Day-night Contrast in the Cloud Water Responses to Aerosols

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Abstract

Clouds play an essential role in the global energy budget but the impact of anthropogenic aerosols on clouds is still poorly understood. We use fifteen-minute temporal resolution geostationary satellite data to study the temporal evolution of polluted cloud tracks detected in the European part of Russia. Previous analysis of polluted cloud tracks shows that cloud water response to aerosols is bidirectional. Here, we show that the day-night contrast in cloud responses partly explains the bidirectional cloud water responses. We have data only for sunlight hours, but we can interpret the cloud responses detected already since the early morning as night-time responses. On average, the decrease in cloud water offsets 46% of the Twomey effect in the study area while the decrease happens during night-time, probably due to aerosol-enhanced entrainment. In the afternoon, cloud water is more likely to increase in the polluted clouds, most probably due to suppressed precipitation. Our findings highlight the need to better account for the temporal evolution of cloud responses to estimate the aerosol radiative forcing more accurately.

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8 9 10 11 12	 Key Points: We demonstrated that geostationary satellite data could be used to study the temporal evolution of pollution tracks Geostationary satellite data indicated that in continental pollution tracks cloud water decreases during night time
13 14	 Cloud water increases in the afternoon, most likely due to suppression of precipitation

15 Abstract

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Clouds play an essential role in the global energy budget but the impact of anthropogenic 17 aerosols on clouds is still poorly understood. We use fifteen-minute temporal resolution 18 geostationary satellite data to study the temporal evolution of polluted cloud tracks detected in 19 the European part of Russia. Previous analysis of polluted cloud tracks shows that cloud water 20 response to aerosols is bidirectional. Here, we show that the day-night contrast in cloud 21 responses partly explains the bidirectional cloud water responses. We have data only for sunlight 22 hours, but we can interpret the cloud responses detected already since the early morning as night-23 time responses. On average, the decrease in cloud water offsets 46% of the Twomey effect in the 24 study area while the decrease happens during night-time, probably due to aerosol-enhanced 25 entrainment. In the afternoon, cloud water is more likely to increase in the polluted clouds, most 26 probably due to suppressed precipitation. Our findings highlight the need to better account for 27 the temporal evolution of cloud responses to estimate the aerosol radiative forcing more 28 accurately. 29

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31 Plain Language Summary

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The global warming induced by anthropogenic greenhouse gases is partly compensated by the 33 aerosol cooling effect while the extent of aerosol cooling is still relatively uncertain. Lately, the 34 analysis of clouds polluted by isolated aerosol sources like isolated factories has provided new 35 insights into aerosol influence on clouds and the resulting cooling effect. Here, we use 36 geostationary satellite data to study the temporal evolution of continental clouds polluted by 37 localized heavy industrial emissions. Polluted clouds become thinner compared to nearby 38 unpolluted clouds during the night. Some of the polluted clouds become thicker compared to the 39 nearby unpolluted clouds in the afternoon. These results improve the process-level understanding 40 of anthropogenic aerosol impacts on clouds. 41

43 **1 Introduction**

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Not only anthropogenic greenhouse gases but also microscopic anthropogenic air pollution particles called aerosols influence Earth's climate. Despite strong research efforts, the aerosol forcing of Earth's climate is still poorly quantified compared to the greenhouse gas (GHG) induced forcing (Bellouin et al., 2020). Considering multiple lines of evidence, total aerosol

effective radiative forcing is estimated to be from -2.0 to -0.4 $\frac{W}{m^2}$ with a 90% likelihood (Bellouin et al., 2020). The fact that aerosols offset a poorly quantified fraction of GHG-induced global warming, makes it challenging to estimate the sensitivity of the Earth's climate to anthropogenic radiative forcing (Stevens et al., 2016) and to improve the reliability of climate projections.

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Besides the direct radiative interactions, aerosols act as cloud condensation nuclei (CCN) and therefore modulate cloud properties. The climate forcing caused by aerosol impacts on clouds is especially poorly quantified (Bellouin et al., 2020). The first indirect effect of aerosols, also called the Twomey effect (Twomey, 1974), refers to increased cloud droplet number concentration (CDNC) in clouds. Twomey effect raises the cloud albedo and therefore induces a cooling effect on the Earth's climate. The Twomey effect is well understood and the cooling effect is confirmed by multiple lines of evidence (Bellouin et al., 2020).

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The second aerosol indirect effect concerns the liquid water path (LWP) and cloud fraction response to increased CDNC (Albrecht, 1989; IPCC, 2013). LWP can increase due to suppressed collision-coalescence efficiency leading to suppressed precipitation (Albrecht, 1989) and decrease due to aerosol-enhanced entrainment (Ackerman et al., 2004; Bretherton et al., 2007; Wood, 2007). But the net cloud water response to aerosols remains relatively poorly constrained (Bellouin et al., 2020).

Polluted cloud tracks – quasi-linear polluted cloud lines induced by localized pollution sources – 70 have recently provided more stringent constraint on LWP response to aerosols (Toll et al., 2019). 71 72 Polluted cloud tracks allow us to directly compare the polluted cloud properties with the properties of the unpolluted clouds as the pollution tracks stand out from the less polluted 73 background. While global climate models assume unidirectional LWP increases (Ghan et al., 74 2016), polluted cloud tracks show bidirectional responses (Toll et al., 2017). Using ship, 75 volcano, industry and fire tracks, Toll et al. (2019) found that on average there is a weak 76 decrease in LWP, partially cancelling out the Twomey effect. Trofimov et al. (2020) found 77 bidirectional LWP responses with weak average LWP response also in the case of larger-scale 78 cloud perturbations. Previous studies on polluted cloud tracks use data from polar-orbiting 79 satellites (Toll et al., 2019, 2017; Trofimov et al., 2020), enabling to analyse only snapshots of 80 cloud responses. 81

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83 In this paper, we analyse the temporal evolution of LWP responses using polluted cloud tracks detected from the geostationary Spinning Enhanced Visible and Infrared Imager (SEVIRI) 84 85 satellite data in the European part of Russia. Gryspeerdt et al. (2020) found a clear temporal evolution of LWP response in ship tracks with a more likely increase in LWP after 10 hours 86 since the initial cloud droplet number perturbation. Diamond et al. (2020) found a clear decrease 87 in LWP in the South-East Atlantic shipping corridor in the afternoon, but a weak LWP response 88 in the morning. Diurnal evolution observed over ocean motivates to analyse the diurnal evolution 89 of LWP response also over land. Glassmeier et al. (2021) suggested that the characteristic cloud 90 water adjustment equilibration time scale in non-precipitating clouds is 20 hours, which should 91 allow us to observe the evolution towards equilibrium state using SEVIRI data. We study if we 92 can capture the temporal evolution of bidirectional cloud water responses and check the 93 94 existence of the day-night contrast in the cloud water response.

96 2 Data and Methods

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98 2.1 General study design

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We use SEVIRI and Moderate Resolution Imaging Spectroradiometer (MODIS) data to compare 100 the properties of the polluted clouds to the properties of the nearby unpolluted clouds. Using 101 102 SEVIRI data, we study polluted cloud tracks affected by anthropogenic aerosols originating from various industrial sources in the European part of Russia (Fig 1 and Table 1). The studied aerosol 103 104 sources include various chemical and heavy production industries as well as mines (Table 1). These strong and localised pollution sources in relatively clean background conditions often 105 provide a clear contrast between polluted and unpolluted clouds (example in Fig 2). In total, we 106 study 23 days with distinct visible pollution tracks in the years 2006 to 2017 (Table 2) using 107 108 SEVIRI data. From these 23 cases, we extracted the time-series of 74 individual pollution tracks with different temporal and geographical extents. We focus especially on the temporal evolution 109 of cloud water response to aerosols. 110



Figure 1. The dependence of spatial resolution of SEVIRI data on geographical location. The spatial resolution of the SEVIRI data decreases further away from the 0° longitude and 0° latitude. The red box marks the approximate area where pollution tracks were observed. Crosses mark the largest industrial sites in the area from where pollution tracks were often originating.

Table 1. List of cities with heavy industry, from where sampled pollution tracks originated.

City	(latitude, longitude)	Type of industry
Cherepovets	(59.13, 37.92)	metallurgy and chemical industry
Yaroslavl	(57.62, 39.85)	machine factory
Chagoda	(59.17, 35.33)	glass factory
Ryazan	(54.60, 39.70)	electronics factory and oil refinery
Kirishi	(59.45, 32.02)	oil refinery and chemical industry
Novomoskovsk	(54.08, 38.22)	chemical industry

Moscow	(55.75, 37.62)	chemical, textile and car-building industry
Veliky Novgorod	(58.52, 31.28)	chemical and radio-electronic industry
Lipetsk	(52.62, 39.60)	metallurgy, machinery, chemical industry
Stary Oskol	(51.30, 37.83)	iron ore mine
Nizhny Novgorod	(56.33, 44.01)	auto industry, ship, and aircraft factories
Saratov	(51.53, 46.02)	oil refinery, aerospace manufacturing industry



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Figure 2. An example of cloud droplet effective radius ($R_{eff} \dot{c}$ data from two different satellite instruments: **a.** SEVIRI, **b.** MODIS. Yellowish wavy areas with reduced droplet sizes represent pollution tracks originating from cities with heavy industry. The pollution tracks can span over several hundred kilometres downwind of emission sources. Although the spatial resolution is lower for SEVIRI data and the contrast between polluted and unpolluted areas is lower, the tracks are still clearly visible.

Table 2. List of dates for which tracks were sampled. The number of tracks sampled for each

125 date is given in the parentheses.

2006 (5) 2007 (4) 2008 (12) 2009 (3) 2011 (10) 2015 (8) 2016 (26) 2017 (6)

10-16 (3)	04-29 (2)	09-16 (7)	10-25 (3)	10-24 (4)	02-13 (3)	10-10 (6)	10-01 (6)
10-26 (2)	10-16 (2)	09-17 (2)		10-27 (1)	02-14 (3)	10-11 (6)	
		09-18 (2)		11-02 (2)	10-20 (2)	10-12 (3)	
		11-06 (1)		11-13 (3)		10-13 (4)	
						10-16 (4)	
						10-19 (3)	

As SEVIRI is onboard geostationary satellite, continuous temporal coverage of cloud properties 127 during each day is available. As the MODIS instrument is onboard polar-orbiting Terra and 128 Aqua satellites, we get snapshots of clouds during various times of the day depending on the 129 location. We use MODIS data from Toll et al. (2019) from various continental sites in Russia, 130 Canada, and Australia. As both SEVIRI and MODIS are passive instruments, we can study cloud 131 responses during sunlight hours only. To compare the diurnal evolution in cloud responses 132 between MODIS and SEVIRI data, we used normalized time-coordinate, where 0 is the local 133 sunrise, 0.5 is the local noon, and 1 represents the local sunset. 134

We compare the changes in cloud optical depth (COD) to the changes in cloud droplet effective radius (R_{eff}) to study the changes in LWP. We assume the following relationship between COD, LWP and R_{eff}

$$COD \ \frac{LWP}{R_{eff}}.$$
 (1)

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139 From this, we derive a relation between logarithmic changes of LWP and R_{eff} as

$$\Delta \ln (COD) = \Delta \ln (LWP) - \Delta \ln (R_{eff}).$$
⁽²⁾

140 Dividing both sides of the equation by $-\Delta ln(R_{eff})$ we derive a simple metric

$$\frac{\Delta \ln(COD)}{-\Delta \ln(R_{eff})} = 1 - \frac{\Delta \ln(LWP)}{\Delta \ln(R_{eff})}$$
(3)

that allows us to compare the total change in COD to the change caused solely by the Twomey

142 effect and ultimately provides a straightforward interpretation of changes in LWP. This ratio has

previously been used by Toll et al. (2019). If the ratio $\frac{\Delta \ln(COD)}{-\Delta \ln(R_{eff})}$ is greater than 1, the LWP has

increased since the changes in R_{eff} are always negative. If the ratio is less than 1, the LWP has decreased in polluted areas, resulting in partial compensation of the Twomey effect. If the ratio equals 0, the decrease in LWP entirely cancels the Twomey effect. If the ratio is negative, the LWP decreases so much that the polluted clouds are optically thinner compared to the unpolluted clouds.

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150 2.2 SEVIRI Data

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We analyse cloud physical properties derived from SEVIRI instrument data on the Meteosat Second Generation (MSG) satellite. SEVIRI has four visible and near-infrared (VNIR) and eight infrared (IR) channels. In the study area of the European part of Russia, the spatial resolution of the cloud properties product is on average about 10 km by 10 km. The SEVIRI satellite instrument rotates at a rate of 100 rotations per minute, which allows making measurements with 157 Instrument resolution (Schmid, 2000). Such 15-minute temporal resolution allows to study the temporal evolution of clouds.

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We use SEVIRI Cloud Physical Properties (CPP) data (Roebeling et al., 2006). Cloud properties 160 in the CPP product are retrieved in three steps. In the first step, cloud-filled, cloud contaminated, 161 162 and cloud-free pixels are detected. For the next step, primary cloud properties (Cloud Top Temperature, Cloud Phase, Cloud Optical Thickness and Cloud Droplet Size) are retrieved. For 163 the last step, secondary cloud properties (Cloud Water Path, Cloud Droplet Number 164 Concentration, Cloud Geometrical Thickness, Surface Solar Irradiance, Precipitation occurrence 165 166 and intensity) are calculated using the values of primary properties achieved in the previous step (Roebeling et al., 2006). 167

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We manually select areas around polluted cloud tracks in SEVIRI data for further analyses. We include only single-layer, liquid-phase and low-level (cloud top lower than 5000 m) clouds and data with the Sun zenith angle less than 80°. We classify the pixels inside the preselected area around the pollution tracks into polluted and unpolluted pixels depending on cloud droplet size(Fig 3).





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We classify the pixels in the areas as polluted and unpolluted by selecting the pixels of 25% of 178 the smallest droplet sizes as polluted. Unpolluted pixels stay between the 30th and 55th percentile 179 180 in droplet size in the masked area, ensuring a roughly similar quantity of pixels in both classes. Due to the CPP algorithm and limitations of the SEVIRI instrument, there were situations where 181 polluted pixels were saturating large areas, causing failures in the first approach. Therefore, 182 additional criteria were introduced to take this issue into account. If the simple counting method 183 resulted in equal or very similar values for the limits of polluted and unpolluted thresholds, the 184 most common value was detected from data (Xth percentile), selected as the polluted pixel 185 threshold. It did not necessarily have to be the 25th percentile, it was usually higher. From that 186

value, we searched the upper $(X+5)^{th}$ and $(X+30)^{th}$ percentile (still covering the 25-percentile range) to be the unpolluted pixels. Such an approach sometimes introduced discrepancies between the number of classified pixels as the percentile range for polluted values could be greater than 25. If the difference grew too large, the time-series were excluded from the final analysis to minimise the effect of outliers.

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Average cloud properties for polluted and unpolluted cloud areas were computed for each 193 timestep. Timeseries of cloud properties thus represent the average values in larger areas 194 (polluted and unpolluted pixels in Fig 3). We included only the cases, where cloud droplet size 195 decreased by at least 20% in the polluted clouds and the total time covered was at least 2 hours. 196 Every timestep was visually inspected for erroneous behaviour in pixel classification and poor 197 data quality. All suspicious timesteps were excluded from the final analysis. In a few cases, there 198 were unexplainable fast and large increases (spikes) in LWP values in SEVIRI data which we 199 considered as errors in data and excluded from the analysis. Also, if the areas consisted of very 200 few pixels (less than 100 pixels), they were excluded. With these additional criteria, we excluded 201 50.7% of initial data points from the analysis. We checked that the results were not sensitive to 202 the data screening. 203

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The difference in the spatial resolution between SEVIRI and MODIS instruments is significant (~10 km vs 1 km, respectively), but only SEVIRI data enables to study the temporal evolution of clouds. Due to lower spatial resolution, the contrast between relatively narrow polluted and unpolluted areas is lower.

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210 2.3 Moderate Resolution Imaging Spectroradiometer (MODIS) data

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Diurnal evolution of cloud response to aerosols was also studied, based on MODIS data for polluted cloud tracks. The MODIS data used here have been previously sampled by Toll et al. (2019). MODIS level 2 cloud products (MOD06_L2 for Terra and MYD06_L2 for Aqua) were used. The dataset included 8379 different pollution track segments over Russia, Australia, and Canada, observed in various seasons. Details of MODIS data screening and classification of MODIS pixels as polluted and unpolluted is given in Toll et al. (2019). Single-layer liquid-water

low-level clouds were studied similarly to SEVIRI data which was newly sampled for this study. 218 For each MODIS image, where the polluted cloud track was visually detected, the centreline of 219 the polluted cloud track was manually sampled, and pixels around this line were classified as 220 polluted or unpolluted, based on near-infrared reflectance using a semi-automated algorithm 221 (Toll et al., 2019). The polluted cloud tracks were sampled for various local times by Toll et al. 222 (2019) so that using all MODIS cases from Terra and Aqua for various locations, continuous 223 temporal coverage between sunrise and sunset is derived. MODIS data consists of snapshots of 224 many pollution tracks from various geographical areas. Therefore, MODIS data does not enable 225 us to study the temporal evolution of the individual pollution tracks. Using SEVIRI data, we 226 study the temporal evolution of individual pollution tracks in time. 227

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229 **3 Results**

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We have found that SEVIRI data is useful for studying polluted cloud tracks. Although the spatial resolution is roughly about 10 times worse for SEVIRI data (about 10 km at given latitude) compared to MODIS data (1 km), we were still able to effectively detect the pollution tracks. In SEVIRI data, similarly to MODIS data, there is a clear contrast between polluted and unpolluted clouds (Fig 2 and Fig 3). On average, the cloud droplet size of the polluted clouds was 27% smaller compared to the nearby less polluted clouds (Table 3).

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Table 3. Average values of cloud optical properties over all the data (2 leftmost columns) and

averages for the orange and green groups from Fig 6. The orange group includes cases with

strong liquid water path (LWP) increase and the green group includes all the other cases.

Averages for cloud droplet effective radius (R_{eff}), LWP and cloud optical depth (COD) together

242 with the standard deviation in the parentheses.

Polluted Unpolluted	Polluted Strong increase cases	Unpolluted Strong increase cases		Polluted other cases	Unpolluted other cases
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R_{eff} (µm)	5.8 (1.4)	7.9 (2.0)	5.3 (0.4)	7.2 (0.6)	6.0 (1.6)	8.1 (2.2)
$ \begin{bmatrix} LWP \\ \left(\frac{g}{m^2}\right) \end{bmatrix} $	58.6 (32.8)	68.1 (34.8)	65.1 (36.9)	49.3 (20.5)	56.3 (30.9)	74.8 (36.3)
COD	15.1 (7.2)	12.6 (4.6)	18.9 (11.0)	10.3 (4.2)	13.7 (4.5)	13.4 (4.5)

Based on both MODIS and SEVIRI data, there is a partial offset of the Twomey effect due to the

decrease in cloud water. The mean value of $\frac{\Delta \ln(COD)}{-\Delta \ln(R_{eff})}$ for MODIS data is 0.74, meaning that on

average decrease in LWP offsets 26% of the Twomey effect. The mean value of $\frac{\Delta \ln(COD)}{-\Delta \ln(R_{eff})}$ for SEVIRI data is 0.54, meaning that on average decrease in LWP offsets 46% of the Twomey effect. Data-points are not distributed evenly throughout the day. In the case of both MODIS and SEVIRI data, we have the largest number of cases around noontime (Fig 4). Due to poor lighting conditions in the very early morning and very late evening, there is only a limited number of data points during these times (Fig 4). Most of the day is still sufficiently covered for both instruments.



Figure 4. Average changes in $\frac{-\Delta ln(COD)}{\Delta ln(R_{eff})}$ (green) distributed over normalised time coordinate 254 from sunrise (0.0) to sunset (1.0). The time coordinate value of 0.5 represents the local noon. 255 Total counts of data points are given in black with relative occurrence in blue (at the top of each 256 column) and graphically in red on the second y-axis. a. MODIS cases and b. SEVIRI cases 257 included in the study. Both based on MODIS and SEVIRI data, decrease in cloud water offsets 258 part of the Twomey effect. There is no clear diurnal evolution in liquid water path (LWP) 259 response based on MODIS data. Based on SEVIRI data, cloud water is more likely to increase in 260 the afternoon. 261

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MODIS and SEVIRI data reveal day-night contrast in the cloud water response to cloud droplet 263 number perturbations. MODIS data shows a uniformly weak decrease in cloud water during 264 sunlight hours, while SEVIRI data shows a substantial decrease in the morning and increase in 265 the afternoon (Fig 4). Both MODIS and SEVIRI data show decreased cloud water since the 266 267 sunrise, suggesting that a decrease in cloud water occurs during the night, potentially through aerosol-enhanced entrainment. In the afternoon, increased cloud water in the polluted clouds is 268 found in SEVIRI data (Fig 4 and Fig 5). This strong increase is caused by cases where cloud 269 water in polluted clouds increases in the afternoon much more than in the unpolluted clouds, 270 most probably due to suppressed precipitation in the polluted clouds (Fig 5 and Fig 6). 271



Figure 5. The ratio $\frac{-\Delta ln(COD)}{\Delta ln(R_{eff})}$ scattered over normalised time coordinate from sunrise (0.0) to

sunset (1.0). The time coordinate value of 0.5 represents the local noon. a. MODIS cases (8379

in total) and **b.** SEVIRI cases (682 in total) included in the study. Red lines are least-square fits

to the data points. Decrease in cloud water offsets part of the Twomey effect in both datasets. In

277 SEVIRI data, a considerable number of data points with strongly increased liquid water path

(LWP) in the afternoon are seen, while no cases with such strong increases in LWP are seen in

the morning.





Figure 6. SEVIRI time-series of individual tracks classified into two groups. The orange group includes cases with strong liquid water path (LWP) increase and the green group includes all the other cases. The most plausible physical interpretation is that the orange group includes cases with suppressed precipitation in the polluted clouds. The following criteria were used to select cases in the orange group: slopes of linear fits are greater than 2.0 and that the maximum value

of the ratio $\frac{-\Delta ln(COD)}{\Delta ln(R_{eff})}$ is greater than 2.0. The orange group shows that the increase in LWP happens in the afternoon. The green group indicates that the decrease in LWP has already occurred during the night and no further decrease occurs during the day in the polluted cloud tracks.

We found two groups of pollution tracks with very different temporal evolutions of the cloud water response in SEVIRI data. Most likely, these groups include cases with suppressed precipitation in polluted clouds and all other cases, respectively. The cases in the orange group in Fig 6 show strong increases in LWP in the afternoon and these are likely the cases where precipitation is suppressed in the polluted clouds compared to the unpolluted clouds. The orange group includes thinner unpolluted clouds. The average LWP for unpolluted clouds within the

orange group is $49.3 \frac{g}{m^2}$ while for the other cases, it is $74.8 \frac{g}{m^2}$. In the orange group, only the polluted clouds can become much thicker during the day.

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In cases, where precipitation in polluted clouds is not suppressed compared to the unpolluted 300 clouds (green group in Fig 6), no apparent change in cloud water response is observed during the 301 sunlight hours. Only three individual tracks were detected, where the cloud water response 302 became more negative during the sunlight hours, which strongly supports the hypothesis that 303 cloud water decreases during the night due to aerosol-enhanced entrainment. In most cases, the 304 LWP of polluted clouds is much lower already at sunrise. For the orange group, the increase in 305 LWP enhances the Twomey effect by 80% on average. For the green group, the decrease in LWP 306 offsets 95% of the Twomey effect. 307

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309 4 Discussion and Conclusions

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We demonstrated that SEVIRI data could be used to study the temporal evolution of polluted 311 cloud tracks. SEVIRI data shows that on average the decrease in cloud water offsets 46% of the 312 Twomey effect in the European part of Russia. The partial offset of the Twomey effect is in good 313 agreement with the analysis of MODIS data by Toll et al (2019) and Trofimov et al (2020). As 314 the number of data points for SEVIRI data is much more limited and only a single geographical 315 316 region is studied, the average cloud water response is likely to be much less representative of the global average cloud water response than the MODIS dataset included in this study. But the 317 318 temporal evolution from SEVIRI data helps to increase the process-level understanding of aerosol-cloud interactions. 319

SEVIRI data reveals day-night contrast in the cloud water response to aerosols. In some cases, 321 322 cloud water strongly increases in the polluted clouds compared to the unpolluted clouds in the afternoon, most likely due to the suppression of precipitation. In most cases, cloud water is 323 decreased in the polluted clouds since the early morning and no further decrease compared to the 324 unpolluted clouds is observed during the day (Fig 6). This suggests that cloud water decreases 325 more in the polluted clouds during the night-time, probably due to aerosol-enhanced entrainment. 326 However, as SEVIRI provides only day-time data, we can only speculate how the cloud water 327 responds during night-time. Our results show that the temporal evolution of cloud responses to 328 aerosols is very important to consider in aerosol radiative forcing calculations. 329 330

Our results disagree with Diamond et al. (2020) who found a more substantial decrease in cloud 331 water in the afternoon compared to the morning in the South-East Atlantic shipping corridor. A 332 possible explanation with the disagreement with Diamond et al. (2020) is that land-based tracks 333 analysed in this study could behave differently compared to the ocean-based tracks analysed by 334 Diamond et al. (2020). In the future, we plan to use SEVIRI data to analyse the temporal 335 evolution of ship tracks to compare track responses over land and ocean. Interestingly, an 336 increase in LWP during a later stage of track evolution in the afternoon agrees with the ship track 337 analysis by Gryspeerdt et al. (2020) and Christensen et al. (2009). Segrin et al. (2007) found a 338 rather similar decrease in LWP in ship tracks in the morning and afternoon. 339 340

Our finding that LWP decreases more in the polluted clouds than in the unpolluted clouds only 341 during the night-time disagrees with process-level modelling by Sandu et al (2008). Sandu et al. 342 343 (2008) suggested that the decrease in cloud water is amplified during the day (Sandu et al. 2008). Glassmeier et al. (2021) discuss that ship tracks are not suitable to inform calculations of 344 radiative forcing due to the short lifetime of the tracks. We plan to study the lifetime of pollution 345 tracks in more detail in future work, but the lifetime of the polluted cloud tracks studied here 346 spans from less than a single day to multiple days. We find no further decrease in LWP of 347 polluted clouds compared to the nearby unpolluted clouds during the daytime also for shorter-348 lived tracks. This suggests that polluted clouds could reach an equilibrium state quicker than 20 349 hours suggested by Glassmeier et al. (2021). Moreover, Glassmeier et al. (2021) might 350

overestimate the decrease in cloud water of non-precipitating clouds as they use only nocturnal

radiation in their simulations. Our results highlight the need to account for the day-night contrast

in the cloud responses as the night-time responses are not representative of the average response.

354

355 Acknowledgements and data availability

356

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363 Author contributions

VT designed the study. JR identified the polluted cloud areas in SEVIRI satellite images and analysed the observations. HT analysed MODIS satellite data. JR and VT wrote the manuscript with contributions from HT and PP.

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