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CHELSA and WorldClim agree on the direction of warming but differ in its magnitude and in precipitation at three mountain sites of the Tien Shan

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Abstract: Mountain climate assessments in Central Asia are sensitive to the choice of gridded climate dataset, particularly in complex terrain where meteorological observations are sparse. This study compared annual air temperature (1980–2019) and precipitation (1980–2018) series extracted from CHELSA v2.1 and WorldClim 2.1 historical monthly data at three mountain sites of southeastern Kazakhstan and the Tien Shan: Kegen Pass, Tekeli Gorge and the Terskey Alatau–Saryzhaz site. Trends were assessed with the Mann–Kendall test with trend-free pre-whitening and Sen's slope, and the temperature series were extended to 2040 with ARIMA models. Both products indicated warming at all three sites, but its magnitude differed. WorldClim showed nearly uniform trends of 0.31–0.38 °C per decade ($p < 0.001$), with decadal means rising by 0.9–1.0 °C between 1980–1989 and 2010–2019, whereas CHELSA showed weaker and more variable trends of 0.14–0.23 °C per decade (0.3–0.7 °C between the same decades); at Kegen Pass the CHELSA trend was only marginally significant. WorldClim was 1.2–4.2 °C warmer than CHELSA in absolute terms. Divergence was greater for precipitation: at Tekeli Gorge CHELSA gave about twice the WorldClim amount (mean 94 vs 48 mm per month), and a significant increase was found only in CHELSA at the Terskey Alatau–Saryzhaz site (+8.6 mm per month per decade, $p < 0.001$) and, more weakly, at Kegen Pass. ARIMA forecasts for 2040 exceeded the 2010–2019 mean by 1.0–1.1 °C in the WorldClim series and by –0.1 to +0.6 °C in the CHELSA series, but the 95% prediction intervals (about ± 1 °C) overlapped, so the forecast differences are not statistically distinguishable. The direction of long-term warming is therefore robust to product choice, whereas absolute values, warming magnitude and precipitation remain product-dependent and should be treated as structural uncertainty in mountain-climate and environmental assessments.

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1 Introduction

Mountains compress strong climatic gradients into short horizontal distances. Elevation, slope orientation, exposure, valley geometry, snow persistence and local circulation create contrasting thermal and moisture regimes within the same mountain system. Warming may intensify with elevation, although its magnitude varies among regions and seasons (Pepin et al., 2015), while observational coverage decreases with elevation, leaving many high-mountain areas poorly represented by long-term meteorological records (Thornton et al., 2022). These limitations are particularly important in Central Asia,

where mountain climates influence water supply, agriculture, rangelands and downstream socio-ecological systems (Saidaliyeva et al., 2024).

The Tien Shan is a clear example. Long-term observations show substantial climatic and hydrological change since the second half of the twentieth century (Aizen et al., 1997; Unger-Shayesteh et al., 2013), and glacier mass declined by about 27% between 1961 and 2012 (Farinotti et al., 2015), raising concern over the stability of the Central Asian “water tower” (Chen et al., 2016). The warming signal is not spatially uniform: temperature and precipitation responses vary with elevation and season (Deng et al., 2015), the overall warming rate was about 0.32 °C per decade during 1960–2016 (Xu et al., 2018), and precipitation trajectories are heterogeneous and difficult to characterize at high elevations because of sparse gauge coverage (Guan et al., 2022; Jin et al., 2024). In Kazakhstan, 74 meteorological stations indicate a median warming of about 0.30 °C per decade during 1981–2023, somewhat stronger above 1500 m (Duissebek et al., 2026).

Because direct observations are sparse, gridded climate products are widely used in studies of vegetation, hydrology, land degradation and climate risk. However, relatively little is known about whether alternative high-resolution products describe the same long-term climatic trajectory at specific mountain locations in southeastern Kazakhstan and the adjacent Tien Shan. Station-based studies quantify regional trends (Deng et al., 2015; Xu et al., 2018; Duissebek et al., 2026) but do not evaluate gridded products, and Kyrgyzbay et al. (2023) compared open climate products with ground observations in the Almaty region and found larger discrepancies in mountainous terrain than on the plains, but did not compare the time series of CHELSA and WorldClim at mountain sites. The present study addresses this gap: it compares the two most widely used kilometre-scale products at the same mountain localities, tests their trends formally and examines how their differences carry over into statistical forecasts.

WorldClim provides interpolated climate surfaces based on station observations and geographic covariates (Hijmans et al., 2005; Fick & Hijmans, 2017), whereas CHELSA uses a topographically informed downscaling of atmospheric reanalysis, including orographic effects on precipitation (Karger et al., 2017). Other products, including CRU TS, TerraClimate and ERA5, differ in resolution, interpolation, data assimilation and intended use (Abatzoglou et al., 2018; Harris et al., 2020; Hersbach et al., 2020). Nominal resolution should not be confused with climatic realism: a kilometre-scale raster inherits uncertainty from sparse observations and unresolved topoclimatic processes. Changing the climate input from WorldClim to CHELSA altered estimates of potential species distribution in the Himalayas (Bobrowski & Schickhoff, 2017), finer-resolution products are not superior for every variable or mountain region (Bobrowski et al., 2021), and streamflow-based evaluation revealed systematic biases in global precipitation climatologies (Beck et al., 2020). Precipitation is particularly sensitive: CHELSA and WorldClim gave similar temperature patterns but different precipitation-based classifications in northern Patagonia (Fierke et al., 2024), and both misrepresented precipitation maxima on tropical mountains (Hemp & Hemp, 2024; Newell et al., 2022). Climate-services and ecological-modelling studies therefore recommend that such uncertainty be characterized and propagated rather than removed by selecting a single dataset (Littell et al., 2011; Otto et al., 2016).

The study has three objectives: (1) to determine whether CHELSA and WorldClim indicate a consistent direction and a comparable magnitude of temperature and precipitation change during 1980–2019; (2) to evaluate whether inter-product disagreement differs among sites and is greater for precipitation than for temperature; and (3) to assess whether historical discrepancies are carried forward into ARIMA-based forecasts to 2040. We expected the direction of warming to be more robust than its local magnitude and precipitation to show the strongest product dependence. The three sites are localities of the rare species *Adonis tianschanica* (Kulymbet et al., 2023); they were chosen because gridded climate layers are routinely used as predictors in species-distribution and habitat models for such localities, so that differences between products translate directly into uncertainty in environmental assessments.

2 Materials and methods

2.1 Study sites

The study covered three mountain sites in southeastern Kazakhstan and the adjacent Tien Shan: Kegen Pass in the Ketmen Ridge (KP), Tekeli Gorge in the Zhetysu (Dzungarian) Alatau (TG) and the Terskey Alatau near Saryzhaz (TAS) (Figure 1). Field reference points were taken from Kulymbet et al. (2023): two points at Kegen Pass (43.143417° N, 79.196194° E and 43.143444° N, 79.189389° E), two in Tekeli Gorge (44.796444° N, 78.994694° E and 44.796167° N, 78.992778° E) and one in the Terskey Alatau (42.874194° N, 79.749556° E). The paired points at Kegen and Tekeli lie only 150–550 m apart, i.e. within one or two adjacent grid cells, and were therefore treated as a single site. The analysis is thus based on point extraction at three sites; the sites represent, but do not spatially sample, the surrounding mountain ranges.

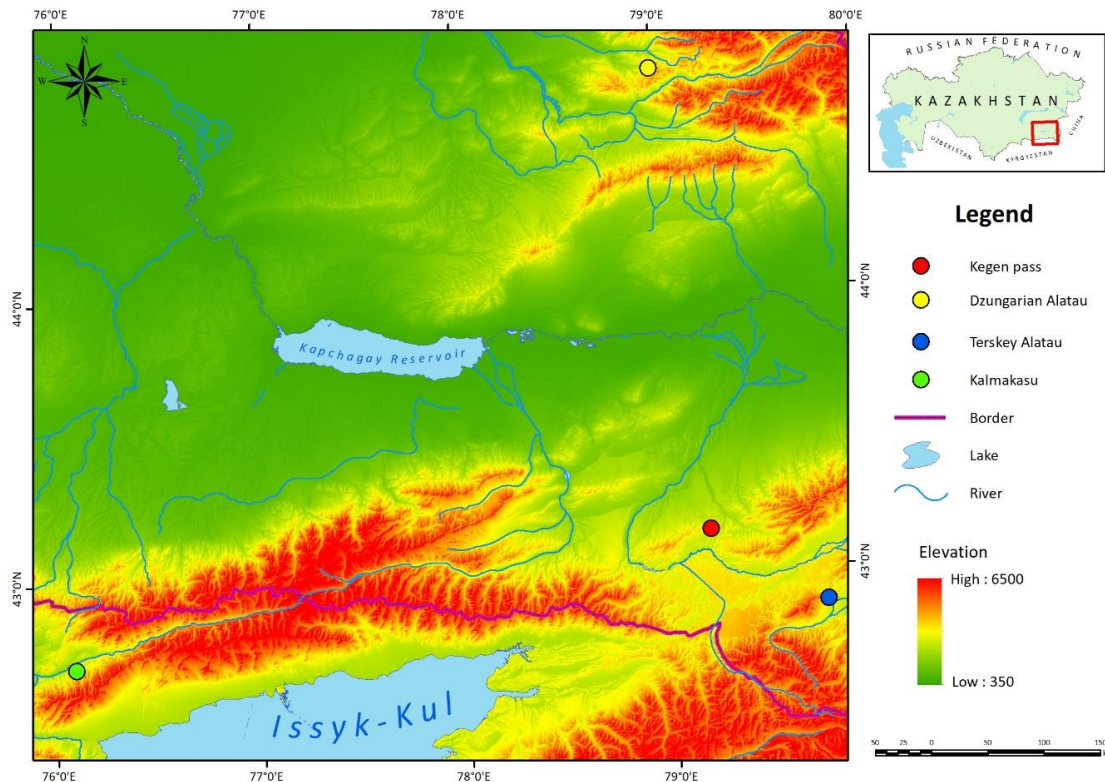


Figure 1. Location of the Kegen Pass, Tekeli Gorge (Dzungarian Alatau) and Terskey Alatau–Saryzhaz study sites. The Kalmakasu point shown in the legend was not used in this study. Background: digital elevation model (m a.s.l.)

The elevations of the reference points and of the surrounding terrain are given in Table 1. The points lie at about 1.950–2.160 m a.s.l. Kegen represents the southeastern part of the Northern Tien Shan in an intermontane setting adjoining the Ketmen Ridge, Tekeli lies farther north in the strongly dissected Zhetysu Alatau, and the Saryzhaz site represents a colder high-mountain environment of the Terskey Alatau.

Table 1. Elevation of the reference points and of the surrounding terrain

Site	Reference point(s), m a.s.l. (SRTM, 30 m)	Terrain at 1 arc-minute (ETOPO1), m	Terrain within the 2.5 arc-minute cell, m (range of four sampled values)
Kegen Pass (KP)	1.953; 2.034	1.892	1.706–1.932
Tekeli Gorge (TG)	2.063; 2.018	2.099	1.759–1.998
Terskey Alatau–Saryzhaz (TAS)	2.159	2.168	2.091–2.686

Source: compiled by the authors from SRTM and ETOPO1 elevation data (OpenTopoData).

2.2 Climate datasets

Candidate global and regional datasets (including CRU TS, TerraClimate, ERA5, CHELSA and WorldClim) were screened using three criteria: (i) availability of monthly temperature and precipitation; (ii) spatial resolution suitable for mountain-scale assessment; and (iii) temporal coverage of several decades. CHELSA and WorldClim were selected because they are the products most widely used as kilometre-scale climate predictors and are based on different temporal data sources.

CHELSA v2.1 monthly time series of mean, maximum and minimum near-surface air temperature (tas, tasmax, tasmin) and precipitation (pr) have a resolution of 30 arc-seconds (about 1 km) and are produced by topographic downscaling of the ERA5 reanalysis (Karger et al., 2017, 2021; Brun et al., 2022; Hersbach et al., 2020). The stored integer values were converted to physical units with the scale and offset given in the technical documentation (temperature: K/10 converted to °C; precipitation: kg m⁻² month⁻¹/100, i.e. mm per month). WorldClim 2.1 historical monthly weather data provide minimum and maximum temperature and precipitation at a resolution of 2.5 arc-minutes (about 4.6 km in latitude); they are produced by applying the monthly anomalies of the CRU TS dataset (0.5° resolution) to the WorldClim 2.1 climatology (Fick & Hijmans, 2017; Harris et al., 2020; WorldClim, 2020). The two products therefore differ in both spatial resolution and temporal source (ERA5 versus interpolated station anomalies of CRU TS), which is essential for interpreting their differences.

The comparison was not designed as a validation of either dataset. Because no independent station records were available for the three sites, differences between CHELSA and WorldClim were interpreted as inter-product divergence rather than as error, and neither product was treated as a reference. Station-based regional trends from the literature (Xu et al., 2018; Duisebek et al., 2026) were used as an external benchmark in the discussion.

2.3 Variables, periods and aggregation

Mean (Tmean), maximum (Tmax) and minimum (Tmin) air temperature and precipitation (P) were analysed. For WorldClim, which does not supply mean temperature, Tmean was calculated as:

$$T_{mean} = (T_{max} + T_{min}) / 2 \quad (1)$$

For CHELSA, the supplied mean temperature (tas) was used. Monthly values were averaged to annual means. Temperature series cover 1980–2019 (40 years) and precipitation series cover 1980–2018 (39 years), the period for which monthly precipitation was available for both products. Precipitation is reported as the mean monthly amount of each year (mm per month), i.e. the annual total divided by 12; annual totals are given alongside for orientation. Decadal means were calculated for 1980–1989, 1990–1999, 2000–2009 and 2010–2019 (2010–2018 for precipitation and for the maps in Figure 2).

2.4 GIS processing

Spatial processing was performed in ArcGIS 10.4 with Spatial Analyst tools. Monthly raster layers were organized by variable, year, month and dataset and clipped to the study region, and the values of the grid cells containing the reference points were extracted (single-cell extraction). Decadal maps of mean temperature were produced for visual comparison (Figure 2). The same reference points and extent were used throughout so that differences between products reflect climatic representation rather than sampling location.

2.5 Trend analysis and inter-product comparison

The warming magnitude was defined in two ways: (i) the difference between the decadal means of 2010–2019 and 1980–1989, and (ii) the linear trend estimated with Sen's slope (Sen, 1968) and its 95% confidence interval, expressed per decade. The significance of monotonic trends was tested with the Mann–Kendall test (Mann, 1945; Kendall, 1975) after trend-free pre-whitening, which accounts for lag-1 autocorrelation (Yue et al., 2002); p-values of the unmodified test are reported where the two differ in

interpretation. The same tests were applied to precipitation. Products were compared by (a) the mean difference of the annual series (WorldClim minus CHELSA), (b) the Pearson correlation between the two annual series at each site, and (c) the agreement in the sign, magnitude and significance of trends. We distinguished signal agreement, where both products indicate change in the same direction, from magnitude agreement, where the size of the change is also comparable. Because only annual series were analysed, seasonal trends were not assessed.

2.6 ARIMA forecasting

To examine how differences between products propagate into near-term statistical forecasts, autoregressive integrated moving-average (ARIMA) models were fitted to each annual temperature series (Box et al., 2015). Because the series are annual, no seasonal component was included. The general model is:

$$\varphi(B)(1 - B)^d y_t = c + \theta(B) \varepsilon_t \quad (2)$$

where y_t is the annual mean temperature in year t , B is the backshift operator, $\varphi(B)$ and $\theta(B)$ are the autoregressive and moving-average polynomials of orders p and q , d is the order of differencing, c is a constant (a drift term when $d = 1$) and ε_t is the residual. Model orders were selected following the procedure of Hyndman and Khandakar (2008): d was determined with the KPSS test (Kwiatkowski et al., 1992) at the 5% level, and p and q (0–2) were chosen by minimizing the corrected Akaike information criterion (AICc). Residual autocorrelation was checked with the Ljung–Box test at lag 10 (Ljung & Box, 1978). Forecast skill was assessed by hold-out validation: models with the selected orders were fitted to 1980–2009 and used to predict 2010–2019, and the root-mean-square error (RMSE) and mean absolute error (MAE) were compared with a naive forecast equal to the 2000–2009 mean. Forecasts were then produced for 2020–2040 with 95% prediction intervals and compared with the 2010–2019 mean. Calculations were carried out in Python with the statsmodels (Seabold & Perktold, 2010) and py Mann-Kendall (Hussain & Mahmud, 2019) packages. The forecasts are statistical extrapolations of each series and not physically based climate scenarios.

3 Results

3.1 Temperature level and inter-product offset

WorldClim gave higher temperatures than CHELSA at all three sites (Table 2). The mean difference of the annual series was 4.19 °C at Kegen Pass, 1.21 °C at Tekeli Gorge and 2.08 °C at the Terskey Alatau–Saryzhaz site. The interannual variability of the two products was nevertheless positively correlated ($r = 0.80, 0.78$ and 0.83 , respectively). The decadal maps show the same general pattern in both products, with the warmest conditions in the lowlands and the coldest along the high ranges (Figure 2); because the two products are mapped with different class limits, the colours are not directly comparable between products.

3.2 Temperature trends

Both products indicated warming at all three sites (Figure 3, Table 2). In the WorldClim series, the decadal mean rose by +1.03 °C at Kegen Pass, +0.87 °C at Tekeli Gorge and +1.05 °C at the Terskey Alatau–Saryzhaz site between 1980–1989 and 2010–2019, and Sen's slopes were 0.37, 0.31 and 0.38 °C per decade, all highly significant ($p < 0.001$). In the CHELSA series the corresponding decadal differences were +0.33, +0.66 and +0.65 °C and the slopes were 0.14, 0.21 and 0.23 °C per decade. The CHELSA trends were significant at Tekeli Gorge ($p = 0.002$) and at the Terskey Alatau–Saryzhaz site ($p < 0.001$), whereas at Kegen Pass the trend was only marginal: $p = 0.024$ after pre-whitening and $p = 0.062$ with the unmodified test, and the confidence interval of the slope includes zero. In the WorldClim series, warming was concentrated between the 1990s and the 2000s, and the 2010–2019 mean was close to that of 2000–2009, whereas the CHELSA series at Tekeli Gorge and the Terskey Alatau–Saryzhaz site continued to rise in the last decade.

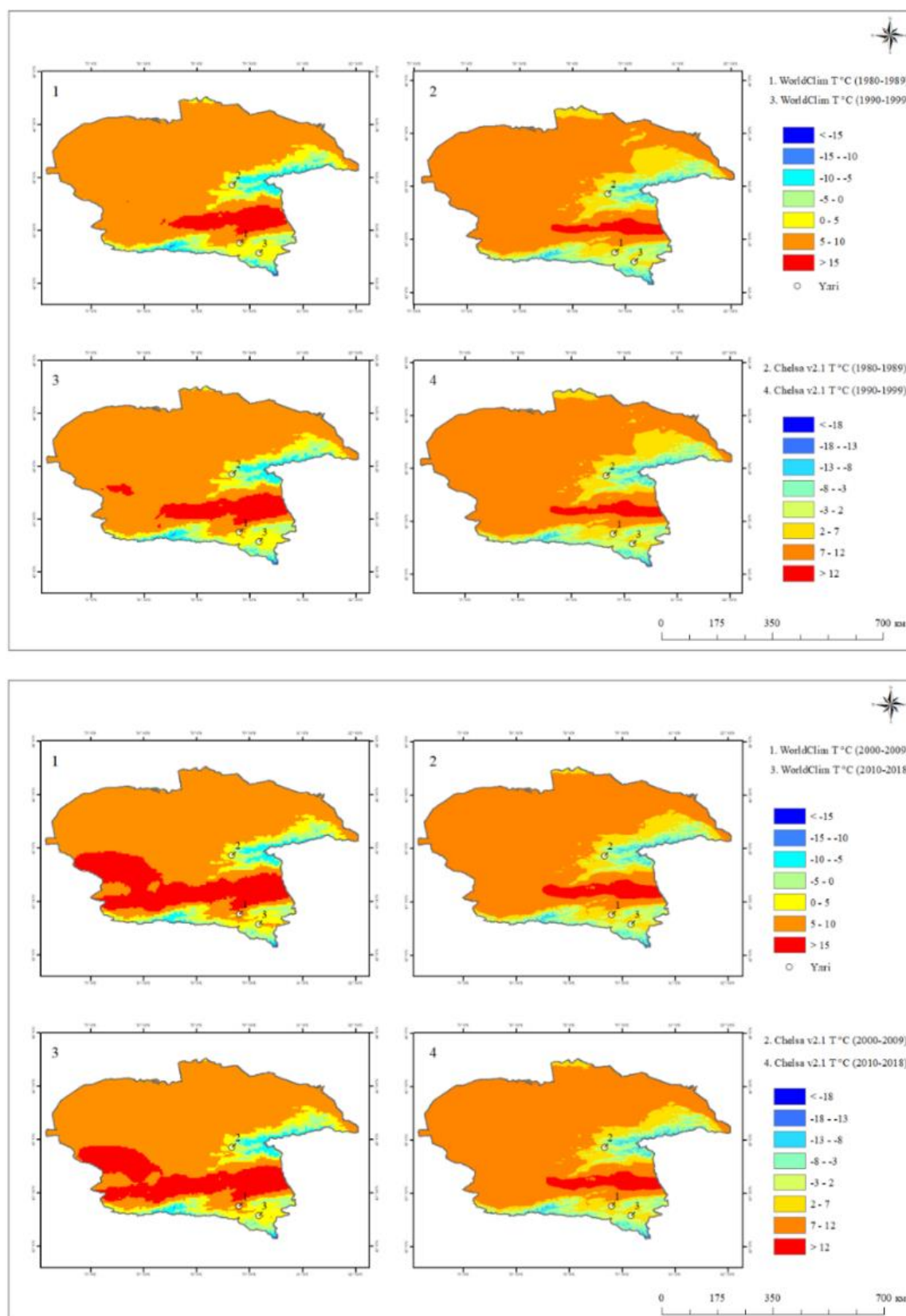


Figure 2. Decadal mean air temperature (°C) in the study region. Upper image: 1980–1989 (panels 1 and 2) and 1990–1999 (panels 3 and 4); lower image: 2000–2009 (panels 1 and 2) and 2010–2018 (panels 3 and 4). Panels 1 and 3 – WorldClim 2.1; panels 2 and 4 – CHELSA v2.1. Circles mark the study sites (1 – Kegen Pass, 2 – Tekeli Gorge, 3 – Terskey Alatau–Saryzhaz). Class limits differ between the two products

Source: compiled by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

Table 2. Decadal mean air temperature (°C) and trend statistics for 1980–2019

Site	Product	1980–1989	1990–1999	2000–2009	2010–2019	Δ , °C	Sen's slope, °C per decade (95% CI)	p
Kegen Pass	WorldClim	4.87	5.22	5.95	5.90	+1.03	+0.37 (0.19; 0.55)	< 0.001
	CHELSA	1.05	1.16	1.61	1.38	+0.33	+0.14 (−0.01; 0.28)	0.024
Tekeli Gorge	WorldClim	1.40	1.72	2.39	2.27	+0.87	+0.31 (0.14; 0.50)	< 0.001
	CHELSA	0.41	0.57	0.91	1.07	+0.66	+0.21 (0.08; 0.39)	0.002
Terskey Alatau–Saryzhaz	WorldClim	1.47	1.82	2.56	2.52	+1.05	+0.38 (0.20; 0.55)	< 0.001
	CHELSA	−0.32	−0.09	0.15	0.33	+0.65	+0.23 (0.09; 0.39)	< 0.001

Note: Δ – difference between the 2010–2019 and 1980–1989 means; p – Mann–Kendall test with trend-free pre-whitening. Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

The two products therefore agree on the sign of the temperature change but not on its magnitude or on its spatial pattern. WorldClim shows strong and nearly uniform warming at all three sites (0.31–0.38 °C per decade), whereas CHELSA shows weaker warming that differs more among sites (0.14–0.23 °C per decade), with the smallest trend at Kegen Pass. The WorldClim series at Kegen Pass and at the Terskey Alatau–Saryzhaz site are almost identical apart from a constant offset of 3.39 °C ($r = 1.00$; standard deviation of the difference 0.03 °C), and the Tekeli series is also very similar ($r = 0.98$). The corresponding correlations between sites in CHELSA are lower ($r = 0.82$ and 0.65). The uniformity of the WorldClim trends thus reflects a shared coarse-scale anomaly signal rather than three independent estimates.

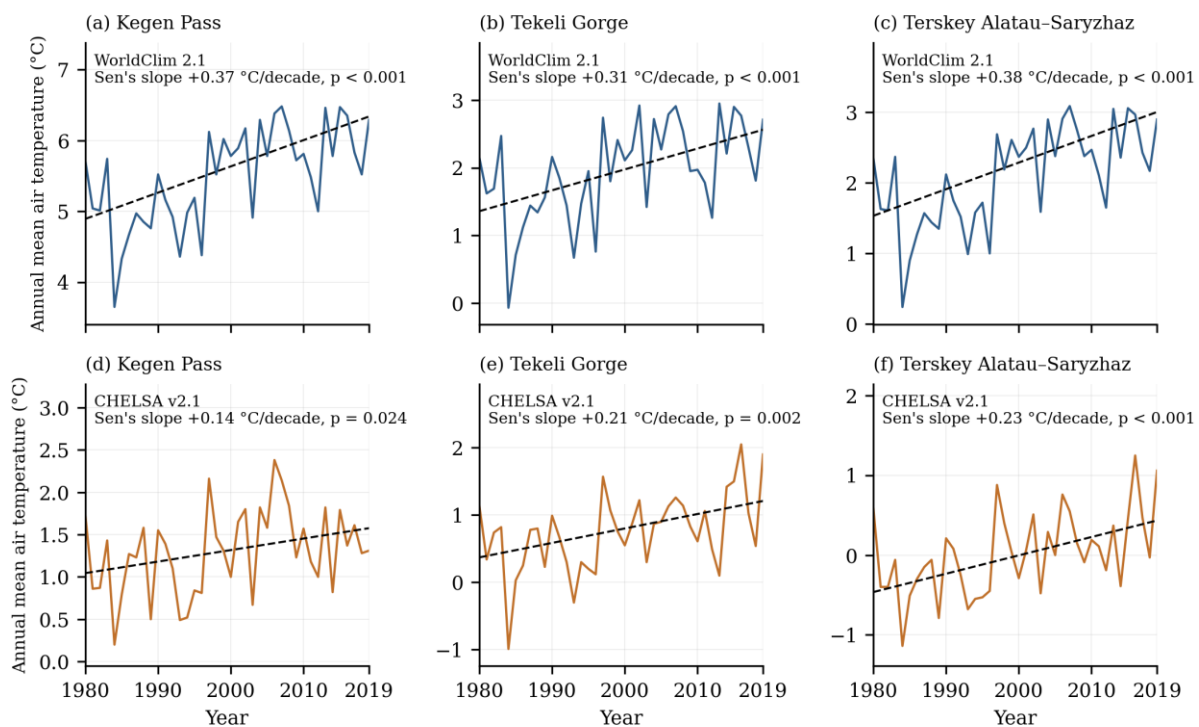


Figure 3. Annual mean air temperature at the three sites in 1980–2019: (a–c) WorldClim 2.1; (d–f) CHELSA v2.1. Dashed lines show the Sen's slope trend; p-values refer to the Mann–Kendall test with trend-free pre-whitening

Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

Maximum and minimum temperature also increased in both products (Table 3). In WorldClim, Tmax increased by 0.60–0.85 °C and Tmin by 0.86–1.00 °C between the earlier (1980–1999) and later (2000–2019) halves of the record, so that their average change (0.73–0.93 °C) is consistent with the change in Tmean between the same periods (0.77–0.89 °C). In CHELSA, Tmax increased by 0.48–0.87 °C and Tmin by 0.48–0.64 °C, compared with 0.39–0.50 °C for Tmean; the correspondence is less close because the CHELSA mean temperature is an independent variable and not the average of Tmax and Tmin. Both products thus indicate less severe low-temperature conditions at all three sites.

Table 3. Change in mean, maximum and minimum air temperature (°C) between 1980–1999 and 2000–2019

Site	Product	Tmean	Tmax	Tmin
Kegen Pass	WorldClim	5.04 → 5.93 (+0.89)	10.89 → 11.73 (+0.84)	−1.14 → −0.17 (+0.97)
	CHELSA	1.10 → 1.49 (+0.39)	6.94 → 7.42 (+0.48)	+0.48
Tekeli Gorge	WorldClim	1.56 → 2.33 (+0.77)	7.40 → 8.00 (+0.60)	−4.58 → −3.72 (+0.86)
	CHELSA	0.49 → 0.99 (+0.50)	5.42 → 6.29 (+0.87)	+0.56
Terskey Alatau–Saryzhaz	WorldClim	1.65 → 2.54 (+0.89)	7.81 → 8.66 (+0.85)	−4.84 → −3.84 (+1.00)
	CHELSA	−0.20 → 0.24 (+0.44)	5.21 → 5.95 (+0.74)	+0.64

Note: for CHELSA Tmin only the change is given. Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

3.3 Precipitation

Inter-product divergence was greater for precipitation than for temperature (Figure 4, Table 4). At Kegen Pass the two products were of similar magnitude, with CHELSA about 18% lower than WorldClim (mean 44 vs 54 mm per month). The strongest divergence occurred at Tekeli Gorge, where CHELSA gave about twice the WorldClim amount in every decade (mean 94 vs 48 mm per month, i.e. roughly 1,100 vs 570 mm per year). At the Terskey Alatau–Saryzhaz site the long-term means were similar (48 vs 46 mm per month), but the temporal behaviour differed: CHELSA increased from 36.6 mm per month in 1980–1989 to 65.3 mm per month in 2010–2018, whereas WorldClim remained between 43.0 and 49.1 mm per month.

The trend tests confirm this contrast. None of the WorldClim precipitation series showed a significant trend ($p = 0.191$ – 0.379). In CHELSA, a strong and highly significant increase was found at the Terskey Alatau–Saryzhaz site ($+8.6$ mm per month per decade, $p < 0.001$), a weaker increase at Kegen Pass ($+2.1$ mm per month per decade, $p = 0.024$; $p = 0.057$ with the unmodified test) and no significant trend at Tekeli Gorge ($p = 0.083$). The interannual correlation between the two products was only moderate ($r = 0.54, 0.33$ and 0.41), much lower than for temperature. For precipitation, the products therefore differ in amount, in interannual variability and in the presence of a trend.

Table 4. Decadal mean monthly precipitation, mm per month (annual total, mm, in parentheses), and trend statistics for 1980–2018

Site	Product	1980–1989	1990–1999	2000–2009	2010–2018	Sen's slope, mm per month per decade (95% CI)	p
Kegen Pass	WorldClim	51.7 (620)	49.2 (590)	56.6 (680)	57.1 (690)	+1.6 (−1.0; 4.7)	0.191
	CHELSA	42.6 (510)	41.7 (500)	43.4 (520)	49.4 (590)	+2.1 (0.0; 4.6)	0.024
Tekeli Gorge	WorldClim	47.0 (560)	44.0 (530)	50.7 (610)	49.1 (590)	+1.2 (−1.1; 3.5)	0.379
	CHELSA	90.9 (1090)	91.6 (1100)	87.0 (1040)	107.3 (1290)	+4.7 (−1.4; 9.8)	0.083
Terskey Alatau–Saryzhaz	WorldClim	44.9 (540)	43.0 (520)	48.1 (580)	49.1 (590)	+1.3 (−1.2; 3.7)	0.269
	CHELSA	36.6 (440)	43.0 (520)	47.2 (570)	65.3 (780)	+8.6 (6.1; 10.8)	< 0.001

Note: annual totals are rounded to 10 mm; p – Mann–Kendall test with trend-free pre-whitening. Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

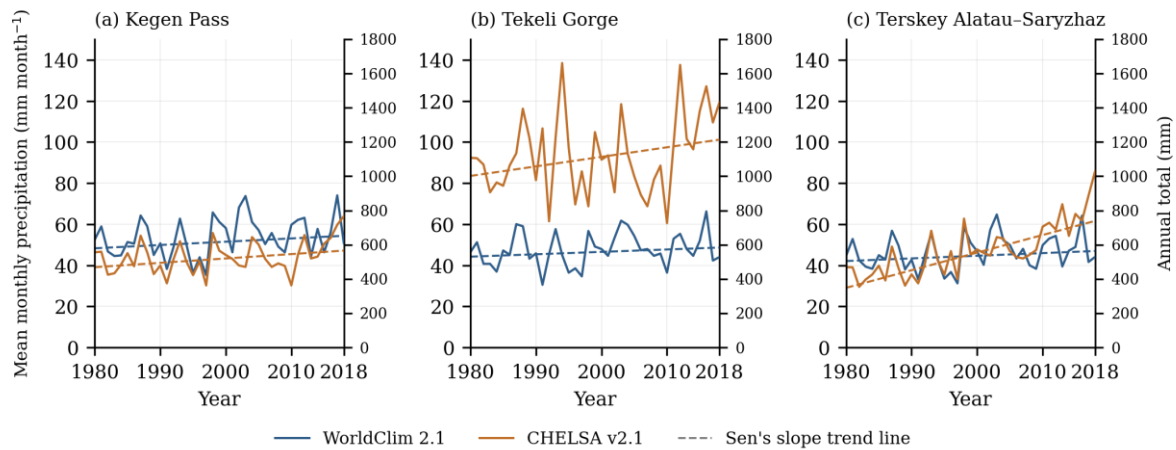


Figure 4. Mean monthly precipitation (left axis) and the corresponding annual total (right axis) at the three sites in 1980–2018 according to WorldClim 2.1 and CHELSA v2.1; dashed lines show the Sen's slope trend

Source: calculated by the authors from WorldClim 2.1 historical monthly data and CHELSA v2.1.

3.4 ARIMA forecasts to 2040

The selected models, diagnostics and forecasts are given in Table 5 and Figure 5. For five of the six series the KPSS test indicated non-stationarity and a model with one difference and a drift term was selected: ARIMA(0,1,1) for the three WorldClim series and for CHELSA at the Terskey Alatau–Saryzhaz site, and ARIMA(1,1,2) for CHELSA at Tekeli Gorge. For CHELSA at Kegen Pass, where the trend is weak, the series was classified as stationary and a constant-mean model, ARIMA(0,0,0), was selected. The Ljung–Box test did not indicate residual autocorrelation in any model ($p = 0.34$ – 0.89). In the hold-out validation for 2010–2019, the RMSE was 0.61 – 0.68 °C for WorldClim and 0.33 – 0.58 °C for CHELSA. The CHELSA models performed slightly better than the naive forecast, whereas the WorldClim models, which extrapolated the earlier warming, performed slightly worse because warming slowed in 2010–2019. Forecast skill at the decadal horizon is therefore limited.

Table 5. ARIMA models, diagnostics and forecasts of annual mean air temperature (°C)

Site	Product	ARIMA (p,d,q)	Ljung–Box Q (df); p	Hold-out RMSE / MAE / naive RMSE	Mean 2010–2019	Forecast mean 2020–2040	Forecast 2040 (95% PI)	2040 minus 2010–2019
Kegen Pass	WorldClim	(0,1,1)	9.9 (9); 0.36	0.62 / 0.50 / 0.47	5.90	6.62	7.00 (5.92; 8.08)	+1.10
	CHELSEA	(0,0,0)	10.4 (10); 0.41	0.33 / 0.27 / 0.39	1.38	1.30	1.30 (0.33; 2.27)	–0.08
Tekeli Gorge	WorldClim	(0,1,1)	7.0 (9); 0.64	0.68 / 0.55 / 0.55	2.27	2.92	3.23 (2.02; 4.44)	+0.97
	CHELSEA	(1,1,2)	7.9 (7); 0.34	0.58 / 0.49 / 0.63	1.07	1.47	1.71 (0.69; 2.72)	+0.64
Terskey Alatau–Saryzhaz	WorldClim	(0,1,1)	9.7 (9); 0.38	0.61 / 0.49 / 0.45	2.52	3.25	3.63 (2.56; 4.70)	+1.11
	CHELSEA	(0,1,1)	4.3 (9); 0.89	0.46 / 0.36 / 0.52	0.33	0.69	0.91 (0.03; 1.80)	+0.59

Note: models with $d = 1$ include a drift term; the model with $d = 0$ includes a constant. PI – prediction interval. Source: calculated by the authors.

In the WorldClim series, the forecast for 2040 exceeded the 2010–2019 mean by $+1.10$ °C at Kegen Pass, $+0.97$ °C at Tekeli Gorge and $+1.11$ °C at the Terskey Alatau–Saryzhaz site; the mean of the whole 2020–2040 forecast was $+0.73$, $+0.65$ and $+0.73$ °C above the 2010–2019 mean. In the CHELSA series, the corresponding changes by 2040 were $–0.08$, $+0.64$ and $+0.59$ °C. The forecasts thus preserve the historical difference between the products: stronger and nearly uniform warming in WorldClim and weaker, site-dependent warming in CHELSA. However, the 95% prediction intervals for 2040 are about ± 0.9 – 1.2 °C

wide and overlap between the products for the projected change at every site. The difference between the WorldClim and CHELSA forecasts (0.3–1.2 °C) is smaller than the forecast uncertainty and is therefore not statistically distinguishable.

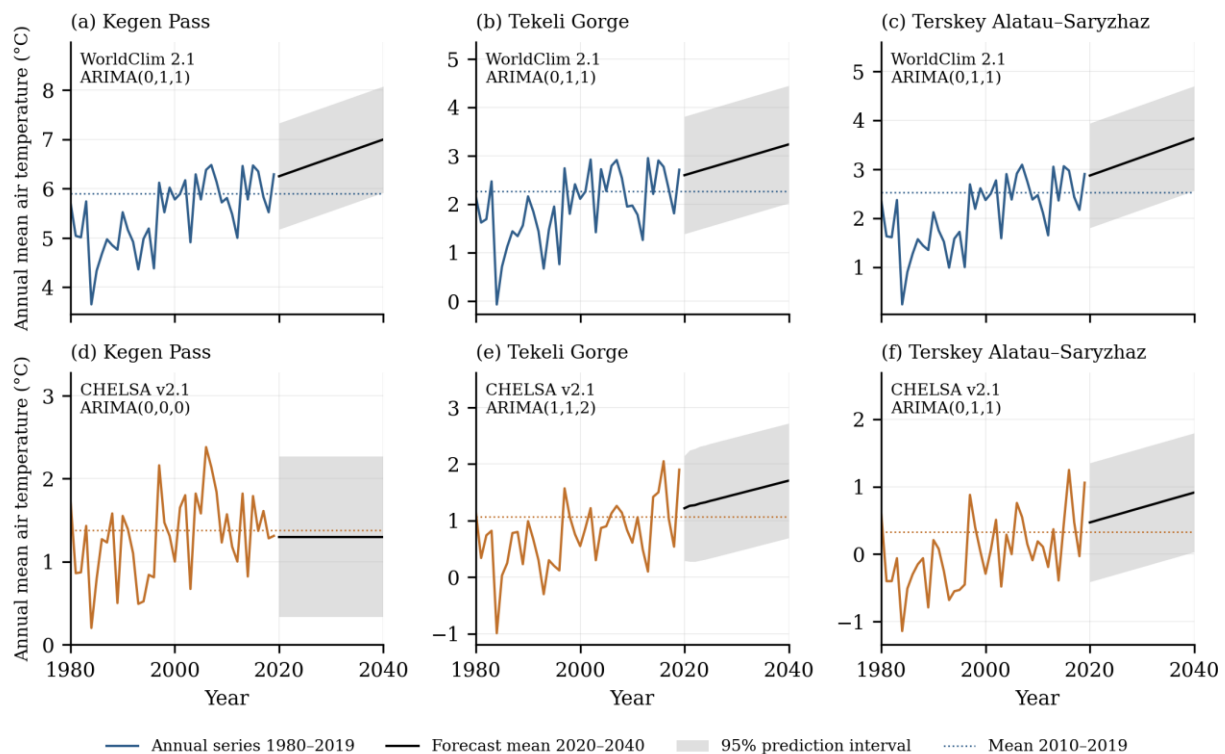


Figure 5. ARIMA forecasts of annual mean air temperature to 2040: (a–c) WorldClim 2.1; (d–f) CHELSA v2.1. Coloured lines – annual series for 1980–2019; black lines – forecast mean; shaded areas – 95% prediction intervals; dotted lines – mean of 2010–2019

Source: calculated by the authors.

4 Discussion

4.1 A robust warming signal with product-dependent magnitude

The most consistent result is the agreement of the two products on the direction of long-term temperature change: both indicate warming at all three sites, including higher minimum temperatures. The magnitude, however, differs by a factor of about two. The WorldClim trends (0.31–0.38 °C per decade) are close to station-based estimates for the region: about 0.32 °C per decade for the Tien Shan in 1960–2016 (Xu et al., 2018) and a median of about 0.30 °C per decade for Kazakhstan in 1981–2023, with somewhat stronger warming above 1500 m (Duissebek et al., 2026). The CHELSA trends (0.14–0.23 °C per decade) are lower than these benchmarks. This comparison does not validate either product at the study sites, but it indicates that the WorldClim series reproduce the regional station signal, whereas CHELSA yields a weaker local trend.

The local trajectories should not be interpreted as responses to elevation alone. Temperature evolution in the Tien Shan is linked to large-scale circulation (Ling et al., 2023), and elevation-dependent warming is not spatially universal; its magnitude and vertical structure depend on region, season, variable and data source (Pepin et al., 2022). The three sites lie within a narrow elevation range (about 1.950–2.160 m) and differ in several other characteristics, so the differences among them cannot be attributed to elevation-dependent warming. Demonstrating such a mechanism would require an elevation-stratified station network and seasonal analysis.

4.2 Why CHELSA and WorldClim differ

The differences between the products can be traced to three mechanisms. The first is the temporal data source. WorldClim historical monthly data take their interannual variability from CRU TS, which interpolates station anomalies onto a 0.5° grid using a large correlation decay distance (Harris et al., 2020). Neighbouring cells therefore carry almost the same anomaly, which explains why the WorldClim series at Kegen Pass and the Terskey Alatau are practically identical apart from a constant offset and why the WorldClim trends are uniform across the three sites. The WorldClim series thus describe the regional station signal shifted to the local climatological level, not independent local trajectories. CHELSA derives its variability from ERA5 (Hersbach et al., 2020; Brun et al., 2022), in which the three sites lie in different reanalysis cells and are downscaled separately; its trends are therefore more site-specific, but they also inherit any trend bias of the reanalysis in complex terrain.

The second mechanism is spatial resolution and grid-cell elevation. A 2.5 arc-minute WorldClim cell covers about 15 km² and averages over valley floors and slopes, whereas a 30 arc-second CHELSA cell covers less than 1 km². At Kegen Pass and Tekeli Gorge the terrain within the WorldClim cell is mostly lower than the reference points (Table 1), which contributes to the warmer WorldClim values. With a typical lapse rate of about 0.6 °C per 100 m, however, an elevation difference of 100–200 m accounts for only about 1 °C of the 4.19 °C offset at Kegen Pass, and at the Terskey Alatau–Saryzhaz site the terrain within the cell is mostly higher than the reference point, which would act in the opposite direction. Most of the offset must therefore arise from the third mechanism, the different climatologies and downscaling methods: WorldClim interpolates station normals with elevation and other covariates, whereas CHELSA applies reanalysis-based lapse rates, and the two approaches can differ by several degrees in intermontane basins and passes where stations are absent. Studies from other mountain systems confirm that such differences are systematic and propagate into environmental interpretations (Bobrowski & Schickhoff, 2017; Bobrowski et al., 2021), and in the Almaty region discrepancies between products and observations were larger in mountainous terrain than on the plains (Kyrgyzbay et al., 2023).

4.3 Precipitation as the principal source of inter-product uncertainty

The strongest divergence occurred for precipitation: a twofold difference in amount at Tekeli Gorge and a significant increasing trend in CHELSA at the Terskey Alatau–Saryzhaz site that is absent in WorldClim. Mountain precipitation is controlled by orographic uplift, exposure, rain-shadow effects and valley geometry, which are difficult to reconstruct from sparse station networks. High-elevation precipitation in the Tien Shan remains poorly constrained (Jin et al., 2024), in situ observations are disproportionately sparse in mountains worldwide (Thornton et al., 2022), and high-resolution precipitation climatologies, including WorldClim and CHELSA, contain systematic biases (Beck et al., 2020). Similar product disagreement has been reported from Patagonia, tropical mountains and the Andes (Fierke et al., 2024; Hemp & Hemp, 2024; Newell et al., 2022).

The higher CHELSA values at Tekeli are consistent with its orographic correction, which enhances precipitation on exposed slopes of the Zhetysu Alatau (Karger et al., 2017), whereas the WorldClim interpolation yields a smoother field and a station-based anomaly signal with little trend. The increase in CHELSA at the Terskey Alatau–Saryzhaz site may reflect a trend in ERA5 precipitation rather than an observed change. Without independent gauges, neither the higher CHELSA amounts nor the more stable WorldClim amounts can be regarded as more realistic; for hydrological, erosion, vegetation or habitat applications, the difference between them should be carried into the analysis as structural uncertainty.

4.4 Forecasts and their limitations

The ARIMA forecasts are statistical extensions of the respective series and are conditional on their historical properties. Models fitted to the strongly trending WorldClim series extrapolate a warming of about 1.0–1.1 °C by 2040 relative to 2010–2019, whereas the weaker CHELSA trends give –0.1 to +0.6 °C. Two qualifications are essential. First, the prediction intervals are wider than the differences between the

products, so the forecasts cannot be said to diverge in a statistical sense; what differs is the central estimate, which simply continues each product's historical trend. Second, hold-out validation showed limited skill at the decadal horizon, particularly for WorldClim, because warming slowed in 2010–2019. The forecasts do not represent greenhouse-gas pathways, land–atmosphere feedbacks or circulation changes and should not be used as climate scenarios. A physically based comparison would use the CMIP6-derived future climatologies available for both products (CHELSA for 2011–2040 and WorldClim for 2021–2040), which is a logical next step.

4.5 Implications for geographical and environmental applications

Environmental analyses commonly select one high-resolution climate dataset and treat its values as fixed predictors. For the localities of Adonis tianschanica examined here, the choice between the two products changes the mean annual temperature by 1.2–4.2 °C and, at Tekeli Gorge, the precipitation by a factor of two. Differences of this size are sufficient to shift bioclimatic predictors and therefore the output of species-distribution and habitat-suitability models (Bobrowski & Schickhoff, 2017; Fierke et al., 2024). Similar effects can be expected in modelling vegetation zones, erosion susceptibility, pasture productivity, snow conditions or hydrological response. A more defensible strategy is to distinguish conclusions that are stable across datasets – here, the occurrence of warming – from those that are product-dependent – absolute temperature, warming magnitude and precipitation – and to report results for more than one product.

4.6 Limitations

The study has several limitations. Values were extracted from single grid cells at three sites, so the results describe these localities and not whole mountain ranges; zonal statistics over elevation bands would give a more representative comparison. No station records or third product were available for independent validation. Only annual series were analysed, so seasonal trends and seasonal forecasting were not addressed. The decadal maps (Figure 2) use different class limits for the two products. Finally, the forecasts are univariate statistical extrapolations with limited skill.

5 Conclusion

CHELSA v2.1 and WorldClim 2.1 agree that the three Tien Shan sites warmed between 1980 and 2019, but they differ in how much. WorldClim indicates nearly uniform trends of 0.31–0.38 °C per decade (about 0.9–1.0 °C between 1980–1989 and 2010–2019), close to station-based regional estimates, whereas CHELSA indicates 0.14–0.23 °C per decade (0.3–0.7 °C), with only a marginal trend at Kegen Pass. WorldClim is 1.2–4.2 °C warmer than CHELSA in absolute terms. The uniform WorldClim trends reflect the coarse CRU TS anomaly signal shared by the sites, while the CHELSA trends reflect the downscaled ERA5 reanalysis.

Precipitation is considerably more product-dependent: CHELSA gives about twice the WorldClim amount at Tekeli Gorge (about 94 vs 48 mm per month), and a significant increase occurs only in CHELSA, most clearly at the Terskey Alatau–Saryzhaz site (+8.6 mm per month per decade). Spatial resolution should therefore not be equated with climatic certainty.

ARIMA forecasts continue the historical trend of each product (+1.0 to +1.1 °C by 2040 relative to 2010–2019 for WorldClim; –0.1 to +0.6 °C for CHELSA), but their 95% prediction intervals overlap, so the forecasts do not differ significantly and have limited skill.

The main limitations are single-cell extraction at three sites, the absence of independent validation and the univariate statistical nature of the forecasts. Future work should combine both products with Kazhydromet station records and a third product such as ERA5-Land or TerraClimate, use zonal statistics over elevation bands, analyse seasonal trends and compare the statistical forecasts with CMIP6-based projections. Until then, environmental studies in the Tien Shan should compare several climate products and separate conclusions that are stable across them from those that depend on the dataset.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Kanat Kulymbet	✓	✓	✓	✓	✓				✓	✓	✓			
Zhassulan Smanov	✓				✓	✓	✓	✓	✓	✓	✓	✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

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