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and
Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

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Prepared by:  Syun-Ichi Akasofu, Director
Larry Hinzman, Deputy Director
John Walsh, Chief Scientist

930 Koyukuk Drive
P.O. Box 757340
Fairbanks, AK  99775-7340

Phone: 907-474-6012
Fax:      907-474-5662
Email: sakasofu@iarc.uaf.edu

Website: http://www.iarc.uaf.edu
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Introduction

JAMSTEC requested in April 2004 that the former Frontier group be integrated with the existing IARC group. The integration has been successful and all of us are working together under the FY2004 contract. Four projects began in 2004 and continue in 2005.

1) Ocean Ecosystem Modeling

In our 1-D modeling effort, an improved parameterization of zooplankton grazing has been employed because zooplankton grazing pressure is an important model element. Further, based on biophysical ice core data collected in the landfast ice off Barrow in 2002 and 2003, a 1-D Ice-Ocean Ecosystem Model was developed and added to the existing ocean-based IARC Physical Ecosystem Model to determine the factors controlling the bottom ice algal community. In addition, we accomplished the following:

- Wave mixing was parameterized to simulate the circulation and tidal currents in the Bering Sea in sync with the 3-D Princeton Ocean Model (Figure 1).

- An IARC regional Coupled Ice-Ocean model was applied to simulate the down-scaling ice and ocean processes with a 4-km resolution.

Figure 1. 1-D PhEcoM-simulated multi-year phytoplankton (blue) versus satellite measured Chl-a (dotted) at the PMEL M2 mooring. Sea ice concentration is in red. The sea ice disappeared in 2001 due to the warming in the Bering Sea.
The Arctic Ocean warming during the 20th century was assessed based on the Tokyo University (CCSR)/FRCGC Model. The results are in agreement with hydrographic observational data.

The contribution of sea ice exports from the Arctic Ocean was assessed based on the Tokyo University (CCSR)/FRCGC Model. The second model of the Arctic oscillation is shown to be of considerable impatience in the export.

The variability of chlorophyll-a (chl-a), sea surface temperature (SST) and sea ice motion in the Beaufort and Chukchi seas was investigated using remote sensing data (Figure 2).

Figure 2. The 3.7 km CIOM-simulated climatological sea ice concentration on July 10. Landfast ice attached along the Alaska Beaufort Sea coast and part of Alaska Chukchi Sea coast is well reproduced.

2) The Arctic Ocean Models and Observations

The inflow of the warm North Atlantic water in the Arctic Ocean has been investigated based on mooring observations of the Russian icebreaker Kapitan Dranitsyn. The analysis shows new pulses of anomalously warm water.
Figure 3. (Left) Evidence of a new warm anomaly entering the central Arctic Ocean. Numerals I–VI indicate temperature sections (°C) taken in 2004. (Right) Observational data showing the arrival into the Arctic Ocean of a pulse of warm water originating from the North Atlantic. Large red and yellow arrows indicate two pulses of warm Atlantic Water. The pathways of Atlantic Water are shown by black arrows. Red stars show locations of moorings. (Top) Depth–time diagram of water temperature (°C). (Middle and bottom) Time series of water temperature (°C) from Fram Strait and Svinoy locations. Blue lines show weekly averaged temperature, red lines show six-month running mean temperature. Modeled de-seasoned six-month running mean water temperature anomalies are shown by black dashed lines. Adapted from Polyakov et al. [2005].

This observation—a previously unknown factor possibly related to shrinking sea ice—is crucial to understanding the present warming of the Arctic. Since the warm water pulse is approaching the Alaska waters, it is our plan to extend the observation cruise.

At the same time, modeling efforts are also in progress, in particular, the variational data assimilation approach is being applied to the circulation in the Bering Sea, Kara Sea, and the Dreik Strait. Diagnostic analysis of freshwater budgets and their role in the North Atlantic deep convection has been continuing.
3) Terrestrial Ecosystem Models and Observations

The carbon budget in the Arctic, especially in the boreal forest and the tundra, is important for understanding present and future climate change in the Arctic, and Earth as a whole.

Winter emissions of CO$_2$ and CH$_4$ measured along a 666.7-km Alaska transect has yielded data that is useful for modeling climate change in the Arctic.

![Figure 4. Locations of CO$_2$ and CH$_4$ observations along an Alaska transect during January 2005 and February 2006.](image)

Winter emission of CO$_2$ has been monitored at a University of Alaska Fairbanks site. This is a unique site, located in the central part of Alaska, and is the standard fixed site for our experiment.

We are also investigating the possible effects of soot from boreal wildfires on sea ice in the Arctic Ocean and Alaska glaciers. Wildfire soot may be an overlooked agent of albedo reduction and summer glacial melting.

4) Arctic Atmosphere

Waning sea ice in the Arctic Ocean has appeared in many headlines recently. We are attempting to model past changes and also predict changes in the future based on several IPCC warming scenarios (A1B, A2, and B1). We find that most models can capture annual mean sea ice area during 1979-99, but cannot reproduce well the changes during the warming in 1920-50. We are evaluating results at the present time. On the other hand,
IPCC scenarios B1, A1B, and A2 call for sea ice reductions of about 21.6, 31.1, and 33.4 percent.

At the recommendation of the Japanese Review Committee last year, we strengthened studies on the Arctic water cycle through our recently initiated project “Arctic Water Cycle Components and Cloudiness: Synthesis of Observation Data and the IPCC AR4 Model Simulations.” The preliminary results show that the north Alaska and the North Pacific sectors are predominant channels that supply water vapor into the Arctic region from low latitudes, while the arctic region loses water through the Eurasian and North American continental sectors.
Projects

Ocean Ecosystem Modeling and CCSR/NIES/FRSCG Global Model Assessment

Jia Wang - Lead Scientist

Participants:
Deal, Clara (co-PI), IARC, UAF, USA
Hu, Haoguo, IARC, UAF, USA
Jin, Meibing (co-PI), IARC, UAF, USA
Mizobata, Kohei (co-PI), IARC, UAF, USA
Polyakov, Igor, IARC, UAF, USA
Zhang, Sheng, IARC, UAF, USA
Xiangdong Zhang, IARC, UAF, USA

1. Other Collaborators or Contacts (Alphabetical) (include their institutions and country)
   Ikeda, Moto, S. Saitoh, and T. Iida, Hokkaido University, Japan
   Shin, Kyung-Hoon, Hanyang University, Korea
   Tanaka, Nari JAXA, Japan
   Takahashi, Jun and T. Suzuki, FRCGC, JAMSTEC, Japan
   Watanabe, Eiji and T. Hasumi, CCSR, University of Tokyo, Japan
   Liu, Qingzhen, State Oceanic Administration (SOA), Beijing, China
   Saucier, Francois, University of Quebec at Rimouski, Canada
   Gerdes, Rudiger, AWI, Germany
   Wu, Bingyi, Chinese Academy of Meteorology, Beijing, China
   Zhang, Shunpu, University of Nebraska, USA

2. Summary of Research Activities and Accomplishments

   Modeling plankton and nutrient dynamics in the Bering Sea middle shelf domain using 1-D PhEcoM (Physical-Ecosystem Model)

   Our modeling studies have shown that zooplankton grazing pressure is a very important factor in the duration of a phytoplankton bloom. We have since added copepod grazing on microzooplankton in the 1-D marine ecosystem model to provide a more defensible parameterization of zooplankton grazing. Also, the model now includes the output of integrated flows between the model compartments, including primary production (Figure 1). This has allowed us to examine controls on primary production and how projected change will impact the various components of production. Preliminary model results suggest that models of primary productivity in the southeastern Bering Sea need to include nitrification.
1-D PhEcoM with sea ice biology:

1) Chukchi Sea seasonal sea ice
Based on biophysical ice core data collected in the landfast ice off Barrow in 2002 and 2003, a 1-D ice-ocean ecosystem model was developed and added to the existing ocean-based IARC Physical Ecosystem Model (PhEcoM, Wang et al., 2003, Jin et al., 2006) to determine the factors controlling the bottom ice algal community (Jin et al., in press). The data and model results revealed a three-stage ice algal bloom: 1) onset and early slow growth stage before middle March, when growth is limited by light; 2) a fast growth stage with increased light and sufficient nutrients; and 3) a decline stage after late May as ice algae are flushed out of the ice bottom. Stages 2 and 3 are either separated by a transition period, as in 2002, or directly connected by ice melting, as in 2003, when in-situ light and nutrient enrichment experiments showed only light limitations. The modeled net primary production of ice algae (NPPAi) from March to June is 1.2 and 1.7 g C/m2 for 2002 and 2003, respectively, within the range of previous observations. Model sensitivity studies found that overall NPPAi increased almost proportionally to the initial nutrient concentrations in the water column. A phytoplankton bloom (if it occurs like in 2002) would compete with ice algae for nutrients and lead to reduced NPPAi. About 45% of the NPPAi was exported to the shallow benthos.

2) Bering Sea marginal ice zone
The ephemeral nature of the Bering Sea ice poses a challenge in adapting the ice ecosystem model from fast ice offshore Barrow to the Bering Sea. To accomplish this, we need to correctly simulate the physical environment (stratification caused by freshwater from melting ice) displayed in assembled observations and see if an ice-related bloom will occur. A multi-year time series (1990-2006) of model runs has been conducted for the Bering Sea middle shelf domain. The model captures the seasonal temperature cycle very well, including the temperature magnitudes in comparison with the NOAA/PMEL M2 mooring temperature data (1995-2004) and satellite observations (Figure 2).

Modeling the 3-D Bering Sea circulation and sea ice using a regional CIOM (Coupled Ice-Ocean Model)

When wave mixing is parameterized, the circulation and the tidal current in the Bering Sea are simulated simultaneously with the 3-D Princeton Ocean Model. The results show that the temperature and salinity of the upper and the bottom layers tend to be uniform by surface wave mixing and the tidal stirring, respectively, which are the main mechanisms forming the seasonal thermocline. The model simulated the observed major currents. The circulation pattern in the BS basin is relatively stable with less seasonal change: The western boundary Kamchatka Current flows along the western side of the basin; the Aleutian North Slope Current flows along the northern Aleutian Islands; the Bering Slope Current is northwestward along about the 1000-m isobaths; the Bering Sea shelf current is weak and northward with seasonal variation. All the described features are consistent with available observations. The results also show that a countercurrent flows southeastward along the 200 m isobaths; this is not
yet documented by any literature and still needs to be validated by observations. There is an upwelling current on the shelf break (120-1000 m) area, which supports the Bering Sea Green Belt in the break-slope area (Figure 3).

**Modeling 3-D downscaling characteristics of sea ice and circulation in the Chukchi/Beaufort seas using CIOM**

We applied an IARC regional CIOM to simulate the downscaling ice and ocean processes with a 4-km resolution. The Beaufort CIOM was nested to the CCSR/NIES/FRCGC high-resolution (1/6 x 1/4 degrees) global coupled atmosphere-sea ice-ocean model. Atmospheric forcing data were derived from the NCEP reanalysis. Simulation of the seasonal cycle was also conducted. In the Chukchi Sea, the Bering inflow separates into three branches: the first main branch, the Alaska Coastal Current (ACC), flows along Alaska’s coast; the second branch flows northward and turns to the right, joining the ACC along the Beaufort coast; and the third branch flows toward the Northwind Ridge. The Beaufort Gyre is well reproduced, superimposed by numerous mesoscale eddies, with anticyclones outnumbering cyclones. We also investigated downscaling sea ice dynamics, such as sea ice ridging, rafting, leads, and landfast ice, which are not resolved in the previous coarse resolution model (Wang et al., 2002; 2005). The approach of combining the global model for the 20th century climate simulation with the regional downscaling/nesting simulation helps understanding of both large-scale sea ice variability and small-scale sea ice dynamics. Sea ice breaks up offshore piece by piece with landfast ice untouched along the Beaufort Sea coast. Sea ice cracks from pack ice with irregular shapes due to 1) complex ocean circulation, coastal currents, and mesoscale eddies, 2) multi-category sea ice dynamics, and 3) complex and high-resolution geometry and topography. Sea ice ridging, rafting, and openings/leads can be well reproduced in sea ice thickness and concentration. Model validation using in-situ observations, satellite measurements, and historical datasets is underway (Figure 4).

**Assessment of the CCSR/NIES/FRCGC model on Arctic Ocean warming episodes in the 20th century caused by the intruding Atlantic Water**

This study investigates the Arctic Ocean warming episodes in the 20th century using both a high-resolution coupled global climate model and historical observations. The model, with no flux adjustment, reproduces well the Atlantic Water core temperature (AWCT) in the Arctic Ocean and shows that the four largest decadal-scale warming episodes occurred in the 1930s, 70s, 80s, and 90s, in agreement with the hydrographic observational data. The difference between models and observations is that there was no pre-warming prior to the 1930s episode, while there were two pre-warming episodes in the 1970s and 80s prior to the 1990s, leading the 1990s into the largest and prolonged warming in the 20th century. Over the last century, the simulated heat transport via Fram Strait and the Barents Sea was estimated to be, on average, 31.32 TW and 14.82 TW, respectively, while the Bering Strait also provides 15.94 TW heat into the western Arctic Ocean. Heat transport into the Arctic Ocean by the Atlantic Water via Fram Strait and the Barents Sea correlates significantly with AWCT (C=0.75) at 0-lag. The modeled North Atlantic Oscillation (NAO) index has a
significant correlation with the heat transport ($C=0.37$). The observed AWCT has a significant correlation with both the modeled AWCT ($C=0.49$) and the heat transport ($C=0.41$). However, the modeled NAO index does not significantly correlate with either the observed AWCT ($C=0.03$) or modeled AWCT ($C=0.16$) at a zero-lag, indicating that the Arctic climate system is far more complex than expected (Figure 5).

Assessment of the CCSR/NIES/FRCGC model on the Arctic Dipole Anomaly and its contribution to sea ice exports in the last 20th century

The winter Dipole Anomaly (DA) in the arctic atmosphere and its contribution to sea ice export are investigated using a high-resolution coupled global general circulation model. The spatial distributions of the first two leading EOF modes of winter mean sea level pressure and geopotential height at 500 hPa north of 70°N, obtained by the long-term simulation (1900-2010) are similar to those derived from the NCEP/NCAR reanalysis datasets (1948-2004). The first leading mode corresponds to the Arctic Oscillation (AO). The DA is defined as the second-leading mode. The AO and DA account for 66% and 13% of the variance, respectively. Composite spatial patterns of sea level pressure, sea ice thickness, and velocity in the extreme years, when both the absolute values of PC1 and PC2 exceed one standard deviation, indicate that the DA plays an important role in sea ice export from the Arctic Ocean to the Greenland Sea due to its strong meridionality. Sea ice export is highly promoted (restricted) in the positive (negative) DA phase. The dependence of sea ice export on the DA is comparable to, or larger than, that on the AO (Figure 6).

Integration/synthesis of satellite measurements of summer chlorophyll and sea ice concentration, and CIOM in the Beaufort/Chukchi seas

The biogeochemical cycling related to sea ice and the circulation in the Beaufort Sea and the Chukchi Sea is investigated due to its high primary productivity. In this study, the variability of chlorophyll-a (chl-a), sea-surface temperature (SST) and sea ice motion in the Beaufort Sea and the Chukchi Sea was investigated using remotely sensed data. We employed the NASA/GSFC SeaWiFS Chl-a, the NASA/JPL AVHRR pathfinder SST Version 5, and NSIDC DMSP/SSM-I sea ice concentration from September 1997 to December 2004.

In the Chukchi Sea, SST and chl-a patterns usually show an increase in the inflow through the Bering Strait and the corresponding outspread of the phytoplankton distributions from July to September. Relatively high SST (~5°C) was also found from the Bering Strait to the Herald Canyon and a similar pattern was revealed in chl-a maps in summer. Over the estuary of the Mackenzie River, heating is evident in every summer season. In particular, wide-spreading high SST (>6~8°C) and the offshore propagation of high chl-a (2~4 mg m$^{-3}$) to the Northwind Ridge were revealed in the summer of 1998, when the maximum sea ice retreat was recorded. This high SST was only situated over the Canadian shelf. Thus, the local heating may be due to river runoff. In the summer (July-September), high chlorophyll-a tend to appear over the Beaufort/Chukchi seas, when sea ice is close to the coast. The offshore displacement of sea ice leads the low chl-a over the open ocean. Mesoscale
eddies and surface current, however, sometimes bring high productive waters to the low chl-a region. These results indicate that the surface circulation pattern is similar to the subsurface flow of the shallow subsurface temperature maximum, and that the three dimensional upper ocean circulation, which is associated with runoff-ocean-ice interaction, needs to be resolved in order to examine the lower trophic level ecosystem in these areas (Figure 7).

3. Web Site Addresses that reflect the Project
http://www.iarc.uaf.edu/highlights/coupled_marine_ecosystem/index.php

4. Graphics

Figure 1. Simulated mixed-layer depth (MLD) against primary production: (a) GPP-Diatom, GPP-Flagellate, NPP-Diatom, NPP-Flagellate, (b) GPP, NPP. G/NPP stands for Gross/Net Primary Production.

Figure 2. 1-D PhEcoM-simulated multi-year phytoplankton (blue) versus satellite measured Chl-a (dotted) at the PMEL M2 mooring. Sea ice concentration is in red. Sea ice disappeared in 2001 due to the warming in the Bering Sea.
Figure 3. Model of the July temperature (degree) structure (see the transect on left, following Overland et al. [1999]). (a) Only the circulation only is modeled; isotherms at the surface layer are straight and flat. The upper mixed layer is only about 5 m, and the thermocline is too weak. (b) The circulation and tides are simulated simultaneously, the bottom mixed-layer forms due to tidal mixing. Vertical temperature has a dome-shaped structure, but the upper mixed layer is still shallow. (c) When wave mixing is considered, the circulation and tidal current are simulated simultaneously. The upper mixed layer shows up and a large-gradient thermocline layer between 10-30 m. The upper mixed-layer now is about 20m due to wave mechanic mixing. (d) Observation, after Overland et al. (1999).
Figure 4. The 3.7km CIOM-simulated climatological sea ice concentration on July 10. Landfast ice attached along the Alaska Beaufort Sea coast and part of Alaska Chukchi Sea coast is well reproduced.

Figure 5. Spatial distributions of the composite sea ice thickness and velocity for climatology (left) and the difference between the DA+ and DA- using the global model simulations in the last century (right). The numbers in yellow boxes are the sea ice transport, while numbers in the purple boxes are the total sea ice transport (in $Sv=10^6 m^3 s^{-1}$).
Figure 6. The annual time series of model-simulated heat transports (in units of $10^{12}$ Watts, or TW) from Fram Strait (gray), the Barents Sea (black), Bering Strait (red), and the total (pink). The observations in Fram Strait with the standard deviations by Schauer et al. (2004) were in blue.

**Simulation results from the Coupled Ice-Ocean Model**

Figure 7. Satellite measured SST from AVHRR (upper left) superimposed by NCEP/NCAR surface wind velocity, chlorophyll-a from SeaWiFS (upper right), and sea ice concentration (in black) from SSM/I. The surface ocean circulation superimposed with the SST (lower) is simulated by the CIOM.
Arctic Ocean Models and Observations
Igor Polyakov - Lead Scientist

Participants:
Hibler, William, III, IARC, U.S.A.
Ivanov, Vladimir, IARC, U.S.A.
Panteleev, Gleb, IARC, U.S.A.
Wang, Jia, IARC, U.S.A.
Zhang, Sheng, IARC, U.S.A.
Zhang, Xiangdong, IARC, U.S.A.

1. Other Collaborators or Contacts
Bieszczynska, Agnezhka, Alfred-Wegener-Institute, Germany
Carmack, Eddy, Institute of Ocean Sciences, BC Canada
Dempsey, Mike, Oceanetic Measurements, BC, Canada
Fahrbach, Eberhard, Alfred-Wegener-Institute, Germany
Fortier, Louis, Laval University, Canada
Golovin, Pavel, Arctic and Antarctic Research Institute, Russia
Johnson, Mark, Institute of Marine Sciences, University of Alaska Fairbanks, USA
Hansen, Edmond, Norwegian Polar Institute, Norway
Karcher, Michael, Alfred-Wegener-Institute, Germany
Maximenko, N., International Pacific Research Center, Honolulu, USA.
Morison, James, Applied Physics Laboratory, University of Washington, USA
Nechaev, Dmitry, Stennis Space Center, University of Southern Mississippi, USA.
Proshutinsky, Andrey, Woods Hole Oceanographic Institution, USA.
Schauer, Ursula, Alfred Wegener Research Institute, Germany
Steele, Michael, Applied Physics Laboratory, University of Washington, USA
Timokhov, Leo, Arctic and Antarctic Research Institute, Russia
Walsh, David, Naval Research Laboratory, Stennis Space Center, USA
Yaremchuk, Max, International Pacific Research Center, Honolulu, USA.

2. Summary of Research Activities and Accomplishments
Our analysis of observational data demonstrated that during the last decade the North Atlantic supply of warm water into the Arctic Ocean has increased (Figure 1). These observations in the Eurasian Basin showed warmer Atlantic water core temperatures (by about 1°C), when compared to climatologies (Polyakov et al., 2005). New pulses of anomalously warm water, including unprecedented warmth at some locations, are on the verge of entering the Arctic Ocean. These anomalies promise to make the polar basin even warmer, with implications for decaying sea ice. These observations also indicate the highly variable nature of the Atlantic water flow, which is characterized by abrupt cooling/warming events, complicating the investigation of Atlantic water variability. We anticipate that these warm anomalies will progress along the Siberian slope towards Alaska as they did in the 1990s, which justifies our desire to expand our program from the Eurasian Basin to the Canadian Basin. This information is featured in our GRL publication (Polyakov et al., 2005), prepared jointly by 23 co-authors from AWI (Germany), NPI and GFI/UIB (Norway), APL/UW, NRL, IMS/UAF (USA), and AARI (Russia), and led by IARC scientists.
The objective of this project was to study the contribution of dense water cascading of the Severnaya Zemlya shelf in the modification of water masses in the Nansen Basin. The approach included a combination of analysis of Russian historical data covering the shelf-slope area of Severnaya Zemlya archipelago and mathematical modeling of cascading at this site. Under the project, specific features characteristic of dense water cascade were analyzed using temperature and salinity measurements in October 1984 and 1985. A Numerical model with realistic bottom topography was used to simulate dense water cascading from the Severnaya Zemlya shelf. Results of these experiments showed that initial spreading of dense water from the shallow shelf occurs in the form of baroclinic eddies (with a typical size of internal Rossby radius), which move along and across isobaths. These eddies efficiently mix the water near the seabed. As a result of mixing a “plume” filled with dense water is formed in the bottom boundary layer. The large-scale motion of the plume is generally in accord with earlier analytical studies, i.e., at a small angle across isobaths off the shelf (Figure 2). It has been shown that topographic irregularities (like canyons) stir the direction of plume motion; however stratification, typical for the studied area, does not change the general evolution of cascade.

During 2005, the variational data assimilation approach was applied for the study of the circulation in the Bering and Kara Seas and in the Dreik Strait. The study of the circulation in the central and northern Bering Sea allowed us to derive the optimized circulation (Figure 3) and obtain a new estimate of the transport through the Kamchatka Strait (24 Sv). Reconstruction of the mean climatological SSH in the Bering Sea can be used as a referenced distribution for the recalculation of the SSH anomaly (Topex/Poseidon data) into the absolute SSH. The optimized circulation in the Kara Sea will be used for the verification of the AOMIP models. The reconstruction of the circulation in the Dreik Strait, through the variational inverse of transect hydrophysical data, SADCP, LADCP and SSH data, reveal the possibility of using the 4Dvar data assimilation approach for the operational hindcast and forecast of the ocean circulation.

We have continued diagnostic analysis of freshwater budgets and their role in North Atlantic deep convection by using model simulations. The last year was a milestone in global climate modeling studies. The IPCC WG1 coordinated international model simulations and projections were completed, representing state-of-the-art GCM modeling efforts. The simulations results from about 15 models for the climate of the 20th century and for the climate projections of the 21st century in the global warming scenarios were archived. The analysis of the sea ice component has been completed and a resultant paper was submitted to the Journal of Climate. The investigation of variability of, and long-term changes in, ocean freshwater budgets and their connection to the North Atlantic deep convection are undergoing. Some of these results were presented at the AGU Ocean Science Meeting in Hawaii.

Using the CCSR/NIES/FRCGC climate model, we calculated the correlations between the modeled and the observed Atlantic Water Core Temperature (AWCT) (C=0.49), as well as NAO index (C=0.16, insignificant, see Figure 4). This implies that the simple correlation between the Arctic AWCT and NAO index does not work.
There must be a feedback mechanism in work; this will be investigated in the near future.

3. Web Site Addresses that reflect the Project
   http://www.frontier.iarc.uaf.edu/NABOS
   http://www.frontier.iarc.uaf.edu/CABOS

4. Graphics
Figure 1. (Top) Evidence of a new warm anomaly entering the central Arctic Ocean. Numerals I–VI indicate temperature sections (°C) taken in 2004. (Bottom) Observational data showing the arrival of a pulse of warm water originating from the North Atlantic into the Arctic Ocean. Large red and yellow arrows indicate two pulses of warm Atlantic Water. The pathways of Atlantic Water are shown schematically by black arrows. Red stars show locations of moorings. (Top) Depth–time diagram of water temperature (°C). (Middle and bottom) Time series of water temperature (°C) from Fram Strait and Svinoy locations. Blue lines show weekly averaged temperature, red lines show six-month running mean temperature. Modeled de-seasoned six-month running mean water temperature anomalies are shown by black dashed lines. Adapted from Polyakov et al. (2005).

Figure 2. Simulated downslope propagation of plume of dense (high-salinity) water at the Severnaya Zemlya slope, eastern Eurasian Basin of the Arctic Ocean. Adapted from Ivanbov and Golovin [2006].
Figure 3. The optimized velocities at 17m (top) and 1000m (bottom). Thick arrows denote the mean velocities observed at several moorings (a) and ARGO velocities at 1000–m (b), which were not assimilated.

Figure 4. Time series of normalized anomalies of modeled Atlantic Water Core Temperature (AWCT, pink, Polyakov et al. 2004), heat transport from both Fram Strait and the Barents Sea (blue), and the modeled winter (DJF) NAO index (black). The correlation between the NAO index and AWCT is 0.16 (not significant) and with the heat transport is 0.37 (significant).
Terrestrial Ecosystem Models and Observations
Yongwon Kim - Lead Scientist

Participants:
David Atkinson, IARC

1. Other Collaborators or Contacts (include their institutions and country)
   Masami Fukuda, Hokkaido University, Japan
   Keiji Kushida, Hokkaido University, Japan
   Yuji Kodama, Hokkaido University, Japan (CliC member)
   Yoshiyuki Ishii, Hokkaido University, Japan (CliC member)
   Hiroshi Enomoto, Kitami Institute of Technology, Japan (CliC member)
   Tomo Tanikawa, Kitami Institute of Technology, Japan
   Gaku Kadosaki, JAXA, Japan

2. Summary of Research Activities and Accomplishments
   Goals of this group are 1) to examine the winter emissions of CO₂ and CH₄, which play significant roles in the regional carbon budget in boreal forests and tundra ecosystems, and 2) to understand the role of black carbon (BC) soot in the Arctic as an agent of climate warming through forcing/feedback of sea ice/glacier albedo. I have collaborated with members of CliC as well as Japanese scientists to enhance international collaboration and broaden our research vision.

   Regional carbon budget in Alaska boreal forest and tundra
   Our main aim is to effectively estimate the regional carbon budget in boreal forest and tundra environments of Alaska. Because vegetation is vulnerable to climate change, flux measurements of CO₂ and CH₄ are required for a better understanding of spatiotemporal variations of CO₂ and CH₄. Though observation stations and the acquired flux-data are limited, this sub-group has also investigated using models and remote sensing techniques.

   Winter emissions of CO₂ and CH₄ along an Alaska transect
   Winter emissions of CO₂ and CH₄ from northern soils are significant sources of atmospheric CO₂ and CH₄ that can account for up to half of the annual emissions of CO₂ and CH₄ from arctic tundra and taiga ecosystems. However, because these sites are limited to specific ecosystems, the spatial and temporal variations of winter CO₂ and CH₄ emissions cannot be elucidated. Here, we conducted winter flux measurements of CO₂ and CH₄ along an Alaska transect that runs 666.7 km along the trans-Alaska pipeline. Each site is located at an interval of 32 km (Figure 1). The ecosystem is boreal forest (taiga) and tundra along the pipeline. We obtained chamber flux measurements of CO₂ and CH₄ as well as the snow depth, snow temperature, whole snow water equivalent (SWE), and density during January 2005 and February 2006. Winter emissions of CO₂ and CH₄ are related to the snow depth; the correlation coefficients of CO₂ and CH₄ (R) are 0.69 and 0.71, suggesting that snow depth plays a significant role in winter CO₂ and CH₄ emissions in snow-covered boreal forests and tundra (Figure 2). Also, the air temperature measured at each site
has a good correlation with winter emissions of CO$_2$ and CH$_4$, which have correlation coefficients (R) of 0.88 and 0.63 during January 2005 (Figure 3), respectively. Therefore, winter emissions of CO$_2$ and CH$_4$ are very significant in the evaluation of winter carbon budget in the Arctic.

*Winter emissions of CO$_2$ and CH$_4$ at UAF*

This research was carried out to estimate the winter fluxes of CO$_2$ and CH$_4$ by the concentration profile method (indirect) and the chamber method (direct) at black spruce forest soils of central Alaska during the winter of 2004/5 (Figure 4). The winter CO$_2$ emission corresponds to 23% of the annual CO$_2$ emitted from Alaska black spruce forest soils, and most of the CO$_2$ was produced from the decomposition of organic matter. The average winter emissions of CO$_2$ and CH$_4$ were 49±13 gCO$_2$-C/m$^2$ and 0.11±0.07 gCH$_4$-C/m$^2$, respectively. This implies that the winter emissions of CO$_2$ and CH$_4$ are an important part of the annual carbon budget in seasonally snow-covered terrain of boreal forest soils.

*Possible effect of boreal wildfire soot on Arctic sea ice and Alaska glaciers*

In-situ measurements of black carbon aerosols and gas byproducts from the FROSTFIRE experiment burn, 8-11 July 1999, were used with a coupled high-resolution wind field/empirical fall-out model to assess transport/dispersion and estimate deposition, showing the temporal variation of the horizontal wind field at 700 hPa over eastern Siberia - Alaska - Canada and the lower Arctic, from 50$^\circ$ N to 80$^\circ$ N and from 180$^\circ$ W to 120$^\circ$ W (Figure 7). Results suggest that BC-aerosols (soot) are quickly transported from central Alaska to the Arctic Ocean region of multi-year sea ice and to southern Alaska glaciers, where up to 20% can be deposited in the area, indicating an average density for gaseous materials and 10 $\mu$m particles in suspension and surface deposition (Figure 8). The estimate of black carbon soot concentration from Alaska boreal wildfires favorably compares to in-situ sea-ice observations made in 1998 and snow albedo observations on Gulkana Glacier in 2001. I hypothesize that northern boreal wildfires are a possible contributor in the reduction of first/multi-year sea ice/glacier extent by enhancing summer melting from albedo reduction. Should the occurrence and severity of northern boreal wildfires continue as in the summers of 2004/5, when more than 1000 km$^2$ burned in the first and third worst wildfire years on record, there will be implications for climate warming.

3. **Web Site Addresses that reflect the Project**

None

4. **Graphics**
Figure 1. Locations of the winter fluxes of CO$_2$ and CH$_4$ observations along an Alaska transect; observations of January 2005 and February 2006.

Figure 2. Relationship between the winter fluxes of CO$_2$ and CH$_4$ and snow depth along an Alaska transect during January 2005.
Figure 3. Relationship between the winter fluxes of CO₂ and CH₄ and atmospheric temperature along an Alaska transect during January 2005.

Figure 4. Temporal variations of a) CO₂ concentration and b) CH₄ concentration in snowpack above the tussock surface and in soil below the Sphagnum moss carpet. The vertically empty column indicates no observation due to a severe weather condition, and the horizontally empty row denotes no data owing to the frozen soil, which has no pore space. The contour interval is 100 ppmv within the snowpack and the soil for CO₂ profile, and 0.5 ppmv within the snowpack and the soil for CH₄ profile during the winter.
Figure 5. Comparison of the relationships between a) 1/CO₂ concentration and the carbon stable isotope ratio of CO₂, b) 1/CH₄ concentration and the carbon stable isotope ratio of CH₄ in air samples collected from soil, snowpack, and from a tower in the boreal forest of central Alaska during the winter season of 2004/5.

Figure 6. Temporal variations of winter CH₄ fluxes estimated by the chamber, profile, and tower observations at the West Ridge site of UAF. The discontinuation of tower CH₄ observation occurred due to the trouble with the CH₄ analyzer since January 2005.
Figure 7. Horizontal wind fields (ECMWF data) at 700 hPa, 00 UTC on day 1 (July 8) through day 12 (July 19). Arrow bar is 20 m/s wind velocity. Small black squares show the location of the FROSTFIRE experiment site. Figure 1c and d show a general flow path for particle transport being influenced by cyclonic and anti-cyclonic weather systems.

Figure 8. Dispersion of carbon-based gas and BC aerosols on day 12 (July 19). Left/right plots show suspended and deposited gas/aerosols respectively. Scale is in density (g m$^{-2}$). Carbon based gas is widely dispersed (a) but is restricted in deposition to Alaska (b). BC aerosols size 10 µm are both widely dispersed (c) and deposited (d).
Arctic Atmosphere: Weather and Climate Variability, Models and Observations
Xiangdong Zhang - Lead Scientist

Participants:
Atkinson, David, IARC, U.S.A.
Bhatt, Uma, GI, U.S.A.
Polyakov, Igor, IARC, U.S.A.
Wang, Jia, IARC, U.S.A.

1. Other Collaborators or Contacts
Alexander, Mike, NOAA/CIRES, Colorado, USA
Dewitt, David, International Research Institute, New York, USA
Forbes, Don and Gavin Manson, Geological Survey of Canada, Canada
Francis-Chythlook, Oceana, TNH Engineering, Alaska, USA
He, Jianxiong, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
Hu, Zeng-Zhen, Center for Ocean-Land-Atmosphere Studies, Maryland, USA
Kattsov, Vladimir, Voeikov Main Geophysical Observatory, St. Petersburg, Russia
Kirtman, Ben, Center for Ocean-Land-Atmosphere Studies, Maryland, USA
Miller, Jack, INE/IARC, Alaska, USA
Ogorodov, Stanislov, Moscow State University, Russia.
Overland, James, NOAA/Pacific Marine Environmental Laboratory, Washington, USA
Rachold, Volker and Annette Rinke, Alfred Wegener Research Institute, Germany
Schneider, Edwin, Center for Ocean-Land-Atmosphere Studies, Maryland, USA
Scott, James, NOAA/CIRES, Colorado, USA
Solomon, Steven, Bedford Institute of Oceanography, Canada
Timlin, Mike, University of Illinois, Illinois, USA
Turner, Jennifer, McGill University, Canada
Walsh, John, IARC, Alaska, USA
Wang, M., University of Washington, Washington, USA
Zhao, Ping, Chinese Academy of Meteorological Sciences, Beijing, China

2. Summary of Research Activities and Accomplishments
We have analyzed the coastal margins over the entire circumpolar regime, along with patterns and trends in a variety of environmental forcing parameters that affect natural processes and human systems. More specifically, work has been undertaken to delineate coastal storm and high-wind activity from observational data; regional trends and patterns of storminess have been produced. We have focused more on Alaska and eastern Russia in the last year.

Strong collaborative links continued with a major international project, Arctic Coastal Dynamics (Alfred Wegener Research Institute, Potsdam), with which one of our group members has been associated since 2002, as a leader of the environmental forcing working group. This year, the circumpolar wave energy totals for the past 20 years were calculated, other circumpolar environmental data layers (melt season length, start and end dates, melting degree day totals) were prepared and transferred.
to the ACD database working group, and one book chapter was submitted under this study. Our wave energy work emphasized the importance of ice in the coastal zone. Wave energy has been dropping rapidly along the north Alaska coast because sea ice concentration has been so low in the past few years (figure 1). Work was also conducted to assess the utility of a major reanalysis data set (figure 2) produced by the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR). This assessment was undertaken to better understand the limitations of this dataset before a detailed storm dataset is derived from it. Problems with the reanalysis dataset have led to additional activity to correct the noted shortcomings. This work indicated a serious, systematic, under-representation of observed wind speed, which is a problem because high wind events have the greatest capacity to do damage to the coastal region; their accurate representation is therefore of specific interest. Two articles and one editorial overview that stem from this work appeared in print.

New instruments were procured and new station setups with telemetry designs were contracted for the weather station at 18,733 feet on Mt. McKinley. A field season was undertaken to transport and install the new units. Park officials agreed to provide instruments for the McKinley medical camp and possibly the high camp.

Investigation of the multidecadal variability (MDV) is still undergoing. Changes in oceanic heat transport from the North Atlantic to the Arctic, via Atlantic water, can have widespread impacts on the arctic climate. Using the 700-year long, 1990s-control simulation from the CCSM3, the MDV of Atlantic water was characterized and examined. Comparisons of Atlantic water volume fluxes and heat transports into the Arctic were done for the Svinøy transect, Fram Strait, and the Barents Sea opening and compared to observations. Warm and cold phases of Atlantic water were examined through composite analysis and quantified with respect to their effects on arctic climate. The model over-estimates Atlantic water temperatures by about 1 °C, but captures reasonable Atlantic water circulation and depth. Atlantic water heat anomalies can be tracked from the Svinøy transect to the Arctic interior with a timescale of 13 years. The Atlantic water core was found to deepen (shoal) during warm (cold) composites. Warm (cold) periods were also characterized by greater Atlantic water transports through the Bering Sea opening (Fram Strait), implying the existence of an internal ocean feedback mechanism that helps to regulate oscillations of Atlantic water between warm/cold periods. There is a coordinated multi-decadal signal in the model atmosphere as evidenced by lower (higher) than normal sea level pressure and warmer (cooler) than normal surface air temperatures during the positive (negative) phase of MDV (Figure 3). This coordinated signal in the ice-ocean-atmosphere system is consistent with observations of MDV. The model presents multiple realizations of MDV that are being investigated to shed light on the associated mechanisms.

In paralleling with the observational data analysis described above, the CCSR/NIES/FRCGC global model simulations were evaluated in reproducing the Arctic Oscillation (AO) and Dipole Anomaly (DA). Based on the global GCM’s simulations (1900-2100, K1 run), the SLP and 500-hPa North of 70°N were analyzed
to derive the AO and DA, which were similar to those derived from the NCEP/NCAR reanalysis datasets (1948-2004). The first leading mode corresponds to the AO. The DA is defined as the second-leading mode. Both modes have important influences on sea ice export, while DA is more important dynamically than the AO (Figure 4).

We also participated in the recent IPCC AR4 activity and has been analysing model simulations for the Arctic climate in collaborating with colleagues at IARC, the University of Washington, NOAA/PMEL, and Voeikov Main Geophysical Observatory in St. Petersburg, Russia. The analyses were focused on a number of selected key and representing parameters, such as sea ice area, surface air temperature, and precipitation/evapotranspiration. The IPCC AR4 model simulations were categorized into two groups (1) simulations for the climate of the 20th century, and (2) climate change projection for the 21st century, under global warming scenarios A1B, A2, and B1.

The simulations for the climate of the 20th century were first evaluated. It is found that most models realistically captured climatological annual mean sea ice area, compared with observations, during 1979-99. Most models also simulated well the trends of sea ice area decreasing and surface air temperature increasing in the last decades. However, a large number of models and model ensemble members don’t perform well in simulating the warming event during 1920-50. The model also generally overestimated area-averaged precipitation over the major river basins. Based on the evaluation on the simulation for the climate of the 20th century, they assessed model projections of sea ice and precipitation. Almost all models present intensified decreasing trends of annual mean sea ice area in the 21st century and the annual cycle of sea ice area would be amplified under the global warming scenarios (Figure 5). These intensified trends are even amplified for multiyear sea ice. The multi-model ensemble mean suggests that an increasingly large area of the Arctic Ocean will most likely covered by seasonal ice. In the last 20-years of this century, the annual mean sea ice area would be reduced by about 21.6, 31.1%, 33.4% in scenarios B1, A1B, and A2, compared with the present-day sea ice area. Model projections also suggest that precipitation over the Arctic Ocean and its watersheds increased through the 21st century, showing much faster percentage increases than the global mean precipitation. Three papers from these analyses were developed. One of them was published in 2006 and the other two are under review. The paper about sea ice analysis has been cited and its two figures are used by the present version of the draft of the IPCC AR4.

At the recommendation by the Joint Review Committee last year, we strengthened studies on the arctic water cycle through a recently initiated project “Arctic Water Cycle Components and Cloudiness: Synthetic Analysis of Observation Data and the IPCC AR4 Model Simulations.” They first tried to understand the origins of, and changes in, the arctic water cycle. They calculated monthly atmospheric meridional moisture transport year-by-year from 1948-2005, using the NCEP/NCAR reanalysis data and the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-Year Re-analysis (ERA-40). The preliminary results show that the North Atlantic and North Pacific sectors are predominant channels that supply water vapor into the Arctic from low latitudes, while the Arctic loses water
through the Eurasian and North American continental sectors (Figure 6). Both maximum northward and southward moisture transport occurs in the summer. However, they cancel each other out, leading to the minimum net moisture into the Arctic. In addition, the long-term time series demonstrates that atmospheric moisture transport exhibits strong interannual variability with obvious seasonal and regional dependence. Fluctuations are generally larger in winter than in summer. This project is ongoing and analysis dealing with cloud cover has also been initiated.

3. Web Site Addresses that reflect the Project
Arctic Coastal Dynamics Project:

Arctic Cyclone Activity Project:
http://www.frontier.iarc.uaf.edu/~xdz/CAI/

4. Graphics

Figure 1. Trends in wave energy for the May-October period, 1979-2003. Wave energy values are determined using a fetch and depth limited wind-water momentum transfer function. The wind field data used to drive the waves come from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) global reanalysis data set. The left plot includes the effects of the presence of sea-ice to limit wave energy. The right plot shows wave energy calculations in the absence of sea ice. Of interest to note is the difference in wave energy trends north of the Alaska North Slope without sea ice there is a slight decreasing trend, due to a general decrease in strong wind events in the last 15 years. However when the effects of sea ice are incorporated, wave energy shows a slight increasing trend, due to the more rapid decrease in sea ice cover.
Figure 2. Comparison of surface wind speeds observed at weather stations with those available from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) global reanalysis data set. Symbol locations coincide with locations of observing stations (over the ocean, a station location is a largely continuous amalgam of multiple drifting ice stations that moved through that location). Symbol type indicates the strength of a correlation performed on time series of wind speed data. Time frame is the May-October period in each year over the 1950-2000 period; wind speeds were correlated only when the observed wind speed exceeded 10 m/s. Generally, correlations are poor, tending to very poor over rugged terrain (e.g., Yukon), moderate over areas of low relief (e.g., interior Canada), poor in exposed coastal areas, and variable over the ocean. In general NCEP/NCAR surface wind data are not very good at capturing specific storm events.

Figure 3. Composites based on periods of warm and cold phases of the multidecadal variability (MDV) for (a) SLP and for (b) Reference Temperature (TREFHT) (°C).
Figure 4. Spatial distributions of the first two leading EOF modes of winter mean sea level pressure (Dec.-Feb.) (left panels) EOF1 (AO) and (right panels) EOF2 (DA) are derived from the K1 run (1900-2010) using the CCSR/NIES/FRCGC global model (upper panels) and the NCEP/NCAR reanalysis data (1948-2004, lower panels). Contour interval is 0.1. White solid and dash lines represent 95% and 99% significant level of correlation coefficient between PCs and winter mean anomalies, respectively. The percentage of the total variance for each mode is also indicated.

Figure 5. Projections of multi-model ensemble mean monthly sea ice area anomalies over the Northern Hemisphere from 2000 to 2100, relative to the 1979-99 climatological monthly mean sea ice area (Zhang and Walsh 2006). Note that all months’ data are included.
Figure 6. Annual cycle of climatological atmospheric meridional moisture transport across 60°N based on the ERA-40 reanalysis data.
External Presentations


Atkinson, D., December 5-9, 2005, Circum-Arctic High-Speed Wind Event Climatology and Trends from Observational Data, American Geophysical Union conference.


Deal, C.J., November 2005, Biological cycles, Department of Atmospheric Sciences, ATM693 Climate Journal Club (1 credit class), guest speaker, oral presentation.


Deal, C.J., September 2005, Seawater photochemistry of the climate-relevant trace gas dimethylsulfide (DMS), Chemistry and Biochemistry Department, University of Alaska Fairbanks, oral presentation.

Kim, Yongwon, Hiroaki Hatsushika, Reginald R. Muskett and Koji Yamazaki, December 12-13, 2005, 6th International Workshop on Global Change: Connection to the Arctic, Tokyo, Japan, Impacts of forest fire on hydrological environments in interior Alaska.


Ishii, Yoshiyuki, Yuji Kodama, Yongwon Kim, Koichiro Harada, Yuki Sawada, and Masami Fukuda, December 12-13, 2005, 6th International Workshop on Global
Change: Connection to the Arctic, Tokyo, Japan, Impacts of forest fire on hydrological environments in interior Alaska.
Ivanov, V., February 2006, Observations and modeling of dense water cascading from the Laptev Sea shelf, Ocean Science Meeting, Honolulu, poster.
Jin, M., C. Deal, and J. Wang, January 2006, Development of coupled ice-ocean ecosystem and application to the ice-core data in land fast ice offshore Barrow, oral presentation.
Kim, Yongwon, Hiroaki Hatsushika, Reginald R. Muskett, and Koji Yamazaki, December 5-9, 2005, Fall AGU Meeting, San Francisco, USA, Possible Effect of Boreal Wildfire Soot on Arctic Sea Ice and Alaska Glaciers.
Kim, Yongwon and Noriyuki Tanaka, September 25-30, 2005, 7th CO2 Conference, Broomfield, Colorado, USA, Fluxes of CO2, N2O and CH4 in northern Japanese grassland soil evaluated by the 222Rn flux and chamber methods.
Kim, Yongwon, Hiroaki Hatsushika, Reginald R. Muskett, and Koji Yamazaki, December 12-13, 2005, 6th International Workshop on Global Change: Connection to the Arctic, Tokyo, Japan, Possible Effect of Boreal Wildfire Soot on Arctic Sea Ice and Alaska Glaciers.
Kim, Yongwon, Masa Ueyama, Noriyuki Tanaka, and Yoshi Harazono, September 25-30, 2005, 7th CO2 Conference, Broomfield, Colorado, USA, Assessment of winter fluxes of CO2 and CH4 in black spruce forest soils of central Alaska estimated by the profile method and chamber method.
Kodama, Yuji, Yoshiyuki Ishii, and Yongwon Kim, December 12-13, 2005, 6th International Workshop on Global Change: Connection to the Arctic, Tokyo, Japan, Observation of soil CO2 efflux at Poker Flat forest fire burned site in 2005.
Mizobata, K. and J. Wang, February 23, 2006, Summer chlorophyll distributions and the association with the runoff and an ocean-ice circulation in the Beaufort/Chukchi Sea (OS42N-05), Ocean Sciences Meeting 2006, Hawaii, USA, oral.
Mizobata, K. and J. Wang, March 6, 2006, Summer chlorophyll distributions and the association with the runoff and an ocean-ice circulation in the Beaufort/Chukchi Sea, Advancing Science and Technology in Arctic Climate Change Research, Fairbanks, oral.
Mizobata, K. and J. Wang, March 6, 2006, Summer chlorophyll distributions in relation to mesoscale features in the Beaufort/Chukchi Sea, Advancing Science and Technology in Arctic Climate Change Research, Fairbanks, poster.


Mizobata, K., S. Saitoh, and J. Wang, March 6, 2006, Biochemical Enhancement Related to Mesoscale Eddies in the Bering Sea Green Belt, Advancing Science and Technology in Arctic Climate Change, Research, Fairbanks, poster.

Mizobata, K., S. Saitoh, and J. Wang, January 24, 2006, Biochemical enhancement related to mesoscale eddies in the Bering Sea Green Belt, Marine Science in Alaska 2006 Symposium, Anchorage, poster.

Panteleev, G., March 2006, Two Examples of 4Dvar Data Assimilation Application for Reanalysis and Short Range Forecast: Tsushima Strait and Bering Sea Circulations, Bedford Institute of Oceanography, Halifax, Canada, invited speaker.

Polyakov, I., April 2006, Recent and long-term changes in the Arctic/North Atlantic ocean, EGU Annual Conference, Vienna, invited speaker

Polyakov, I., April 2006, Recent changes and long-term variations in the Arctic/North Atlantic Colloquium, IFM-GEOMAR, Kiel, invited speaker.

Polyakov, I., March 2005, Arctic climate change, JAMSTEC Symposium, Yokohama, Japan, invited.

Polyakov, I., March 2006, MAOOS/NABOS: Preparation for the IPY, Arctic Week AOSB Meeting, Potsdam, invited speaker.

Polyakov, I., March 2006, Recent and long-term changes in the Arctic and North Atlantic, AARI Seminar, St.-Petersburg, Russia, invited speaker.

Polyakov, I., November 2005, Recent high-latitude changes and long-term climate variations, 3D Trans-Atlantic Conference, Washington D.C., invited speaker.

Polyakov, I., April 2006, Recent and long-term changes in the Arctic/North Atlantic Ocean, EGU Annual Conference, Vienna, invited.

Polyakov, I., April 2006, Recent changes and long-term variations in the Arctic/North Atlantic Colloquium, IFM-GEOMAR, Kiel, invited.

Polyakov, I., November 2005, Recent high-latitude changes and long-term climate variations, 3d Trans-Atlantic Conference, Washington D.C., invited.

Polyakov, I., March 2006, NABOS/PAG: Preparation for the IPY, Arctic Week PAG Meeting, Potsdam, invited speaker.

Ueyama, Masahito, Yoshi Harazono, Yongwon Kim, Noriyuki Tanaka, December 5-9, 2005 Fall AGU Meeting, San Francisco, USA, Simulating net ecosystem productivity and the sensitivity of a sub-arctic boreal forest ecosystem.
Wang, J. and M. Jin, February 14, 2006, Sea ice-ocean-oil spill modeling system (SIOMS) for the near-shore Beaufort and Chukchi Seas: improvement and parameterization (Phase II).
Wang, J., March 6, 2006, IARC Arctic Modeling Group Activities: Modeling and climate change studies, Advancing Science and Technology in Arctic Climate Change Research, Fairbanks, invited.
Zhang, S. and J. Wang, February 20-24, 2006, Coupling the CICE3.1 to ROMS, Ocean Science Meeting, Honolulu, poster.
Zhang, X., August 2-11, 2005, Arctic sea ice changes and the underlying physical mechanisms: Multi-model investigations in the framework of IPCC AR4, IPCC Special Session, International Association of Meteorology and Atmospheric Sciences Scientific Assembly, Beijing, China, invited.
Zhang, X., J.E. Walsh, and A. Sorteberg, December 5-9, 2005, Arctic Regional and Seasonal Variability and Changes of Storm Activity in Present and Future Projected Climate, AGU Fall Meeting, San Francisco, CA, USA.

Atkinson, D.E., Preliminary Wave energy hindcast results for the circumarctic region, Alaska Pacific Region Integrated Data Enterprise workshop, August 2-3, 2005, Anchorage, AK.


Kim, Yongwon, Special lecture, Dynamics of Greenhouse Gases in Terrestrial Ecosystem, Pukyung University, Pusan, Korea, November 16, 2005.

Kim, Y., What happens to Alaska during Arctic Warming? Special lecture, Kitami Institute of Technology and Tohoku University, Japan, October 25-27, 2005.

Mizobata, K., S. Saitoh, and J. Wang, Biochemical enhancement related to mesoscale eddies in the Bering Sea Green Belt, UAF/School of Fisheries and Ocean Sciences Seminar, University of Alaska Fairbanks, Fairbanks, April 21, 2006.


Panteleev, G., Investigation of the Arctic Ocean circulation employing a variational data assimilation technique, AOMIP meeting, Montreal, Canada, June 5-9, 2005.


Polyakov, I., Recent and long-term changes in the Arctic and North Atlantic, AARI Seminar, St.-Petersburg, Russia, March 2006, invited.


Zhang, X., Northern high latitude climate change and variability: Recent manifestation in the real world and future projection by the IPCC AR4 climate models, Chinese Academy of Meteorological Sciences, Beijing, China, August 10, 2005, invited.

Hosted Visitors or Other Special Guests

Dacey, John, Woods Hole Oceanographic Institution, March 18-March 27.
He, Juanxiong, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, February 23 - March 31, 2006.
Iida, Tokahiro, Hokkaido University, Japan, March 1-12, 2006.
Nechaev, Dmitry, Stennis Space Center, University of Southern Mississippi, USA, August 1-10.
Timokhov, Leo, Arctic and Antarctic Research Institute, Russia, February 25 – March 11, 2006.
Yaremchuk, Max, International Pacific Research Center, Honolulu, USA, March 27- April 03.
Zhao, Ping, Chinese Academy of Meteorological Sciences, Beijing, China, February 10 – March 31, 2006.


Ishii, Yoshiyuki, Yuji Kodama, Yongwon Kim, Koichiro Harada, Yuki Sawada, and Masami Fukuda, Impacts of forest fire on hydrological environments in interior Alaska, Proceedings of 6th International Workshop on Global Change: Connection to the Arctic, 144-147, 2005.


Kattsov, V., J.E. Walsh, V. Govorkova, T. Pavlova, and X. Zhang, Arctic Ocean freshwater budget components in simulations with the IPCC AR4 AOGCMs, J. Hydrometeor, submitted, 2005.


Kodama, Yuji, Yoshiyuki Ishii, and Yongwon Kim, Observation of soil CO$_2$ efflux at Poker Flat forest fire burned site in 2005, *Proceedings of 6th International Workshop on Global Change: Connection to the Arctic*, 137, 2005.


Wildfire in central Alaska during the summer of 2004/5 was extensive. We have measured the following:

- Temporal variation of CO₂ and CH₄ before and after the wildfire season
- Emission ratios of trace gases from wildfire

We have also collaborated on wildfire emissions with researchers involved with the JAXA project (PI: Masami Fukuda, 2005-2007).

Verification of snow depth by on-site observation and microwave remote sensing was also accomplished, including:

- Modification of algorithm by on-site observation of the snow depth
- Winter fluxes of CO₂ and CH₄ through the snowpack

We have collaborated on this project with researchers involved with the JAXA project (PI: Hiroshi Enomoto, 2005-2007).