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Executive SUMMARY

The MONARCH-A study approach has been organized around four main activities, notably: (i) changes in carbon-water interaction; (ii) changes in sea level and ocean circulation; (iii) changes in marine carbon cycle; and (iv) synthesis and interaction with the scientific community on climate change research. 11 multidisciplinary Essential Climate Variables (ECVs) relevant for high latitude and Arctic regions have been generated and made available in the information package. Arranged according to the GCOS ECVs domain they include:

- Terrestrial: snow cover, river discharge, permafrost and ice sheet mass balance;
- Ocean: sea level, sea ice volume, sea ice drift, ocean current, ocean colour, CO2 partial pressure;
- Atmosphere: near surface wind field

The corresponding 11 time series and products have then been assessed and synthesized with respect to mutual forcing and feedback mechanisms associated with changes in terrestrial carbon and water fluxes, sea level and ocean circulation and the marine carbon cycle in the high latitude and Arctic regions. Moreover, the data are generally provided with given quality and uncertainty estimation making the data sets more attractive for model validation, reanalyses and initial boundary conditions. These multidisciplinary time series integrated and combined with existing complementary information on land cover, fire, sea ice extent and concentration, sea ice thickness, sea surface temperature and sea level are open and freely available (directly or linked to other data repositories) to assist and support climate change research at the web portal (http://monarch-a.nersc.no).

The influence of the Arctic on climate change is likely to grow in near future. For instance, the summer sea ice area in the Arctic encountered the record minimum ever observed in September 2012, and for the first time surface temperature above freezing was recorded over the entire Greenland ice sheet. In contrast to the Arctic warming and the reduction of Arctic sea ice, North America, Europe, and East Asia have experienced anomalously cold conditions with record high snowfalls in recent years. Possible impacts of such reduced autumn sea ice cover and severe winter weather as well as summer sea ice loss and more (persistent) extreme summer climate conditions with drought or flooding are now increasingly discussed by scientists. Moreover, changes in the temperature and salinity of the surface water in the Arctic Ocean and Nordic Seas, and the flow of dense water through Denmark Strait, are known to be precursors to changes in the Atlantic Meridional Overturning Circulation (AMOC) with a lead-time of around 10 years. This links changes in the high latitude and Arctic with far reaching influences on regional and northern hemisphere/global environment and climate variability.

Improving our understanding of causes and mechanisms of the ongoing changes in the high latitude and Arctic region as part of the global climate system and improving our capabilities of projecting future climate variability in the Arctic is needed in order to develop relevant adaptation and response measures. Reduced sea ice cover, increased ice sheet melting, changes in snow cover and snow water equivalent, sea level rise and changes in the marine carbon cycle may have far reaching socio-economic consequences that, in turn, will impact the political landscape.

Table of Contents

List of Figures

I Summary Description of the Project and the Main Objectives

Targeting the high latitude and Arctic regions the MONARCH-A study approach was executed around four main activities or themes, notably: (i) changes in carbon-water interaction; (ii) changes in sea level and ocean circulation; (iii) changes in marine carbon cycle; and (iv) synthesis and interaction with the scientific community on climate change research. In so doing 11 multidisciplinary ECVs relevant for high latitude and Arctic regions have been generated, quality checked and assessed including: river discharge, snow cover, ice sheet mass balance and permafrost; sea ice drift and sea ice volume, sea level, current, ocean color and CO2 partial pressure; and near surface wind field. The 11 ECVs were further complemented and extended by existing land cover and fire datasets, time series of sea ice extent and concentration, sea ice thickness and sea surface temperature. The project also studied mutual forcing and feedback mechanisms between these ECVs as driven by changes in terrestrial carbon and water fluxes, sea level and ocean circulation and the marine carbon cycle. Moreover, reanalyses and simulations using forced coupled sea ice-ocean models, terrestrial carbon and water flux models and coupled atmosphere - sea ice – ocean –l and climate models were used to assess the trends and consistency of the multidisciplinary ECVs.

The scientific and technical methodologies and approaches undertaken in the four themes are specified in the following.

Theme 1 was primarily concerned with:

(i) Decadal change in snow properties: snow cover, snow depth and snow cover period are all indicators of climate change but also have strong effects on water availability for plant growth, vegetation growing periods, flow of fresh water into the Arctic Ocean and albedo.

(ii) The decadal dynamics of high latitude water bodies: the huge numbers of lakes forming in the summer season at high latitudes are important for greenhouse gas exchange, evapo-transpiration, runoff and groundwater.

(iii) Decadal changes in permafrost location and depth: these are strong indicators of climate change and have very important consequences for greenhouse gas emissions (both methane and carbon dioxide), water availability in root zones (and hence land cover) and energy transfer between the land and atmosphere.

(iv) Land cover and fire regimes: land cover is a crucial determinant of land-atmosphere fluxes, while changes in fire regimes are both an indicator of climate change and are likely to be strongly affected by climate change, with consequences for carbon emissions and sequestration.

Addressing the coupled water and carbon cycles automatically lead to consideration of variables that were also needed for evaluating land-atmosphere interactions through transfer of energy, momentum, water and trace gases, and land-ocean interactions through fresh water discharge into the Arctic Ocean from river run-off (the dynamics of land ice, especially the Greenland ice sheet, are dealt with in WP2). The land components dealt with included hydrology, the soil-vegetation–atmosphere complex and the cryosphere, as represented by the dynamics of snow and permafrost. These components interact strongly at high latitudes and hence datasets gathered to investigate the behaviour of each of them affects the others. Quantitative understanding of these interactions relies very much on availability of comprehensive models, especially to investigate feedback processes. However, many models grow the snow-pack using climate data, with no use of actual snow measurements. In MONARCH-A the observations of the different ECVs were moreover amalgamated in a single modelling framework to elucidate their interactions and allow for exploitation in hydrological models, Dynamic Vegetation Models and climate models.

Theme 2 overall goal was to improve the understanding of the role the high latitude seas and Arctic Ocean plays in water mass transformation, in contributing to the global circulation and in changing sea level on both regional and northern hemisphere scale.

Without a detailed picture of the Arctic Ocean circulation, it is rather difficult to understand the role of the high latitude and Arctic Ocean in shaping the global ocean circulation and sea level changes due to mass loss from the Greenland ice sheet. Moreover, changing conditions in the Arctic permafrost regions are also expected to lead to changes in fresh water input into the Arctic from Siberian rivers and hence the understanding of the circulation in the Arctic Ocean and its exchange with the sub-Arctic seas such as the Norwegian, Greenland and Barents Seas. Finally, ongoing rapid changes of sea ice cover suggest that the Arctic may become an important economic region, e.g., for shipping from Europe to Asian countries and possible exploitation of large natural gas reserves located on the Siberian shelves. This calls for a dedicated Arctic Ocean Reanalysis Effort over the last 30-50 years in order to establish a comprehensive understanding of the mean state and variability. However, the unfortunate lack of reliable, quality controlled long in-situ time series at adequate spatial and temporal coverage limit such reanalyses effort. For instance, the quality and availability of satellite altimetry sea surface height measurements are hampered by the presence of sea ice and require careful processing and correction followed by dedicated validation. In view of this deficit and lack of a balanced observation data sets the MONARCH-A, in stead used models and simulations run to advance the interpretation capability.

Theme 3 addressed the need to advance the understanding of the changes of the marine carbon cycle through: - building up an inventory of existing in-situ and remotely-sensed observations and collate respective data sets; - collocate the respective data with each other and physical variables (such as SST and wind speed) and perform quality control; and - use these data for validating time dependent hind-cast model simulations and for producing basin-wide fields of pCO_2, pH, and carbonate saturation states. However, with respect to carbon data the situation for the high latitude seas and the Arctic Ocean are considered as largely “under-sampled”. Hitherto it has therefore not been possible to adequately keep track of oceanic CO_2 uptake and changes in surface carbonate saturation in high latitude seas and the Arctic Ocean.

In the MONARCH-A project the approach was therefore based on combined use of bottom-up computations of air sea carbon fluxes and biological production rates of POC (particulate organic carbon), DOC (dissolved organic carbon), and $CaCO_3$ (calcium carbonate or PIC, particulate inorganic carbon) through the state-of-the-art coupled physical-biogeochemical ocean model (MICOM-HAMOCC model). In order to arrive at mapped distributions of pCO_2, pH and calcium carbonate saturation states that can be used as future references as well as fed into the model, new extrapolation techniques which take advantage of correlations between seawater CO_2 parameters and other variables with large spatial and temporal coverage were used. These proxy techniques were applied to the production of basin-wide fields of pCO_2 estimates. Moreover, ocean biological primary production of organic carbon in the Arctic including pelagic and coastal regions was derived as times series from ocean colour satellite measurement archives (MERIS, MODIS sensors; MyOcean) and application of suitable algorithms.

Theme 4 adopted a multidisciplinary Earth system approach in order to quantify the combined and interrelated changes in: - terrestrial carbon and water fluxes; - sea level and ocean circulation; and - the marine carbon cycle in the high latitude and Arctic regions. The time series of ECVs were assessed for consistency, variability and trends together with the 3D fields from the model simulations and reanalyzes. The synthesis targeted the need to establish a more comprehensive quantitative understanding of the climate changes in the high latitude and Arctic region over the last 30 – 50 years. In particular, this included:

- New and more accurate characterization of the state and variability of river discharge, snow cover and snow water equivalent, permafrost extent and seasonal variability of frozen ground; sea level and Greenland ice sheet mass loss, ocean currents and sea ice drift as well as ocean mass and heat transport, CO2 partial pressure, and near surface wind field.

- New and better quantification of mutual forcing and feedback mechanisms of the high latitude and Arctic climate system, including natural and anthropogenic contributions;

- New knowledge and support to the attribution of the causes of high latitude and Arctic climate change;

- New knowledge and support to interannual-to-decadal prediction of high latitude climate change, in particular through generation of more accurate initial conditions;

- New knowledge and support to advanced understanding of the two-way connections between global and regional climate change.

Altogether the integrated science and technology achievements from themes 1 to 3 together with the results of the synthesis and interaction with the scientific climate change community in Theme 4 are considered to make a new advanced knowledge base that can feed into an overall assessment of priorities, design and implementation of a multidisciplinary high latitude and Arctic monitoring system for climate change. This will be essential for future advances in operational decadal scale climate and environmental prediction and services targeted the high latitude and Arctic regions.

II Description of the Main S&T Results

The ultimate goal of MONARCH-A was to generate a dedicated information package tailored to a subset of multidisciplinary Essential Climate Variables (ECVs) and their mutual forcing and feedback mechanisms associated with changes in terrestrial carbon and water fluxes, sea level and ocean circulation and the marine carbon cycle in the high latitude and Arctic regions. Adopting an Earth system approach MONARCH-A has attempted to generate tailored information and products to assist climate change research and generate and make available reliable, up-to-date scientific input for the elaboration and implementation of European and international policies and strategies on climate change and society. The information package is based on generation of time series of observation datasets and reprocessing and reanalyses of past observational data to enable adequate descriptions of the status and evolution of the high latitude and Arctic region Earth system components.

The MONARCH-A approach has been organized around four main activities, notably: (i) changes in carbon-water interaction; (ii) changes in sea level and ocean circulation; (iii) changes in marine carbon cycle; and (iv) synthesis and interaction with the scientific community on climate change research. 11 multidisciplinary Essential Climate Variables (ECVs) relevant for high latitude and Arctic regions have been generated and made available in the information package. Arranged according to the GCOS ECVs domain they include:

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- Atmospheric: near surface wind field

The activity of MONARCH-A project during the 3rd and last year has focused on assembling, refining, quality checking and completing data sets and model runs of relevance regarding these 11 Essential Climate Variables. Moreover, the time series and products have then been assessed and synthesized with respect to mutual forcing and feedback mechanisms associated with changes in terrestrial carbon and water fluxes, sea level and ocean circulation and the marine carbon cycle in the high latitude and Arctic regions. They are available at the MONARCH-A web portal (monarch-a.nersc.no), either directly or linked to other existing data repositories.

Some highlights of the main scientific and technical achievements include:

Snow Cover

- Clear indication of a decrease in snow cover extent during spring and earlier snow disappearance for the majority of northern latitudes for the period 1989-2009 from both observations and models. This agrees with recent studies [e.g. *Derksen and Brown*, 2012]. However, over this period, snow cover extent and the dates of snow appearance remain largely unchanged during autumn.

- The last 30 years of Globsnow data show varying trends in snow water equivalent (SWE) in different parts of the boreal region; nonetheless, for the period 1989-2009, areas of significant decrease in SWE dominate northern latitudes and spatially correlate with regions exhibiting earlier snow disappearance dates. This raises the question of whether reduced spring snow extent and earlier disappearance of snow is mainly a consequence of decreases in snowfall. However, reductions in SWE over the past 20 years average only 3-4%, but the dates of snow disappearance have shifted by about a month. This suggests that other factors have contributed, most likely the increase in air temperature observed over northern latitudes.

- By using transect field data collected in the former Soviet Union from 1966 to 1996 [*Krenke*, 2004] the SWE retrieval of Globsnow was evaluated, and was found to capture not only the magnitude of SWE in the region but also the seasonal and inter-annual variation observed in the field data. Globsnow was therefore used to produce trends of SWE for 1980-1996, and these were compared with trends produced by land surface models over the same period. All models captured the major trends observed in northern latitudes over that period, mainly a significant negative trend in Europe and a positive one in central Siberia. However, the inter-annual variation observed in Globsnow was described correctly only by one model, JULES.

River Discharge

- Detailed comparison between the Global River Data Center (GRDC) and model runoff is carried out for the Fraser, Yenesei and Ob basins. GRDC data shows that the Fraser decadal mean runoff decreased between the 1990s and the 1970s, while for the Yenesei it increased, and for the Ob it was stable but with significant inter-annual variability. The model captures the trend in the Fraser but less well in the Yenesei, while it tracks the variability on the Ob very well. However, it shows greater inter-annual variability than the data.

Permafrost

- The permafrost temperature is observed to be increasing at most sites where we have long records, but there are only a few such sites, so instead focus is set on active layer depth (ALD), the permafrost parameter with the best available spatial distribution and temporal duration of data. The ALD has tended to increase in the Russian sub-arctic zone, Mongolia and China over the last decade(s). The strongest trends have been observed in the Russian European North and Chukotka. Different parts of Alaska and Canada exhibit different trends. Increases in ALD are observed at sites in the interior, but both increasing and decreasing trends have been detected in areas close to the ocean. Drawing general conclusions from these data is hampered by the sparse, non-uniform spatial sampling of the observations and the fact that ALD has substantial spatial variability, since it depends on soil composition and very different values of ALD can be measured at points several kilometers apart. The trends in ALD observed at these sites can also be different.

Ice Sheet Mass Balance

- Spatial–temporal variability and changes of Greenland ice sheet elevation from 1992 to 2010 are analyzed from merged ERS-1, ERS-2 and Envisat satellite radar altimeter data. A methodology for determining inter-satellite biases was developed and applied, in order to merge measurements from these different satellites and to create continuous and consistent time series of ice sheet elevations. An average elevation change rate of 1.9±0.3 cm/year from 1992 to 2010 over 81% of the Greenland ice sheet area.

- Surface height changes for the Greenland Ice Sheet were also estimated based on NASA's laser altimetry satellite mission ICESat giving a distinct thinning of the ice sheet along the southeast and west coasts, and a smaller but consistent thickening in the interior part of the ice sheet. This is in agreement with the trends derived from ERS/ENVISAT.

- The GRACE estimate of the total mass changes for the entire ICESat period (October 2003-March 2008) is -204 +/- 21 Gt/yr. In comparison, the conversion of the ICESat heights into mass changes using firn densification and snow density models, results in a larger estimate of -240 +/- 28 Gt/yr.

Sea Level

- On average over the 60-year time span (1950-2009), we find a positive Arctic Coastal Mean Sea Level (CMSL) trend of 1.62 +/- 0.11 mm/yr (after correcting for GIA and IB). The results indicate that between 1950 and the mid-to-late 1990s, Arctic CMSL was mostly driven by internal climate modes, in particular the AO, possibly through changes in wind-stress and associated ocean circulation (although quantitative analyses of the latter effects remain to be performed), as well as ocean mass changes. Since the mid-to-late 1990s, Arctic CMSL shows a marked rise of 4.07 +/- 0.65 mm/yr.

- In order to generate a new dataset suitable to study sea level variability and trend in the Arctic Ocean, satellite altimetry data from the T/P, ERS-1, ERS-2, GFO, Envisat, Jason-1 and Jason-2 missions have been reprocessed to reduce uncertainties associated with presence of sea ice, tidal influences, uneven sampling and lack of spatial coverage. The improvements concern: (1) the mean sea surface; (2) the ocean tide model; (3) the regional multi-mission merging; (4) the sea level grid computation using the objective analysis approach. These improvements lead to a much larger availability of the sea level data in the Arctic region.

- Model results clearly show that in the North Atlantic, Nordic Seas and coastal zones of Norway and even Russia, significant changes also affected sea level as of mid-to-late 1990s, in agreement with other recently reported changes in Arctic climate during the last 1-2 decades (i.e., Serreze and Barry, 2011). This period (last 15 years) may represent a transition in the Earth system evolution as recently suggested by Peltier and Lutchke (2009) and Roy and Peltier (2011). The results also show an increase of the ocean mass component along the Norwegian coast, at least partly explained by the recent acceleration in land ice loss as reported by numerous recent studies.

Sea Ice Volume

- Sea ice freeboard heights and dynamic topography of the Arctic Ocean observed from ICESat altietry 2003-2008 have been updated on a spatial resolution 0.1°x0.2°. The sea ice freeboard heights show good spatial correlation between the distribution of first year ice and multiyear ice observed by QuikSCAT scatterometer data. Overall, a decrease in the Arctic Ocean mean freeboard heights of approximately 10-15 cm is observed since the beginning of the ICESat observations in 2003.

Sea Ice Drift

- Sea ice drift from sea ice models have been compared to observations from satellite and in situ buoys and drift station measurements over the last 30-50 years.

- Sea ice extent estimates from evaluated ocean multi-model reanalyses as well as from remote sensing data have been intercompared and assessed. Dramatic reduction in summer sea ice extend have been encountered in the last decade with the record minimum sea ice extent in September 2012.

Ocean Current

- The GOCE based MDT shape and spatial pattern representing the mean from 1993-2009 for the North Atlantic, Nordic Seas and the Arctic Ocean show elevation changes from the high in the Arctic Ocean to the low in the sub-polar gyre in the North Atlantic reaching about 0.9 m. The regional shape of the MDT with the orientation of the dominant slopes in the different sub-domains reveals the presence of the circulation pathways in: (i) the sub-polar gyre south of Greenland; (ii) the inflow of Atlantic Water respectively between Iceland and the Faroe Islands and between the Faroe and Shetland Islands; (iii) the continuous northward flowing Atlantic Water towards the Arctic Ocean; (iv) the southward flowing East Greenland Current; (v) the Beaufort Gyre; and (vi) the transpolar drift in the Arctic Ocean.

- Model/data intercomparison of the MDT show that there is a large spread among models.

CO2 Partial Pressure

- The investigation of surface-water CO2 partial pressure, atmospheric CO2 partial pressure, primary production, and suspended calcium carbonate showed that both the oceanic and the atmospheric CO2 partial pressure are very consistent variables which have a very regular annual cycle and a very similar behaviour all over the Arctic. In contrast, both primary production and suspended calcium carbonate show an irregular annual cycle in both range and form varying over the Arctic.

Ocean Colour

- The correlations of the temporal comparison per grid point reveal that the model reproduces the temporal behavior of Primary Production well. Biases are as well moderate except for relatively high biases at the northern Greenland coast and the Russian coast section at the Barents Sea. Nevertheless, monthly correlations and bias are less good/moderate showing that the model is able to produce the general temporal behavior, but not the monthly trend. Furthermore, it becomes apparent that the model is not able to produce the annual peak of Primary Production in coastal regions in August/September.

- Comparison between observed and modelled suspended inorganic carbon show poor correlations for both spatial and temporal distributions, most likely due to the fact that the non-zero concentrations of the data-product appear mainly in coastal regions (specifically north of Norway) while the non-zero concentrations of the model appear all over the GIN-seas and the Barents Sea. Furthermore the data-product has a peak in concentrations in August for most of the data-points, but the model output has a peak in concentrations in June. Finally the model shows a regular annual cycle in both form and magnitude while form and magnitude of the annual cycle of the data-product are varying a lot.

Near Surface Wind

- It is found that satellite-derived wind products have a higher spatial resolution, and has much better performance with regard to detection of strong (storm) wind patterns. However, the model wind is also a first requirement and a constraint for the satellite-based wind retrieval procedure. A comparison between several wind products shows that, although the remotely sensed winds are assimilated in ERA Interim, the weather model cannot adequately resolve the small-scale (100-200 km) storm tracks and corresponding wind speeds. QuikSCAT, CERSAT/IFREMER blend and PO.DAAC blend seem to be quite successful in storm detection, whereas ASCAT and ERAI fail in detection of the wind speeds exceeding 20 m/s.

The corresponding 11 time series and products have then been assessed and synthesized with respect to mutual forcing and feedback mechanisms associated with changes in terrestrial carbon and water fluxes, sea level and ocean circulation and the marine carbon cycle in the high latitude and Arctic regions. Moreover, the data are generally provided with given quality and uncertainty estimation making the data sets more attractive for model validation, reanalyses and initial boundary conditions. These multidisciplinary time series integrated and combined with existing complementary information on land cover, fire, sea ice extent and concentration, sea ice thickness, sea surface temperature and sea level are open and freely available (directly or linked to other data repositories) to assist and support climate change research at the web portal (http://monarch-a.nersc.no).

Theme 1: Changes in terrestrial carbon-water interaction. Models provide the most effective means of synthesizing the land variables, since they not only contain most of these variables, but inherently contain the interactions between them through the processes embodied in the models. Hence model analysis and model runs have been used to answer the following questions:

1. Do the models exhibit the observed trends (or lack of them) for the ECVs considered, both globally and regionally?
2. What effects do these trends or their absence have on the carbon and water balances?

Note that these questions are not considered for the surface water and fire ECVs. Surface water is not represented in the models, and fire is omitted for two reasons:

- the data series is too short to investigate trends
- the disparity between models and data is so great that investigation of trends using the models would not be meaningful.

Snow cover: The results clearly indicate a decrease in snow cover extent during spring and earlier snow disappearance for the majority of northern latitudes for the period 1989-2009 as shown in Figure 1. However, over this period, snow cover extent and the dates of snow appearance remain largely unchanged during autumn. The last 30 years of Globsnow data show varying trends in SWE in different parts of the boreal region; nonetheless, for the period 1989-2009, areas of significant decrease in SWE dominate northern latitudes and spatially correlate with regions exhibiting earlier snow disappearance dates. This raises the question of whether reduced spring snow extent and earlier disappearance of snow is mainly a consequence of decreases in snowfall. However, reductions in SWE over the past 20 years average only 3-4%, but the dates of snow disappearance have shifted by about a month. This suggests that other factors have contributed, most likely the increase in air temperature observed over northern latitudes.

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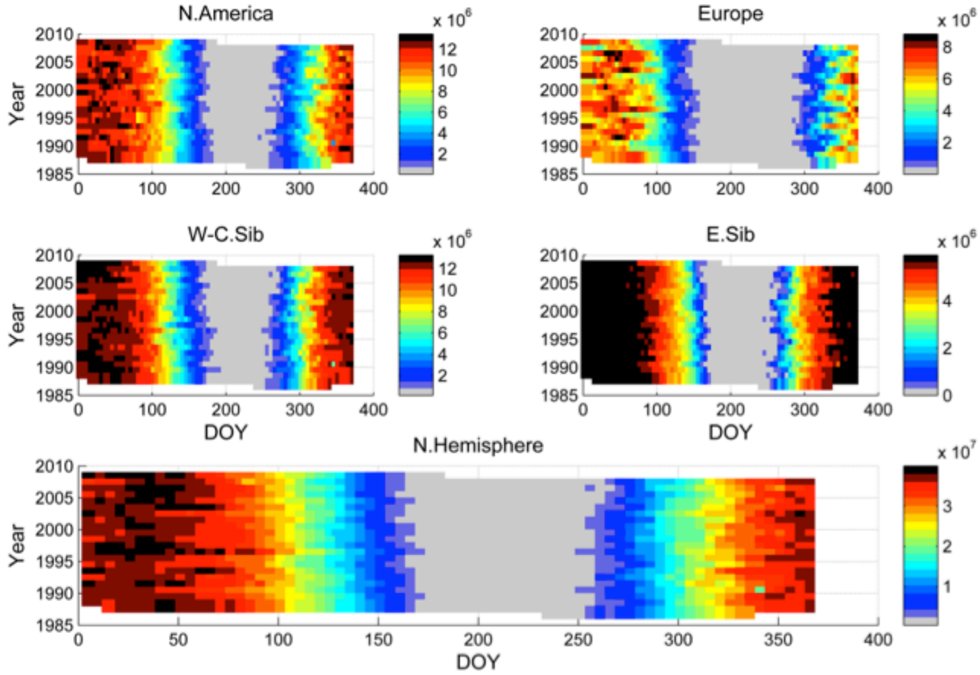

Figure 1 *Snow covered area (km^2) as a function of day of the year over the period 1987-2009 for N. America, Europe, West & Central Siberia and Eastern Siberia, and the whole Northern Hemisphere.*

Pan-boreal water balance: Driving the Sheffield Dynamic Global Vegetation Model (SDGVM) with the CRU data set produces a gradual increase in pan-boreal runoff of ~10% up until 2000 followed by a decrease to 2006. A longer time series would be required for both climate data and runoff observations to determine whether the modeled drop in runoff after 2000 is significant. These overall trends in run-off mask significant differences between basins, mainly driven by precipitation, as indicated by the spatial patterns of mean runoff difference between the 1990s and 1970s in several large high-latitude basins. The model and data agree on the sign of the trends except in the Ob, where GRDC shows little change while SDGVM indicates increased runoff. Greater decreases in runoff are given by the model than the data in the Mackenzie and Lena basins. A more detailed comparison between GRDC and model runoff is given in for the Fraser, Yenisei and Ob basinsb (see Figure 2). GRDC data shows that the Fraser decadal mean runoff decreased between the 1990s and the 1970s, while for the Yenisei it increased, and for the Ob it was stable but with significant inter-annual variability. The model captured the trend in the Fraser but less well in the Yenisei, and it tracked the variability on the Ob very well. However, it showed greater inter-annual variability than the data, and this may be the cause of the apparent difference between the data and model for the Ob.

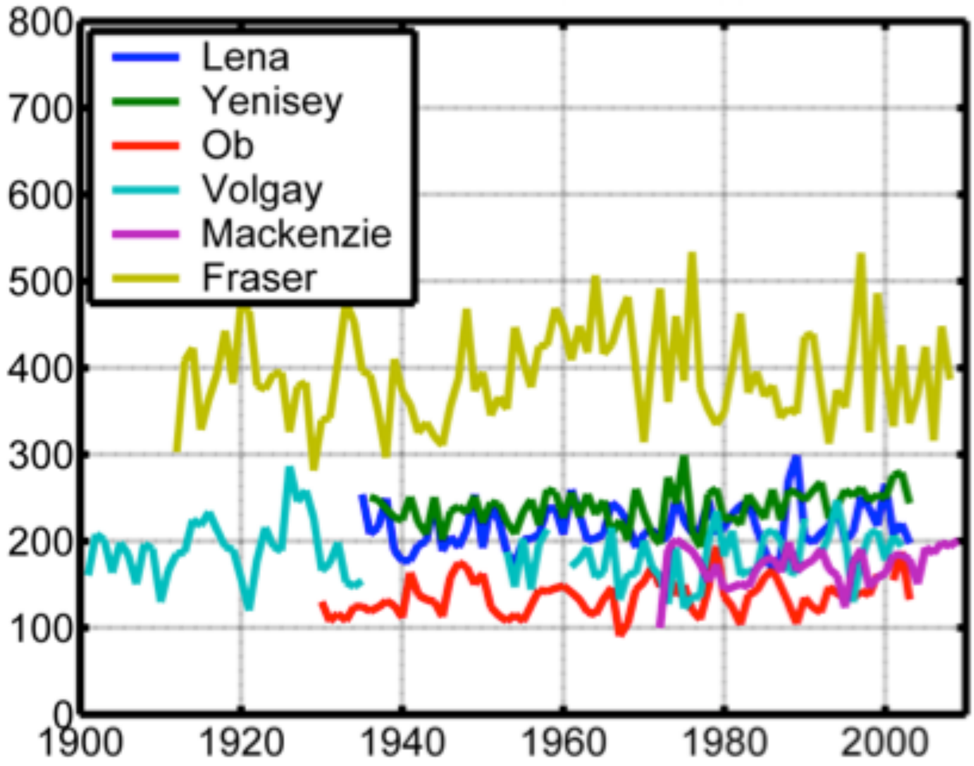

Figure 2. *Observed runoff from GRDC data over the period 1900-2006 for several large high latitude basins.*

There are strong connections between fire, permafrost, biomass, land cover and net carbon balance (Net Biome Production-NBP). The mean annual magnitude of all the fluxes making up the carbon balance over the period 1981-2006 for latitudes northward of 50 degree North reveal that fire is a very significant contributor to the net carbon balance, but models differ considerably as regards both its absolute magnitude and its magnitude relative to NBP. The available time series of data on carbon cycle processes, especially fire, are at present too short to provide statistically significant evidence of trends over the last few decades, particularly since the area burnt by boreal fires exhibits large inter-annual variability. The models all exhibit much too small temporal and spatial variability in burned area compared to the satellite record, so the current model representation of fire in models is clearly inadequate. This casts doubt on their ability to estimate other important processes, such as the dynamics of permafrost. Since fire is a very significant factor in determining the magnitude and even the sign of the net carbon flux at high latitudes, the model-based estimates of the net carbon flux must therefore be considered as provisional. This is a deficiency that needs to be urgently considered with respect to the present and future capacity and design of the observing system

In comparison, the situation is much better for the water balance, with long time series of both high quality satellite-derived estimates of Snow Water Equivalent and runoff data for all the major high latitude basins. Models and data are in broad agreement, so that the data can be interpreted in terms of processes. In addition, model-data and model-model differences can be explained in terms of driving data (especially precipitation) and differences in model representations and parameterizations.

Theme 2: Changes in sea level and ocean circulation. The altimetry-based mean sea level along the Siberian and Norwegian coast averaging individual time series at the 11 tide gauge sites are shown in Figure 3. Both curves are highly correlated and show an increasing sea level trend of 3.32 +/- 0.65 mm/yr (from tide gauges) and 4.23 +/- 0.23 mm/yr (from satellite altimetry) over the altimetry period (1993-2009). The trend difference (0.9 mm/yr) is only slightly larger than the tide gauge trend uncertainty. Thus the altimetry data clearly confirm the recent sea level increase in that particular region. It is also noteworthy that the rate of sea level rise in this high latitude and Arctic region is very similar to the global mean rate (of 3.3 mm/yr over 1993-2009). The green-curve represents the mass-variation along the coast from GRACE converted to sea level change for the period 2003 to 2010. Some degree of similar variability are depicted, while the differences are most likely explained by the contribution from the wind field to the sea level changes.

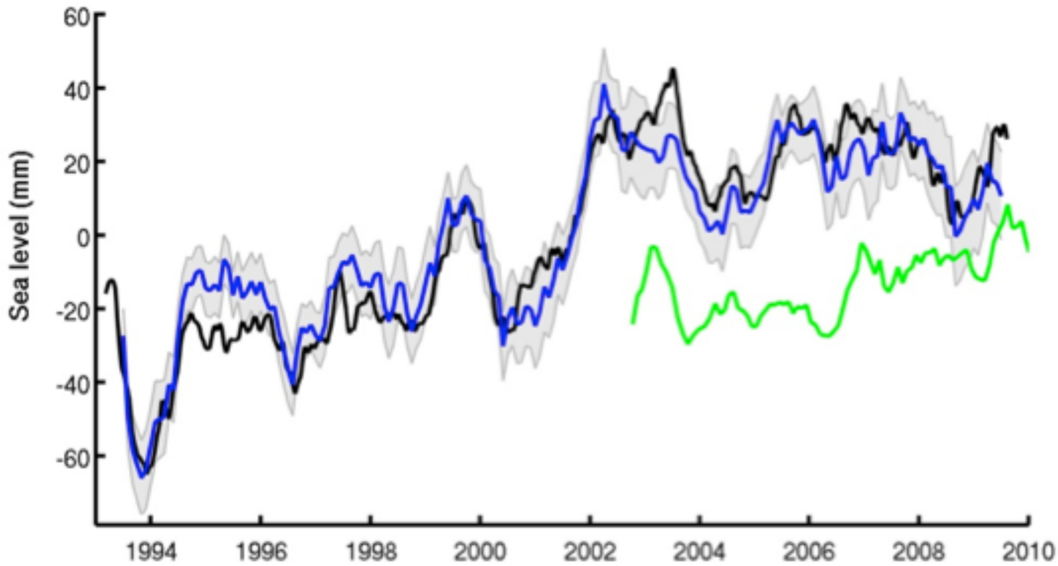

Figure 3 *Coastal mean sea level from tide gauge records over 1993-2009 for the Arctic sector (Russian and Norwegian, blue curve) and from altimetry (interpolated to each TG sites, black curve), the green curve is the coastal mean ocean mass from GRACE/CSR (interpolated at each TG sites).*

Model results show that there is increase in curl of surface ocean currents in the Beaufort Gyre (BGR). A possible reason for this is less sea cover ice and thinner ice. After the mid of 1990s episodes of decrease in the September sea ice minima and strengthening of surface current curl coincide, while for sea ice thickness correlation is not well established. The relative role of changes in ice properties and atmospheric characteristics for ocean currents variability should also be further investigated. Faster and more “anticyclonic” currents in the BGR lead to accumulation of freshwater in the upper part of the water column. Model simulations indicate that since the middle of the 1990s there has been a steady increase of freshwater content in BRG, that accelerated after 2005. This increase is also observed from direct oceanographic measurements, and is also indicated by satellite SSH data (see Figure 4).

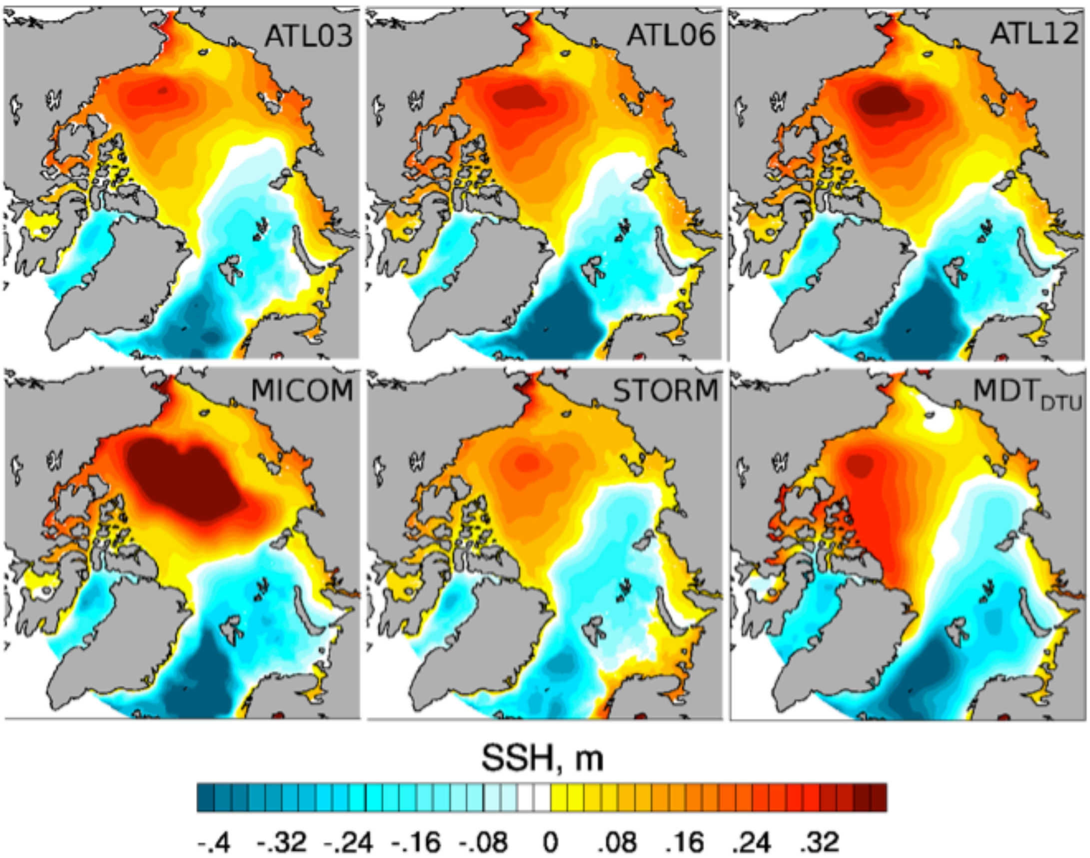

Figure 4. *Example of model/observations intercomparison. Mean sea surface height for the period 1993-2009 as simulated by several models and measured by satellites. Satellite data are reprocessed in the framework of the MONARCH-A.*

Reprocessed data of sea level anomalies let us investigate, at least to some extent, the variability of SSH in BGR. Sea ice cover prevents satellites from getting sufficient amount of information during winter time, so only yearly mean values are shown. Both model and data agree on the large positive SSH trend since the mid 1990s. The model results also indicate that this trend is the largest one since at least 1970. It is possible, that the ocean in the BGR have experienced some sort of a shift in its state during the last 15 years. This shift involves both sea ice and the upper ocean. Whether the same shift is observed for the whole Arctic Ocean is not clear, but there are also considerable changes in other regions of the Arctic Ocean, and in the North Atlantic Warming in the Nordic Seas reduces heat loss in the Atlantic water implying that warmer water propagates into the Arctic region. The MONARCH-A results clearly show that in the North Atlantic, Nordic Seas and coastal zones of Norway and even Russia, significant changes also affected sea level as of mid-to-late 1990s. Finally the results also show an increase of the ocean mass component along the Norwegian coast, at least partly explained by the recent acceleration in land ice loss as observed from GRACE and altimetry. The SSH is an important integral parameter, that reflects changes in many characteristics of the Earth system. It is therefore important to continue and improve its observational record. Moreover, in order to understand the relative contributions of different processes and their interaction it is also important to observe and provide model estimates of additional quantities, such as freshwater content.

Theme 3: The marine carbon cycle. The investigation of surface-water CO_2 partial pressure, atmospheric CO_2 partial pressure, primary production, and suspended calcium carbonate showed that both the oceanic and the atmospheric CO_2 partial pressure are very consistent variables which have a very regular annual cycle and a very similar behavior all over the Arctic. In contrast, both primary production and suspended calcium carbonate show an irregular annual cycle in both range and form varying over the Arctic.

While a few well distributed measurement stations with monthly observations are sufficient to get a comprehensive picture for consistent ECVs, it is relatively difficult and costly to get a comprehensive picture of non-consistent ECVs (e.g. primary production and calcium carbonate production). Here, widespread measurements for at least 40 years are needed to capture both different regional behavior (e.g. coastal versus non-coastal behavior) and their trends (for relatively short timescales it is very likely that the calculated linear trend is governed by just a few extreme values which are not representative for a general trend in the ECV). Unfortunately the provided data-sets of the non-consistent ECVs cover both relatively short time-scales, so it was neither possible to confidently validate the model nor to determine significant trends. Nevertheless the collected information of both primary production and calcium carbonate production allows for a first data-model comparison as show in Figure 5. However, it is highly important that the observations for both these variables are continued and sustained so that a confident analysis with a determination of significant trends is hopefully possible.

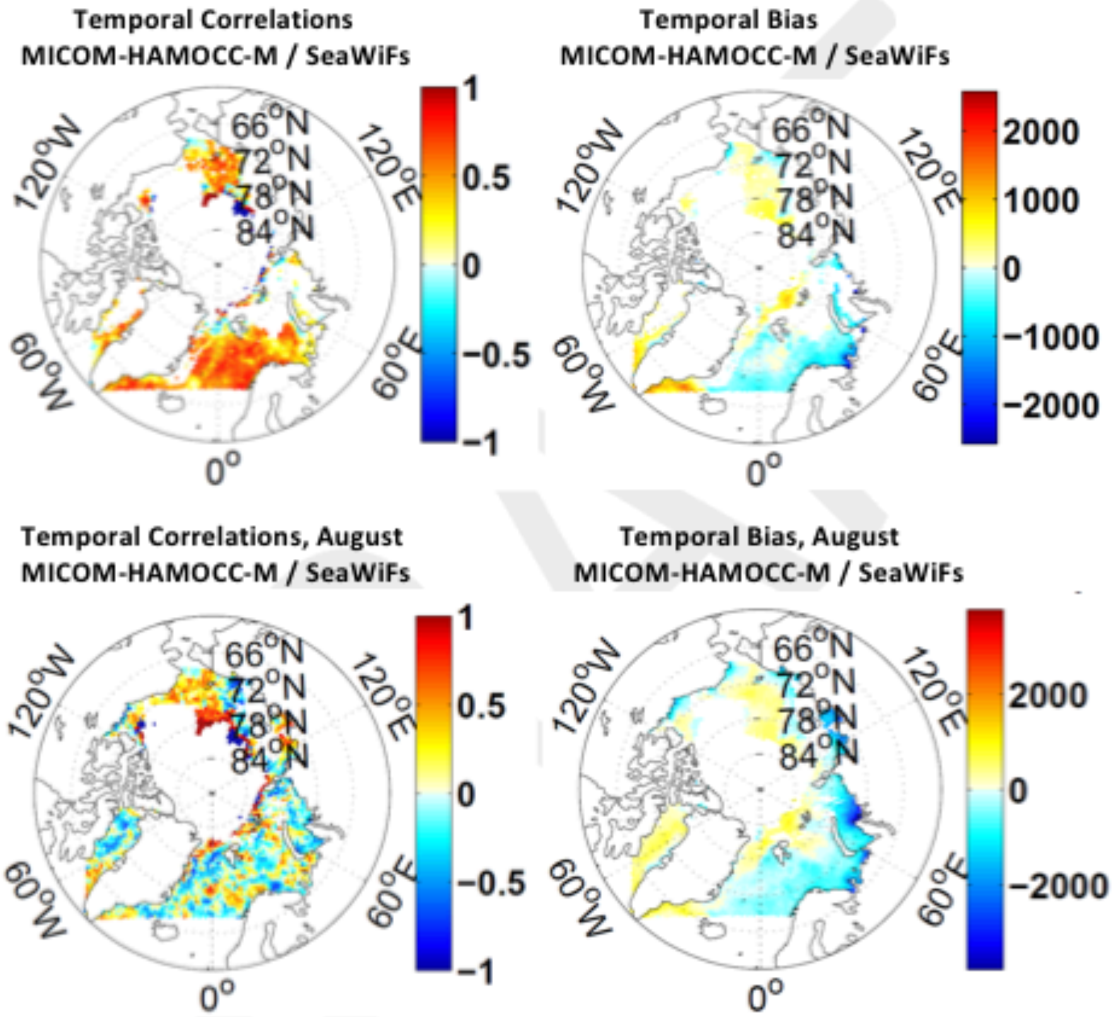

Figure 5. *Temporal Primary Production Correlations (left) and Biases (right) of the data-model-comparison between the data-product SeaWiFs and the model MICOM-HAMOCC-M for the time period 1998-2010. Depicted are both Correlations and Biases for the whole time period (top row) as well as Correlations and Biases for only the month August (bottom row).*

The datasets for the consistent ECVs oceanic and atmospheric pCO_2 are by far more comprehensive and allow for a more confident data-model comparison (for oceanic pCO_2 at least within the region between 60°W and 30°E) as shown in Figure 6. The 8 measurement stations of atmospheric CO_2, at well distributed locations, provide a continuous and very good characterization of CO_2 changes demonstrating its value versus just a large amount of widespread observations. A similar measurement network would be desirable for oceanic pCO_2. Still the LDEO/SOCAT database allows for confident statements about the trends of pCO_2^{sea} in the region between 60°W and 30°E. Here, the model MICOM-HAMOCC-M calculates an increasing trend for 1961-1986 varying from 0.2 ppm to 2.0 ppm, while the trend for 1986-2011 varies from 1.25 ppm to 2.6 ppm. Meanwhile the trend of pCO_2^{atm} is 1.176 ppm for 1961-1986 and 1.72 ppm for the same period. Hence, at some grid points the trend of pCO_2^{sea} is higher than the trend of pCO_2^{atm} leading to a decreasing CO_2 uptake in the ocean.

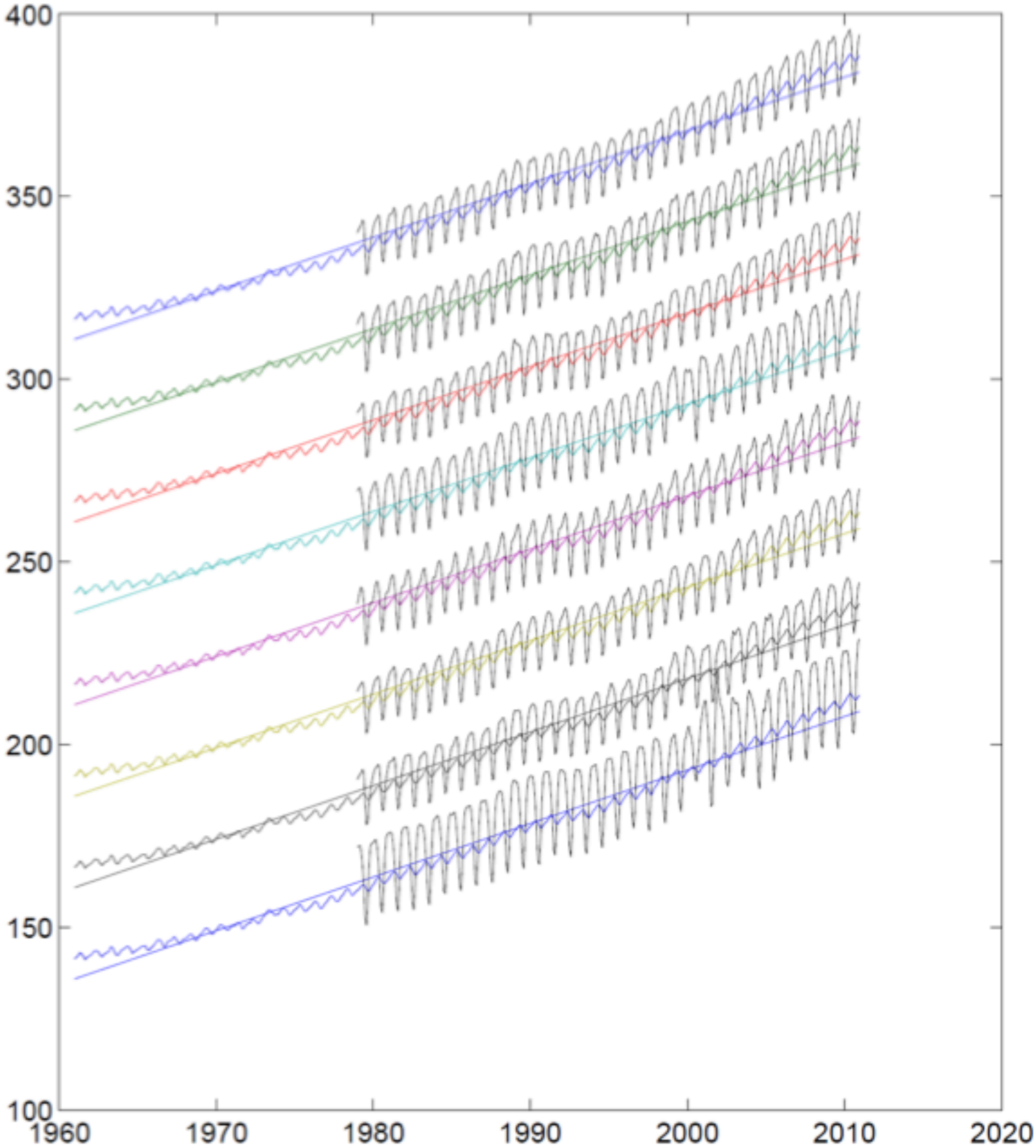

Figure 6: *Selected pCO_2^{atm} Timeseries and Trends for 1961-2011 as modelled by MICOM-HAMOCC-M (colored lines). Extended GLOBALVIEW-records are marked by black lines. Associated offsets and coordinates are denoted in the right panel.*

Theme 4: Synthesis of interaction and mutual feedback. The three first distinct themes studied in MONARCH-A, notably: - changes in terrestrial carbon and water fluxes; - changes in sea level and ocean circulation; - and changes in marine carbon cycle are indeed strongly interrelated and interacting as part of the complex multidisciplinary functionality of the Earth system as suggested in Figure 7. As such several of the Essential Climate Variables (ECVs) display seasonal and interannual variations that are mutually influenced (e.g. reinforced or damped) at a broad range of spatial scales. In the following some of the interdisciplinary processes and their mutual feedbacks connected with these ECVs investigated in the

MONARCH-A project are further discussed according to the water cycle, sea level and marine carbon cycle.

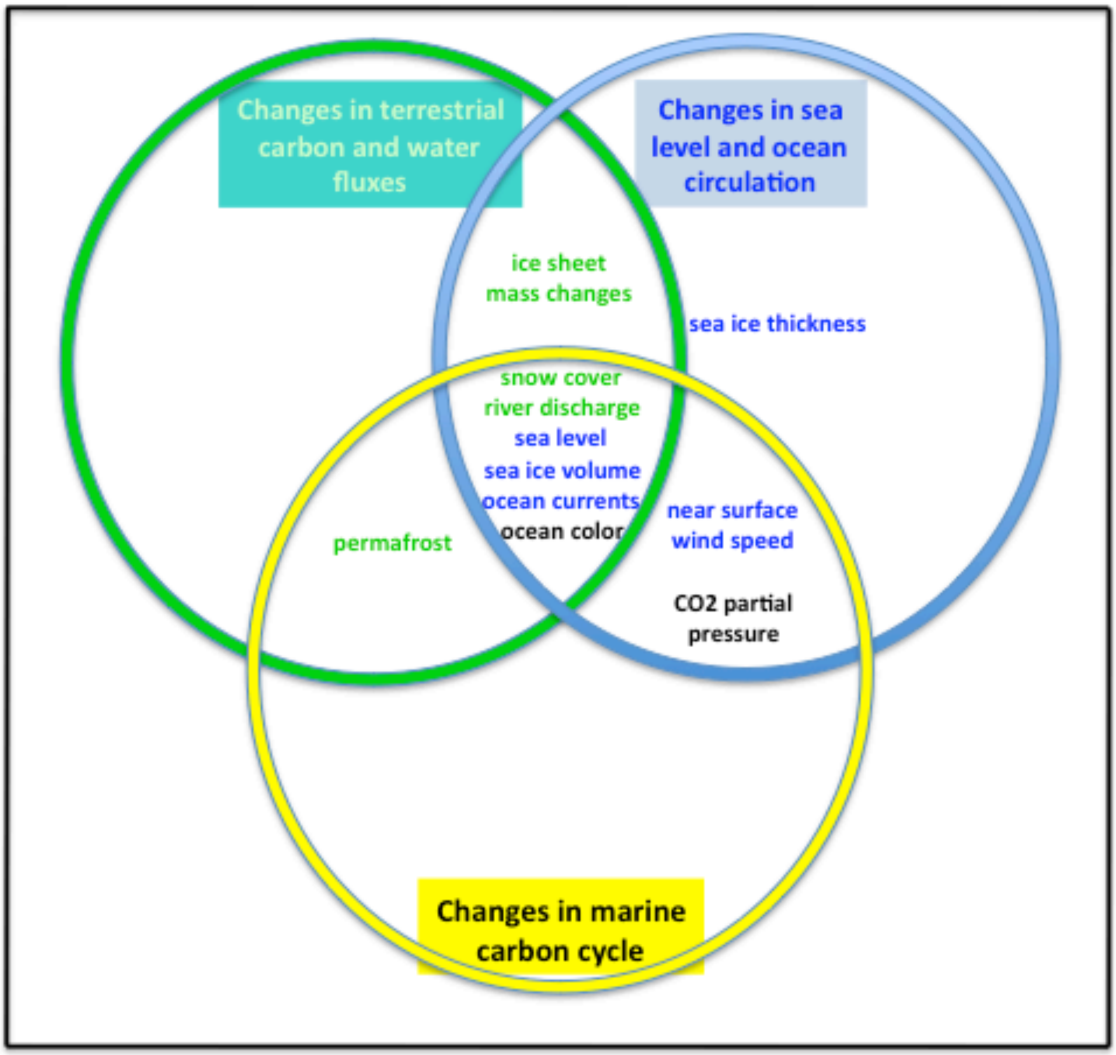

Figure 7. *Schematic illustration of the intersections and interactions between the three major research themes addressed in the MONARCH-A project. The location of the ECVs inside the different intersections of the three themes signals their cross-disciplinary interactions and feedback.*

High latitude and Arctic regional water cycle: This encapsulates processes and dynamics in the biosphere, the cryosphere, the atmosphere (not addressed in this MONARCH-A project) and the hydrosphere as well as complementary and mutual cross–sphere interactions and feedbacks. Regarding the two former spheres the changes in snow cover and snow water equivalent, river discharges, permafrost extent and ice sheet and glacier elevations are all features of the water cycle with its distinct seasonal to annual variability. Moreover, for the hydrosphere the gradual retreat in sea ice concentration, extent and volume indirectly influence the water cycle through changes in the ocean-atmosphere fluxes (e.g. evaporation and sensible heat) that, in turn, might enhance the regional precipitation. Monitoring and prediction of the water cycle at high latitude and Arctic region may seem simple but, in contrary, it is extremely challenging as weak and strong changes, interactions and mutual feedback between the ECVs occur over a broad range of temporal and spatial scales that is not properly incorporated into the design and operation of the observing system. In result, we lack process understanding. Combined with model deficiencies in spatial resolution and reliable parameterizations the predictive skill of the water cycle is also rather limited.

The sea level budget: The increasing area of open water in the Arctic Ocean and the sub Arctic-seas in the presence of a decline in the sea ice extent alter the upper layer hydrographic conditions and hence the steric height contribution to sea level change. Moreover, changes in the mean and variable freshwater runoff from the biopshere and the cryosphere (including meltwater from permafrost areas) lead to a freshening of the ocean surface layer and a sea level change. The presence of sea ice further complicates the retrieval of the mean sea surface from satellite altimetry. In particular thin ice with equivalent ice freeboard height ranging up to about 10 cm poses a great challenge to be precisely measured. In view of the rather tiny signal of the mean global annual trend in sea level rise of about 2-3 mm/year the accuracy of the correction of the altimeter surface height measurement to the sea ice freeboard signal is therefore highly demanding. Lack of adequate validation limits the ability to quantify the accuracy of this correction and hence the uncertainty in the mean sea surface determination in the permanent sea ice covered interior Arctic Ocean. Changes in the transport of heat with the ocean currents from the North Atlantic to the Arctic Ocean may also change the steric height contribution to changes in the mean regional sea level. Finally, the mass loss associated with melting ice sheets also lead to glacial isostatic adjustment (GIA) that must be corrected before the corresponding regional seasonal to decadal sea level budget can be accurately closed.

The marine carbon cycle. The high latitude seasonal land vegetation cycle (influenced by changes in the snow cover and SWE) influences the atmospheric CO_2 concentration and its seasonal cycle, while the influence of the ocean seasonality on the atmospheric CO_2 record is fairly small in high latitude and Arctic waters. The atmospheric CO2 record at Point Barrow, Alaska, USA (Keeling et al., 2008) shows a fairly strong seasonal amplitude slowly increasing (e.g., Wu and Lynch, 2000) with time pointing towards a gradual intensifying of the spring-growth/autumn-degradation pattern of the terrestrial biomass (supporting evidence for an increase in CO_2 fertilization for land plants). This pattern could lead to a (very slight) bias towards reduced oceanic uptake of CO_2 during the ice free months (when also the atmospheric CO_2 is minimal). However, this effect will probably be smaller than other errors in present ocean biogeochemical circulation models although it could indicate that ocean biogeochemistry in the high latitude and Arctic Ocean may be less affected by rising CO_2 (apart from the severe impact due to ocean acidification). Further investigations are needed to verify this hypothesis.

The river discharges and their concentration of carbon, nutrients and other dissolved inorganic and organic matter (e.g. alkalinity) also modify the biological carbon pump and the inorganic solubility pump. If more nutrients than carbon are released, then under assumption of stable "Redfield ratios", a net drawdown of the CO_2 partial pressure could be the consequence and vice versa. At present, the oceanic data base of nutrients and carbon is not sufficient to reveal such potential modifications. The remotely sensed primary production record (through ocean color and chlorophyll estimates) may allow documenting such changes along the coastal zones and continental margin over time provided the separation of chlorophyll from dissolved organic matter can be obtained with satisfactory accuracy. Overall, a quantification of the respective forcing and feedback mechanisms and their change over time are not yet feasible largely due to lack of sustainable observations providing long time series.

For the linkage between ocean physical processes and the marine carbon cycle, a number of additional processes need to be considered. Phytoplankton blooms, specifically under development of more permanently ice-free areas in the Arctic could potentially accelerate warming and hence melting processes if the biomass in the euphotic layer of the ocean indeed would absorb radiation and this contribute to warming. Changes in temperature and salinity (due to both advection and convection) also influence directly the solubility of CO_2 (worse under warming) and buffer capacity (better under warming). These partially compensating effects can in principle be fairly well established (e.g. Tjiputra et al., 2010a), if sufficient time series data are available. However, the combined action of reducing sea ice coverage, surface warming, potential changes in freshwater supply from land, and changing inflows from the Atlantic (Barents Sea, Fram Strait) and Pacific (Bering Strait) and related synergistic effects on ocean carbon cycling are difficult to predict. In order to establish respective changes unambiguously from observations, a seasonal coverage of sea surface pCO_2 measurements in concert with remotely sensed primary production rates would be needed. It is not yet established what the net effect of sea ice growth and melting is on ocean carbon cycling, potentially sea ice formation can result in out-gassing of CO_2 from the ocean (Miller et al., 2011). Whether this temporary release is compensated for by other effects during the seasonal cycle is not established, although it appears that the primary production in the Arctic shelf seas have increased as a result of decline in the sea ice extent (Petrenko et al., 2013) potentially favoring a stronger biological pump.

Implication for the Observing System. The MONARCH-A project has revealed deficiency in the in-situ observing system for the high latitude and Arctic region. In combination with multidisciplinary satellite observations its therefore necessary to develop and sustain the system in order to advance the process understanding, cross-disciplinary interaction and mutual feedbacks. Only via the implementation and operation of a regionally and globally balanced observing system will it be possible to consistently monitor the state and variability of the Earth System.

<u>Terrestrial carbon and water fluxes:</u> Reliable estimate of the seasonal and decadal changes in snow water equivalent (SEW) relies on accurate observations of the ***snow cover*** extent, snow depth and snow density. Whereas satellites are giving very good observations of the snow cover measurements of snow thickness and density are scattered and irregular in time. As such the accuracy of the estimation of the SWE can be questioned. The in-situ observing capacity should therefore improve in order to have more precise figures for the SWE and

hence its contribution to ***river discharges***. Likewise is the need to secure sustainable in-situ observations of ***permafrost*** and its contribution to river discharges at adequate temporal and spatial resolution. Proper estimation of the meltwater fluxes from the Greenland ***Ice Sheet*** to the Arctic Ocean is also challenging as in-situ observations are limited and we can only rely on coarse resolution observations of mass changes from satellite. Another major challenge regarding river discharges is also the fluxes of carbon, nutrients, dissolved inorganic and organic matter, and other natural and man-made substances to the shelf seas. As long as the in-situ observations are insufficient we are faced with a major challenge to properly characterize the biogeochemical state and its interaction with the physical state of the ocean. This, in turn, implies knowledge gaps both regarding the marine carbon cycle and the marine ecosystem functionality.

Sea level and ocean circulation: ***Sea ice thickness*** and freeboard height needs to be precisely measured from in-situ observation system with sufficient spatial coverage across all seasons to complement and validate satellite observations (Cryosat, SMOS) as well as forced coupled ocean-sea ice models and coupled climate models. This will yield improved correction of the sea ice freeboard signal for reconstruction of the mean sea surface and ***sea level*** change with known uncertainties from altimetry as well as more reliable estimate of changes in the ***sea ice volume*** in both the Arctic Ocean and its export through the Fram Strait. The in-situ observations should also ensure measurements of the sea ice deformation field occurring under different atmospheric conditions and at different seasons in order to gain better quantitative understanding of the mechanical behavior of sea ice and, in turn, more reliable parameterization of sea ice rheology in models. Advances in the knowledge of the state and variability of the hydrographic conditions and ***ocean currents*** in the Arctic Ocean at seasonal time scales and mesoscale spatial resolution are moreover needed to quantify the thermohaline circulation and the Atlantic Meriodional Overturning Circulation (AMOC) with known uncertainties as well as to validate forced and coupled models and improve reanalyses.

Marine carbon cycle: The effect of increased absorption of CO_2 by the ocean with the consequence of a chemical state shift towards lower pH and lower carbonate saturation ("ocean acidification") can have short and longer-term consequences for marine ecosystems (e.g., Riebesell et al., 2007; Müller et al., 2010; Büdenbender et al., 2012), though also acclimation effects have been recorded (e.g., Form and Riebesell, 2012). Sustainable monitoring of the ocean carbon cycle in the Arctic surface layer is therefore essential. Next to observations of ***surface ocean*** pCO_2, ***ocean color*** and primary production of organic carbon, and suspended CaCO3 material (as done in MONARCH-A), the measurement of other state variables would be needed (such as the carbonate ion concentration). Moreover it would be desirable to have time series of calcite and aragonite production available. A further issue is the potentially advanced released of CH4 from gas hydrates around the Arctic Ocean continental margin. The stability of these hydrates is determined among other factors by the ocean temperature and the ambient pressure. A warming of seawater could potentially release the methane stored in the hydrates (Biastoch et al., 2011) and hence contribute to ocean acidification. Sustainable observations of methane release to the ocean is therefore urgently needed and should be complemented to include systematic measurement of ***permafrost*** change with sufficient spatial coverage.

In order to best possible predict changes in high latitude seawater pH and carbonate ion concentration, respective benchmark values from observations for marine carbon cycling are highly desirable. For this purpose, total dissolved inorganic carbon (DIC) and alkalinity (Alk) would be needed. Biogeochemical tracers such as DIC, Alk, nutrients, and oxygen can also be used to validate flow fields of the ocean and can provide valuable additional constraints for oceanic physical state estimation. However, due to the overall not very high biological production rates, a statistical significant Alk signal in the Arctic ocean would probably require several decades of measurements in order to show a large scale increase in Alk (due to less uptake of CO_3^{2-} ions by organisms), whereas a corresponding signal in the tropical Pacific may be a better early warning indicator (Ilyina et al., 2009).

The influence of the Arctic on climate change is likely to grow in near future. For instance, the summer sea ice area in the Arctic encountered the record minimum ever observed in September 2012, and for the first time surface temperature above freezing was recorded over the entire Greenland ice sheet. In contrast to the Arctic warming and the reduction of Arctic sea ice, North America, Europe, and East Asia have experienced anomalously cold conditions with record high snowfalls in recent years. Possible impacts of such reduced autumn sea ice cover and severe winter weather as well as summer sea ice loss and more (persistent) extreme summer climate conditions with drought or flooding are now increasingly discussed by scientists. Moreover, changes in the temperature and salinity of the surface water in the Arctic Ocean and Nordic Seas, and the flow of dense water through Denmark Strait, are known to be precursors to changes in the Atlantic Meridional Overturning Circulation (AMOC) with a lead-time of around 10 years. This links changes in the high latitude and Arctic with far reaching influences on regional and northern hemisphere/global environment and climate variability.

The scientific findings and achievements in the MONARCH-A project study are therefore expected to become valuable for the elaboration and implementation of European and international policies and strategies on the environment and society, including climate adaptation strategies addressing European, national, regional and local levels, such as:

- characterization of the state of a subset of dominant multidisciplinary ECVs and their variability in high latitude and Arctic areas;
- establish a multidisciplinary and sustainable observing system of the forcing and variability of the high latitude climate system, including natural and anthropogenic contributions, at regional and local scales;
- support the attribution of the causes of high latitude climate change;
- support prediction of high latitude climate change;

- enable advanced understanding of the two-way connections between global and regional climate change.

Improving our understanding of causes and mechanisms of the ongoing changes in the high latitude and Arctic region as part of the global climate system and improving our capabilities of projecting future climate variability in the Arctic is needed in order to develop relevant adaptation and response measures. Reduced sea ice cover, increased ice sheet melting, changes in snow cover and snow water equivalent, sea level rise and changes in the marine carbon cycle may have far reaching socio-economic consequences that, in turn, will impact the political landscape.

III Description of Potential Impact

The scientific findings achieved in the MONARCH-A project study is expected o become valuable for the elaboration and implementation of European and international policies and strategies on the environment and society, including climate adaptation strategies addressing European, national, regional and local levels, such as:

- characterization of the state of a subset of dominant multidisciplinary ECVs and their variability in high latitude and Arctic areas;
- monitoring the forcing and variability of the high latitude climate system, including natural and anthropogenic contributions, at regional and local scales;
- support the attribution of the causes of high latitude climate change;
- support prediction of high latitude climate change
- enable advanced understanding of the two-way connections between global and regional climate change.

Improving our understanding of causes and mechanisms of the ongoing changes in the Arctic as part of the global climate system and improving our capabilities of projecting future climate variability in the Arctic is needed in order to develop relevant adaptation and response measures. Reduced sea ice cover, increased ice sheet melting and sea level rise will in particular have far reaching consequences in terms of new and shorter shipping routes and at the same time create problems for low lying coastal areas and islands. In order to understand the impacts on Arctic and non-Arctic societies updated knowledge about biophysical conditions must be coupled with knowledge about changes occurring in socio-economic and political conditions.

The influence of the Arctic on climate change is likely to grow in near future. For instance, the summer sea ice area in the Arctic encountered the record minimum ever observed in September 2012, and for the first time surface temperature above freezing was recorded over the entire Greenland ice sheet. In contrast to the Arctic warming and the reduction of Arctic sea ice, North America, Europe, and East Asia have experienced anomalously cold conditions with record high snowfalls in recent years. Several papers have discussed possible impacts of such reduced autumn sea ice cover and severe winter weather (e.g. Overland and Wang, 2010; Liu et al., 2012) and summer sea ice loss and more (persistent) extreme summer climate conditions with drought or flooding. Moreover, rapid changes in the temperature and salinity of the surface water in the Arctic Ocean and Nordic Seas, and the flow of dense water through Denmark Strait, are known to be precursors to rapid changes in the Atlantic Meridional Overturning Circulation (AMOC) with a lead-time of around 10 years. The Atlantic waters entering the sub-Arctic seas and Arctic Ocean with anomalously high heat content change the temperature and sea ice extent in the Atlantic Arctic as well as in the central Arctic downstream up to Laptev Sea. This links changes in the Arctic with far reaching influences on regional and northern hemisphere/global environment and climate variability as well as major socio-economic impacts in and beyond the Arctic including insurance costs.

A major part of the communication and interaction of the MONARCH-A project and its main findings and achievements with the scientific communities and stakeholders have frequently occurred through participation to conferences, workshops and collocation meetings including:

- Workshop on Evaluation of Satellite-Related Global Climate Datasets, 18-20 April 2011, Frascati, Italy. (A report of the workshop is available at http://www.wmo.int/pages/prog/gcos/TOPCXIII/7.1_WOAP_Workshop.pdf.)

- Lets Embrace Space Conference, 11-12 May, Budapest, Romania. (The conference program, documents and presentation material is available at the website http://ec.europa.eu/enterprise/newsroom/cf/itemdetail.cfm?item_id=4845.

- GMES and CLIMATE CHANGE Forum, 16th -17th June 2011, Dynamicum, Finnish Meteorological Institute (FMI), Helsinki, Finland. The conference program, documents, reports and presentation material is available at the website http://ec.europa.eu/enterprise/newsroom/.

- WCRP Open Science Conference, 24-28 October 2011, Denver, Co, USA. The conference program, documents, reports and presentation material is available at the website http://www.wcrp-climate.org/conference2011/.

- Earth Observation for Ocean-Atmosphere Interactions Science conference, 29 November-2 December 2011, ESA-ESRIN, Frascati, Italy. The conference program, documents, reports and presentation material is available at the website http://www.eo4oceanatmosphere.info/.

- ISSI workshop on The Earth´s Hydrological Cycle, 6- 10 February, 2012, International Space Science Institute, Bern, Switzerland. The conference program, documents, reports and presentation material is available at the website http://www.issibern.ch/workshops/hydro/.
- The WCRP 4th Reanalysis conference, held in May 7 – 11 2012, Silver Spring, Maryland, USA. D. Stammer provided an overview talk on ocean and Arctic reanalysis, highlighting MONARCH-A efforts and results.

- The workshop on ECV data exchange and information issues in FP7 climate projects hosted by REA in Brussels on 11-12 September 2012. Other EU FP7 projects represented at the workshop included: CARBONES, CRYOLAND, CORE-CLIMAX, EURO4M, GeoLand2, ICE2SEA, MACC II, and MyOcean2. Moreover, DG Enterprise, DG CLIMA and DG RTD were represented in addition to REA.

- The third International Symposium on Arctic Research: Detecting the change in the Arctic System and searching global influence, 14-17 January 2013, Tokyo, Japan.

- The collocation meeting arranged by the CORE-CLIMAX project at REA in Brussels on 15-16 May 2013. Other FP7 projects, in addition to MONARCH-A attending this meeting included: MACII, MyOcean2, GeoLand2, EURO4M, ERA-CLIM, CARBONES, CHARMe and CRYOLAND. In addition representatives from DG CLIMA, EEA, JRC, EUMETNET, Copernicus Unit and ESA were present.

The main objective of the first community driven workshop at REA on 11-12 September 2012 was to enhance cooperation among FP7 projects which are dealing with similar issues, amongst others data products, data access and quality and metadata information. Furthermore, discussions focused on synergy and how relevant information can be exchanged between projects, i.e. in scope of related ECVs, and how information developed during the projects can be sustained. The key conclusions included the following recommendations:

➢ Coordination meetings on regular bases should be organised to allow projects to coordinate and share information among each other. Overall the projects appreciated the initiative and suggested to organise annual or 6-months base workshop with a more service oriented perspective where dedicated technical discussion e.g. on relevant group of ECVs, can be targeted. The CCI projects should also be involved as well as representatives of the FP7 Capacities – Infrastructure programme, EUMETSAT and EEA.

⇨ ESA: will report on the outcomes of this workshop to the next CCI projects collocation meeting and include a dedicate session on ECVs in which FP7 projects and ESA CCIs will be jointly presented in the next "Living Planet" symposium planned in Edinburg on 9-13 September 2013 (Note that the MONARCH-A project is invited to present the final achievements and outcome at this symposium).

➢ ECVs table: A table summarising where we stand in terms of ECVs production and what is missing is a concrete step to support the discussion on the GMES climate change service.

Such a table should be a matrix where all the ECVs datasets provided in the frame of the FP7 projects are listed with their technical characteristics (e.g. spatial resolution, temporal resolution, etc..) and their level of accuracy. Additional information (e.g. ECV metadata descriptor, project contact person for the related ECV, website, indication of maturity, examples of 'good use', etc…) will be included, eventually in a separate fact sheet. At a second stage, the table will be extended with input from the ESA CCI projects.

The ECVs table could be used by the projects to identify potential areas for cooperation but will be also used by the GMES Bureau to promote project results towards the users at both EU level (e.g. DG CLIMA/DG ENTR), MSs level (through the users forum) and other external users increasing also visibility on the status of the GMES Climate change service. Including examples of 'good use' of ECV data in the table would in this sense add value.

The aim of the collocation meeting at REA on 15-16 May 2013 was to coordinate with the different FP7, ESA & EUMETSAT ECV projects the processes of generating, validating and updating (including reanalysis) ECVs and to understand the gaps between the ECVs and user needs in climate change adaptation and mitigation. The meeting focused on the following 5 specific issues:

- Expectations towards "ECV capability assessment" from policy makers
- European capacity for generating ECVs
- Validation processes in ECVs
- Reanalysis feedbacks to ECV/CDR updates
- Identifying gaps between ECVs as physical variables and user-needs for adaptation and mitigation

In particular, the CORE-CLIMAX project objective is to ensure that the output from different ongoing and completed climate change projects, including the MONARCH-A project, will be made visible to inform relevant organizations that that information can be picked up by upcoming projects.

Furthermore two of the MONARCH-A project members are lead authors of Chapter 13 of the IPCC AR5 on sea level change. The 11 ECVs to be delivered by MONARCH-A have also high priorities for several activities related to global and regional analyses of the climate system. This includes specifically activities within the WCRP, such as CLIVAR and CLIC as well as OOPC under GCOS and the ESA CCI program. Regarding the latter MONARCH-A maintains strong ties and direct link to the following ESA Climate Change Initiative projects:

- The sea level CCI lead by G. Larnicol/A. Cazenave (CLS/LEGOS, France);
- The sea ice CCI lead by S. Sandven (NERSC, Norway);
- The ice sheet CCI lead by R. Fosberg (TUD, Denmark).

In addition NERSC is also a partner in the Arctic European Climate Research Alliance (ECRA). ECRA is developing a Collaborative Programme on Arctic Climate Stability and Change which is a challenging theme for European research and has been addressed by the "Arctic Communication" of the European Commission. There is growing concern about the rapid climatic changes occurring in the Arctic and the impact of these changes for future development of the European and global climate have to be understood. All recent assessments indicate that there is an urgent need to increase observations in the Arctic and a demand for open exchange of data in order to improve model predictions of future changes. Areas of particular concern are the rapid warming trend in the last decades with consequences for sea ice coverage of the Arctic Ocean, loss of ice mass from the Greenland glaciers, thawing of the permafrost regions, changes in the hydrological cycle in the northern hemisphere, impacts on biodiversity and ecosystem functioning.

Climate observations in the polar areas depend heavily on availability of adequate infrastructures, such as ice-breakers, polar research stations, air planes or long term observations of different variables. It is recognized that increased international collaboration is urgently required in order to accomplish the high demand on polar climate research. To further elaborate a potential Collaborative Programme in this area of research a workshop will be held to address collaboration in scientific work, sharing of infrastructure and exchange of scientists and technicians. This workshop is planned for 13-15 November 2013 and MONARCH-A will be presented.

The MONARCH-A project web page (http://monarch-a.nersc.no/) is running and has been extensively used as a data portal as new project data have gradually become available. All material, such as presentations from project meetings, reports etc., is uploaded on the web page. At the termination of the project the 11 ECVs are either directly free and openly available at the project website or provided with a link to existing data repositories where the data, in turn, can be downloaded.

Finally, an element of the legacy of the MONARCH-A project findings and achievements is also viewed in the context of the publications in peer review journals, conference proceedings and workshop reports as listed below.

IV Referenecs

Andersen, O. B., The DTU10 Mean sea surface for and with Cryosat-2 data in the Arctic Ocean. ESA CRYOSAT-2 symposium, ESA Special Publication SP-687, 2011.

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