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Projected decline in spring snow depth on Arctic sea ice caused by progressively later autumn open ocean freeze-up this century

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[1] We present the first analysis of snow depth on Arctic sea ice in the Coupled Model Intercomparison Project 5 (CMIP5) because of its importance for sea ice thermodynamics and ringed seal (*Phoca hispida*) habitat. Snow depths in April on Arctic sea ice decrease over the 21st century in RCP2.6, RCP4.5, and RCP8.5 scenarios. The chief cause is loss of sea ice area in autumn and, to a lesser extent, winter. By the end of the 21st century in the RCP8.5 scenario, snowfall accumulation is delayed by about three months compared to the late 20th century in the multi-model mean. Mean April snow depth north of 70°N declines from about 28 cm to 16 cm. Precipitation increases as expected in a warmer climate, but much of this increase in the Arctic occurs as rainfall. The seasonality of snowfall rate grows, with increasing rates in winter and decreasing rates in summer and autumn, but the cumulative snowfall from September to April does not change. Ringed seals depend on spring snow cover on Arctic sea ice to create subnivean birth lairs. The area with snow depths above 20 cm — a threshold needed for ringed seals to build snow caves — declines by 70%. **Citation:** Hezel, P. J., X. Zhang, C. M. Bitz, B. P. Kelly, and F. Massonnet (2012), Projected decline in spring snow depth on Arctic sea ice caused by progressively later autumn open ocean freeze-up this century, *Geophys. Res. Lett.*, *39*, L17505, doi:10.1029/2012GL052794.

1. Introduction

[2] Despite its importance for physical and biological systems, little is known about current trends in snow depths on sea ice and how snow depths will respond to climate change in the future. It is expected that spring snow depths on sea ice are sensitive to changes in both the sea ice extent and the hydrologic cycle. Competing effects in a warmer climate could drive snow depths in either direction compared to today. It is unclear *a priori* which effect will dominate.

[3] In contrast, the retreat of Arctic sea ice is a well-studied problem. There is clear evidence of a decline in sea ice extent and thickness in the past few decades [e.g., *Kwok and Rothrock*, 2009; *Comiso and Nishio*, 2008], and climate models predict declines will continue at an equally rapid or, in some cases, an even faster pace through this century [e.g., *Arzel et al.*, 2006; *Zhang and Walsh*, 2006]. A change in snow depth is thought to be a factor in sea ice loss but also with competing effects. Snow accumulation on top of sea ice insulates the sea ice and reduces ocean heat loss to the atmosphere, leading to reduced sea ice growth rates. Reduced snow depth should therefore enhance sea ice growth rates. If this were the only consideration, a decrease in snow depth resulting from the loss of autumn and winter sea ice area would in turn slow the reduction of sea ice area into the future, a negative feedback described in more detail by *Notz* [2009]. At the same time, reduced snow depth would melt earlier in spring and more rapidly reveal bare sea ice with its lower surface albedo, a positive feedback which would tend to melt more sea ice.

[4] In a warmer climate the atmospheric moisture flux convergence into the Arctic is expected to increase from rising evaporation rates in lower latitudes. A higher moisture flux combined with greater moisture recycling should increase the precipitation rate, as found in recent observations and in climate models [*Kattsov et al.*, 2007; *Rawlins et al.*, 2010]. If this increase occurs when air temperatures are below freezing, snowfall rates should rise. The question remains whether the rise occurs seasonally when sea ice is present to capture it.

[5] Snow cover on sea ice in spring also provides critical habitat for ringed seals (*Phoca hispida*) to create subnivean birth lairs [e.g., *Smith and Stirling*, 1975; *Smith and Lydersen*, 1991]. To successfully rear young, ringed seals in the central Arctic need on-ice snow depths in April of at least 50 cm in which to form subnivean lairs. Such depths are found in snow drifts next to ridges at times when depths on level ice are at least 20 cm. Thus, the period over which snow accumulates on ice is considered to be "the primary factor influencing the quality of ringed seal breeding habitat" [*Smith and Lydersen*, 1991]. Inadequate snow depths increase pup mortality through exposure and predation [e.g., *Kelly*, 2001; *Ferguson et al.*, 2005; *Lukin et al.*, 2006].

[6] For the first time the CMIP has archived snow depth on sea ice. Here we show the evolution of snow depth on Arctic sea ice in 20th and 21st century integrations. We consider these snow depth changes in the context of the changing Arctic sea ice area and snowfall rates. We focus attention on the time evolution of snow depth in April as a measure of integrated snow accumulation at the end of the ice-growth season. April also coincides with the time when ringed seals most depend on snow to raise their young.

2. Methods and Validation

[7] We use model output from historical and 21st century integrations from the CMIP5 archive [*Taylor et al.*, 2012].

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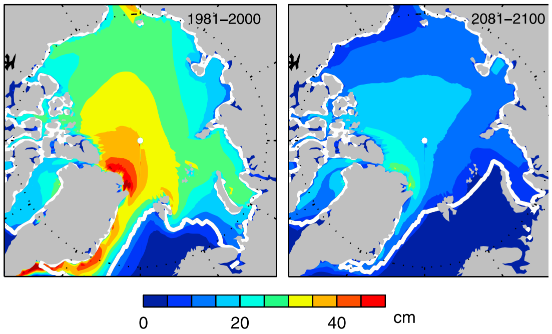

Figure 1. Multi-model mean April snow depth (cm) on sea ice for the periods (left) 1981–2000 and (right) 2081–2100 for RCP8.5. The multi-model mean is calculated from the time-mean snow depths on sea ice for each model (or from each model ensemble), including zeros from models when sea ice is absent. The white line is the multi-model mean 15% ice concentration line for each period.

We show results for Representative Concentration Pathway (RCP) 8.5 for the 21st century scenario. We choose this scenario because it has the highest radiative forcing and hence is an upper bound of available scenarios. Declines in snow depth in the RCP2.6 and RCP4.5 scenarios (shown in the auxiliary material) occur on a slower timescale.[1] We use all models that archive snow data on sea ice and every available ensemble member (see Table S1) except where the CMIP5 archived data appeared incorrect. Ensemble means are computed for each model, and then each model mean is weighted uniformly in the multi-model means.

[8] In the CMIP5 archive, the variable for snow depth on sea ice is the average over the ocean covered portion of a grid cell (i.e., snow volume normalized by ocean area), with zero depth over open water. We are interested in the snow depth on sea ice (i.e., snow volume normalized by the sea ice area in each grid cell), so we divide the snow depth per unit ocean area by the sea ice fraction per unit ocean area. We then compute monthly averages of snow depth (normalized by sea ice area) weighted by area for sea ice-covered portion of the ocean north of 70°N using the minimum threshold of 15% ice concentration on the ocean grid. Henceforth in this paper we refer to this quantity as the snow depth north of 70°N.

[9] In spring to first order, the depth of accumulated snow on sea ice depends on the timing of autumn freeze-up and the winter snowfall rates. Second order impacts are discussed at the end of this section. We assess the influence of both of these factors on April snow depths. April is minimally affected by intermodel differences in melt-onset, and therefore, analysis of April focuses our analysis on the cumulative effect of winter processes only. Snow depths on flat ice of 20–32 cm are necessary to adequately protect young ringed seals from predation and hypothermia [*Lydersen et al.*, 1990; *Hammill and Smith*, 1991; *Smith and Lydersen*, 1991; *Ferguson et al.*, 2005]. For this analysis, we choose a conservative threshold of 20 cm of snow in April to compare changes in area of sufficient snow depth for ringed seal habitat.

[10] Mean precipitation (both snow and rain) in the Arctic is computed for the Arctic ocean area north of 70°N as area-weighted averages on the atmospheric grid. We compute mean monthly precipitation from November to March as a conservative estimate of winter precipitation occurring after freeze-up and before melt-onset. In a given model over a given time period, the fraction of precipitation that falls as snow is roughly uniform from November to March, though this fraction differs among models (see Figure S5).

[11] The multi-model mean April snow depth in the central Arctic (Figure 1) compares well with observational estimates from two sources. *Warren et al.* [1999] produced a climatological mean from measurements made by the Soviet North Pole drifting stations from 1954–1991 over a domain occupied by the stations in the central Arctic. In the same years over the same domain, the multi-model mean April snow depth is 30.1 cm, about 10% below the estimate from the drifting stations, and the root mean square error (RMSE) after removing the area mean bias is 2.4 cm. *Warren et al.* [1999] note that the drifting station depths are measured only for multiyear ice and leads refrozen in early autumn, and they argue that new ice forming after the first snow in September occupies only about 1% of the area of the central Arctic in April. *Kwok et al.* [2011] provide a more recent snow depth estimate using microwave radar measurements along three ~2000 km transects in April 2009 primarily over the western central Arctic from Operation IceBridge. The multi-model mean along the same transects for 2009 is 31.6 cm, about 11% below the IceBridge depths. The individual models have spatial means in the range ±30% of the multi-model mean, and more than 1/3 of the models have spatial means that are greater than observed. The spatial pattern in the multi-model mean (Figure 1) agrees well with the drifting station climatology [see *Warren et al.*, 1999, Figure 9]. Given this satisfactory agreement between model and observations, we proceed with an analysis of the future change in snow depths.

[12] The physical processes associated with snow cover in the sea ice component of climate models are often simplified compared to those in the land component because of the computational expense involved with advection of every variable that describes sea ice conditions. We are unaware of any fully-coupled climate models in which the sea ice component has a time-varying snow density, takes into account degradation of snow from rain and refreezing, or explicitly allows wind-blown snow redistribution (though some redistribute snow during ice deformation events). The models also do not distinguish between level and ridged ice or between multiyear and first-year ice, and so we are unable to characterize responses among these different ice conditions. We discuss the consequences of these model simplifications later.

3. Results

[13] Arctic snow depths averaged north of 70°N in April from 1850–2100 have little trend prior to the 21st century in the multi-model mean and among individual models (Figure 2a), but snow depths in every model decrease substantially by the end of the period. In the RCP8.5 scenario, the multi-model mean snow depth in April is 28 ± 7 cm for 1981–2000 and 16 ± 5 cm for 2081–2100. The uncertainty represents the intermodel spread and is calculated as one

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL052794.

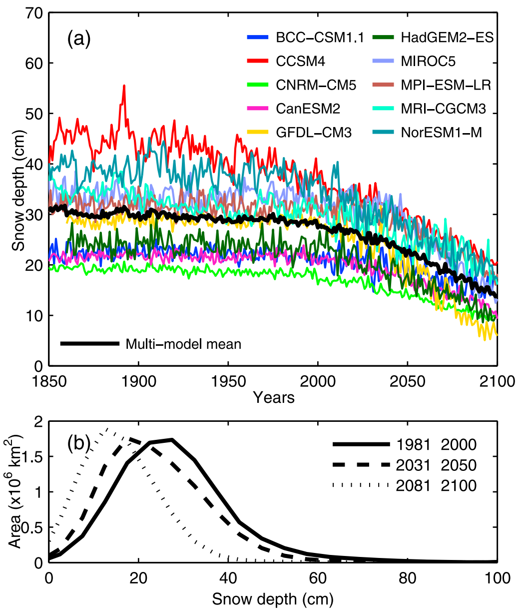

Figure 2. (a) 1850–2100 April snow depth averaged north of 70°N on sea ice, RCP8.5, for ensemble means of individual CMIP5 models and the multi-model ensemble mean (black). (b) Multi-model mean snow depth distribution in area for April, in 5 cm bins for the periods 1981–2000, 2031–2050, and 2081–2100. The distributions are calculated as the mean of the snow depth distribution obtained for each model over each time period for north of 70°N where the sea ice concentration is >15%. This is different from the distribution for the multi-model mean snow depth shown in Figure 1, for which the variance has been much reduced as a result of the averaging.

standard deviation of the monthly means for all models over each period. In the RCP4.5 (RCP2.6) scenario, multi-model mean snow depth in April is 22 ± 6 cm (25 ± 6 cm) for 2081–2100, which corresponds to the mean snow depth for a 20-year period centered at 2053 (2034) under the RCP8.5 scenario. The multi-model mean of the relative decline in snow depth in each model (i.e., relative decline of mean at 2081–2100 compared to 1981–2000) for the RCP8.5 (RCP4.5, RCP2.6) scenario is 45 ± 12% (23 ± 7%, 13 ± 6%) (see Figure S1). We also note that the relationship between snow depth in April versus global mean annual temperature (a proxy for radiative forcing) is approximately linear across models. The same can be said for the relationship between April snow depth and the minimum sea ice area in September until perennial sea ice disappears. That the slopes of these relationships are similar under each RCP scenario indicates that modeled snow depth responds in the same way in each model to both the forcing and the ice area, with only slightly different sensitivities among models (see Figure S2).

[14] The decline in model spread over time (Figure 2a) indicates that the models with larger initial snow depths have greater rates of decline. Similar behavior is seen for the intermodel spread in sea ice thickness averaged north of 70°N but not for Arctic sea ice area [*Bitz*, 2008]. This similarity between transient rates of change in snow depth and sea ice thickness across models is perhaps unsurprising considering that greater snow depths tend to accumulate on thicker sea ice found along the Canadian archipelago — a behavior also seen in spatial maps of snow depth from the drifting stations [*Warren et al.*, 1999] and in an across-model correlation of 1981–2000 April means of snow depth and sea ice thickness for averages north of 70°N (R = 0.56, no implied causality).

[15] To demonstrate the impact on potential seal habitat, we show the multi-model mean snow depth distribution in area for April in RCP8.5 (Figure 2b). This indicates a substantial loss of coverage for snow depths >20 cm over the 21st century. The total area of snow depth >20 cm declines in RCP8.5 (RCP4.5) from a multi-model mean of 7.4 ± 1.8 × 10^6 km^2 in 1981–2000 to 2.4 ± 1.9 × 10^6 km^2 (4.7 ± 2.4 × 10^6 km^2) in 2081–2100. The multi-model mean relative decline in the area of snow depth >20 cm across all models in RCP8.5 (RCP4.5) is 69 ± 21% (39 ± 22%). The distributions are constructed as the average of the distribution for each model for each time period, and thus retain information about the variance that is lost in the spatial plot of multi-model mean snow depth as shown in Figure 1. The spatial maps of multi-model mean snow depth (Figure 1) show the spatial pattern of decline by the end of the 21st century. The relative decline in snow depth between the two periods is similar across models and is in the range of 30 to 50% over most of the Arctic basin from the 20th to the 21st century (not shown), which is consistent with the decline in the mean snow depth. (See Figures S3 and S4 for spatial maps of snow depth in individual models.)

[16] The decrease in April snow cover occurs in spite of an increase in snowfall in winter months over the Arctic ocean (Figure 3). The total precipitation (rain plus snow) in winter months increases through the 21st century because moisture convergence into the Arctic increases roughly according to the temperature dependence of the Clausius-Clapeyron equation. This effect is seen in Figure 3 and has been demonstrated in other studies of future climate projections [*Bengtsson et al.*, 2011]. For the months of November to March, the multi-model mean snowfall rate increases in all models from 1981–2000 to 2081–2100, with a mean increase of 27 ± 16%, and a range from 5% to 51%. In the

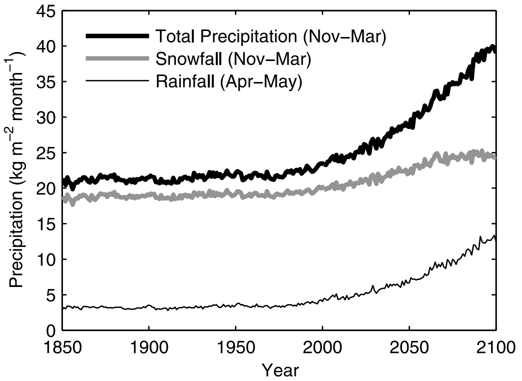

Figure 3. Timeseries of multi-model mean November-March total precipitation (thick black) and snowfall (thick grey) (kg m^{-2} month^{-1}) from 1850–2100 in RCP8.5. Note the increase in rainfall (the difference between these two curves) toward the end of the 21st century. April–May mean rainfall (thin black) (kg m^{-2} month^{-1}) also shows a strong increase over the same period and would contribute to faster spring melting of snow.

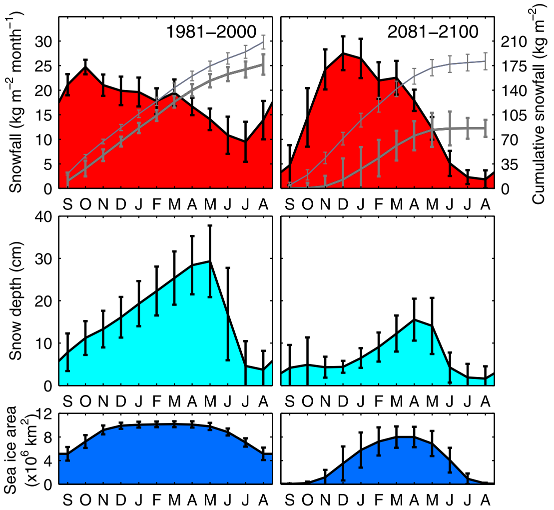

Figure 4. Multi-model mean climatology of (top) snowfall (kg m^{-2} month^{-1}), (middle) snow depth (cm), and (bottom) sea ice area ($\times 10^6$ km^2) for the periods (left) 1981–2000 and (right) 2081–2100. The area-weighted monthly means are computed for north of 70°N over ocean and for sea ice concentrations >15%, and the error bars represent one standard deviation in monthly means across CMIP5 models used in this study. The top panel also shows the cumulative snowfall beginning in September (thin grey line, right axis, kg m^{-2} month^{-1}) and the cumulative snowfall weighted by sea ice area and normalized by the maximum climatological sea ice area from 1981–2000 (thick grey line, right axis, kg m^{-2} month^{-1}). Months are from September through August.

same months the multi-model mean increase in total precipitation is 69 ± 21%, and so a substantial fraction of the increase in precipitation occurs as rain.

[17] The time series of muti-model mean monthly rainfall averaged over April and May shows an increase through the end of the 21st century in RCP8.5 (the lowest curve in Figure 3). The fraction of precipitation that falls as rain in April and May increases from 19 ± 7% to 44 ± 7% in the multi-model mean over these two periods. Snowfall is roughly constant in the multi-model mean for April and May, and therefore almost all of the increase in precipitation in these months is in the form of rain.

[18] We find that most of the change in snow depth in April during the 21st century is caused by the delay in open water freeze-up, as illustrated by the multi-model mean climatology of snowfall rate, snow depth on sea ice, and sea ice area for the two periods 1981–2000 and 2081–2100 (Figure 4). The end of the 20th century has a roughly uniform snowfall rate in autumn and winter months with a slight peak in October. The nearly linear increase in snow depth on sea ice follows the linear increase in cumulative snowfall from September through the beginning of the melt season in April. The sea ice area is lowest in September, but grows rapidly to reach a plateau of maximum area in the region north of 70°N from December until the start of the melt season.

[19] By the end of the 21st century, the multi-model mean snowfall rates averaged north of 70°N have a larger seasonal variation, with a higher peak in winter and lower trough in summer compared to the end of the 20th century (Figure 4, top). In addition, the timing of the snowfall peak shifts from October to December, as more of the precipitation falls as rain in autumn months. The cumulative snowfall averaged north of 70°N increases slowly at first and then roughly linearly after December before plateauing by May. The cumulative snowfall by April changes little over the 21st century (thin grey lines in Figure 4, top). Over the period 2081–2100, mean snow depths do not follow the seasonal timing of cumulative snowfall, however. Instead, snow depths begin their seasonal increase only in December and then increase linearly through April. Snow on sea ice does not deepen in autumn for lack of sea ice on which to accumulate. By the end of the 21st century, the multi-model mean April snow depth north of 70°N is 55% as deep as at the end of the 20th century. The cumulative sum of snowfall weighted by the sea ice area (thick grey lines in Figure 4, top) in April in 2081–2100 is 54% as large as in 1981–2000, indicating that the reduction in sea ice area in autumn and early winter is the primary cause of the decline in April snow depth. (See Figure S5 for climatology of snowfall, rainfall, snow depth, and sea ice area for individual models.)

4. Discussion and Conclusions

[20] In CMIP5 models April snow depths in the central Arctic hold fairly steady throughout the 20th century and then decline sharply during the 21st. Mean April snow depths north of 70°N decrease by 45% in the RCP8.5 scenario at the end of the 21st century compared to the 20th century. Regions with deeper snow decrease fastest, as do models with unusually deep snow.

[21] The decrease in snow depths is caused by the decrease in sea ice area in the autumn and early winter in the 21st century, corresponding to a reduction in the area of ice that survives the melt season (hence a loss of multiyear sea ice). Though the winter snowfall rate increases, there is a compensating decrease in snowfall rate during autumn, so the cumulative snowfall from September to April is nearly unchanged at the end of the 21st century. When accounting for the loss of sea ice as a platform to collect snow in autumn and early winter, the amount of snowfall that can accumulate is greatly reduced over the 21st century.

[22] The observed distribution of snow depths across the Arctic today and recent sharp decline in multiyear sea ice lend support to our findings. April snow depths are greatest where sea ice is thick and concentrations are highest in early autumn (in observations, *Warren et al.* [1999], and models, Figure 1). In contrast snow depths are usually below average where much of the area is covered by firstyear sea ice. Even in regions that have a mixed population of firstyear and multiyear sea ice, April snow depths on multiyear sea ice are about double those on firstyear ice [*Kurtz and Farrell*, 2011]. A characteristic of Arctic sea ice trends is the faster pace of decline of thicker, multiyear sea ice compared to firstyear sea ice [*Comiso*, 2012], so it stands to reason that there would be a corresponding reduction in the mean snow depth in April.

[23] Our conclusions about the controls on 21st century snow depths hinge on only a modest increase in winter snowfall rates as demonstrated by the models. However, from the cumulative snowfall rates in (Figure 4, thick gray lines), we estimate that by end of the 21st century in RCP8.5

snowfall rates would need to double from September through April to compensate for the effect of the later freeze-up of autumn sea ice.

[24] Modeling studies show that artificially enhancing the snow depth causes sea ice to become thinner via reduced growth rates at either pole [*Maykut and Untersteiner*, 1971; *Huwald et al.*, 2005; *Powell et al.*, 2005], provided the snow mass is insufficient to drive the sea ice-snow interface below sea level and cause snow-to-ice conversion. The CCSM4, which has among the deepest snow covers among the models we analyzed, has a negligible amount of snow-to-ice conversion in the Arctic and it remains negligible throughout the 21st century even for RCP8.5. Since decreases in snow depth induce enhanced growth rates, we infer that reduced snow depths as the Arctic warms in the 21st century will lessen the thinning of sea ice.

[25] Based solely on a 20 cm April snow depth threshold, we estimate that the mean area of potential habitat for ringed seal reproduction north of 70°N decreases by nearly 70% over the 21st century in RCP8.5 in the CMIP5 models. Ringed seals build subnivean lairs in snow drifts that form near hummocks of deformed sea ice, and survival of seal pups diminishes in locations without at least 20 cm of snow on level sea ice in April [e.g., *Hammill and Smith*, 1991; *Ferguson et al.*, 2005; *Lukin et al.*, 2006]. We have used the lower estimate (20 cm) for the minimum snow depth on level ice necessary for seal subnivean lair success, though *Ferguson et al.* [2005] found that the snow depth needs to be greater than 32 cm. These studies also show that sea ice deformation is a necessary but not a sufficient condition for lair success. We have not excluded deformation-free regions in our analysis of the snow depth distribution in the models because deformation data are absent in the CMIP5 archive. Rain events in the Arctic spring are also known to cause the collapse of snow caves [*Stirling and Smith*, 2004]. We note therefore that an increase in April and May rainfall as simulated in the CMIP5 models would further impact seal habitat, an impact not quantified here. Though the calculated change in area of suitable ringed seal habitat depends in part on knowledge of the relevant snow depth threshold, the effect of a different choice of threshold can be ascertained from Figure 2b.

[26] To the best of our knowledge, the sea ice in CMIP5 models is generally unaffected by rainfall since rainfall is deposited directly into the ocean in the models, with no interaction with snow or sea ice. In reality rain falling during the ice growth season would likely affect snow aging, density, and thermodynamic processes associated with ice growth. Rain falling on sea ice during the melt season would affect snow morphology and albedo, accelerate snow loss during the beginning of the melt season and potentially accelerate ice loss. These and other thermodynamic effects associated with snow on sea ice are only now being investigated in the context of a global model (O. Lecomte, personal communication, 2012).

[27] For a given forcing scenario, CMIP5 models may underestimate the decrease in wintertime accumulated snow depth for at least two reasons. First, rainfall rates in CMIP5 models increase during both the winter and spring, though the effect on net snow accumulation and morphology is not fully considered in the sea ice components of global climate models. Second, decreases in sea ice concentration in the autumn and early winter could also cause loss of drifting snow into leads. Changes to the sea ice surface topography (hummock height and distribution) are expected due to changes in the deformation rate as well as the proportion of firstyear and multiyear ice. The nature and seasonality of these changes and their effect on drifting snow, and by extension seal habitat, is unknown. The considerable decline in 21st century snow depths in the CMIP5 models and the relevance for seal habitat motivate further investigation into the impact of these additional factors.

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References

Arzel, O., T. Fichefet, and H. Goosse (2006), Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs, *Ocean Modell.*, *12*, 401–415.

Bengtsson, J., K. I. Hodges, S. Koumoutsaris, M. Zahn, and N. Keelyside (2011), The changing atmospheric water cycle in polar regions in a warmer climate, *Tellus, Ser. A*, *63*, 907–920.

Bitz, C. M. (2008), Some aspects of uncertainty in predicting sea ice thinning, in *Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications*, *Geophys. Monogr. Ser.*, vol. 180, edited by E. T. DeWeaver, C. M. Bitz, and L.-B. Tremblay, pp. 63–76, AGU, Washington, D. C.

Comiso, J. C. (2012), Large decadal decline of the Arctic multiyear ice cover, *J. Clim.*, *25*, 1176–1193.

Comiso, J. C., and F. Nishio (2008), Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res.*, *113*, C02S07, doi:10.1029/2007JC004257.

Ferguson, S. H., I. Stirling, and P. McLoughlin (2005), Climate change and ringed seal (*Phoca hispida*) recruitment in western Hudson Bay, *Mar. Mammal Sci.*, *21*, 121–135.

Hammill, M. O., and T. G. Smith (1991), The role of predation in the ecology of the ringed seal in Barrow Strait, Northwest Territories, Canada, *Mar. Mammal Sci.*, *7*, 123–135.

Huwald, H., L.-B. Tremblay, and H. Blatter (2005), A multilayer sigma-coordinate thermodynamic sea ice model: Validation against Surface Heat Budget of the Arctic Ocean (SHEBA)/Sea Ice Model Intercomparison Project Part 2 (SIMIP2) data, *J. Geophys. Res.*, *110*, C05010, doi:10.1029/2004JC002328.

Kattsov, V. M., J. E. Walsh, W. L. Chapman, V. A. Govorkova, T. V. Pavlova, and X. Zhang (2007), Simulation and projection of arctic freshwater budget components by the IPCC AR4 global climate models, *J. Hydrometeorol.*, *8*, 571–589.

Kelly, B. P. (2001), Climate change and ice breeding pinnepeds, in *"Fingerprints" of Climate Change—Adapted Behavior and Shifting Species Ranges*, edited by G. Walther, C. A. Burga, and P. J. Edwards, pp. 43–55, Kluwer Acad., New York.

Kurtz, N. T., and S. L. Farrell (2011), Large-scale surveys of snow depth on Arctic sea ice from Operation IceBridge, *Geophys. Res. Lett.*, *38*, L20505, doi:10.1029/2011GL049216.

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.

Kwok, R., B. Panzer, C. Leuschen, S. Pang, T. Markus, B. Holt, and S. Gogineni (2011), Airborne surveys of snow depth over Arctic sea ice, *J. Geophys. Res.*, *116*, C11018, doi:10.1029/2011JC007371.

Lukin, L. P., G. N. Ognetov, and N. S. Boiko (2006), *Ecology of the Ringed Seal in the White Sea*, UrO RAN, Ekaterinburg, Russia.

Lydersen, C., P. Jensen, and E. Lydersen (1990), A survey of the Vanmijen Fjord, Svalbard, as habitat for ringed seals, Phoca-hispida, *Holarctic Ecol.*, *13*, 130–133.

Maykut, G. A., and N. Untersteiner (1971), Some results from a time-dependent thermodynamic model of sea ice, *J. Geophys. Res.*, *76*, 1550–1575.

Notz, D. (2009), The future of ice sheets and sea ice: Between reversible retreat and unstoppable loss, *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 20,590–20,595.

Powell, D. C., T. Markus, and A. Stössel (2005), Effects of snow depth forcing on Southern Ocean sea ice simulations, *J. Geophys. Res.*, *110*, C06001, doi:10.1029/2003JC002212.

Rawlins, M. A., et al. (2010), Analysis of the arctic system for freshwater cycle intensification: Observations and expectations, *J. Clim.*, *23*, 5715–5737.

Smith, T. G., and C. Lydersen (1991), Availability of suitable land-fast ice and predation as factors limiting ringed seal populations, *Phoca hispida*, in Svalbard, *Polar Res.*, *10*, 585–594.

Smith, T. G., and I. Stirling (1975), The breeding habitat of the ringed seal *(Phoca hispida).* The birth lair and associated structures, *Can. J. Zool.*, *53*, 1297–1305.

Stirling, I., and T. G. Smith (2004), Implications of warm temperatures, and an unusual rain event for the survival of ringed seals on the coast of southeastern Baffin Island, *Arctic*, *57*, 59–67.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of CMIP5 and the experiment design, *Bull. Am. Meteorol. Soc.*, *93*, 485–498.

Warren, S. G., I. G. Rigor, N. Untersteiner, V. F. Radionov, N. N. Bryazgin, Y. I. Aleksandrov, and R. Colony (1999), Snow depth on Arctic sea ice, *J. Clim.*, *12*, 1814–1829.

Zhang, X., and J. Walsh (2006), Toward a seasonally ice-covered Arctic Ocean: Scenarios from the IPCC AR4 model simulations, *J. Clim.*, *19*, 1730–1747.