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Deliverable title	Indices associated with climate variability
Description	Evaluation of the most critical observations and analysis of AMOC related changes in heat-, freshwater- and carbon budgets and subsurface temperature in the subpolar North Atlantic and the subtropical South Atlantic
Work Package number	5
Work Package title	Integrated regional observing systems
Lead beneficiary	CNRS
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Contributors	SAMOC, OSNAP and RAPID consortium.
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Comments	

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Stakeholder engagement <u>relating to this task</u>*

WHO are your most important stakeholders?	☐ Private company If yes, is it an SME ☐ or a large company ☐? x National governmental body x International organization x NGO x others Please give the name(s) of the stakeholder(s): Scientific Community
WHERE is/are the company(ies) or organization(s) from?	x Your own country x Another country in the EU x Another country outside the EU Please name the country(ies): France, Germany, UK, Denmark, USA, Canada, Brazil, South Africa
Is this deliverable a success story? If yes, why? **If not, why?**	x Yes, because with the research done for this deliverable a summary of important climate indices was generated and new indices were included – considering the observational data base require to generate such indices. ☐ No, because …..
Will this deliverable be used? **If yes, who will use it?** **If not, why will it not be used?**	☐ Yes, this indices list may serve as a proposal for the generation of indices in an operational mode e.g by the EEA or Copernicus climate change service (climate.copernicus.eu). See concluding remarks section in this deliverable. ☐ No, because …..

Executive summary

This deliverable is concerned with the integrating of observational data (in-situ and satellite) for exploratory generation of climate indices. The focus is on overturning, heat and freshwater transports on a regional scale. We provide a comprehensive census for such climate indices for both the subpolar and subtropical North Atlantic and subtropical South Atlantic during a period with intense in-situ observation activities. These climate indices are relevant to the Copernicus climate change service (climate.copernicus.eu).

1. North Atlantic Subpolar and Subpolar Gyres

In the following a listing of established indices for the subpolar gyre are introduced. A summary of the indices, the data basis and the variable are given in Table 1.

1.1 Deep ocean convection

Purpose: describes the interannual variability of the intensity of ocean convection occurring in the Labrador Sea during winter.

Indices approach: indicated by the maximum mixed layer depth [Yashayaev and Loder, 2016, 2017; Piron et al., 2016, 2017], the thickness or density of Labrador Sea Water [Yang et al., 2016], or the volume of North Atlantic Deep Water [Galaasen et al., 2014].

Data used: based on monthly observations provided by Argo since 2003 [Yashayaev and Loder, 2017; Piron et al., 2016, 2017] or annual hydrographic observations in the Labrador Sea since the 1930s [Yashayaev and Loder, 2016], objective analyses of hydrographic observations since 1950s (using the EN4.0.2 dataset from the Hadley Centre), averaged over three-year periods, or sediment cores covering the last interglacial period 116.1 to 128.0 ky [Galaasen et al., 2014], or flow speed of the deep western boundary current [e.g. Thornalley et al. 2018].

1.2 Subpolar gyre intensity

Purpose: describes the interannual variability of the subpolar gyre circulation intensity

Indices approach: indicated by the salinity of the Atlantic Water inflow to the Nordic Seas/Irminger Sea [Hátún et al., 2005], the ocean heat content in the subpolar gyre [Häkkinen et al., 2013], the range of the sea level anomalies, i.e. the maximum sea level anomaly minus the minimum sea level anomaly over the subpolar gyre [Foukal and Lozier, 2017], the first empirical orthogonal function of the sea level anomaly in the subpolar region [Berx and Payne, 2017] or the second empirical orthogonal function of the windstress curl over the North Atlantic region [Häkkinen et al., 2011]

Data used: based on model output and hydrographic observations from the Irminger Sea extending back since 1960 [Hátún et al., 2005] or satellite-derived sea level height observations since 1993 [Hátún et al., 2005, Häkkinen et al., 2011, 2013, Foukal and Lozier, 2017]

1.3 Heatflux over Subpolar North Atlantic (winter)

Purpose: describes the variability of the wintertime surface heat fluxes in the subpolar North Atlantic region, mostly over the Labrador Sea.

Indices approach: indicated by the negative North Atlantic Oscillation index [Hurrell, 1995] or the Greenland Blocking Index [Hanna et al., 2016].

Data used: based on meteorological observations since 1864 [Hurrell, 1995; Jones et al., 1997] and atmospheric reanalysis data since 1851 [Hanna et al., 2016].

1.4 Freshwater

1.4.1 Freshwater content in the Irminger Sea and the Labrador Sea in summer:

Purpose: describes the interannual variability of the sea surface salinity and freshwater content (averaged over the upper 30 m) in the Irminger Sea at the end of the summer (beginning of September), when the sea surface salinity reaches its annual minimum value. Winter convection and heat flux depend critically on this preconditioning.

Indices approach: indicated by the mean sea surface temperature in the Irminger Sea in August, high temperature being correlated in summer with high freshwater content [Oltmanns et al., 2018]

Data used: based on correlations of 13-year long hydrographic time series from 2002 through 2014 of SST and air-sea heat fluxes [Oltmanns et al., 2018]

1.4.2 Freshwater from Arctic/Greenland:

Purpose: describes the interannual variability of freshwater fluxes from Greenland and the Arctic, including ice sheet melt from Greenland and glaciers in the Canadian Archipelago, runoff from snowmelt in the tundra in Greenland, the Canadian Archipelago and Arctic sea ice [Yang et al., 2016], or only from Greenland [Bamber et al., 2012].

Indices approach: estimates are derived from various sources, in particular GRACE gravity data [Yang et al., 2016], as well as from a reconstruction of the surface mass balance over the ice sheet, using a regional climate model forced with an atmospheric reanalysis. Operational products of surface mass loss are available [http://polarportal.dk/en/greenland/surface-conditions/]

Data used: based on time series that extend back since 1980 [Yang et al., 2016] or, considering Greenland only, since 1958 [Bamber et al., 2012]

1.5 - Meridional Overturning Circulation indices

1.5.1 - MOC, Scotland-Iceland:

Purpose: describes the variability of heat and freshwater transports across a hydrographic section from Scotland to Iceland (the Extended Ellet Line) into the Nordic Seas as part of the Atlantic Meridional Overturning Circulation [Holliday et al., 2015, Gary et al., 2018]

Indices approach: transport estimates are derived from 61 full-depth stations at a horizontal resolution of 10–50 km

Data used: based on annual surveys since 1996

1.5.2 - MOC, 59.5N:

Describes the poleward heat and freshwater transports between Greenland and Scotland Ridge, as part of the Atlantic Meridional Overturning Circulation [Rossby et al., 2017]

Indices approach: estimates include data from shipboard ADCP profiles, which cover the surface to 700 m depth, and from Argo profiles, sampling the upper 2000 m

Data used: the section is surveyed 3-weekly by a ship for the period from late 2012 to early 2016

1.5.3 - MOC, OSNAP

Purpose: describes the interannual variability of volume, heat and freshwater in relation to the AMOC across nominal 60°N (Lozier et al., 2017).

Indices approach: investigates changes in overturning transport (Labrador Sea, Eastern basin, subpolar gyre)

Data used: mooring data combined with ship measurements, floats and autonomous underwater glider data since 2014

1.5.4 - MOC, Greenland-Portugal Ovide section:

Purpose: describes the interannual variability of heat and freshwater transports between Greenland and Portugal (the OVIDE section), as part of the Atlantic Meridional Overturning Circulation (data set: DOI: 10.17882/46445)

Indices approach: investigates changes in the circulation, transports, water mass properties by integrating data from ship cruises, satellite data and model studies

Data used: the section has been surveyed by ships (bi-annual) since 2002 and calculated back to 1993 by satellite-altimetry data

1.5.5 - 53°N-Array (DWBC)

Purpose: describes the variability of the Deep Western Boundary Current at 53N (the 53N array), as part of the Atlantic Meridional Overturning Circulation [Zantopp et al., 2017]

Indices approach: transport estimates of volume, heat and freshwater in the DWBC and its recirculation's.

Data used: data from a mooring array in combination with ship surveys; started in 1997.

1.5.6 - MOC, 41°N heat and freshwater transport (AMOC):

Purpose: describes the variability of heat and freshwater transports at 41N, as part of the Atlantic Meridional Overturning Circulation [Willis, 2010]

Indices approach: estimates combine satellite-derived altimetry data with Argo profiles

Data used: hydrographic time series from Argo floats extend back since 2002, satellite-altimetry since 1993

1.5.7 - MOC, 38°N/Line W (DWBC)

Purpose: describes the variability of the deep western boundary current at 38 N (Line W), as part of the Atlantic Meridional Overturning Circulation [Toole et al., 2017].

Indices approach: transport estimates are derived from mooring at six locations, spanning the continental slope southeast of Cape Cod between depths of 2238 m and 4700 m.

Data used: mooring observations extend back until 2002 but stopped in 2014.

1.5.8 - MOC, 26°N/RAPID-MOCHA

Purpose: describes heat, freshwater transports at 26°N across the RAPID array, as part of the Atlantic Meridional Overturning Circulation [McCarthy et al., 2012, 2015, McDonagh et al 2015]

Indices approach: estimates include observations from a large number of moorings, Argo floats, samplers and oxygen and carbonate system sensors across the North Atlantic (>19)

Data used: data from the moorings at high temporal resolution are available since 2004, mapped Argo floats of same time period, GO_SHIP repeat hydrography every 5-6 years, NOAA cable and repeat hydrography measurements across Florida Straits.

1.5.9 - 16°N/MOVE (AMOC)

Purpose: describes the variability of the zonally-integrated meridional heat and freshwater transports at 16N (the MOVE array), as part of the Atlantic Meridional Overturning Circulation [Kanzow et al., 2008]

Indices approach: volume transport estimates

Data used: based on moorings observations since 2000

2. South Atlantic Subtropical Gyre

24°S: MOC, circulation and property transports

Purpose: describes overturning and gyre circulation and associated, heat, freshwater, inorganic nutrients and carbon transports at 24S, using observations from GO-SHIP and Argo floats

Indices approach: include observations from Argo floats and GO-SHIP repeat hydrography

Data used: data from GO_SHIP repeat hydrography every 10 years and mapped data from Argo floats

24°S: composition of thermocline and intermediate waters

Purpose: to discern the relative proportions of South Indian and Drake Passage water in the subtropical South Atlantic. using observations from GO-SHIP and Argo programmes

Indices approach: include observations from Argo floats with oxygen sensors and GO-SHIP repeat hydrography as in McCarthy et al 2011

Data used: data from GO_SHIP repeat hydrography every 10 years and Argo floats with oxygen sensors

34.5°S/SAMBA

Purpose: describes overturning strength using data from SAMBA array, [Meinen et al, 2018]

Indices approach: estimates include observations from a large number of moorings, CPIES, and repeat hydrography

Data used: data from the moorings at high temporal resolution are available.

Investigated variable	Index	Data basis	Reference
deep ocean convection	max. MLD	CTD profiles, moorings, Argo floats	Yashayaev and Loder [2016, 2017], Piron et al. [2017]
	LSW thickness	objective analyses	Yang et al. [2016]
	NADW volume	sediment cores	Galaasen et al. [2014]
SPD intensity	S of Atlantic inflow	hydrogr. obs. and model output	Hatun et al. [2005]
	OHC	SLA from satellites	Häkkinen et al. [2013]
	range of SLA	SLA from satellites	Foukal and Lozier [2017]
	1st EOF of SLA	SLA from satellites	Berx and Payne [2017]
	2nd EOF of WSC	atmospheric reanalysis	Häkkinen et al. [2011]
HFX in SPNA, winter	NAO	meteor. observations, ice cores	Hurrel [1995], online data bases
	GBI	atmospheric reanalysis	Hanna et al. [2016], online data bases
FW in IS, summer	SST in IS	satellite and in situ data	Oltmanns et al. [2018]

FW in LS, summer	neg. NAO	meteor. observations	Oltmanns et al. [2018]
FW from Arctic/Greenland	obs.-based estimates	GRACE data and other sources	Bamber et al. [2012], Yang et al. [2016]
MOC, Scotland-Iceland	EEL transports	hydrogr. sections	Holliday et al. [2015], Gary et al. [2018]
MOC, 59.5 N	transport estimates	shiboard ADCP, Argo profiles	Rossby et al. [2017]
MOC, Greenland-Portugal	OVIDE transports	Argo and satellite-derived	DOI: 10.17882/46445, Mercier et al. [2017]
MOC, 53 N	DWBC transports	mooring array	Zantopp et al. [2017]
MOC, 41 N	DWBC transport estimates	satellite and Argo data	Willis [2010]
MOC, 38 N	Line W transports	mooring array	Toole et al. [2017]
MOC, 26 N	RAPID transports	mooring array	McCarthy et al. [2012,2015]
MOC, 16 N	MOVE transports	mooring array	Kanzow et al. [2008]
MOC, 24 S		Go-Ship and Argo	
MOC 36.5 S	SAMBA	Moorings and repeat hydrography	Meinen et al., [2018]

Table 1: Climate indices for meridional overturning circulation, heat and freshwater transports in the subpolar North Atlantic and the subtropical North and South Atlantic

3. Concluding remarks

The two different sets of indices presented in this deliverable – routinely generated and new indices (and associated base line data) derived by AtlantOS R&D in the context of WP5. It should be mentioned that the R&D was only possible through the coordinated activities in different AtlantOS workpackages: in particular, it benefited from the enhancement of the observing capabilities of ship based (WP2 and its subtasks) and autonomous observing networks (WP3 and its subtasks) and the enhancement of data access (WP7). Moreover, and maybe even more important from an AtlantOS legacy perspective, it benefited from what AtlantOS as a whole contributed in a substantial way: an improved operational service of established ocean observing networks (JCOMM) and (meta-)data management facilities (Coriolis, EMODnet) and linked to a data integration facility, most importantly the Copernicus marine environmental Monitoring Service providing for example satellite data, reanalysis data.

A future routine generation of these indices should closely link with the Copernicus climate change service (climate.copernicus.eu) and the European Environment Agency (www.eea.europa.eu/data-and-maps/indicators). At these levels the link with other climate indices can be created (e.g. WP5 deliverable D5.2: Indices associated with Primary productivity and carbon export). Such linkages have been shown to be very successful in supporting and guiding advice strategies (see e.g. EU reports such as “Climate Change and European Fisheries” https://publications.europa.eu/s/go3l) for example in the context of specific services such as ecosystem services for fisheries by ICES.

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