# Objective Classification of Suspended Dust Weather in the Tarim Basin: Postprint

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## Abstract

This study utilizes multi-station dust day data from the Tarim Basin for the period 2011–2020, identifying 396 dust suspension days. Employing ERA5 meteorological reanalysis data, the PCT algorithm is applied to objectively classify surface and upper-air circulation patterns on dust suspension days in the Tarim Basin, with typical cases analyzed to reveal the relationship between dust suspension and weather circulation in the lower and upper levels. The results demonstrate that surface weather patterns can be categorized into pre-high-pressure type, bottom-of-high-pressure type, and uniform pressure field type, with distinct differences in meteorological conditions and pollutant concentration characteristics observed under different surface weather patterns. The evolution of surface weather systems follows the sequence of pre-high-pressure type → bottom-of-high-pressure type → uniform pressure field type, while the evolution of upper-level weather systems transitions from alternating post-western-trough and high-pressure ridge types to zonal straight-flow type. When the surface Siberian cold high moves eastward and southward, and the upper level is controlled by the post-trough and Iranian high, dust suspension weather is in its occurrence and development stage, with elevated surface PM10 concentrations. When the surface presents a uniform pressure field with no significant pressure system activity, and the upper level exhibits zonal straight-flow circulation, dust suspension weather tends to dissipate.

## Full Text

### Objective Weather Classification of Persistent Floating Dust Weather in the Tarim Basin

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## Abstract

This study utilized multi-station observational data on floating dust days across the Tarim Basin from 2011 to 2020, identifying 396 days characterized by persistent floating dust. Employing ERA5 meteorological reanalysis data, the PCT algorithm was applied to objectively classify near-surface and upper-air circulation patterns during persistent floating dust episodes in the Tarim Basin. Typical cases were analyzed to reveal the relationship between persistent floating dust and synoptic circulation at various altitudes. The results demonstrate that near-surface weather patterns can be categorized into three types: high-pressure front, high-pressure bottom, and uniform pressure field, each exhibiting distinct meteorological conditions and pollutant concentration characteristics. The evolution of near-surface weather systems follows a sequence from high-pressure front to high-pressure bottom, culminating in uniform pressure field, while upper-air systems alternate between post-trough westerly and high-pressure ridge patterns before transitioning to a zonal latitudinal pattern. When the Siberian cold high-pressure system moves eastward and southward at the surface, with upper-air circulation controlled by post-trough westerlies and the Iranian high, persistent floating dust events emerge and intensify, accompanied by elevated surface PM10 concentrations. Conversely, when a near-surface uniform pressure field prevails with minimal pressure system activity and upper-air circulation assumes a zonal latitudinal pattern, persistent floating dust events tend to dissipate.

**Keywords:** persistent floating dust; objective weather classification; principal component analysis in T-mode; Tarim Basin

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# 1. Data and Methods

## 1.1 Data Sources and Processing

To identify large-scale persistent floating dust events in the Tarim Basin, we utilized observational data from three stations—Tazhong, Minfeng, and Maigaiti—spanning 2011-2020. These stations, located in the central, southern, and western regions of the basin respectively, represent high-value monitoring sites for floating dust in each area. Simultaneous floating dust occurrence at all three stations was taken to indicate a large-scale floating dust event across the Tarim Basin. Events persisting for two or more days were defined as persistent floating dust episodes, yielding a total of 396 such days.

Meteorological data for weather classification and vertical circulation analysis were obtained from the ERA5 reanalysis dataset published by the European Centre for Medium-Range Weather Forecasts (ECMWF), covering 2011-2020 with a spatial resolution of 0.25°$×$0.25°. The dataset includes sea-level pressure fields and 10 m wind fields, geopotential height and wind fields (U, V) at 500 hPa and 700 hPa, as well as temperature, vertical velocity, horizontal wind (U), and divergence fields from 1000 hPa to 200 hPa. The study domain spans 75°-90°E and 35°-43°N.

PM10 concentration data were sourced from the China Air Quality Online Monitoring Platform (https://www.aqistudy.cn/historydata/), representing four cities in the Tarim Basin with severe dust pollution: Kashgar, Hotan, Korla, and Aksu. Daily PM10 concentrations were calculated as the 24-hour sliding average of daily maximum values from these national environmental monitoring stations. For brevity, subsequent references use PM10 to denote this concentration metric. Meteorological data for condition analysis were obtained from station observations (2011-2020), including temperature and horizontal wind speed.

### 1.2 Research Methods

This study employed the PCT algorithm developed by the EU COST733 project for weather classification. This method decomposes original high-dimensional data (Z) into principal component and loading matrices, selects components with large variance contributions, performs oblique rotation, and finally classifies each time step's weather pattern based on loadings. Specifically, the original high-dimensional data (Z) is decomposed into two low-dimensional matrices F and A, where Z = FA^T. Here, rows represent N spatial grid points, columns represent M observation times, F is the principal component matrix (PC), and A is the PC loading matrix. All principal components are sorted by their corresponding eigenvalues, with larger eigenvalues indicating greater contribution to the original data. Components are retained until their cumulative contribution exceeds a specified percentage (typically 85%-95%), achieving dimensionality reduction. The retained principal component matrix F (M×K) is then obliquely rotated, and weather patterns are classified according to loading magnitudes for each time step.

The PCT method performs multivariate oblique rotation on meteorological reanalysis data fields (pressure, geopotential height, or wind), simultaneously representing spatial distributions and inter-variable spatial relationships as a unified spatiotemporal expansion, yielding accurate circulation classification results.

Previous evaluations have demonstrated that PCT exhibits good classification stability and accurately reflects original circulation field characteristics, with reliability increasing as meteorological data time series lengthen and precision improves.

To minimize the influence of local small-scale systems and focus on synoptic-scale features, we classified the average sea-level pressure field at four daily observation times (02:00, 08:00, 14:00, and 20:00 UTC) for each persistent floating dust day. The PCT method identified three surface weather types: high-pressure front, high-pressure bottom, and uniform pressure field. For each type, we averaged the sea-level pressure fields across all persistent floating dust days. Similarly, we classified circulation patterns at 500 hPa and 700 hPa using 08:00 UTC geopotential height fields, as ERA5 reanalysis at this time assimilates global surface and sounding observations with highest accuracy.

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## 2. Results and Analysis

### 2.1 Interannual Variation Characteristics of Persistent Floating Dust in the Tarim Basin

Analysis of interannual variation in persistent floating dust days reveals a unimodal trend (Figure 2). Between 2011 and 2020, the number of persistent floating dust days peaked in 2015, with fewer days in 2011-2014. The year 2015 saw a surge in persistent floating dust days, after which numbers decreased significantly and fluctuated without exceeding the 2015 peak. Since 2017, atmospheric visibility observations transitioned from manual to instrumental measurements, introducing substantial biases that may affect recent floating dust analyses. The interannual variation in PM10 concentration showed a similar unimodal pattern, with lower concentrations during 2011-2014, a sharp increase in 2015, and subsequent fluctuating declines.

### 2.2 Near-Surface Weather Pattern Characteristics

The PCT classification of near-surface weather patterns during persistent floating dust days yielded three distinct types: high-pressure front, high-pressure bottom, and uniform pressure field. Monthly variation characteristics for each pattern (Table 1) and daily average PM10 concentrations and meteorological elements under each pattern (Table 2) reveal significant differences.

**High-pressure front type** (Figure 3a) features a closed high-pressure system centered near Lake Balkhash, typically representing a cold high extending west-to-east. The high-pressure range stretches from east of the Ural Mountains to north of Lake Baikal in Mongolia. Northern Xinjiang experiences northerly winds ahead of the high, while the northern Tarim Basin lies in a dense isobaric zone between the cold high front and the basin’ s thermal low, with the entire basin under thermal low control. Before the cold front enters the basin, strong development and maintenance of the thermal low occurs due to dynamic convergence ahead of the front and low-level warm advection, resulting in above-normal temperatures at all stations. The Tarim Basin thermal low and rear cold high create a pressure field higher in the northwest and lower in the southeast. Cold air accumulates north of the Tianshan Mountains, and the substantial pressure gradient, influenced by basin topography, generates mountain-crossing and eastward-penetrating winds across the Tarim Basin. Increased surface wind speeds in the western and northeastern basin trigger large-scale dust events, with basin-wide average PM10 concentrations reaching 625 g · m$^{-3}$. This pattern commonly occurs during the initial stage of persistent floating dust processes. Over the past decade, the high-pressure front type accounted for 112 days (28.3% of total persistent floating dust days), predominantly in spring with a peak in May.

**High-pressure bottom type** (Figure 3b) features a closed high-pressure center north of Xinjiang, with most mid-latitude regions under cold high control. The high-pressure range extends from west of the Ural Mountains to eastern Mongolia, often reaching 1030 hPa at its center. As the cold high intensifies and moves eastward and southward to the northern Tarim Basin, the basin’ s thermal low weakens and shifts southwestward. All stations experience significant cooling while wind speeds increase in central and southern basin areas, triggering intense dust storms with average PM10 concentrations of 837 g · m$^{-3}$. This pattern typically follows the high-pressure front type, occurring on 138 days (34.8% of total persistent floating dust days), mainly concentrated in spring with a peak in April.

**Uniform pressure field type** (Figure 3c) exhibits stable synoptic conditions, with weak high-pressure activity commonly observed west of Lake Baikal and uniform pressure fields across most mid-latitude regions featuring small pressure gradients and no distinct weather systems. As cold air moves out of southern Xinjiang and severe dust storms subside, temperatures at basin stations gradually recover. Strong sensible heating over desert surfaces and thermal differences between mountains and basin create low-level convergence and upward motion, allowing the basin thermal low to develop and intensify. Weak horizontal winds within the basin are unfavorable for horizontal transport of dust aerosols, resulting in floating dust accumulation. This pattern commonly appears after surface cold highs move eastward and southward, persisting for extended durations. Over the past decade, the uniform pressure field type occurred on 146 days (36.9% of total persistent floating dust days), primarily in spring and summer with a peak in June. Seasonally, spring sees relatively high occurrence frequencies for all three surface weather types. Summer, with weakened cold high activity, predominantly features the uniform pressure field type during persistent floating dust days.

### 2.3 Circulation Patterns at 500 hPa and 700 hPa

Circulation patterns at 500 hPa and 700 hPa during persistent floating dust days can each be categorized into three types: zonal latitudinal, post-trough westerly, and high-pressure ridge. At 500 hPa, the zonal latitudinal pattern (Figure 5a) features straight westerlies across mid-to-high latitudes west of 100°E. Under this stable circulation, the Tarim Basin experiences consistent westerly flow with no significant cold or warm advection. This large-scale stability favors formation and maintenance of near-surface uniform pressure fields. This pattern occurred on 213 days (53.8% of total persistent floating dust days). The post-trough westerly pattern (Figure 5b) involves eastward-moving shortwave troughs split from Central Asian low vortices, with trough zones over the Mongolian Plateau and eastern Xinjiang. The Tarim Basin, controlled by northwesterly flow behind the trough, experiences strong cold air advection from polar regions that intensifies the trough and moves the surface high eastward, bringing severe dust weather. This pattern occurred on 109 days (27.6% of total persistent floating dust days). The high-pressure ridge pattern (Figure 5c) features eastward and northward extension of the Iranian subtropical high, placing the Tarim Basin under its control with sustained temperature increases. This pattern occurred on 74 days (18.6% of total persistent floating dust days).

At 700 hPa, circulation patterns show similar characteristics to 500 hPa, also classifiable into zonal latitudinal, post-trough westerly, and high-pressure ridge types. The zonal latitudinal pattern at 700 hPa occurred on 195 days (49.1% of total persistent floating dust days), the high-pressure ridge type on 121 days (30.8%), and the post-trough westerly type on 80 days (20.1%).

### 2.4 Configuration Analysis of Weather Systems

#### 2.4.1 Configuration of Near-Surface and Upper-Air Weather Systems

The movement, development, and evolution of near-surface weather systems are intimately connected with upper-air circulation patterns. To analyze these relationships, we compiled statistics on configurations of high-low altitude weather systems and their coupling with surface systems during persistent floating dust days (Figure 6). Among high-low altitude system configurations, the combination of zonal latitudinal patterns at both 500 hPa and 700 hPa was most frequent, exceeding 40% of cases. This configuration favors formation and maintenance of near-surface uniform pressure fields. The combination of high-pressure ridge types at both levels accounted for 15.4% of cases, during which surface cold high intensity weakens and the Tarim Basin thermal low develops, also favoring uniform pressure field maintenance. Other frequent configurations included 500 hPa zonal latitudinal with 700 hPa post-trough westerly (9.1%), and 500 hPa post-trough westerly with 700 hPa high-pressure ridge (8.1%).

In configurations coupling high-low altitude and near-surface systems, three combinations dominated: both 500 hPa and 700 hPa zonal latitudinal paired with surface uniform pressure field, high-pressure bottom, and high-pressure front types, accounting for 20.7%, 11.6%, and 9.1% respectively. These results demonstrate that the occurrence and development of near-surface weather systems during persistent floating dust events are substantially influenced by large-scale upper-air circulation patterns.

**2.4.2 PM10 Concentration Characteristics Under Different System Configurations** By selecting seven common configurations of high-low altitude and near-surface weather systems during persistent floating dust days, and using PM10 data from the four severely affected cities (Kashgar, Hotan, Korla, and Aksu) to represent basin-wide dust concentrations, we analyzed how different system combinations affect surface PM10 levels. As shown in Figure 7, when upper-air systems are controlled by troughs or ridges with strong northwesterly flow behind troughs and ahead of ridges, Siberian cold air continuously transports from northwest to southeast. Coupled with surface high-pressure front or bottom types and southward-moving cold fronts, this generates mountain-crossing and eastward-penetrating winds that trigger intense dust storms, yielding extremely high PM10 concentrations exceeding 1000 g · m$^{-3}$. When upper-air systems transition from troughs to ridges while surface cold highs retreat under uniform pressure field control, PM10 concentrations remain below 300 g · m$^{-3}$. When both upper-air levels exhibit zonal latitudinal flow with mid-latitude westerlies, the basin experiences straight westerly flow unfavorable for surface high development, resulting in extensive uniform pressure areas with weak horizontal winds that cause local dust accumulation and floating dust formation, with PM10 concentrations also remaining below 300 g · m$^{-3}$. These findings indicate that different configurations of high-low altitude and near-surface weather systems exert varying impacts on surface PM10 concentrations during persistent floating dust days.

### 2.5 Typical Case Analysis of Persistent Floating Dust

To further investigate how weather system evolution and circulation patterns affect PM10 characteristics during persistent floating dust events, we selected a large-scale springtime episode from May 14-20, 2016. During this period, stations along the eastern (Korla), northern (Aksu), western (Kashgar), and southern (Hotan) margins of the Tarim Basin experienced varying degrees of sandstorms, floating dust, and blowing sand. Based on temporal PM10 variations, the event was divided into three stages: onset (May 14-15), development (May 16-17), and dissipation (May 18-20).

During the onset stage, Kashgar’ s PM10 concentration rose from 249 g · m$^{-3}$ to 1049 g · m$^{-3}$, while Hotan’ s concentration exceeded 1000 g · m$^{-3}$. Korla and Aksu also surpassed 500 g · m$^{-3}$. During the development stage, PM10 concentrations soared to 826 g · m$^{-3}$, far exceeding the 420 g · m$^{-3}$ threshold for severe pollution according to HJ633-2012. During the dissipation stage (May 18-20), dust intensity gradually weakened as stations transitioned to floating dust and blowing sand conditions that persisted until May 20.

**2.5.1 Circulation Field Analysis of the Typical Case** **Onset stage (May 14-15):** This period featured eastward and southward movement of a cold high. On May 14, the surface pattern was a uniform pressure field with weak pressure gradients across mid-latitudes. By May 15, the cold high had moved to the Ural-Siberian region with its center north of the Aral Sea, reaching 1032 hPa. Northern Xinjiang experienced northerly flow ahead of the high, while the Tarim Basin remained under thermal low control. Cold air split from the main high accumulated north of the Tianshan Mountains, creating mountain-crossing and eastward-penetrating winds that caused strong winds and cooling across the basin. At 500 hPa, the trough zone on May 14 was located west of Xinjiang and north of the Balkhash Lake, moving rapidly eastward with strong cold advection behind the trough. By May 15, the trough had shifted to eastern Xinjiang and Outer Mongolia, with the Tarim Basin under northwesterly post-trough flow. The Iranian subtropical high extended eastward, and the 500 hPa circulation transitioned from high-pressure ridge to post-trough westerly pattern. At 700 hPa, circulation was similar but with the trough more southeastward, indicating a low-level trough lagging behind the upper-level trough that favored trough intensification (Figure 8).

**Development stage (May 16-17):** Surface patterns transitioned from high-pressure front to high-pressure bottom types as the cold high intensified and moved further eastward and southward. On May 16, the high moved to the Balkhash Lake region west of Xinjiang, weakening to 1028 hPa. The pressure difference between the northern Xinjiang cold high and the Tarim Basin thermal low reached 30 hPa. By May 17, the high' s main body had moved to the Mongolian Plateau east of Xinjiang, continuing to weaken. Split cold air kept moving southward across mountains and eastward penetration, weakening the basin' s thermal low and sustaining severe dust storms. At 500 hPa and 700 hPa, circulation patterns were high-pressure ridge types transitioning to post-trough westerly patterns. After the trough moved out of Xinjiang on May 16, the Iranian high extended eastward and northward, controlling the basin region and causing slight temperature recovery. A high-latitude low vortex activity on May 17 split a low trough that guided cold air southward.

**Dissipation stage (May 18-20):** Surface patterns became uniform pressure fields. Most mid-latitude regions exhibited uniform pressure with weak gradients and no distinct systems, except for weak high-pressure activity north of Lake Baikal west of the Mongolian Plateau. Basin temperatures slowly recovered, severe dust storms subsided, and winds gradually weakened. Both 500 hPa and 700 hPa patterns transitioned from high-pressure ridge to zonal latitudinal types, with the Tarim Basin under stable westerly flow.

**2.5.2 Atmospheric Dynamic Conditions of the Typical Case** Analysis of temperature change, vertical velocity, zonal wind, and divergence fields along 39°N for the three stages reveals distinct dynamic characteristics (Figure 9). During the onset stage, under the influence of eastward-penetrating and mountain-crossing cold air, the entire layer below 600 hPa in the Tarim Basin experienced cooling, with a maximum cooling center at 850–700 hPa reaching 8°C. Divergence and vertical velocity fields show convergence below 800 hPa in central and eastern basin areas, divergence at 800–550 hPa with centers reaching 1.5$×10^{-5}$ $\mathrm{s}^{-1}$, and strong upward motion with vertical velocities up to -1.9$×10^{-1}$ $\mathrm{Pa \cdot s}^{-1}$, favoring dust uplift and transport. Western basin areas showed subsidence with mid-low level easterly flow transporting dust westward, causing ground PM10 surges.

During the development stage, cold air continued invading the basin but with reduced intensity, while mid-low levels experienced slight warming. Divergence and vertical velocity patterns resembled the onset stage, with near-surface convergence and divergence at 800–550 hPa (weakened to 1.0$×10^{-5}$ $\mathrm{s}^{-1}$). Central and eastern basins maintained upward motion, preventing dust settling while easterly flow continued transporting dust westward.

During the dissipation stage, temperatures rebounded significantly throughout the layer below 600 hPa with warming of 4-6°C. The basin exhibited low-level divergence and upper-level convergence below 500 hPa, with western basin divergence centers reaching 2.6$×10^{-5}$ $\mathrm{s}^{-1}$. Dominant subsidence with vertical velocities of 2.6$×10^{-1}$ $\mathrm{Pa \cdot s}^{-1}$ facilitated dust particle settling and reduced surface pollution.

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## 3. Conclusions

To investigate synoptic evolution characteristics during persistent floating dust events in the Tarim Basin, we identified persistent floating dust days from 2011–2020 and applied the PCT algorithm to objectively classify near-surface, 500 hPa, and 700 hPa circulation patterns. By analyzing typical cases and atmospheric dynamic conditions, we elucidated relationships between weather systems and dust aerosol emissions, reaching the following conclusions:

1) Near-surface weather patterns during persistent floating dust days can be summarized as high-pressure front, high-pressure bottom, and uniform pressure field types, each exhibiting distinct meteorological conditions and pollutant concentrations. The high-pressure front and bottom types generate high PM10 concentrations with strong winds and cooling, while the uniform pressure field type features light winds and warming with lower PM10 concentrations. The development of near-surface weather systems is substantially influenced by large-scale upper-air circulation patterns. Both 500 hPa and 700 hPa geopotential height fields can be categorized into zonal latitudinal, post-trough westerly, and high-pressure ridge types, with different high-low altitude and near-surface system configurations producing varying impacts on surface PM10 concentrations.

2) Case analysis reveals that near-surface weather systems evolve from high-

> pressure front through high-pressure bottom to uniform pressure field types, while upper-air systems alternate between post-trough westerly and high-pressure ridge patterns before transitioning to zonal latitudinal flow. When the Siberian cold high moves eastward and southward at the surface and upper-air circulation is controlled by post-trough westerlies and the Iranian high, persistent floating dust events initiate and develop. Under basin easterly flow and upward motion, dust is uplifted and transported westward, intensifying dust weather and causing PM10 surges. When near-surface uniform pressure fields prevail with minimal system activity and upper-air circulation becomes zonal latitudinal, basin horizontal winds weaken and subsidence causes dust settling, reducing surface PM10 pollution and ending the persistent floating dust event.

The PCT algorithm' s reliability increases with longer, higher-precision meteorological time series. This study classified 396 persistent floating dust days, though longer observational records would further improve accuracy. Additionally, we focused on large-scale circulation modulation of basin-wide persistent floating dust; future work should integrate long-term, high-resolution satellite and ground-based observations with synoptic diagnosis and numerical modeling to comprehensively investigate regional floating dust mechanisms, including mesoscale systems (shear lines, convergence centers), for a more complete understanding of dust formation and evolution in the Tarim Basin.

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