

**WMO/ICSU/IOC
WORLD CLIMATE RESEARCH PROGRAMME**

**JSC-31/Doc. 4.2/1
(1.2.2010)**

JOINT SCIENTIFIC COMMITTEE

Item number

**THIRTY-FIRST SESSION
ANTALYA, TURKEY
15-19 FEBRUARY 2010**

RAPID LOSS OF SEA ICE IN THE ARCTIC

**(Submitted by Drs Vladimir Kattsov, Vladimir Ryabinin, Cecilia Bitz,
Professor Antonio Busalacchi, Drs James Overland, Mark Serreze,
Professor Martin Visbeck and Dr John Walsh)**

RAPID LOSS OF SEA ICE IN THE ARCTIC

(WCRP white paper)

Vladimir Kattsov¹, Vladimir Ryabinin², Cecilia Bitz³, Antonio Busalacchi⁴,
James Overland⁵, Mark Serreze⁶, Martin Visbeck⁷, John Walsh⁸

[Introduction]

Over the period of modern satellite observations (1979-present), Arctic sea-ice extent at the end of the melt season (September) has declined at a rate of more than 11% per decade, and there is evidence that the rate of decline has accelerated during the last decade. Every September since 1996 the sea-ice extent has been below the 1979-1999 mean. The winter ice extent has been also declining, but slower. The sea ice cover has been also thinning (e.g., Rothrock and Maykut, 1999). According to Kwok et al. (2009), the Arctic Ocean has lost 40% of its multiyear ice in the last 5 years.

The WCRP CMIP3 coupled global atmosphere-ocean general circulation models (AOGCMs) are the main source of climate projections assessed by IPCC in its 4th Assessment Report (AR4: IPCC, 2007). While there is a significant inter-model scatter in simulations of the Arctic sea ice (Arzel et al., 2006; Zhang and Walsh, 2006; Kattsov et al., 2007), they all project decreasing ice mass and extent through the 21st century. For the most aggressive GHG emission scenarios (e.g. A2), some CMIP3 AOGCMs project total disappearance of the Arctic ice in late summer by the end of the century. However, *as an ensemble*, the CMIP3 AOGCMs are conservative in simulating the observed September ice extent trend. The ability of most of the models to realistically project the 21st century sea-ice response to GHG forcing is thus an ongoing concern. A number of studies suggest that the Arctic Ocean may lose its multi-year ice cover in the early to mid-21st (Holland et al., 2006; Stroeve et al., 2007; Wang and Overland, 2009; Alekseev et al., 2009).

The future of Arctic sea ice cover is of enormous economic significance (e.g., ACIA, 2005). Due to several climatic feedbacks, in which sea-ice is a factor, the ability of climate models to realistically project the future of the Arctic sea-ice is an important condition for adequately projecting the global climate (e.g. Bony et al., 2006).

The main goal of this paper is to consider possible reasons behind the apparent discrepancy between observation and model simulations, and to suggest steps towards minimizing uncertainties in predicting/projecting the future of the Arctic sea ice.

[Observation uncertainties]

Addressing the problem of rapid ice loss requires accurate information on ice thickness, velocity, age, salinity, density, snow cover and other factors. Data on some of these variables are absolutely necessary, while records for others are helpful. Satellite passive microwave (PMW) sensors are the main data source for estimates of ice extent. The accuracy of algorithms for sea-ice PMW concentration estimates has been examined in many studies (Meier, 2005; Meier and Stroeve, 2008; etc.), and there is continuing disagreement regarding which of many sea-ice extent products is most accurate. As an example of this problem, in 2009 NSIDC reported a September

¹ Voeikov Main Geophysical Observatory of Roshydromet, St.Petersburg, Russia

² World Climate Research Programme, Geneva, Switzerland

³ University of Washington, Seattle, USA

⁴ University of Maryland, College Park, USA

⁵ NOAA, PMEL, Seattle, USA

⁶ NSIDC, Boulder, Colorado, USA

⁷ IFM-GEOMAR, Kiel, Germany

⁸ University of Alaska, Fairbanks, USA

minimum of 5.1 M km² on 12 September (NSIDC website, 2009), whereas the Arctic Regional Ocean Observing System (Arctic ROOS based at the Nansen Environmental and Remote Sensing Center in Bergen, Norway) estimate shows a 6.0 M km² minimum on that day (Arctic ROOS website). The significant difference of the order of 20% is characteristic for both daily and monthly means and seems to relate to the algorithm used. Differences of the same order of magnitude can be found between products from other centres. There is hence a clear need for further product intercomparison and verification.

It is even more difficult to assess uncertainties in sea-ice thickness estimates. Both the analysis of satellite-derived sea-ice age data and a new proxy record of ice thickness for past decades (Maslanik et al., 2007; Kwok et al., 2009; Kwok and Rothrock, 2009) suggest that in addition to an overall reduction of multi-year ice in the Arctic, the mean age and thickness of the remaining multi-year pack have decreased. This reflects loss of the oldest ice types. The remaining relatively old and thick ice is now confined to a much smaller portion of the Arctic Ocean than in the earlier years. Given this, the sea-ice cover is increasingly susceptible to pronounced summer ice loss or an anomalous ice drift.

Climate model evaluation requires data on the oceanic and atmospheric conditions. Global reanalyses, such as ERA-40, ERA-Interim and JRA-25, are presently the best sources of gridded atmospheric data. Significant attention has been given to improving their accuracy in the Arctic/ Shortcomings in representation of the Arctic precipitation are particularly problematic (Serreze and Hurst, 2000). Almost all fields from reanalysis products in the Arctic have large errors (Walsh et al., 2009). The ongoing Arctic System Reanalysis (Bromwich et al., 2010) may help to address some of these shortcomings. New data sets, to be produced by IPY projects, several ESA projects (e.g., GlobIce, GlobSnow, GlobGlacier, GlobPermafrost), composites of cryospheric parameters generated by the IPY GIIPSY project, and output of several other related activities, will provide a useful data base for verification studies. Observations directed at identifying and quantifying the physical processes, especially feedbacks, are the highest priority.

Many ocean regions have seen systematic data synthesis efforts spearheaded by the WCRP CLIVAR Project and its Global Synthesis and Observations Panel (GSOP). At present there is no attempt to produce a long-term data synthesis for either the Arctic Ocean or the southern Ocean

[Model uncertainties]

The sensitivity of AOGCM sea-ice components to GHG forcing has been a research focus for more than a decade. The 0- through 1-D simple thermodynamic parameterizations of sea ice were the state-of-the-art in mid-1990s and reflected in AOGCMs that took part in CMIP and CMIP2. Such parameterizations were found to be overly sensitive to external forcing/ Emerging dynamic-thermodynamic models were giving reasons to expect a major improvement in the sensitivity over the thermodynamic models (Hilmer and Lemke, 2000).

One of the major developments in modelling over the past decade has been the implementation of sea-ice dynamics in almost all AOGCMs (Randall et al., 2007). Sea-ice components of CMIP3 AOGCMs usually predict ice thickness (or volume), fractional cover, snow depth, surface and internal temperatures (or energy) and horizontal velocity. Sea-ice albedo is typically prescribed, with only crude dependence on ice thickness, snow cover and puddling effects. The complexity of sea-ice dynamics varies from the relatively simple 'cavitating fluid' approach to more comprehensive viscous-plastic and elastic-viscous-plastic models. Sea-ice thermodynamics modules in climate models typically use constant conductivity and heat capacities for ice and snow (if represented) and account for a heat reservoir simulating the effect of brine pockets in the ice. Some models include snow ice formation, which occurs when a part of the ice floe is submerged under the weight of the overlying snow and the flooded snow layer refreezes. As a significant advance over the previous decade, a few modern sea-ice models (even with relatively high resolution) incorporate sub-grid scale ice thickness distributions with several thickness 'categories', rather than considering the ice as a uniform slab with inclusions of open

water. Although parameterizations of ridging mechanics and their relationship with the ice thickness distribution have improved, inclusion of advanced ridging parameterizations has lagged development of other aspects of sea-ice dynamics (rheology, in particular) owing to a lack of observational constraints.

The most reliably measured characteristic of sea ice for model evaluation is still its seasonally varying extent. Despite the significant differences between models, the CMIP3 multi-model mean of sea-ice extent agrees reasonably well with observations. The mean extent of simulated sea ice extent (concentrations above 15%) exceeds the observed values by up to roughly 1 M km² throughout the year (Arzel et al., 2006). This difference is with respect to the Hadley Centre Sea Ice and SST dataset (HadISST, Rayner et al., 2003), and is of the same order as differences between various sea-ice extent products (see discussion above). In many models the regional distribution of sea ice is poorly simulated, even if the hemispheric extent is approximately correct (Arzel et al., 2006; Zhang and Walsh, 2006). The biases may influence the model climate sensitivity. There is a tendency for models with relatively large sea-ice extent in the present climate to have higher sensitivity. This is apparently especially true for models with low to moderate polar amplification (Holland and Bitz, 2003).

Among the primary causes of biases in simulated sea ice (especially its geographical distribution) are problems with high-latitude winds (Bitz et al., 2002), ocean heat advection (Bitz, in prep.) and vertical and horizontal mixing in the ocean (Arzel et al., 2006). Also important are errors in surface energy fluxes (Sorteberg et al., 2007), which may result from inadequate parameterizations of the atmospheric boundary layer in the Arctic and from generally poor simulation of high-latitude cloudiness which is evident from the large inter-model scatter (Vavrus et al., 2009). Ice transport out of the Arctic Ocean through the Fram Strait (e.g., Tsukernik et al., 2009) also needs to be adequately represented in AOGCMs.

[Outstanding issues]

One likely contributor to the observed rapid decline of the Arctic ice extent and thickness is multi-year and decadal climate variability. This includes factors such as heat storage in the upper layer of the ocean during the summer and ocean heat transport from the Atlantic and Pacific to the Arctic Ocean. Due to their coarse resolution, the AOGCMs tend to underestimate the amount of heat delivered to the sea ice by the horizontal oceanic heat transport. As shown in (Bitz, in prep.), faster rates of decline in sea ice extent were produced in the climate models with larger heat transports to the Arctic Ocean from Atlantic.

There are a number of ways in which sea ice is influenced by and interacts with the atmosphere and ocean; and the nature and magnitude of associated feedbacks, both positive and negative, are still poorly quantified (e.g. NRC, 2003; Overland and Wang, 2010). Additionally, potentially important small scale processes, such as convection in brine pockets or in melt ponds, are not included in the sea-ice components of current AOGCMs. Possible impacts of black carbon aerosols that induce atmospheric warming and black carbon on snow and ice that decreases the surface albedo (e.g. AMAP, 2009) have so far only been examined in climate models in idealized model simulations (e.g. Hansen and Nazarenko, 2004).

In principle, the possibility exists that the sharp downward trend in ice extent is a statistically rare event associated with natural (unforced) climate variability. Until concentrations of GHGs reach higher values, climate signals from natural climate variability may be comparable in magnitude to those from external forcing. The CMIP3 ensemble arguably does not have enough members to capture low probability events. Additionally, the CMIP3 models appear to have limited abilities to generate unforced atmospheric variability with magnitude comparable to observations, e.g., the major Arctic warming event in the first half of the 20th century (Wang et al., 2007). On the other hand, at least some of the CMIP3 models do simulate rapid changes in the Arctic sea ice due mainly to natural variability. The timing of the rapid ice decline events simulated by a model cannot be expected to match the ones observed, but at least the general character of the simulated (rapid) changes in some models resembles well the observed behaviour of the ice cover. Together with

the possibility that the observational data for 1953-1978 (pre-satellite) may overestimate the earlier ice extent this means that the models may not be so bad after all at sea-ice hindcasting.

Improving predictions of sea ice conditions on seasonal through interannual timescales also bears on predicting its longer-term (century-long) fate. The eventual goal is a timescale-independent “seamless prediction” system. Motivated by the recent dramatic changes in Arctic sea ice, several groups (e.g. Drobot 2007; Lindsay et al. 2008; Zhang et al., 2008), have started to issue seasonal forecasts of Arctic sea ice conditions. So far these efforts have been either purely statistical or have used a sea ice-ocean model with atmospheric forcing prescribed from past years to predict the future sea-ice cover. These methods show a promise because sea ice exhibits autocorrelation, with a several months’ lag for the sea-ice extent (Drobot et al. 2006, Lindsay 2008) and with a several years’ lag for the sea-ice volume (Bitz et al., 1996; Flato et al. 2004; L’Heveder and Houssais, 2001). Mixed layer heat storage in the ocean also offers some additional predictability (Lindsay 2008). A number of other groups are providing seasonal predictions of seasonal minimum extent for the SEARCH Sea-Ice Outlook Project. These groups also use a combination of statistical and uncoupled model estimates and expert knowledge. Only one group appears to use the statistics from a fully-coupled model, and none uses a coupled climate system model, akin to the methods employed e.g. for the ENSO prediction.

[Conclusions and recommendations]

Meaningful prediction/projection of the Arctic sea ice conditions for the coming decades and beyond requires progress in several interconnected areas of research and observations including:

- Determining priorities of observational and modelling developments (e.g. dedicated ice thickness satellite missions, sea-ice modelling allowing data assimilation, etc.) aimed at improving credibility of the sea-ice predictions and projections;
- Better understanding of the predictability of sea ice conditions on seasonal, interannual, decadal, and centennial time scales in the wider context of the polar climate predictability;
- Detection and attribution of the Arctic sea-ice change (i.e. quantification of the interplay of its forced and unforced aspects) and evaluation of the ability of the state-of-the art climate models to reproduce the observed sea-ice behaviour as a part of the broader climate system, with as full as possible accounting of ice-atmosphere-ocean processes, interactions and feedbacks.

CMIP5 will provide an opportunity to address some of these issues. We recommend undertaking a coordinated multi-aspect study of the Arctic sea-ice loss based on CMIP5 output (along with other diagnostic CMIP5 subprojects exploring different environmental problems). The WCRP could facilitate this effort, taking into account the timeline of AR5, by compiling a list of major study areas and approaching individual scientists and research groups with a request to organize and coordinate corresponding targeted diagnostic projects. Such a collective approach, coexisting with the previous “individualist’s” approach of CMIP3, may help the scientific community to study complex environmental problems, one of them being the Arctic ice loss, within the time limits of AR5 preparation.

Predictions and hindcasts on seasonal through decadal time scales will require model initialization, which was not done for the CMIP3 simulations. To draw conclusions about the success or failure in hindcasting the observed loss of the Arctic ice, reliable regional observations will be needed to initialize a number of fields, e.g. the sea-ice thickness distribution (because of the strong impact of the initial sea ice thickness on the change in ice extent) and enable verification. The same is true for the thermohaline structure of the ocean. In the absence of the data needed for the initialization, a possibility of generating a proxy of initial conditions through the use of regional models of the Arctic Ocean forced with the observed (reanalysed) atmospheric fields could be explored (Gerdes and Koberle, 2007). Some ongoing activities, especially the Arctic System Reanalysis, promise an important contribution towards solving this problem.

The record sea-ice extent minimum over the satellite record took place in September 2007, during the International Polar Year 2007-2008 (IPY). IPY efforts, many of which are ongoing, have

generated a wealth of data. Also, there have been several projects directed at Arctic system prediction, including sea ice. Nevertheless, there has yet to be study that would unify efforts of the climate research community in analyzing available data in its entirety and using it to improve the prediction of the Arctic climate at different time scales. WCRP could propose to the climate and Arctic research communities to prepare a roadmap to an **ARctic Climate HI**ndcasting, **Mo**delling and **Pr**EDiction **Ex**periments (ARCHIMEDES). This initiative could benefit from a synthesis of work at very high resolution (e.g. a new SHEBA-like campaign – to better understand local processes, include sea-ice biogeochemical connections and validate various remote sensing algorithms), and as well regional and global observational, modelling, and data synthesis efforts. Such an initiative could become a cornerstone for the proposed International Polar Decade. An inventory of all Arctic data would help this major synthesizing activity.

References

- ACIA, 2005: Arctic Climate Impact Assessment. Cambridge, Cambridge University Press. pp. 1042.
- Alekseev, G.V., A.I. Danilov, V.M. Kattsov, S.I. Kuzmina, and N.E. Ivanov, 2009: Changes in the climate and sea ice of the Northern hemisphere in the 20th and 21st centuries from data of observation and modeling. *Izvestia of Russian Academy of Sciences: Physics of Atmosphere and Ocean*, 45, 6, 723–735.
- AMAP, 2009: Update on Selected Climate Issues of Concern, AMAP, Oslo, 2009, v+15 pp., ISBN 978-82-7971-049-3
- Arzel, O., T. Fichefet, and H. Goosse, 2006: Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs, *Ocean Modelling*, 12, 401–415.
- Bitz, C.M, D. S. Battisti, R. E. Moritz, and J. A. Beesley, 1996: Low Frequency Variability in the Arctic Atmosphere, Sea Ice, and Upper Ocean Climate System. - *Journal of Climate*, 9, 394–408.
- Bitz C., G. Flato, J. Fyfe, 2002: Sea ice response to wind forcing from AMIP models. *J.Climate*. 15, 523–535.
- Bony, S., R. Colman, V. Kattsov, R. Allan, C. Bretherton, J.-L. Dufrense, A. Hall, S. Hallegatte, M. Holland, W. Ingram, D. Randall, B. Soden, G. Tselioudis, M. Webb, 2006: How Well do we Understand and Evaluate Climate Change Feedback Processes? *J.Climate*, 19, 3445–3482.
- Bromwich, D. H, Y.-H. Kuo, M. Serreze, J. Walsh, L.-H. Bai, M. Barlage, K. Hines, and A. Slater, 2010: Arctic System Reanalysis: Call for community involvement. *EOS Trans. AGU*, in press.
- Drobot, S. D., J. A. Maslanik, and C. F. Fowler, 2006: A long-range forecast of Arctic summer sea-ice minimum extent, *Geophys. Res. Lett.*, 33, L10501, doi:10.1029/2006GL026216.
- Drobot, S. D. 2007: Using remote sensing data to develop seasonal outlooks for Arctic regional sea-ice minimum extent. -*Remote Sens. Environ.*, 111, 136–147, doi:10.1016/j.rse.2007.03.024.
- Flato, G.M. and CMIP contributors, 2004: Sea-ice climate and sensitivity as simulated by global climate models, *Climate Dynamics*, 23: 229–241.
- Gerdes R., and C. Koberle, 2007: Comparison of Arctic sea ice thickness variability in IPCC Climate of the 20th Century experiments and in ocean–sea ice hindcasts. *J.Geophys.Res*, **112**, doi:10.1029/2006JC003616
- Hansen, J., and L. Nazarenko, 2004: Soot climate forcing via snow and ice albedos. - *Proc. Natl. Acad. Sci.*, 101, 423–428, doi:10.1073/pnas.2237157100.
- Hilmer, M. and P. Lemke, 2000: On the decrease of Arctic sea ice volume. *Geophys. Res. Lett.*, 27(22), 3751–3754.
- Holland, M.M., C.M. Bitz, and B. Tremblay, 2006: Future Abrupt Reductions in the Summer Arctic Sea Ice, *Geophys. Res. Lett.*, 33, L23503, doi: 10.1029/2006GL028024.
- IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
- Kattsov, V.M., G.A. Alekseev, T.V. Pavlova, P.V. Sporyshev, R.V. Bekryaev, V.A. Govorkova, 2007: Modeling the evolution of the World Ocean ice cover in the 20th and 21st centuries. *Izvestia of Russian Academy of Sciences: Physics of Atmosphere and Ocean*, 43, 2, 165–181.
- Kwok, R., G. F. Cunningham, M. Wensnahan, I. Rigor, H. J. Zwally, and D. Yi, 2009: Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, *J. Geophys. Res.*, 114, C07005, doi:10.1029/2009JC005312.
- Kwok, R., and D. A. Rothrock, 2009: Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008, *Geophys. Res. Lett.*, 36, L15501, doi:10.1029/2009GL039035.
- Lindsay, R. W., J. Zhang, A. J. Schweiger, and M. A. Steele, 2008: Seasonal predictions of ice extent in the Arctic Ocean, *J. Geophys. Res.*, 113, C02023, doi:10.1029/2007JC004259.

- L'Heveder, B., M.-N. Houssais, 2001: Investigating the variability of the Arctic sea ice thickness in response to a stochastic thermodynamic atmospheric forcing. - *Clim. Dyn.*, 17, no. 2-3, pp. 107-125.
- Maslanik, J.A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D.Yi, and W. Emery, 2007: A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss, *Geophys. Res. Lett.*, 34, L24501, doi: 10.1029/2007GL032043.
- Meier, W. M. 2005. Comparison of passive microwave ice concentration algorithm retrievals with AVHRR imagery in Arctic peripheral seas. *IEEE Transactions in Geoscience and Remote Sensing* 43(6): 1324-1337, doi:10.1109/TGRS.2005.846151.
- Meier, W. N., and J. Stroeve, 2008. Comparison of sea ice extent and ice edge location estimates from passive microwave and enhanced-resolution scatterometer data. *Annals of Glaciology* 48(1): 65-70, doi:10.3189/172756408784700743.
- NRC, 2003: National Research Council of the National Academies. Understanding climate change feedbacks. Washington D.C., National Academies Press, 2003, 152 p.
- Overland, J. and M. Wang, 2010. Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. *Tellus*, 62A, 1-9.
- Perovich, D., R. Kwok, W. Meier, S. Nghiem, J. Richter-Menge, 2009: Arctic Report Card, Update for 2009. Sea-Ice Cover. October 19, 2009
- Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor, 2007: Climate Models and Their Evaluation. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA.
- Rayner, N., et al. 2003: Global Analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *JGR*, 108(D14), doi: 10.1029/2002JD002670.
- Rothrock, D.A., Yu, Y. and Maykut, G.A., 1999: Thinning of the Arctic sea ice cover. *Geophys. Res. Lett.* 26: 3469-3472.
- Serreze, M.C. and C. M. Hurst, 2000: Representation of Mean Arctic Precipitation in NCEP–NCAR and ERA Reanalyses, *J. Climate*, 13, pp. 182-201.
- Sorteberg, A., V. Kattsov, J.E. Walsh, T.Pavlova, 2007: The Arctic Surface Energy Budget as Simulated with the IPCC AR4 AOGCMs. *Climate Dynamics*, doi:10.1007/s00382-006-0222-9
- Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline: Faster than forecast. *Geophys. Res. Lett.*, 34, L09501, doi:10.1029/2007GL029703.
- Tsukernik, M., C. Deser, M. Alexander, R. Tomas, 2009: Atmospheric forcing of Fram Strait sea ice export: a closer look. – *Climate Dynamics*, doi: 10.1007/s00382-009-0647-z.
- Vavrus, S., D. Waliser, A. Schweiger, and J. Francis. 2009: Simulations of 20th and 21st century Arctic clouds in the global climate models assessed in the IPCC AR4. *Climate Dynamics*, 33, 1099-1115.
- Walsh, J.E., W. L. Chapman, D. H. Portis. 2009: Arctic Cloud Fraction and Radiative Fluxes in Atmospheric Reanalyses. – *J. Climate*, 22, 2316–2334.
- Wang M., Overland J.E., Kattsov V., Walsh J.E., Zhang X., Pavlova T., 2007: Intrinsic versus forced variation in coupled climate model simulations over the Arctic during the 20th Century. *J. Climate*, 20, 1084-1098.
- Wang, M., and J. E. Overland, 2009: A sea ice free summer Arctic within 30 years? *Geophys. Res. Lett.*, 36, L07502, doi:10.1029/2009GL037820
- Zhang, J., M. Steele, R. Lindsay, A. Schweiger, J. Morison, 2008: Ensemble 1-Year predictions of Arctic sea ice for the spring and summer of 2008, *Geophys. Res. Lett.*, 35, L08502, doi:10.1029/2008GL033244
- Zhang, X., and J.E. Walsh, 2006: Toward a seasonally ice-covered Arctic Ocean: scenarios from the IPCC AR4 model simulations. *J. Climate*, 19, 1730-1747.