When will the Summer Arctic be Nearly Sea Ice Free?

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Abstract

The observed rapid loss of thick, multi-year sea ice over the last seven years and September 2012 Arctic sea ice extent reduction of 49 % relative to the 1979-2000 climatology are inconsistent with projections of a nearly sea ice free summer Arctic from model estimates of 2070 and beyond made just a few years ago. Three recent approaches to predictions in the scientific literature are: 1) extrapolation of sea ice volume data, 2) assuming several more rapid loss events such as 2007 and 2012, and 3) climate model projections. Time horizons for a nearly sea ice free summer for these three approaches are roughly 2020 or earlier, 2030± 10 yrs, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. It is not possible to clearly choose one approach over another as this depends on the relative weights given to data versus models. Observations and citations support the conclusion that most Global Climate Models results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two.

1. Introduction

The large observed shifts in the current Arctic environment represent major indicators of regional and global climate change. Whether a nearly sea ice free Arctic occurs in the first or second half of the 21st century is of great economic, social, and wildlife management interest. There is a gap in understanding however, in how to reconcile what is currently happening with sea ice in the Arctic and climate model projections of Arctic sea ice loss. September 2012 showed a reduction in sea ice extent of 49 % relative to the 1979-2000 baseline of 7.0 M km^2 (Figure 1 and 2a). Further, the extent of thick multiyear sea ice has been reduced by the same percentage (roughly a reduction from 4 M km^2 for 2000 through 2005 to 2 M km^2 in 2012; Kwok and Untersteiner, 2011-updated, Comiso 2012). It is difficult to reconcile this current rate of loss with climate model projection dates of summer sea ice loss of 2070 (IPCC 2007) or 2100 (Boe et al. 2009a) made just a few years ago.

The question, however, is not as straight forward as simply comparing data timeseries with model results. Global Climate Models (GCMs) are often run several times, referred to as ensemble members, with slightly different initial conditions to simulate a possible range of natural variability in addition to steady increasing greenhouse gas forcing. Data, in contrast, is a single realization of a range of possible climate states. Observations confound signal (global warming forcing) and noise (natural variability). Thus it is not completely valid to compare the ensemble mean of a model or several models, which could be considered the expected value of the climate state, with the single data realization. A better approach is to look at the range of ensemble members and to determine if the data timeseries could be considered a possible member of the population of ensemble members. Unfortunately, there are seldom enough ensemble members to test this hypothesis. The science question becomes: is the observed rapid loss of sea ice in the real world consistent with model ensemble members with the fastest rate of loss? Multiple Groups (AMAP, WCRP, various national programs), as well as the climate research community and the general public, are interested in this question for adaptation planning and as a popular indicator of climate change.

When will the summer Arctic be nearly sea ice free? A first issue is the phrase, “nearly.” It is expected that some sea ice will remain as a refuge north of the Canadian Archipelago and Greenland at the end of summer. Thus the practical limit for sea ice loss is arbitrary, but several sources have converged on 1.0 M km^2 as a minimum transition point. There are three scientific approaches to the posed question in the scientific literature. The first is based on extrapolation of sea ice volume data. The second considers that it will take several more rapid loss events such as the losses in 2007 and 2012 to reach the minimum. The third approach is to base predictions on fast track model ensemble member projections. We refer to the three approaches as, *trendsetters, stochasters,* and *modelers.* Time horizons for summer sea ice loss of these three approaches turns out to be roughly 2020, 2030, and 2040, as discussed below. At present it is not possible to completely choose one approach over another, as it depends on the weight given to data, understanding of Arctic change processes, and the use and purpose of model projections. The next sections address these three approaches.

2. *Trendsetters*

Two groups are most active in this approach which extrapolates sea ice volume (Schweiger et al. 2011, Maslowski 2012). Their main points are that sea ice volume is decreasing at a rate that is faster than sea ice extent, and that volume is a better variable than extent to use for sea ice loss. Schweiger and Zhang’s group uses the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS), which assimilates sea ice concentration and sea surface temperature and hindcasts using NCEP Reanalyses into a high resolution sea ice model. PIOMAS results have recently been confirmed by satellite ice thickness measurements (Laxon et al. 2013). PIOMAS monthly averaged ice volume for September 2012 was 3,400 km^3 (Figure 2b). This value is 72% lower than the mean over 1979-2012 and 2.0 standard deviations below the 1979-2012 trend line. September 2012 ice volume was about 800 km^3 less than the prior minimum in September 2011. In contrast to the dramatic reduction in 2012 sea ice extent, the 2011 to 2012 change in sea ice volume was similar to the volume losses that occurred in the previous two years. The long term trend is about -3.1×10^3 km^3 $decade^{-1}$. While the PIOMAS team does not directly extrapolate, the already major volume loss of 70-80 % and recent losses suggest that extrapolation into the future from the current volume amount shows that Arctic sea ice is vulnerable within the next decade.

Monthly mean Arctic sea ice volumes from the NAME model and recent satellite estimates show sea ice volume changed little during the 1980s through the mid-1990s (Maslowski et al. 2012). After 1995 one can estimate a negative trend of -1.1×10^3 km^3 yr^{-1} from combined model and most recent observational estimates for October–November 1996–2007. Given this estimated trend and the volume estimate for October–November of 2007 at less than 9,000 km^3, one can project a nearly ice-free summer Arctic Ocean before 2020 (Maslowski et al. 2012).

3. Stochasters

In the recent half decade young, melt-prone sea ice has come to dominate the Arctic sea ice pack which supports the arguments of the *trendsetters*. However, the paper of Kay et al. (2011) suggests that there can be a modifying influence from natural variability especially for the timing of sea ice loss. They show a widening of the distribution of possible ten and twenty year trends in sea ice extent in the Community Climate System Model 4.0 (CCSM4) model due to increased vulnerability of sea ice to large meteorological or oceanic events. Kay et al. (2011, their Figure 3) show that over a future 20 year period, sea ice loss can vary over a range of 0-80 %. Both

CCSM3 and CCSM4 models show rapid ice loss events with different timing in different ensemble members (Holland et al 2006, Vavrus et al. 2012). The key argument of the *Stochasters* is that it will take several rapid loss events such as occurred in 2007 and 2012 to reach the 1.0 M km^2 sea ice extent threshold. If we select the 5 yr interval that occurred between the 2007 and 2012 sea ice loss events as an expected value, then three more events puts a nearly sea ice free timing at 2028. Serreze (2011) states that we should be looking at sea ice-free summers only a few decades from now.

Holland et al. (2006) and Wang and Overland (2009, 2012) show a large range of timing of sea ice loss for different ensemble members of the same GCM. Based on a subset of available GCMs, Wang and Overland (2012) estimated the time for a nearly sea ice free summer Arctic to be reached starting from a value of 4.5 M km^2 (the observed 2007 value) ranged from 14 years to 36 years with a median of 28 years based on individual ensemble members, which puts the loss event in the 2030s with a large range. Given that most sea ice trends in models are slower than observed trends for 1979-2011 (Stroeve, et al. 2012, their Figure 3, see next section), we should select a value at the earlier end of this range, i.e. 2030± 10 yrs.

Stochasters are further supported by recent papers that suggest that there is no tipping point associated with sea ice loss, again based on modeling studies (Amstrup et al. 2010, Armour et al. 2011, Ridley et al. 2011). Tietsche et al. (2011) suggest that anomalous loss of Arctic sea ice during a single summer is reversible, as the ice–albedo feedback is alleviated by large-scale recovery mechanisms. That is, continued sea ice loss requires continued increases in green house gases. However, consensus is not universal, as adequately representing cloud feedbacks in GCMs may be placing too much faith in them (Lenton 2012).

Thus it is suggested that the *stochasters* would require 20 years or more after 2007 or around 2030 with a wide range of uncertainty to have several rapid ice loss events occur and to reach nearly sea ice free conditions. While not unreasonable, *stochasters* is the most *ad hoc* of the three approaches.

4. Modelers

GCMs are major quantitative tools available to provide future climate projections based on physical laws that control the dynamic and thermodynamic processes of the atmosphere, ocean, land and sea ice. Recently, modeling groups around the world have improved their GCMs and made their results available to the wider scientific community through the archive at the Program for Climate Model Diagnosis and Intercomparison (PCMDI). This constitutes the fifth phase of the Coupled Model Intercomparison Project (CMIP5) following the successful third phase (CMIP3). Typically, results from more than twenty models are available. All models show loss of sea ice as greenhouse gas concentrations increase and that Arctic warms faster than lower latitudes. Multiple models simulations are particularly useful in assessing uncertainty due to differences in model structure, natural variability, and different greenhouse gas emission scenarios (Hodson et al. 2012).

A first major difficulty is the wide spread of model hindcast results; they vary by model, location, variable and evaluation metric (Figure 3, Overland et al. 2011, Kwok 2011). Figure 3 is based on the high greenhouse gas emission RCP8.5 scenario (Moss et al. 2010). A second major difficulty is that 80 % of 56 CMIP5 ensemble members have trends for 1979-2011 that are of less magnitude than the two standard deviation bound for the observations (Stroeve et al. 2012, their Figure 3). Thus, there is no ideal all purpose model for the Arctic. It is difficult to pin down the reasons for these two difficulties (Walsh et al. 2008). For example DeWeaver et al. (2008) , Eisenman et al. (2008), Hodson et al. (2012) and Holland et al. (2012) note that the Arctic radiation budget results from complex balances and tradeoffs between sea ice amounts, albedo parameterization, and cloud properties. Another issue is that real world Arctic conditions (sea ice, snow cover) are evolving substantially faster than ensemble means of models (Stroeve et al. 2012, Dirksen et al. 2012). The time series of the grand mean of CMIP5 ensemble members based on the high greenhouse gas emission RCP8.5 scenario for September sea ice (yellow line in Figure 3) never reaches the nearly sea ice free definition of 1.0 M km^2 by 2100. Winton (2011) shows that climate models underestimate the sensitivity of Arctic sea ice cover to global temperature change. Further, Boe et al. (2009b) conclude that GCMs' Arctic response to anthropogenic forcing is generally too small. Thus there is ground to consider that models provide a range of projections based on their individual assumptions, rather than providing a collective definitive Arctic climate prediction.

Pavlova et al. (2011) note that the multi-model ensemble mean is closer to the data curve for the late 20th and early 21st centuries for CMIP5 relative to CMIP3 results. However the spread of hindcasts and future trajectories remains large in CMIP5 models (Figure 3, also see Figure 1 in Massonnet et al. 2012). Boe et al. (2010), Hodson et al. (2012) and Massonnet et al. (2012), among others, note that the rate of sea ice loss in models depends on the amount of sea ice present. Thus there is concern with projections from models that do not simulate the amount of observed sea ice near the end of the 20th century.

There are four major evaluations of sea ice projections in the set of CMIP5 GCMs: Pavlova et al. (2011), Stroeve et al. (2012), Wang and Overland (2012), and Massonnet et al. (2012), and one detailed review for the CCSM4 model (Vavrus et al 2012) and the EC-Earth model (Koenigk et al 2012). The median value for each year of all available CMIP5 ensemble members (blue line in Figure 3) reaches the nearly sea ice free condition near 2060 based on a nearly sea ice free definition of 1.0 M km^2. But given the large observed rate of sea ice loss, we are primarily interested in those model ensemble members with the most rapid sea ice loss. The ensemble members of seven models which track closely to recent observed sea ice extents (Wang and Overland 2012) had their earliest nearly sea ice free dates occurring in 2027, 2033, 2035, 2045, 2048, 2049, and 2060, with a mean of 2042. Some individual ensemble members in Figure 3 reach the nearly sea ice free threshold at earlier dates, but many of these ensemble members start with unrealistic low sea ice extents for the late 20th century. Several of the ensemble members of CCSM4 reach the sea ice loss threshold near 2060; this was ten years later than their previous model CCSM3.The EC-Earth model also becomes nearly sea ice free near 2060, but the authors suggest shifting this to 2040 based on the model's overestimate of the amount of sea ice in the twentieth century. Thus we put the early limit for sea ice loss based on GCM projections near 2040

This paper should not be used as an argument against further modeling, but quite the opposite. The Arctic community needs credible quantitative climate projections with multiple ensemble members. As noted above, the spread in Figure 3 is not only due to sea ice physics but is related to treatment of clouds, radiation, and atmospheric and ocean dynamics. For the next round of model results, CMIP6, the major goal should be reduction of model uncertainty. Perhaps more model intercomparisons would be a way forward, rather than results provided from a large number of modeling centers produced under short time schedules.

5. Discussion and conclusions

We have investigated three approaches to predicting 21st century summer Arctic sea ice loss as represented by *trendsetters, stochasters,* and *modelers.* At present it is not possible to completely choose one approach over another, as all approaches have strengths and weaknesses. Models are quantitative, based on physical understanding, and can provide estimates of uncertainty. They all predict an eventual sea ice free Arctic based on increases in greenhouse gas forcing. *Modelers'* projections for a nearly sea ice free Arctic summer, are mostly in the range of 2030-2060 or later, with a composite of earliest removals near 2040. Yet it is not clear that the observed rapid sea ice loss is represented in the range of model GCM results. Extrapolating current sea ice volume trends seems to capture the influence of the recent rapid loss of multi-year sea ice, yet it will be hard to remove the last sea ice near the North Pole; in 2007 removal of this sea ice required a strong atmospheric and sea ice advection event (Zhang et al. 2008).

Direct extrapolation of sea ice volume, by *trendsetters,* gives loss projections of 2016 (Maslowski et al 2012, Peter Wadhams 2012, personal communication), which may be minimizing the potential effects of year to year variability. *Stochasters* acknowledge current conditions and the range of projections suggested by model results, yet point to the lack of being able to forecast the next rapid sea ice loss event. They are saved in part as it will possibly take several such events to reach the nearly sea ice free threshold, thus adding some averaging to the final date prediction (hence stochastic). Observations and citations in this article support the conclusion that current rapid Arctic change, especially loss of multiyear sea ice, is likely out of sample for most CMIP5 models. Thus time horizons for summer sea ice loss of these three approaches turns out to be roughly 2020, 2030, and 2040 respectively for *trendsetters, stochasters, and modelers.* Predictions depend on the weight given to data, understanding of Arctic change processes, and the use of model projections. It is reasonable to conclude Arctic sea ice loss is very likely to occur in the first rather than the second half of the 21st Century, with a possibility of loss within a decade or two.

The title of this paper is certainly one of the major questions of interest to Arctic and non-Arctic science and management communities. Large shifts in the Arctic environment represent major observed indicators of global climate change. Available evidence suggests that scientists have been conservative in their climate projections, with a late bias in dates for change (Brysse et al. 2012). Ignoring the rate of observed loss of multi-year Arctic sea ice in favor of multi-model results primarily from GCMs may be a further example. The possibility of a nearly sea ice free Arctic within the next three decades, in addition to the precautionary principle, supports the Duarte et al. (2012) conclusion that society should start managing for the reality of climate change in the Arctic.

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References

Amstrup, S. C., E. T. DeWeaver, D. C. Douglas, B. G. Marcot, G. M. Durner, C. M. Bitz, and D. A. Bailey (2010), Greenhouse gas mitigation can reduce sea ice loss and increase polar bear persistence, *Nature.* 468, 955-958.

Armour, K. C., I. Eisenman, E. Blanchard-Wrigglesworth, K. E. McCusker, and C. M. Bitz (2011), The reversibility of sea ice loss in a state-of-the-art climate model, *Geophys. Res. Lett.*, 38, L16705, doi:10.1029/2011GL048739.

Boé, J., A. Hall, and X. Qu (2009a), September sea-ice cover in the Arctic Ocean projected to vanish by 2100, *Nat. Geosci*., 2, 341–343, doi:10.1038/ngeo467.

Boé, J., A. Hall, and X. Qu (2009b), Current GCMs' unrealistic negative feedback in the Arctic, *J. Climate*, 22, 4682-4695.

Boé, J., A. Hall, and X. Qu (2010), Sources of spread in simulations of Arctic sea ice loss over the twenty-first century, *Climatic Change*, 99, 637-645.

Brysse, K., N. Oreskes, J. O'Reilly, and M Oppenheimer (2012), Climate change prediction: Erring on the side of least drama, *Global Environmental Change*, http://dx.doi.org/10.1016/j.gloenvcha.2012.10.008, in press.

Comiso, J. (2012), Large decadal decline of the Arctic multiyear ice cover*, J. Climate*, 25, 1176–1193, doi:10.1175/JCLI-D-11-00113.1.

Derksen, C. and R. Brown (2012), Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections, *Geophys. Res. Lett.*, 39, L19504, doi:10.1029/2012GL053387.

Duarte, C., T. Lenton, P. Wadhams and P. Wassmann (2012), Abrupt climate change in the Arctic. *Nature Climate Change*, 2, 60-62

Eisenman, I., N. Untersteiner, and J. S. Wettlaufer (2008), Reply to comment by E. T. DeWeaver et al. on "On the reliability of simulated Arctic sea ice in global climate models", *Geophys. Res. Lett.*, 35, L04502, doi:10.1029/2007GL032173.

Hodson, D., S. Keeley, A. West, J. Ridley, E. Hawkins and H. Hewit (2012), Identifying uncertainties in Arctic climate change projections, *Climate Dynamics*, DOI: 10.1007/s00382-012-1512-z.

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.

Holland, M.M., D.A. Bailey, B.P. Briegleb, B. Light, and E. Hunke (2012), Improved sea ice shortwave radiation physics in CCSM4: The impact of melt ponds and black carbon, *J. Climate*, 25,1413-1430. doi:10.1175/JCLI-D-11-00078.1

IPCC (2007), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Kay, J. E., M. M. Holland, and A. Jahn (2011), Inter-annual to multidecadal Arctic sea ice extent trends in a warming world*, Geophys. Res. Lett.*, 38, L15708, doi:10.1029/2011GL048008.

Koenigk, T., L. Brodeau, R. G. Graversen, J. Karlsson, G. Svensson, M. Tjernström, U. Willén, and K. Wyser (2012), Arctic climate change in 21st century CMIP5 simulations with EC-Earth. *Climate Dynamics*, DOI:10.1007/s00382-012-1505-y.

Kwok, R. (2011), Observational assessments of Arctic Ocean sea ice motion, export, and thickness in CMIP3 climate simulations, *J. Geophys. Res*., doi:10.1029/2011JC007004.

Kwok, R., and N. Untersteiner (2011), The thinning of Arctic sea ice, *Phys. Today*, 64, 36–41, doi:10.1063/1.3580491.

Laxon, S. W., and coauthors (2013), CryoSat-2 estimates of Arctic sea ice thickness and volume, *Geophys. Res. Lett.,* DOI: 10.1002/grl.50193.

Lenton, T. (2012), Arctic climate tipping points, *Ambio,* 41, 10-22.

Massonnet, F., T. Fichefet, H. Goosse, C.Bitz, G. Philippon-Berthier, M. Holland, and P.-Y. Barriat (2012), Constraining projections of summer Arctic sea ice*, The Cryosphere Discuss*., 6, 2931-2959, doi:10.5194/tcd-6-2931-2012.

Maslowski, W., J.C. Kinney, M. Higgins,and A. Roberts (2012), The Future of Arctic Sea Ice *Annual Review of Earth and Planetary Sciences*, 40, 625 -654.

Moss, R. H., et al. (2010), The next generation of scenarios for climate change research and assessment, *Nature*, 463, 747–756, doi:10.1038/nature08823.

Overland, J. E., M. Wang, N. A. Bond, J. E. Walsh, V. M. Kattsov, and W. L. Chapman (2011), Considerations in the selection of global climate models for regional climate projections: The Arctic as a case study*, J. Climate*, 24, 1583–1597, doi:10.1175/2010JCLI3462.1.

Pavlova, T. V., V. M. Kattsov, and V. F. Govorkova (2011), Sea ice in CMIP5 models: Closer to reality?, *Tr. GGO*, 564, 7–18.

Ridley, J., J. Lowe, and H Hewitt (2011), How reversible is sea ice loss? *The Cryosphere Discuss.* 5, 2349-2363.

Serreze, M. (2011), Rethinking the sea-ice tipping point, *Nature,* 471, 47-48.

Stroeve, J., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W. N. Meier (2012), Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations, *Geophys. Res. Lett.,* doi:10.1029/2012GL052676.

Schweiger, A., R. Lindsay, J. Zhang, M. Steele, H. Stern, and R. Kwok (2011), Uncertainty in modeled Arctic sea ice volume, *J. Geophys. Res*., 116, C00D06, doi:10.1029/2011JC007084.

Tietsche, S., D. Notz, J. H. Jungclaus, and J. Marotzke (2011), Recovery mechanisms of Arctic summer sea ice, *Geophys. Res. Lett.*, 38, L02707, doi:10.1029/2010GL045698.

Vavrus, S. J., M. Holland, A. Jahn, D. Bailey, and B. Blazey (2012), Twenty-First-Century Arctic Climate Change in CCSM4, *J. Climate*, **25**, 2696–2710.

Walsh, J.E., W.L. Chapman, V.E. Romanovsky, J.H. Christensen, M. Stendel (2008), Global climate model performance over Alaska and Greenland, *J. Climate*. 21, 6156-6174.

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.

Wang, M., and J.E. Overland (2012), A sea ice free summer Arctic within 30 years-an update from CMIP5 models. *Geophys. Res. Lett*., 39, L18501, doi: 10.1029/2012GL052868.

Winton, M. (2011), Do climate models underestimate the sensitivity of Northern Hemisphere sea ice cover? *J. Climate*, 24, doi:10.1175/2011JCLI4146.1.

Zhang, J., R. Lindsay, M. Steele, and A. Schweiger (2008), What drove the dramatic retreat of arctic sea ice during summer 2007?, *Geophys. Res. Lett.*, 35, L11505, doi:10.1029/2008GL034005.

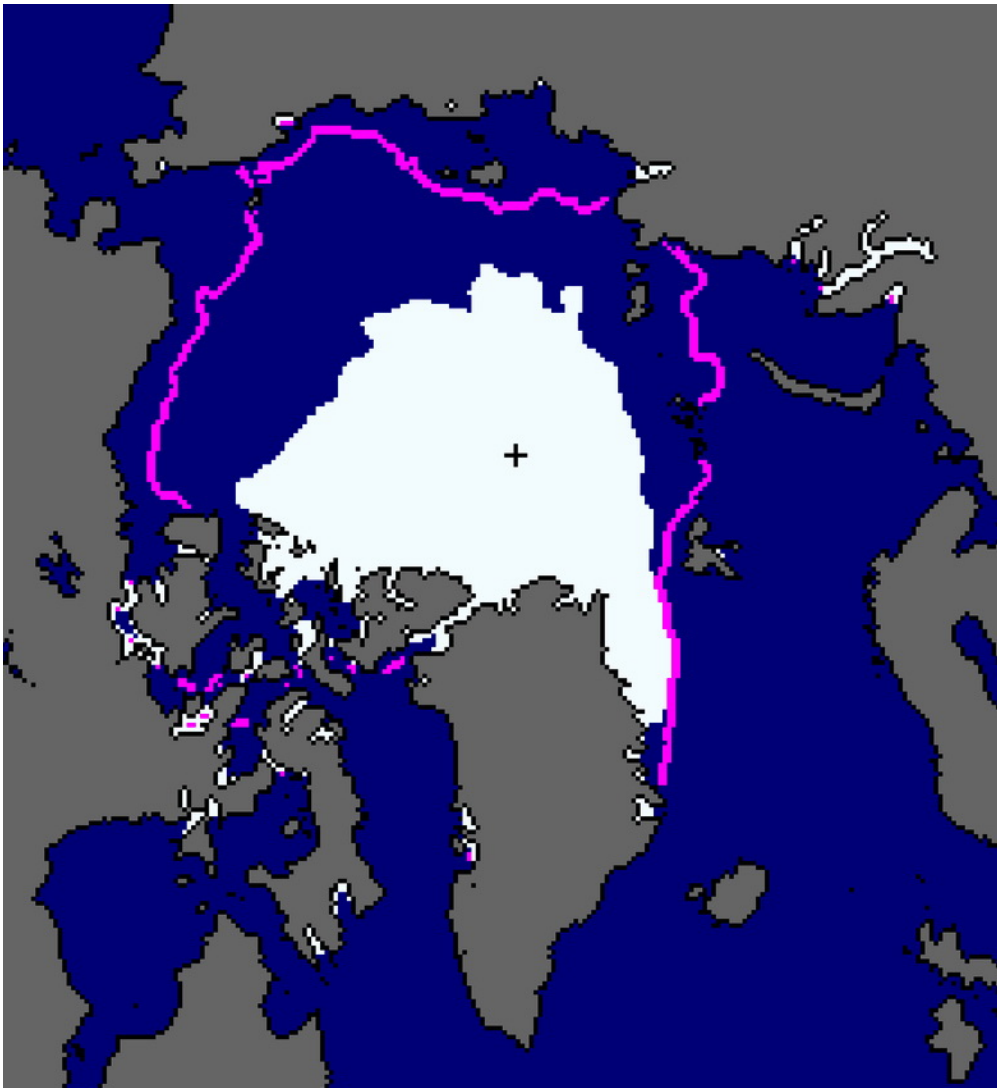

Figure 1. Arctic sea ice extent for September 2012 (white areas) at 3.6 M km^2. The magenta line indicates the median climatology for 1979-2011. September 2012 represents a 49 % decline. The black cross is the geographic North Pole. Credit: National Snow and Ice Data Center.

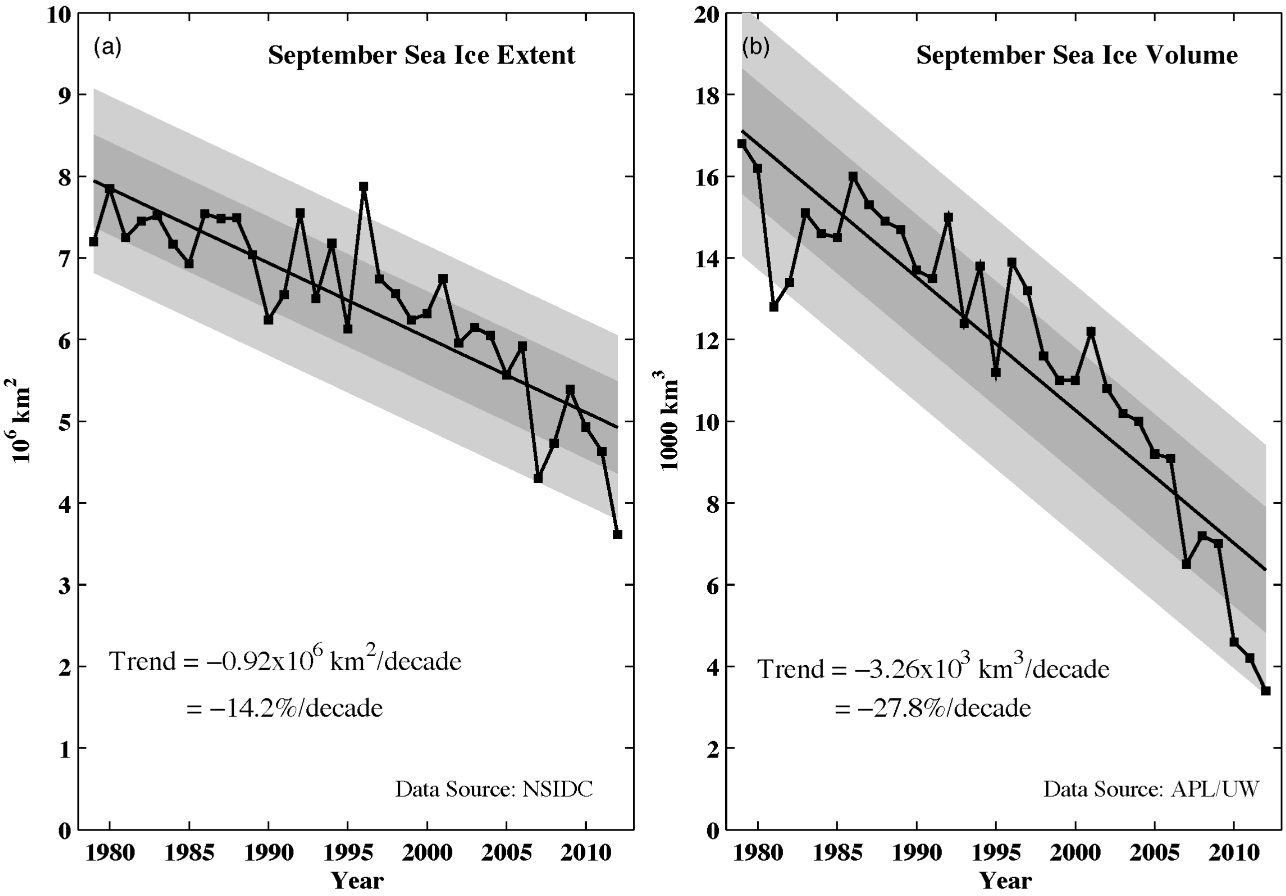

Figure 2. Time series of September Arctic (a) sea ice extent from NSIDC, and (b) sea ice volume as computed from PIOMAS of APL/UW. The trend line for 1979-2012 is shown in solid black with shaded areas showing a one and two standard deviation from the trend. Units are in M km^2 for (a), and 1000 km^3 for (b). When expressed in terms of percentage of change, the declining trend in the sea ice volume is larger than the sea ice extent. http://psc.apl.washington.edu/wordpress/research/projects/arctic-sea-ice-volume-anomaly/

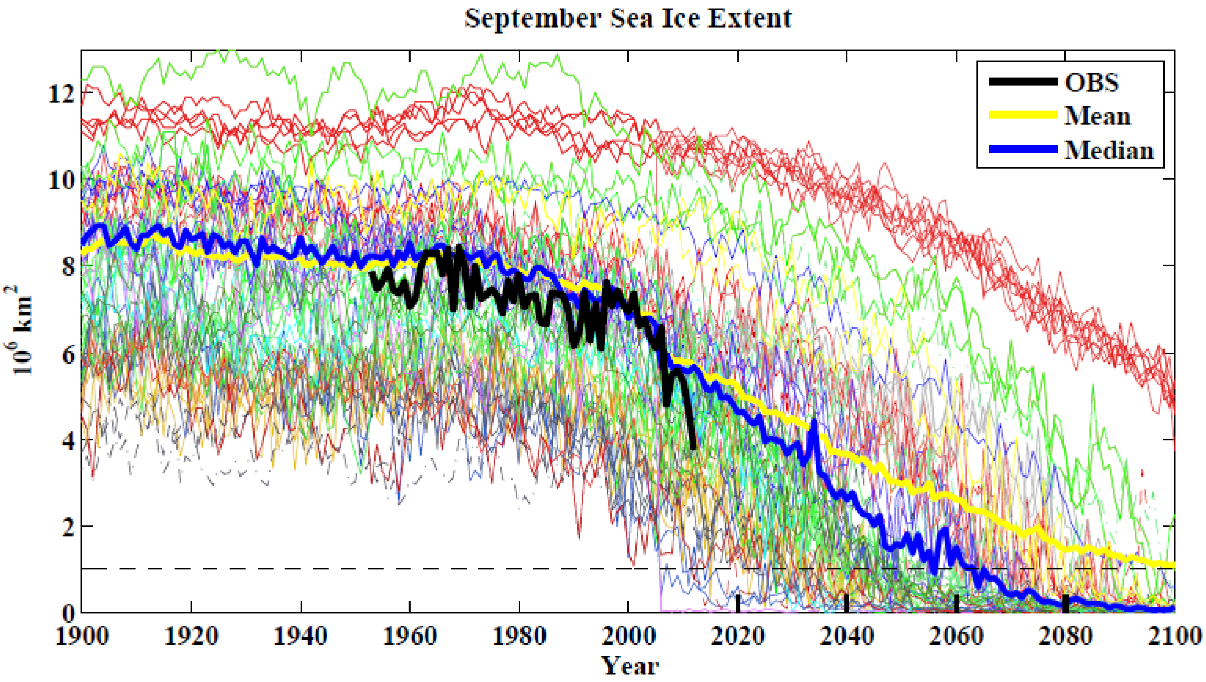

Figure 3. September sea ice extent based on 89 ensemble members from 36 CMIP5 models under the RCP8.5 (high) emissions scenario. Each thin colored line represents one ensemble member from the model. The thick yellow line is the arithmetic mean of all ensemble members and the blue line is their median value. The thick black line represents observations based on adjusted HadleyISST_ice analysis for the period 1953-1978, and NSIDC from 1979-2012. Observation data were provided by Meier, NSIDC. The horizontal black dashed line marks the 1.0 M km^2 value, which indicates nearly sea ice free summer Arctic.