

# JGR Atmospheres

## RESEARCH ARTICLE

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### Key Points:

- Strong continental anthropogenic cloud perturbations occur on 20%–37% of days with liquid-phase clouds
- Strong perturbations tend to form in clean and thin clouds under stable and dry conditions
- Large-scale atmospheric circulation largely determines the occurrence of conditions which favor strong perturbations

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Meteorological Conditions Favorable for Strong Anthropogenic Aerosol Impacts on Clouds

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**Abstract** Ship-track-like polluted cloud tracks provide a direct way to study aerosol-cloud interactions. Here, we study environmental conditions favorable for pollution tracks' formation. We study polluted cloud tracks forming downwind of localized anthropogenic air pollution hot spots of Norilsk and Cherepovets in Russia and Thompson in Canada. Polluted cloud tracks form on 20%–37% of days with liquid-phase clouds. The large-scale atmospheric circulation largely determines the occurrence of track-favoring conditions. Tracks tend to form in clean and thin clouds under stable and dry conditions that are more often associated with anticyclonic large-scale flow in the studied locations.

**Plain Language Summary** Tiny solid and liquid air pollution particles called aerosols offset an unknown fraction of the greenhouse gas warming. Here, we study under which conditions aerosols have strong impacts on clouds leading to a cooling effect on Earth's climate. We study clouds downwind of anthropogenic air pollution hot spots. We compare the conditions where air pollution changes the properties of clouds to the conditions where the influence of air pollution is not seen. Anthropogenic air pollution particles more readily lead to changes in the properties of clean and thin clouds under stable and dry conditions that are more often associated with anticyclonic large-scale airflow in the studied locations. Our results help reduce the uncertainty related to the anthropogenic aerosol impacts on clouds and Earth's climate.

## 1. Introduction

Aerosols, acting as cloud condensation nuclei, modulate the radiative properties of clouds. The influence of aerosols on Earth's climate is the most uncertain mechanism of anthropogenic climate forcing (Forster et al., 2021). Our limited knowledge about the extent to which aerosol offset the greenhouse gas warming impedes estimating the sensitivity of the Earth's climate to anthropogenic radiative forcing (Stevens et al., 2016), limiting the reliability of future climate projections.

Most of the uncertainty associated with aerosol climate forcing comes from the poorly understood aerosol-cloud interactions (Bellouin et al., 2020). At fixed liquid water content, aerosols raise the cloud albedo by increasing cloud droplet number concentration (CDNC) and decreasing the size of cloud droplets, known as the first aerosol indirect effect (Twomey, 1974). Other aerosol indirect effects concern the changes in cloud thickness, cloud coverage, and lifetime (e.g., Albrecht, 1989). These adjustments can induce further changes in the albedo of a cloud field.

Environmental conditions influence aerosol-cloud interactions. However, as meteorological conditions affect both aerosols and clouds (Liu et al., 2018), it can be difficult to disentangle the influence of anthropogenic aerosols on clouds (Quaas et al., 2020; Stevens & Feingold, 2009). The susceptibility of cloud droplet number concentration to aerosols depends on the geographical region and cloud regime (Chen et al., 2016; Lu et al., 2012; Myhre et al., 2007; Oreopoulos et al., 2020; Quaas et al., 2008). Meteorological conditions also influence the formation of aerosol particles and pollution levels (Zhong et al., 2017, 2019), the vertical transport of aerosols (Lu et al., 2012) and the properties of unpolluted clouds (Oreopoulos et al., 2020). In addition, atmospheric static stability influences the aerosol impact on clouds: pronounced aerosol influences on clouds are seen in stable conditions (Christensen et al., 2020).

Knowing the meteorological conditions favorable for strong aerosol impacts on clouds would help quantify the aerosol indirect radiative forcing more accurately. Relationships between aerosols and clouds have been used to calculate the global average magnitude of the Twomey effect (Quaas et al., 2008; McCoy et al., 2017; Gryspeerdt



**Figure 1.** Classification of days. Zero day means there is either no cloud or no suitable cloud. Only cloud day means a suitable cloud exists where a pollution track could form, but no such track is visible. Track day means that a pollution track has formed in a suitable cloud. These images show the area surrounding Thompson, Canada, a known pollution hot-spot, which is marked with a red “x.” Green and red on the leftmost image signify vegetation and ice/snow, respectively. There is an ice cloud on this image, in which pollution tracks rarely form. Therefore, it is classified as a 0 day. The pollution track is the brighter part of the cloud in the rightmost image, which flows out from Thompson as from a point source.

et al., 2017). However, nonlinearities resulting from intermittent behavior of aerosol impacts on clouds might lead to errors in radiative forcing estimates. The very strong ship-track-like aerosol perturbations (Toll et al., 2019; Trofimov et al., 2020) provide an alternative method to calculate these aerosol-cloud relationships. The global climate impact of isolated aerosol sources is unclear (Lauer et al., 2007; Schreier et al., 2007), but if weaker large-scale anthropogenic cloud perturbations and tracks behave similarly, then tracks can show under which circumstances anthropogenic air pollution strongly impacts the climate.

Here, we study the meteorological conditions favorable for strong anthropogenic aerosol impacts on clouds using isolated pollution sources over land. By strong impact we mean a strong relative change in cloud droplet effective radii. In visible tracks which have formed over land, aerosol pollution decreases the radius of cloud droplets on average by 30%–50% (Toll et al., 2019; Trofimov et al., 2020). Polluted cloud tracks provide a means to study causal relationships between meteorological conditions and aerosol-cloud interactions (Toll et al., 2019). If the pollution hot-spot is located

in an area with relatively clean air, aerosol-polluted clouds form ship-track-like quasi-linear polluted cloud lines (Toll et al., 2019). Polluted cloud tracks stand out against the background of nonpolluted clouds with larger droplets. Thus, we expect to detect a larger number of polluted clouds in regions with more frequent occurrence of pristine clouds. However, weaker tracks may not be easily identifiable (Possner et al., 2018; Yuan et al., 2019).

Previous work on conditions favorable for pollution tracks has focused on ship tracks (Durkee et al., 2000; Grynspeerdt et al., 2019). Ship track formation has been found to depend on static stability, boundary layer height, cloud top height, background cloud droplet number concentration, and cloud-top relative humidity (Durkee et al., 2000; Grynspeerdt et al., 2019). Here, we analyze the conditions controlling pollution track formation over land, the source of the majority of anthropogenic aerosol.

## 2. Methods

We analyze the meteorological conditions favorable for strong anthropogenic aerosol impacts on clouds by comparing the meteorological conditions of the track days to days with liquid-phase clouds suitable for track formation with no tracks present. We define track days as the days when we can visually detect polluted cloud tracks on the near-infrared composite Terra Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images. The tracks stand out in the near-infrared composite images due to elevated near-infrared reflectance due to the Twomey effect. We use National Aeronautics and Space Administration (NASA) Global Imagery Browse Services (GIBS) images where the composite of bands corresponding to wavelengths 0.459–0.479, 1.628–1.652, and 2.105–2.155  $\mu\text{m}$  are used (MODIS channels 3, 6, and 7).

As polluted cloud tracks form most frequently in liquid-phase clouds, we distinguish among the no-track days if liquid-phase clouds (including supercooled liquid clouds) exist at the studied location or not. This leads to the three-part classification of 0 days (no cloud or there is an ice or mixed-phase cloud), only cloud days (suitable liquid cloud, but no track), and track days (Figure 1). In order to reduce the amount of false positive and false negative events, we also classified a day as a 0 day in cases where it was difficult to decide whether a track had formed or not, or where liquid-phase clouds were present but did not cover the immediate surrounding of the pollution source, where small tracks might form. The number of such days was much smaller compared to the number of track days.

For analysis, we chose three pollution hot spots where pollution tracks frequently form: Norilsk and Cherepovets in Russia and Thompson in Canada (Table 1). These locations were chosen, because there is only one isolated pollution source in otherwise pristine location, which makes it easy to detect the pollution tracks. Using MODIS images from NASA GIBS, we manually classified each day from 2000 to 2019 into one of the three categories shown in Figure 1, separately for each location. We chose an area covering about 200 by 200 kilometers around each site. We saved the classification for each day based on the Terra MODIS image of this area. By concentrating

**Table 1**  
*The Pollution Hot Spots Used for the Analysis*

| Site of study | Coordinates      | Elevation above sea level | The main source of air pollution         |
|---------------|------------------|---------------------------|------------------------------------------|
| Norilsk       | 69.33°N, 88.22°E | 90 m                      | The smelting and concentrating of nickel |
| Thompson      | 55.74°N, 97.85°W | 224 m                     | The smelting and concentrating of nickel |
| Cherepovets   | 59.12°N, 37.9°E  | 130 m                     | Processes of iron and steel production   |

on Terra alone, some tracks forming in the afternoon may have gone undetected. Suitable liquid-phase clouds occurred on 8.7%, 13.5%, and 13% of days in Norilsk, Thompson, and Cherepovets, respectively (Table 3).

We chose the study locations close to synoptic stations: 18 km from Cherepovets (station id 27113), 6 km from Thompson (station id 71079), and 2 km from Norilsk (station id 23078). The observations are made in these stations each day at the main synoptic times of 00, 06, 12, 18 UTC and the intermediate synoptic hours of 03, 09, 15, 21 UTC. We chose the times for the meteorological observations to align as closely as possible the average passing time of the Terra satellite: 06 UTC for Norilsk, 18 UTC for Thompson, and 09 UTC for Cherepovets. We analyzed seven variables from the synoptic stations. In addition to in-situ measurements, we also analyzed 8 pressure-level and 12 single-level meteorological variables from ERA5 reanalysis (Table 2).

We further selected for analysis six area-averaged cloud properties derived from MODIS data (Table 2), using the standard 2.1  $\mu\text{m}$  retrievals (Platnick et al., 2016). We averaged these properties over an area covering 150 km times 150 km around each location. We calculated cloud droplet number concentration (CDNC) from MODIS data according to Brenguier et al. (2000):

$$\text{CDNC} = K \cdot R_{\text{eff}}^{-2.5} \cdot \text{COD}^{0.5}, \quad (1)$$

where  $R_{\text{eff}}$  refers to cloud droplet effective radius, COD to cloud optical depth, and  $K = 1.125 \cdot 10^{-6} \text{ m}^{-0.5}$ . The interpretation of constant K is given by Painemal and Zuidema (2011). We calculated lower tropospheric stability (LTS) from reanalysis data according to the formula

$$\text{LTS} = T_{700} \cdot \left( \frac{1000}{700} \right)^{0.286} - T_{1000}, \quad (2)$$

where  $T_{700}$  and  $T_{1000}$  refer to temperatures at 700 and 1,000 hPa levels (Klein & Hartmann, 1993).

**Table 2**  
*Analyzed Meteorological Variables and Cloud Properties*

| Synoptic stations                                          | ERA5 reanalysis single level variables | ERA5 reanalysis variables on 500, 700, 1,000 hPa pressure levels | MODIS                                 |
|------------------------------------------------------------|----------------------------------------|------------------------------------------------------------------|---------------------------------------|
| <b>Air temperature</b>                                     | 2m dewpoint temperature                | Temperature                                                      | <b>Cloud droplet effective radius</b> |
| Dewpoint temperature                                       | 10m u component of wind                | Potential vorticity                                              | Cloud fraction                        |
| Wind speed                                                 | 10m v component of wind                | Geopotential                                                     | <b>Cloud optical thickness</b>        |
| Wind direction                                             | <b>Boundary layer height</b>           | <b>U component of wind</b>                                       | <b>Cloud top pressure</b>             |
| <b>Mean sea level pressure</b>                             | <b>Cloud base height</b>               | <b>V component of wind</b>                                       | Cloud top temperature                 |
| Cloud ceiling                                              | Convective available potential energy  | <b>Vertical velocity</b>                                         | <b>Liquid water path</b>              |
| Visibility                                                 | Convective inhibition                  | Vorticity                                                        |                                       |
|                                                            | Low cloud cover                        | <b>Relative humidity</b>                                         |                                       |
|                                                            | Mean sea level pressure                |                                                                  |                                       |
|                                                            | Total precipitation                    |                                                                  |                                       |
|                                                            | Zero degree level                      |                                                                  |                                       |
| Derived variables                                          |                                        |                                                                  |                                       |
| Cloud droplet number concentration (CDNC, from MODIS data) |                                        |                                                                  |                                       |
| Lower tropospheric stability (LTS, from reanalysis data)   |                                        |                                                                  |                                       |
| Relative humidity (from station data)                      |                                        |                                                                  |                                       |

*Note.* “Derived variables” were calculated using the variables from the other columns. The variables included in the final analysis presented in this paper are marked in bold. Other variables did not show any correlation to track formation, or in case multiple data sources had the same or similar variable, we used only one of them.

**Table 3**  
*Occurrence Frequency of Cloud and Track Days*

|             | Total number of days in years 2000–2019 |                     |                | Percentages         |                 |                   |
|-------------|-----------------------------------------|---------------------|----------------|---------------------|-----------------|-------------------|
|             | Zero days (Z)                           | Only cloud days (C) | Track days (T) | $\frac{C+T}{C+T+Z}$ | $\frac{T}{C+T}$ | $\frac{T}{C+T+Z}$ |
| Norilsk     | 6,664                                   | 403                 | 237            | 8.7%                | 37.0%           | 3.2%              |
| Thompson    | 6,324                                   | 781                 | 199            | 13.5%               | 20.3%           | 2.7%              |
| Cherepovets | 6,349                                   | 700                 | 255            | 13.0%               | 26.7%           | 3.5%              |

We expect that the synoptic-scale atmospheric circulation influences the formation of clouds suitable for track formation and tracks themselves. An easy way to describe atmospheric circulation is by classifying air pressure fields into types. There are no explicit modes of variability in the synoptic scale of circulation. Therefore, we use various methods to show that the result is robust (Beck & Philipp, 2010). We applied software *cost733class* (Philipp et al., 2016) to calculate three different classifications: Jenkinson Collison (1977), Grosswettertypen (Beck et al., 2007), and a K-means clustering technique. All three classifications showed similar dependence of cloud and track occurrence on the circulation. Therefore, we present results using Jenkinson Collison types (JCT), an easily interpretable synoptic-scale circulation classification method. Depending on the strength of two circulation indices, resultant flow  $F$  and vorticity of the airflow  $Z$ , we classify each day into 1 of 10 classes. If the resultant flow is larger than the vorticity, airflow is straight, and the atmospheric circulation is organized into eight directional circulation types according to the airflow direction (N, NE, E, SE, S, SW, W, NW). In the rest of the days, atmospheric circulation is classified into cyclonic ( $C, Z > 0$ ) or anticyclonic ( $A, Z < 0$ ) type depending on the direction of the rotation.

Four geostrophic flow indices, westerly and southerly flows and westerly and southerly shear vorticities, are calculated using data from 16 points in  $20^\circ$  latitude  $\times$   $30^\circ$  longitude grid (Supporting Information S1). Combining the southerly and westerly geostrophic airflow indices gives the resultant flow  $F$  and the direction of the flow. The sum of the westerly shear vorticity and southerly shear vorticity gives the total vorticity  $Z$ . The equations for these indices can be found in Jenkinson and Collison (1977) or Jones et al. (1993). The resultant geostrophic flow  $F$  is expressed in units of gpm per  $10^\circ$  latitude at the latitude of the central point of the grid. The (geostrophic) vorticity  $Z$  is expressed as gpm per  $10^\circ$  at the latitude of the central point of the grid, per  $10^\circ$  latitude. We use  $Z$  values to show whether tracks tend to form in the cyclonic or anticyclonic airflows.

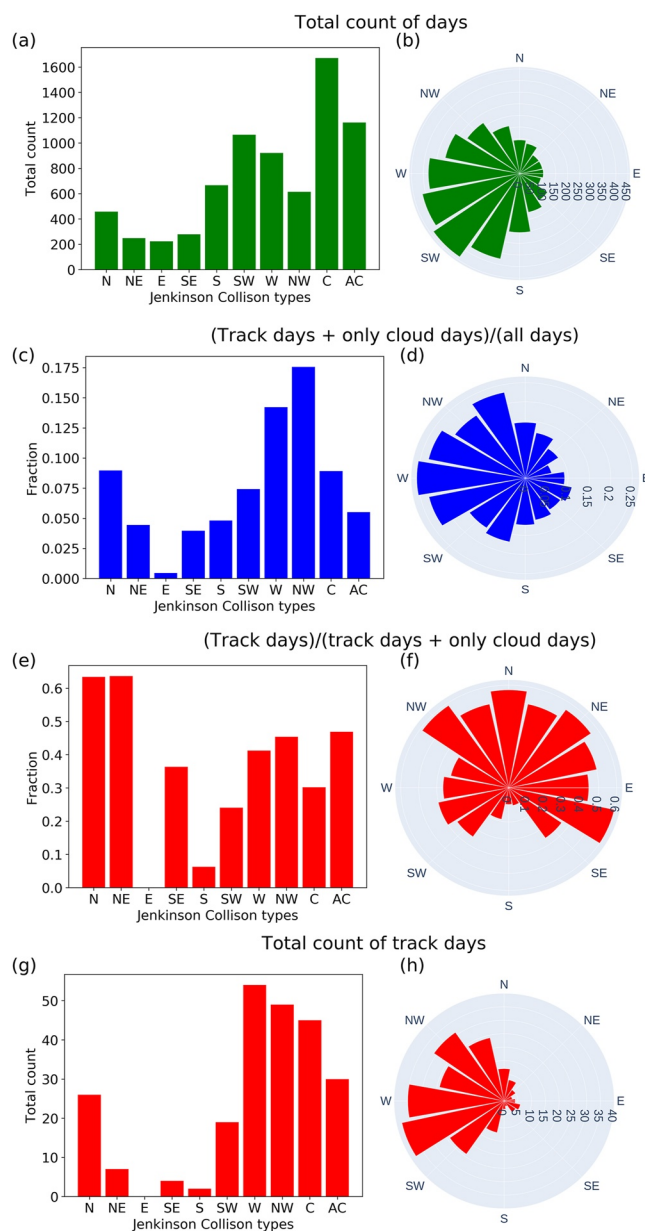
We applied the JCT classification for three domains centered on the studied pollution hot spots. We used geopotential height data at 850 hPa pressure level at 12 UTC from ERA5 reanalysis (Hersbach et al., 2020). The maps with 16 data points centered in all three hotspots and the maps of typical patterns of 10 JCT-s are presented in the Supporting Information S1.

Apart from circulation patterns, we show the results on meteorological dependence of track occurrence for all three studied locations together, as the results for all individual sites were similar. The results for individual sites are presented in the Supporting Information S1.

### 3. Results

The frequency of occurrence of liquid-phase clouds and tracks is different for each location. Liquid-phase clouds occurred on about 12% of all days. Out of the days with liquid-phase clouds, tracks occurred on 20%–37% of days, depending on the location (Table 3); 10 to 12 track days per location occurred each year on average. We concentrated on the differences between track days and only cloud days in the subsequent analysis of meteorological data.

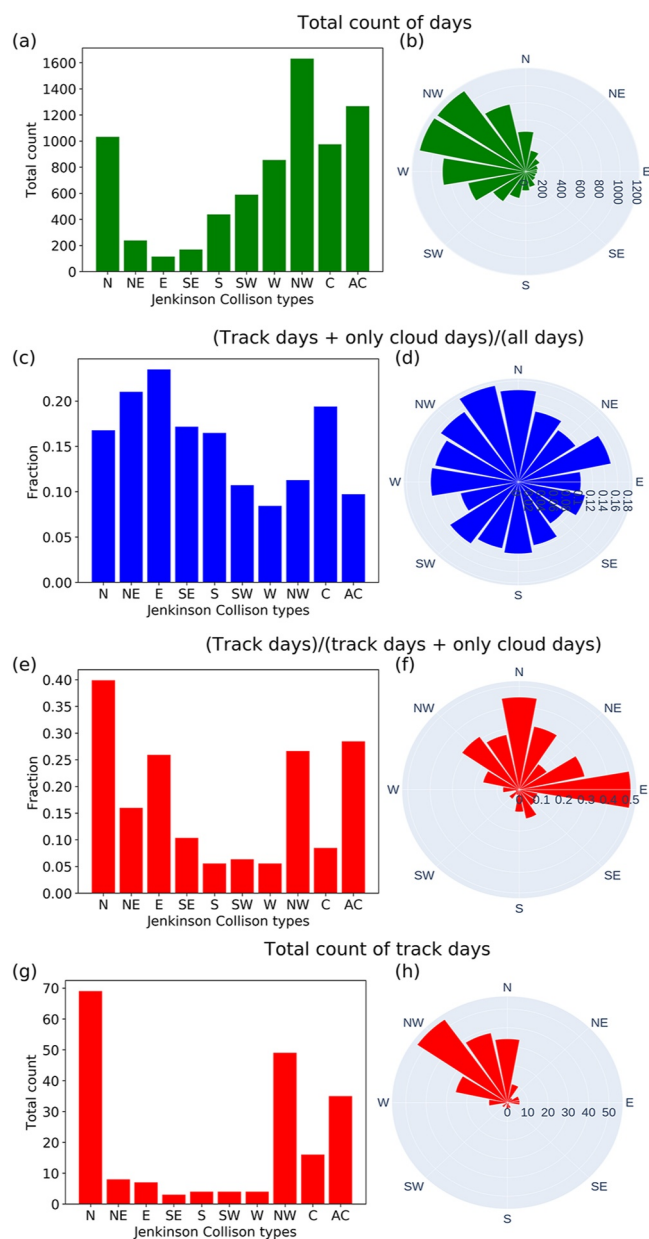
The three locations have different predominant circulation types and wind directions (Figures 2a, 2b, 3a, 3b, 4a, 4b). All three sites are in the higher mid-latitude region, where the prevailing airflow is from the west. Still, each location has variations that come from the exact longitudinal position of the site. For Thompson, there is relatively little variability in the flow direction, and winds from NW are strongly dominant. Norilsk has the largest variability out of the three locations, but winds from SW are more prevalent than others. For Cherepovets, westerly winds are prevailing. The circulation classification adds details compared to only wind directions information.



**Figure 2.** The distributions of Jenkinson Collision circulation types and wind directions at 700 hPa for Norilsk. Panels (a) and (b) show the total number of days for each circulation type and wind direction. Panels (c) and (d) show the fraction of liquid-phase cloud days (including track and only cloud days) out of all days in each circulation type/wind direction. Panels (e) and (f) show the fraction of track days out of liquid-phase cloud days. Panels (g) and (h) show the total number of track days for each circulation type and wind direction.

For example, the predominant circulation type in Norilsk is C, but in Cherepovets AC, which is typical for this classification in North-Eastern Europe.

Large-scale atmospheric circulation strongly controls whether liquid-phase clouds and tracks occur or not. The occurrence of liquid-phase clouds is more frequent for cyclonic flows (Figures 2c, 3c and 4c) and westerly, north-westerly, northerly, and north-easterly flows (Figures 2d, 3d and 4d). Among the days when liquid-phase clouds occur, cyclonic flows are in each location more dominant than they are in general climatology. The wind directions under which liquid phase clouds are more likely to occur are shifted from the general climatology in the clockwise direction. In Norilsk SW winds are prevailing, but liquid-phase clouds are more likely to occur with NW winds, and westerly winds dominate in Cherepovets, but liquid-phase clouds are most likely to occur with



**Figure 3.** Same as Figure 2 for Thompson.

NE winds. There is no single wind direction favorable for liquid phase clouds in Thompson, even though it is dominated by winds from the NW.

Tracks form on a subset of days with liquid-phase clouds, and there are apparent differences in atmospheric circulation between track days and only cloud days. While there are more liquid phase clouds under cyclonic conditions (Figures 2c, 3c and 4c), there is a strong tendency of tracks to form in these liquid-phase clouds under anticyclonic conditions in all three locations (Figures 2e, 3e and 4e and 5a). Stronger large-scale descent (Figure 5b) and higher mean sea level pressure (Figure 5c) on track days compared to only cloud days support the finding that the anticyclonic conditions favor tracks.

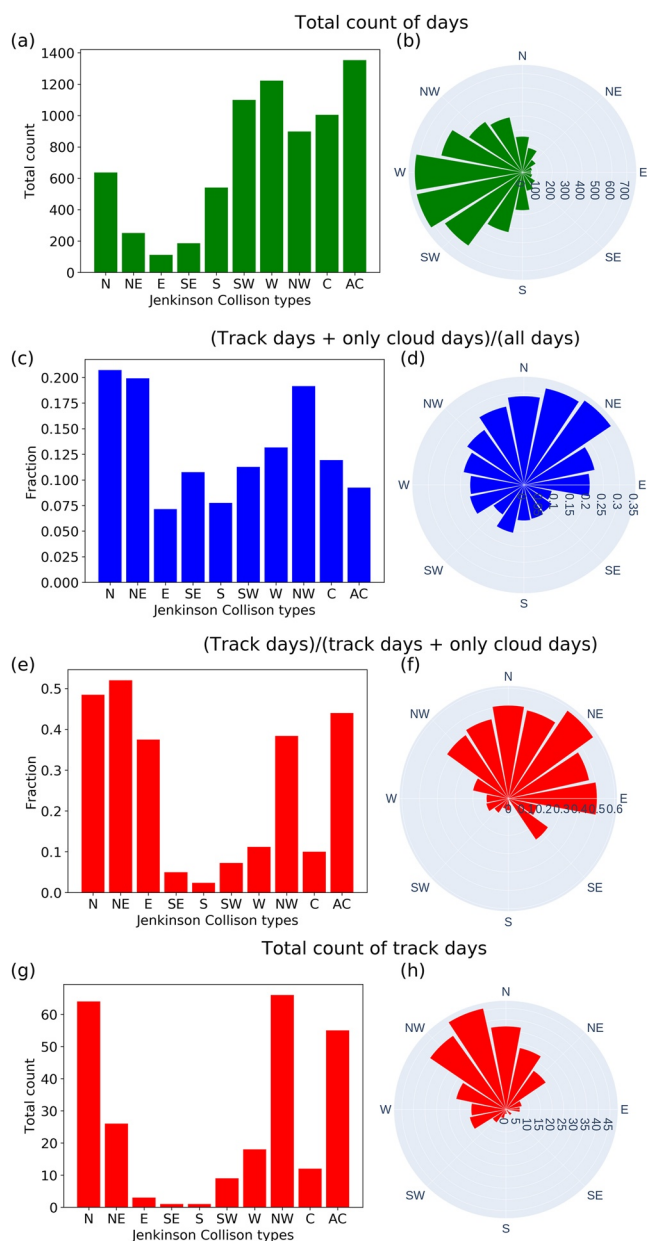
The wind directions under which tracks are more likely to form differ from general climatology and the directions that favor only cloud conditions. By the total count of days, most tracks form when the wind is from N and NW in Norilsk (Figures 2g and 2h), from NW in Thompson (Figures 3g and 3h) and W and NW in Cherepovets (Figures 4g and 4h). In Thompson, where the sector of prevailing wind directions is narrow compared to others, this aligns with the general climatology. In Norilsk and Cherepovets, these directions are shifted clockwise, compared to winds that prevail in general. There are only a few track days under easterly flows, which are rare in given locations, but when liquid-phase clouds occur under easterly flow, tracks are likely to occur. If liquid-phase clouds are present, the wind directions under which tracks are most likely to form are shifted even more strongly clockwise, compared to both climatology and wind directions that favor liquid-phase clouds. The most track-favorable winds are NW to NE in Norilsk (Figures 2e and 2f), N and E in Thompson (Figures 3e and 3f), and N to E in Cherepovets (Figures 4e and 4f).

Tracks tend to form in clean and thin clouds. Larger cloud droplet radii (Figure 6a) and lower cloud droplet number concentration (Figure 6b) favor track formation: cleaner clouds that have not been strongly influenced by anthropogenic aerosol pollution are more sensitive to it. Tracks form more frequently in thin clouds and in clouds with higher cloud bases and lower cloud tops, compared to liquid-phase clouds where tracks have not formed (Figures 7a and 7b). The analysis of MODIS liquid water path for track days and only cloud days confirms that tracks form in thinner clouds (Figure 7c).

Pollution tracks can form only when aerosols from industrial point source reach the clouds. In some cases, track formation seems to be precluded by the limited vertical transport of aerosols. Tracks tend to form on days with higher boundary layers compared to only cloud days (Figure 8a). Boundary layer height largely limits the vertical height to which pollution disperses. There are fewer tracks on days when the cloud base is higher than the boundary

layer (Figure 8b). We did not find any tracks forming in the most stable conditions (Figure 8c). In very stable conditions, the vertical transport is more limited, and aerosols probably do not reach the clouds. We note that overall, tracks are more likely to form in relatively stable conditions that favor low clouds and high aerosol concentrations due to poor dispersion.

Track days are characterized by lower humidity both at the surface and above clouds, compared to only cloud days (Figure 9). Lower relative humidity on track days was seen on all analyzed pressure levels from reanalysis data and was most impressive on the 700 hPa level; 700 hPa is the average cloud top pressure value over all days with liquid-phase clouds. Gryspeerd et al. (2019) note a similar relationship between relative humidity and track formation for ship tracks. However, for tracks forming over the ocean, there was a sharp decline in the number of track days when relative humidity at 850 hPa was greater than 50%, with only 8.5% of tracks forming on such days. Our results show a much milder decline, with 45% of tracks forming on days when relative humidity is



**Figure 4.** Same as Figures 2 and 3 for Cherepovets.

higher than 50%. Dry air leads to stronger cloud-top radiative cooling and in-cloud updraughts (Zheng et al., 2016), which increases cloud sensitivity to aerosol perturbation (Twomey, 1959) and could explain the dependence of track formation on relative humidity (Gryspeerd et al., 2019). Dry air above cloud tops also leads to lower LWP and thinner clouds, where large relative increases in CDNC occur more easily (Chen et al., 2012). However, the occurrence of low relative humidity conditions is correlated to the direction of the large-scale airflow along with other track favoring conditions (Figure 10), obscuring the exact nature of the causal relationship.

To further examine the importance of atmospheric circulation for track formation, we compare conditions characteristic for NW and SW wind directions (Figure 10). NW flow is more typical for tracks and SW for only cloud days by the total count of days. We defined NW wind direction as the direction between 270° and 360° and SW wind direction as the direction between 180° and 270° (although the track favoring wind directions varied slightly by location). In Figure 10, we have used data from all the days, not only from days with liquid-phase clouds. Similar signals (or lack of a signal) were found when comparing wind direction variations (NW vs. SW) to track formation (track vs. only cloud) for all variables other than temperature. This shows that wind direction is strongly correlated to the meteorological factors that support track formation, suggesting that the synoptic dependence of track formation is due to the types of clouds correlated to each meteorological situation. The differences in meteorological conditions between NW and SW flow remained similar for all variables when we looked only at relatively clean cases (where cloud droplet effective radius was larger than 13.5 μm), suggesting that the dependence is not explained solely by the background air pollution levels.

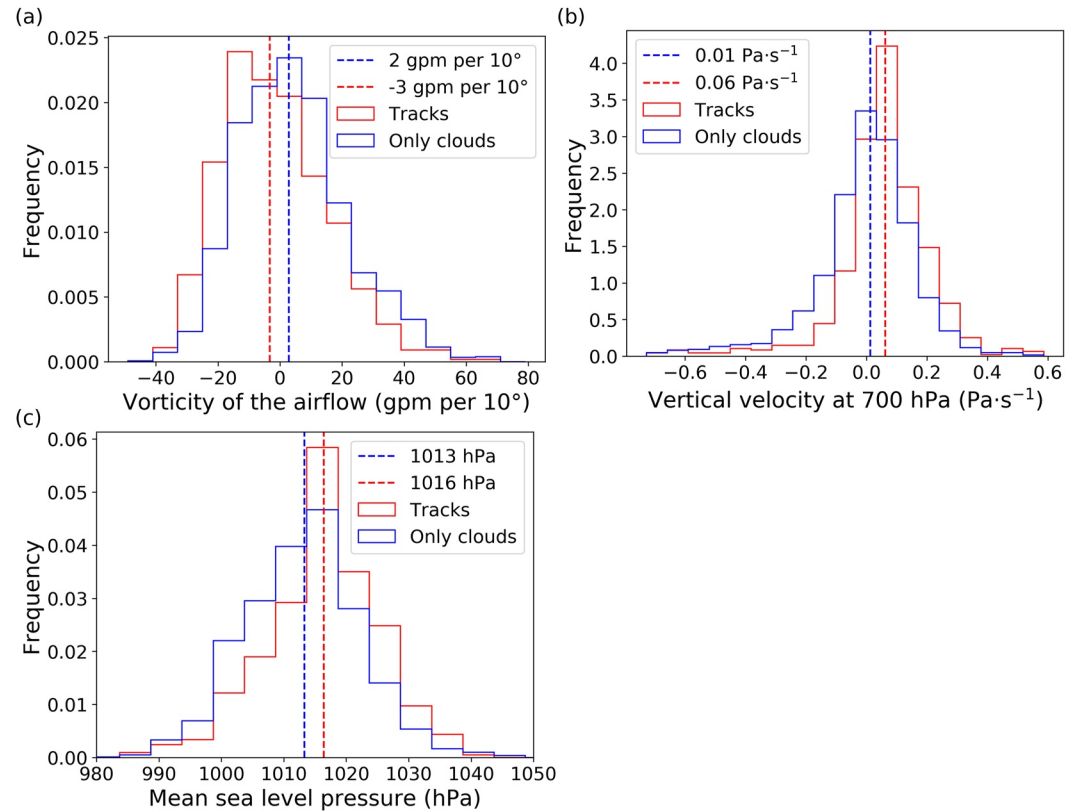
## 4. Discussion and Conclusions

Anthropogenic aerosols have strong impacts on clouds only under favorable meteorological conditions. We studied ship-track-like polluted cloud tracks forming downwind of continuously emitting localized anthropogenic air pollution hot spots of Norilsk and Cherepovets in Russia and Thompson in Canada (Tables 1 and 3). Tracks form in relatively clean background cloud decks, in thin clouds, and under stable conditions. These conditions are in qualitative agreement with previous work on polluted cloud tracks (Durkee et al., 2000; Toll et al., 2019). Compared to the only cloud days, track days are characterized by higher mean sea level pressure, stronger large-scale descent, a higher boundary layer, higher cloud base, and lower cloud top, along with lower relative humidity above clouds and at the surface.

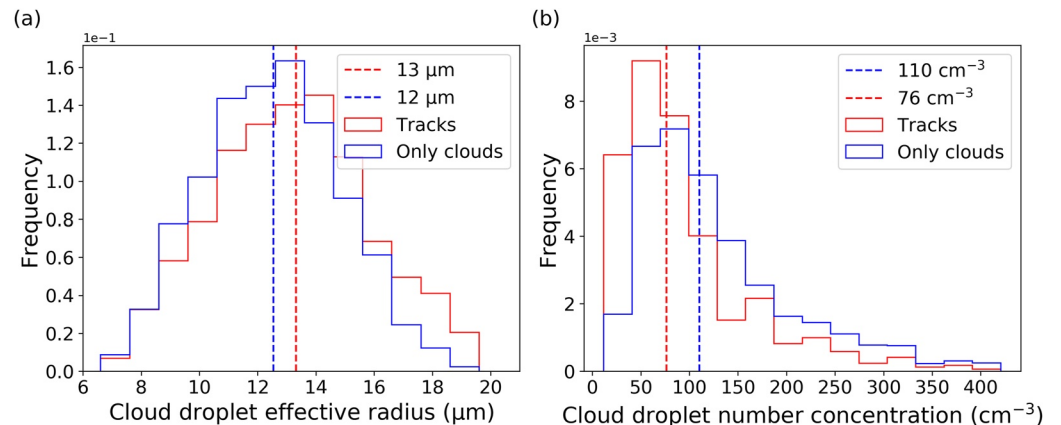
The occurrence of track-favoring conditions is, to a large extent, determined by the large-scale atmospheric circulation. First, circulation dictates whether

the clouds form or not. Cyclones and westerly, north-westerly, northerly, and north-easterly flows favor the occurrence of liquid-phase clouds in the studied locations (Figures 2–4). Second, circulation dictates whether anthropogenic aerosols perturb clouds or not. Anticyclones and easterly, northerly, north-westerly, and north-easterly flows favor the occurrence of tracks (Figures 2–4). Although cyclonic conditions mean more clouds, anticyclonic conditions favor the anthropogenic perturbations on clouds (Figures 2–5) because anticyclonic conditions are correlated with cleaner air, lower humidity and a higher boundary layer top.

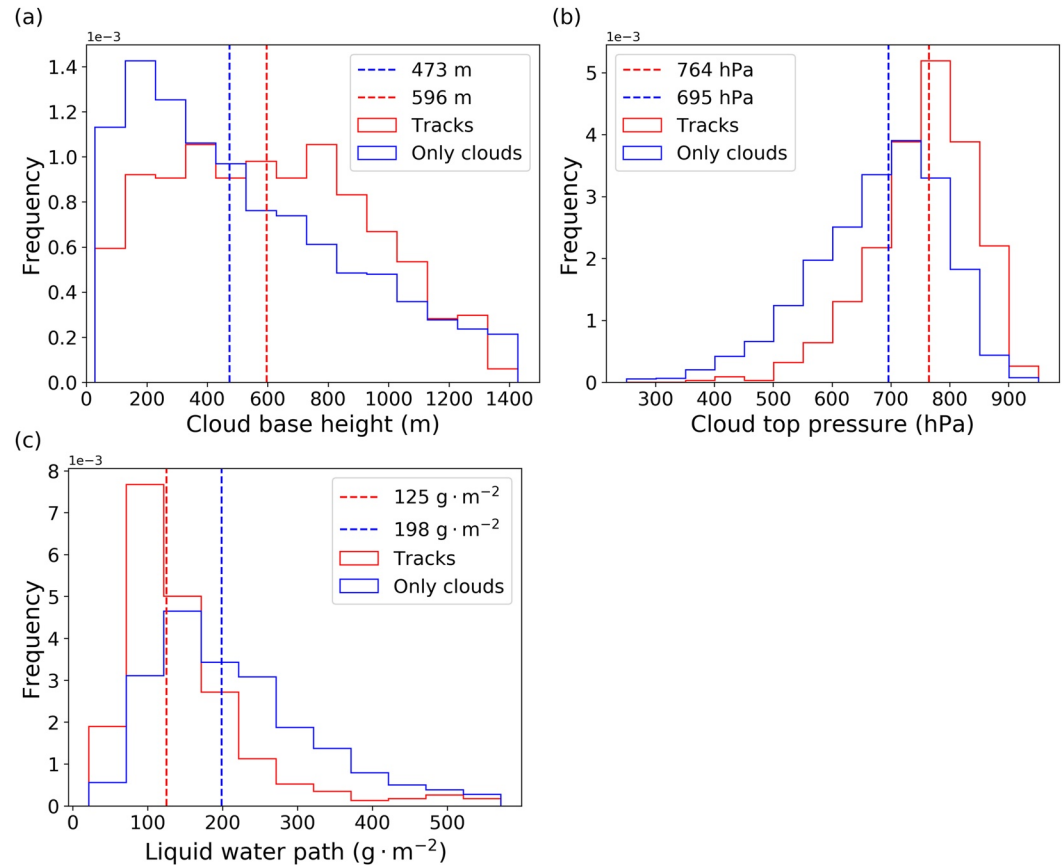
It remains somewhat unclear if the dependence on meteorological conditions is similar for weak perturbations. If the occurrence of tracks is similar to large-scale anthropogenic cloud perturbations, then our findings of meteorological conditions favorable for strong aerosol impacts on clouds can be used to validate the meteorological



**Figure 5.** (a) Distributions of the vorticity of the airflow for track days (red) and only cloud days (blue). The units of vorticity  $Z$  are gpm per  $10^\circ$  at the latitude of the central point of the grid, per  $10^\circ$  latitude. The bin width is 8 gpm. The negative values of  $Z$  signify anti-cyclonic airflow and positive values signify cyclonic airflow. (b) Vertical velocity distributions at 700 hPa level for track days (red) and cloud-only days (blue). Negative values of vertical velocity indicate upward motion. The bin width is  $0.06 \text{ Pa}\cdot\text{s}^{-1}$ . (c) Mean sea level pressure distributions for track days (red) and only cloud days (blue). Station data is used for this figure. Bin width is 5 hPa. The dashed lines show the median values of respective distributions on each image.



**Figure 6.** (a) Distribution of cloud effective radius for track days (red) and only cloud days (blue). Bin width is  $1 \mu\text{m}$ . (b) Cloud droplet number concentration distributions for track days (red) and cloud-only days (blue). Bin width is  $29 \text{ cm}^{-3}$ . Dashed lines show the median values of respective distributions on each image.

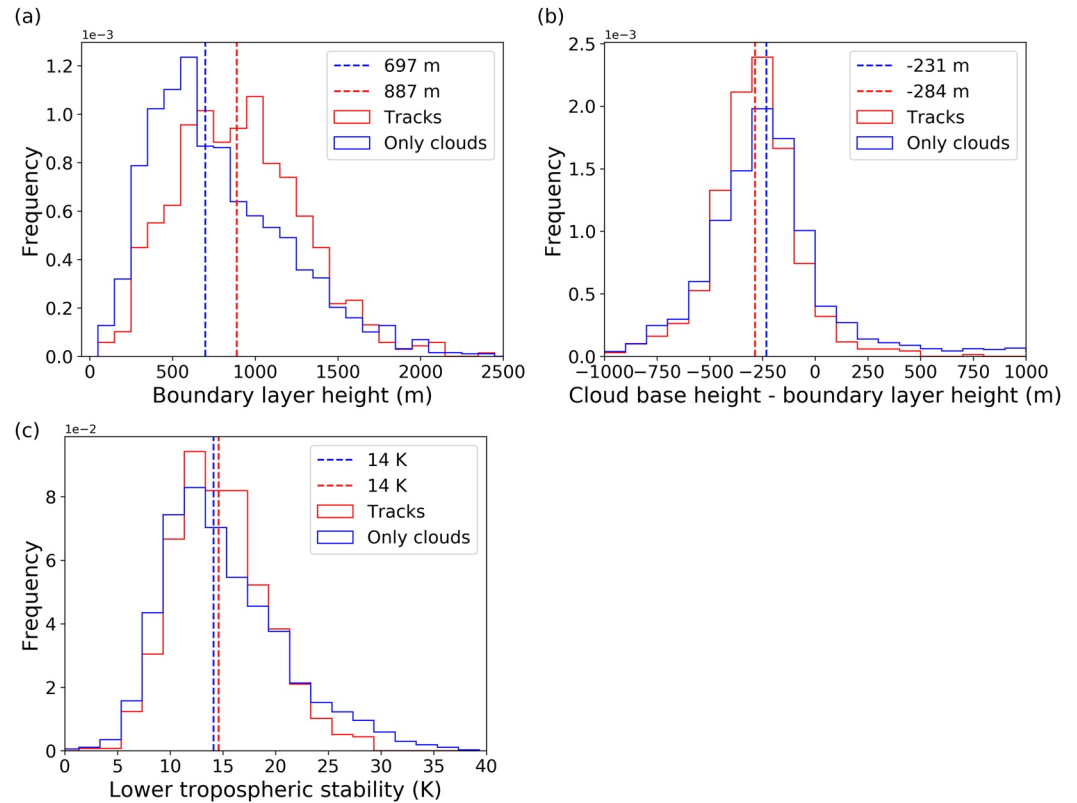


**Figure 7.** Cloud base height (a), cloud top pressure (b) and liquid water path (c) distributions for track days (red) and only cloud days (blue). Reanalysis data are used on (a), and MODIS data are used on (b) and (c). The bin width is 100 m on (a), 50 hPa on (b) and 50  $\text{g} \cdot \text{m}^{-2}$  on (c). Dashed lines show the median values of respective distributions on each image.

dependence of aerosol impacts on clouds as simulated by climate models or derived from large-scale statistics of satellite data. However, it requires further work to analyze if weaker perturbations and tracks behave similarly. Previous work has shown that pronounced aerosol impact occurs under stable conditions (e.g., Christensen et al., 2020). Still, here we showed that under extremely stable conditions, strong perturbations might not occur (Figure 8). The aerosol impact on clouds as simulated by climate models depends on the dynamical regime, but there is a large spread among different models (Gryspeerdt et al., 2020; Zelinka et al., 2014; Zhang et al., 2016). The locations studied here are situated at mid- and high-latitudes. There is a strong similarity in circulation patterns favoring strong aerosol impacts on clouds for the studied locations, for example, in terms of the direction of atmospheric flow. This suggests that our results could be representative of the mid- and high-latitudes in general.

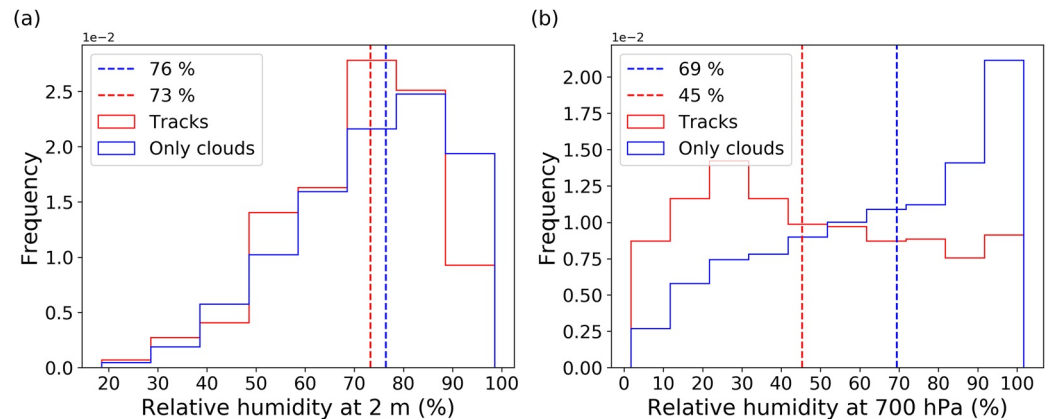
In case of ship tracks it has been shown that aerosol pollution can have substantial radiative effect without forming visible tracks, and this effect may also substantially differ from that of tracks alone (Glassmeier et al., 2021; Possner et al., 2018). In addition, at least in case of ship tracks the lifetime of anthropogenic perturbation is much shorter compared to the full lifetime of stratocumulus clouds (Glassmeier et al., 2021). At the same time, aerosol-induced cloud perturbations which cover hundreds by hundreds of kilometers and behave similar to tracks are shown to exist in various regions over the world, which suggests that meteorological dependence of track occurrence might represent substantial fraction of global aerosol impacts on clouds (Trofimov et al., 2020).

The intermittent occurrence of strong aerosol impact on clouds has substantial implications for quantifying aerosol radiative forcing. Suppose strong intermittent perturbations caused a large part of the aerosol radiative forcing. In that case, it is critical to capture the frequency and magnitude of the strong perturbations to reliably quantify the average aerosol forcing (Mülmenstädt & Feingold, 2018). Due to such nonlinearities in aerosol im-

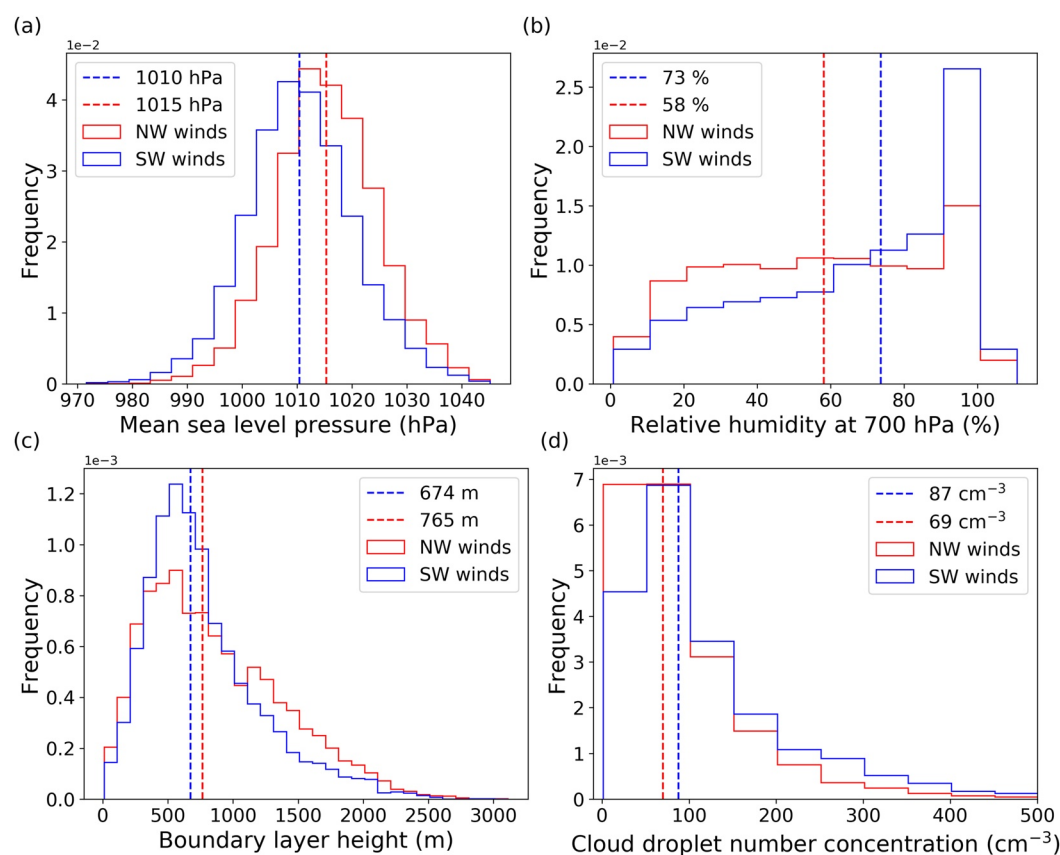


**Figure 8.** (a) Boundary layer height distributions for track days (red) and only cloud days (blue), bin width is 100 m. (b) Distributions of the gap between cloud base and boundary layer for track days (red) and only cloud days (blue), bin width is 100 m. (c) Lower tropospheric stability (LTS) distributions for track (red) and only cloud (blue) days. No tracks form when LTS values are over 29 K. The bin width is 4 K. Dashed lines show the median values of respective distributions on each image.

pacts on clouds, using long-term average sensitivities of clouds to aerosols can lead to biased forcing estimates. Strong anthropogenic cloud perturbations can occur at broad spatial scales (hundreds of kilometers; Trofimov et al., 2020), and form an important part of our toolbox for understanding and quantifying aerosol-cloud interactions under a variety of meteorological conditions.



**Figure 9.** Relative humidity distributions for track days (red) and only cloud days (blue). Panel (a) shows station data and (b) reanalysis data at 700 hPa. The bin width is 10% in both figures. Dashed lines show the median values of respective distributions on each image.



**Figure 10.** (a) Mean sea level pressure (bin width 5 hPa), (b) relative humidity at 700 hPa (bin width 5.5%), (c) boundary layer height (bin width is 100 m) and (d) cloud droplet number concentration (bin width 50 cm<sup>-3</sup>) distributions for north-west (red) and south-west (blue) winds. Tracks tend to form on days with NW winds and not form on days with SW winds. Data from all days are used for this figure. Dashed lines show the median values of respective distributions on each image.

## Data Availability Statement

The lists of dates of track days, only cloud days and 0 days for each study site are available at <https://datadot.earthdata.nasa.gov/handle/33/424>. The RGB images (MODIS channels 3–6–7) used for the visual detection of polluted clouds from <https://worldview.earthdata.nasa.gov/> were used. The data from synoptic stations were downloaded from National Oceanic and Atmospheric Administration's (NOAA) webpage at <https://www.ncei.noaa.gov/access/search/data-search/global-hourly>. ERA5 hourly data was downloaded from Climate Data Store (CDS), from <https://doi.org/10.24381/cds.adbb2d47> for single levels and from <https://doi.org/10.24381/cds.bd0915c6> for pressure levels. The MODIS data was downloaded from <https://giovanni.gsfc.nasa.gov/giovanni/>. The software cost733class for calculating circulation types was worked out during COST action 733 “Harmonisation and Applications of Weather Types Classifications for European Regions,” and we are grateful to its creators.

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