ATMOSPHERIC AND OCEANIC SCIENCE LETTERS, 2008, VOL. 1, NO. 1, 51–56

Decreasing Arctic Sea Ice Mirrors Increasing CO_2 on Decadal Time Scale

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Received 24 June 2008; revised 23 July 2008; accepted 23 July 2008; published 16 November 2008

Abstract Arctic sea ice is a keystone indicator of greenhouse-gas induced global climate change, which is expected to be amplified in the Arctic. Here we directly compare observed variations in arctic sea-ice extent and CO_2 since the beginning of the 20th century, identifying a strengthening linkage, such that in recent decades the rate of sea-ice decrease mirrors the increase in CO_2, with $r \sim -0.95$ over the last four decades, thereby indicating that 90% ($r^2 \sim 0.90$) of the decreasing sea-ice extent is empirically "accounted for" by the increasing CO_2 in the atmosphere. The author presents an empirical relation between annual sea-ice extent and global atmospheric CO_2 concentrations, in which sea-ice reductions are linearly, inversely proportional to the magnitude of increase of CO_2 over the last few decades. This approximates sea-ice changes during the most recent four decades, with a proportionality constant of 0.030 million km^2 per ppmv CO_2. When applied to future emission scenarios of the Intergovernmental Panel on Climate Change (IPCC), this relationship results in substantially faster ice decreases up to 2050 than predicted by IPCC models. However, departures from this projection may arise from non-linear feedback effects and/or temporary natural variations on interannual timescales, such as the record minimum of sea-ice extent observed in September 2007.

Keywords: CO_2 increase, ice decrease, ice projection to 2050

Citation: Johannessen, O. M., 2008: Decreasing arctic sea ice mirrors increasing CO_2 on decadal time scale, *Atmos. and Oceanic Sci. Lett.*, **1**, 51–56.

1 Introduction

Sea-ice extent (i.e., area enclosed within the ice-ocean margin) is a widely used and well-constrained metric for summarizing the state of the climate system. During the nearly three decades of satellite measurements, consensus estimates of annual and summer sea-ice decreases for the Arctic are about 3%–4% and 7%–9% per decade, respectively (Johannessen et al., 1999 and 2004; Comiso, 2002; Comiso et al., 2008; Serreze et al., 2007; Stroeve et al., 2007). Furthermore the CO_2 has increased by about 30% while the annual ice extent has decreased by about 18% since 1900 (Fig. 1a). This implies that the increasing CO_2 and other greenhouse gas (GHG) forcing may play a major role in diminishing the sea ice cover, a hypothesis qualitatively supported by multi-model comparisons of sea-ice response to increasing GHGs (Johannessen et al., 2004; IPCC, 2007; Serreze et al., 2007; Stroeve et al., 2007). However the question remains how to quantify the degree to which sea ice is related to CO_2 forcing versus natural variability.

It is well known that natural variability on seasonal, interannual and decadal timescales plays a significant role in changes in the ice cover. For example, during the early 20th-century warming event, Russian observations of annual sea-ice extent covering 77% of the Arctic region showed a reduction of 0.6×10^6 km^2 from 1915–35, concurrent with an increase of 2.3ºC in surface air temperature (SAT) in the latitude band 70–90ºN during the same period (Fig. 5 in Johannessen et al., 2004). This early warming event was most likely caused by the natural multidecadal fluctuations arising from the Atlantic Ocean (Zhang et al., 2007), including stronger westerlies and advection of warmer water into the Barents Sea, thereby reducing the ice extent and causing increased heat flux into the atmosphere as a positive feedback process (Bengtsson et al., 2004).

A more recent but opposite event was the large increase of 1.4×10^6 km^2 in sea-ice extent occurring during the summer of 1996, probably caused by an extreme temporary reversal of the North Atlantic Oscillation (NAO) in the winter of 1995/96, which lowered the SAT, thereby freezing more sea ice (Fig. 3 in Johannessen et al., 2004).

In the most recent years (2000–07) record lows in the September sea-ice extent minima have been observed (e.g., Serreze et al., 2003; Johannessen et al., 2004; Rigor et al., 2004; Stroeve et al., 2005, 2006 and 2008; Maslanik et al., 2007; Meier et al., 2007; Comiso et al., 2008). The record thus far was observed in mid September 2007, with an abnormal decrease in the western and central sector of the Arctic Ocean resulting in a minimum sea-ice extent of 4.1×10^6 km^2, or 24% lower than the previous record low of 5.4×10^6 km^2 reached in September 2005 and about 37% lower than the September 1979–2007 satellite climatological average (Comiso et al., 2008). Comiso et al. (2008) also concluded that "satellite surface temperature data indicate that the growth of sea ice was likely hindered and the retreat likely enhanced by anomalously high temperature in previous months, especially in February and April 2007. Southerly winds, which advect warm air from lower latitudes, were prevalent during the summer, and this is also likely to have en-

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hanced the ice retreat, through northward transport of the sea ice, lessened ice growth and increased melt”, while Stroeve et al. (2008) also pointed to other factors such as the thinning ice pack and unusually clear skies during the summer months of 2007.

A reasonable interpretation of the record low sea-ice extent in September 2007 is that it is probably another example of a natural variability, however caused by a mechanism other than the Atlantic-driven warming event between 1915–35 and the NAO event in 1996—both described above. The record low in September 2007 can possibly be explained by the Overland and Wang (2005) mechanism that “internal processes in the western Arctic may have a larger role in shaping the present persistence of the Arctic change than has been previously recognized during recent years when the Arctic Oscillation (AO) has been near-neutral.” One should also note that after the minimum ice extent in September 2007, the ice extent rebounded rapidly to a winter maximum in March 2008 that was actually higher than in the previous four years[1].

Therefore we can reasonably expect similar, strong natural variability events in the future, causing both decreases and increases of the arctic sea-ice cover on seasonal to decadal time scales, superposed on the general trend of a decreasing ice cover projected by IPCC models (IPCC, 2007).

Sea-ice variability is complex, dependent on both dynamic and thermodynamic factors—e.g., SAT, downwelling radiation, albedo effects, ocean heat flux and atmospheric heat transport (Rothrock et al., 1999; Comiso et al., 2008)—which are enforced through both radiative and advective processes in both the atmosphere (e.g., Stroeve et al., 2008) and ocean (e.g., Steele et al., 2008). The complexity of these factors, linkages and feedbacks—which moreover span across a range of time scales—confounds attribution of the observed changes in sea ice. Even advanced, state-of-the-art, numerical models struggle to accurately represent the natural spatial and temporal variability in sea ice (IPCC, 2007; Stroeve et al., 2007), let alone its GHG response and feedback processes. The acknowledged mismatch between models and observations is underlain by two different error sources: 1) Response of sea ice to anthropogenic increases in GHGs, and 2) Natural variability of sea ice, e.g., related to the NAO/AO/Northern Annular Mode (NAM) and other atmospheric-ocean circulation patterns (e.g., Overland and Wang, 2005; Maslanik et al., 2007; Serreze et al., 2007; Stroeve et al., 2007, 2008; Comiso et al., 2008) including the aforementioned Atlantic-driven multidecadal fluctuations (Bengtsson et al., 2004; Zhang et al., 2007). Another reason for the more rapid decrease of the summer ice than the coupled models predict could be the change of the albedo due to increasing soot on the snow and ice (Flanner et al., 2007; McConnell et al., 2007).

For these reasons, the challenge remains to (1) Estimate how much of the observed sea-ice losses are effecttively caused by CO_2 increases, and (2) Develop a simple alternative to the complex physics-based models which underestimate the sea-ice response to observed CO_2 increases (Stroeve et al., 2007). Therefore, here we put forth a straightforward approach of directly comparing CO_2 and sea-ice extent in order to estimate the empirical relationship, thereby providing an integrated generalization of the effective CO_2 signal for arctic sea ice, and a pragmatic alternative to estimate the sea-ice response to future increases in CO_2. The latter is analogous to the Rahmstorf approach to projecting changes in sea level through the 21st century (Rahmstorf, 2007a), and not merely an extrapolation of observed sea-ice trends (e.g., Comiso, 2002; Meier et al., 2007).

2 Empirical relationship between carbon dioxide and sea ice

2.1 Estimating the bivariate relationship

Here, we develop an empirical relationship that quantifies changes in annual sea-ice extent with atmospheric CO_2 concentrations as the driver. Physically, such a simple relationship using an indirect driver is justified in that atmospheric CO_2 and other GHGs affect air temperature, ocean temperature, cloudiness, and atmospheric and ocean circulation—each of which may impact the sea-ice cover through complex processes and feedbacks that moreover have varying seasonal-dependencies and are beyond comprehensive modeling capabilities. Therefore, we directly compare annual observational data of CO_2 (ppmv) and ice extent (15% concentration) through the 20th and early 21st centuries, enabling us to quantify the degree to which the sea-ice decrease may reflect CO_2 increases. In section 3, we use this relationship to project sea-ice extent to 2050 under two different IPCC emissions scenarios, and compare our results with an ensemble of 15 IPCC models (IPCC, 2007).

Annual values for CO_2 concentration (IPCC, 2007) and sea-ice extent since 1900 are compared in Fig. 1a. For the period 1900–78, we have used the annual values of sea-ice extent from the Walsh and Chapman “Northern Hemisphere Sea Ice Data Set” retrieved directly from their webpage[2].We have merged this with sea-ice extent data from satellite passive-microwave data[3] using the NORSEX algorithm (Svendsen et al., 1983) updated through 2007 after Johannessen et al. (2004). The NORSEX retrievals were adjusted by 0.33×10^6 km^2 based on an overlap period from 1979–83 with the Walsh and Chapman data, in order to have consistent time series. Furthermore, Walsh and Chapman note on their website that “the pre 1953 data is either climatology or interpolation data and the users are cautioned to use this with care”. We have followed this advice and base our analysis primarily on data after 1953. However in order to see if there was a general link between the CO_2 and ice extent, we plotted the data for the 1900–2007 period in Fig. 1a.

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[1] http://www.nersc.no/~knutal/NORSEX_current.html

[2] http://arctic.atmos.uiuc.edu/SEAICE

[3] http://nsidc.org

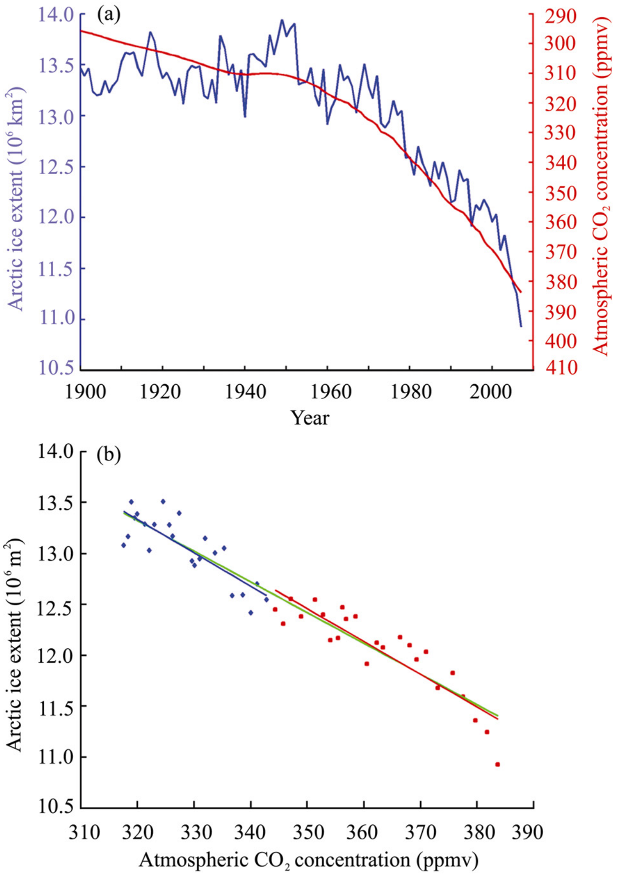

Figure 1 Arctic sea-ice extent and CO_2 (a) Time series of annual arctic sea-ice extent and atmospheric concentrations of CO_2 for the period 1900–2007. The sea-ice extent observations are from the Walsh and Chapman dataset 1900–78, merged with sea-ice concentration retrieved from satellite passive-microwave data (1979–2007) using the NORSEX algorithm, with ice extent updated to 2007, after Johannessen et al. (2004). Note that the CO_2 scale is inverted. (b) Scatterplot and regression lines indicate the correlation of CO_2 and sea-ice extent for the periods 1961–85 (blue) and 1986–2007 (red). The regression line (green) for 1961–2007 is sea-ice extent = –0.030 $\times CO_2 + 22.97$, $r^2 \sim 0.90$.

Sea-ice variability on interannual to decadal time scales is inherently greater than for the CO_2 variability (Fig. 1a). As mentioned before, some of the sea-ice variations before 1953 are probably not accurate. Nevertheless, common for sea ice and CO_2 are a gradual decrease and increase, respectively, which to a large extent mirror each other, particularly in the last few decades. However it is clearly evident (Fig. 1a) that the decreasing summer minima have lowered the annual means of the ice extent more rapidly for the last three years compared with previous years. To identify how this correlation varied through the period starting from 1954, we computed the running correlation using a 30-year embedding window according to meteorological standard period. From the 30-year period starting from 1961, the correlation varied between –0.85 to –0.95 with a nearly constant slope of –0.03 for the regression line. This indicates that the correlation and slope are robust during this period. We therefore also computed the correlation and regression for the whole period from 1961 through 2007 with the following results: The change in sea-ice extent (10^6 km^2) per unit CO_2 (ppmv) is –0.030 CO_2, with a correlation r = –0.95 and r^2 = 0.90, which can be interpreted that approximately 90% of the decreasing sea-ice extent may be "accounted for" by the increasing atmospheric CO_2 concentration over the last four decades.

However it should also be mentioned that the increasing CO_2 is a major driver for the observed increase in global mean SAT (IPCC, 2007) enhanced in the Arctic region (e.g., Johannessen et al., 2004; Bengtsson et al., 2004; Kuzmina et al., 2008), which again is one of the major physical variables that melts ice. Correlation analysis between the annual mean zonal SAT from 70° to the North Pole (Kuzmina et al., 2008) and the annual values for the ice extent for the same period (1961–2007) resulted in a correlation of r = –0.80, r^2 = 0.64, implying that about 60% of the ice decrease could be accounted for by SAT alone. This can be interpreted that the SAT is one of the major physical variables that directly influences the melt and the decreasing ice extent.

Because CO_2 and SAT are not independent variables—the correlation between them for the 1961–2007 period is r = 0.76—both of them cannot meaningfully be used simultaneously as predictors in a multiple-regression analysis for the decreasing ice extent (predictand). Therefore the higher correlation, r = –0.95, between ice extent and CO_2, which also integrates other processes in addition to the SAT, is used here for further study.

2.2 Significance of the relationship

For the case of two time series consisting mainly of a constant trend plus superimposed variability in only one (sea-ice extent) series, but not the other (CO_2), it is challenging to assess correlation in the purely statistical sense. Here, the estimated correlations are significant ($p < 0.01$), not adjusted for the inherent autocorrelation in CO_2 and sea ice. There are different points-of-view on autocorrelation and its effect on the significance of the cross-correlation (e.g., Rahmstorf, 2007a, b; Schmith et al., 2007). Whether an analysis with trend or after removal of a trend is more meaningful depends on the purpose of the analysis. In our case, the mirroring trends of CO_2 and arctic sea ice are the most striking aspect of the data—indeed the basic idea stems from these features, Fig. 1a. Here, our goal is an empirical projection based on fitted relationships, comparable to the temperature and sea-level relationship developed and applied by Rahmstorf (2007a)—therefore, the form and slope of the relationship are of primary interest rather than classical hypothesis testing.

Nonetheless, we further tested this relationship by splitting our time series (1961–2007) in two parts, in order to see how well the results from the first half fit the second half. In Fig. 1b we have plotted the first half of the data (blue line, blue points) and the second half of the data (red line, red points), together with the regression line (green) for the whole period. The correlation for the first half of the data (blue) was –0.85 with a slope of –0.033 while the correlation for the second half (red) was –0.90 with a slope of –0.033. This implies that result from the first half of the time series can "reproduce" the second half of the time series and furthermore that the relationship is robust.

As mentioned above, the green regression line in Fig. 1b is for the whole period (1961–2007) with a correlation of –0.95 and a slope of –0.030. However we again note that the annual means of sea ice extent for the last three years, in particular for 2007, fall below the regression line (green), indicating a temporary natural fluctuation (described in the Introduction) or that non-linear effects have started to act.

2.3 Expanding on the relationship

In order to explore the remainder of the variance not accounted for by CO_2, we investigated the possible effect of natural variability forcing on the sea-ice extent described in the introduction. We investigated the effect of the predominant modes of atmospheric variability in the northern high latitudes, namely the NAO and AO, which are the modes most frequently invoked in studies distinguishing natural versus anthropogenically-forced sea-ice variability and trends (e.g., Serreze et al., 2007), although the Pacific North American Pattern (PNA) plays an important role in warming southern Alaska and western Canada (Turner et al., 2007). The NAO winter index has been shown to be imprinted regionally on sea-ice variability on seasonal to interannual time scales (Deser et al., 2000; Rigor et al., 2004). However, in our analysis the annual NAO and AO indices are found to have insignificant power for predicting annual arctic sea-ice extent during the 1961–2007 period, where r varied between ±0.4 using the 30-year embedding window from 1961. Therefore, the variance in the annual sea-ice extent unexplained by CO_2 may be accounted for by a stochastic component and/or natural climate-system variability on longer time scales, e.g., multidecadal variability arising from the Atlantic Ocean (Zhang et al., 2007) such as that expressed as the Atlantic Multidecadal Oscillation (Kerr, 2005), whose impact on sea ice is plausible but strong observational evidence is lacking.

It should also be mentioned that a similar relationship between CO_2 and ice extent does not yet exists for the Antarctica in contrast to the CO_2 driven decrease of the sea ice extent in the hindcast simulation for Antarctica for the last century (IPCC, 2007). Actually the ice extent increases slightly with 0.47% per decade in the 1978–2006 period which is not statistically significant (IPCC, 2007) while the SAT exhibit a moderate increase south of 65°S, when compared to the enhanced increase north of 65°N (IPCC, 2007; Turner et al., 2007) including also a warming of the southern ocean (Gille, 2002). This apparent paradox has been interpreted to be caused by a suppression of ocean convective overturning, leading to a decrease in the upward ocean heat transport to melt the ice (Zhang, 2007), causing a delay of the global warming effect on the ice extent in Antarctica.

To summarize section 2, we find that external forcing from CO_2 dominates the annual sea-ice response, especially in recent decades, during which the curves for sea-ice extent and CO_2 mirror each other. In the four most recent decades, CO_2 is found to account for approximately 90% of the annual decreases in sea-ice extent ($r \sim -0.95$, $r^2 \sim 0.90$).

3 CO_2-ice relationship applied for projecting sea ice

The linear form and slope of this relationship can be used to project annual sea-ice extent to 2050, using statistics based on a period of comparable length, i.e., the previous 47 years (1961–2007). We assume that this linear relationship is a reasonable and conservative first approximation, which however excludes possible non-linear effects in future. Here we compare our empirical projection with 15 IPCC AR4 models. We consider a range of two 21st-century CO_2 emission scenarios of the IPCC (2007): A2 and B1, corresponding to CO_2 concentrations in 2050 ranging from 475 ppmv (B1) to 520 ppmv (A2), given the 1990 base-level of 350 ppmv. For each scenario, we have made projection based on linear relationships estimated for the 1961–2007 period, when the rate of change in sea-ice extent (10^6 km^2) per unit CO_2 (ppmv) is –0.030 CO_2. The sea-ice projection from our empirical relationship and those from 15 IPCC models for B1 and A2 are summarized in Fig. 2. Note that the model ensemble mean from the IPCC models underestimates its recent downward trend from 1970.

For the B1 emission scenario, our projected annual sea-ice extent is expected to decline to ~8.4×10^6 km^2 in 2050, vis-à-vis the IPCC 15-model ensemble mean of ~11.7×10^6 km^2. For the A2 scenario, our model projects a

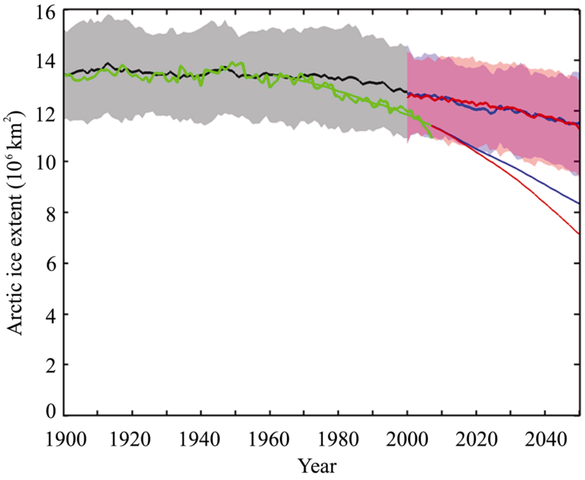

Figure 2 Arctic sea ice in the 20th and 21st centuries. Annual sea-ice extent 1900–2007 (observed—green, and IPCC modeled mean ensemble—black) and predictions for 2007–50 under projected CO_2 scenarios of the IPCC. The ensemble mean of 15 IPCC numerical-model experiments are thick lines: B1—blue; A2—red. Shading indicates ±1 s.d. uncertainty. Projections based on empirical relationship are thin lines, B1—blue; A2—red. The projections are based on a linear regression of CO_2 and sea-ice extent data from 1961–2007. The empirical projection does not include natural fluctuations that would be superposed on the trends, as seen in the observations (green).

decrease to ~7.0×10^6 km^2, in comparison to the IPCC ensemble mean of ~11.7×10^6 km^2, which is the same as the B1 scenario. For both scenarios, our projections for sea-ice extent in 2050 are several million km^2 lower than the IPCC ensemble mean. This possibility needs to be kept in mind when assessing the impact of future climate change and its associated risks.

The linear approximation developed and applied here is of course a simplistic first-order conservative approximation to a number of complex processes with different time scales. Nevertheless, this approach—similar to that used to project sea-level rise (Rahmstorf, 2007a)—may provide a pragmatic alternative to the spread range of complex numerical models that may substantially underestimate the sea-ice response to GHG forcing (Stroeve et al., 2007). Moreover, as years pass, this empirical relationship can be readily updated for projecting annual ice extent including more realistic future CO_2 scenarios, with minimal computer resources required. It is emphasized that this empirical method give no information of natural variability on interannual time scale.

There are however some caveats, in that these projections assume that the linear relationship between sea-ice extent and CO_2 identified here is robust and that other, non-linear factors do not influence the trajectories. Statistical projection or extrapolation (e.g., Comiso, 2002) is inherently uncertain, particularly when conditions may be rapidly changing as seems apparent for the arctic summer sea ice (e.g., Comiso et al., 2008; Stroeve et al., 2008). For example, non-linearity in the sea-ice response to CO_2 forcing or natural variability is plausible, such that passing a critical "tipping point" for sea ice (Lindsay and Zhang, 2005) may lead to abrupt reductions without a commensurate change in external forcing (e.g., Holland et al., 2006). As a case in point, the extreme record low minimum in sea-ice extent observed in September 2007 may represent crossing such a threshold towards a new state. On the other hand, it may well be merely a temporary excursion due to a conjunction of anomalous conditions (Kerr, 2007; Comiso et al., 2008; Stroeve et al., 2008). By the end of July 2008 our calculation of the ice extent by using NORSEX algorithm (Svendsen et al., 1983) on the online passive microwave data[1] was 7.5 million km^2—about 1 million km^2 higher than at the end of July 2007[2]. This probably indicates that the September 2008 will not be a new minimum ice extent year—only time will tell.

Acknowledgments. This work has been supported by the Mohn-Sverdrup Center for Global Ocean Studies and Operational Oceanography at the Nansen Center and the Research Council of Norway, and is a contribution to the International Polar Year—Climate of the Arctic and its Role for Europe (IPY-CARE) project, headed by the author. Thanks are to Ingo Bethke, Cathrine Myrmehl, Elena Shalina, Svetlana Kuzmina, Tor I. Olaussen and Natalia Ivanova for carrying out the calculations and preparing the figures, and Martin Miles and Klaus Hasselmann for consultation. Also thanks to one of the reviewer who raised the Antarctic issue.

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[1] http://nsidc. org

[2] http://arctic-roos.org

References

Bengtsson L., V. A. Semenov, and O. M. Johannessen, 2004: The early twentieth-century warming in the arctic–a possible mechanism, *J. Climate*, **17**, 4045–4057.

Comiso, J. C., 2002: A rapidly declining perennial sea ice cover in the Arctic, *Geophys. Res. Lett.*, **29**, 1956, doi:10.1029/2002GL015650.

Comiso, J. C., C. L. Parkinson, R. Gersten, et al., 2008: Accelerated decline in the Arctic sea ice cover, *Geophys. Res. Lett.*, **35**, L01703, doi:10.1029/2007GL031972.

Deser, C. A., J. E. Walsh, and M. S. Timlin, 2000: Arctic sea ice variability in the context of recent atmospheric circulation trends, *J. Climate*, **13**, 617–633.

Flanner, M. G., C. S. Zender, J. T. Randerson, et al., 2007: Present-day climate forcing and response from black carbon in snow, *J. Geophys. Res.*, **112**, D11202, doi:10.1029/2006JD008003.

Gille, S. T., 2002: Warming of the Southern Ocean since 1950s, *Science*, **295**, 1275–1277.

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.

Intergovernmental Panel on Climate Change (IPCC), 2007: The physical science basis. *Working Group I Contribution to the Fourth Assessment Report of the IPCC.* Cambridge University Press, Cambridge, UK.

Johannessen, O. M., E. V. Shalina, and M. W. Miles, 1999: Satellite evidence for an arctic sea ice cover in transformation, *Science*, **286**, 1937–1939.

Johannessen, O. M., L. Bengtsson, M. W. Miles, et al., 2004: Arctic climate change-observed and modelled temperature and sea ice, *Tellus*, **56**(A), 328–341.

Kerr, R. A., 2005: Atlantic climate pacemaker for millennia past, decades hence? *Science*, **309**, 41–42.

Kerr, R. A., 2007: Is battered arctic sea ice down for the count? *Science*, **309**, 33–34.

Kuzmina, S., O. M. Johannessen, L. Bengtsson, et al.,2008: High northern latitude surface air temperature: Comparison of existing data and creation of a new gridded dataset 1900-2000, *Tellus,* **60**(A), 289–304.

Lindsay, R. W., and J. Zhang, 2005: The thinning of Arctic sea ice, 1988-2003: Have we passed a tipping point? *J. Climate*, **18**, 4879–4894.

Maslanik, J., S. Drobot, C. Fowler, et al., 2007: On the Arctic climate paradox and the continuing role of atmospheric circulation in affecting sea ice conditions, *Geophys. Res. Lett.*, **34**, L03711, doi:10.1029/2006GL028269.

McConnell, J. R., R. Edwards, G. L. Kok, et al., 2007: 20th-century industrial black carbon emissions altered arctic climate forcing, *Science*, **317**, 1381–1384.

Meier, W., J. C. Stroeve, and F. Fetterer, 2007: Whither arctic sea ice?: A clear signal regionally, seasonally, and extending beyond the satellite record, *Ann. Glac.*, **46**, 428–434.

Overland, J. E., and M. Wang, 2005: The Arctic climate paradox: The recent decrease of the Arctic Oscillation, *Geophys. Res. Lett.*, **32**, L06701, doi:10.1029/2004GL021752.

Rahmstorf, S., 2007a: Semi-empirical approach to projecting future sea-level rise, *Science*, **315**, 368–370.

Rahmstorf, S., 2007b: Response to comments on "Semi-empirical approach to projecting future sea-level rise", *Science*, **317**, 1866d.

Rigor, I. G., J. M. Wallace, and R. L. Colony, 2004: Response of sea ice to the Arctic oscillation, *J. Climate*, **15**, 2648–2663.

Rothrock, D. A., Y. Yu, and G. A. Maykut, 1999: Thinning of the arctic sea-ice cover, *Geophys. Res. Lett.*, **26**, 3469–3472.

Schmith, T., S. Johansen, and P. Thejll, 2007: Comment on "Semi-empirical approach to projecting future sea-level rise", *Science*, **317**, 1866c.

Serreze, M. C., J. A. Maslanik, T. A. Scambos, et al., 2003: A record minimum arctic sea ice extent and area in 2002, *Geophys. Res. Lett.*, **30**, L1110, doi:10.1029/2002GL016406.

Serreze, M. C., M. M. Holland, and J. C. Stroeve, 2007: Perspectives on the Arctic's shrinking sea-ice cover, *Science*, **315**, 1533–1536.

Steele, M., W. Ermold, and J. Zhang, 2008: Arctic Ocean surface warming trends over the past 100 years, *Geophys. Res. Lett.*, **35**, L02614, doi:10.1029/2007GL031651.

Stroeve, J. C., M. C. Serreze, F. Fetterer, et al., 2005: Tracking the Arctic's shrinking ice cover: another extreme September minimum in 2004, *Geophys. Res. Lett.*, **32**, L04501, doi:10.1029/2004GL021810.

Stroeve, J., T. Markus, W. N. Meier, et al., 2006: Recent changes in the Arctic melt season, *Ann. Glaciol.*, **44**, 367–374.

Stroeve, J. C., M. M. Holland, W. Meier, et al., 2007: Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, **34**, L090501, doi:10.1029/2007GL029703.

Stroeve J., M. Serreze, S. Drobot, et al., 2008: Arctic sea ice extent plummets in 2007, *Eos, Trans. Amer. Geophys. Union*, **89**(2), 13–20.

Svendsen, E., K. Kloster, B. Farrelly, et al., 1983: Norwegian Remote Sensing Experiment: Evaluation of the Nimbus-7 Scanning Multichannel Microwave Radiometer for Sea Ice Research, *Journal of Geophysical Research*, **88**(C5), 2781–2791.

Turner, J., J. E. Overland, and J. E. Walsh, 2007: An Arctic and Antarctic perspective on recent climate change, *Int. J. Climatol*., **27**, 277–293.

Zhang, J., 2007: Increasing Antarctic sea ice under warming atmospheric and oceanic conditions, *J. Climate*, **20**, 2515–2529, doi:10.1175/JCLI136.1.

Zhang, R., T. L. Delworth, and I. M. Held, 2007: Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature? *Geophys. Res. Lett*., **34**, L02709, doi:10.1029/2006GL028683.