Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections

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[1] Analysis of Northern Hemisphere spring terrestrial snow cover extent (SCE) from the NOAA snow chart Climate Data Record (CDR) for the April to June period (when snow cover is mainly located over the Arctic) has revealed statistically significant reductions in May and June SCE. Successive records for the lowest June SCE have been set each year for Eurasia since 2008, and in 3 of the past 5 years for North America. The rate of loss of June snow cover extent between 1979 and 2011 (-17.8% decade^{-1}) is greater than the loss of September sea ice extent (-10.6% decade^{-1}) over the same period. Analysis of Coupled Model Intercomparison Project Phase 5 (CMIP5) model output shows the marked reductions in June SCE observed since 2005 fall below the zone of model consensus defined by +/−1 standard deviation from the multi-model ensemble mean. **Citation:** 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.

1. Introduction

[2] Reliable information is needed on ongoing and future changes in terrestrial snow cover for a wide range of geophysical applications, to advise policy and decision makers, and inform impact and adaptation activities. Of particular importance is the timing of snow melt in spring, due to the climatological, hydrological, and ecosystem impacts of this seasonal transition of the land surface [*Callaghan et al.*, 2011]. Contemporary variability and trends in Arctic snow cover are occurring in the context of amplified increases in observed high latitude temperature relative to other regions [*Serreze et al.*, 2009] with climate model scenarios showing this warming is expected to continue [*Vavrus et al.*, 2012].

[3] Monitoring Arctic snow cover is complicated by a lack of surface observations, and the high degree of spatial variability relative to other snow covered regions [*Liston*, 2004] due to pronounced topographic and vegetative controls on wind-induced snow catchment and redistribution. In turn, this heterogeneity introduces uncertainty into gridded snow datasets, including satellite-derived time series [i.e., *Takala et al.*, 2011], conventional analyses [i.e., *Brasnett*, 1999], and reanalysis products [i.e., *Dee et al.*, 2011]. While this creates distinct challenges to the determination of trends in Arctic snow depth or snow water equivalent, analysis of multiple datasets has shown that we now have a good understanding of the uncertainty in snow cover extent (SCE) time series across the Arctic, particularly in spring [*Brown et al.*, 2010]. The longest available satellite-derived time series of SCE are the weekly NOAA snow charts produced from manual analysis of primarily optical satellite imagery [*Robinson et al.*, 1993]. This dataset is widely used within the climate community and has been subject to detailed evaluation in the spring period [e.g., *Wang et al.*, 2005; *Brown et al.*, 2007, 2010; *Frei and Lee*, 2010].

[4] Here we utilize the NOAA snow chart time series (1967–2012) to (1) report the latest trends in snow cover during the spring period when snow cover is confined largely to the Arctic, and temperature induced albedo feedbacks are strongest across high latitudes [*Groisman et al.*, 1994; *Déry and Brown*, 2007] and (2) place these trends in the context of recent CMIP5 climate model simulations.

2. Data Sets

[5] We focus on the recently released NOAA snow chart climate data record (CDR) [see *Brown and Robinson*, 2011] maintained and housed at the Rutgers University Global Snow Lab. The dataset was acquired (from http://climate.rutgers.edu/snowcover/) following the update of continental monthly SCE through June 2012. The CDR combines the original 190 km resolution NOAA snow charts (1967–1999) [*Robinson et al.*, 1993] with the 24 km resolution Interactive Multi-Sensor (IMS) snow product (1999-present) described in *Ramsay* [1998] and updated by *Helfrich et al.* [2007]. Production of the CDR resulted in minor modifications to the IMS product, primarily by increasing the snow extent in mountainous areas. The NOAA snow chart data record has been found to agree well with other independent SCE datasets during the Arctic spring melt period [*Brown et al.*, 2010].

[6] Northern Hemisphere spring terrestrial snow cover extent (SCE) anomalies (excluding Greenland) for April, May, and June (when snow cover is confined largely to the Arctic) were calculated for the 1967–2012 period to investigate trends and variability during the satellite era. July and August were not considered because the exceptionally small SCE values during these months make the time series very sensitive to small departures from the mean. Separate snow cover series were generated for North American and Eurasian land areas due to potentially unique relationships with low frequency atmospheric circulation during spring, including the Arctic Oscillation [*Tedesco et al.*, 2009].

[7] Trends in terrestrial snow cover were compared to trends in summer minimum sea ice extent over the period

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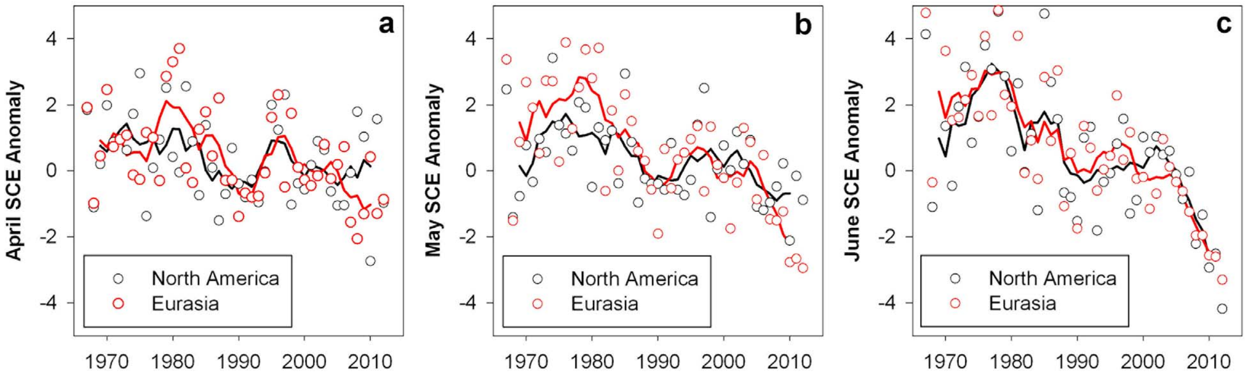

Figure 1. Snow cover extent (SCE) anomaly time series (with respect to 1988–2007) from the NOAA snow chart CDR for (a) April, (b) May, and (c) June. Solid line denotes 5-yr running mean.

since 1979, the latter representing a key indicator of recent change in the Arctic cryosphere [*Stroeve et al.*, 2007]. The time series of mean September (i.e. minimum) sea ice extent from 1979–2011 was produced from two satellite passive microwave datasets: a historical dataset covering 1979–2010 [*Cavalieri et al.*, 1996] updated for 2011 with ice extent estimates produced from real time data [*Maslanik and Stroeve*, 1999]. All ice extent estimates were produced with the NASA Team algorithm [*Cavalieri et al.*, 1997], but the near real time data used for 2011 received a lower level of quality control than the historical data. This combined sea ice extent time series is maintained at the National Snow and Ice Data Center (http://nsidc.org/data/seaice_index/archives/). Temperature change information for Arctic land areas (north of 60°) was obtained from the University of East Anglia Climatic Research Unit (CRU) CRUtem3v data set [*Brohan et al.*, 2006] gridded (5° × 5°) surface air temperature dataset (http://www.cru.uea.ac.uk/cru/data/temperature/).

[8] Standardized anomalies for monthly SCE and air temperature were calculated for 1967 through 2012 using a 1988 to 2007 reference period. These reference years were selected because they cover median continental-scale snow conditions preceded by more extensive snow cover during the 1970's early 1980's, and less extensive snow cover observed in recent years [*Brown and Robinson*, 2011].

[9] Trends in continentally averaged SCE and surface temperature during spring were calculated using the Mann-Kendall (MK) statistic derived from the time series following the removal of serial correlation based on the method described in *Zhang et al.* [2000]. A significance level of 0.05 was applied to determine statistical significance.

3. Results

3.1. SCE Trends

[10] The SCE anomaly series (Figure 1) all show evidence of decreases over the NOAA satellite record, which are statistically significant in May and June, the primary months of snow line retreat across the Arctic (Table 1). The increasingly negative trends as spring progresses are consistent with the poleward amplification of SCE sensitivity to warming air temperatures as described in *Déry and Brown* [2007]. A striking feature of the May and June series is the acceleration in snow cover loss evident since the early 2000's. Record low June SCE across Eurasia has occurred for the past 5 consecutive years, with a new record for North America set in 3 of the past 5 years. June 2012 marked record low SCE in both sectors of the Arctic. Record low May SCE also occurred over both continents in 2010, with a new record low May SCE established over Eurasia in 2012. The rate of snow cover loss over Northern Hemisphere land areas in June between 1979 and 2011 is −17.8% decade^{-1}. This is almost double the rate of September sea ice loss (from the combined datasets described in Section 2) over the same time period (−10.8% decade^{-1}) (Figure 2). When 2012 is included, the rate of June SCE loss is −21.5% decade^{-1}.

[11] Variability in spring SCE across high latitudes is strongly controlled by surface temperature anomalies [*Brown et al.*, 2007]. Trends in surface temperature during the Arctic spring (April, May, June) were calculated using the MK statistic, and show statistically significant warming during the satellite era (Table 1). Correlation of monthly SCE and air temperature anomalies shows this relationship peaks in June for North America, and May across Eurasia (Table 1). The relationship between SCE and air temperature anomalies in April is relatively weak because Arctic temperatures remain sufficiently below zero during this period, so increasing temperatures at this point in time have minimal impact on continental scale SCE. Correlation analysis of the SCE anomaly time series for both Arctic sectors with the primary modes of low-frequency atmospheric (NAO; AO) and oceanic (Nino3.4; PDO) circulation identified no statistically significant correlations at 95% (not shown), which agrees with the findings of *Brown et al.* [2010] that spring

Table 1. Linear Trends (1967–2012) in SCE (km^2 × 10^6 × decade^{-1}) Derived From the NOAA Snow Chart CDR, and Surface Temperature Averaged Over Land Areas North of 60°N, Derived From CRUtem3v (°C × decade^{-1})[a]

	SCE (km^2 × 10^6 × decade^{-1})		Temperature (°C × decade^{-1})		SCE vs Temp (r)	
Month	NA	EUR	NA	EUR	NA	EUR
April	−0.20	−0.38	***0.55***	***0.54***	−0.29	***−0.46***
May	**−0.22**	***−0.73***	***0.30***	***0.43***	**−0.31**	***−0.60***
June	***−0.41***	***−0.83***	***0.32***	***0.32***	***−0.59***	***−0.57***

[a]Correlation coefficient (r) of monthly SCE vs. surface temperature. Bold indicates significant values at 95%; bold italics indicate significant values at 99%.

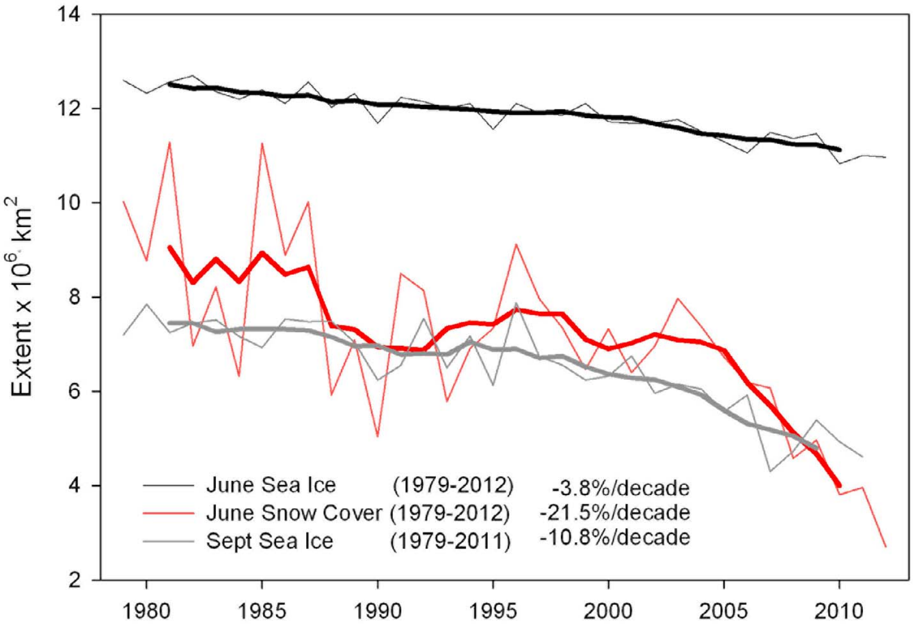

Figure 2. Time series of Northern Hemisphere June snow cover (NOAA snow chart CDR) and sea ice extent (NASA TEAM) for 1979–2012 (1979–2011 for sea ice). Thick line denotes 5-yr running mean.

SCE declines are being driven largely by pervasive warming pan-Arctic temperatures (as described in *Screen et al.* [2012]), independent of these low-frequency climate variables.

3.2. CMIP Simulations of Arctic Snow Cover

[12] Monthly snow cover fraction ('snc') output from 8 CMIP5 models (Table 2) were acquired from the CMIP5 data portal (http://cmip-pcmdi.llnl.gov/cmip5/index.html) to place the observed record low spring values in the context of projected changes following *Stroeve et al.* [2007, 2012] for summer sea ice extent. The 8 model subset represents available snc output when the CMIP5 archive was consulted in spring 2012 (some models were not included due to missing snc output). Output from the "Historical" experiment for 1850–2005 (takes into account observed climate forcing including anthropogenic and volcanic influences on atmospheric composition, solar forcing, aerosols, and land use change) were combined with output from the future "high emissions" representative concentration pathway scenario rcp8.5 [*Riahi et al.*, 2011] (2006 to 2100) to create a 150-year time series of model simulated and projected snow cover. One model run (typically the first member) was selected from each model and monthly normalized SCE series generated over NH land areas for the period 1900–2099. Snow covered area was normalized for each month by the maximum monthly area simulated by each model in the 1900–2099 period.

[13] Comparison of the NOAA CDR and CMIP5 SCE series for April, May and June (Figures 3a–3c) shows that the NOAA observations are mostly within ± 1 standard deviation of the multi-model ensemble in April, start to diverge from the model consensus in recent years in May, and diverge markedly from the model consensus in June since 2005. The uncertainty range in simulated SCE shown in Figures 3a–3c is actually a conservative underestimate because the CMIP5 simulations contain reduced interannual variability compared to observed SCE from the NOAA snow chart CDR (Figure 4). However, even when the inter-model range in June simulation

Table 2. CMIP5 Models Used to Examine Simulated and Projected Changes in Arctic Snow Cover Extent and Air Temperature

Acronym	Institution	Resolution (deg)
CanESM2	CCCma (Canadian Centre for Climate Modelling and Analysis, Canada)	2.81 × 2.81
CCSM4	NCAR (National Center for Atmospheric Research, USA)	0.93 × 1.25
CNRM-CM5	CNRM-CERFACS (Centre National de Recherches Meteorologiques/ Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, France)	1.40 × 1.40
GISS-E2-R	NASA-GISS (NASA-Goddard Institute for Space Studies, USA)	2.00 × 2.50
INMCM4	Institute for Numerical Mathematics, Russian Academy of Sciences, Russia	1.50 × 2.00
MIROC5	AORI (Atmosphere and Ocean Research Institute, The University of Tokyo, Japan), NIES (National Institute for Environmental Studies, Japan), and JAMSTEC (Japan Agency for Marine-Earth Science and Technology)	1.40 × 1.40
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	1.88 × 1.88
MRI-CGCM3	Meteorological Research Institute, Tsukuba, Japan	1.13 × 1.13

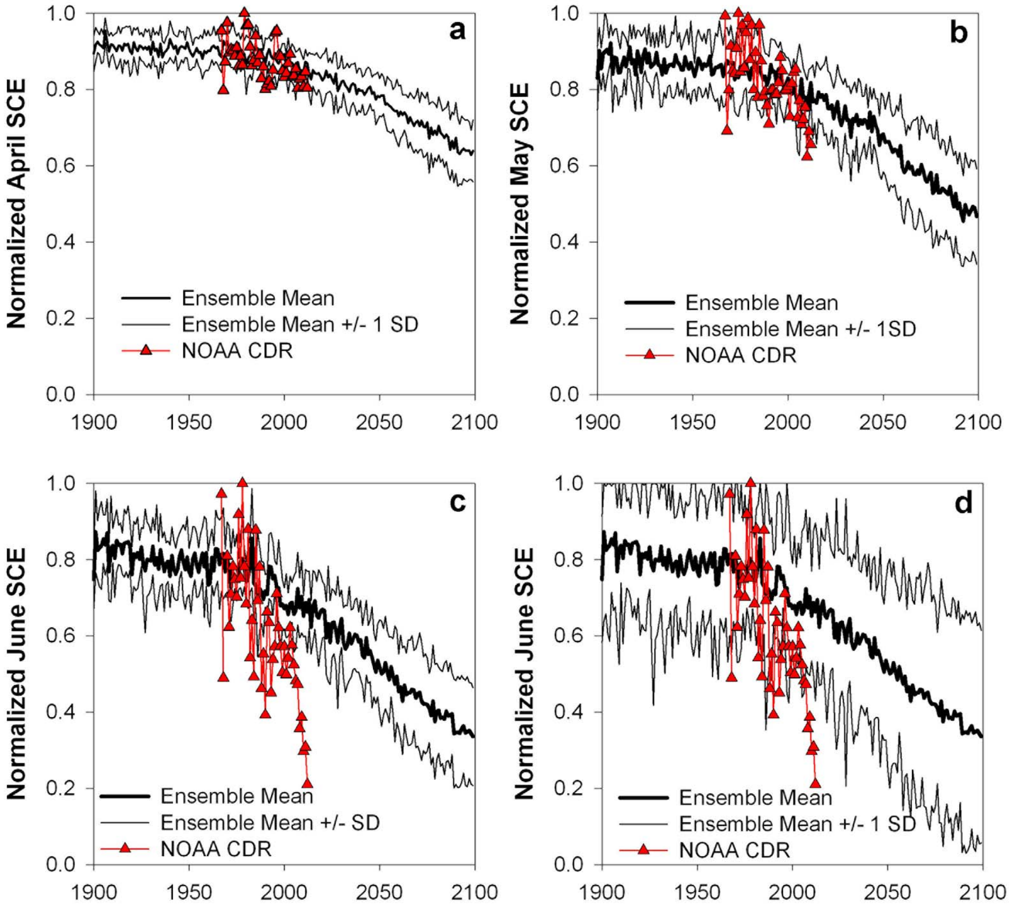

Figure 3. Simulated ("historical" experiment) and projected change (rcp85 scenario) in snow covered area in (a) April, (b) May (c) June over NH land areas. Snow covered area is normalized by the maximum area simulated by each model. Symbols show normalized values of SCE from the NOAA snow chart CDR. (d) June results with model variability increased by a factor of 2.18 to match the observed variability in SCE over the NOAA satellite record.

results are adjusted to match the observed interannual variability in SCE, the recent June values still diverge markedly from the model consensus since 2008 (Figure 3d).

4. Discussion and Conclusions

[14] There is increasing evidence of profound recent changes in terrestrial SCE in May and June. The five lowest June SCE values in the satellite era (since 1967) have all occurred over the past five seasons (2008–2012). Successive records for the lowest June SCE in the satellite era were set each year for Eurasia since 2008, and in 4 of the past 5 years for North America, and the rate of terrestrial snow extent loss in June between 1979 and 2011 (-17.8% decade^{-1}) is greater than the loss of September sea ice (-10.6% decade^{-1}) over the same period.

[15] The reductions in spring snow cover since 1967 reported in this study are consistent with observed rates of change in spring snow cover duration (SCD – number of days with snow depth >2 cm from February to July) over the Canadian Arctic derived from daily snow depth observations at 9 stations with consistent data over the 1972–2009 period (updated from *Brown and Braaten* [1998]). Both the station and NOAA anomaly series showed comparable significant (0.05 level) rates of change over the 1971–2008 period (-3.3 days decade^{-1} for NOAA and -2.8 days decade^{-1} for the stations). It was unfortunately not possible to evaluate NOAA SCE across Arctic Canada during the period after

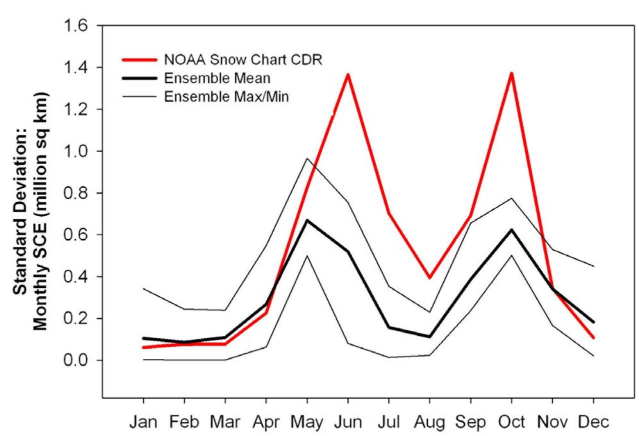

Figure 4. Standard deviation in monthly SCE from NOAA observations and CMIP5 model simulations.

2008 as there are now too few stations reporting snow depth observations. Other independent verification of the NOAA spring SCE trends can be found in surface snow depth observations from Russia, which show widespread decreases in snow cover duration over northern regions of European Russia over the period from 1966–2007 [*Bulygina et al.*, 2009], and passive microwave satellite data that show melt onset date advancing by an average 5.0 days decade^{-1} over the pan-Arctic region for the period 1979–2008 [*Tedesco et al.*, 2009]. A high resolution reanalysis-driven simulation of Arctic snow cover [*Liston and Hiemstra*, 2011] identified shorter pan-Arctic snow cover duration of -2.49 days decade^{-1} over the 1979–2009 period.

[16] It is important to characterize trends and variability in spring terrestrial snow cover for climatological, hydrological, and ecological applications. Previous studies have noted that the contribution from reductions in snow cover to an overall decline in cryospheric cooling is of the same magnitude as sea ice loss [*Flanner et al.*, 2011]. The observed reductions in spring snow cover extent and duration are consistent with phenological changes in Arctic vegetation [*Jia et al.*, 2009], and have been linked to observed changes in wildlife (for example *Drever et al.* [2011]). Early snow melt and subsequent warm temperatures in spring and summer also have a strong influence on ground temperatures, and can induce a thicker active layer [*Woo et al.*, 2007].

[17] The observed decreases in June SCE were found to diverge markedly from the rate of snow cover loss projected by CMIP5 climate model simulations since 2008 (historical + rcp8.5 simulations) even when the model uncertainty was adjusted upward to match the interannual variability in the observations. This conclusion is consistent with similar analysis applied to CMIP5 simulations of summer sea ice extent [*Stroeve et al.*, 2012]. When considered alongside the documented changes to the cryosphere including warming permafrost, reduction in summer sea ice extent, increased mass loss from glaciers, and thinning and break-up of the remaining Canadian ice shelves [*Derksen et al.*, 2012, and references therein] there is increasing evidence of an accelerating cryospheric response to global warming.

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