Spatiotemporal analysis of the relationship between near-surface air temperature and troposphere thickness over Iran

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Abstract
The correlation between the thickness of the troposphere (THK) and observed temperature over Iran is investigated. To achieve this goal, the monthly observed temperature data for the period between January 1, 1979 and December 31, 2013, from 42 meteorological stations throughout Iran were used. Atmospheric thickness, defined as the vertical distances between the 500, 700, 850 and 1,000 hPa pressure surfaces, is directly related to near-surface air temperature. The results show that the magnitude of the correlation between near-surface air temperature and the THK vary in different months and from region to region. The strongest significant correlation was observed between December and March when air temperature is low. The correlation was particularly high in the eastern part of the study area at layer 1,000–850 hPa, while the strongest correlation was observed at layer 1,000–700 hPa in the mountainous western parts of the country. The study area’s average correlation co-efficient in March fluctuated between 0.900 at layer 1,000–500 hPa to 0.918 at layer 1,000–700 hPa. The magnitude of the correlation co-efficients and the spatial extent of the significant positive correlation gradually decreased with increasing air temperature, reaching a minimum during the summer. Low-level troposphere thickness (1,000–700 hPa) plays an important role in impacting near-surface temperature comparable with the effect of mid-level troposphere thickness.

Keywords
air temperature, atmospheric thickness, Iran

1 INTRODUCTION

Near-surface air temperature, typically measured at the standard height of 2 m, is one of the most important climate variables widely used in meteorology, climatology and environmental health studies (Zhange, 2017), and it plays a very important role in management, planning, industry and agriculture (Seetharam, 2005). The distribution of near-surface air temperature over Iran is strongly influenced by the topographical features of two main mountain ranges: the Zagros in the west and the Alborz in the north (Alijani, 1996; Masoodian, 2011; Asakereh and Shadman, 2018).
FIGURE 1  (a) Study area along with the spatial distribution of meteorological stations (blue circles) with European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim) database grid points (black circles); and (b) topographic features over Iran

FIGURE 2  Long-term mean of temperature (a); and thickness of the troposphere (THK) in different layers of the troposphere: (b) 1,000–850 hPa; (c) 1,000–700 hPa; and (d) 1,000–500 hPa
Previous studies have shown that the tropospheric circulation patterns, such as pressure patterns or upper-level height anomalies, play an important role in the spatial patterns of near-surface air temperature (e.g. Yarnal, 1993; Masoodian and Darand, 2011, 2012, 2013; Asakereh et al., 2014; Darand et al., 2018).

Near-surface air temperature could change significantly in response to changes in the thickness of the troposphere (THK). Lamb (1955), Wagner (1957) and Alijani (2011) have demonstrated that thickness maps are a potentially more useful tool for predicting precipitation type, snow or ice limit, and front location. Masoodian and Darand (2015) studied the relationship between atmospheric thickness anomalies and extreme cold temperatures over Iran, and indicated that the extreme low temperatures are associated with a negative thickness anomaly over Siberia and northeastern parts of Iran, and with a positive thickness anomaly over the Barents Sea and Europe.

There is a rising concern that, as a result of global warming, the THK and near-surface air temperature will increase. Atmospheric thickness is defined as the vertical distance between two pressure levels, and is calculated as follows (Holton, 1992): 

$$ \frac{R_d T_v}{g} \ln \left( \frac{p_2}{p_1} \right) = z_2 - z_1 = dz $$

where $T_v$ is the mean layer temperature (°K); $g$ is the acceleration of gravity (m·s$^{-2}$); $dz$ is the layer thickness (m); $R_d$ is the universal gas constant; and $p_1$ and $p_2$ are
the pressures at the bottom and top of the layer, respectively. Owing to approximately 1°C warming of the troposphere, the thickness of the troposphere has increased by 66.5 m (Alijani, 2006). Atmospheric thickness is a function of two properties of layer atmospheric temperature and water vapour content, and thus provides an excellent indicator of layer temperature and water vapour content (Zhang et al., 2001). The variations in atmospheric thickness are affected by advection of cold or warm air masses, dynamic ascending or descending of air, and warming or cooling of the Earth’s surface (Alijani, 2006).

Several investigations have attempted to link near-surface air temperature to atmospheric thickness through various methods in different parts of the world. Struthwolf (1995) found a linear relationship between ambient afternoon surface temperature and observed low-level thickness (850–700 hPa) at 1200 UTC over Utah in the United States. Massie and Rose (1997) predicted daily maximum temperatures using linear regression and eta geopotential thickness forecasts. Their findings indicated that atmospheric thickness at layer 1,000–850 hPa has a strong linear relationship with surface temperature. Rose (2000) used 1,000–925 hPa thickness to forecast minimum temperatures in Nashville, Tennessee, again in the United States. Their findings indicated a strong linear relationship between 1,000 and 925 hPa thickness, and they observed minimum temperatures that could successfully be applied to an operational forecast. Zhang et al. (2001) found that atmospheric thickness has a positive impact on downwelling long wave radiation, ranging from approximately 130 W·m⁻² for an atmospheric thickness of 4,850 m to approximately 280 W·m⁻² for an atmospheric thickness of 5,450 m. Tatlı et al. (2004) analysed surface air temperature variability over Turkey in

**FIGURE 4** Time series of area-averaged near-surface air temperature and thickness of the troposphere (THK) with scatterplots during the winter in three layers over Iran: (a, b) 1,000–850 hPa; (c, d) 1,000–700 hPa; and (e, f) 1,000–500 hPa.
connection with large-scale upper air circulation by multivariate techniques. Their findings showed that there is a significant correlation between geopotential height at 500 hPa and maximum temperature over western and northern parts of Turkey in summer and spring. Rousta et al. (2016, 2019) elucidated that pervasive frosts and 500 hPa geopotential heights are strongly associated with the thicknesses of the troposphere over Iran, particularly during cold seasons (autumn and winter).

A study of existing literature demonstrates that the correlation between near-surface air temperature and THK over Iran has not yet been a subject of study. The objective of the paper is to investigate this correlation. Its results will help to improve the understanding and prediction of near-surface air temperature.

The paper is structured as follows. Section 2 outlines the data used and methods of analysis. The results are presented in Section 3. The conclusions are outlined in Section 4.

2 | DATA AND METHODOLOGY

The study area, Iran, is located in the southwest of Asia and has a land mass area of 1.648 million km², extending from 25° to 40° N and from 44° to 64° E (Figure 1a). The terrain is complex, with elevations ranging from 0 to > 3,000 masl (Figure 1b). The west is mostly mountains, high plateaus and hills. Plains and deserts are characteristics of central areas of the country. The study used monthly observed temperature data from 42 meteorological stations throughout Iran between January 1, 1979, and December 31, 2013, to investigate the relationship between temperature and atmospheric thickness. In order to identify atmospheric thickness over Iran, monthly averages of the THK daily means from the surface up to 500 hPa at three commonly use troposphere pressure levels (1,000–850, 1,000–700 and 1,000–500 hPa), with a spatial resolution of 0.125 geographic degrees (9,965 grid points in Iran’s political
boundary), were extracted from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim) database. The distribution of meteorological stations in addition to ERA-Interim grids are shown in Figure 1. The nearest-neighbour function was used to find individual grid points corresponding to the station locations and to correlate the THK with temperature obtained from the stations. All point-to-point correlations were calculated using Pearson’s correlation co-efficient at a 95% confidence level.

3 | RESULTS AND DISCUSSION

The climatology of temperature and the THK at different layers over 35 years between 1979 and 2013 are shown in Figure 2. The climatology for temperature (Figure 2a) indicates its high spatial differences over Iran, from 7.5°C in the mountainous areas in the northwest, northeast and west to 28.5°C along the south coast of the Oman Sea and Persian Gulf in the south. Figure 2b shows the spatial distribution of the THK for the layer 1,000–850 hPa. The mountainous cold regions in the northwest, northeast and west are characterized by a low THK, and the southern hot regions are dominated by a high THK. Figures 2c, d also reveal that areas dominated by high temperatures correspond well to areas featured by a high THK, and vice versa, implying a direct correlation between temperatures and the THK.

Figure 3 illustrates the spatial distribution of correlation co-efficients between near-surface air temperature and atmospheric thickness at three layers of the troposphere on an annual timescale. There is a significant high positive correlation (> 0.9) between near-surface air temperature and the THK at all studied layers of the
troposphere. In general, 2 m air temperature increases with increasing atmospheric thickness. Variations in atmospheric thickness have a significant effect on the downwelling long wave radiation to the Earth’s surface (Zhang et al., 2001), and consequently on near-surface air temperature. Zhang et al. (2001) reported that changes of ±110 m in atmospheric thickness would change the downwelling long wave radiation by approximately ±28 W·m⁻².

The correlation coefficients are greater for layers 1,000–700 and 1,000–850 hPa than for layer 1,000–500 hPa. In terms of spatial distribution, the highest correlation coefficient (0.99–1.0) is observed in the southern parts of the country at layer 1,000–850 hPa and over the northern areas at layer 1,000–500 hPa. For most regions, the high correlation coefficient (0.99–1.0) is observed at layer 1,000–700 hPa.

The area-average standardized time series of near-surface air temperature is linearly related to atmospheric thickness in different seasons (Figures 4–7). Overall, the near-surface air temperatures are in close agreement with atmospheric thickness in all seasons over the study period. The near-surface air temperature increases with increasing atmospheric thickness, and vice versa. Note that the near-surface air temperatures are more positively correlated with the THK (1,000–700 hPa) than (1,000–500 hPa), indicating that near-surface air temperature is more impacted by low-level thermal properties than upper-level ones. The correlation between near-surface air temperature and the THK is strong in the spring and autumn (> 0.97) and slightly weaker during the winter and summer (> 0.90).

The linear pattern of the area-average standardized time series of the THK at different atmospheric layers during different seasons revealed that the highest positive
and rising THK occurred during the winter, with a magnitude of 0.085 m per decade at layer 1,000–850 hPa, 0.078 m per decade at layer 1000–700 hPa, and 0.063 m per decade at layer 1000–500 hPa (Figures 4–7). Darand (2015) also found the highest increasing rate of atmospheric air temperature in the first layer (1,000–850 hPa). The lowest increasing trend of the THK was observed during the autumn. The same result was found by Darand and Zandkarimi (2019) for the atmospheric boundary layer height (ABLH) over Iran.

The correlation co-efficients between the observed near-surface air temperature and atmospheric thickness at three layers during different months of the year are shown in Figures 8–11, allowing the relationships between the THK and near-surface air temperature temporally to be better distinguished. As has been shown, there is a significant positive correlation between near-surface air temperature and the THK at three layers at a 95% confidence level. The highest number of weather stations with a significant positive correlation was found in winter. The correlation was particularly high in the eastern part of the study area at layer 1,000–850 hPa, and the strongest correlation was observed at layer 1,000–700 hPa in the mountainous western parts. Correlation analysis showed that the relationship between near-surface air temperature and the THK is stronger at layer 1,000–700 hPa than at the other layers. Overall, the correlation co-efficient was greater in March than in January or February. The area-average correlation co-efficient in March fluctuated between 0.9 at layer 1,000–500 hPa and 0.918 at layer 1,000–700 hPa (Table 1).
In low elevation areas, monthly near-surface temperature was more sensitive to the lower layer THK (1,000–850 hPa) changes than the other layers, which is in line with the findings of Keeter and Cline (1991) for North Carolina in the United States. They noted that, relative to the 1,000–500 hPa thickness, low-level thicknesses of 1,000–850 and 1,000–700 hPa were more effective for forecasting maximum surface temperatures, since they were more sensitive to low-level thermal structures. Kim and Lee (2015) also found the same results when analysing the relationships between atmospheric thickness and winter precipitation.

The relationship between near-surface air temperature and the THK in April is shown in Figure 9, which is similar to that in winter, except in that the correlation co-efficients gradually decrease with increasing air temperature. For June, the spatial extent of the significant positive correlation was small, covering almost 50% of the studied stations, which is much smaller than the coverage for March. In terms of spatial distribution, the strongest correlation co-efficient was observed in the central and northwestern parts of the country because of humidity in the troposphere and the uniformity of the troposphere in this region.

The spatial extent of the area for which a significant positive correlation existed was smaller in the warm months of the year than in the cold months, particularly at layer 1,000–500 hPa, which reached a minimum during the summer. Correlation co-efficients became smaller as the temperature progressed from boreal spring to summer (Figure 10). The area-average correlation co-efficient decreased to 0.689 at layer 1,000–500 hPa in July.
Furthermore, in terms of spatial distribution, a difference in correlation co-efficients over Iran became smaller at the three layers, except for the southern coastal parts of the Caspian Sea and northwestern parts of the country because of the dominance of subtropical high pressure in June–September (Darand and Mirzaei, 2019; Darand and Zandkarimi, 2019). The relatively high correlation co-efficients at layer 1,000–850 hPa in the southern parts of the Caspian Sea were different to a greater extent compared with the two other layers of 1,000–700 and 1,000–500 hPa. During the summer, the expansion of a significant positive correlation decreased gradually from the low layer of 1,000–850 hPa to the upper layers of 1,000–700 and 1,000–500 hPa. The calculated correlation co-efficient was not statistically significant over the southern parts of the country in summer, particularly at layer 1,000–500 hPa.

The sensitivity of the ABLH to temperature and relative humidity was reported by Darand and Zandkarimi (2019), who stated that the drier the air, the greater the ABLH. Massie and Rose (1997) also found that dramatic changes in air temperature and humidity could have a significant effect on temperature forecasting through troposphere thickness. This concurs with the present research finding of the greater effectiveness of low-level troposphere thickness in temperature forecasting.

The strength of correlation and the spatial extent of the area with a significant positive correlation increases from north to south during the seasonal change from summer to autumn because of the re-emergence of westerly winds and decreases in atmospheric air temperature (Darand and Mirzaei, 2019). In terms of spatial distribution, the strongest correlation co-efficient was observed...
in the northern parts of Iran owing to the emergence of westerly winds from this region and of decreases of air temperature in the troposphere (Darand and Zandkarimi, 2019).

Figure 11 illustrates the spatial distribution of the station’s correlation co-efficients during the autumn. A positive high correlation co-efficient increased gradually from the north up to October as a result of a weakening of the summer atmospheric pattern as the subtropical high pressure recedes to the south (Darand and Mirzaei, 2019). As has been shown, the correlation co-efficients decreased from north to south and from west to east in the autumn. Correlation co-efficients for December became even spatially as the temperature decreased from boreal autumn to winter. The area of a high positive correlation (0.9 to 1.0) was greater in October than in November–December. In all seasons, the correlation co-efficients decreased from the low layer (1,000–850 hPa) to the upper layer (1,000–500 hPa).

4 | CONCLUSIONS

The study focused on quantifying the correlation between near-surface air temperature and troposphere thickness over Iran on monthly and annual timescales during the period 1979–2013. Overall, there was a significant positive correlation between near-surface air temperature and the thickness of the troposphere (THK). Correlation analysis indicated that the mountainous western parts of the country were more sensitive to the THK at layer 1,000–700 hPa compared with the eastern parts. The correlation co-efficients between the THK and near-surface air temperature differed from season to season because of
substantial changes in atmospheric synoptic circulation. Correlations were stronger for the lower troposphere (1,000–700 hPa) than for the mid-troposphere (1,000–500 hPa) between December and March. Moreover, the spatial extent of the area where a significant positive correlation existed was smaller in the warmer months of the year than in the colder months, particularly at layer 1,000–500 hPa, reaching a minimum during the summer. Increases in the strength and spatial extent of the area with a significant positive correlation during the cold months was because of decreases in air temperature and the height of the THK, as well as increases in humidity in the atmosphere brought by westerly winds. For the warmer and drier period of May–September, during which a gradual increase in the dominance of the subtropical high over Iran at 500 hPa occurred, there was a significant decrease in both the correlation co-efficients and the spatial extent of the area with significant positive correlations.

Finally, the present study is an important first step toward understanding the spatio-temporal correlation between near-surface air temperature and the THK. It also provides useful information on the reliability of tropospheric thickness data when used as a forecasting tool. The inclusion of air humidity and cloudiness in the study of atmospheric thickness in future will help improve the accuracy of the correlation co-efficients obtained. This would be a valuable future exercise.

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