MONARCH-A

Collaborative Project

Deliverable 2.4.1 - Assessment of existing descriptions of the Arctic Ocean circulation and its transport properties.

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1. Deliverable in framework of MONARCH-A project

1.1 Main objectives of MONARCH-A project

The Arctic and northern hemisphere high latitude regions experience significant changes during past few decades, associated with climate change. Arctic itself is an important part of the climate system, and changes that occur in this region, in turn, influence the rest of the Planet.

Due to harsh environmental conditions and inaccessibility of some of the Arctic areas, especially during the winter, there is a lack of consistent historical and modern observational data. As a result, our understanding of Arctic climate related processes and ability to predict consequences of changes in this region for Europe is limited.

The ultimate objective of the MONARCH-A project is to provide the scientific community with subset of multidisciplinary Essential Climate Variables for the Arctic region. The information package will be based on generation of time series of observation datasets and reanalyses of past observational data enabling adequate descriptions of the status and evolution of the high latitude and Arctic region Earth system components.

1.2 WP 2.4 Assessing uncertainty of existing reanalyses and simulations over the Arctic

Despite its importance for processes related to global thermohaline circulation, Arctic Basin remains one of the most under-sampled regions of the World Ocean. Sea ice coverage limits access of research vessels and make it hard for satellites to measure characteristics of the upper ocean layers.

Available observations of ocean parameters are very sparse both spatially and temporally. On this basis it is hard to make solid conclusions about details of the large-scale circulation in the Arctic Ocean, and especially about its interannual and decadal variability.

One of the main goals of WP 2 (Changes in Sea Level and Ocean Circulation) is to provide dynamically consistent reanalysis of the Arctic Ocean over the last 50 years, allowing better understanding of water mass formation, circulation, sea level and sea ice change in this region. Long time period of the reanalysis will connect long-term Arctic Ocean variability with IPY era, when more observations are available.

1.3 D2.4.1 - Assessment of existing descriptions of the Arctic Ocean circulation and its transport properties

As a first step towards Arctic Ocean reanalysis we exploit several existent long-term simulations of the Arctic Ocean in order to evaluate quality of recent products provided by modern ocean models forced only by atmospheric forcing, without data assimilation. This allows us to reveal main challenges and improvements that should be done in simulations of the Arctic Ocean water and sea ice variability. Analysis of previous experiences also gives us an opportunity to choose parameters of model setup that will be used for data assimilation during the reanalysis, such as model domain, resolution, parameterisations and so on. Were it is possible, we try to compare model results with best available observations.

2. Participating Models

We evaluate quality of three different regional coupled ice/ocean models with respect of their simulation of basic properties of the Arctic Ocean. Models participating in the comparison are the following:

- Regional setup of MITgcm model ATL (Serra et al., 2010) in three different resolutions from the Institute of Oceanography, University of Hamburg
- Regional setup of MICOM model (Hátún et al., 2005) from the Nansen Environmental and Remote Sensing Center.
- Global setup of MPIOM model (project STORM https://verc.enes.org/community/projects/national-projects/german-projects/storm/) from the Max Planck Institute for Meteorology.

All models are forced by 6 hourly NCEP RA 1 reanalysis (Kalnay et al., 1996) Details of model setups presented in the Table 1.

Table 1.

Model run	Region	Mean spatial resolution in the Arctic	Period of integration	Vertical grid
ATL03	Atlantic Ocean north of 33◦S including the Nordic Seas and the Arctic Ocean.	~ 30 km	1948-2009	z-coordinates, 50 levels
ATL06	Atlantic Ocean north of 33◦S including the Nordic Seas and the Arctic Ocean.	~ 15 km	1948-2007	z-coordinates, 50 levels
ATL12	Atlantic Ocean north of 33 S including the Nordic Seas and the Arctic Ocean.	~8 km	1948-2009	z-coordinates, 50 levels
MICOM	North of 30 S with Nordic Seas and Arctic Ocean included	~15 km	1948-2007	σ-coordinates, 35 levels
MPIOM	Global	~7 km	1948-2010	z-coordinates, 80 levels

Arctic ocean setup of MITgcm model is planned to be used for production of dynamically consistent Arctic ocean reanalysis (WP 2.5). Analysis of three different resolutions of

Atlantic-Arctic setup of this model (ATL) give us advantage to explore properly effects of the model resolution and choose optimal characteristics for future Arctic reanalysis setup. In addition the impact of the use of different vertical coordinate systems (z-level versus sigma) might also be assessed.

What are the ATL model fields used?

The following monthly MICOM model output at a spatial resolution of ~15 km from 1948-2007 has been provided by NERSC:

- 3 dimensional fields of temperature, salinity and ocean circulation given in Cartesian coordinates (U and V components);
- 2 dimensional fields of sea ice concentration, extent and thickness,
- 2 dimensional fields of sea ice drift velocities in U and V components;
- 2 dimensional fields of sea surface height;
- 2 dimensional fields of ocean bottom pressure.

3. Surface ocean circulation

There are no direct measurements of the large scale surface ocean circulation in the Arctic Ocean, apart from large scale sea ice drift detected from ice buoys and satellite observations, and until recently there were no estimates of dynamical ocean topography for this region due to sea ice coverage and lack of detailed quantitative knowledge of the geoid. . For this purpose we use Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors data set (Fowler, 2003) that combine satellite and buoy data and cover period from 1978 to 2006.

Comparison of the simulated mean 1978-2006 surface currents with mean sea ice transport from satellite data for the same period (Fig. 1) show that two main features of surface circulation of the Arctic Ocean - Beaufort Gyre and Transpolar Drift are relatively well represented in the simulations.

In all three ATL runs centre of the Beaufort Gyre located in the Beaufort Sea, close to the Canadian Coast which is in good agreement with satellite data. Transpolar drift transports water from the north of the East-Siberian and the Laptev Seas thought the North Pole to the Fram Strait. With increase of the resolution in MITgcm spatial characteristics of surface transport do not experience any significant changes and velocity field remains almost the same. This probably indicates that sea ice drift and surface transport is determined mostly by dominating model parameters and the atmospheric forcing field, while model resolution at the range from 30 to 8 km have lesser effect.

There are two pronounced centres of convergence in Amerasian basin of the Arctic ocean in mean fields of surface circulation of MICOM and MPIOM models, that are not represented in satellite data. This might be reflection of the strong reaction of the surface circulation in the models to migration of the Arctic High centre that is resulted in averaged fields as two convergence centres. Transpolar drift in MICOM model have largest velocities, reaching 5 cm/s. Flow of transpolar drift in MPIOM model crossed by branch of the current that is directed westward further joining Beaufort Gyre. This might lead to the lack of sea ice export and accumulation of the thick sea ice in the basin of the Arctic Ocean.

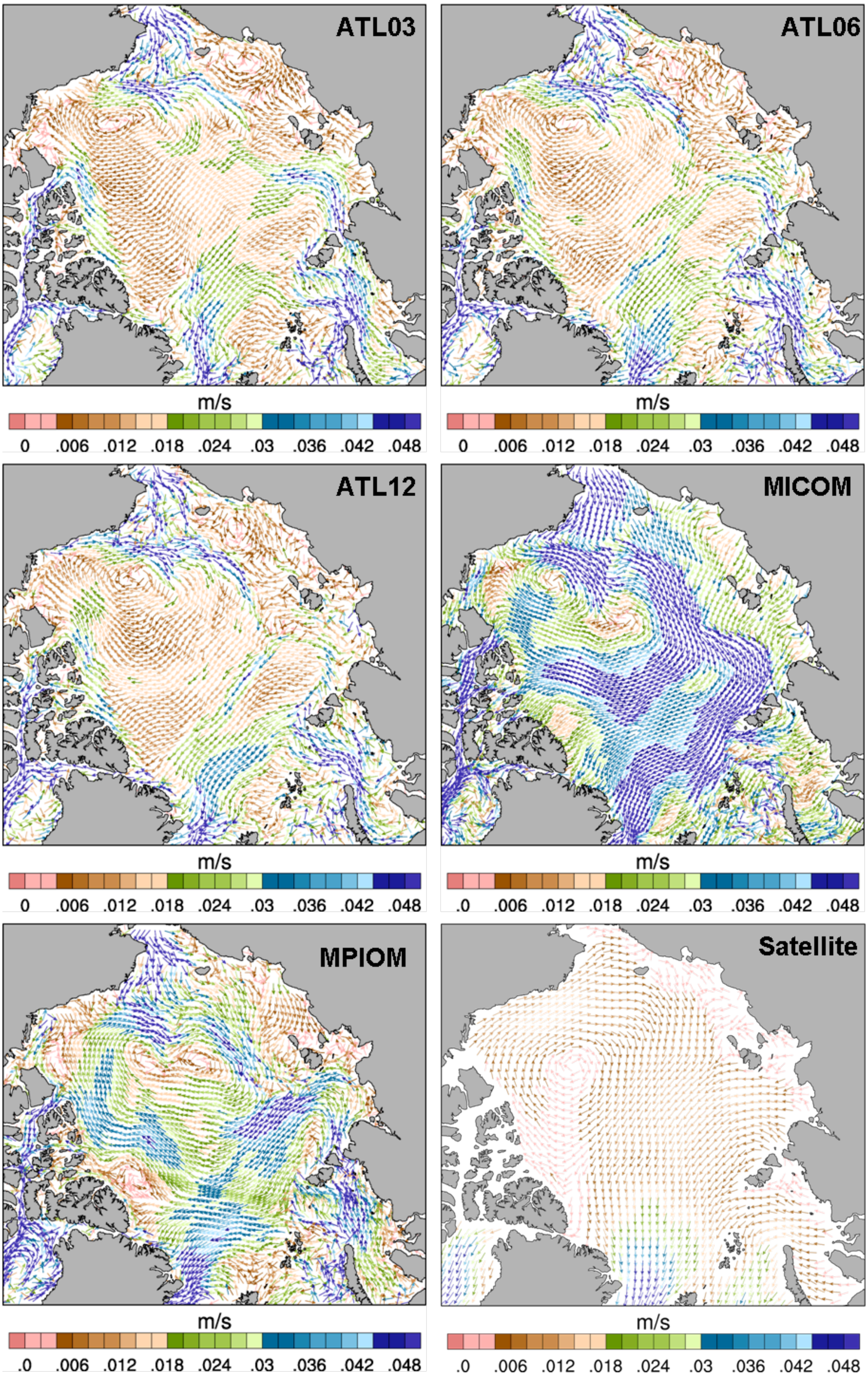

Fig 1. Mean 1979-2006 surface circulation in the models and sea ice circulation for the same period according to satellite observations (lower right).

4. Intermediate water circulation

There is constant inflow of Atlantic origin waters (AW) to the Arctic Ocean through the Fram strait and Barents Sea opening. This waters are transported along the continental slope as topographically trapped current and gradually deepened, forming (along with waters of Pacific origin) intermediate layer with relatively larger water temperatures with respect to overlaying and underlying waters. Due to limited amount of current observations in the Arctic ocean, details of the AW circulation is still not very well known, however conceptual scheme presented by (Rudlels, et al., 1994) find supporting evidences in available observations.

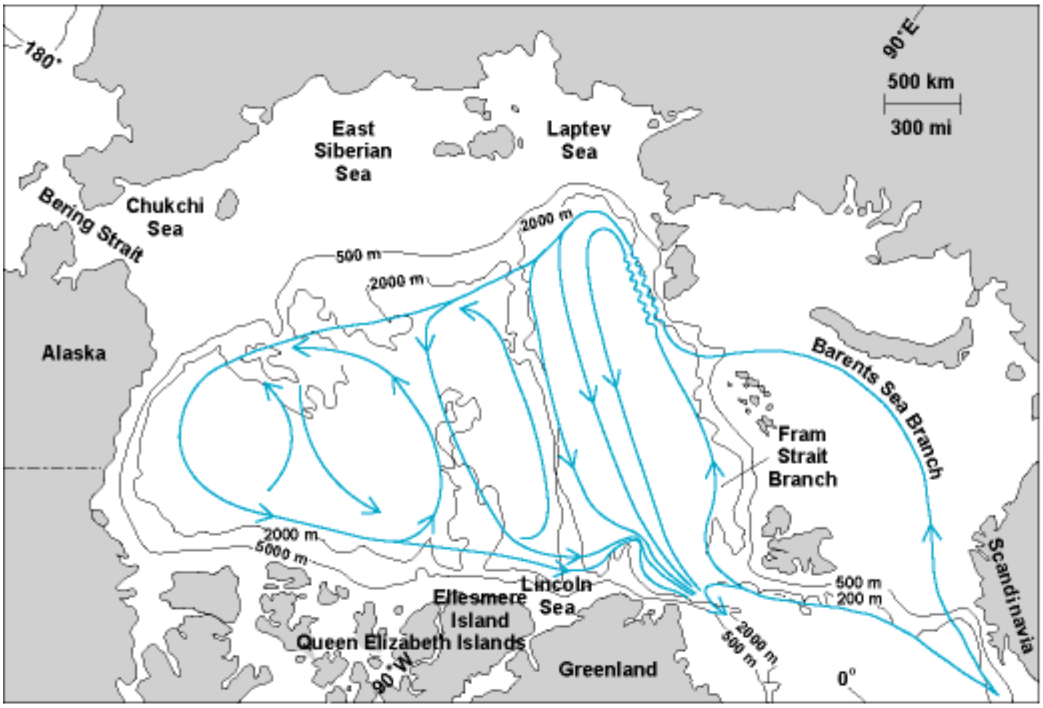

Fig. 2 Mean circulation of the Atlantic Layer and Upper Polar Deep Water. (*After B. Rudels et al.,1994*) Copyright © The McGraw-Hill Companies. (Get it from here:http://accessscience.com/popup.aspx?figID=049100FG0050&id=049100&name=figure

According to this scheme intermediate waters move cyclonically along the Arctic continental shelf break margins with several branches crossing the Arctic basin associated with topographic steering. We analyse if 300 meter water circulation in the models agree with the scheme.

In general all three runs of MITgcm fairly well reproduce large scale intermediate water circulation. With increase of the resolution detalization of the circulation gradually becomes better. For example, in 30 km resolution run (ATL03) current along the Lomonosov ridge is underrepresented, while in 15 km resolution run (ATL06) is already very well developed and in 8 km resolution run (ATL12) along with current parallel to the Lomonosov ridge in the Nansen and Amundsen Basins there is a clearly outlined current along the Gakkel ridge.

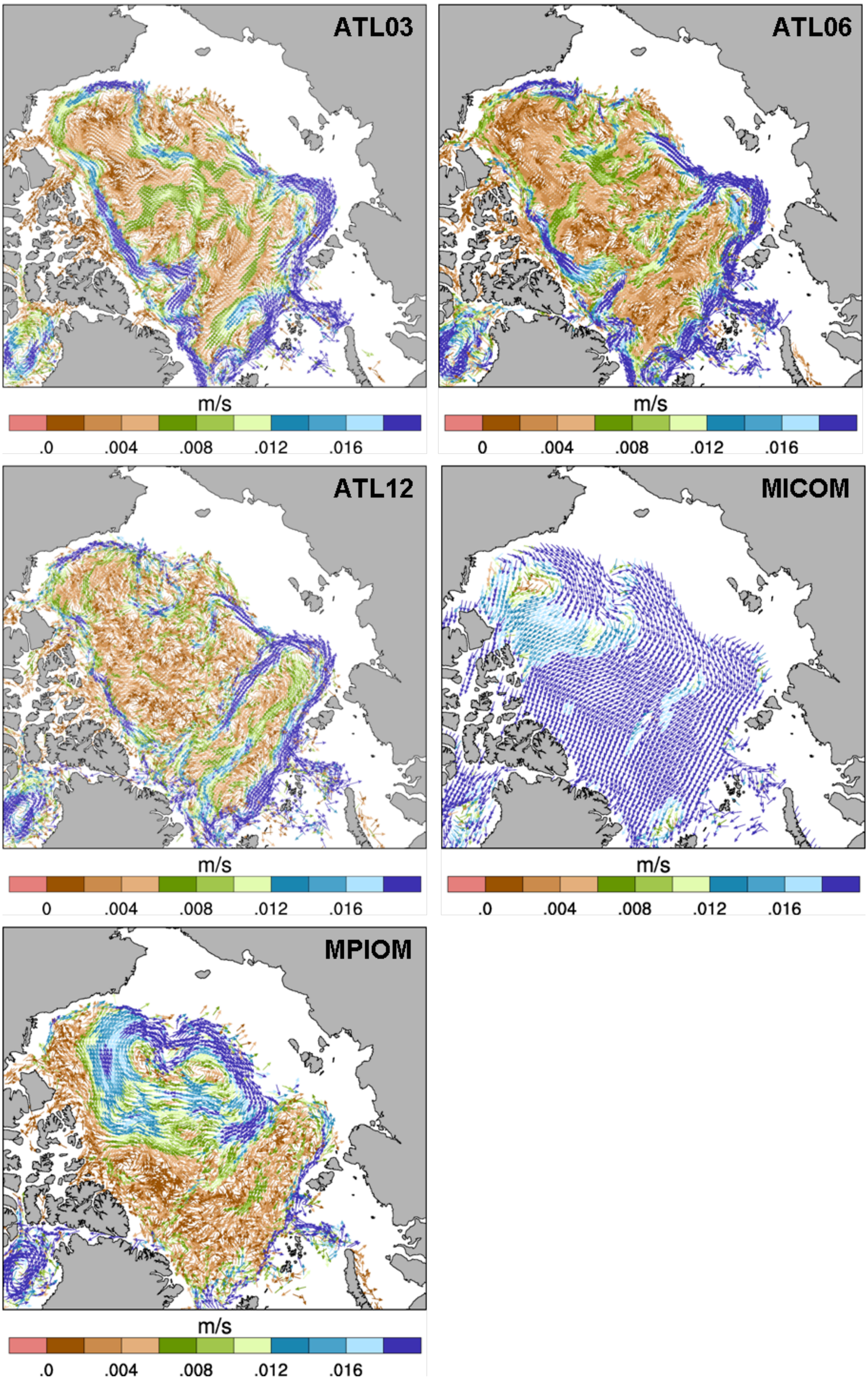

Fig 3. Mean 1979-2006 circulation in the models at 300m depth.

Intermediate water circulation in the MICOM model show very little resemblance with the scheme of (Rudels, et al.,1994). Circulation dominated by the outflow from the Arctic ocean and current velocities are largest among analysed models. In the Amerasian Basin there is a pattern that resemble surface circulation, with two centres of convergence. Inflow of AW through the Fram Strait and St.Anna Through observed in the model. However the inflow in the Fram Strait quite rapidly recirculated back and in case of the St.Anna Through transported towards the Fram Strait and escaped the Arctic Ocean. This leads to very low temperatures of intermediate waters in the Arctic Basin, as it will be shown during the discussion of temperature. All in all this intermediate water circulation in MICOM seems to be controlled by surface atmospheric circulation, which is similar to findings of Kauker et al., (2007) for AOMIP models.

This is probably also true for the intermediate water circulation in the Amerasian Basin of MPIOM model. There pathways of the currents are in a close agreement with surface circulation, forming strong anticyclonic gyre with two pronounced centers of convergence. However circulation in Eurasian Basin of MPIOM is close to the scheme from Rudlels, et al., (1994), with currents along continental slope, Lomonosov ridge and Gakkel ridge.

5. Temperature and salinity

In order to show trends and variability of water properties in the upper 1500 meters of the Arctic Ocean, we adopt approach used by Holloway et al., (2007) for comparison of water properties in 10 models participated in Arctic Ocean Model Intercomparison (AOMIP) project. Temperatures and salinities are averaged over the Eurasian and Amerasian Basins of the Arctic Ocean for every month and plotted as function of the depth and time. This gives us an opportunity to compare results of models we analyse with AOMIP models.

In the beginning of the 1990s oceanographic data collected by Soviet Union and United States in the Arctic ocean were combined together to produce Environmental Working Group Joint U.S.-Russian Atlas of the Arctic Ocean (EWG Atlas). In 2001 data from this atlas were merged with World Ocean Atlas 1998 (WOA1998, Antonov et al. 1989) to obtain global Polar science center Hydrographic Climatology (PHC) (Steel, 2001). We will use later dataset for general comparison of water properties.

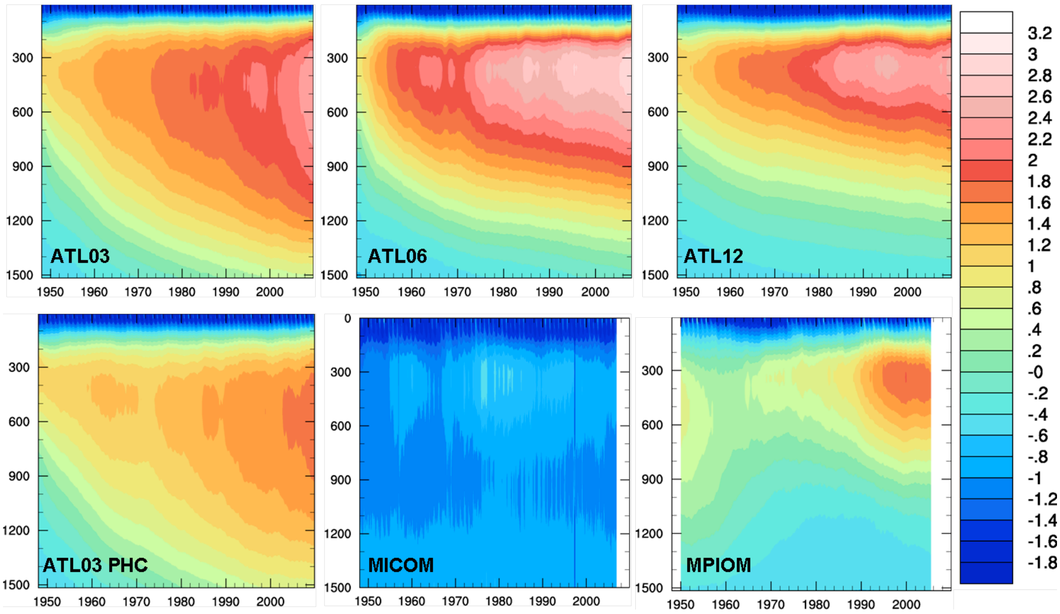

Fig.4. Potential temperature diagrams plotted as function of depth and time

On temperature diagrams plotted as function of depth and time all models, except MICOM, demonstrate intermediate Atlantic Water Layer (AWL) (waters with temperatures above 0°C). Thickness of the AWL and its temperature is overestimated in ATL runs and is in good agreement in MPIOM run compared to PHC.

Due to the incomparable and strange or erroneous circulation at intermediate level, the MICOM model demonstrates very low temperatures in the interior of the ocean. The reason is probably the very fast and distinct recirculation of Atlantic water in the Fram Strait, that limit the spread through the Arctic basin.

With increase of the resolution in ATL model runs thickness of AWL decrease, and become closer to PHC values. However our analysis of Atlantic water inflow thought the Fram Strait shows that this is more likely related not to the processes in the Arctic Ocean itself, rather than to better representation of water modification in the northern North Atlantic. Properties of intermediate waters in the Arctic to a large extend determined by AW modifications in the North Atlantic and Barents Sea, hence for future Arctic ocean state estimate (WP 2.5) it is crucial to have good data coverage in this regions. Additional experiment that we perform with 15 km resolution ATL model could serve as one of conforming evidences of the later statement (see next paragraph).

In ATL runs the model sea surface salinity (SSS) relaxed to the WOA2005 monthly climatology (Boyer et al., 2005), that underestimate values of SSS in northern Barents and Kara Seas especially in winter. We rerun 30 km resolution ATL03 model with relaxation to more realistic PHC monthly SSS climatology (ATL03_PHC). As a result mean temperature in the core of the AWL decreased by about 0.8 °C with respect to run with WOA2005 SSS relaxation and become much closer to climatology. However thickness of the AWL stays too large.

As can be seen at Fig. 4 even at the end of the ATL model runs adjustment from climatological initial conditions is seems to continue, especially for ATL03. In order to see how long it will take for the model to reach equilibrium in the interior of the Arctic Ocean, we analyse repeated runs of ATL03 and ATL06, started from the velocity and density fields reached at the end of the initial runs (ATL03_r and ATL06_r). For depths below 900 meters

ATL06_r seems to reach equilibrium after first 20 years of the integration, while in ATL03_r one can observe continuous drift towards higher temperatures at this depths.

In order to compare model results with climatology, we calculate mean vertical temperature and salinity profiles over Eurasian basin of the Arctic Ocean for winter (March, April, May) period of 1980-1989, when models expect to be at least close to the equilibrium and data used for the PHC climatology have good coverage.

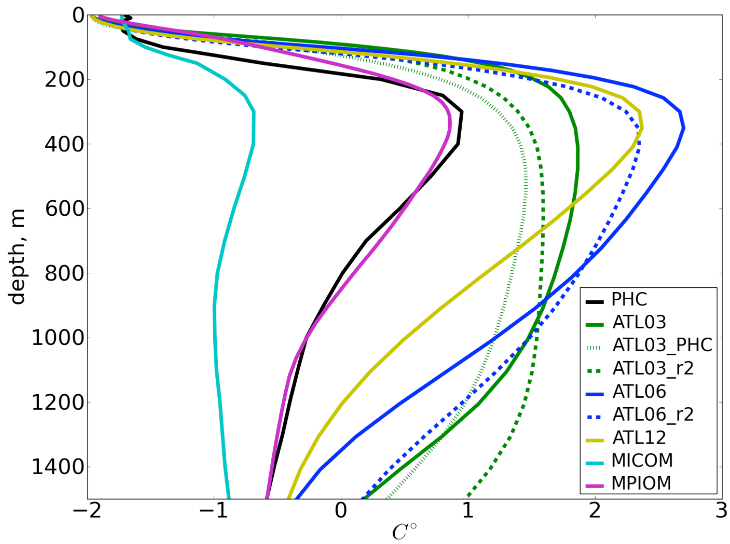

Fig.5. Vertical potential temperature profile averaged for Eurasian Basin of the Arctic ocean for winter (March, April, May) 1980-1989

Mean temperature profile shows that ATL and MPIOM model runs are colder at the surface compared to PHC and that there is essentially no mixed layer presented. The MICOM model show well developed mixed layer with values close to the climatology. Ocean interior is warmer than PHC climatology in ATL runs, colder in MICOM model and in almost perfect agreement in MPIOM.

Depth of the AW core in ATL06 and ATL12 runs is in the right position and the core itself is well developed. Repeated integrations (ATL03_r and ATL06_r) have lower temperatures above 1000 metes and higher temperatures below 1000 meters compared with runs started from climatology. This might indicate accumulation of heat in the deep parts of the Arctic ocean. Among all ATL runs, ATL12 is closest to climatology deeper than 750 meters, while temperature values of ATL03 with PHC SSS relaxation are closest to climatology in upper 750 meters.

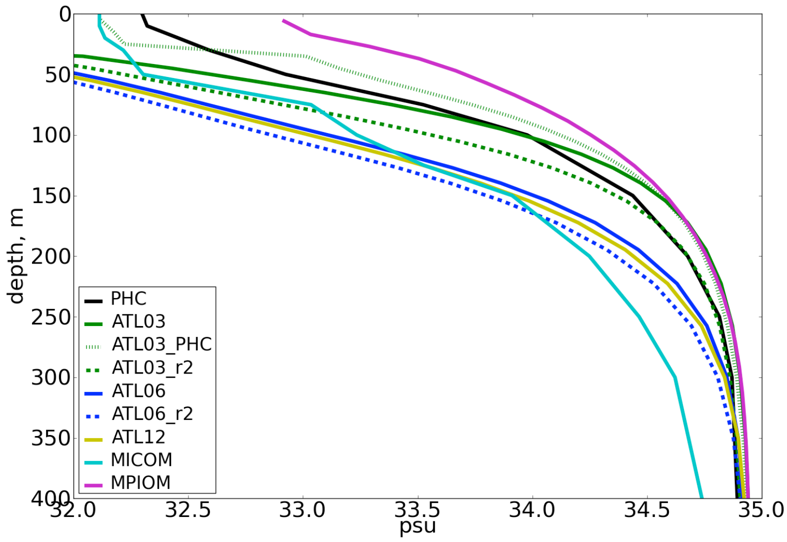

Fig.6. Vertical salinity profile averaged for Eurasian Basin of the Arctic ocean for winter (March, April, May) 1980-1989

In terms of salinity in Eurasian sector of the Arctic Ocean ATL model runs and MICOM are fresher at the surface compared with climatology, while MPIOM is more saline. On average values of ATL03_PHC run are closest to climatology in the first 400 meters, again showing importance of the proper SSS relaxation. Deeper than 400 meters, salinity in all models is in close agreement with climatology, except for MICOM, where salinity continue to gradually increase.

6. Sea ice extent

Sea ice extent (SIE) in models is compared with satellite data from Goddard Space Flight Center (GSFC) NASA Team algorithm (Cavalieri et al., 1996). We consider period from 1979 to 2007 and region to the north of 65N. Sea ice extent is defined as sum of the area of all gridpoints with sea ice concentrations greater than 15%.

Seasonal cycle of the sea ice is well captured by all models. ATL06 and ATL12 have minimum of sea ice extent in August, instead of September. Thermo-dynamic part of the sea ice model used in ATL runs is the so-called zero-layer formulation following the Appendix in Semtner (1976), which is known for exaggeration of sea ice seasonal cycle. MICOM model show SIE values that are closest to values obtained by satellite observations.

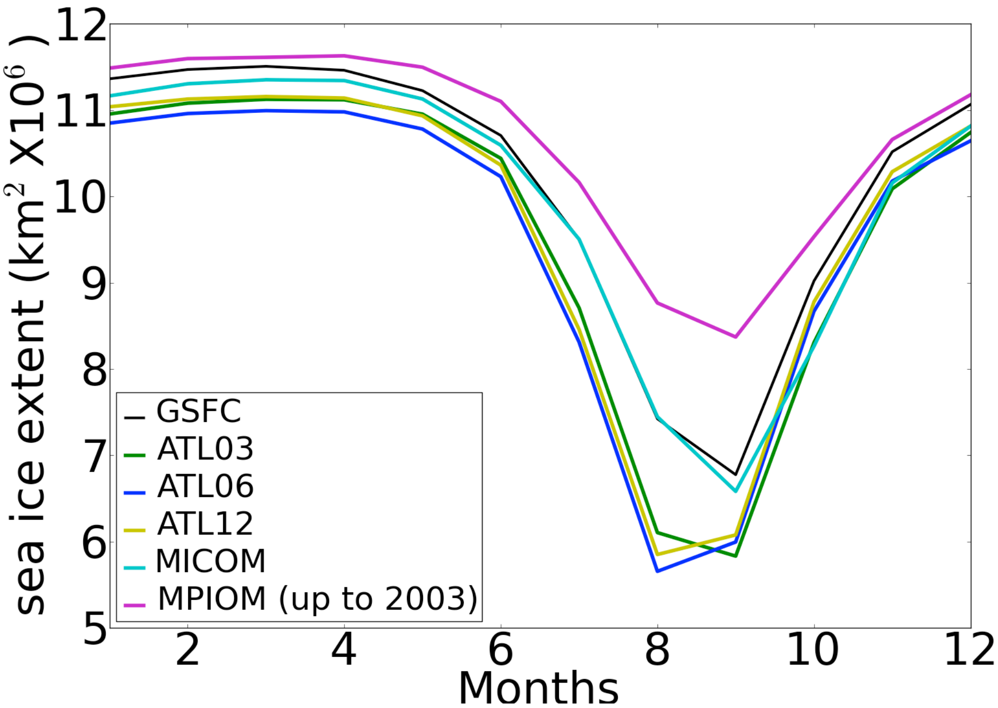

Fig.7. Season cycle of SIE averaged for the period 1979-2007

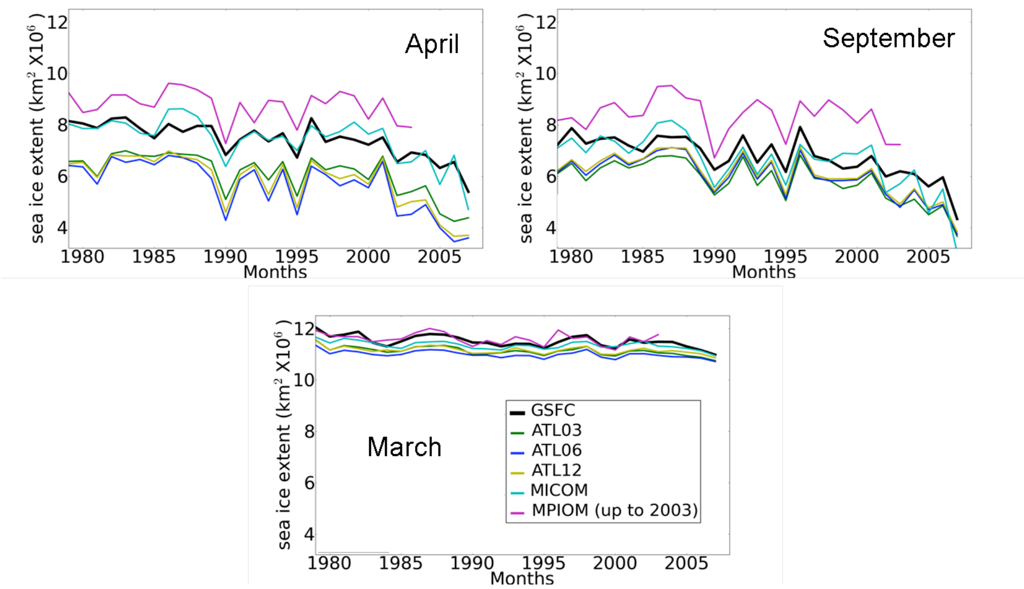

Fig.8. Inerannual variability of SIE for the period 1979-2007.

In general models are good in reproducing inter-annual variability. ATL model runs underestimates SIE, MPIOM overestimate it, while SIE values in MICOM are on average in good agreement with observations. Differences between ATL model runs and observations in September are quite consistent, possibly implying some systematic error. Differences between ATL model runs themselves are relatively small except for the April during 2000s, when runs with higher resolution (ATL06 and ATL12) tend to have even lesser SIE than lower resolution run (ATL03).

Repeated integrations (ATL03_r and ATL06_r) have almost exactly the same seasonal and interannual variability of SIE as respective initial integrations. This imply that differences in the deep ocean state practically do not have an effect on SIE, and it is determined mostly by surface atmospheric forcing and resolution. The former is strongly affected by the presence of sea ice. Same is true for ATL03_PHC run.

7. Sea surface height

Obtaining of SSH from satellites in the Arctic Ocean is largely restricted by presence of the sea ice cover. There is only few estimates of SSH in the Arctic Ocean appeared recently from satellite measurements in open leads. For our analysis we compare mean model values for 1970-2007 with estimates of Kwok et al., (2011), obtained on the basis of six years (2004-2008) ICESat satellite observations. Note that we do not remove the mean for the Arctic from the data and scales are different.

Generally models reproduce overall spatial structure of the SSH in the Arctic ocean with higher values in Amerasian part of the basin and lower values in Eurasian part. Differences in SSH values between these two basins are about 80-100 cm, in agreement with Kwok et al., (2011).

Details of the SSH spatial distribution are better represented in ATL model runs. There largest values of SSH located close to Canadian coast. Large values also propagate along Canadian Archipelago and towards East Siberian Sea in agreement with observations.

MPIOM have weakest SSH gradient across the basin and the largest values of SSH located closer to the centre of the basin. MICOM also have maximum value of SSH close to the center of the Arctic Ocean. There is local maximum of SSH in the Laptev and East-Siberian seas that presented in all ATL runs and MICOM model, but absent in MPIOM model.

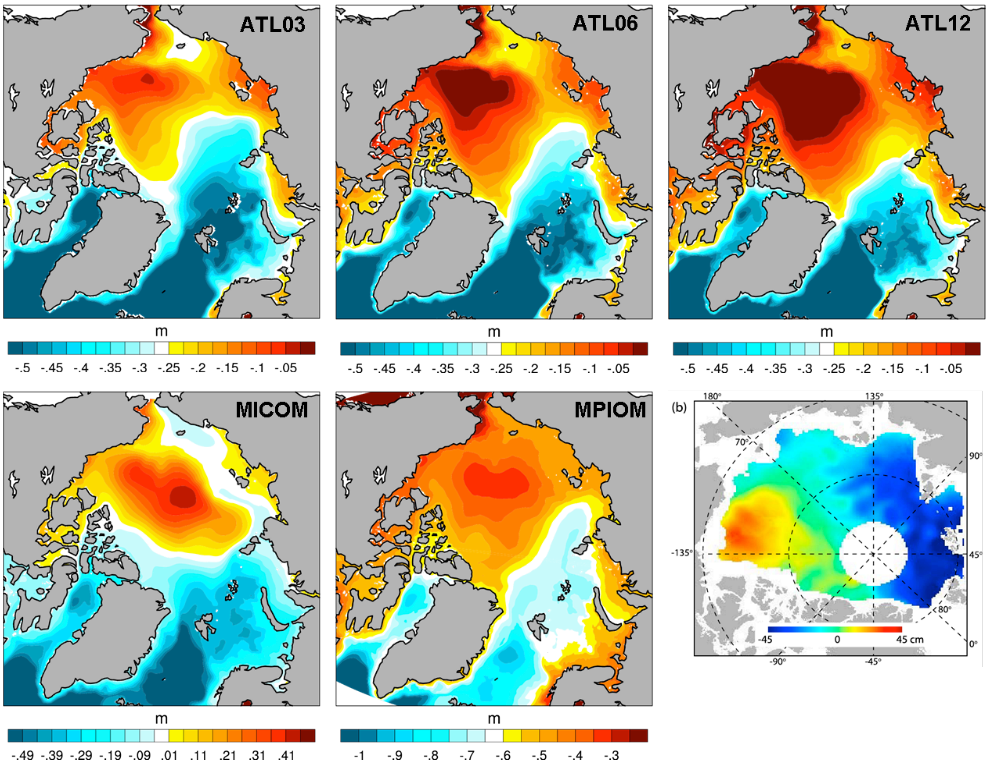

Fig.9. Mean SSH for the period 1970-2007 and (in lower right) Dynamical Ocean Topography estimate for 2004-2008 (Kwok et al., (2011)

8. Conclusions

We compare simulation of Arctic Ocean characteristics in several regional and global models, forced by NCEP RA 1 atmospheric reanalysis against available observations and climatologies. There is a large spread among models, however the different models appear to have distinct strength and weaknesses in simulating different parameters.

ATL set of model runs very well reproduce both surface and intermediate circulation of the Arctic Ocean, as well as spatial distribution of the SSH. MPIOM have almost perfect agreement of temperature and salinity in Eurasian Basin with climatology, but have wrong circulation of intermediate layer in Amerasion sector of the Arctic. MICOM have very cool intermediate waters, but well reproduce mixed layer, have signs of Cold Halocline and is the best among analysed models in simulating mean seasonal cycle of SIE.

The variability in ocean surface circulation together with sea ice drift and sea ice extent are to a large degree determined by the atmospheric forcing and sea ice model formulation, rather than model resolution and behaviour of the deeper ocran circulation. Improvements are needed in getting SIE absolute values closer to observed by satellites.

Model resolution plays an important role for the Arctic Ocean interior simulations both in terms of circulation and water properties. Higher resolution ATL runs reproduce more details of the water flow, and vertical structure of the water column is also improved, while absolute values of temperature and salinity still differ from the climatology. It takes a long time (more than 60 years) to adjust interior of the ocean from climatology to equilibrium, and the lower the resolution the longer it takes.

We believe that for future reanalysis it is sufficient to have MITgcm model setup with 15 km resolution. This will allow the reproduction of the ocean circulation with sufficient details, being relatively not demanding on super computer resources. Taking into account all analysed variables, their spatial structure and variability, MITgcm based simulations are quite close to observations. Consequently, during data assimilation disagreements between dynamics of the model and assimilated observations should not be very large.

9. References

Antonov, J. I., S. Levitus, T. P. Boyer, M. E. Conkright, T. D. O'Brien, and C. Stephens, 1998: *World Ocean Atlas 1998 Vol. 1: Temperature of the Atlantic Ocean.* NOAA Atlas NESDIS 27, 166 pp.

Arctic Climatology Project. 1997. *Environmental Working Group joint U.S.-Russian atlas of the Arctic Ocean - winter period*. Edited by L. Timokhov and F. Tanis. Ann Arbor, MI: Environmental Research Institute of Michigan in association with the National Snow and Ice Data Center. CD-ROM.

Arctic Climatology Project. 1998. *Environmental Working Group joint U.S.-Russian atlas of the Arctic Ocean - summer period*. Edited by L. Timokhov and F. Tanis. Ann Arbor, MI: Environmental Research Institute of Michigan in association with the National Snow and Ice Data Center. CD-ROM.

Boyer, T., Levitus, S., Garcia, H., Locarnini, R., Stephens, C. and coauthors. 2005. Objective analyses of annual, seasonal, and monthly temperature and salinity for the World Ocean on a 0.25◦ grid. *Int. J. Climatol.* **25**(7), 931–945.

Cavalieri, D., C. Parkinson, P. Gloersen, and H. J. Zwally, 1996, updated 2008: Sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I passive microwave data 1980–1999. National Snow and Ice Data Center, digital media. [Available online at http://nsidc.org/data/nsidc-0051.html.]

Fowler, C. 2003, updated 2008. *Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors*. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Gao, Y., 2004. Simulating transport of non-Chernobyl 137Cs and 90Sr in the north Atlantic–Arctic region. Journal of Environmental Radioactivity 71 (1), 1-16.

Hátún, H., Sandø, A. B., Drange, H., Hansen, B., Valdimarsson, H., Sep. 2005. Influence of the Atlantic subpolar gyre on the thermohaline circulation. Science 309 (5742), 1841-1844.

Holloway, G., Dupont, F., Golubeva, E., Häkkinen, S., Hunke, E., Jin, M., Karcher, M., Kauker, F., Maltrud, M., Morales Maqueda, M. A., Maslowski, W., Platov, G., Stark, D., Steele, M., Suzuki, T., Wang, J., Zhang, J., Mar. 2007. Water properties and circulation in arctic ocean models. Journal of Geophysical Research 112 (C4), C04S03+.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, B., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., Joseph, D., Mar. 1996. The NCEP/NCAR 40-Year reanalysis project. Bulletin of the American Meteorological Society 77 (3), 437-471.

Karcher, M., Kauker, F., Gerdes, R., Hunke, E., Zhang, J., Apr. 2007. On the dynamics of atlantic water circulation in the arctic ocean. Journal of Geophysical Research 112 (C4), C04S02+.

Kwok, R., Morison, J., Jan. 2011. Dynamic topography of the ice-covered arctic ocean from ICESat. Geophysical Research Letters 38 (2), L02501+.

Rudels, B., Jones, E.P. and Anderson, L.G., 1994. On the intermediate depth waters of the Arctic Ocean. In: Johannessesn, O.M., Muench, R.D. and Overland, J.E., Editors, 1994. The polar oceans and their role in shaping the global environment, The Nansen Centennial Volume, pp. 33–46.

Semtner, A. J.: A model for the thermodynamic growth of sea ice in numerical investigations of climate, J. Phys. Oceanogr., 6, 379–389, 1976.

Serra, N., Käse, R. H., Köhl, A., Stammer, D., Quadfasel, D., 2010. On the low-frequency phase relation between the denmark strait and the Faroe-Bank channel overflows. Tellus A 62 (4), 530-550.

Steele, M., R. Morley, and W. Ermold, PHC: A global ocean hydrography with a high quality Arctic Ocean, J. Climate, 14, 2079-2087, 2001.