nature climate change

SUPPLEMENTARY INFORMATION
https://doi.org/10.1038/s41558-019-0588-4

In the format provided by the authors and unedited.

Climate change causes functionally colder winters for snow cover-dependent organisms

Likai Zhu[1]*, Anthony R. Ives[2], Chi Zhang[1], Yuanyuan Guo[1]* and Volker C. Radeloff[3]

[1]Shandong Provincial Key Laboratory of Water and Soil Conservation and Environmental Protection, College of Resources and Environment, Linyi University, Linyi, China. [2]Department of Integrative Biology, University of Wisconsin-Madison, Madison, WI, USA. [3]SILVIS Lab, Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, Madison, WI, USA. *e-mail: zhulikai@lyu.edu.cn; yygpku@163.com

Supplementary Information

Climate change causes functionally colder winters for snow cover-dependent organisms

Likai Zhu[1*], Anthony R. Ives[2], Chi Zhang[1], Yuanyuan Guo[1*], Volker C. Radeloff[3]

[1] Shandong Provincial Key Laboratory of Water and Soil Conservation & Environmental Protection, College of Resources and Environment, Linyi University, Linyi276005, China;

[2] Department of Integrative Biology, University of Wisconsin-Madison, Madison, WI53706;

[3] SILVIS Lab, Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, Madison, WI 53706

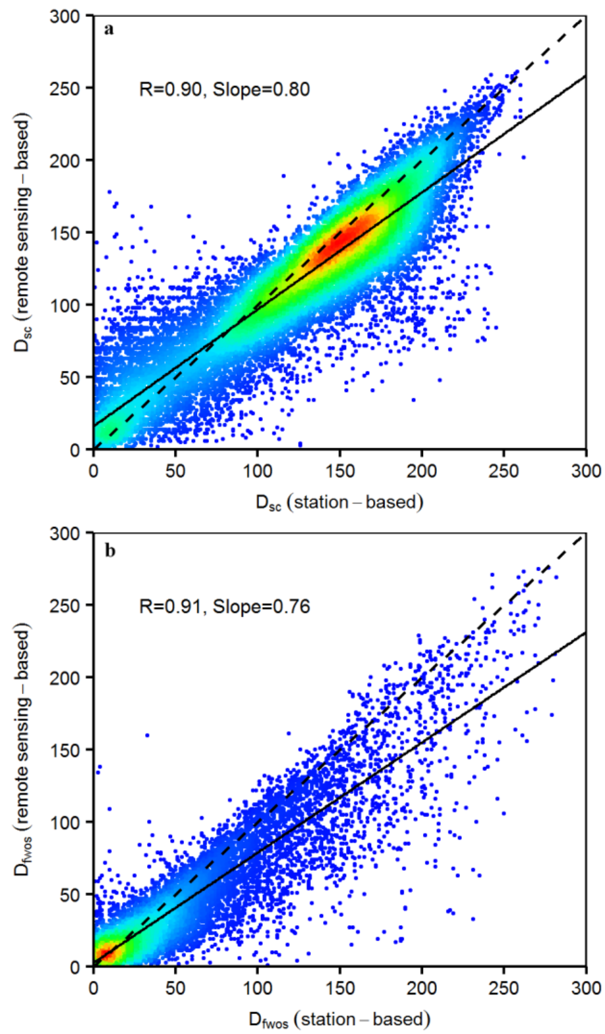
[*]Corresponding author

Likai Zhu

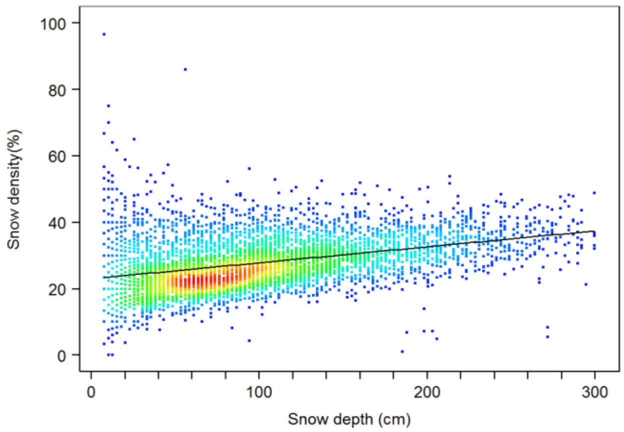
Email: zhulikai@lyu.edu.cn

Yuanyuan Guo

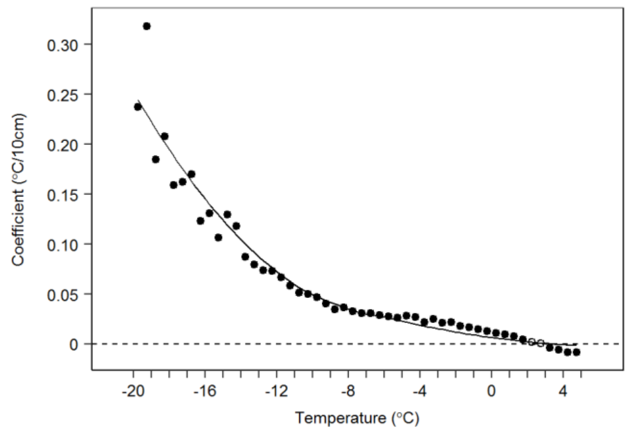
Email: yygpku@163.com



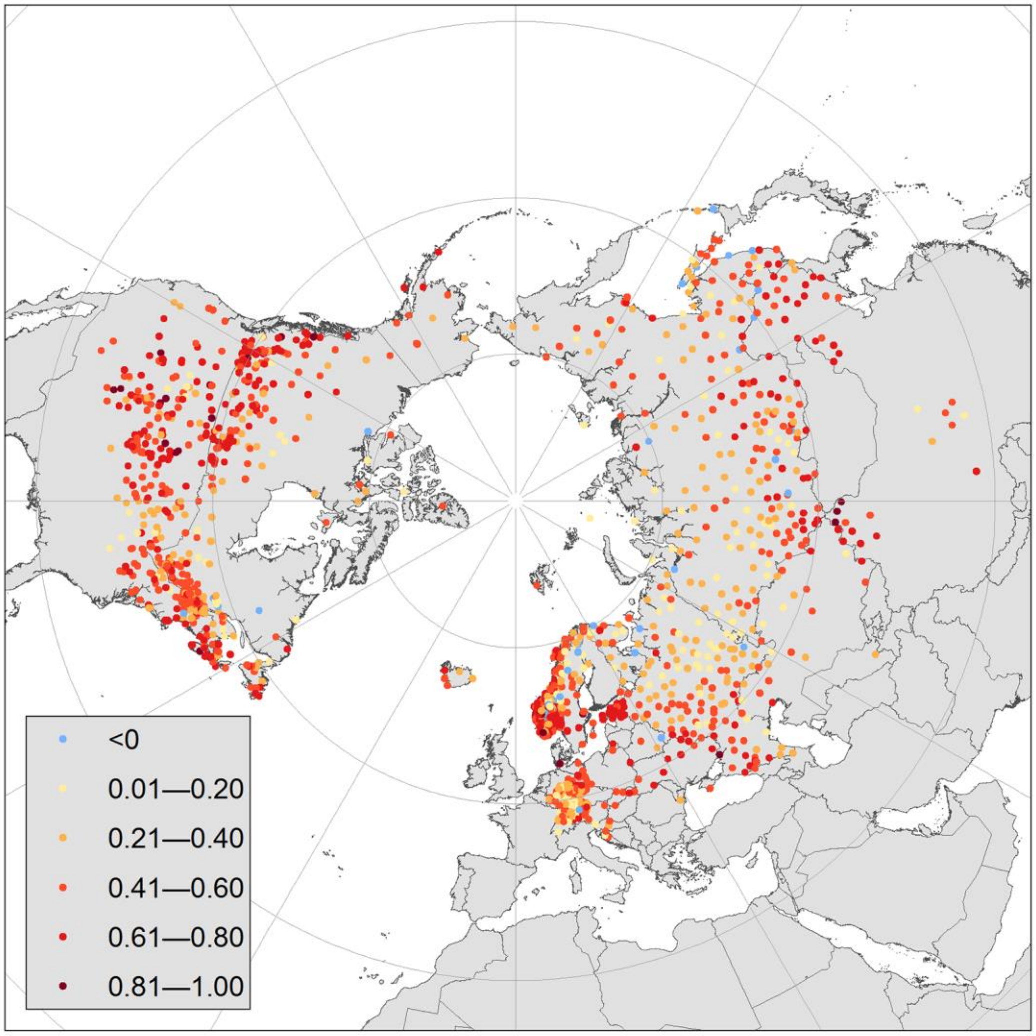
Supplementary Figure 1. Accuracy assessment of remote sensing-based *Dsc* and *Dfwos*. a. Scatterplot showing the close correlation between station-based *Dsc* and remote sensing-based *Dsc*. b. Scatterplots showing the close correlation between station-based *Dfwos* and remote sensing-based *Dfwos*.



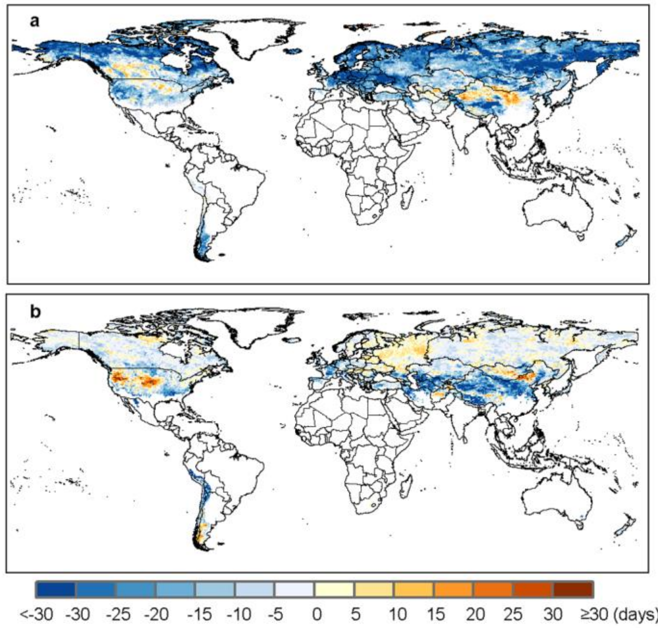
Supplementary Figure 2. Scatterplot showing the relationship between snow depth and density within the frozen season. Snow density was generally higher where snow was deeper



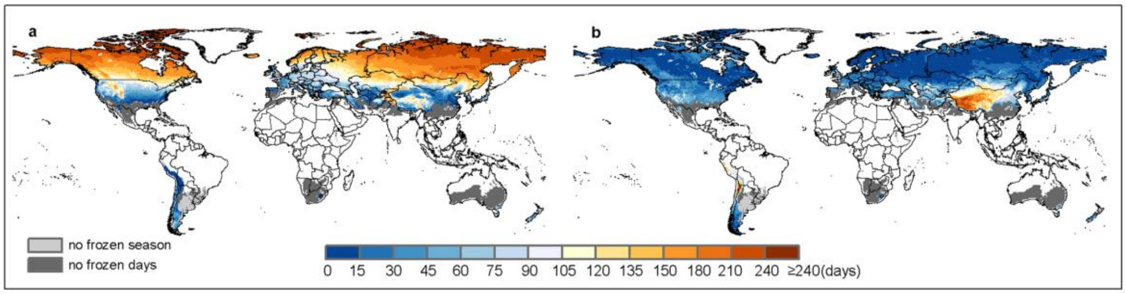
Supplementary Figure 3. Relationships between snow depth and ground temperatures. The coefficients are obtained by regressing ground temperatures against snow depth within different intervals of air temperatures. Deeper snow cover generally causes higher ground temperatures, though the effects vary with the intervals of air temperatures.



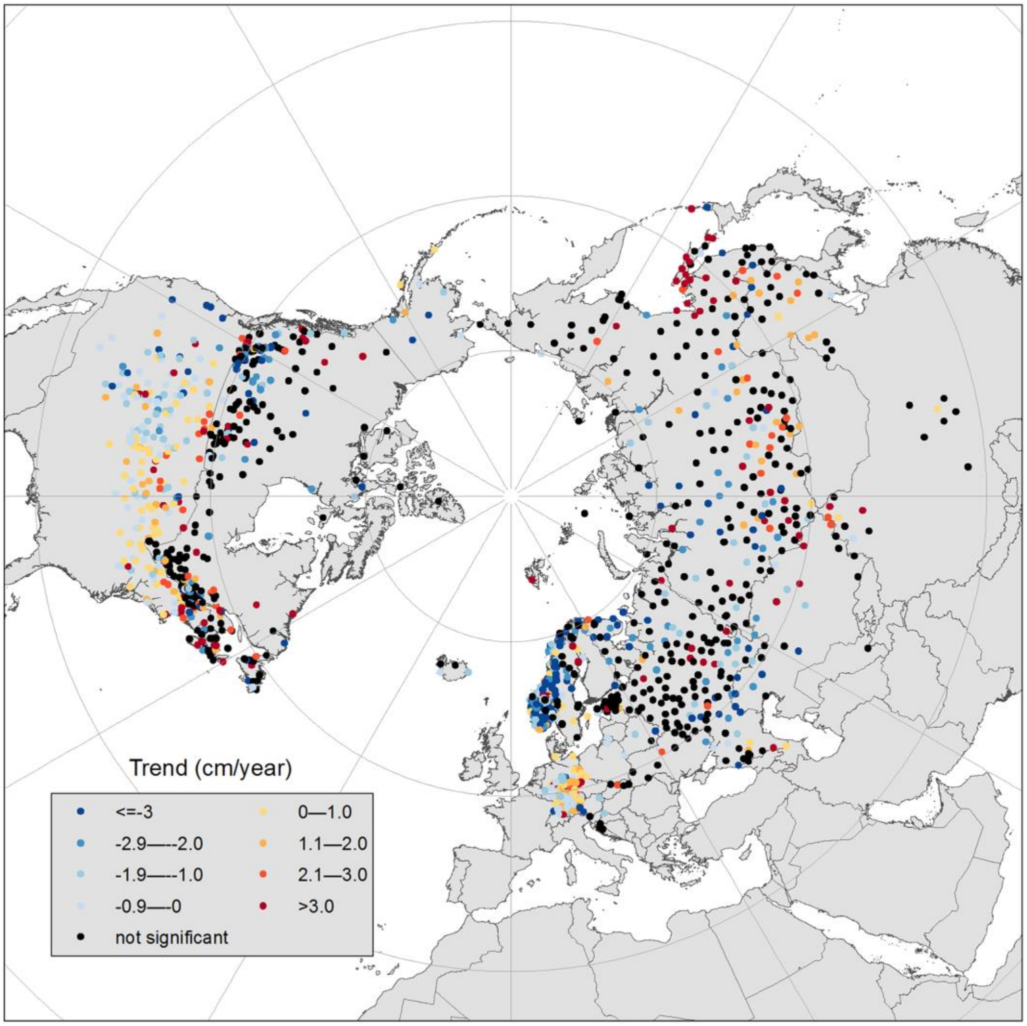
Supplementary Figure 4. Spatial pattern of the coefficients of correlation between snow depth and duration of frozen ground with snow cover (*Dsc*). *Dsc* shows a strong and positive correlation with mean snow depth of the winter period.



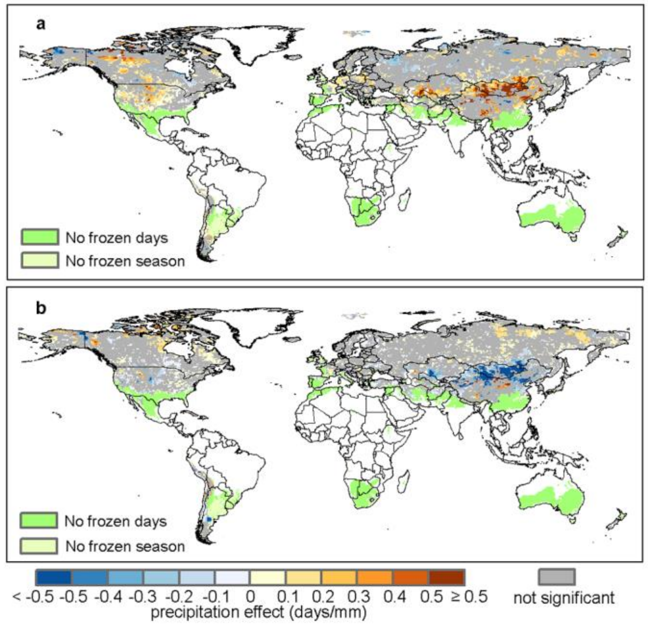
Supplementary Figure 5. Global patterns of the differences in *Dsc* and *Dfwos* between the past (1982-1986) and current (2010-2014) periods. a. The differences in *Dsc* which show a widespread decrease in *Dsc*. b. The differences in *Dfwos* which shows that *Dfwos* had noticeable increases, especially in mid-latitudes.



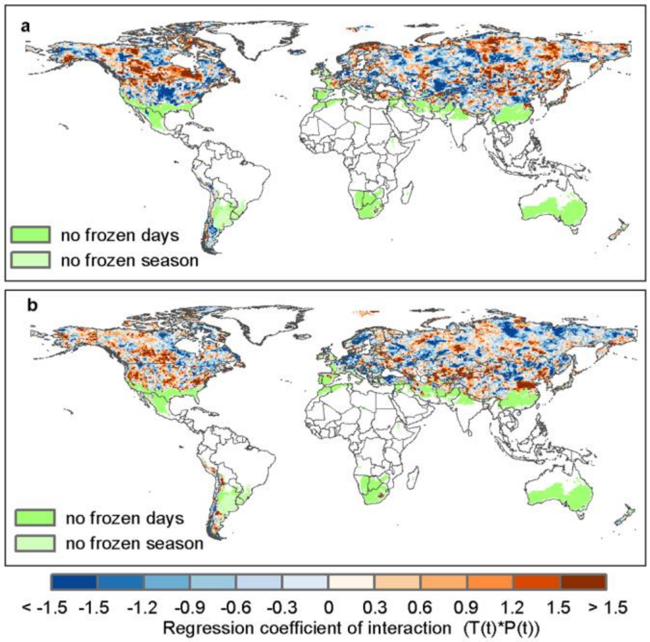
Supplementary Figure 6. Global patterns of the average *Dsc* and *Dfwos* for 1982-1986. a. Global pattern of the average *Dsc* which shows that *Dsc* was highest at higher latitudes. b. Global pattern of the average *Dfwos* while shows that *Dfwos* is, counter-intuitively, highest at mid-latitudes.



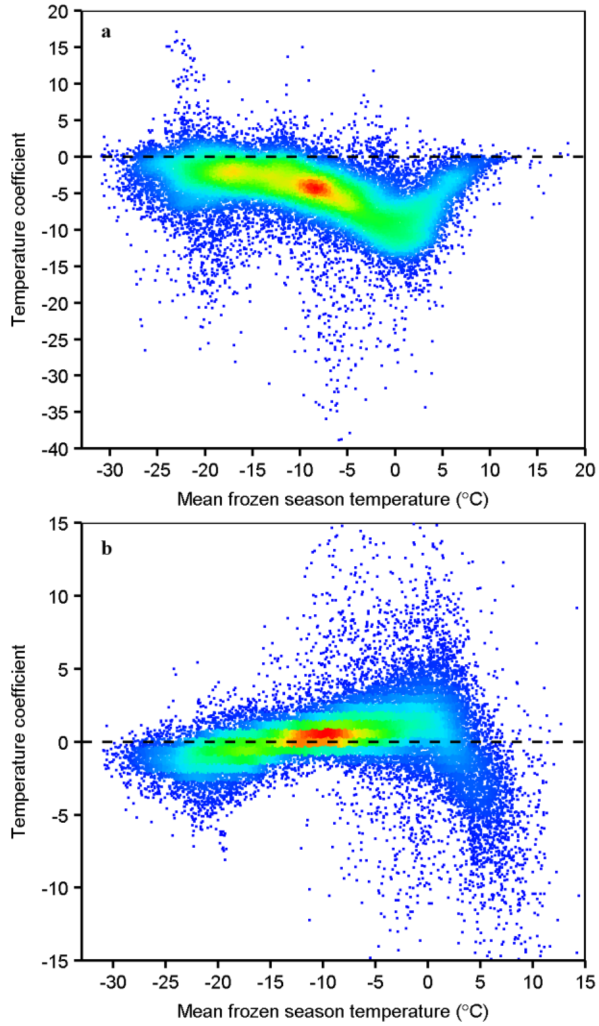
Supplementary Figure 7. Spatial pattern of the trends of mean snow depth for the period of frozen ground with snow cover. Significant decreases in mean snow depth are observed in the western United States and Europe. Stations with non-significant trends at the 0.05 level are displayed with black points.



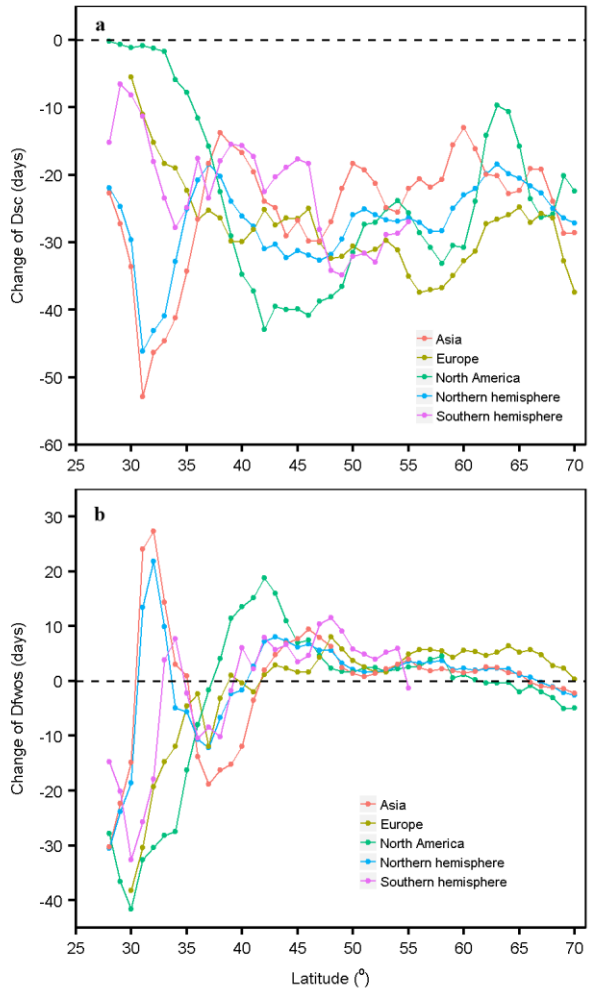
Supplementary Figure 8. Global pattern of the effects of winter precipitation on *Dsc* and *Dfwos*. a. The pattern of the effects on *Dsc* shows significant and positive correlations between winter precipitation and *Dsc* in mid-latitude areas. b. The pattern of the effects on *Dfwos* shows that the relationships between *Dfwos* and winter precipitation are generally not significant. Pixels with non-significant effects are displayed as grey.



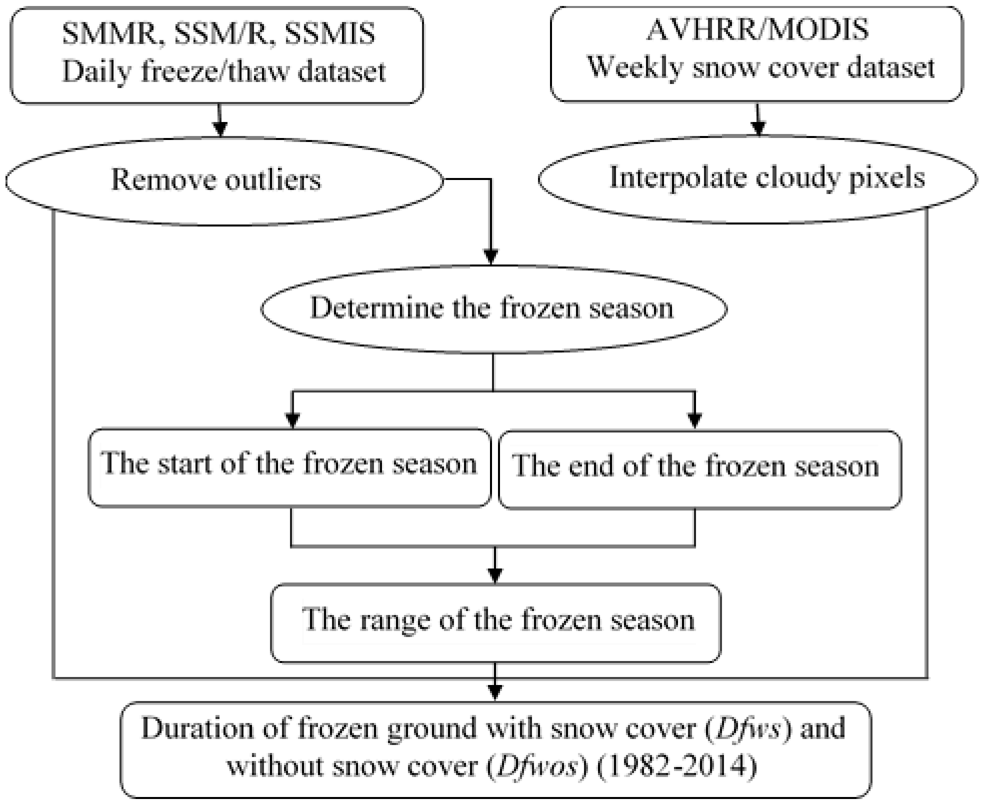
Supplementary Figure 9. Global patterns of the effects of the interaction between winter temperature and precipitation on *Dsc* and *Dfwos* which are measured by the regression coefficient c_{TP} in equation (4). a. The pattern for *Dsc* where negative coefficients indicate that increased precipitation may offset the decrease in *Dsc* due to rising temperatures. b. The pattern for *Dfwos* where positive coefficients indicate that increased precipitation may offset the increase in *Dfwos* due to increased temperatures



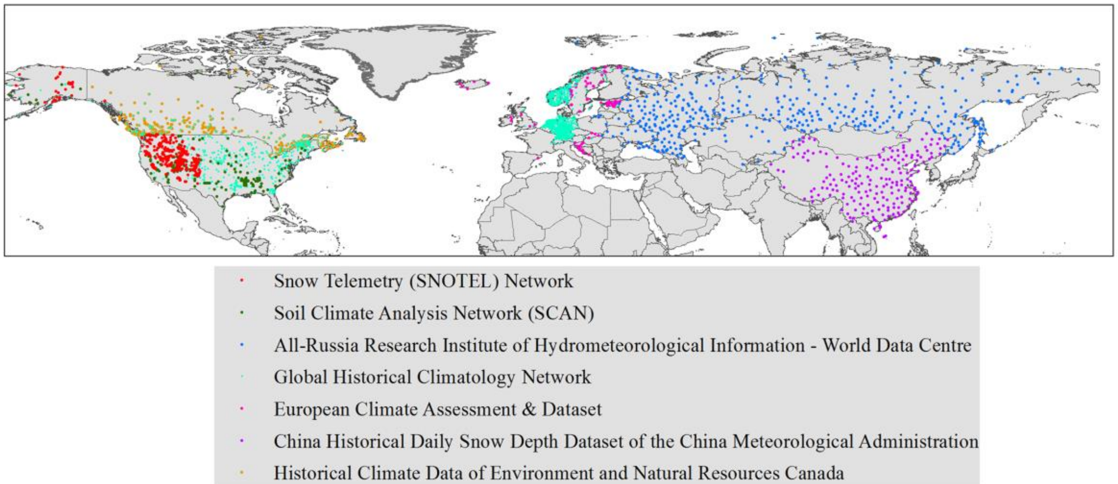
Supplementary Figure 10. Regression coefficient for the effect of winter temperatures on *Dsc* and *Dfwos* plotted against the mean winter temperature averaged over the period 1982-2014. a. *Dsc*. b. *Dfwos*. In the regions where the mean winter temperatures are relatively high, both *Dsc* and *Dfwos* are more sensitive to climate warming.



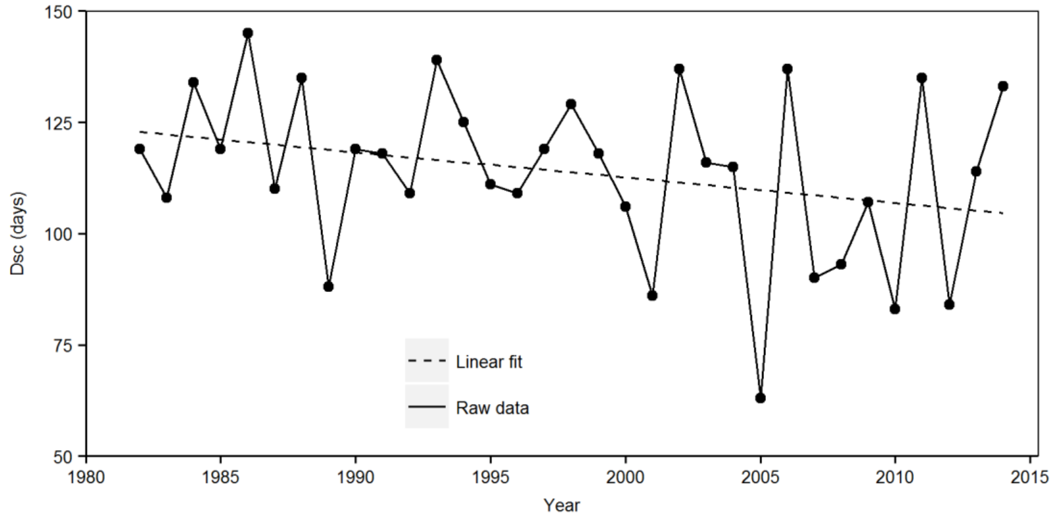
Supplementary Figure 11. Future changes in *Dsc* and *Dfwos* by latitude during the late 21st century (2071-2100), relative to the historical period (1982-2014). The changes in (a) *Dsc* and (b) *Dfwos* by latitude indicate that the greatest decreases in *Dsc* and the greatest increases in *Dfwos* are predicted to occur between 40°N and 50°N in the Northern Hemisphere.



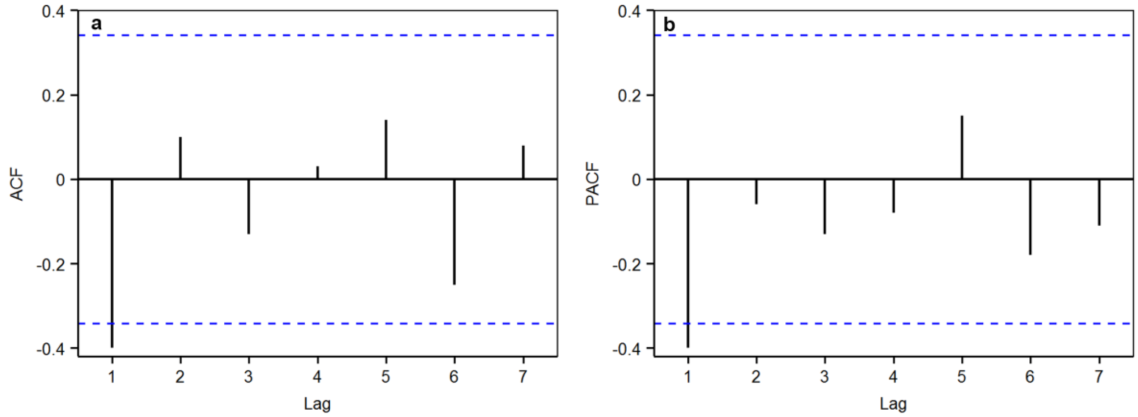
Supplementary Figure 12. Procedures of our data processing to derive global *Dsc* and *Dfwos* from 1982 to 2014



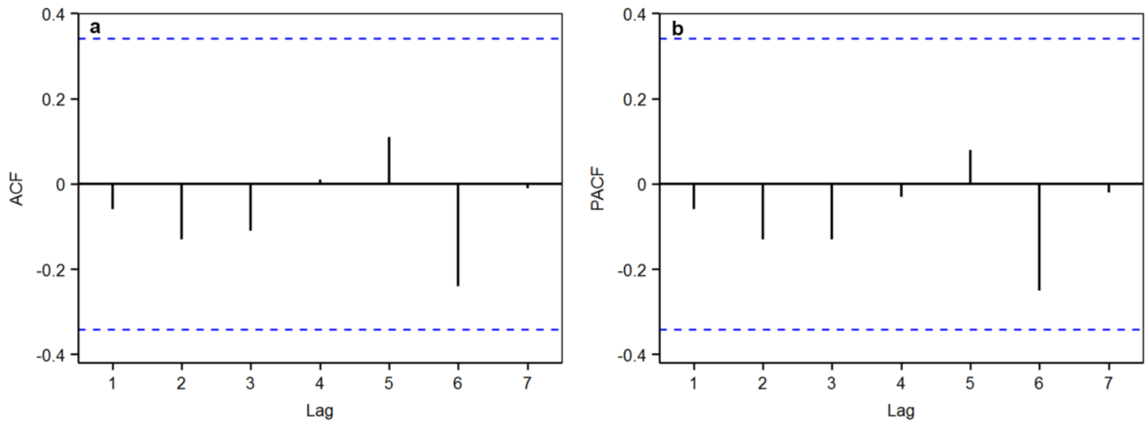
Supplementary Figure 13. Stations from different data sources which are used to verify the remotely sensed *Dsc* and *Dfwos* and to test whether *Dsc* and *Dfwos* are effective and representative proxies of the subnivium. Stations with uninterrupted daily snow depth records for 20 years from 1982 to 2014 are displayed.



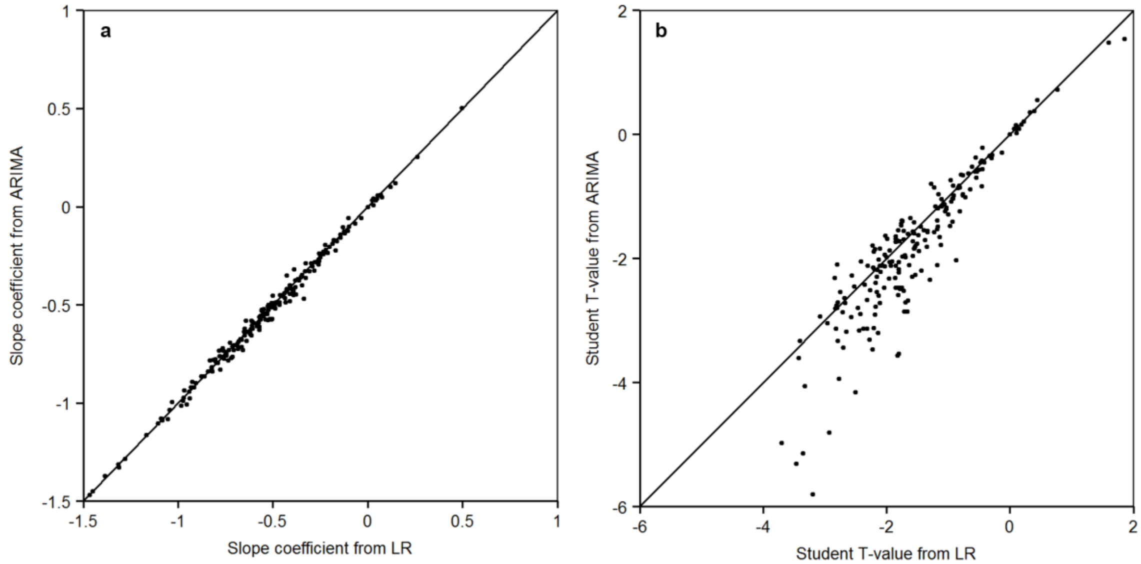
Supplementary Figure 14. *Dsc* time series from 1982 to 2014 of a specific pixel. The dashed line shows linear regression fit whose equation was *Dsc*=1256-0.57**t*, and the student T-test value for the slope coefficient is -1.66



Supplementary Figure 15. Autocorrelations of linear regression residuals. The (a) autocorrelation function (ACF) and (b) partial autocorrelation function (PACF) values show that the residuals have strong autocorrelation at lag 1. The blue dashed lines show the 5% critical values at any given lag d, which are calculated by $\pm\frac{1.96}{\sqrt{N-d}}$ (N is the sample size, and here N=33).



Supplementary Figure 16. Autocorrelations of residuals for linear regression model with autocorrelated errors. The (a) autocorrelation function (ACF) and (b) partial autocorrelation function (PACF) values show that the residuals have no significant autocorrelation. The student T-test value for slope coefficient is -2.86, which is significant at 0.05 level.



Supplementary Figure 17. Comparisons of slope coefficients and their student T-test values from linear regression (LR) and linear regression with autocorrelated errors (ARIMA) using *Dsc* time series of 200 random pixels. (a) Slope coefficients and (b) their student T-test values from both methods are generally consistent, but there are slight differences for some pixels.

Supplementary Table 1. Multiple data sources of snow depth, ground and air temperature

Source	Data access website	Used elements
Snow Telemetry (SNOTEL) Network	https://www.wcc.nrcs.usda.gov/snow/	Snow depth, snow water equivalent, soil temperature at 2 inches, air temperature
Soil Climate Analysis Network (SCAN)	https://www.wcc.nrcs.usda.gov/scan/	Soil temperature at 2inches, air temperature
Global Historical Climatology Network (GHCN) Daily Data	https://www.ncdc.noaa.gov/ghcnd-data-access	Snow depth
European Climate Assessment & Dataset (ECA&D)	https://www.ecad.eu//dailydata/predefinedseries.php	Snow depth
All-Russia Research Institute of Hydrometeorological Information - World Data Centre (RIHMI-WDC)	http://meteo.ru/english/climate/snow.php	Snow depth
Historical Climate Data of Environment and Natural Resources Canada	http://climate.weather.gc.ca/	Snow depth
China Historical Daily Snow Depth Dataset of the China Meteorological Administration	http://data.cma.cn/	Snow depth

Supplementary Table 2. Correlation coefficients and linear regression coefficients between station-based *Dsc* and remote sensing-based *Dfwos* show the difference in the accuracy of remotely sensed variables by latitude (°N)

	R				Regression slope			
Latitude	<40	40-45	45-50	>50	<40	40-45	45-50	>50
Dsc	0.92	0.90	0.83	0.89	0.77	0.71	0.72	0.91
Dfwos	0.90	0.84	0.84	0.70	0.80	0.71	0.60	0.47

Supplementary Table 3. Correlation coefficients and linear regression slopes between station-based *Dsc* and remote sensing-based *Dfwos* show the difference in the accuracy of remotely sensed variables by elevation category.

	R				Regression slope			
Elevation	0-300m	300-600m	600-900m	>900m	0-300m	300-600m	600-900m	>900m
Dsc	0.95	0.90	0.86	0.90	0.89	0.86	0.79	0.72
Dfwos	0.81	0.85	0.87	0.86	0.63	0.72	0.74	0.76

Supplementary Table 4. Correlation coefficients and linear regression slopes between station-based *Dsc* or *Dfwos* and remote sensing-based *Dsc* or *Dfwos* show the difference in the accuracy of remotely sensed variables by land-cover type.

	R				Regression slope			
Land cover	forest	grassland	cropland	barren	forest	grassland	cropland	barren
Dsc	0.89	0.89	0.94	0.94	0.92	0.74	0.84	0.85
Dfwos	0.84	0.88	0.85	0.91	0.67	0.76	0.69	0.80