When and how will the Millennium Silk Road witness 1.5 °C and 2 °C warmer worlds?

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\textbf{ABSTRACT}

Western China and central Asia are positioned centrally along the Millennium Silk Road, which is regarded as a core region bridging the East and the West. Understanding the potential changes in climate over this core region is important to the successful implementation of the so-called ‘Belt and Road Initiative’ (a $1 trillion regional investment in infrastructure). In this study, both mean and extreme climate changes are projected using the ensemble mean of CMIP5 models. The results show a warming of ~1.5, 2.9, 3.6, and 6.0 °C under RCP2.6, 4.5, 6.0, and 8.5, respectively, by the end of the twenty-first century, with respect to the 1986–2005 baseline period. Meanwhile, the annual mean precipitation amount increases consistently across all RCPs, with an increase by ~14% with respect to 1986–2005 under RCP8.5. The warming over the Millennium Silk Road region reaches 1.5 °C before 2020 under all the emission scenarios. The 2020s (2030s) see a 2 °C warming under the RCP8.5 (RCP4.5) scenario. Global warming that is 0.5 °C lower (i.e. a warming of 1.5 °C) could result in the avoidance of otherwise significant impacts in the Silk Road core region—specifically, a further warming of 0.73 °C (with an interquartile range of 0.49%–0.94 °C) and an increase in the number of extreme heat days by 4.2, at a cost of a reduced increase of 2.72% (0.47%–3.82%) in annual precipitation. The change in consecutive dry days is region-dependent.

1. Introduction

The Silk Road is a historically important international trade route between China and the Mediterranean. As a network of trade routes, formally established during the Han Dynasty of China around 130 BCE (before common era to open trade with the west, the Millennium Silk Road has served as a thoroughfare from east to west and linked the regions of the ancient world in commerce. Because China’s silk comprised a large proportion of the trade along this ancient road, in 1877 it was named the ‘Silk Road’
Recent decades have seen a wetting trend along with warming conditions in some regions of the Millennium Silk Road. Efforts have been devoted to understanding observed past changes. A warming trend larger than the global mean during recent decades has been found for Northwest China (Hu et al. 2014; Li, Chen, and Shi 2012). Meanwhile, associated with the increased specific humidity and southward displacement of the Asian subtropical westerly jet, a significant wetting trend has been seen in this region (Peng and Zhou 2017). Many factors have been suggested to affect the climate of central Asia, including the interannual variability of the Asian westerly jet (Zhao et al. 2014), El Niño–Southern Oscillation (Mariotti 2007), the Indian summer monsoon (Wei et al. 2017), and circumglobal teleconnection (Ding and Wang 2005; Huang et al. 2015). These studies generally focused on interpreting observed climate changes, whereas less effort has been devoted to climate change projection (Huang et al. 2014; Wang et al. 2017), as compared to the many publications on the projection of East and South Asian climate change (Chen, Xu, and Yao 2015; Chen and Zhou 2015; Chen and Zhou 2017; Guo et al. 2016, 2017; He and Zhou 2015; Kitoh et al. 2013; Li, Zou, and Zhou 2017; Peng et al. 2016; Xu et al. 2017; Zou and Zhou 2015, 2016).

The parties of the United Nations Framework Convention on Climate Change (UNFCCC) signed the Paris Agreement in December 2015. The Paris Agreement stated a long-term goal for climate protection as ‘holding the increase in the global average temperature to well below 2.0 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.’ (UNFCCC 2015). As a result of the Paris Agreement, there is considerable interest in the scientific community to provide input on the projected climate impacts under a climate warming scenario that stabilizes at 1.5 °C in terms of water availability, temperature and precipitation extremes, as well as ecological and agricultural impacts (Hulme 2016; King, Karoly, and Henley 2017; Li et al. 2018; Mitchell et al. 2016; Schleussner et al. 2016a, 2016b). For China specifically, extreme precipitation days (annual number of days with precipitation greater than 50 mm) and total precipitation during days when daily precipitation exceeds the 99th percentile, are projected to increase by 25.81% and 69.14%, respectively, with respect to the 1971–2000 base period, as determined by model ensemble data from phase 5 of the Coupled Model Intercomparison Project (CMIP5; Guo et al. 2016). The Intergovernmental Panel on Climate Change (IPCC) has accepted an invitation from the UNFCCC to provide a special report on the impacts of global warming of 1.5 °C above pre-industrial levels. However, information on climate change over the regions of the Millennium Silk Road in a 1.5 and 2 °C global warming world remains quite limited. Accordingly, this study aims to answer the following questions: (1) How will temperature and precipitation change over the SRC region in the coming century under

Figure 1. The (a) topography (units: m) and (b) annual mean precipitation amount (units: mm yr⁻¹) over the Eurasian continent. The thick black lines indicate the Silk Road core region.
different warming scenarios? (2) When will the Millennium Silk Road witness warming of 1.5 and 2 °C? (3) How will the mean state and extreme climate events change over the SRC region in a 1.5 and 2 °C global warming future?

2. Data and methods

The historical simulations and projections under different Representative Concentration Pathways (RCPs) from coupled climate models in CMIP5 (Taylor, Stouffer, and Meehl 2012) are analyzed. The models used in the construction of the analysis fields given in this study vary with the research focus, since we hope to use as many model results as possible to reduce the uncertainties. As summarized in Table 1, data from 24 models are used to calculate the regional average annual mean surface air temperature (SAT) and precipitation under all four RCP scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), shown in Figure 2. The projected SAT under two RCPs (RCP4.5 and RCP8.5) is derived from 40 CMIP5 climate/earth system models (Table 1) and used to calculate the 1.5 and 2 °C threshold-crossing times shown in Figure 3. Taking 2 °C warming for example, this is defined as the SAT anomalies larger than 2 °C relative to the mean state during 1861–1890 in the historical simulation. To reduce the uncertainty in calculating the threshold-crossing time due to interannual variability, a nine-year running average is used to smooth the time series of SAT anomalies. Then, the 2 °C threshold-crossing time is defined as the

| Model | Institute/Country | Atmosphere (latitude × longitude, level) | Ocean (latitude × longitude, level) |
|-------|-------------------|-----------------------------------------|-----------------------------------|
| ACCESS1.0 | CSIRO–BOM/Australia | 145 × 192, L38 | 300 × 360, L50 |
| ACCESS1.3 | CSIRO–BOM/Australia | 145 × 192, L38 | 300 × 360, L50 |
| BCC_CSM1.1 | BCC–China Meteorological Administration (CMA)/China | 64 × 128, L26 | 232 × 360, L40 |
| BCC_CSM1.1(m) | BCC–CMAC/China | 160 × 320, L26 | 232 × 360, L40 |
| BNU-ESM | Beijing Normal University/China | 64 × 128, L26 | 200 × 360, L50 |
| CanESM2 | CCCma/Canada | 64 × 128, L35 | 192 × 256, L40 |
| CCSR | NS–DOE–NCAR/USA | 192 × 288, L27 | 384 × 360, L60 |
| CESM1(BGC) | NS–DOE–NCAR/USA | 192 × 288, L27 | 384 × 360, L60 |
| CESM1(CMA) | NS–DOE–NCAR/USA | 192 × 288, L27 | 384 × 360, L60 |
| CESM1(WACCM) | NS–DOE–NCAR/USA | 192 × 288, L27 | 384 × 360, L60 |
| CMCC-CM | CMCC/Italy | 240 × 480, L27 | 149 × 182, L31 |
| CMCC-CMS | CMCC/Italy | 96 × 192, L35 | 149 × 182, L31 |
| CNRM-CM5 | Centre National de Recherches | 128 × 256, L31 | 292 × 362, L42 |
| CESM1(E2) | CSIRO–QCCCE/Australia | 96 × 192, L18 | 189 × 192, L31 |
| EC-EARTH | Irish Centre for High-End Computing/Nether- | 160 × 320, L62 | 292 × 362, L31 |
| FGOALS-g2 | LSGG–Center for Earth System Science/China | 60 × 128, L26 | 196 × 360, L30 |
| FGOALS-s2 | LSGG–IAP/China | 64 × 128, L26 | 196 × 360, L30 |
| FIO-ESM | First Institute of Oceanography/China | 64 × 128, L26 | 384 × 320, L40 |
| GFDL CM3 | NOOA–GFDL/USA | 90 × 144, L48 | 200 × 360, L50 |
| GFDL ESM2G | NOOA–GFDL/USA | 90 × 144, L48 | 210 × 360, L63 |
| GFDL ESM2 M | NOOA–GFDL/USA | 90 × 144, L48 | 200 × 360, L50 |
| GISS-E2-H | NASA–GISS/USA | 89 × 144, L40 | 180 × 288, L32 |
| GISS-E2-H/CC | NASA–GISS/USA | 89 × 144, L40 | 180 × 288, L32 |
| GISS-E2/R | NASA–GISS/USA | 89 × 144, L40 | 180 × 288, L32 |
| GISS-E2/R-CC | NASA–GISS/USA | 89 × 144, L40 | 180 × 288, L32 |
| HadGEM2-ES | National Institute of Meteorological Research– | 144 × 192, L60 | 216 × 360, L40 |
| HadGEM2-AO | Korea Meteorological Administration/South Korea | | |
| HadGEM2-CC | UKMO Hadley Centre/UK | 144 × 192, L60 | 216 × 360, L40 |
| HadGEM2-ES | UKMO Hadley Centre/UK | 144 × 192, L38 | 216 × 360, L40 |
| INM-CM4 | Institute of Numerical Mathematics/Russia | | |
| IPSL-CM5A-LR | IPSL/France | 96 × 96, L39 | 149 × 182, L31 |
| IPSL-CM5A-LR | IPSL/France | 143 × 144, L39 | 149 × 182, L31 |
| IPSL-CM5B-LR | IPSL/France | 96 × 96, L39 | 149 × 182, L31 |
| MIROC5 | JAMSTEC, AORI, NIES/Japan | 128 × 256, L40 | 224 × 256, L50 |
| MIROC-ESM | JAMSTEC, AORI, NIES/Japan | 64 × 128, L80 | 192 × 256, L44 |
| MIROC-ESM-CHEM | JAMSTEC, AORI, NIES/Japan | 64 × 128, L80 | 192 × 256, L44 |
| MPI-ESM-LR | MPI–Meteorology/Germany | 96 × 192, L47 | 220 × 256, L40 |
| MPI-ESM-MR | MPI–Meteorology/Germany | 96 × 192, L96 | 404 × 802, L40 |
| MRI-CGCM3 | Meteorological Research Institute/Japan | 160 × 320, L48 | 368 × 360, L51 |
| NorESM1-M | Norwegian Climate Centre (NCC)–Norwegian Meteorological Institute (NMI)/Norway | 96 × 144, L26 | 384 × 320, L53 |
| NorESM1-ME | NCC–NMI/Norway | 96 × 144, L26 | 384 × 320, L53 |

Note: “A” indicates that the full name of JAMSTEC, AORI, NIES is “Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology”.
the 1.5 and 2 °C warming scenarios are aggregated from the nine-year windows centered on the years when 1.5 and 2 °C warming above pre-industrial levels (1861–90) is reached. The climate changes in a 1.5 or 2 °C warmer world are calculated for each model separately to derive multi-model ensembles.

3. Results

We begin the analysis from the projected changes of annual mean SAT and precipitation over the Silk Road core (SRC) region (outlined in black in Figure 1). Changes are relative to the 1986–2005 mean, with nine-year smoothing applied. Thick lines show the multi-model mean, and shading the interquartile ranges. Dotted (dashed) lines show the timing of 1.5 °C (2 °C) warming over the SRC region and the corresponding changes in the multi-model mean.

First year when the SAT anomalies reach 2 °C. The model outputs are remapped onto a 5° × 5° grid by bilinear interpolation for reliable large-scale information.

The data from the 24 models in bold type in Table 1 are used to derive the extreme indices presented later in the paper because daily data is only provided by these models. The standard definitions of the extreme indices are adapted from the Expert Team on Climate Change Detection and Indices (Zhang et al. 2011). Two indices are used in our analysis. The first is ‘consecutive dry days’ (CDD), which is defined as the largest number of consecutive days with daily precipitation less than 1 mm. The second is ‘extreme heat event’, which is defined as the annual count of days when the daily maximum temperature is greater than 35 °C. The extreme indices are calculated on the native grids of the individual models and then regridded to a common resolution of 1° × 1° to derive multi-model ensembles.

In our analysis, to account for future deviations from the current climate, a common reference period of 1986–2005 is referred to as the baseline scenario. The results for the 1.5 and 2 °C warming scenarios are aggregated from the nine-year windows centered on the years when 1.5 and 2 °C warming above pre-industrial levels (1861–90) is reached. The climate changes in a 1.5 or 2 °C warmer world are calculated for each model separately to derive multi-model ensembles.
These warming magnitudes are around 0.2–0.8 °C greater than the global land average, and 0.5–2.0 °C greater than the global mean (Figures 3 and 4). The more severe the emissions scenario, the greater the difference in warming. Such an amplification of warming in dry regions is related to the positive land surface feedback, as reported in Huang et al. (2017).

The annual mean precipitation amount increases consistently across all RCPs, although the model spread is large (Figure 2(b)). The percentage increases are faster than the global average (Figures 3(b) and 4(b)). For example, the annual mean precipitation amount is projected to increase by ~14% with respect to 1986–2005 over the SRC region by the end of the twenty-first century, as compared to ~6.5% for the global land area and ~6.8% for the global mean, under RCP8.5 (compare Figure 2(b) with Figures 3(b) and 4(b)).

But when will the Millennium Silk Road reach a 1.5 and 2 °C warming? The respective timings under different emission scenarios and the corresponding changes are shown in Figure 2. Also, more specifically, we show the spatial patterns of the 1.5 and 2 °C threshold-crossing time under the RCP4.5 and RCP8.5 scenarios over the Eurasian continent in Figure 5. For the multi-model ensemble mean, the 1.5 °C threshold-crossing time in the SRC region is projected to be reached before 2020, under all the emission scenarios. The 2 °C threshold is projected to be breached no later than 2030. Under RCP8.5, this could be as early as 2022. It is unsurprising to see an expected earlier threshold-crossing time under the higher emission scenarios. However, it should be noted that there is large spread among the

**Figure 4.** Projected changes in annual mean surface air temperature and precipitation over the globe. Changes are relative to the 1986–2005 mean, with nine-year smoothing applied. Thick lines show the multi-model mean, and shading the interquartile ranges. Dotted (dashed) lines show the timing of 1.5 °C (2 °C) warming over the globe and the corresponding changes in the multi-model mean. Note that 2 °C warming will not be reached under RCP2.6.

**Figure 5.** The (a, c) 1.5 °C and (b, d) 2 °C threshold-crossing time under the (a, b) RCP4.5 and (c, d) RCP8.5 scenarios over the Eurasian continent. The black outline denotes the Silk Road core region.
CMIP5 models in the projection of the 1.5 and 2 °C threshold-crossing times (not shown), which can be explained in terms of different climate sensitivities to anthropogenic forcing in different models (Chen and Zhou 2016).

The threshold-crossing time over the SRC region is earlier than that over the global land area or global mean (compare Figure 2(a) with Figures 3(a) and 4(a)). Under the RCP8.5 scenario, for example, a regional 1.5 °C (2 °C) warming over the SRC region is breached in 2010 (2022), whereas over the global land area and for the global mean the years are 2015 (2028) and 2025 (2039), respectively.

But how will the pattern of annual mean SAT and precipitation change over the regions of the Millennium Silk Road under the 1.5 and 2 °C global warming scenarios? Based on Figure 6, we examine the multi-model ensemble mean changes of annual mean SAT between the 1.5 or 2.0 °C warmer world relative to the base period (1986–2005).

Crucially, although generally a warmer and wetter climate mean state is expected under the 1.5 and 2 °C global warming scenarios, the specific changes between a 1.5 and 2 °C warmer world are regionally dependent. For instance, a 1.5 °C warmer world induces a regional annual mean warming of 1.24 °C relative to the 1986–2005 base period over the SRC region, with an interquartile range of 0.92–1.63 °C. Compared with the 1.5 °C warmer world, however, the additional 0.5 °C under global warming of 2 °C leads to a further warming by 0.73 °C (interquartile range is 0.49–0.94 °C, similarly hereinafter) over the SRC region, which is much greater than the global mean level.

The annual mean precipitation amount increases by 4.77% (2.31%–8.59%) under warming of 1.5 °C relative to the baseline, but the extra 0.5 °C under global warming of 2 °C brings a further 2.72% (0.47%–3.82%) increase in precipitation over the SRC region. The spatial pattern features

![Figure 6](image_url)

**Figure 6.** Multimodel ensemble mean changes in annual mean surface air temperature (a) between a 1.5 °C warmer world and the 1986–2005 baseline period, (b) between a 2 °C warmer world and the baseline period, and (c) between a 2 and 1.5 °C warmer world. (d–f) As in (a–c) but for the percentage changes in annual precipitation relative to 1986–2005. Projections under RCP8.5 are employed. Dots denote where at least two-thirds of the models agree in the sign of change.
Based on Figure 8, we further examine the changes in extreme heat events associated with warming. The changes in extreme heat events exhibit a uniform increase over the SRC region, especially over central Asia (38°–50°N, 50°–70°E) and Xinjiang Province (38°–45°N, 65°–90°E). Changes over most of the SRC region are statistically significant at the 0.1% level, except those in Qinghai Province and southern Gansu Province. The additional 0.5 °C under warming of 2 °C increases (decreases) CDD by up to six (five) days in the southwestern (northeastern) part of SRC region.

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4. Summary and concluding remarks

Western China and central Asia are positioned centrally along the Silk Road, and are together referred to as the Millennium SRC region. This region encompasses arid and semi-arid climate and is thus sensitive to climate change. The Belt and Road Initiative is a sophisticated network of
(4) Changes in CDD are regionally dependent, with longer (shorter) dry spells in the southwestern (northeastern) part. The additional 0.5 °C under warming of 2 °C increases (decreases) the CDD by up to six (five) days in the southwestern (northeastern) part of the SRC region. A uniform increase in extreme heat is seen across the SRC region under the 1.5 °C warming scenario, with the additional 0.5 °C under the 2 °C global warming scenario significantly increasing the number of extreme heat events.

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