G2–O1

MONITORING THIN SEA ICE THICKNESS WITH MODIS

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Sea Ice is an important component of the climatic system. It affects the global energy budget as well as the oceanic circulation. Sea Ice is also an indicator variable of climate change. The thin sea ice is most vulnerable to summer sea melt, and thus allows for more heat transfer. Therefore, this type of sea ice deserves some particular attention.

Currently, earth observation methods are accurate and well validated for estimating sea ice concentration of multi-year ice and consolidated first-year ice. However, they are less reliable and accurate for the youngest stages of sea ice development. Alternative algorithms, making use of different sensors for observing young, seasonal sea ice are therefore valuable. We will here present an on-going project where the goal is an algorithm for fully automatic estimation of thin sea ice thickness, well suited for evaluating time series of data, using optical satellite data from the MODIS sensor.

The model is closely based on Yu & Rothrock (1996) [1] in that the heat balance on the ice surface is described as a sum of the contributing heat fluxes. Each of the component heat fluxes are then expressed using various empirical models. Several of the heat fluxes are dependent on the ice thickness, in particular the conductive heat flux, which describes the heat transfer from the water to the ice surface. This flux is assumed to be inversely proportional to the ice thickness. We further assume thermal equilibrium, resulting in an equation which may be solved with respect to ice thickness. This is done independently for every pixel in the data.

Night and daytime images have different properties with respect to cloud masking and accuracy of the estimate. These aspects will also be discussed.

As input we use data from the MODIS sensor on board the Aqua and Terra satellites, using the thermal bands to estimate the surface temperature. The algorithm also makes use of some atmospheric variables (e.g. air temperature, wind speed, air pressure), which are acquired from re-analyzed ERA data.

Since this algorithm aims to estimate the thickness of young, thin ice, we also use passive microwave data from AMSR-E and AMSR2 to separate (thick) first- and multiyear ice from potential (thin) new ice and water.

We also plan to include SAR data into the processing, in order to account for partially ice-covered MODIS pixels.

In this presentation we will describe the approach, and present and discuss some preliminary results, including estimates of extent and thickness of thin sea ice from time series of both night and daytime images.

[1] Yu, Y. and Rothrock, D. A., 1996. Thin ice thickness from satellite imagery. *Journal of Geophysical Research,* 101 (C10), 25753.

G2-O2

Cancelled

G2–O3

SEA-ICE MELT ONSET ASSOCIATED WITH ICE DEFORMATION EVENTS DURING EARLY SUMMER

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In the central Arctic Ocean, autonomous observations of ocean mixed layer and ice documented the transition from cold spring to early summer. Our ice-motion measurements using GPS drifters captured three events of lead opening and ice ridge formation in May and June. We clarify how these ice deformation events are linked with the onset of sea ice melt. In early June, the buoy array detected a shear deformation coincident with a temperature peak at 7 m below the ice bottom. At this time, an autonomous profiler shows there was a gentle decrease of temperature with depth and nearly homogeneous salinity profiles, with persistently stable mixed layer. We use a one-dimensional numerical simulation incorporating the Local Turbulence Closure (LTC) scheme to investigate the mechanisms controlling basal melt onset. According to the simulation, a combination of the extremely slow ice motion and incoming solar energy input at the open lead, followed by a transient low pressure system, produced a thin, low density surface layer by advection of warm lead water under the ice. This enhanced stratification near the surface facilitates storage of solar radiation within the thin layer, instead of exchange with deeper layers, leading to early onset of basal ice melt preceding the upper surface melt.

G2–O4

HOW DOES ARCTIC SUMMER WIND MODULATE OCEAN HEAT BUDGET IN SEA ICE REDUCTION ZONE?

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It is expected that the Arctic summer wind has a significant impact on sea ice distribution and ocean heat budget via various kinds of processes. Basin-wide anti-cyclonic wind circulation promotes sea ice export from the Arctic Ocean to the Greenland Sea. This pattern can eventually cause a new record minimum of sea ice extent as observed in 2007. On the other hand, synoptic cyclones produce mechanical sea ice divergence and Ekman upwelling. Both enhanced absorption of shortwave radiation in newly formed open water area and vertical heat flux from a subsurface temperature maximum layer would work on thermal reduction of sea ice. Our previous modeling experiments demonstrated that an eddy-induced transport of warm shelf water preferably occurs under summertime westerly wind in the western Arctic. The westerly shelf wind has a linkage with low sea level pressure in the basin area. This finding indicates that lateral heat transport in the ocean surface layer is also activated by cyclonic wind pattern. However, the relative contribution of each process to ocean heat budget in sea ice reduction zone has not been estimated. We performed numerical experiments on seasonal to decadal timescales using a newly configured pan-Arctic ice-ocean model and then addressed these issues.

G2–O5

ARCTIC ICE-OCEAN MODELING STRATEGY: HOW TO VERIFY MODELS OF CLIMATE CHANGE WITH EXISTING DATA

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Although the main stream of modeling for the Arctic climate change is to develop sophisticated models with high resolution and realistic conditions, an alternative way is to use idealized models with an aim at exploring key mechanisms in a projection of the sea ice cover trend. The former strategy requires extensive data collections for verification of the models, while the latter strategy provides potential of utilizing the existing data. An attempt was made on the sea ice cover and ocean interior showing decadal-to-interannual variability caused by atmospheric forcing.

For the recent 50 years, valuable geochemical data in the ocean interior were analyzed, along with the sea ice and atmospheric data, and used to verify a coupled ice-ocean model with idealized configuration in the Arctic Basin, which is fundamentally driven by buoyancy flux in addition to atmospheric circulation and cooling. The dominant atmospheric mode shifted from the Northern Annular Mode (NAM) to the Arctic Dipole Mode (ADM) around 1990. The sea ice cover variability was explained by these two modes sequentially: i.e., the decadal ice cover variability was well correlated with the NAM until 1990, and then, the several-year cycle variability with the ADM. The low sea ice cover matched with the peaks of the NAM over the East Siberian-Laptev Sea, and then, 2 years later showed the low anomaly in the Barents-Kara Sea and the high one in the Beaufort-Chukchi Sea. As presented with the coupled ice-ocean model and the geochemical fields, the positive NAM induced the oceanic variability with the Transpolar Drift Flow shifting toward Canadian side in 3 or 4 years. After 1980, the positive phase of the ADM with a low anomaly over Siberia and a high anomaly over Greenland induced low (high) ice cover in the Pacific (Atlantic) sector in 1 year. The ADM produced the ocean general circulation and made the Pacific water spread toward the Atlantic side in 2 years.

On the top of these fundamental mechanisms, the models with high resolution and realistic conditions should be verified against data collected by dedicated observations so that various important mechanisms may be reproduced in the models: e.g., sea ice ridging, ice band formation, inertial oscillation, double diffusion, step-like stratification, wind-wave in polynya, shelf wave and others.

G2–O6

RECONSTRUCTION OF WATER CIRCULATION IN THE PACIFIC SECTOR OF THE ARCTIC OCEAN

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Circulation in the Pacific sector of the Arctic Ocean was reconstructed for 1900-2006 and for cyclonic (1989-1997) and anticyclonic (1997-2006) climate states through the use of modeling with 4Dvar data assimilation. The comparison of these climatological states with reconstructed circulation for 2008 (July-October) reveals significant changes in water motion between climate states. These differences were caused by changes in model forcing—namely, wind forcing and sea ice conditions. Reconstructed circulation for 2008 was additionally validated with respect to available velocity observations, which were not assimilated

ARCTIC OCEAN LIQUID FRESHWATER STORAGE TREND 1992-2011

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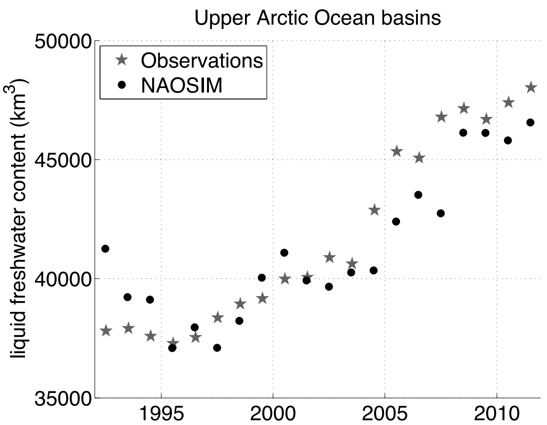
The upper Arctic Ocean has experienced significant freshening from the 1990s to late 2000s. A very strong Beaufort Gyre and a freshened Transpolar Drift raise the question how much longer the Arctic Ocean can accumulate freshwater. Since 2006, autonomous CTD profilers have allowed to estimate upper ocean properties in the Arctic through all seasons. In combination with observations from other platforms, these data show a continuous increase in liquid freshwater into the second decade of the 21st century: the trend from 1992 to 2011 was about $600 \pm 300\ km^3 yr^{-1}$.

Excellent agreement between these observational estimates and results from the North Atlantic Arctic Ocean Sea Ice Model (NAOSIM) allows to view this in the context of physical processes in the model: Ekman pumping from the ocean surface stress in the simulation strongly covaries with the vertical movement of the top of the lower halocline, represented by the 34 isohaline. Whereas downward Ekman Pumping shows no noticeable trend in the Eurasian Basin, it shows an increase in the Amerasian Basin from the mid-1990s to 2008.

On a longer timescale, the model shows that a freshwater minimum in the mid-1990s was preceded by a maximum near the end of the 1960s. The level in 2011 is similar to the one around 1980, and it remains to be seen if liquid freshwater levels will supersede that of the end 1960s. Furthermore, our results raise the question where and when this additional freshwater will be released from the Arctic Ocean to the regions of deep-water formation in the North Atlantic in future years.



G2–O8

TEMPORAL VARIATION OF OCEAN CURRENT STRUCTURE CAUSED BY SEA ICE MOTION

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The reduction rate of Arctic sea ice extent and volume exceed the rate of surface temperature warming. This suggests that the changes in the horizontal and vertical ocean heat fluxes are the key components to understand the rapid reduction of sea ice. Shimada et al. (2006) showed the recent warming of upper ocean in the Canada Basin associated with substantial activation of sea ice motion. However, only the ocean warming below the surface mixed layer cannot cause the warming in the surface mixed layer interacting with sea ice. Increase in vertical heat flux associated with turbulent mixing would be a key process to understand the rapid reduction. At the first step of our studies, we examine current structure and its variation caused by inertial motion of sea ice using an ice-mounted mooring and continuous CTD profiling data during the Araon 2012 cruise.

Clear structures of oscillatory horizontal currents were detected under the inertial oscillation of sea ice (Fig.1). The observed vertical shear of horizontal currents accompanied large temporal variation. This suggests that the actual vertical mixing results in quite different effect on vertical ocean heat flux from that without inertial motion of sea ice. Detailed joint analysis using current and density stratification will be made.

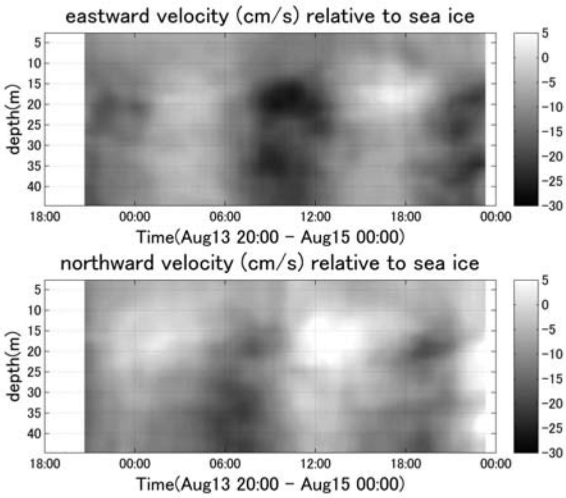

Fig.1: Time series of horizontal currents relative to sea ice obtained by ADCP.

G2–O9

ESTIMATION OF VOLUME TRANSPORT AND HEAT FLUX THROUGH BARROW CANYON

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The Pacific water through Barrow Canyon is critical for determining heat, fresh water and nutrient flux. In particular, heat flux due to the Pacific water through Barrow Canyon is directly linked to heat content in subsurface layer around the Northwind Ridge area, where drastic decrease of sea ice has been evident. First of all, we attempt to build the method to estimate volume transport. The data from moored ADCP and CTD (2001 October to 2007 September) at Barrow Canyon was examined. The variability of volume transport (or barotropic transport) is well correlated with NCEP 45^{o} (northeastward) wind component observed 27 hours before around Pt. Hope. 60^{o} Wind component at Barrow Canyon was secondary. The multiple linear regression model using 45^{o} wind component (Pt. Hope, 27-hour before) and 60^{o} wind component (Barrow Canyon, 13-hour before) was made (R^2=0.575). The empirical orthogonal function (EOF) analysis shows that vertical structure of the first EOF of velocity is typical baroclinic 1st mode explaining about 70% of total variance. The variability of 1st EOF of velocity has weak correlation with 45^{o} wind component (Pt. Hope, 30-hour before, R^2=0.346). Hence, near real-time forecasting of volume transport and baroclinic component using wind data can be made by the regression model proposed here. The offset of the regression model is 0.77 (Sv), which is almost same as mean transport of the Bering Strait, i.e., most of the Bering Strait inflow flows down Barrow Canyon, even under the variable wind filed. In the next, we also developed the regression model for vertical profile of temperature to estimate heat flux using CTD data described above and satellite sea surface temperature data. Data analysis shows temperature at Barrow Canyon has positive correlation with SST near Cape Lisburne 5 days before (R^2=0.49). Estimated heat flux through Barrow Canyon using all estimated parameters described above is well comparable to in-situ measured heat flux.

G2–O10

SHIFTS IN SEA ICE CONDITIONS OF SIBERIAN SHELF SEAS IMPACT THE HALOCLINE OF THE ARCTIC OCEAN

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The signature of the upper halocline of the Arctic Ocean is formed in Siberian Seas largely by a combination of mineralization of organic matter and release of decay products to the sea ice brine enriched bottom water. In 2008 exceptionally high nutrient concentrations and low pH were observed in the bottom waters of the East Siberian Sea. These waters typically had between 5% and 10% of sea ice brine contribution as computed from salinity and oxygen-18 values. In the northern East Siberian Sea the silicate maximum was found over a wider salinity range than traditionally found in the Canada Basin, in agreement with observations east of the Chukchi Plateau during one expedition in 2004 [*Nishino et al.*, 2009]. As all waters containing high nutrient concentrations at the shelf break had a deficit in nitrate, indicating a low oxygen environment during mineralization as well as a brine contribution of about 6% it is suggested that the shelves are a source for these waters. The variable salinity distribution, together with signs of a double peak in nutrient conditions, suggest at least two different areas for the formation of this nutrient rich halocline within the East Siberian Sea. These areas must have some different physical and biochemical environments in order to sustain the observed conditions, for instance a different surface water salinity. One plausible explanation is that brine is produced along a large north-south gradient within the shelf sea by sea ice formation, where the salinity of the outer region is much less impacted by river runoff. This would require that a much larger area of the East Siberian Sea has been sea ice free in the summers over the last 5-10 years. The satellite record shows substantial changes in the amount of open water in September during the last 30 years from around 60% sea ice coverage in the 1980s to a low of about 20% in the early 1990s, back to about 50% in the late 1990s and then a dramatic decrease with less than 10% since 2003. More open water also favor primary production through improved light conditions, adding to the organic matter at the sediment surface.

Observational data will be presented together with satellite records of sea ice coverage and plausible scenarios for halocline water formation will be discussed.

Nishino, S, K. Shimada, M. Itoh, and S. Chiba (2009), Vertical Double Silicate Maxima in the Sea-Ice Reduction Region of the Western Arctic Ocean: Implications for an Enhanced Biological Pump due to Sea-Ice Reduction *J. Oceanogr,* 65, 871 to 883.

G2–O11

SHOALING OF THE NUTRICLINE WITH AN INCREASE IN NEAR-FREEZING TEMPERATURE WATER IN THE MAKAROV BASIN

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The water mass changes in the Makarov Basin and adjacent areas associated with the recent loss of Arctic sea ice had not been studied in detail. We combined data obtained from multiple cruises in these regions and used chemical tracers to investigate the spatial and temporal changes in water masses. Our data show that a previously present temperature maximum water has disappeared from the Makarov Basin and Chukchi Abyssal Plain due to enhanced cooling and convection in the East Siberian Sea. In addition, a large volume of water has formed by cooling and convection and is flowing into the Makarov Basin, producing a temperature minimum with relatively high nutrients and resulting in a shoaling of the nutricline. This temperature minimum water likely originated from the eastern part of the East Siberian Sea, where significant open water areas appeared after 2005 in the freeze-up season. The water mass boundary between this temperature minimum water and the Pacific-origin temperature minimum water shifted westward from the Chukchi Plateau in the early 2000s to the Mendeleyev Ridge in the late 2000s, probably owing to a westward flow of the enhanced Beaufort Gyre associated with recent sea ice loss in the Canada Basin. Although the shoaling of the nutricline in the Makarov Basin could increase phytoplankton production, such production could decrease in the southern Makarov Basin because a large amount of sea ice meltwater covers that region and might decrease the nutrient supply from the subsurface layer.

G2–O12

SPATIAL AND TEMPORAL VARIABILITY OF AIR-SEA CO_2 EXCHANGE OF ALONGSHORE WATERS NEAR BARROW, ALASKA

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Alongshore waters near Barrow, Alaska feature unique characteristics being at the intersection of four aquatic locations: Chukchi Sea, Beaufort Sea, north and south Elson Lagoon. Partial pressure of CO_2 (pCO_2) measured at the alongshore waters in summer, 2007 and 2008 showed that the average pCO_2 was the lowest in the Chukchi Sea side and that of the south Elson Lagoon side was the highest. The difference in pCO_2 between locations appeared due to differences in water temperature that controls the solubility of seawater for CO_2. The temporal variations in pCO_2 within each location were highly controlled biologically as inferred from the relation between pCO_2 and apparent oxygen utility (AOU). No significant difference in pCO_2 corrected to 3 °C between locations and the low AOU in the south Elson Lagoon side suggested that a potential of carbon source from the region due to coastal erosions and terrestrial runoff was offset by biological carbon uptake. The average CO_2 flux estimated from pCO_2 over all locations showed a sink of CO_2. Our data and others (e.g., Oechel et al., 2000) suggested that the coastal ecosystem including the wet sedge tundra that dominates the terrestrial coastal margin and the coastal water near Barrow was a sink for CO_2 during the summer growing season. CO_2 flux measured by the eddy covariance technique also showed a sink of CO_2 overall, but the presence of ice sheets inhibited a gas transfer.

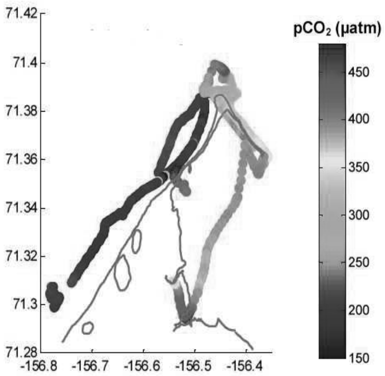

Fig. 1 Boat cruise measurements for pCO_2 in 2007.

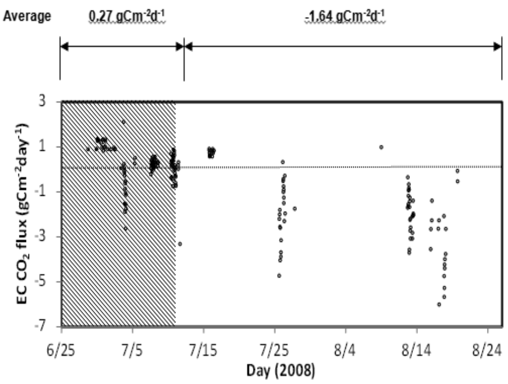

Fig. 2 CO_2 flux measured by the EC technique for the Beaufort Sea. The gray area indicates the period with ice sheets.

G2–O13

FATE OF TERRESTRIAL COLORED DISSOLVED ORGANIC MATTER (CDOM) IN THE ARCTIC OCEAN: EXPORTED OR REMOVED?

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Colored dissolved organic matter (CDOM) was measured with hydrographic parameters (salinity, $\delta^{18}O$ and inorganic nutrients) annually across Fram Strait in 2009 to 2011.
East Greenland Current (EGC) surface waters showed a pronounced CDOM absorption maximum between 30 and 120 m depth associated with both river and sea ice brine-enriched water, characteristic of polar mixed layer water and upper halocline water. Lowest CDOM was found in the Atlantic inflow within the West Spitsbergen Current (WSC).
Although applied elsewhere in the Arctic, we show that the salinity–CDOM relationship is not suitable for evaluating the mixing behavior of CDOM (conservative vs. nonconservative) in Fram Strait. The strong correlation between meteoric water and optical properties of CDOM are indicative of the terrigenous origin of CDOM in the EGC and marine origin in WSC.
Based on CDOM absorption in Polar Water and comparison with an Arctic river discharge weighted mean, we estimate that a 68% integrated loss of CDOM absorption across 250-600 nm has occurred, with a preferential removal of absorption at longer wavelengths reflecting the loss of high molecular weight material.
Budget calculations of CDOM exports through Fram Strait using modeled volume transports indicate that the net southward export of CDOM in Fram Strait equals about 50% of the total riverine CDOM inputs to the Arctic Ocean, thus physical export can be a major sink of CDOM.
These constrasting results indicate that both removal and loss within the Arctic Ocean and export are major sinks for CDOM, this suggest that several of the possible sinks need to be better quantified. This means improving our knowledge of export with sea ice, seasonality and transport on the East Greenland Shelf, photo-oxidation of CDOM, and the transports through the Canadian Arctic Archipelago need to be quantified.
We surmise that the changes in the characteristics of CDOM exported in Fram Strait in recent years are a result of changes in freshwater pathways in the Arctic Ocean, especially the residence time will affect the integrated effect on the fate of CDOM. This will also leave a fingerprint on the carbon export from the Arctic Ocean to the North Atlantic.