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**ROLA WIROWOŚCI POTENCJALNEJ W KONTEKŚCIE
ODDZIAŁYWAŃ MIĘDZY STRATOSFERĄ A TROPOSFERĄ
I JEJ WPŁYW NA UJEMNE ANOMALIE TERMICZNE
W IRANIE W CHŁODNEJ PORZE ROKU**

**THE ROLE OF STRATOSPHERE-TROPOSPHERE ANOMALIES
IN THE OCCURRENCE OF WIDESPREAD EXTREME LOW
TEMPERATURES IN IRAN'S COLD SEASON FROM
THE PERSPECTIVE OF POTENTIAL VORTICITY**

Introduction

The variable nature of atmospheric circulation can explain many anomalies in climatic elements. Anomalies in climatic elements, in terms of content, persistence, and magnitude, can be related to the climate system and the stability of atmospheric circulation patterns in time and space (Latysheva et al. 2007). Understanding the causes and nature of climatic extremes is one of the most important goals of monitoring climatic phenomena (Rahimi 2022). In classical dynamic meteorology texts (e.g., Bluestein 1992; Holton 2004), the behavior of tropospheric weather systems is attributed to tropospheric processes, although it is acknowledged that stratospheric air may enter these systems through tropopause folding (Colucci 2010). However, recent studies have shown that the stratosphere also actively plays a role in meteorological processes at the Earth's surface (Borhani et al. 2020; Wrona 2024). On one hand, tropospheric flows and circulations are influenced by stratospheric circulations, and on the other hand, disturbances resulting from changes in tropospheric circulations also affect stratospheric flow (Rahimi 2022).

The stratosphere can influence the troposphere and the surface through various chemical, radiative, and dynamic processes. This coupling between the troposphere and stratosphere, often referred to as the “downward influence” of stratospheric variability, provides long-term information for the primary modes of tropospheric variability and associated extreme weather events (Yu et al. 2022).

Dynamic coupling between the stratosphere and troposphere is an important aspect of the climate system with significant meteorological implications. The correlation between stratospheric and tropospheric variability is particularly important for forecasts beyond two weeks, as the dynamics of these two layers operate on distinctly different timescales, typically ranging from days in the troposphere to weeks in the stratosphere. Therefore, a comprehensive understanding of the fundamental principles of troposphere-stratosphere interactions can improve the accuracy of weather forecasts and climate predictions and extend the relevant predictable timeframes (Rupp et al. 2022). Baldwin and Dunkerton (2001) were the first to demonstrate the downward propagation of atmospheric signals from the stratosphere to the troposphere and ultimately to the Earth’s surface during the Northern Hemisphere winter. They showed that the spatial pattern of surface pressure anomalies associated with changes in the stratospheric polar vortex is similar to the annular mode (Karami et al. 2018; Marsz, Styszyńska 2021). Since then, numerous studies have been conducted in this area. For example, Haynes et al. (2021) studied the influence of the stratosphere on the tropical troposphere and found that the stratosphere has a significant impact on the tropical troposphere. In another study, Karami et al. (2018) showed that the direct reflection of wave activity from the stratosphere to the troposphere or the absorption and emission of these waves in the stratosphere is minimal. During the January-March period, the stratosphere exhibits a reflective state, and the highest likelihood of coupling between the stratosphere and troposphere occurs through the reflection of Rossby waves in mid-winter and early spring. Domeisen et al. (2020) concluded that the stratosphere plays a role in subseasonal to seasonal (S2S) predictions, and accurate simulation of stratospheric variability and dynamic stratosphere-troposphere coupling are important elements in winter S2S predictions. Additionally, Wang et al. (2021, 2022) investigated stratosphere-troposphere exchanges. Many other studies have also been conducted in this field using various methods.

Among these, one method for examining stratospheric and tropospheric anomalies is the potential vorticity (PV) quantity, which was first introduced by Rossby (1940) and generalized by Ertel (1942). However, it was the article by Hoskins et al. (1985) that led to the widespread use of potential vorticity in a broad range of atmospheric problems (Lambert et al. 2004). This quantity is one of the key tools used to understand the dynamics of atmospheric and oceanic phenomena. Due to its unique characteristics, as detailed

in the foundational article by Hoskins et al. (1985), there has been increasing interest in using this quantity to study various atmospheric phenomena. Using this quantity, some atmospheric processes can be described in terms of the interaction of potential vorticity anomalies with the background atmospheric structure. For example, when a strong potential vorticity anomaly in the upper levels moves over a surface low-pressure area, cyclogenesis typically occurs, and secondary circulations (vertical motions) contribute to its development. Additionally, assuming negligible nonlinear effects, the principle of superposition can be used to describe the interaction of potential vorticity anomalies at different atmospheric levels, leading to changes in the circulations of these levels (Ahmadi Givi et al. 2006). Given the importance of this quantity in atmospheric studies, numerous investigations have been conducted in this area. Black (2002) and Hines et al. (2010, 2011) showed that changes in lower stratospheric potential vorticity affect tropospheric winds. Liang et al. (2010) studied the diagnostic of generalized moist potential vorticity in a non-uniform saturated atmosphere with heavy precipitation. The results showed that generalized moist potential vorticity can accurately track the location of precipitation. Ran et al. (2013) studied diagnostic quantities of heavy precipitation using potential vorticity (simulated potential vorticity and simulated vorticity) and found that SV and PSV are good indicators of heavy precipitation and can be used as predictive parameters for precipitation. Vanniere et al. (2016) examined the effect of potential vorticity on the cold sector of extratropical cyclones. The results showed that negative potential vorticity at the surface can be used to identify the cold sector.

Colucci et al. (2020) investigated stratosphere-troposphere interactions and O₃ variability in the lower stratosphere and upper troposphere over the Irene SHADOZ site in South Africa. Using potential vorticity maps, they showed that the transport of air masses at high latitudes reduces O₃ in the lower stratosphere over Irene, coinciding with an increase in ozone in the upper troposphere. Additionally, during stratosphere-troposphere interactions, high PV values penetrate from the stratosphere into the troposphere. Crespo et al. (2021) examined the effect of upper-level potential vorticity structures on surface cyclogenesis in eastern South America and found that PV streams and cutoffs occasionally coincide with cyclogenesis events.

Therefore, understanding the relationship between stratospheric conditions and surface weather not only enhances our knowledge of the dynamics of different atmospheric layers but also has implications for improving weather and climate predictions in any region (Abbaszadeh Aghdam et al. 2008). Given the importance of stratosphere-troposphere interactions in surface weather events, this study uses potential vorticity to investigate the role of stratospheric and tropospheric anomalies in the occurrence of extreme low temperatures during Iran's cold season over a 50-year period (1960-2010).

Research methodology

This study uses two datasets: the first consists of daily temperature data from 35 synoptic stations with a common statistical period from 1960 to 2010 (September-March), obtained from the Iranian Meteorological Organization. The second dataset includes upper-air variables for case study days with widespread low temperatures, extracted from the NCEP/NCAR reanalysis on a $2.5^\circ \times 2.5^\circ$ grid, available on the CDC/REANALYSIS website (<http://www.esrl.noaa.gov/psd>). After extracting the initial data, missing data were reconstructed using linear regression. Then, based on the lowest 20% extreme temperatures, cold periods during the cold half of the year (September-March) were identified, and the most severe period was selected. To analyze the dynamical patterns governing the most severe cold period, days with widespread very low temperatures were determined as case studies for each season. It should be noted that by 'widespread extreme minimum temperatures', we refer to cold events that occur simultaneously in more than 60% of selected weather stations across Iran.

Finally, to examine the role of stratospheric and tropospheric anomalies in the occurrence of widespread extreme low temperatures during Iran's cold season, synoptic circulation patterns were first analyzed using geopotential height and temperature data at 1000 and 500 hPa levels over the selected region (0° to 80° E longitude and 10° to 60° N latitude) at 00:00 UTC, plotted and analyzed using Surfer software. Dynamical patterns of potential vorticity at pressure (500 and 50 hPa) and isentropic levels (330 K) were then plotted and analyzed. Additionally, specific humidity at 700 hPa and vertical velocity at 500 and 1000 hPa levels were examined to identify the origin of the potential vorticity anomalies. To better understand the synoptic and dynamical patterns governing the case studies, maps for two days before and after the event were also analyzed. However, to reduce the volume of content, only the maps for the day of widespread extreme low temperatures at 00:00 UTC are presented.

Research findings

Analysis of synoptic patterns of height fields in the lower and middle atmosphere during cold season case studies

Autumn Case Study

Figure 1 shows the 1000 hPa geopotential height fields at 00:00 UTC on November 30, 1964, representing the most widespread day of extreme low temperatures in

autumn across Iran during the study period. A high-pressure system is active over the study region, with its maximum core of 240 gpm (geopotential meters) extending from Lake Balkhash to northeastern Iran in a northeast-southwest direction. Based on the height fields from the previous two days, this anticyclonic system is a merged system formed by the eastward migration of a high-pressure system and the westward extension of the Siberian high. On this day, it affects the region, particularly Iran, as the western part of the Siberian high. The system is influenced by the intensification of low-pressure systems at high latitudes, especially the low-pressure system over northern Russia, and its meridional-zonal extension, which has shifted southward. This has intensified cold air advection and increased the height gradient in eastern Iran. Under these conditions, the westward anticyclonic flows of the system rapidly advect cold air toward eastern Iran, leading to a significant temperature reduction across the country, particularly in the northeast-southwest direction. As a result, minimum temperatures of 270 K are observed in the northeastern and eastern parts of the country, while maximum temperatures of 285 K are confined to narrow areas in the southeast (Fig. 1).

The circulation pattern at the 500 hPa level at 00:00 UTC shows a deep ridge extending from the subtropical high over North Africa to the northern Baltic Sea in a southwest-northeast direction. Additionally, a deep trough associated with the low-pressure system over northern Russia extends southward to the northern Arabian Sea. The shape of these cyclonic and anticyclonic flows (troughs and ridges) indicates an omega-blocking pattern affecting the study region. The western arm of the blocking pattern includes the southward cyclonic trough extending from the northern Baltic Sea to North Africa, while the eastern arm is the deep trough over northern Russia, extending to the southern Arabian Sea. The system is in its mature and peak phase, leading to the stagnation of active circulation patterns in the region. Under these conditions, Iran is influenced by the southward cold flows of the eastern arm of the blocking pattern, which have flowed cyclonically from the ridge into the trough. As a result, the deepening of the trough has intensified cold air advection into Iran, leading to a temperature reduction compared to the previous day. This cooling trend is more pronounced in the southern half of the country. Thus, Iran is significantly influenced by the eastern arm of the blocking system, which has prolonged the presence of cold flows in the region. It is noteworthy that the active cyclonic flows over Iran are highly wavy, indicating the dominance of southward meridional cold flows. The strong height gradient over the country reflects the intensity of the cold air advection (Fig. 2).

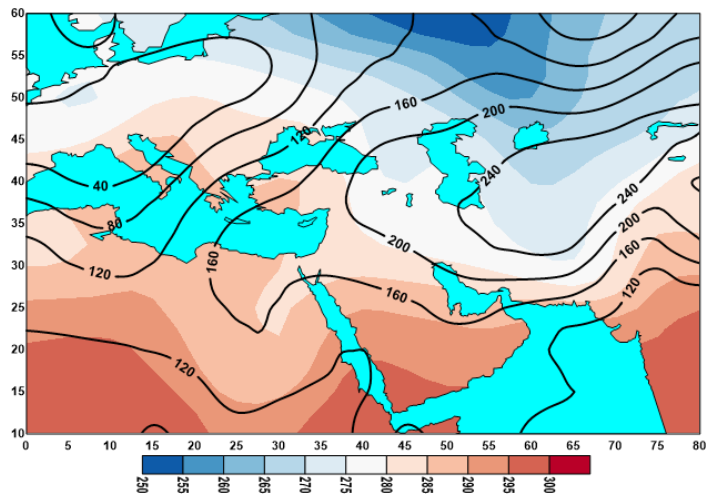


Fig. 1. Geopotential Height and Temperature Fields at the 1000 hPa Level at 0000 UTC on November 30, 1964.

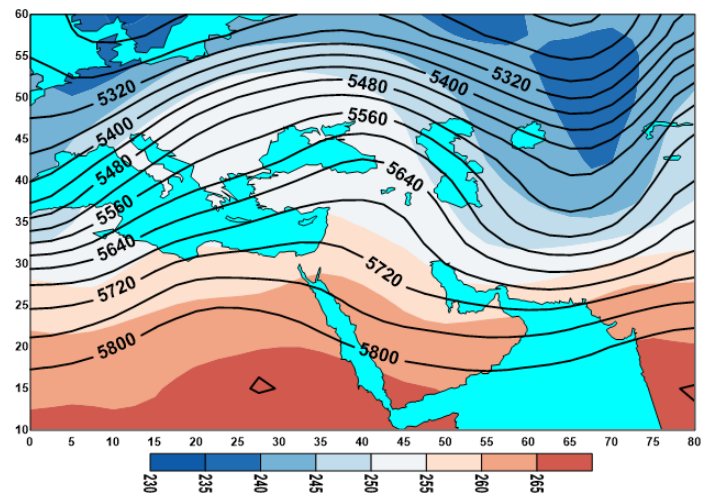


Fig. 2. Geopotential Height and Temperature Fields at the 500 hPa Level at 0000 UTC on November 30, 1964

Winter case study

The circulation pattern at the 1000 hPa level on January 20, 1964, at 00:00 UTC shows a migratory high-pressure system with a central height of 280 gpm over Europe. Its meridional ridge extends in a northwest-southeast direction to the eastern strip of Iran. As

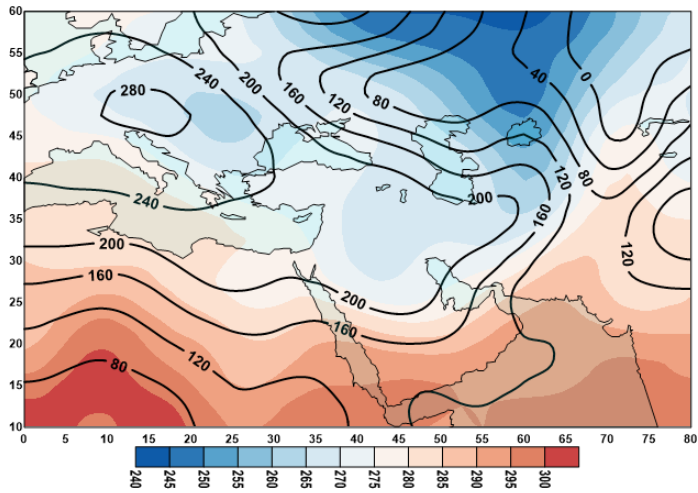


Fig. 3. Geopotential Height and Temperature Fields at the 1000 hPa Level at 0000 UTC on January 20, 1964.

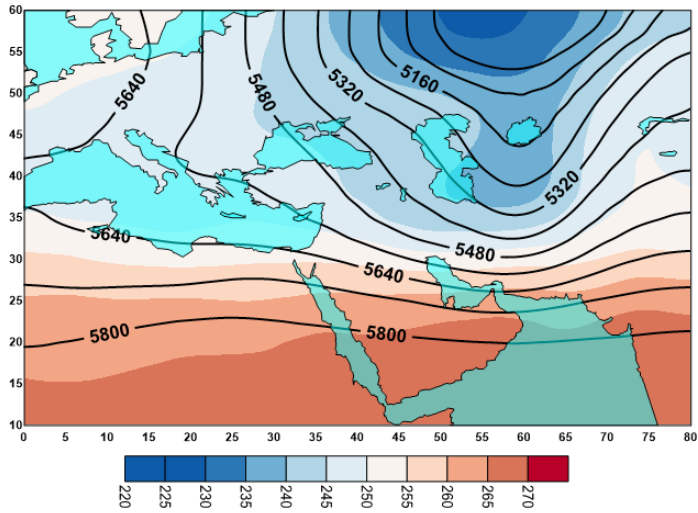


Fig. 4. Geopotential Height and Temperature Fields at the 500 hPa Level at 0000 UTC on January 20, 1964.

a result, cold air from higher latitudes is advected by the anticyclonic flows on the outer edge of this system, which has shifted southward under the influence of the low-pressure system over northern Russia. This has led to a significant drop in temperature across Iran compared to previous days. It is worth noting that a strong pressure gradient aligns with

the path of the anticyclonic flows entering the eastern strip of the country, indicating high wind speeds in these areas (Fig. 3).

The synoptic pattern at the 500 hPa level also indicates that a powerful low-pressure system is active over the study region, with its core at 5000 gpm over northern Russia. Under the influence of the cold cyclonic flows of this system, which have penetrated meridionally from north to south to around 25°N, the subtropical high has retreated to lower latitudes. Consequently, with the influx of polar cold air, temperatures across the region at this level have decreased compared to previous days. Since Iran is located ahead of the deep trough axis of the low-pressure system over northern Russia, it is influenced by the cold wavy flows from the western part of the trough, which are directed toward the country from the western and northern strips. Due to these meridional wavy flows, a strong height gradient has formed across Iran, reflecting the high intensity of the flows over the country. As a result, the cold and dry air from the western part of the mid-level trough converges intensely toward the lower atmospheric layers, strengthening the migratory high-pressure system at the surface (Fig. 4).

Analysis of dynamical patterns governing cold season case studies from the perspective of potential vorticity

Autumn Case Study (30 November 1964)

The potential vorticity (PV) fields at the 50 hPa level, aligned with the trough axis of the eastern and western arms of the omega blocking pattern, show high values. The maximum cores are located over the Baltic Sea with a value of 4.5 PVU (potential vorticity units) and over the eastern Black Sea and northeastern Turkey with a value of 4 PVU. Over Iran, maximum values between 3 and 3.5 PVU are observed, which have intensified compared to previous days (Fig. 6). A similar pattern is observed on the 330 K isentropic surface, where high PV values have increased compared to previous days and align with the activity of the eastern and western arms of the omega blocking pattern. Over Iran, aligned with the eastern arm of the blocking pattern in a northeast-southwest direction, the PV fields show maximum values ranging from 1 to 1.5 PVU (Fig. 7).

Consistent with the upper levels, the PV pattern at the mid-levels (500 hPa) also shows positive values of 0.55 PVU aligned with the meridional trough axis of the eastern arm of the blocking pattern (Fig. 5). The alignment of maximum positive PV anomalies at mid-levels with upper levels, along with low humidity and specific humidity in these regions (Fig. 8), the absence of upward motions (Fig. 9), and the lack of cyclonic activity at the surface (Fig. 1), indicate that the PVs at mid-levels do not originate from the tropo-

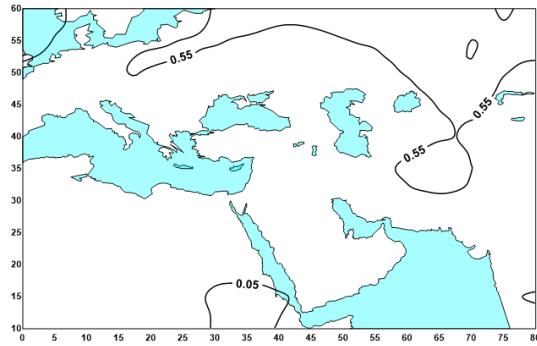


Fig. 5. Spatial Distribution of Rossby-Ertel Potential Vorticity at the 500 hPa Level at 0000 UTC on November 30, 1964.

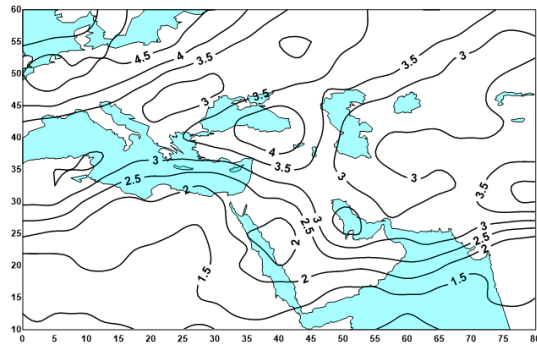


Fig. 6. Spatial Distribution of Rossby-Ertel Potential Vorticity at the 50 hPa Level at 0000 UTC on November 30, 1964.

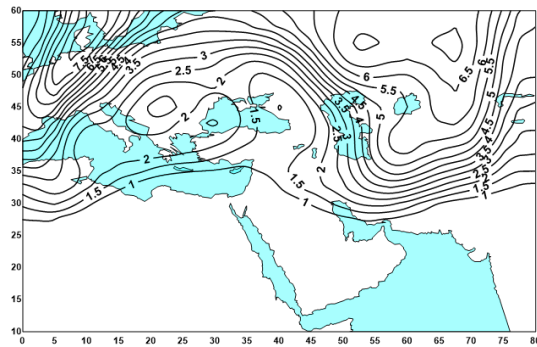


Fig. 7. Spatial Distribution of Potential Vorticity on the 330 K Isentropic Surface at 0000 UTC on November 30, 1964.

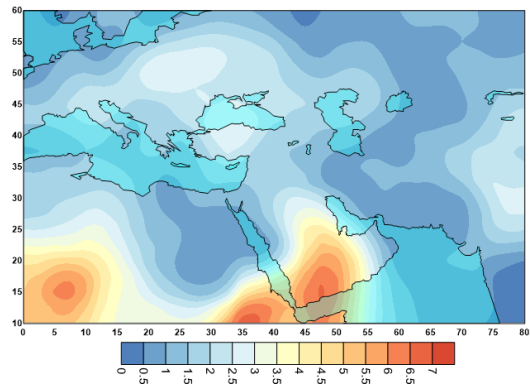


Fig. 8. Specific Humidity Fields at the 700 hPa Level at 0000 UTC on November 30, 1964.

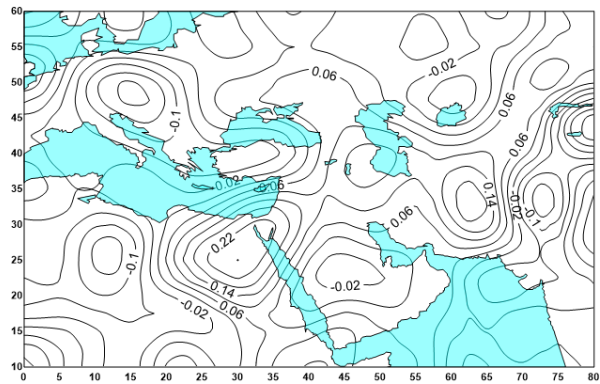


Fig. 9. Vertical Velocity at the 500 hPa Level (in Pa/s) at 0000 UTC on November 30, 1964.

sphere but are influenced by upper-level dynamics. This is directly related to increased tropopause folding and a decrease in the average extratropical height, resulting in the intrusion of upper-level PVs into the lower atmospheric layers.

Winter case study (20 January 1964)

The potential vorticity (PV) pattern at the 50 hPa level, aligned with the deep north-south trough axis of the low-pressure system over northern Russia and coinciding with the advective flow paths, shows high positive values that have increased compared to previous days. In this context, there are three maximum cores: one over northern Russia, one over northeastern Iran, and another over northern Pakistan. Over Iran, maximum PV values between 3 and 5 PVU are observed, with the highest value of 5 PVU located in the northeastern regions. The increase in PV values over Iran compared to the previous

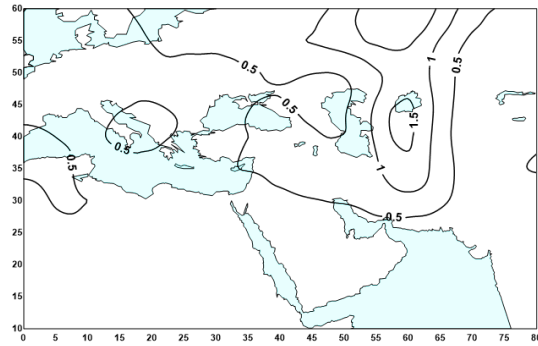


Fig. 10. Spatial Distribution of Rossby-Ertel Potential Vorticity at the 500 hPa Level at 0000 UTC on January 20, 1964.

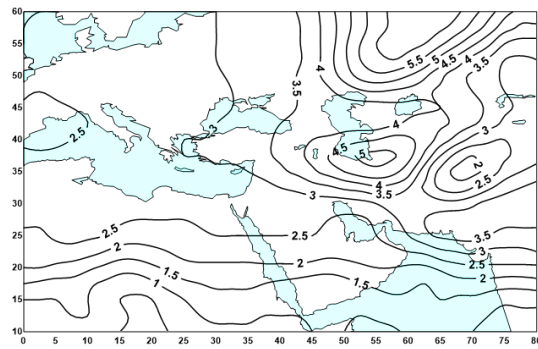


Fig. 11. Spatial Distribution of Rossby-Ertel Potential Vorticity at the 50 hPa Level at 0000 UTC on January 20, 1964.

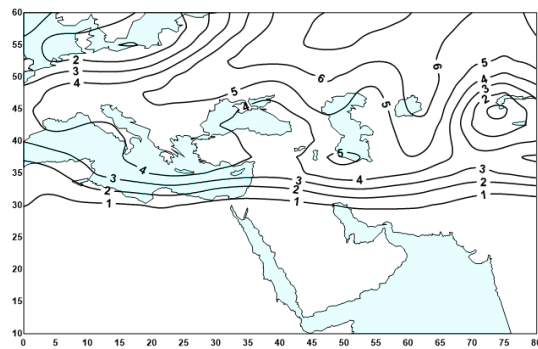


Fig. 12. Spatial Distribution of Potential Vorticity on the 330 K Isentropic Surface at 0000 UTC on January 20, 1964.

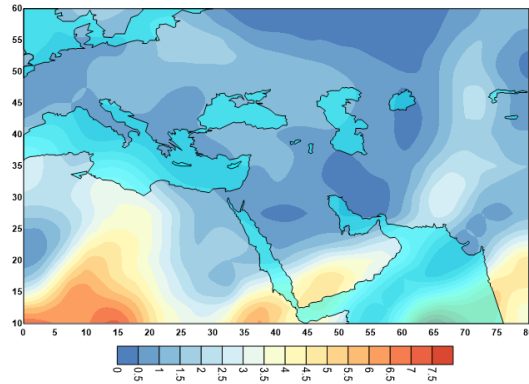


Fig. 13. Specific Humidity Fields at the 700 hPa Level at 0000 UTC on January 20, 1964.

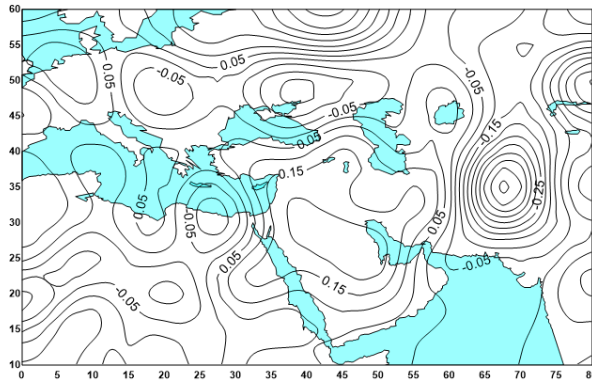


Fig. 14. Vertical Velocity at the 500 hPa Level (in Pa/s) at 0000 UTC on January 20, 1964.

day is associated with the intensification and deepening of the meridional trough in the upper levels (Fig. 11). A similar pattern is observed on the 330 K isentropic surface (Fig. 12), where PV values have increased across the study region in line with the strengthening and expansion of the meridional trough. This trend is also evident in the Rossby-Ertel potential vorticity pattern at the 500 hPa level (Fig. 10).

It is important to note that due to very low specific humidity in the mid-levels and the absence of upward motions, the PVs at mid-levels do not originate from the troposphere, and no cyclonic activity is observed at the surface (Figs 3, 13, and 14). The primary reason for this is the further reduction in the extratropical tropopause height and weak static stability of the atmosphere, which has facilitated the downward transfer of stratospheric air with high PV into the lower atmospheric layers. This highlights the role of stratospheric anomalies in the significant temperature drop observed on this day.

Conclusions

The analysis of height fields in the middle and lower atmospheric layers during the selected cold period case studies revealed that during the occurrence of widespread extreme low temperatures in autumn, the cyclonic flows of the eastern arm of the omega blocking pattern in the mid-levels of the atmosphere halted atmospheric circulation patterns and converged cold flows toward the lower layers, strengthening the powerful anticyclonic system at the surface. In winter, the presence of convergent cyclonic flows in the deep meridional trough in the mid-levels and divergent flows of the migratory anticyclone at the surface contributed to the occurrence of widespread minimum temperatures in Iran. It is noteworthy that the anticyclonic and cyclonic systems in the mid- and lower layers were in their mature phase.

The examination of potential vorticity fields showed that during the occurrence of widespread extreme low temperatures in the cold season, PV anomalies in the upper and mid-levels of the atmosphere increased compared to previous days. The anomalies in the mid-levels did not originate from the troposphere but were associated with stratospheric anomalies. Specifically, the reduction in the average extratropical tropopause height and increased tropopause folding allowed stratospheric air with high PV to intrude into the lower atmospheric layers, resulting in positive PV anomalies in these layers. Consequently, anomalies in the upper and mid-levels played a key role in the development of surface anticyclonic systems and mid-level cyclones.

From the perspective of potential vorticity, it can be concluded that the coupling of PV anomalies in the upper and mid-levels of the atmosphere, with a stratospheric origin, was the main factor behind the occurrence of widespread minimum temperatures. This clearly demonstrates the connection between stratospheric and tropospheric changes in the creation of widespread extreme low temperatures during the cold season in the studied period.

The results of this study align with findings from several key studies on stratosphere-troposphere interactions: Zhang et al. (2023) demonstrated the synergistic role of stratosphere-troposphere coupling in generating extreme cold temperatures in late November 2022 in China, Tomassini et al. (2012) identified this mechanism in severe winter cold events in Northern Europe, and Gečaitė (2022) linked stratosphere-troposphere coupling to extreme winter temperature events in the eastern Baltic Sea region.

In contrast, existing studies in Iran have primarily focused on the role of stratosphere-troposphere anomalies in heavy precipitation events and cyclogenesis. Therefore, this study represents one of the first investigations examining the influence of stratosphere-troposphere anomalies on the occurrence of extreme minimum temperatures in Iran.

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S t r e s z c z e n i e

Niniejsze badanie analizuje rolę anomalii stratosferycznych i troposferycznych w występowaniu niskich temperatur powietrza w Iranie podczas sezonu chłodnego przy wykorzystaniu indeksu wirowości potencjalnej (PV) w latach 1960–2010. Na podstawie 20% zanotowanych przypadków najniższych wartości temperatury zidentyfikowano rozległe przestrzennie fale chłodu w okresie od września do marca. Dni charakteryzujące się najniższymi wartościami temperatur posłużyły jako studia przypadków w celu analizy warunków cyrkulacyjnych determinujących wystąpienie silnego ochłodzenia. Oceniono współzmiennność z wysokością geopotencjału na poziomach 1000 i 500 hPa oraz wirowość potencjalną na poziomach 50 i 500 hPa, a także na powierzchni izotropowej 330 K. W celu identyfikacji źródeł anomalii PV przeanalizowano także wilgotność właściwą na poziomie 700 hPa oraz dynamikę ruchów pionowych powietrza na poziomach 500 i 1000 hPa. Uzyskane wyniki wykazały, że anomalie wirowości potencjalnej w stratosferze oraz jej intruzje w dolne warstwy troposfery były głównymi czynnikami determinującymi występowanie fal chłodu w Iranie w okresie od września do marca.

Słowa kluczowe: wirowość potencjalna, stratosfera, troposfera, niska temperatura, Iran.

A b s t r a c t

This study investigates the role of stratosphere-troposphere anomalies in the occurrence of widespread extreme low temperatures in Iran's cold season using the potential vorticity index from 1960 to 2010. Based on the lowest 20% of extreme temperatures, widespread cold periods during the cold half of the year (September-March) were identified, and the most severe period was selected. Days with widespread very low temperatures were chosen as case studies for each season to analyze the dynamical and synoptic patterns governing the severe cold period. Synoptic circulation patterns, including geopotential height at 1000 and 500 hPa levels, and dynamical patterns such as potential vorticity at 50 and 500 hPa levels and on the 330 K isentropic surface, were plotted and analyzed. Specific humidity at the 700 hPa level and vertical velocity at 500 and 1000 hPa levels were also examined to identify the origin of potential vorticity anomalies. The results revealed that dynamical anomalies of stratospheric potential vorticity and its downward intrusion into the troposphere were the main factors behind the occurrence of widespread extreme low temperatures in Iran's cold season. This highlights the role of stratosphere-troposphere exchanges in the occurrence of widespread extreme low temperatures during the studied period.

Key words: Potential vorticity, stratosphere, troposphere, low temperature, Iran.

