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A First Evaluation of ERA5-Land Reanalysis Temperature Product Over the Chinese Qilian Mountains

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Reanalysis temperature products are important datasets for temperature estimates over high-elevation areas with few meteorological stations. In this study, surface 2 m air temperature data from 17 meteorological stations from 1979 to 2017 in the Qilian Mountains (QLM) are used for comparison with the newest reanalysis product: ERA5-Land derived from the European Centre for Medium-Range Weather Forecasts (ECMWF). In general, the ERA5-Land temperature product can reproduce the observation variation at different time scales very well. A high monthly correlation coefficient that ranges from 0.978 to 0.998 suggests that ERA5-Land reanalysis temperature could capture the observations very well. However, attention should be paid before using ERA5-Land at individual sites because of the average root-mean-square-error (RMSE) of 2.2°C of all stations. The biases between ERA5-Land temperature and observations are mainly caused by the elevation differences between ERA5-Land grid points and meteorological sites. The annual mean temperature shows a significant warming trend (0.488°C/decade) from 1979 to 2017 based on the observations. ERA5-Land reanalysis temperature captures the increasing trend very well (0.379°C/decade). The biggest positive warming trends of observations and ERA5-Land are both found in summer with values of 0.574°C/decade and 0.496°C/decade, respectively. We suggest that ERA5-Land generally reproduces the temperature trend very well for observations and is reliable for scientific research over the QLM.

Keywords: reanalysis, air temperature, ERA5-Land, Qilian Mountains, warming trend

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1 INTRODUCTION

The Qilian Mountains (QLM) comprise an important ecological protection barrier and one of the most important sources of water to northwestern China. The mountain range is extremely important for assessing climatic and environmental changes across China (Lin et al., 2017; Wang et al., 2019). The QLM system not only is the source of many rivers but also hosts a unique desert oasis ecosystem (Sun and Liu, 2013; Wang et al., 2019). However, most glaciers in the QLM exhibit accelerated degradation because of recent climate warming (Qian et al., 2019).

In general, previous studies about temperature change characteristics in the QLM were completed by using observations. However, surface meteorological stations are spare in the QLM, especially above 3000 m. Thus, limited observations or remote sensing products are the commonly used data resources in previous studies about climate change in the QLM. Jia (2012) used observational data and found that the extremes of seasonal high temperature in the QLM showed a significantly increasing trend, and the extremes of seasonal low temperature showed a significantly decreasing trend. Zhang et al. (2009) used observational data and found that temperature changes in the QLM were well synchronized with those in the entire northwestern region and that temperature changes in the western part of the QLM were more significant than those in the eastern and middle sections. Wang et al. (2019) studied the temperature variability at annual and seasonal scales during 1960–2016 using monthly observational data in the QLM, results found that the changes in winter temperature made the greatest contribution to the annual temperature changes. Lin et al. (2017) used observational data and found that temperature extremes in the QLM exhibited a significant warming trend, consistent with global warming. Warming trends in autumn and winter were greater than in spring and summer. Cao et al. (2018) analyzed the temporal variability and spatial distribution of air temperature in the south slope of QLM from 1960 to 2014 by using observational data, and the results showed that the increasing trends of mean annual air temperature, minimum, and maximum temperatures in the QLM are 0.35°C/decade, 0.27°C/decade, and 0.47°C/decade, respectively. Fu et al. (2018) used observational data and found that the temperature mutation of multiannual, maximum, and minimum temperatures in the QLM occurred in 1991, 1995, and 1990, respectively. Wang et al. (2019) analyzed the annual and seasonal variability in temperature during 1960–2016 using monthly data from meteorological stations in the QLM, and the results showed that temperature in the whole regions, oasis, and mountains increased at the rate of 0.32°C/decade, 0.32°C/decade, and 0.33°C/decade, respectively. Cao et al. (2018) analyzed the variability of air temperature in the south slope of the QLM by using observational data from 1960 to 2014, and the results showed that the mean annual air temperature exhibited a unanimously fluctuating increasing trend with the rate of 0.35°C/decade.

Compared with varied reanalysis products, some shortages exist in the observations from meteorological stations, such as shorter time series and low spatial density, especially in high-elevation areas. Various interpolation methods often cause large biases because of the limitations of the spatial interpolation itself, such as the density and uneven distribution of stations (Gao et al., 2018). Reanalysis products have been commonly applied in previous studies because of their high spatial resolution and long-time series (Gao et al., 2018; Zhang et al., 2021). However, there some biases may exist between reanalysis data and observations, which suggest that caution is needed before using reanalysis data. For example, Wang et al. (2018) evaluated the reliability of ERA-Interim reanalysis precipitation and temperature data in mainland China, and the results indicated that caution should be paid when using ERA-Interim precipitation and temperature in areas with complex orography. Jiao et al. (2021) showed that the accuracy of the ERA5 reanalysis precipitation products was strongly correlated with topographic distribution and climatic divisions in China. Therefore, it is still a necessity to assess the quality and bias of reanalysis data, especially in areas with complex topography.

Many studies are concentrating on the evaluation of ERA5-Land in different regions. Xin et al. (2021) evaluated and compared the ability of two ERA5 precipitation products, ERA5-Land and ERA5-HRES, in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) using observations from over 3000 rain gauges in a high-density network during 2018, and the results showed that ERA5-Land data with finer spatial resolution fail to deliver any preferable results than ERA5-HRES. Zou et al. (2022) evaluated the ERA5-Land air temperature data in the GBA by using the observations of 1080 automatic weather stations in 2018, and the results showed that ERA5-Land underestimates temperature (an average bias of 0.90°C) and performs better at low temperatures than at high temperatures. The spatial pattern of ERA5-Land is generally consistent with that of stations but relatively poor in urban areas. In addition, ERA5-Land properly captures daily and monthly variations, as well as intraday temperature fluctuations (Zou et al., 2022). Chen et al. (2021) found that the high-resolution ERA5-Land and ERA5 datasets well present the observed spatial pattern of precipitation but with a generally overestimated amount in the southern slope of central Himalaya. Hong et al. (2021) found that ERA5 and ERA5-Land precipitation products have similar spatiotemporal error characteristics, and ERA5-Land performs better than ERA5 over Jiangxi Province in 2019. Wu et al. (2021) evaluated the ERA5-Land soil moisture (SM) datasets in China, and the results indicated that ERA5-Land showed a larger bias in (semi-) humid areas (0.06 m^3/m^3 on an average) and had higher temporal precision in the southern areas in China, which are mostly determined by their SM climatology. Cao et al. (2020) concluded that ERA5-Land soil data are not well suited for informing permafrost research and decision making directly.

In the QLM, there were some evaluations of the reliability of reanalysis data in previous studies. For example, Zhao et al. (2020) evaluated the reliability of ERA-Interim temperature data over the QLM, and the results showed that ERA-Interim temperature is generally reliable for climate change research over the QLM. Huai et al. (2021) evaluated the applicability of ERA5, JRA-55, ERA-Interim, and HAR reanalysis in the QLM, and the results showed that ERA5 outperforms for most variables in correlation coefficients, especially for wind speed, but is not significantly improved than ERA-Interim of other variables. ERA5-Land is a state-of-the-art global reanalysis data set for land applications. However, there is very little research on the evaluation of the reliability of ERA5-Land reanalysis data in the QLM, indicating that the capabilities of land-surface climate in the QLM are unknown. Thus, this evaluation results of ERA5-Land products could provide a reference when using reanalysis data in the QLM.

This study uses 17 meteorological stations in the QLM during the period of 1979–2017 to assess the monthly 2 m air temperature in ERA5-Land products. This important evaluation could help understand the reliability of ERA5-Land reanalysis for the local climate studies. The structure of this study is divided into three aspects. **Section 1** introduces the ERA5-Land monthly average temperature reanalysis data and observations as well as the evaluation methods. The results and discussion are given in **Section 2**, and finally, the conclusions are presented in **Section 3**.

2 DATA AND METHODS

2.1 ERA5-Land Reanalysis Data (T_e)

ERA5-Land is the ECMWF's newest reanalysis data set, which is a state-of-the-art global reanalysis data set for land applications

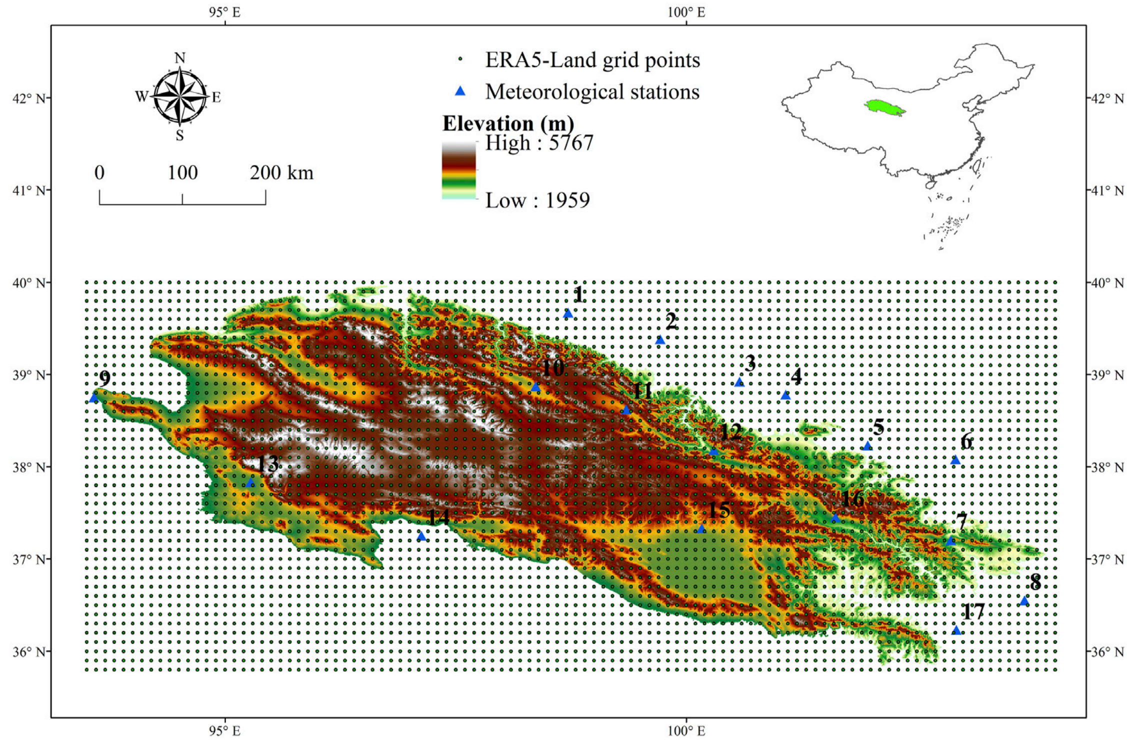

FIGURE 1 | Spatial distribution of ERA5-Land grid points and meteorological stations over the QLM.

TABLE 1 | Meteorological stations information.

No	Site Name	Latitude (°)	Longitude (°)	Altitude (m)	H_{ERA} (m)	H_{ERA}-H_{Obs} (m)
1	Jiu Quan	39.67	98.72	1470	1397	–73
2	Gao Tai	39.38	99.72	1357	1342	–15
3	Zhang Ye	38.92	100.58	1550	1500	–50
4	Shan Dan	38.78	101.08	1760	1801	41
5	Yong Chang	38.23	101.97	1987	2022	35
6	Wu Wei	38.08	102.92	1525	1498	–27
7	Wu Shaoling	37.2	102.87	3045	3431	386
8	Gao Lan	36.55	103.67	2032	2033	1
9	Leng Hu	38.75	93.58	2762	3244	482
10	Tuo Te	38.87	98.37	3460	3621	161
11	Ye Niugou	38.62	99.35	3200	3575	375
12	Qi Lian	38.18	100.3	2800	3098	298
13	Da Chaidan	37.83	95.28	3000	3257	257
14	De Lingha	37.25	97.13	2762	2914	152
15	Gang Cha	37.33	100.17	3100	3275	175
16	Men Yuan	37.45	101.62	2800	4109	1309
17	Min He	36.23	102.93	1900	2144	244

H_{ERA} is the ERA5-Land grid-point height (m).

(Joaquín et al., 2021). ERA5-Land has a higher resolution than ERA-Interim and ERA5. The spatial resolution and horizontal resolution of ERA5-Land are 0.1° × 0.1° and 10 km, respectively. The time series of ERA5-Land covers the period 1950 to the present. The ERA5-Land dataset includes hourly and monthly dynamic data representing 50 indicators from 1950 to the present (A. and G.B., 2021; The Alexander and Gregor, 2020; Cao et al., 2020; Jiang et al., 2020; Jiao et al., 2021; Joaquín et al., 2021; Konstantinos et al., 2021; Luis and Johannes, 2020; Pelosi et al., 2020; Wu et al., 2021; Pelosi and Chirico, 2021; Xu et al., 2022).

In this study, ERA5-Land monthly averaged 2 m air temperature data were used. The period ranged from January 1979 to December 2017, and the geographical locations ranged from 35.8 to 40.0°N and from 93.5 to 104.0°E. The ERA5-Land grid point covers all of the QLM region (**Figure 1**). The grid-point altitude information was extracted from digital elevation model

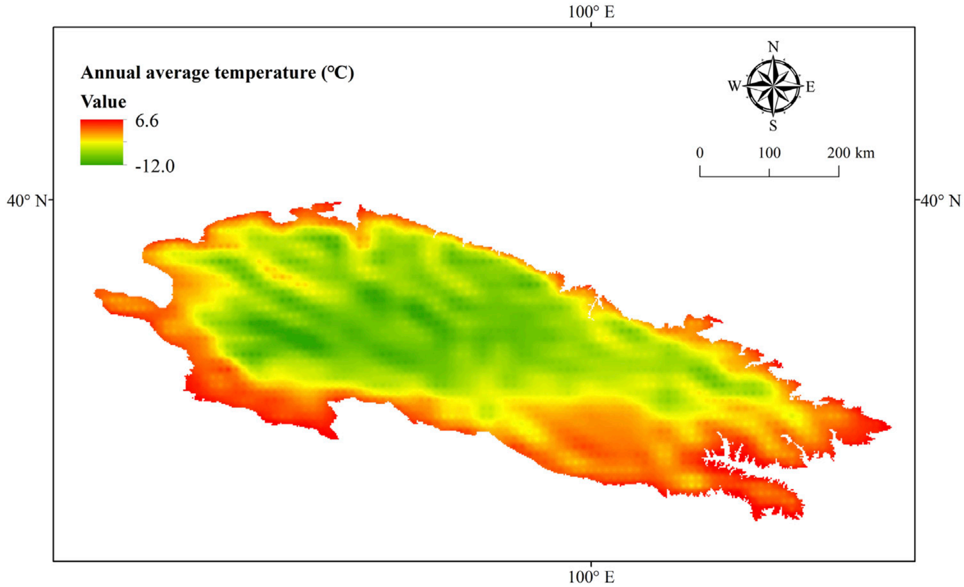

FIGURE 2 | Spatial distribution of annual mean ERA5-Land temperature in the QLM.

data downloaded from Geospatial Data Cloud (https://www.gscloud.cn) for the QLM (**Table 1**).

2.2 Observations (T_o)

We obtained observational temperature data and altitude information for this study from the China Meteorological data-sharing service system (http://cdc.cma.gov.cn/index.jsp). The quality of temperature data was controlled and verified by the provider. After strict quality control, the quality and completeness of temperature data are significantly improved, so that it can be applied directly in climate change research. Temperature data for 1979 to 2017 from 17 ground observational stations in the QLM were extracted and sorted into seasonal and annual scales. Among the 17 meteorological stations in the QLM, nine stations were from Qinghai Province and the other eight stations were from Gansu Province. The 17 stations are located within altitude ranges from 1000 to 3500 m; in that, five stations were higher than 3000 m, of which station No.10 (station Tuo Le) is the highest with an elevation of 3460 m. A detailed description of the information and spatial distribution of 17 stations is shown in **Figure 1** and **Table 1**. ERA5-Land grid points nearest to each meteorological station were selected for comparison based on the longitude and latitude coordinates of 17 meteorological stations, which can avoid the error caused by multigrid spatial interpolation (Zhao et al., 2020). Seasons were identified for the purpose of this study as follows: spring (March to May), summer (June to August), autumn (September to November), and winter (December to February).

2.3 Evaluation Methods

To evaluate the quality of the ERA5-Land data set, correlation coefficient (*r*), bias, and root-mean-square-error (RMSE) were computed for comparison of the ERA5-Land and observed temperatures at the 17 meteorological stations at monthly, seasonal, and annual temporal scales.

3 RESULTS AND DISCUSSION

3.1 Spatial Analysis of Average Annual and Seasonal Mean Temperature

We analyze the spatial distribution characteristics of temperature using 1983 ERA5-Land grid points within the QLM from 1979 to 2017. In general, the climatology is reflected by interpolating observations. However, this process is completed by the density of observational stations. Just a few stations are suited at the high-elevation areas within QLM (especially above 3000 m), which causes an inaccuracy for the plateau-wide temperature climatology. **Figure 2** shows the spatial distribution of annual mean temperature over the QLM based on the ERA5-Land reanalysis. The green part represents the low-temperature area, and the red part represents the high-temperature area. The annual temperatures in the central QLM are below 0°C (**Figure 2**). The annual mean temperature ranged from −12°C to 6.6°C, with an average temperature of 2.4°C/year. Furthermore, the mean temperature of ERA5-Land decreases from the edge area to the interior area, which demonstrates that ERA5-Land could capture the climatology difference derived from topographic features. **Figure 3** shows the spatial distribution characteristics of average seasonal mean temperatures across the QLM for 1979–2017 based on the ERA5-Land reanalysis. In the whole QLM, the average mean temperatures in winter are below 0°C. The temperatures in central QLM are lower than in the surrounding regions. The temperature for the four seasons

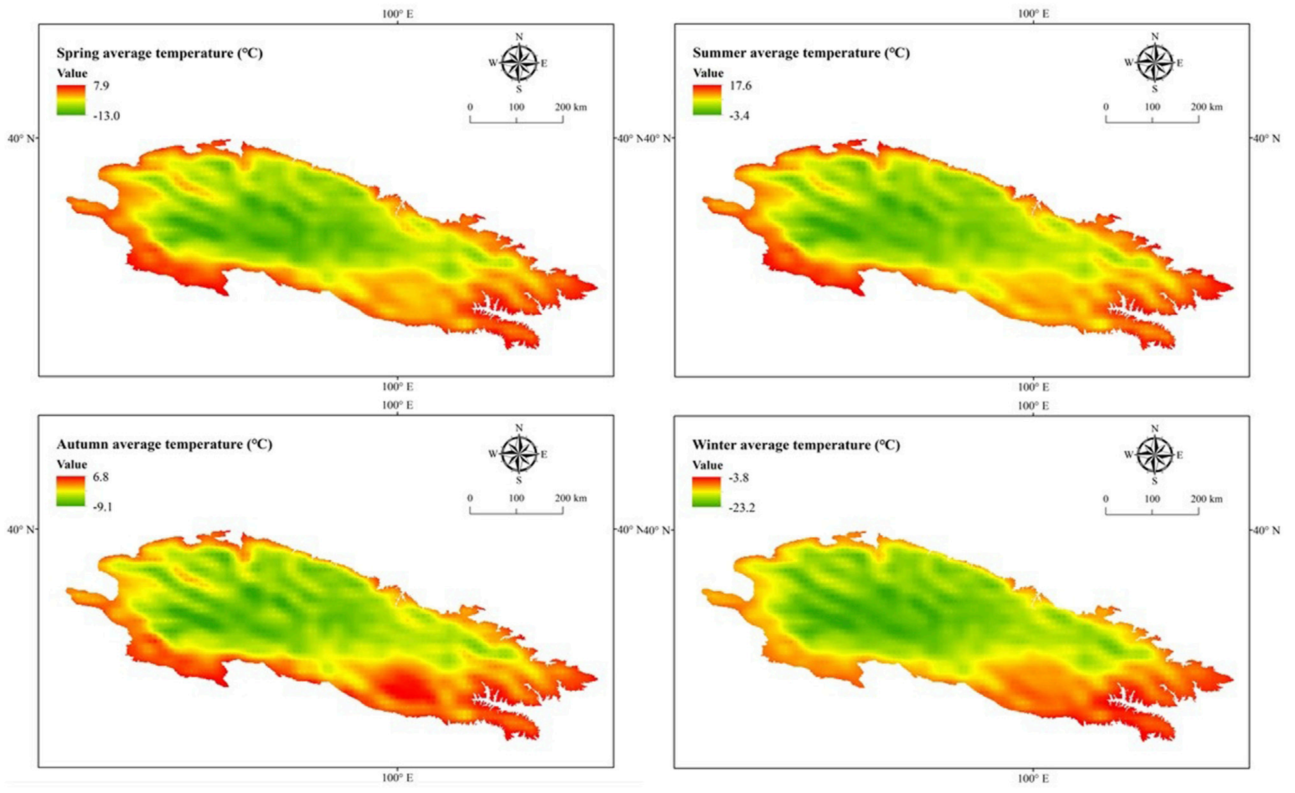

FIGURE 3 | Spatial distribution of seasonal mean ERA5-Land temperature in the QLM.

TABLE 2 | Comparison of ERA5-Land monthly averaged temperatures with observations at all 17 stations.

No	*r*	Bias (°C)	RMSE (°C)
1	0.997	0.0	0.9
2	0.996	1.6	1.9
3	0.997	0.6	1.3
4	0.998	−0.7	1.0
5	0.997	−0.6	1.0
6	0.997	0.5	1.0
7	0.993	−0.4	1.5
8	0.995	−1.6	2.1
9	0.998	−1.2	1.6
10	0.983	−2.3	3.0
11	0.982	−4.6	4.9
12	0.982	−4.4	4.8
13	0.994	−2.3	2.6
14	0.997	−0.1	0.8
15	0.997	0.0	0.9
16	0.978	−5.6	6.0
17	0.995	−1.5	1.8

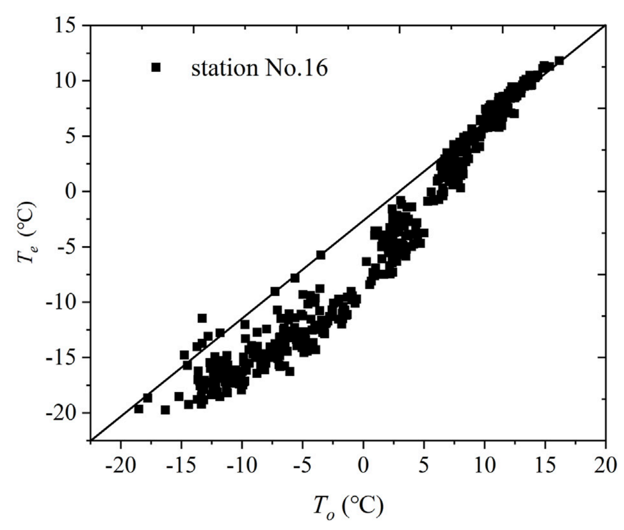

FIGURE 4 | Scatter plots of comparison of ERA5-Land monthly temperature with observations at station No. 16 in 1979–2017. The solid line is 1:1 line.

followed the order of summer > spring > autumn > winter. The temperature changes show a strong spatial variance across the QLM.

3.2 Monthly Temperature Comparisons

Table 2 shows the comparison results of ERA5-Land monthly temperature and observations in the corresponding period. The correlation coefficient (r) ranged from 0.978 to 0.998 at all stations with an average r of 0.993, which reveals that T_e could capture the observations annual cycle very well. The biases change from −5.6 to 1.6°C with an average of −1.3°C for all stations. Nine meteorological

TABLE 3 | Comparison of ERA5-Land seasonal mean temperature with observations at all 17 stations.

No.	*r*				Bias (°C)				RMSE (°C)			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
1	0.977	0.964	0.938	0.914	−0.8	−0.3	0.1	1.0	0.8	0.4	0.4	1.1
2	0.931	0.856	0.822	0.857	1.1	2.1	1.7	1.5	1.2	2.1	1.8	1.7
3	0.973	0.962	0.842	0.851	−0.3	−0.1	0.9	2.0	0.4	0.3	1.0	2.1
4	0.956	0.959	0.844	0.863	−0.7	−0.8	−0.8	−0.4	0.8	0.8	0.9	0.8
5	0.939	0.942	0.810	0.842	−1.0	−0.1	−0.8	−0.5	1.0	0.3	1.0	0.9
6	0.927	0.893	0.765	0.895	0.3	1.1	0.3	0.0	0.6	1.2	0.8	0.7
7	0.912	0.980	0.806	0.768	−0.1	0.7	−0.2	−1.9	0.5	0.7	0.8	2.1
8	0.950	0.908	0.781	0.890	−2.6	−2.2	−1.7	0.1	2.6	2.2	1.8	0.5
9	0.931	0.940	0.921	0.898	−1.5	−2.4	−0.8	−0.1	1.5	2.4	0.9	0.5
10	0.604	0.953	0.332	0.569	−3.3	−3.0	−2.4	−0.3	3.4	3.0	2.9	1.1
11	0.617	0.970	0.544	0.773	−6.2	−3.8	−5.0	−3.4	6.3	3.8	5.2	3.5
12	0.772	0.967	0.521	0.559	−6.1	−3.1	−4.5	−4.0	6.1	3.1	4.7	4.1
13	0.778	0.922	0.604	0.742	−2.9	−2.9	−1.6	−1.9	3.0	2.9	1.8	2.0
14	0.917	0.945	0.851	0.836	−0.4	0.4	0.3	−0.7	0.6	0.5	0.5	1.0
15	0.871	0.971	0.779	0.753	−1.6	−0.3	0.0	−0.6	1.6	0.4	0.5	1.1
16	0.854	0.952	0.628	0.439	−7.6	−3.9	−5.7	−5.2	7.6	3.9	5.8	5.4
17	0.949	0.945	0.780	0.912	−2.1	−1.0	−1.4	−1.5	2.1	1.1	1.6	1.7

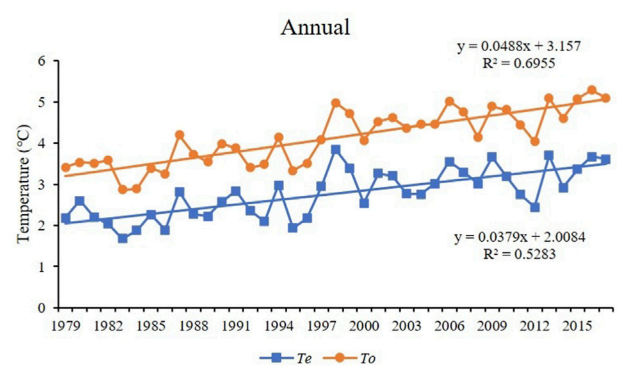

FIGURE 5 | Average annual mean temperature from station time series and ERA5-Land in the 1979–2017 period for QLM.

sites have a bias from −1°C to 1°C. The positive values of bias represent that T_e is warmer than T_o, and the negative ones indicate that T_e is cooler than T_o. The largest negative bias (−5.6°C) happens at station No.16, namely, station Men Yuan in the southeastern QLM with an elevation of 2800 m. However, the ERA5-Land grid height at station No.16 is 4109 m. **Figure 4** shows the comparison of ERA5-Land with observations for station No.16 (largest negative bias) in their corresponding periods. ERA5-Land obviously underestimates observations for station No.16. The largest RMSE is also found at station No.16, whereas the smallest one is found at station No.14. The RMSE changes from 0.8°C to 6.0°C with an average of 2.2°C for all stations, which suggests that T_e could not be used directly in scientific research.

3.3 Seasonal and Annual Temperature Comparisons

The high seasonal and annual *r* reflect the good consistency between T_e and T_o. However, it does not reflect the consistent interannual and seasonal variability. **Table 3** shows the *r*, bias, and RMSE between T_e and T_o at a seasonal scale. The averaged values of *r* for all stations in spring, summer, autumn, and winter are 0.874, 0.943, 0.739, and 0.786, respectively. Thirteen stations have correlation coefficients of more than 0.8 in spring, whereas 8 and 10 stations meet this standard during autumn and winter, respectively. All stations have a correlation exceeding 0.8 in

TABLE 4 | Comparison of ERA5-Land annual mean temperature with observations at all 17 stations.

No	*r*	Bias	RMSE
1	0.953	0.0	0.2
2	0.900	1.6	1.6
3	0.936	0.6	0.7
4	0.931	−0.7	0.7
5	0.873	−0.6	0.7
6	0.863	0.5	0.7
7	0.881	−0.4	0.5
8	0.894	−1.6	1.6
9	0.918	−1.2	1.2
10	0.632	−2.3	2.4
11	0.783	−4.6	4.6
12	0.745	−4.4	4.5
13	0.788	−2.3	2.4
14	0.906	−0.1	0.3
15	0.844	−0.6	0.7
16	0.749	−5.6	5.6
17	0.917	−1.5	1.5

TABLE 5 | Temperature warming trends (°C/decade) in all seasons from station time series and ERA5-Land reanalysis in 1979–2017.

Temperature	Spring	Summer	Autumn	Winter	Annual
T_o	0.538	0.574	0.447	0.393	0.488
T_e	0.459	0.496	0.328	0.235	0.379
T_o-T_e	0.079	0.078	0.119	0.158	0.109

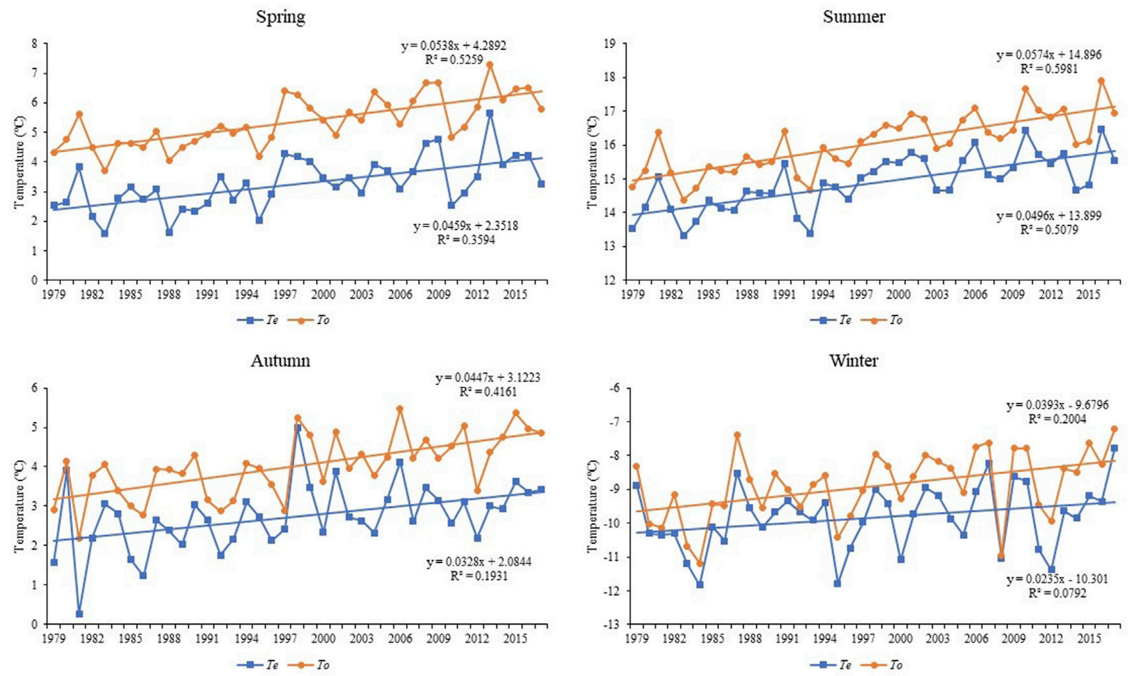

FIGURE 6 | Average seasonal mean temperature from station time series and ERA5-Land in the 1979–2017 period for QLM.

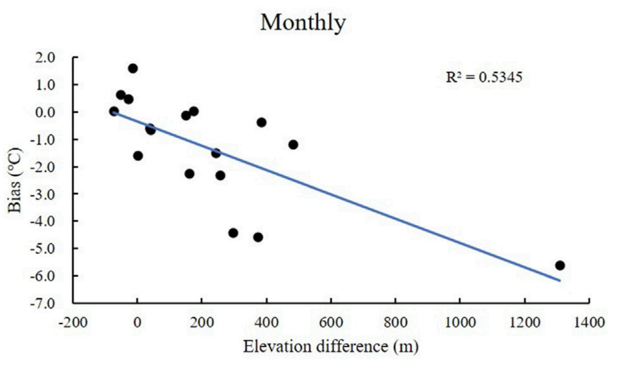

FIGURE 7 | Relationship of bias and elevation differences between monthly observations and ERA5-Land during the 1979–2017 period.

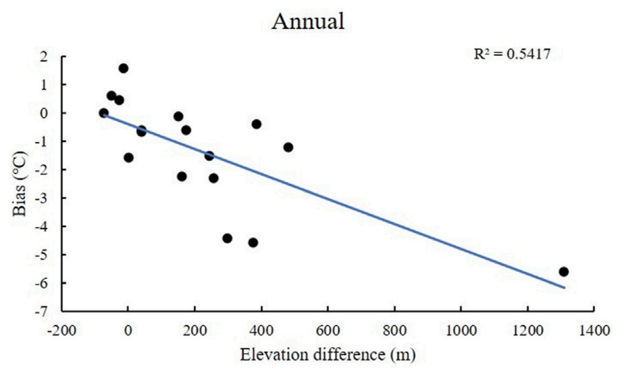

FIGURE 8 | Relationship of bias and elevation differences between annual observations and ERA5-Land during the 1979–2017 period.

summer. The r of T_e is varied from different stations in general. For instance, stations No.1 and No.3 perform the best correlation coefficient in spring. However, for stations No.7 and No.15, the best correlation is found in summer. It indicates an important spatial variance across the QLM. The largest negative bias for all seasons is also found at station No.16, which is consistent with the monthly bias. Station No.16 performs the largest RMSE in all seasons. The averaged values of RMSE for spring, summer, autumn, and winter are 2.4°C, 1.7°C, 1.9°C, and 1.8°C for all 17 stations, respectively. The r, bias, and RMSE of annual mean temperature between the two data sets are shown in **Table 4**. The value of r between T_e and T_o changes from 0.632 to 0.953 with an average r of 0.854 for all meteorological sites. Twelve stations have r greater than 0.8. Just station No.10 has a lower r than 0.7. Station No.16 also performs the largest negative bias (−5.6°C) and the largest RMSE (5.6°C). The smallest RMSE (0.2°C) happened at station No.1. The average RMSE of annual mean temperature over all stations reaches 1.8°C.

3.4 Warming Trends of ERA5-Land Temperature and Observations

The annual and seasonal temperature-increasing trends of T_e and T_o during the period of 1979–2017 over the QLM are shown in

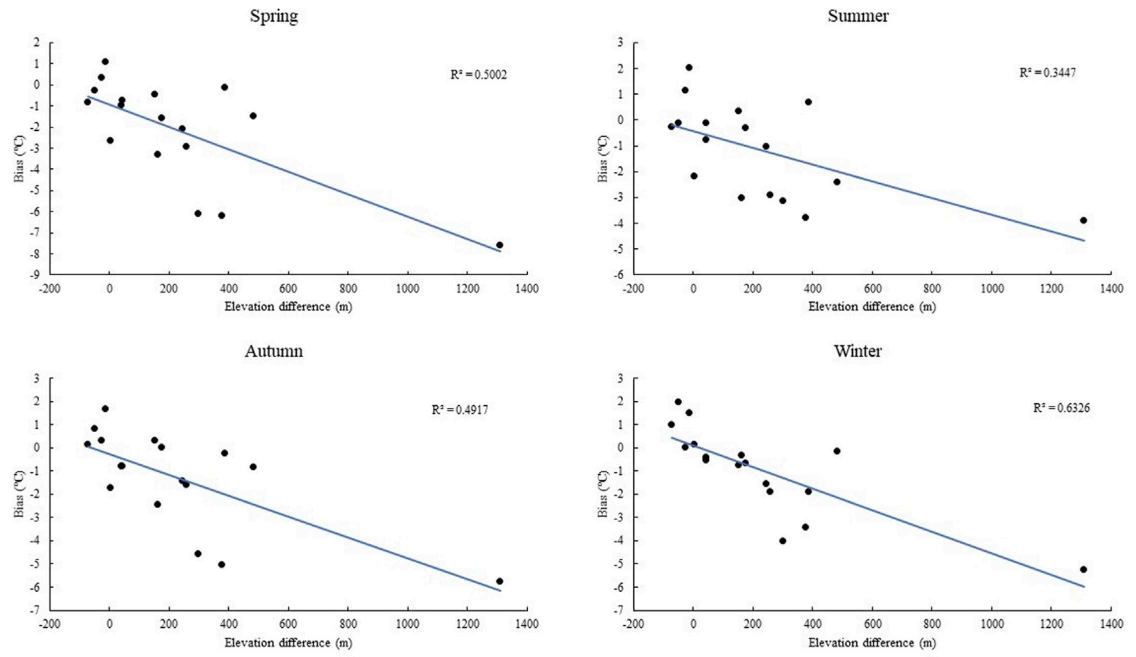

FIGURE 9 | Relationship of bias and elevation differences between seasonal observations and ERA5-Land during the 1979–2017 period.

Figure 5 and **Figure 6**. The linear warming rate of T_o reaches 0.488°C/decade from 1979 to 2017. The linear warming rate of T_e is 0.379°C/decade, which suggests that ERA5-Land reanalysis temperature can capture the warming trend well in general (**Table 5**). The difference in annual mean temperature-increasing trends between T_e and T_o reaches 0.109°C/decade. Winter temperature performs the largest trend difference between T_e and T_o (0.158°C/decade). ERA5-Land can capture the temperature trends in other seasons very well, with values of 0.079°C/decade in spring, 0.078°C/decade in summer, and 0.119°C/decade in autumn. This trend difference between T_e and T_o may be caused by the sparse observations in the high-elevation regions in the QLM, especially above 3000 m. In general, T_e is reliable for capturing the temperature-increasing trend over the QLM for its averaged trend difference of 0.109°C/decade against T_o. However, T_e should attract attention to reduce its bias with T_o before applying it to scientific research because of the averaged RMSE (2.2°C) (i.e., bias correction).

3.5 Bias Analysis

The results of **Figure 5** and **Figure 6** show that the reanalysis underestimated temperature over the QLM, which is similar to the previous studies (Zhao et al., 2020; Huai et al., 2021). Station No.16 performs the largest negative bias, and the larger difference in altitude between the reanalysis and the actual altitude at station No.16 causes errors in temperature. Correcting the temperature of the reanalysis based on the elevation difference may reduce the error of the temperature reanalysis and improve the accuracy (Gao et al., 2018). The linear relationship between monthly biases and elevation differences between T_e and T_o is shown in **Figure 7**. Please note that bias and elevation difference between T_e and T_o were calculated by T_e minus T_o. The monthly biases are caused by the elevation differences between T_e and T_o, because the correlation of determination (R^2) measuring the fit reaches 0.535. Thus, there exists a possibility to reduce the bias between T_e and T_o by using a bias correction model, to improve the applicability of ERA5-Land (Gao et al., 2014). **Figure 8** and **Figure 9** show that the R^2 value of annual correlation reaches 0.542, and the R^2 values for spring, summer, autumn, and winter are 0.500, 0.345, 0.492, and 0.633, respectively, which indicates again that the altitude differences between T_e and T_o cause the biases. Moreover, in winter temperature, the elevation difference is the main factor that affects biases, which suggests that it is possible to reduce the bias by using an elevation correction model and further strengthen the reliability of ERA5-Land products. Other errors, such as in assimilation data, model system, and interpolation, are also possible factors that affect the bias (Zhao et al., 2020). The 2 m temperature in high altitude areas will be affected by the underlying surface, such as terrain complex, glaciers, and lakes, which also lead to errors. After analyzing the bias, correlation coefficients, and RMSE at all stations, we learn that smaller correlation coefficients, bigger bias, and bigger RMSE were found in those stations located within the QLM. In other words, the error between reanalysis data and observations is higher within the QLM than that in the oasis regions, which may be caused by the terrain complex within the QLM.

4 CONCLUSION

In this study, ERA5-Land temperatures (T_e) are compared with observations (T_o) from 17 individual meteorological stations (T_o)

over the QLM of China at different temporal scales. High monthly correlations from 0.978 to 0.998 indicate that ERA5-Land could capture the cycle for the individual sites very well. The biases changing from −5.6°C to 1.6°C are mainly caused by the elevation differences between the ERA5-Land grid points and the individual meteorological sites ($R^2 = 0.535$). The results of this comparison suggest that T_e could not be used directly in scientific studies because of the larger average RMSE of 2.2°C for all stations.

The seasonal and annual results of the comparison are similar to the monthly results. The average correlation coefficients for spring, summer, autumn, and winter are 0.874, 0.943, 0.739, and 0.786, respectively, indicating that ERA5-Land can capture the interannual variability of observations over the QLM. The averaged values of RMSE for spring, summer, autumn, and winter for all stations reach 2.4°C, 1.7°C, 1.9°C, and 1.8°C, respectively, which also suggests that caution should be taken seriously before using ERA5-Land temperature in scientific studies in the QLM. The biases in temperatures are mainly attributed to altitude differences between ERA5-Land grid points and observational sites, especially during the winter ($R^2 = 0.633$). This indicates that errors between ERA5-Land and observations can be reduced by using the elevation correction method and further improved the quality of ERA5-Land reanalysis. The R^2 values between bias and elevation differences in spring, summer, and autumn are 0.500, 0.345, and 0.492, respectively. An average correlation between T_e and T_o on an annual scale for all stations reaches 0.854. The average annual RMSE between T_e and T_o on an annual scale for all stations is 1.8°C, which also indicates that T_e could not be used directly in scientific research. Zhao et al. (2020) found that the average RMSE between observational temperature and ERA-Interim temperature is 2.7°C in the QLM, which is larger than that of ERA5-Land in our study. Huai et al. (2021) found that ERA5 temperature products exhibit higher correlations with R values of >0.97 at all stations in the QLM, which is better than the results in our study.

A significant temperature-increasing rate (0.488°C/decade) is found over the QLM based on the T_o during 1979–2017. ERA5-Land can capture the warming trend well (0.379°C/decade). The largest warming rates are both found in summer for the observations (0.574°C/decade) and ERA5-Land (0.496°C/decade). In general, ERA5-Land is reliable for capturing the warming trend over the QLM.

Up to now, this evaluation has been limited to 17 meteorological stations ranging from 1000 to 3500 m. Further comparisons can be analyzed by using more meteorological stations located in the surrounding regions. It would be a meaningful attempt to evaluate other meteorological elements of ERA5-Land reanalysis data sets (e.g., precipitation and humidity) over the QLM.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

ZP designed the study, collected the meteorological data, and wrote the article. ZH performed the final edit and provided fund support.

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