (2012), but the CPR value was equally low in 1999, not an especially warm year.



Summary of comparison of CPR and AZMP annual average abundances trends and relationships with environmental variables, 1999-2013

- Zooplankton abundances showed variability but few trends

Taxon	Region	Trends CPR/AZMP	CPR vs. AZMP	CPR vs. SST	CPR vs. SSChl	CPR vs. Diatoms	AZMP vs. SST	AZMP vs. SSChl	AZMP vs. Diatoms
C. typicus	WSS/HL2	No trend/↓		0.41*		0.33*			
T. longicornis		No trends	0.66**		0.49*				
Calanus I-IV		No trends			0.36*				
C. finmarchicus V-VI		No trends					0.49**		
M. longa		No trends	0.42*						
M.lucens		↑/No trend							
C. hamatus	NS/Str 27	No trends			0.46*				
T. longicornis		No trends			0.49*				0.60**
Calanus I-IV		No trend/↓			0.46*		0.32*		
C. finmarchicus V-VI		No trend/↓							
M. longa		No trends							

Numbers are r^2 values. Numbers in black (red) denote positive (negative) correlations, *P<0.05, **P<0.01.

Summary of comparison of CPR and AZMP annual average abundances trends and relationships with environmental variables, 1999-2013

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				SST	SSChl	Diatoms	SST	SSChl	Diatoms
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- AZMP annual abundances may reflect indirect environmental effects so that, for example, for the two *Calanus* taxa the negative relationships with temperature may be related to changes in source waters.
- Other taxa gave similar results, *e.g.* CPR abundances for *Pseudocalanus* spp. were positively correlated with phytoplankton and AZMP abundances for *C. glacialis* and *C. hyperboreus* were negatively correlated with SST.

Taxon	Region	Trends	CPR vs.	CPR vs.			AZMP vs.		
		CPR/AZMP	AZMP	SST	SSChl	Diatoms	SST	SSChl	Diatoms
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Long-term changes in zooplankton abundance and environmental conditions in the NW Atlantic - CPR sample inventory for the WSS, NS and SPG regions

Month

Year

WSS

Year/Month	1	2	3	4	5	6	7	8	9	10	11	12
1957												
1958												
1959												
1960												
1961							11	10	8	9	7	
1962	7	9	9		9	10	9		9	10		
1963		7	1			5	8	5		2		
1964	1				6	2	7		9	2		6
1965			7		6		9	5	1	4		2
1966			7		6		2	7	1	7	6	
1967	10		7	7		8					10	
1968	8	7		7	9	5	7		6	9	3	1
1969		1	3			9	9	14		19		3
1970	7		9	7	7		9	7		10	7	
1971	7		10	9		7		7	7		5	
1972		9	8				8		7		8	
1973	7				4	9		7		7		
1974					7					2		
1975												10
1976		1		9	2							
1977												
1978												
1979												
1980												
1981												
1982												
1983												
1984												
1985												
1986												
1987												
1988												
1989												
1990												
1991			9		9	5	10		8	1	10	
1992	8	10	6	4		8	10	11	5	3	19	8
1993	6	7	18		14	13	8	8	11	3	11	11
1994	7		11	2	8	11	3	10	7	21	9	10
1995		11	10	10	12	9	10	9	10	10	9	11
1996	9	10	10		10	10	5		9	10	9	10
1997	9	10	17	11	8	9	8		9	9	9	10
1998	10	10	20	10	10	11	9	7	6	3	7	6
1999	6	10	15	3	11	3	10	8	11	9	10	10
2000	19		20	9	3		10	8	10	10	7	3
2001	10	11	3	9	10	10	20	9	10	10	10	9
2002	9	10	10		11	10		9	9		2	10
2003	9	9	10	10	9	9	10	11	10	9	9	9
2004	10	9	8	10	10	9	8	8	6	12	17	7
2005	2	7	10	10		10	7	9	10	15	2	9
2006	8	9	9	7	10	9	10	9	10	19	9	7
2007	9	10	11	5	4	9						
2008					7	3	7	3		10		
2009	7	8	1	10	6	3		7	5	3	8	6
2010	6		6	1		7	5		8	6	8	
2011	9		7	6	8	7	9	9	7		8	5
2012		9	4	9	10	8	9		8	9	7	8
2013	7		7	2	8	7	9	9		14		6

NS

Year/Month	1	2	3	4	5	6	7	8	9	10	11	12
1957												
1958												
1959												
1960		13	3	7								
1961			7		11							
1962	15	1	14	24	2	6						8
1963		16	16	8	7					1		8
1964	15	16	7	7	8	14						11
1965		9	14	10	9				24			9
1966		23	14	11	13		3			21	14	
1967		12	7	12	3	11	11	4			5	
1968	7	15	10	7	13	13	4					4
1969	17	14	12	17	2	1	14		3	2		13
1970	16		16	16	15	12	3	3		3	3	19
1971		10		13	11	11	14	11	15		3	12
1972			2		6	10	3	9	10		6	6
1973		1				7		15	3	7		10
1974		1			3	4	13	11	10	10		11
1975				8			9	11		10	6	
1976	15			14		10						8
1977	13		8	6		5		15	9			11
1978	7	13		2				10				14
1979			4									
1980												
1981												
1982												
1983												
1984												
1985												
1986												
1987												
1988												
1989												
1990												
1991					24	9	14	7	13	12	12	
1992	24	4	14			14	14	12	11	14	13	12
1993	11	8		7		14	27	9	12		17	8
1994	14		2	6	10	10	13	9	11	13	11	24
1995		11	5	14	13	12	10	11	13	12	21	4
1996	12	13	14	17	13	14	12		13	11	3	13
1997	11	5	13	18	15		11	8	14	13	15	14
1998	14	15	14	26	13	13	9	11	13	13	10	13
1999	10		12	31	20	14	10	13	12	14	14	15
2000	14	19	28	17	12		10	12	11	16	14	14
2001	13	13	16	13	13	13	14	25	11	13	11	9
2002	18	16	8		20	13		14	10	8	13	14
2003	13	17	4	17	8	12	11	10	4	19	13	14
2004		25	13	13	12	10	12	12	13	13	14	13
2005	25	18	14	17			13		13	12		24
2006	14	14	14	13	14	13	13	14	12	14	22	3
2007	5	16	17			11						
2008							5			1		13
2009	14	14		6	9							3
2010	22	14	14	15	19		3			1	15	
2011	13	14	19	14	3	3	3		4		1	
2012	13	14	16		14	4		6	11	2	14	4
2013	14	16	15	15	14	11	7	9	9	18		24

SPG

Year/Month	1	2	3	4	5	6	7	8	9	10	11	12
1957								2		1		3
1958					1		3		2			
1959					10	9	9		3	10		3
1960		4	12	17			10		10	2	8	11
1961			14		13			8	6			
1962	9			11	13		9	9		18		17
1963		2	7	11	8	6	6		6	5	7	6
1964	2	4	8	8	8			5	6	7		11
1965			13	15	13		10	8	23		9	7
1966		6	17	1	12	22		9		10	8	10
1967		9	11	23		22	11		8	8	5	15
1968	5	7	8		26	13		8			10	10
1969	10	2	14	1	12	16	12		9	10	10	11
1970			12	11	12	12		10	9	9	9	3
1971		8	17	9	12		2	12	9	14	9	
1972		12	15	5	28	14	13	19	12		20	11
1973	2		16	16	15	12	4	12	9	12	9	6
1974		8	13		8	11	11	12	12	14	7	11
1975		4	9					11	9	11		
1976	9			12		12	8	9	9	11	9	11
1977	10		13	11		12	5	11	13		12	10
1978	5	7	28	12				9	12			
1979	3	10	15	12	12		9	9	5	12	7	11
1980			9	12	12	13			3			
1981				11	3	8		4				
1982		6					9	11	9			
1983			2		7	12	12	8	12	9		
1984			11	6	11	11	9	2	9		7	
1985			13	15	11		24	9	10		9	
1986			11	9	12		9	10	15	4		
1987												
1988												
1989												
1990												
1991			14		25	12	3	11	12	11	11	
1992	2	14	8		6	7	12	1	11	11	12	10
1993	1		7	17		7	18	17	12	10	13	11
1994	10		14	11	9	12	12	12	12	11	10	11
1995	12	12	15	13	11	12	12	12	13	11	12	9
1996	10	11		14		22	12		11	12		
1997	7				12		8	12	12	12	12	5
1998	7	10	8	11	23	12	12	11		11	11	12
1999	7	8	13	19	15	11	9	12		11	11	11
2000	6	11	11	13	25		12	4	10	11	12	8
2001	5	6	12	12	11	12	11	12	24	12	10	12
2002	8	12	14		13	6		2		6	9	6
2003	10	6	13		9	8	8	8	8	8	17	10
2004		18	11	9	12	12	10	12	12	11	13	
2005	13	7	13	12		11	11	12	12		12	9
2006	17		11	11	12	11	12	12	11	12	11	14
2007	6	8	14	11		8						
2008						10	9	10	9	10	14	12
2009	12			13	13				9	12	11	9
2010	8	8	12	11	11	10	9	10	10	9		8
2011	10	1	12	10					9		8	8
2012	10	3	11		22	9		9	10		11	10
2013	12	11	11	12	11	21	9	23		7	11	10

1960s

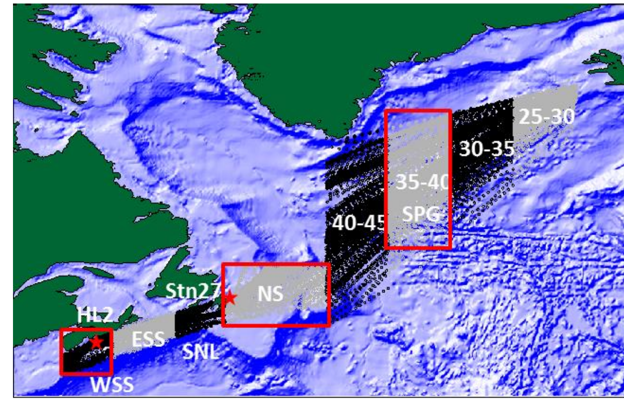
1970s

1980s

1990s

2000s

2010s



Sampling in the WSS and NS regions was “patchy” before the 1990s.

Metrics of plankton abundance used here:

Annual averages - calculated for years with ≥8 months of sampling and no gaps >2 months, using linear interpolation to fill in for gaps ≤2 months

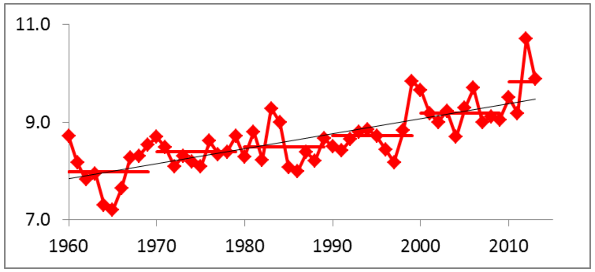
Decadal annual averages - calculated by averaging monthly data for each month within a decade (as shown by brackets) and by averaging these decadal monthly averages to give decadal annual averages

Long-term changes in environmental conditions in the NW Atlantic
- Sea-surface temperatures and CPR diatom abundances

WSS NS SPG

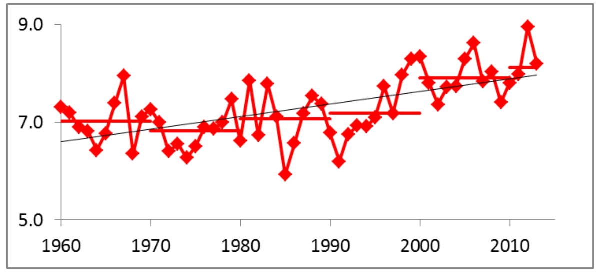
Annual average sea-surface temperature (SST, °C) - influenced by the NAO, currents and solar heating (latitude) – thanks to Todd O'Brien for these data

WSS



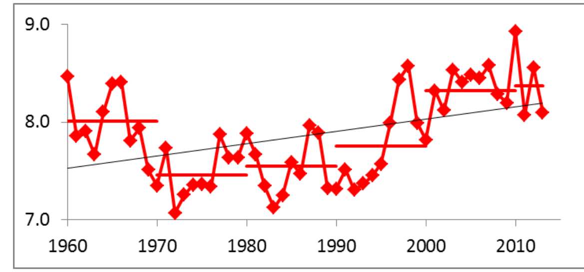
- increasing since the 1960s

NS



- increasing especially since the mid-1980s

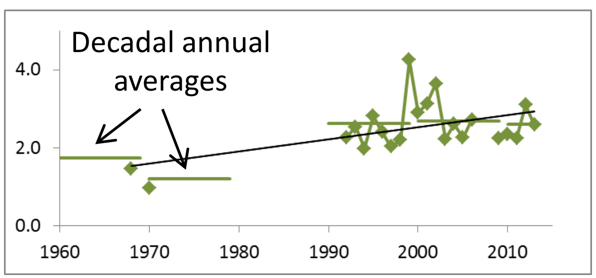
SPG



- increasing especially since the 1970s

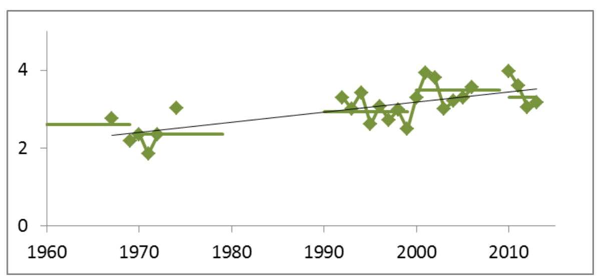
Annual average CPR diatom abundance ($Log_{10}(N+1)$) - influenced by stratification, nutrients, light and temperature

WSS



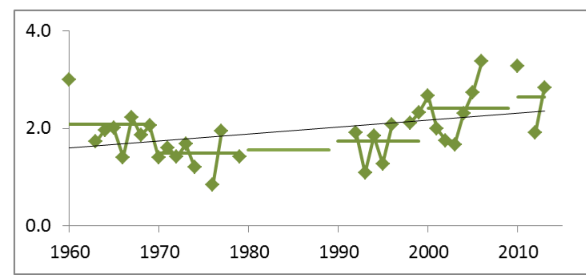
- higher since the 1990s, correlated with SST ($r^2 = 0.23$, $P<0.05$)

NS



- higher since the 1990s, not related to SST

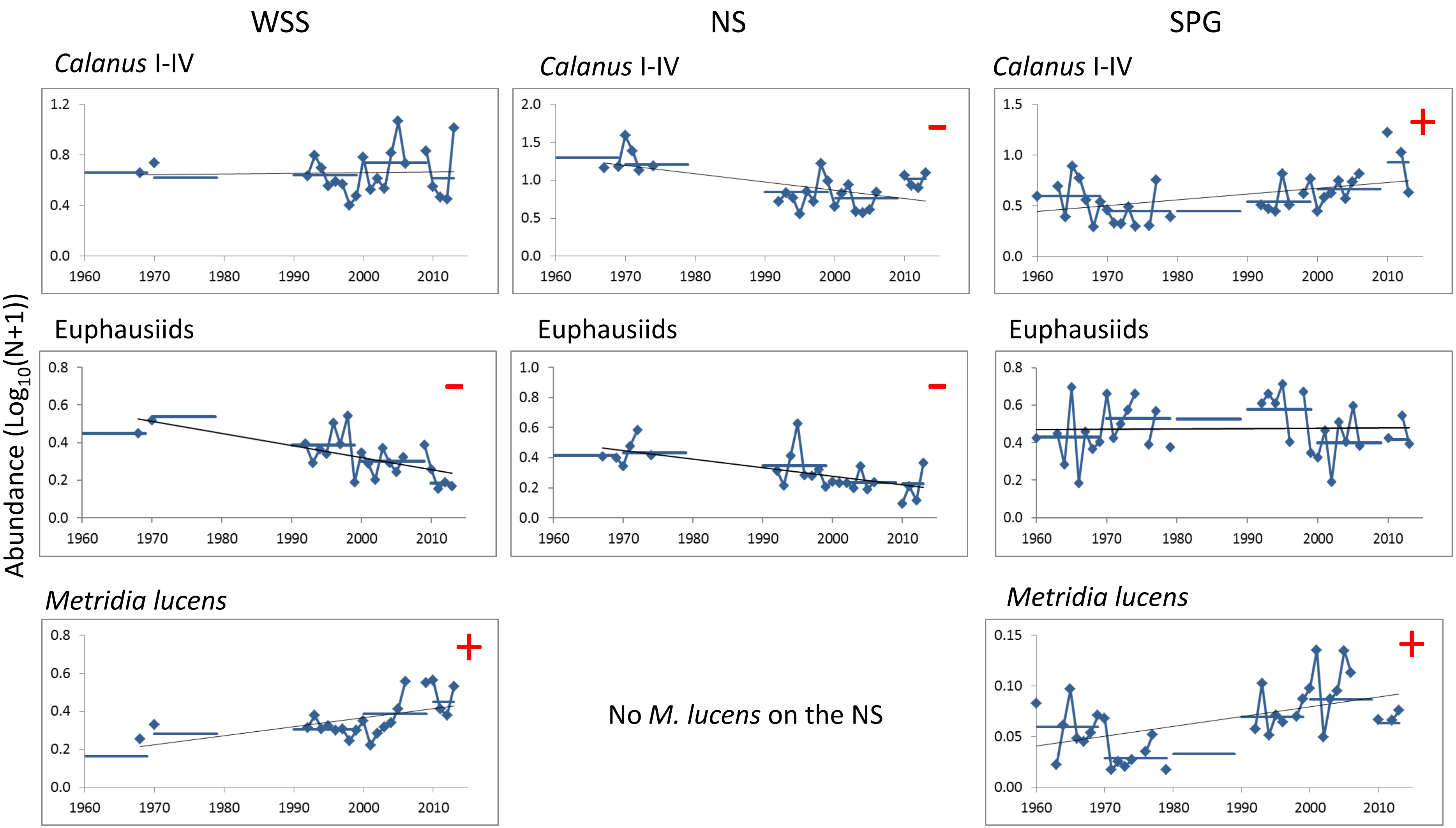
SPG



- increasing since the 1970s, correlated with SST ($r^2 = 0.39$, $P<0.001$)

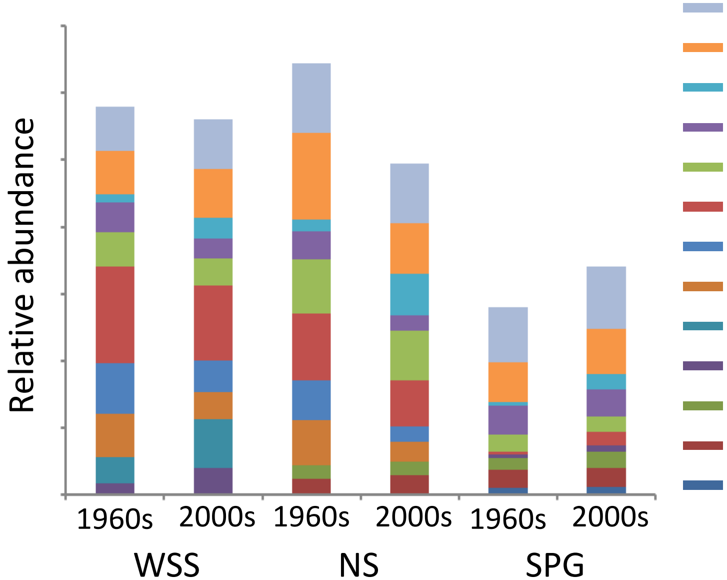
Long-term trends and variability in the abundance for three zooplankton taxa in the NW Atlantic

- Among the 10 most abundant taxa at each site only 11 of the 30 taxa/region combinations showed significant long-term trends.
- For these and other taxon/region combinations trends were up or down, depending on which years are included.



Long-term (1960-2013) trends in CPR annual average abundances for the ten most abundant zooplankton taxa in the WSS, NS and SPG regions

Relative abundance of the 10 most abundant taxa in the 1960s and 2000s



Trends in abundance and correlations with SST and diatom abundance

Region	WSS			NS			SPG		
Taxon	Trend	SST	Diatoms	Trend	SST	Diatoms	Trend	SST	Diatoms
C. finmarchicus V-VI									
Calanus I-IV				↓		0.20*	↑	0.48**	0.24**
Copepod nauplii			0.21*	↑	0.21*	0.41**	↑	0.17*	0.31**
Euphausiids	↓	0.42**	0.39**	↓	0.39**	0.35**			
Oithona spp.									
Para/Pseudocalanus							↑	0.33**	0.42**
Pseudocalanus spp.									
T. longicornis									
C. typicus		0.52**							
M. lucens	↑	0.20*					↑	0.28**	0.26**
Hyperiid amphipods									
Limacina spp.				↑		0.27**		0.14*	
Euchaeta norvegica							↑		

Numbers are r^2 values. Numbers in black (red) denote positive (negative) correlations, *P<0.05, **P<0.01.

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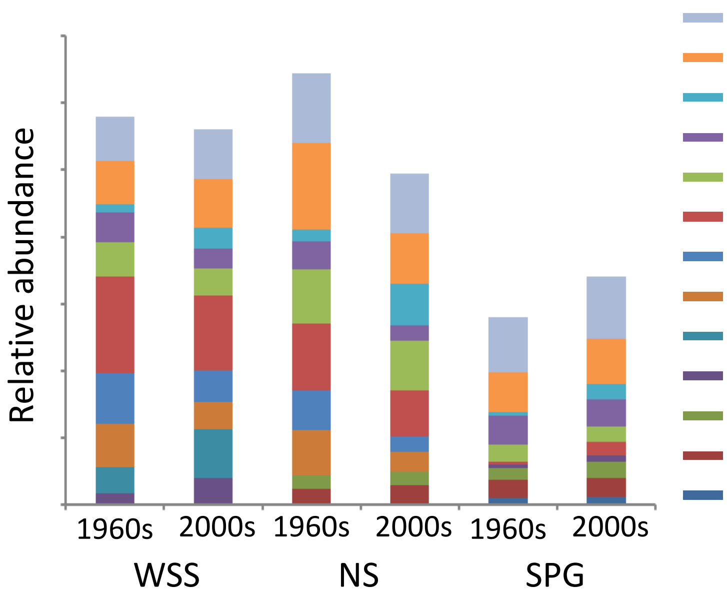

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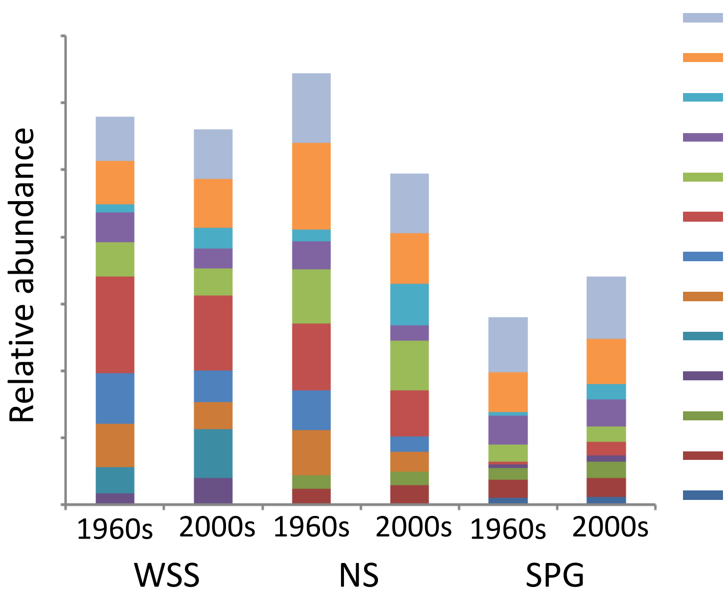

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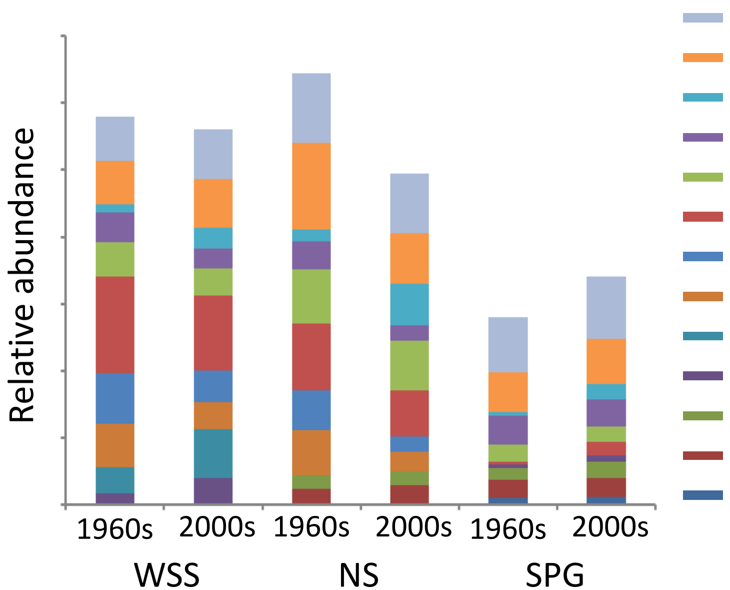

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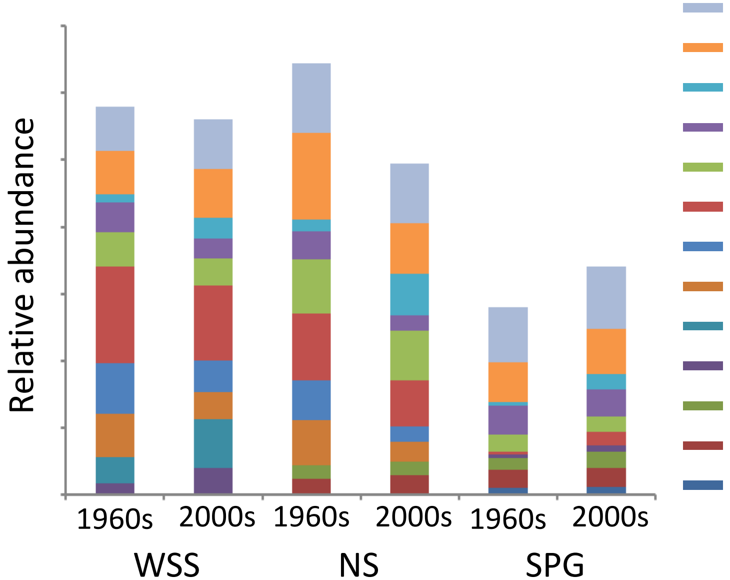

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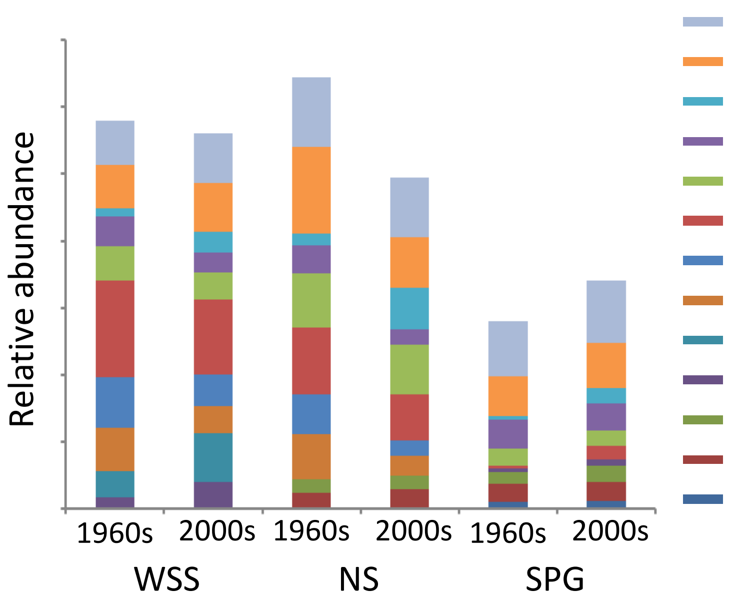
Relative abundance of the 10 most abundant taxa in the 1960s and 2000s



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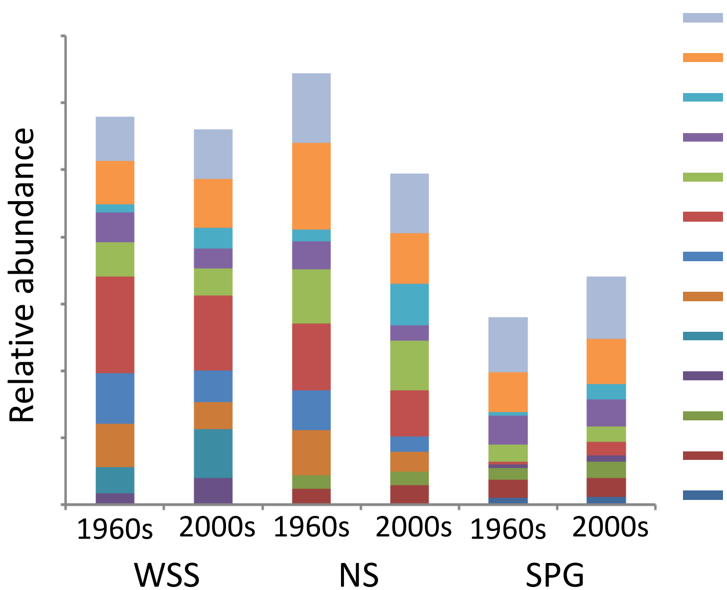
- Correlations with environmental variables may sometimes be spurious.

Relative abundance of the 10 most abundant taxa in the 1960s and 2000s



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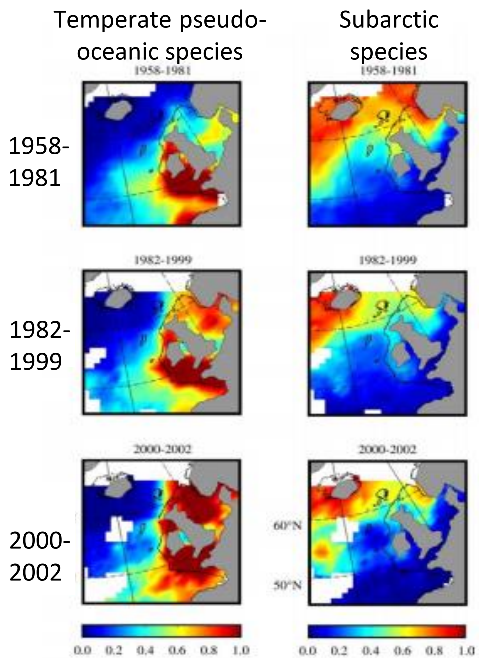
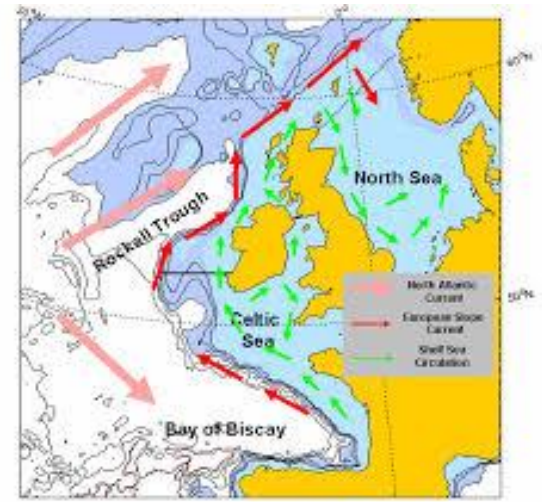
Contrasting long-term abundance trends in the NE and NW Atlantic

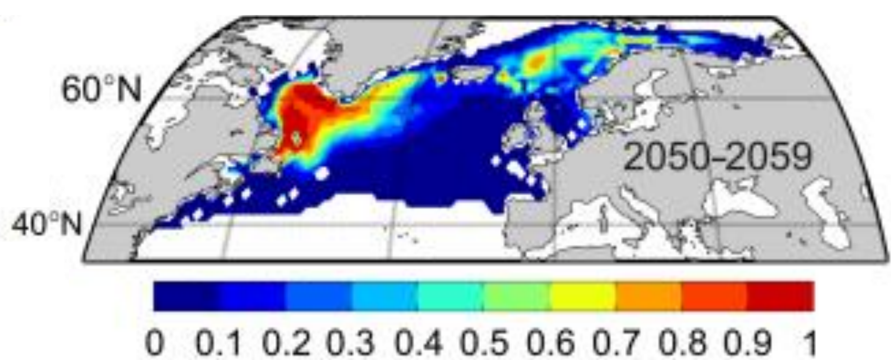


Mean no. of species per sample
From Beaugrand et al. (2005)

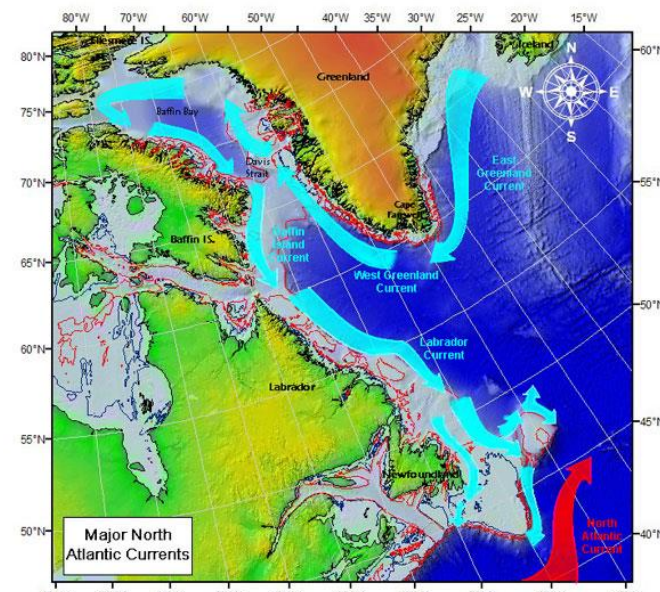
In the NE Atlantic there has been a northward retreat of “subarctic” species and northerly range expansion by more “temperate” species, but these changes have been facilitated by the circulation.

In the NW Atlantic a northward retreat has been projected for the “subarctic” species *Calanus finmarchicus* over the long term, but here the circulation works against this, since the Labrador Current brings water and plankton from the north along and on the continental shelf.





Probability of occurrence of *C. finmarchicus*
From Reygondeau and Beaugrand (2010)



Overall summary and conclusions

For the 1999-2013 period

CPR and AZMP observations are complementary.

- Seasonal patterns of abundance reveal seasonal differences in vertical distributions for multi-year averages
  - but what about inter-annual changes (i.e. in phenology)?
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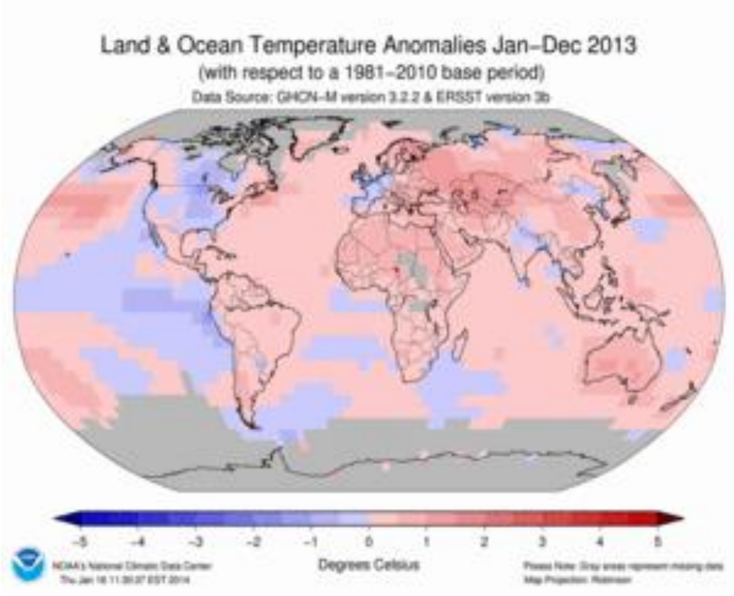
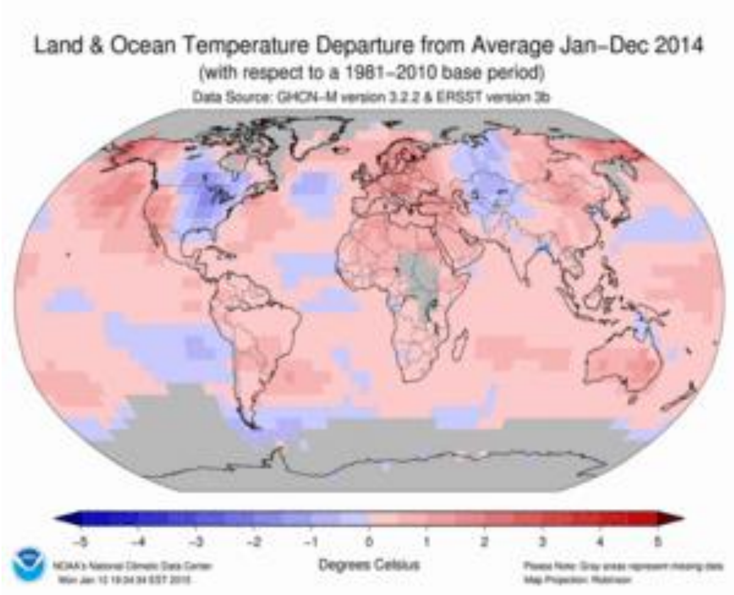
For the 1960s to 2013 period

- Sea-surface temperatures increased for shelf and deep water regions of the Northwest Atlantic, although with inter-annual and inter-decadal variations related to atmospheric processes
- Diatom abundances increased, most likely in response to increasing stratification
- The abundance of *Calanus finmarchicus* did not change, but that of young stage *Calanus* did
  - but the delivery of individuals from northerly regions suggest the continued dominance of *C. finmarchicus* in shelf regions, even as summer temperatures rise
- Euphausiid abundance has been decreasing steadily on the Canadian continental shelf
  - why is a mystery

And finally, needless to say, we ended our analysis when things got interesting!

Global annual temperature anomalies 2013 and 2014



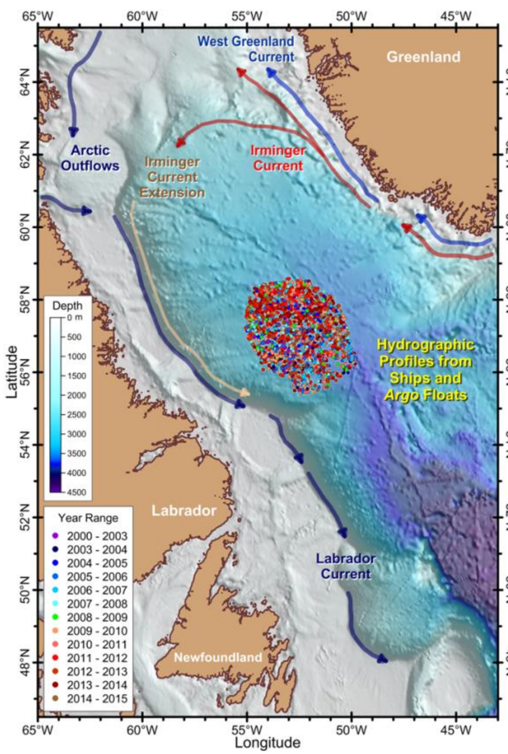


https://www.ncdc.noaa.gov/sotc/global

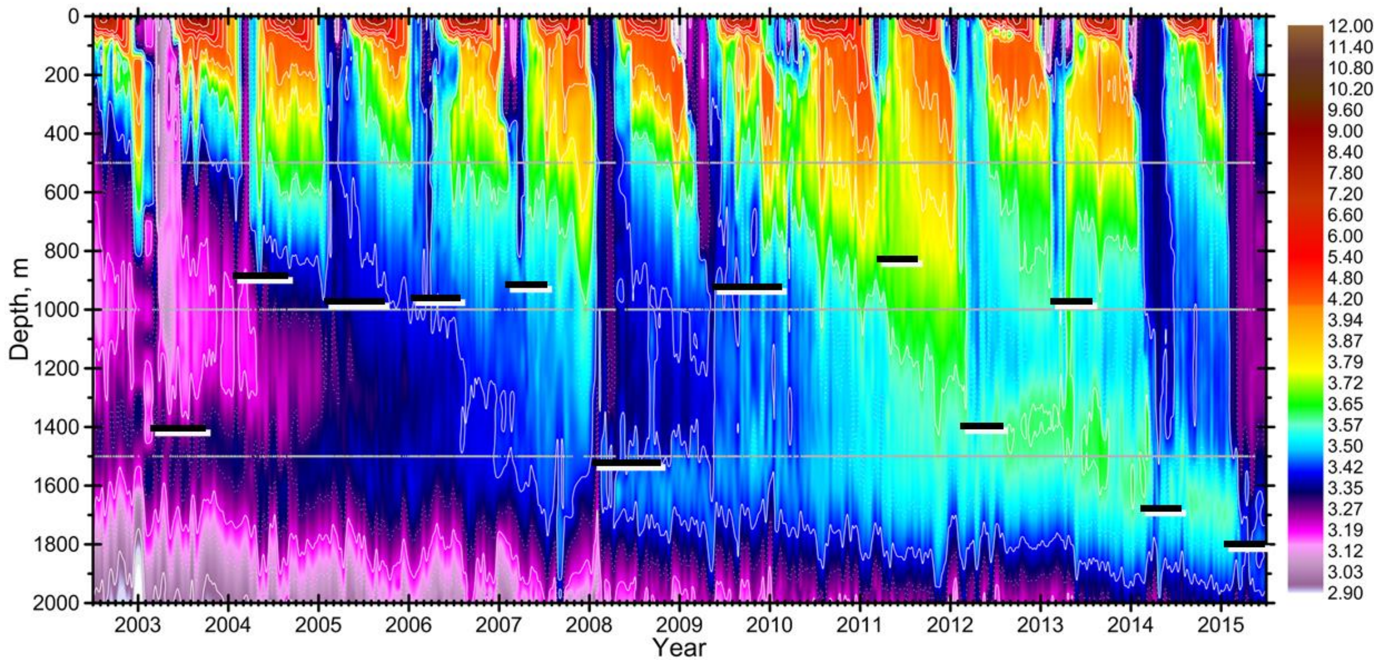
Results from DFO monitoring in the Labrador Sea

ARGO float observations of temperatures 0-2000 m in the region of deep convection in the Labrador Sea 2003-2015 - Figures courtesy of Igor Yashayaev

Positions of ARGO floats providing profiles for the time series



Time series of temperature profiles collected by ARGO floats within the region of deep convection between 2002 and 2015



Both 2014 and 2015 were years with deep convection.