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To cite this article: Joseph M Finnegan and James R Miller 2022 *Environ. Res. Lett.* **17** 114002

ENVIRONMENTAL RESEARCH
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RECEIVED
8 June 2022

REVISED
28 September 2022

ACCEPTED FOR PUBLICATION
6 October 2022

PUBLISHED
18 October 2022

LETTER

Elevation dependence of projected hydro-climatic change in eastern Siberia

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Keywords: elevation-dependent climate change, eastern Siberia, Arctic amplification, snow cover change

Supplementary material for this article is available online

Abstract

Over the last several decades, eastern Siberia has experienced some of the largest temperature increases worldwide. We use the RCP8.5 simulation of the Community Climate System Model version 4 to examine how projected monthly changes in temperature and hydro-climatic variables in eastern Siberia depend on latitude and elevation. Temperature increases are largest at the highest latitudes in winter and late fall and are smaller at higher elevations. For precipitation and snowfall, there is a latitudinal dependence in autumn and spring, with precipitation, snowfall, and snow depth mostly increasing between 60 and 70° N. Although snow cover extent (SCE) decreases almost everywhere, the largest changes occur during the transition seasons which we define as spring and autumn, and the timing of the changes depends on latitude, elevation, and the specific month within seasons. The decreases in SCE are larger at lower latitudes and lower elevations in April and November and larger at higher elevations and higher latitudes in June and September. For the highest latitudes, snow depth actually increases, and increases more at higher elevations. These projections are generally consistent with those of four other climate models. For precipitation, all models project increases in non-summer seasons, but they are not consistent with respect to the direction of the elevation dependence of precipitation. We discuss the complex interactions among the projected changes in all the variables.

1. Introduction

The Arctic is one of the fastest warming regions on Earth owing to the phenomenon of Arctic amplification (Serreze and Francis 2006, Serreze *et al* 2009). Two recent papers indicate that this amplification is even stronger than previous studies suggest (Chylek *et al* 2022, Rantanen *et al* 2022). There are important feedbacks among temperature and hydro-climatic variables that contribute to this enhanced warming, but it is difficult to quantify the various feedbacks between the atmosphere, land surface, ice, and ocean (Miller *et al* 2007, Goose *et al* 2018). In recent decades, some of the most significant changes in climate have occurred at high northern latitudes in Eurasia (Groisman *et al* 2017). Ciavarella (2021) analyzed the highly anomalous Siberian heat wave in the summer of 2020 and found that the Arctic Ocean low pressure system in 2020 extended southward over the land region of Siberia in winter and spring thus maintaining a warmer climate than normal because of more clouds and/or precipitation. This was followed by an anomalous high-pressure system in summer, leading to fewer clouds than normal and increasing the incident radiation and temperature.

In addition to temperature, a consistent result from both observations and models is for increasing precipitation in much of Siberia and increased snow depth at the highest latitudes because the effect of increased precipitation outweighs the effect of increased temperatures that are still below freezing in winter (Rawlins *et al* 2010, Krasting *et al* 2013, Danco *et al* 2016). An additional factor that affects climate change throughout most of Siberia is melting permafrost that can release particles that act as condensation nuclei for cloud formation (Creamean *et al* 2020) as well as being a source of carbon to the atmosphere. Arctic climate change is important for its local effects, but may also be important beyond the Arctic. Ghatak *et al* (2012) used a set of climate model experiments to show that Siberian snow depth could be affected by surface conditions in the Arctic Ocean. Although other studies have found that declining sea ice can affect mid-latitude weather (Francis and Vavrus 2012, Cohen *et al* 2013, Francis and Vavrus 2015), Cohen *et al* (2020) concluded that more research is needed to understand the linkage with mid-latitude weather and extreme events. For our analysis here we generally refer to mid-latitudes as regions south of 50° N.

Elevations in eastern Siberia range from sea level to more than 3000 m. Both observations and model projections suggest that future warming rates may depend on elevation (Diaz and Bradley 1997, Ohmura 2012, Rangwala and Miller 2012, Pepin *et al* 2015, Wang *et al* 2016). Most studies of elevation dependent warming (EDW) have been conducted equatorward of 50° latitude, and many of them find that warming rates increase with increasing elevation. However, our recent work found that warming rates in eastern Siberia actually decreased with elevation, particularly in winter owing to strong temperature inversions (Miller *et al* 2021, hereafter referred to as M21). M21 only examined changes in temperature in the winter and summer seasons. There has been a recent emphasis on extending previous EDW studies to consider how projected changes in other climate variables depend on elevation (Thornton *et al* 2021, Pepin *et al* 2022). It is also important to examine other seasons, specific months, elevations and latitudes to understand how the temporal changes evolve.

There are still many unresolved questions about high-latitude Siberian climate change including (a) how will monthly values of temperature and hydro-climatic variables change during the 21st century and (b) how will the projected monthly changes and their interactions be affected by Arctic amplification, latitude, and elevation. Our objective here is to address these questions by examining projected monthly temperature and hydro-climatic changes in eastern Siberia including precipitation, specific humidity, snow cover extent (SCE), snow-to-precipitation ratio (SPR), snow depth, and clouds. Our primary focus is on the effects of elevation, the monthly timing of these changes, and the interactions and feedbacks among these changes. The methodology and data sets are described in the next section followed by projected seasonal changes in section 3, monthly changes in section 4, with conclusions presented in section 5.

2. Methodology

We use a global climate model to examine projected 21st century changes in temperature and hydro-climatic variables in eastern Siberia. The primary model is the Community Climate System Model version 4 (CCSM4, Gent *et al* 2011) from the Coupled Model Intercomparison Project fifth phase (CMIP5). We compare the results with several other CMIP5 models. The analysis period (2006–2100) and study region (land area only in figure 1(a) from 50° N to 70° N and 80° E to 180° E) are the same as in M21. The resolution of CCSM4 (1° × 1.25° in latitude and longitude, respectively) is among the finest resolutions of the CMIP5 models. As noted in M21, CCSM4 temperatures are in good agreement with climatology, and precipitation in the region is mostly within 0.5 mm d^{-1} of the Global Precipitation Climatology Project (GPCP) climatology (Huffman *et al* 1997, Gent *et al* 2011). To ensure a sufficient response to future changes in greenhouse gases, we use the Intergovernmental Panel on Climate Change (IPCC) RCP8.5 simulation which is sometimes referred to as business as usual.

Our analysis includes only land cells. CCSM4 grid cell elevations range from sea level to 2374 m with generally more mountainous regions in the northeast and along the southern border. We examine projected future changes in the various climate variables by subtracting the average value of the change of a six-member CCSM4 ensemble for the current climate (2006–2025) from the end of the century (2081–2100) projections. When we discuss changes in variables throughout the paper, we use initial values to denote values for the current climate. These 20 year periods are consistent with the 20 year averages used by Solomon *et al* (2007). When we discuss seasonal changes, we define winter as December, January, and February and the other 3 month seasons follow. Transition seasons are defined as spring and autumn. Seasonal changes are established by calculating the mean value of the monthly changes in those seasons. The projected changes represent the mean changes that would be experienced in a month of that season. To establish that the changes shown are outside inherent uncertainty, a two-sample t-test is performed using the average model grid cell values for the first 20 years of the century compared to the values for the last 20 years of the century, with a 5% significance level. This test was performed for temperature, precipitation, and snow cover extent, all of which rejected the null hypothesis. To produce the line plots of projected changes against elevation in section 4, grid cells in the latitude bands shown are binned into the nearest 100 m elevation, with grid cells containing elevations below 50 m being rejected as non-land grid cells. For the line slopes in figure 4, the p-value of Pearson's linear correlation coefficient between the elevation of the grid cells and their projected changes is computed; if the p-value is less than 0.05 the linear regression line is shown in figure 4.

3. Spatial variation in seasonal changes

Figures 1(b) and (c) show 21st century spring and autumn temperature projections; corresponding figures for winter and summer are in M21. At the

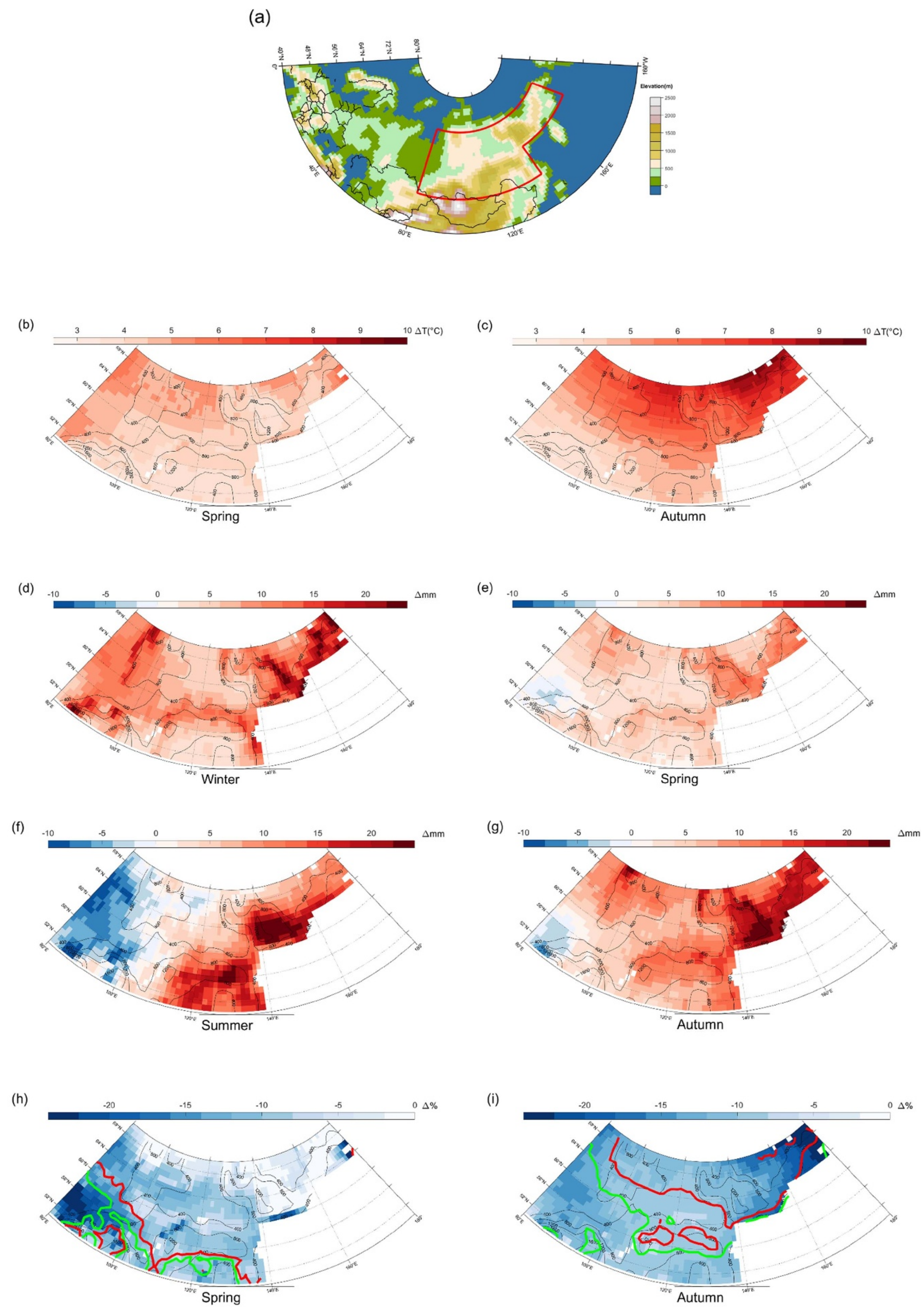

Figure 1. (a) Map of study region in eastern Siberia (land area only: 50° N–70° N, 80° E–180° E) from M21 and projected 21st century changes in temperature in (b) spring and (c) autumn, precipitation in (d) winter, (e) spring, (f) summer, and (g) autumn. SCE in (h) spring and (i) autumn with contours for initial (current climate) SCE margin (green) and end of century SCE margin (red). 21st century changes are defined as monthly average of years 2081–2100 minus years 2006–2025. Black contour lines show elevation in meters.

highest latitudes, the maximum model grid cell elevation is 1288 m which is not particularly high compared to elevations at mid and low latitudes, but the strong temperature inversions lead to significant differences in warming rates between the surface and 1000 m, particularly in winter (M21). The warming rate clearly increases to the north. Projected seasonal precipitation changes are mostly positive (figures 1(d)–(g)). Although there are regional changes by season, precipitation increases consistently in the northeastern region in all seasons, with the largest increases in autumn, often by more than 15 mm mon^{-1}. There are also precipitation decreases, particularly in the western region in summer. For the highest peaks in the southwestern corner of figure 1, precipitation increases in winter but is little changed or generally decreases in other seasons. Figures 1(h) and (i) show changes in SCE for spring and autumn with the average snow margin position over the first 20 years of the study period and the last 20 years of the study period overlain; changes are small in summer and winter and are not shown. In summer, SCE changes are small because the initial SCE is small; initial refers to the SCE for the current climate. In winter, the initial SCE is near 100%, and in spite of large temperature increases, it is still mostly below freezing by 2100. Some of the largest increases in temperature and largest decreases in SCE occur in the southwestern corner of figure 1, indicating a likely role for the shortwave radiation snow–albedo feedback.

Figures 2(a)–(c) show the latitudinal variation of projected seasonal changes of the variables in figure 1. For temperature the latitudinal gradient is large and positive in autumn (0.23 °C deg^{-1}) and winter (0.18 °C deg^{-1}), small in spring, and near zero in summer. Temperature changes in the transition seasons are not symmetric, with spring being more like summer and autumn like winter. We discuss interactions between monthly changes in temperature and hydro-climatic variables in section 4. Figure 2(b) shows that the zonally-averaged precipitation changes are positive in all seasons, which means that any negative changes in specific grid cells are outweighed by the net positive changes across the entire latitude band. Latitudinal gradients between 50 and 66° N are positive in all seasons except summer and generally monotonic in spring and autumn. The largest increase with latitude (0.52 mm mon^{-1} deg^{-1}) occurs in autumn. There is no clear latitudinal trend in summer.

Figure 2(c) shows latitudinal averages of projected seasonal SCE changes. In spring temperatures at all latitudes are projected to increase by approximately 4 °C, but because lower latitudes are initially warmer than higher latitudes, SCE decreases more at lower latitudes. Figure 2(c) shows that the same latitudes that were still too cold to experience significant changes in spring are the only ones that experience snow cover decreases in summer. For autumn, there is not much of a latitudinal difference, although the largest decreases in SCE are in the northeast. This difference in snow cover changes between spring and autumn is partly attributed to the stronger north–south gradient of temperature change in autumn than in spring. Even though autumn temperatures at lower latitudes are initially warmer and closer to the freezing point than those at higher latitudes, the projected temperature increase is almost twice as large at higher latitudes so that snow cover changes at approximately the same rate at high and low latitudes. The differences in latitudinal snow cover changes can be partially attributed to the difference in snow margin position for autumn and spring. There is a significant difference between autumn and spring in both the initial (current climate) and end of century position of the snow margin, with both margins more northward in autumn. In addition figures 1(h) and (i) show that the change in the margin is greater in autumn than in spring. This asymmetry between climatic responses in spring and autumn is discussed further in the next section, but a major factor for the disparity in the snow margin position is that there is already snow on the ground at the beginning of spring and none, or very little, on the ground at the beginning of autumn. Projected changes in the SPR are similar to those for SCE and are discussed in the next section.

4. Zonally averaged monthly changes and effects of elevation

To better understand intra-seasonal changes, particularly in spring and autumn, we next examine specific months. Figures 3(a)–(f) show how the projected monthly changes of zonally-averaged temperature, precipitation, and SCE vary with elevation for the two highest latitude 5° bands. For temperature (figures 3(a) and (b)), the maximum decrease in warming rate with elevation between the surface and 1000 m occurs in November for the northernmost band, and the pattern is similar for the 60–65° N band, but with less steep slopes. There is generally less decrease with elevation above 1000 m. Supplementary figure S1(a) shows how the elevation dependence in November varies for other latitude bands, with the magnitude of the elevation gradients decreasing from north to south.

Figures 3(b) and (c) show that most of the elevation dependence in precipitation change occurs between approximately 500 and 800 m. The large increase in precipitation in the northeastern region likely amplifies the elevation gradients because many of the higher-elevation grid cells are in the northeast (see figure 1(c)). The largest increase in precipitation with elevation occurs in August in the 60–65° N latitude band, varying from slightly negative to 35 mm mon^{-1} at 1200 m (figure 3(d)). For the lowest latitude band where elevations reach

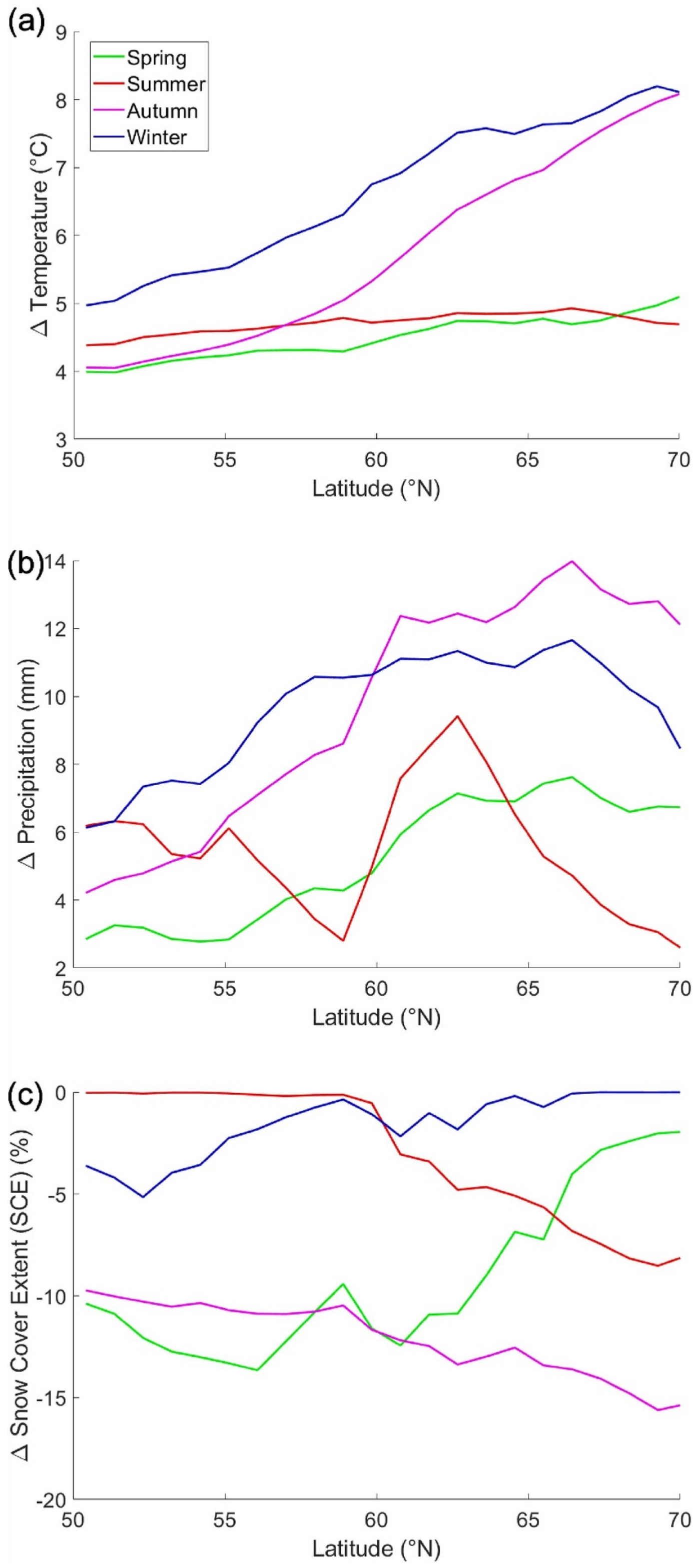

Figure 2. Seasonal variation with latitude of projected changes in variables in figure 1 for (a) temperature, with summer and winter values from M21, (b) precipitation (c) snow cover extent.

2000 m in the southwestern corner of the figure, precipitation is projected to decrease by approximately 5 mm mon^{-1} at elevations above 1200 m. There are elevational gradients in SCE changes in most seasons (figures 3(e) and (f)), but the magnitude and direction of the gradients varies by month, sometimes within the same season. The sign of the elevation gradient for SCE switches from positive in May to negative in September (i.e. SCE decreases faster at lower elevations in May and at higher elevations in September). The reason that SCE changes so little at lower elevations in September is because there is

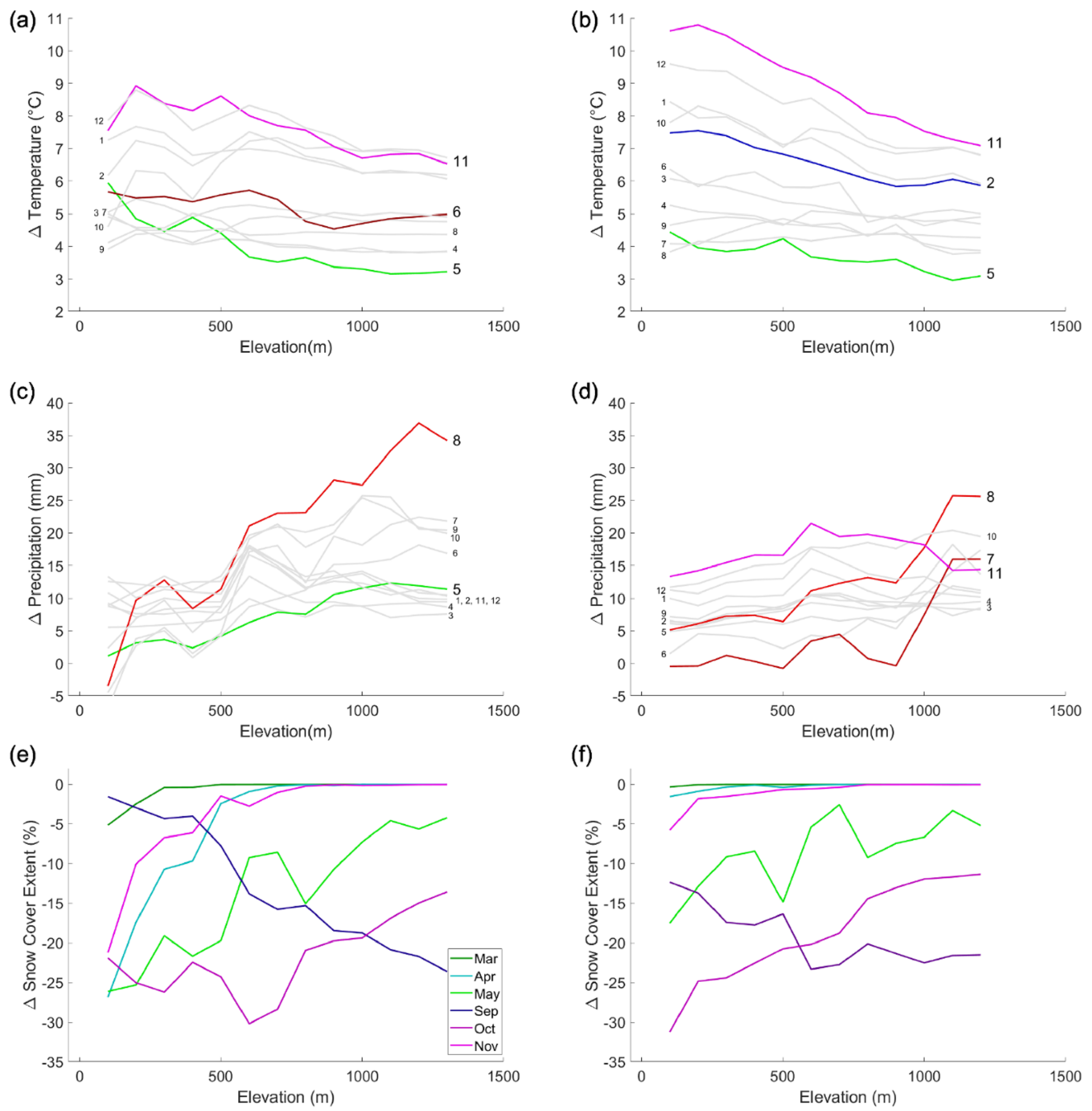

Figure 3. Monthly variation of projected changes with elevation for the two highest 5° latitude bands (60°–65° N on the left, 65°–70° N on the right) for (a, b) temperature, (c, d) precipitation, and (e, f) snow cover. Months have been highlighted in (a–d) and identified by month number to provide rough upper and lower bounds to the changes.

little snow there to melt, but as snow accumulates between September and October, SCE decreases at a rate of approximately 25% mon^{-1}. At higher elevations, SCE does not decrease as fast in October, and does not decrease at all by November. This highlights the importance of examining projected changes in snow cover, as well as other variables, on a monthly rather than seasonal basis, particularly during spring and autumn.

Figures 4(a)–(f) show the zonally-averaged projected changes in temperature, precipitation, SPR, SCE, snow depth, and cloud cover as a function of latitude and month, and figure S3 shows the changes in specific humidity and snowfall. Figure 4(a) shows the strongest warming at the highest latitudes in November and the surrounding 2 months, consistent with Vavrus *et al* (2012). When a variable in a specific cell is increasing, a positively sloped line within the cell indicates that the variable is increasing faster at higher elevation. When a variable is decreasing, a line with a positive slope indicates that it is decreasing more slowly at higher elevations. At the highest latitudes in winter, the line slopes in figure 4(a) are mostly negative meaning that higher elevations warm more slowly than lower elevations. In spring, the largest slopes occur at lower latitudes in March, middle latitudes in April, and higher latitudes in May.

Figure 4(b) shows a large increase in precipitation in late autumn and early winter at the highest latitudes, with larger increases at higher elevations. The smallest increases occur in May/June for the lower latitude bands but shift to later in the season (June/July) in the north. The asymmetric response of the transition seasons is most extreme for the higher latitude bands where October and November precipitation increases are much greater than for any of the spring months. There is little elevation dependence at the lowest latitude where the highest elevations occur.

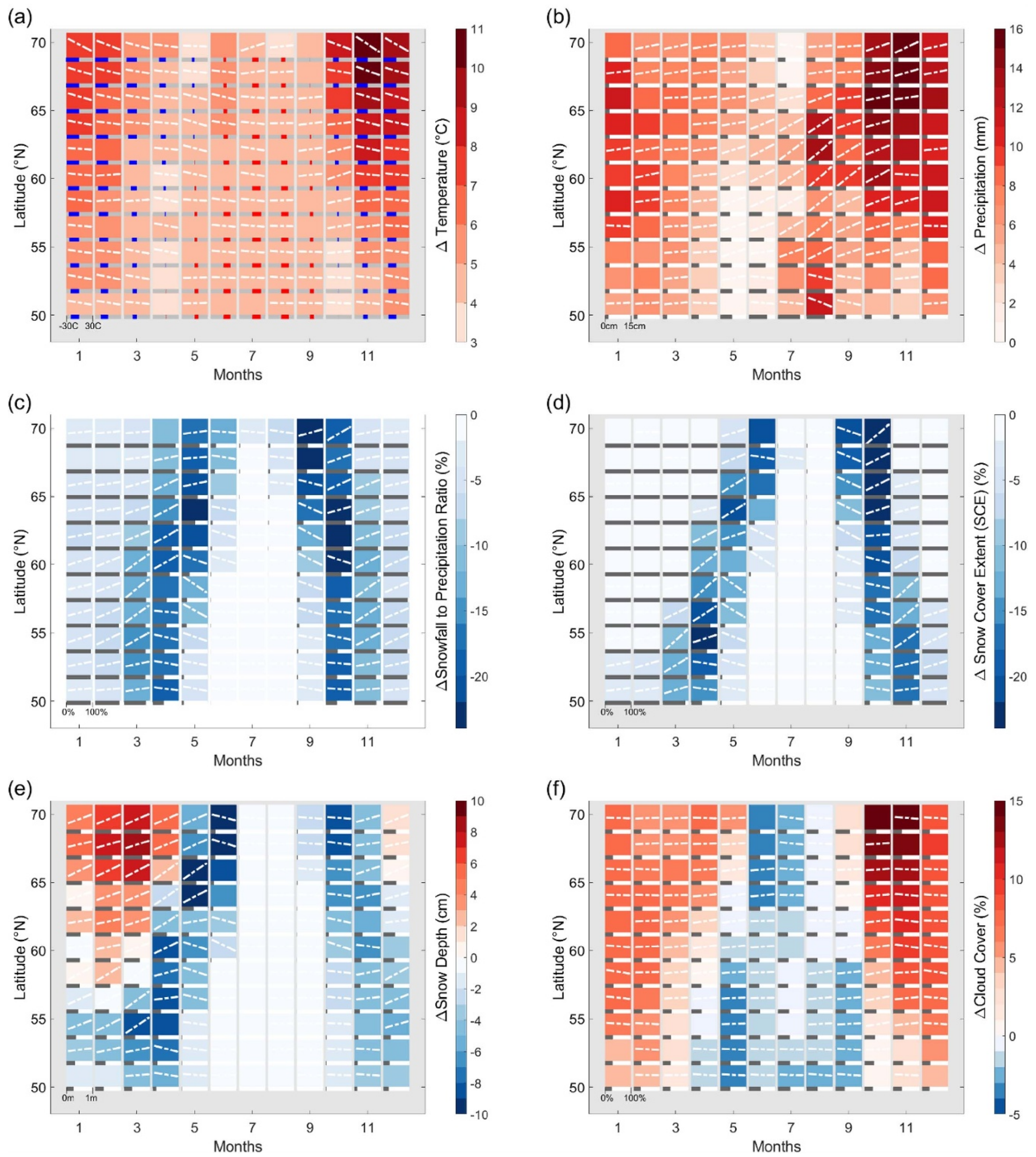

Figure 4. Variation of projected zonally-averaged changes in (a) temperature, (b) precipitation, (c) SPR, (d) SCE, (e) snow depth and (f) cloud cover. Colors indicate magnitude of projected changes. The small horizontal bar at the bottom of each box shows the latitudinal average of the initial value of the variable for the 2006–2025 period (current climate); for temperature, the scale varies between −/+ 30 °C with (blue, red) colors being initially (less, greater) than zero. Line slopes inside boxes show elevation dependence of variables with (positive, negative) slopes indicating that they increase (more, less) at higher elevations and are only shown if statistically significant at the 5% level. Note that when initial values of a change are negative a positive slope indicates that the decreases are smaller at higher elevations.

There is a large positive elevational dependence that occurs for the middle latitudes particularly between late spring and early autumn, peaking in August, consistent with figure 3(c).

For all months, SPR decreases for all latitude bands with the largest changes (∼20%–25%) in early spring and late autumn at the lowest latitudes, and in late spring and early autumn at the highest latitudes (figure 4(c)). The changes are small in summer, with larger decreases in the north. In winter, the decreases range up to 10%, consistent with changes in temperature. Even though temperatures increase more rapidly at higher latitudes than at lower latitudes, the northern temperatures remain below freezing in winter so that SPR changes there are small. Although SPR decreases in all months and at all latitudes, the rate of decrease varies with elevation, mostly decreasing faster at lower elevations than at higher elevations, except in May and September in the lower half of the region. Supplementary figure 3(b) shows that snowfall, although mostly decreasing, actually increases in 3 months at lower latitudes and 6 months at higher latitudes during the cold season, as well as increasing at higher rates at higher elevations.

The pattern of projected monthly decrease in SCE is similar to the change in SPR, with little change in summer or winter when SCE is near zero or 100% (figure 4(d)). As expected, major decreases occur during spring and autumn. For the highest latitudes, November and March are similar to winter, and the major decreases in SCE occur in early summer (June) and in early autumn (September and October). At lower latitudes, these decreases occur earlier in spring (April) and later in autumn (October and November). Therefore, the main features are the change in timing of snow cover retreat in spring (melts approximately 1 month earlier) and accumulation in autumn (begins approximately 1 month later).

The largest decrease in snow depth occurs in spring, advancing from early spring in the south to late spring in the north (figure 4(e)). In autumn, the largest decreases in snow depth occur in early autumn in the north and late autumn in the south. At the highest latitudes in late winter, snow depth increases because precipitation increases. Even though SPR also decreases, snowfall is increasing and leads to the largest increases in snow depth at the highest elevations from 65 to 70° N. Although temperature there increases the most in winter, temperature is still below freezing, and warming rates are lower at higher elevations (figure 4(a)). When all these factors are considered (i.e. those that tend to reduce snow depth and those that tend to increase snow depth in winter), snow depth increases for the highest latitude bands in winter and early spring, and increases more at higher elevations. One reason for examining monthly changes is demonstrated clearly for the two highest latitude bands where the slopes inside the cells switch sign from May to June. Although the snow depth is decreasing in both months, figure 4(d) shows that there is less snow initially to melt in June and most is at higher elevations. Another example of the asymmetry between spring and autumn responses to warming is that the changes in SCE in October in the northernmost band are much higher (∼25%) than in May (∼2%). One factor that affects the extent to which SCE decreases is its initial value. If there is little snow initially, the decrease in SCE is small. So, a major reason why SCE changes at different rates at different elevations in the transition seasons is because there will be more snow to melt at higher elevations later in the spring and earlier in autumn. However, the spring–autumn asymmetry also appears to depend on the initial snow depth (figure 4(e)). Because May is at the end of the snow accumulation season and October at the beginning, there is more snow mass on the ground to melt in May, even when SCE is the same for both months; thus, even if the same amount of snow were to melt in both months, SCE would not change as much in May. Hence, a factor that affects spring/autumn asymmetries to a warming climate is snow depth since early spring starts with more snow already on the ground while autumn starts with bare ground.

Figure 4(f) shows that there are small decreases in cloud cover in summer, with decreases extending to April through September at lower latitudes. Cloud cover increases at all latitudes from October through March, with the largest increases (∼15%) in October and November at the highest latitudes. The changes in cloud cover are not very dependent on elevation. Although cloud cover decreases in summer, the elevation dependence can be positive or negative. In April/May and September/October cloud cover tends to increase more (or decrease less) at higher elevations, except for the lowest two latitude bands. Increasing clouds and water vapor both contribute to increasing temperatures in the 65–70° N band, but are still not sufficient to reduce snow depth there. Supplemental figure S3(a) shows that atmospheric water vapor increases everywhere, consistent with increases in temperature, and the largest increases occur in the warm season. The changes are small (∼0.5 g kg^{-1}) in winter, but initial values are also small, so that the ratio of the change to the initial values is larger in winter than in summer. The sensitivity of downward longwave radiation to changes in water vapor is much higher in winter than in summer (Chen *et al* 2003, Ghatak and Miller 2013). This is consistent with Ye *et al* (2014) who found increased atmospheric water vapor in winter and summer; they found that increased water vapor contributes to increased precipitation in winter but does not lead to higher precipitation in summer because of the warmer temperatures. Temperatures increase the most at high latitudes in November, where precipitation and cloud cover also increase the most, which indicates that the cloud longwave radiation feedback is a factor. Ciavarella *et al* (2021) analyzed the highly anomalous heat wave that occurred in Siberia in the summer of 2020 and found that the Arctic Ocean low pressure system extended southward in winter and spring to maintain warmer than the normal temperatures. There were fewer clouds the following summer, leading to warmer temperatures. Our projected future trends in the 60–70° N band show more precipitation and cloud cover in winter, followed by fewer clouds in summer, both of which lead to warmer temperatures.

5. Summary and conclusions

We have examined how CCSM4 21st century model projections of temperature and hydro-climatic variables depend on month, latitude and elevation for eastern Siberia. Among the most robust results are projections of (a) the largest temperature increases at the highest latitudes in November with larger warming rates at lower elevations; (b) precipitation increasing for most latitude bands with larger increases in winter and late fall, smaller increases in summer, and evidence of elevation dependence whose direction depends upon month; (c) increasing snow depth at the highest latitudes with larger increases at higher elevations in winter and spring; (d) decreasing SCE and SPR primarily in spring and autumn, depending on both latitude and elevation; (e) decreasing cloud cover almost everywhere in summer, with mixed changes in other seasons and a latitudinal dependence in all seasons, with cloud cover decreasing less at higher latitudes in summer and increasing more there in other seasons; and (f) increased atmospheric water vapor throughout the region. Although SCE decreases almost everywhere, the largest changes occur during spring and autumn, and the timing of the changes depends on latitude, elevation, and the specific month. The decreases in SCE are larger at lower latitudes and lower elevations in April and November and larger at higher elevations and higher latitudes in June and September.

One of the major limitations of this study is that the results are based on an ensemble of six simulations from one climate model. Supplementary tables S1–S5 provide a detailed comparison with four other climate models. There is good agreement among all models that temperatures will increase everywhere in all seasons, with the largest increases in winter and autumn when there are also strong latitudinal and elevational gradients. There is good agreement on the timing of decreases in SCE and its dependence on both latitude and elevation. All models project increasing precipitation in non-summer seasons, but some (including CCSM4) project more precipitation at higher elevations and others project less. There is general agreement that cloud cover increases in non-summer seasons (CCSM4 is the high-end outlier) with larger increases in the north in spring and autumn. Within seasons, the effects of latitude and elevation may depend on specific months. For example, most of the models indicate that SCE and SPR changes depend on latitude and elevation, with larger decreases at lower elevations or lower latitudes in March and November because it is still well below freezing at higher latitudes. However, there are larger decreases at higher elevations or higher latitudes in May and September because there is more snow there to melt.

Another limitation of our study is that we have not discussed possible changes in atmospheric circulation or how precipitation might change. Two recent papers suggest that snow-atmosphere coupling can drive changes in atmospheric circulation in the Northern Hemisphere (Henderson *et al* 2018, Yang and Fan 2021). Chernokulsky *et al* (2019) found that precipitation has been increasing in northern Eurasia during the last five decades and can primarily be attributed to an increase in the convective component of precipitation. Melting permafrost throughout most of our region can release particles that act as condensation nuclei for cloud formation (Creamean *et al* 2020) in addition to being a source of carbon to the atmosphere.

Since the Arctic is, and is projected to be, one of the fastest warming places on earth, it is imperative that we develop a better understanding of how these Arctic interactions and feedbacks work by using combinations of observations and models. Our findings indicate the importance of accounting for elevational effects when examining climate change at high latitudes, particularly for changes in temperature and snow cover and depth. Although we find that projected changes in precipitation may depend on elevation for some months, this result does not appear to be consistent among different models. We also show the importance of examining monthly rather than seasonal changes to understand the timing of changes in snow cover and snow depth, the asymmetric response of the changes between spring and autumn, and how these changes depend on cloud cover and water vapor. Melting permafrost throughout most of eastern Siberia depends on changes in both temperature and snow cover and is likely to provide another positive feedback on high-latitude temperature projections. In summary, we find that to fully understand and quantify the role of high latitude feedbacks in projected climate change, the effects of elevation and monthly timing of changes should be considered.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

JMF acknowledges support from the Rutgers University Aresty Center Research Program. This work is supported by the USDA National Institute of Food and Agriculture, acc no 1025934.

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