Impact of Rocket Launch Emissions on Polar Mesospheric Cloud Formation using AIM/CIPS Data.

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Rocket launches inject water vapor into the upper atmosphere and may influence polar mesospheric cloud (PMC) occurrence under favorable mesospheric conditions. Clouds further up in the atmosphere, like PMCs, will trap escaping longwave radiation and re-emit heat into the lower atmosphere, potentially resulting in an increase in global temperature. This paper uses NASA AIM/CIPS observations to examine whether July PMC frequency in the Northern Hemisphere covaries with the number of successful rocket launches. The total number of rocket launches is shifted in time to account for transport and cloud-formation timelines. July-averaged cloud frequencies are computed from AIM/CIPS Level 3C data for latitude bands between 56° N and 80° N and compared to shifts in day and time of launches. The strongest correlations occur at higher latitudes, with peak values generally appearing for launch windows shifted about 4–6 days earlier. However, the relationship is weak to moderate outside the highest-latitude band and is sensitive to analysis choices, so the results should be interpreted as exploratory rather than predictive. Overall, the analysis suggests that launch activity may contribute to interannual PMC variability, but rocket launches alone are not sufficient to predict future cloud frequency.

I. Nomenclature

PMC = Polar Mesospheric Cloud
AIM = Aeronomy of Ice Mission
$CIPS$ = Cloud Imaging and Particle Size instrument

II. Introduction

Although scientists are unsure of the exact impact of cloud cover, it is clear that clouds affect the global climate [1]. High clouds, like polar mesospheric clouds (PMCs), absorb the long-wave radiation and send it back to the surface, thereby increasing global temperature [2]. These PMCs are the highest clouds in our atmosphere, and they form when water-ice crystals condense on debris from meteors that have burned up in the atmosphere [3]. Because rocket launches exhaust water vapor into the atmosphere, this could increase cloud formation under favorable conditions. Additionally, there could be some dependence on the local time of the rocket launches due to wind carrying exhaust polewards [4]. The occurrence of PMCs depends strongly on the temperature and water content in the mesosphere, meaning they can be used to indicate changes in the environment.

In 2018, researchers in Alaska explosively released 220 kg of water into the atmosphere at around 85 km, the altitude at which PMCs typically occur. Within 18 seconds, a cloud formed despite unfavorable weather conditions for cloud formation. The high water vapor concentration cools the upper mesosphere and raises the frost point, resulting in a higher likelihood of cloud formation [5]. While the amount of water deposited was much more than a typical rocket launch, this experiment demonstrated that a sufficiently concentrated water release near PMC altitudes can induce mesospheric cloud formation under otherwise favorable conditions. Furthermore, case studies examined in Stevens et al. [4], show that water vapor exhaust from Florida space shuttle launches led to an increase in cloud brightness and frequency at the poles.

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To study the formation of PMCs, NASA's Aeronomy of Ice in the Mesosphere (AIM) [6] was launched with the Cloud Imaging and Particle Size (CIPS) instrument onboard. During the summer of each hemisphere, AIM/CIPS captured photos of ultraviolet radiation scattered by the PMCs over about 15 orbits a day from 2007 to 2023. The orbit strip photos have since been post-processed into cloud data and uploaded publicly on the LASP University of Colorado website [6].

Stevens et al. [4] analyzed cloud formation using AIM/CIPS data for 56-60° N latitude bands and found that there is some correlation between frequency of rocket launches and cloud frequency for the month of July. The number of rocket launches is taken from June 21st to July 21st to account for transport and cloud formation timelines. It is noted that the results include a set of rocket launches from 23 to 10 local time, and that this correction greatly increases the correlation. Mukherjee et al. [7] find that at 80° N, there is much less dependence of local launches, with the highest correlations having 17-21 hr launch window widths.

This paper will discuss trends across all latitudes in the northern hemisphere to connect the gap between previous work. There will also be a comparison of correlation coefficients to the visual trend between cloud frequency and rocket launches, as well as determining the statistical significance of these trends. The goal of this work is to determine whether interannual variations in launch activity are associated with interannual variations in July PMC frequency observed by AIM/CIPS, and if future cloud frequencies could be predicted by the number of rocket launches.

III. Methodology

Results were obtained using the level 3C version 8 AIM/CIPS files. These files are a collection of all the data for a given season, i.e., the Northern Hemisphere summer of 2021. The data in these files has already been post-processed from the raw data, pictures known as orbit strips, into variables such as the number of clouds in a day for a given latitude bin. Due to orbital precession of the AIM/CIPS satellite, data points for 2007-2016 are on the descending node of the orbit, and 2018-2022 are on the ascending node [6]. The satellite was unable to collect data for 2017, so this point is omitted from the analysis.

The process for calculating the cloud frequency in July of each year is as follows. The data for the number of cloud observations and the number of clouds detected is pulled for a chosen albedo threshold. In this case, the albedo threshold is 6×10^{-6} sr^{-1} as Stevens et al. [4] uses a 5×10^{-6} sr^{-1} and Mukherjee et al. [7] uses a 6×10^{-6} sr^{-1} threshold. A lower albedo threshold will result in a higher cloud frequency, but potentially includes more false cloud detections. A higher threshold means more robust measurements, but dimmer clouds will be missed, resulting in underestimated cloud frequencies [6].

This data is organized by latitude bins and days for each albedo threshold. The indices corresponding to the 1st and last day of July are found, and the data is narrowed down to this time period. Then, the sum of the number of clouds detected is divided by the sum of the number of cloud observations for the given time period. This gives the average July PMC frequency for a given year.

Successful rocket launches were taken from Gunter's Space Page [8], a publicly available database of global launches. The number of rocket launches is determined by a day-shift back from July 1st to 31st. No shift indicates July 1st to 31st, while a ten-day shift back corresponds to June 21st to July 21st. This delay is important to allow time for cloud formation, as found by previous research and observation of PMCs [4, 5, 7]. The cloud frequencies can then be plotted versus the number of rocket launches in the given shifted time period for each year. The number of rocket launches is normalized by twice the mean of the data to be relatively between 0 and 1 for comparison between the variables.

Additionally, dependence on the local time launch window width was investigated, as this may have an effect on the strength of the correlation [4]. Each rocket launch has a local time of liftoff, which is used here. A 2-hour local launch time window means that successful rocket launches between 11 am and 1 pm are considered. A 24-hour time window indicates that all successful launches are considered for each day shift.

Additionally, cloud frequencies are averaged over the following latitudes: 56-60° N, 61-65° N, 66-70° N, 71-76° N, 76-80° N, and 80° N. The outer bounds (56-60° N and 80° N) are chosen based on previous work [4, 7]. The latitudes between are grouped evenly based on similar values of cloud frequency. The data outside these bounds is more incomplete in terms of cloud detection and observations, resulting in undefined values. As such, these latitudes are not included.

IV. Results

The correlation coefficients for half of the latitude groups are plotted in Fig. 1. As the latitude increases, the correlation coefficients increase. In accordance with previous research [7], 80° N has very little dependency on launch time window width and has the highest correlation around a shift of five days. The peak correlation at a 5-day shift is nominally significant at the 0.05 level. However, because many shift and launch-window combinations are examined, this result should be interpreted as exploratory unless a multiple-comparison correction is applied. The latitudes below 80° N also appear to have little dependence on launch window width. All latitudes appear to have some connection to the time period shift; however, the mid-latitudes have decreasing correlation values. For 56-60° N, the highest r-value is 0.22, occurring multiple times in the 1-day shift column. These correspond to a p-value of 0.42 to 0.44, indicating no statistical significance.

The correlation coefficients for the 24-hour window are plotted in Fig. 2, which shows the increasing correlation with increasing latitude. Additionally, the maximum correlation coefficient is between 4 and 6 days for most of the latitudes. As discussed previously, the correlation is higher at higher latitudes, while the p-value shows the opposite trend. Above 70° N, there is an overlapping trend in the correlation coefficient, indicating less sensitivity to change in latitude at the higher latitudes.

Fig. 3 clearly shows increasing cloud frequency with increasing latitude. By visual inspection, there also appears to be a positive trend between rocket launches and cloud frequency that increases with latitude, which matches the trend of the correlation coefficients with latitude.

Fig. 4 takes a closer look at the extremes of the latitude groups. At 56-60° N, the data points appear to be in a relatively vertical column and span a very small change in cloud frequency, about 3% overall. The time span of 7-day shift to 12-day shift is chosen based on Stevens et al [4] finding a higher correlation at 10 days for a different, smaller launch window width of 11 hours center around 4:30 am. The numbers given here are for a full 24-hour cycle based on the results in Fig. 1. For 80° N, the best correlation is found at a 5-day shift, with there appearing to be a more generally-positive trend. However, from visual inspection, there does not seem to be a trend that could be used to predict future cloud frequencies given a number of rocket launches.

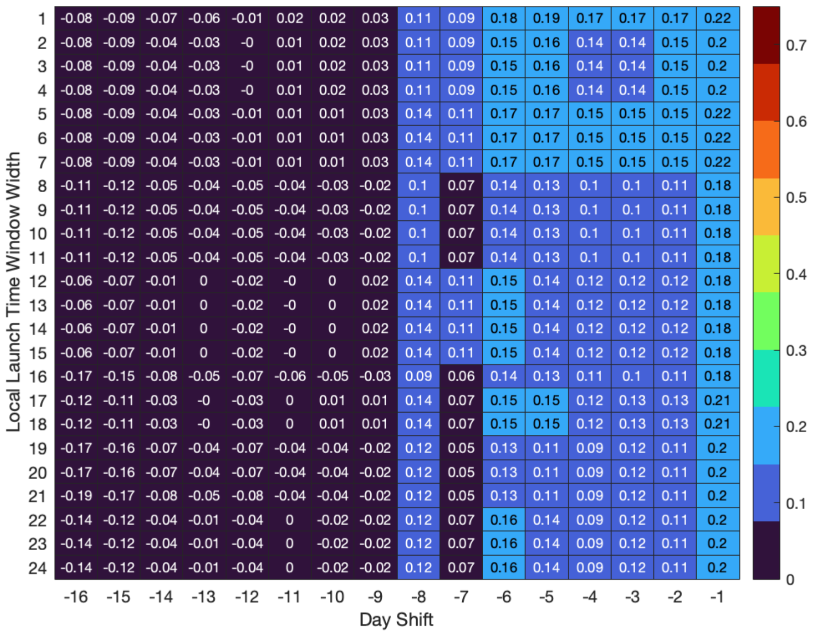
One point to note is that the 2022 data point has a substantially higher amount of rocket launches. This point has high leverage, particularly at the mid-latitudes. As a sensitivity check, the 2022 data point is removed. As seen in Fig. 5, removing this data point at 56-60° N does increase the r-value, but it still does not indicate a strong correlation. Additionally, the p-value does decrease at the point of highest correlation, which is at a 5-day shift with a local launch time window of 1 hour to 7 hours. This indicates some sensitivity to individual years but not a stronger physical relationship. However, the trend still appears to be relatively vertical. Also a launch time window of 1 hour, where the highest correlation seems to occur, seems to be unlikely to be the main driving factor between cloud frequency and rocket launches as this is a much smaller portion of rocket launches compared to the global number of rocket launches. This effect decreases at higher latitudes, with the removal of the 2022 data point barely affecting the 80° N results.

V. Conclusion

July PMC frequency and launch counts are more strongly correlated at higher northern latitudes than at mid-latitudes, which the highest correlations falling between earlier shifts, around 4 to 6 days earlier than the July averaging window. However, this evidence remains exploratory. Below the higher latitudes, the correlations are weak to moderate and not robust enough prediction. Even at 80° N, interpretation is limited by the number of data points available, the switching of CIPS sampling from descending to ascending, and the large number of shifts and times examined. Therefore, any interpretations made must be taken with caution. Launch activity may contribute to interannual PMC variability, but this data set alone does not establish a predictive or causal relationship at any latitude. Additionally, clouds depend on many varying environmental factors that could be effecting this dataset.

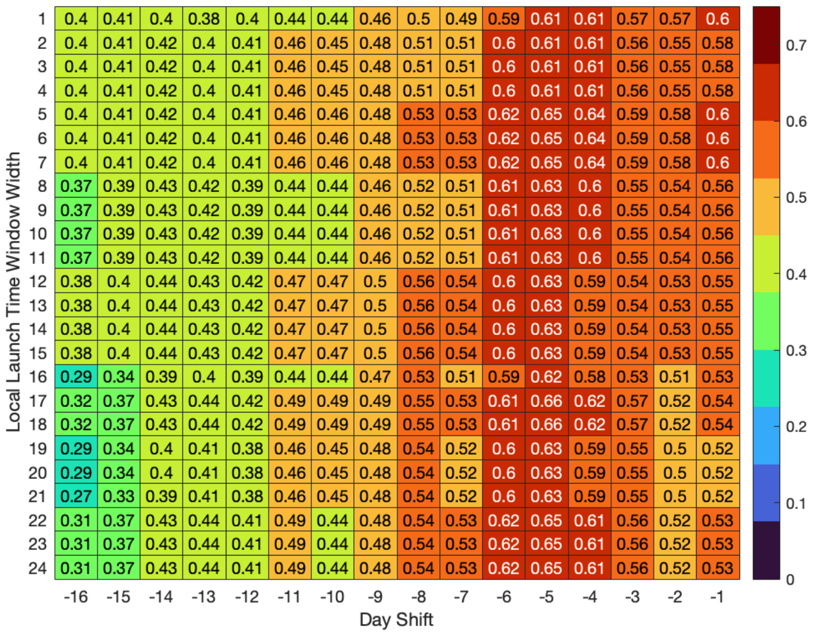
For future work, it would be relevant to produce results for the southern hemisphere, as these are also not available in the current literature. This would help see how the southern hemisphere clouds compare to the northern hemisphere, and see if the trends found in this work are reflected there. It would also be pertinent to explore varying the albedo threshold to see if similar trends can be found at varying altitudes by looking only at the brightest clouds at each section, or if increasing the albedo threshold increases or decreases the correlation.

Additionally, there is the question of determining what magnitude of change in cloud frequency will have a significant impact on the environment. Will a 1% change at lower latitudes versus a 15% change in higher latitudes have the same or different effect magnitude on the environment? As Marvel notes, climate scientists agree that there is warming with an increase in cloud frequency in the upper atmosphere, but models disagree on exactly how much it affects



	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1
1	-0.08	-0.09	-0.07	-0.06	-0.01	0.02	0.02	0.03	0.11	0.09	0.18	0.19	0.17	0.17	0.17	0.22
2	-0.08	-0.09	-0.04	-0.03	-0	0.01	0.02	0.03	0.11	0.09	0.15	0.16	0.14	0.14	0.15	0.2
3	-0.08	-0.09	-0.04	-0.03	-0	0.01	0.02	0.03	0.11	0.09	0.15	0.16	0.14	0.14	0.15	0.2
4	-0.08	-0.09	-0.04	-0.03	-0	0.01	0.02	0.03	0.11	0.09	0.15	0.16	0.14	0.14	0.15	0.2
5	-0.08	-0.09	-0.04	-0.03	-0.01	0.01	0.01	0.03	0.14	0.11	0.17	0.17	0.15	0.15	0.15	0.22
6	-0.08	-0.09	-0.04	-0.03	-0.01	0.01	0.01	0.03	0.14	0.11	0.17	0.17	0.15	0.15	0.15	0.22
7	-0.08	-0.09	-0.04	-0.03	-0.01	0.01	0.01	0.03	0.14	0.11	0.17	0.17	0.15	0.15	0.15	0.22
8	-0.11	-0.12	-0.05	-0.04	-0.05	-0.04	-0.03	-0.02	0.1	0.07	0.14	0.13	0.1	0.1	0.11	0.18
9	-0.11	-0.12	-0.05	-0.04	-0.05	-0.04	-0.03	-0.02	0.1	0.07	0.14	0.13	0.1	0.1	0.11	0.18
10	-0.11	-0.12	-0.05	-0.04	-0.05	-0.04	-0.03	-0.02	0.1	0.07	0.14	0.13	0.1	0.1	0.11	0.18
11	-0.11	-0.12	-0.05	-0.04	-0.05	-0.04	-0.03	-0.02	0.1	0.07	0.14	0.13	0.1	0.1	0.11	0.18
12	-0.06	-0.07	-0.01	0	-0.02	-0	0	0.02	0.14	0.11	0.15	0.14	0.12	0.12	0.12	0.18
13	-0.06	-0.07	-0.01	0	-0.02	-0	0	0.02	0.14	0.11	0.15	0.14	0.12	0.12	0.12	0.18
14	-0.06	-0.07	-0.01	0	-0.02	-0	0	0.02	0.14	0.11	0.15	0.14	0.12	0.12	0.12	0.18
15	-0.06	-0.07	-0.01	0	-0.02	-0	0	0.02	0.14	0.11	0.15	0.14	0.12	0.12	0.12	0.18
16	-0.17	-0.15	-0.08	-0.05	-0.07	-0.06	-0.05	-0.03	0.09	0.06	0.14	0.13	0.11	0.1	0.11	0.18
17	-0.12	-0.11	-0.03	-0	-0.03	0	0.01	0.01	0.14	0.07	0.15	0.15	0.12	0.13	0.13	0.21
18	-0.12	-0.11	-0.03	-0	-0.03	0	0.01	0.01	0.14	0.07	0.15	0.15	0.12	0.13	0.13	0.21
19	-0.17	-0.16	-0.07	-0.04	-0.07	-0.04	-0.04	-0.02	0.12	0.05	0.13	0.11	0.09	0.12	0.11	0.2
20	-0.17	-0.16	-0.07	-0.04	-0.07	-0.04	-0.04	-0.02	0.12	0.05	0.13	0.11	0.09	0.12	0.11	0.2
21	-0.19	-0.17	-0.08	-0.05	-0.08	-0.04	-0.04	-0.02	0.12	0.05	0.13	0.11	0.09	0.12	0.11	0.2
22	-0.14	-0.12	-0.04	-0.01	-0.04	0	-0.02	-0.02	0.12	0.07	0.16	0.14	0.09	0.12	0.11	0.2
23	-0.14	-0.12	-0.04	-0.01	-0.04	0	-0.02	-0.02	0.12	0.07	0.16	0.14	0.09	0.12	0.11	0.2
24	-0.14	-0.12	-0.04	-0.01	-0.04	0	-0.02	-0.02	0.12	0.07	0.16	0.14	0.09	0.12	0.11	0.2

(a) 56-60° N



	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1
1	0.4	0.41	0.4	0.38	0.4	0.44	0.44	0.46	0.5	0.49	0.59	0.61	0.61	0.57	0.57	0.6
2	0.4	0.41	0.42	0.4	0.41	0.46	0.45	0.48	0.51	0.51	0.6	0.61	0.61	0.56	0.55	0.58
3	0.4	0.41	0.42	0.4	0.41	0.46	0.45	0.48	0.51	0.51	0.6	0.61	0.61	0.56	0.55	0.58
4	0.4	0.41	0.42	0.4	0.41	0.46	0.45	0.48	0.51	0.51	0.6	0.61	0.61	0.56	0.55	0.58
5	0.4	0.41	0.42	0.4	0.41	0.46	0.46	0.48	0.53	0.53	0.62	0.65	0.64	0.59	0.58	0.6
6	0.4	0.41	0.42	0.4	0.41	0.46	0.46	0.48	0.53	0.53	0.62	0.65	0.64	0.59	0.58	0.6
7	0.4	0.41	0.42	0.4	0.41	0.46	0.46	0.48	0.53	0.53	0.62	0.65	0.64	0.59	0.58	0.6
8	0.37	0.39	0.43	0.42	0.39	0.44	0.44	0.46	0.52	0.51	0.61	0.63	0.6	0.55	0.54	0.56
9	0.37	0.39	0.43	0.42	0.39	0.44	0.44	0.46	0.52	0.51	0.61	0.63	0.6	0.55	0.54	0.56
10	0.37	0.39	0.43	0.42	0.39	0.44	0.44	0.46	0.52	0.51	0.61	0.63	0.6	0.55	0.54	0.56
11	0.37	0.39	0.43	0.42	0.39	0.44	0.44	0.46	0.52	0.51	0.61	0.63	0.6	0.55	0.54	0.56
12	0.38	0.4	0.44	0.43	0.42	0.47	0.47	0.5	0.56	0.54	0.6	0.63	0.59	0.54	0.53	0.55
13	0.38	0.4	0.44	0.43	0.42	0.47	0.47	0.5	0.56	0.54	0.6	0.63	0.59	0.54	0.53	0.55
14	0.38	0.4	0.44	0.43	0.42	0.47	0.47	0.5	0.56	0.54	0.6	0.63	0.59	0.54	0.53	0.55
15	0.38	0.4	0.44	0.43	0.42	0.47	0.47	0.5	0.56	0.54	0.6	0.63	0.59	0.54	0.53	0.55
16	0.29	0.34	0.39	0.4	0.39	0.44	0.44	0.47	0.53	0.51	0.59	0.62	0.58	0.53	0.51	0.53
17	0.32	0.37	0.43	0.44	0.42	0.49	0.49	0.49	0.55	0.53	0.61	0.66	0.62	0.57	0.52	0.54
18	0.32	0.37	0.43	0.44	0.42	0.49	0.49	0.49	0.55	0.53	0.61	0.66	0.62	0.57	0.52	0.54
19	0.29	0.34	0.4	0.41	0.38	0.46	0.45	0.48	0.54	0.52	0.6	0.63	0.59	0.55	0.5	0.52
20	0.29	0.34	0.4	0.41	0.38	0.46	0.45	0.48	0.54	0.52	0.6	0.63	0.59	0.55	0.5	0.52
21	0.27	0.33	0.39	0.41	0.38	0.46	0.45	0.48	0.54	0.52	0.6	0.63	0.59	0.55	0.5	0.52
22	0.31	0.37	0.43	0.44	0.41	0.49	0.44	0.48	0.54	0.53	0.62	0.65	0.61	0.56	0.52	0.53
23	0.31	0.37	0.43	0.44	0.41	0.49	0.44	0.48	0.54	0.53	0.62	0.65	0.61	0.56	0.52	0.53
24	0.31	0.37	0.43	0.44	0.41	0.49	0.44	0.48	0.54	0.53	0.62	0.65	0.61	0.56	0.52	0.53

(b) 80° N

Fig. 1 Correlation coefficients for cloud frequency compared to shifted rocket launch time periods. The x-axis represents the shifted time period, i.e., -1 means shifted one day back (June 30th to July 30th) and -10 means shifted 10 days back (June 21st to July 21st). The y-axis represents the rocket launch window width centered around noon, i.e., a launch window width of 2 hours means launches from 11 am to 1 pm, whereas 24 hour launch window width means all launches in a given day.

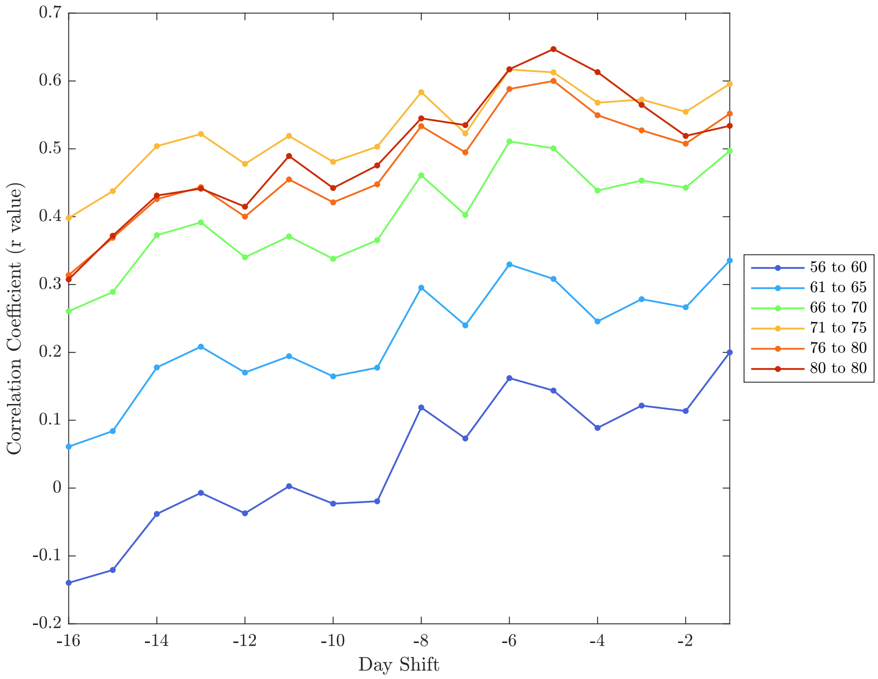


Fig. 2 Correlation coefficient vs. Day Shift for latitude bands.

the environment [1]. Nonetheless, rocket launch water vapor exhaust should be considered in future environmental aerospace work.

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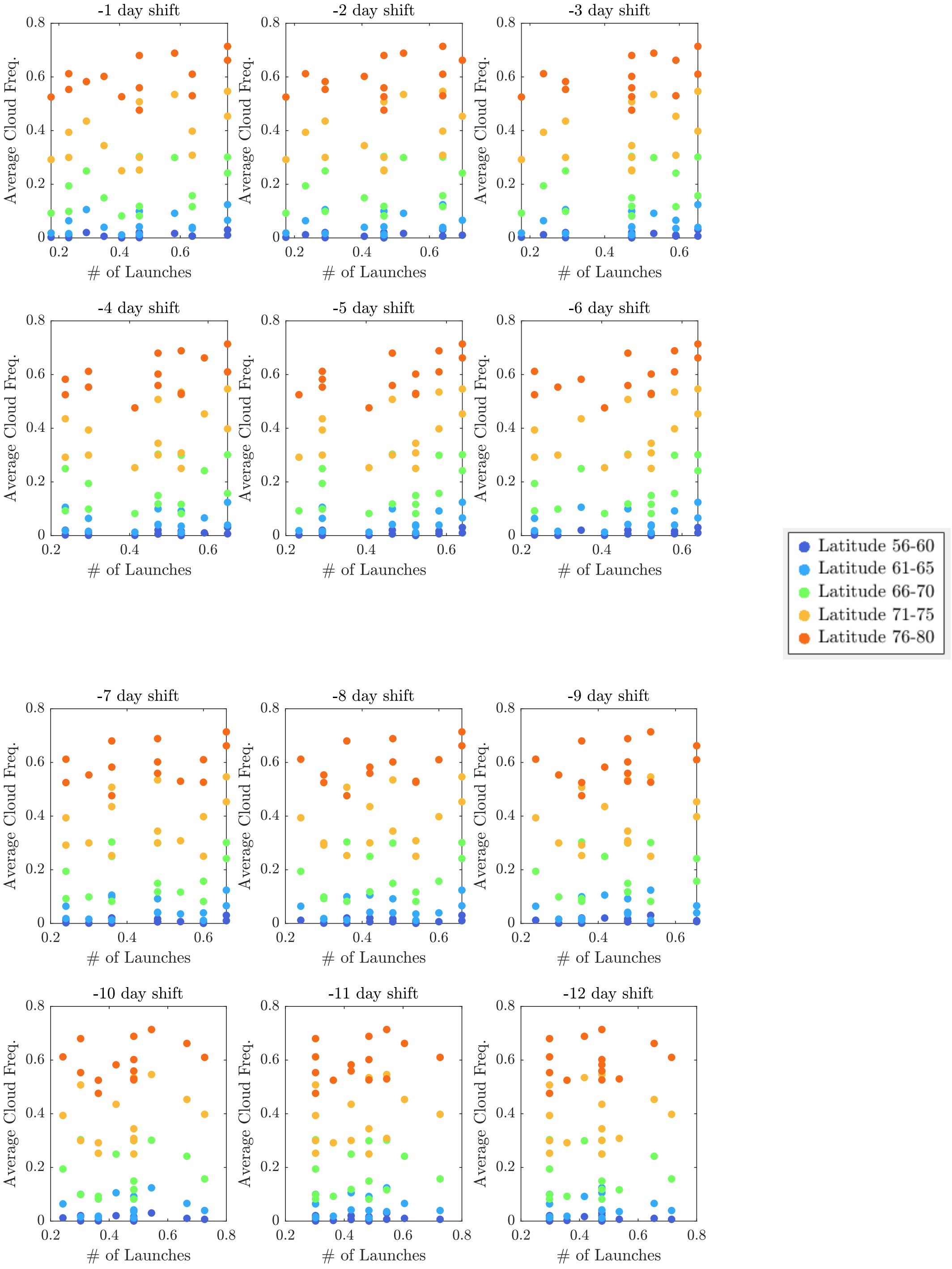
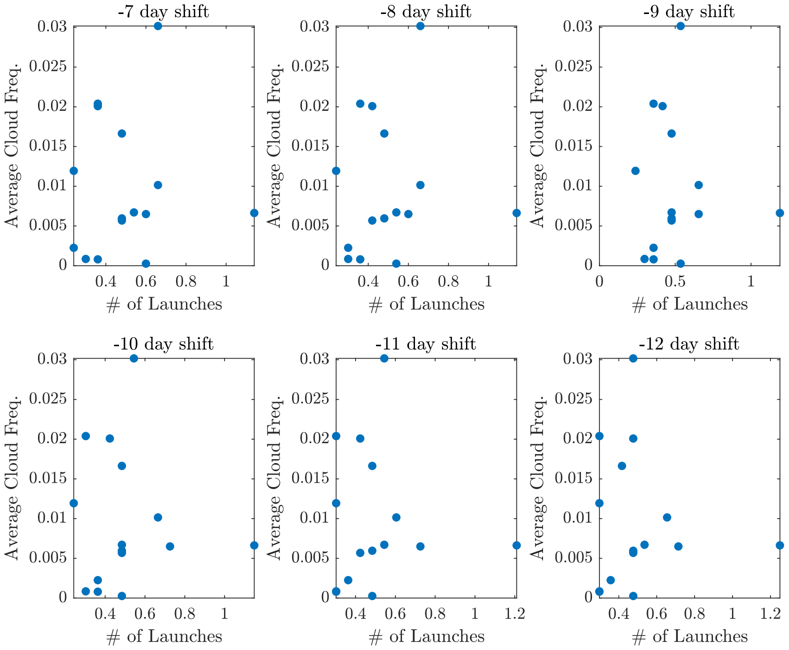
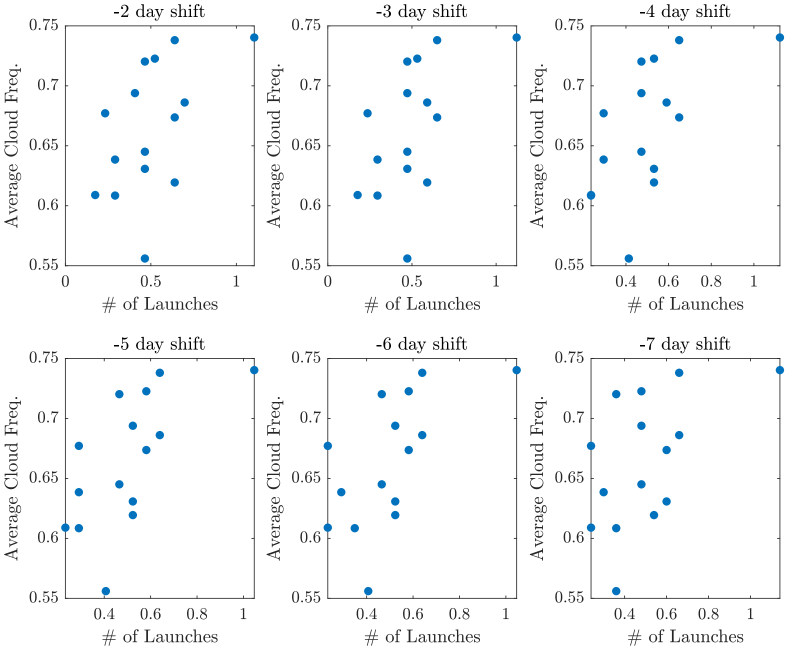


Fig. 3 **Average cloud frequency for given latitudes compared to the normalized number of rocket launches for a given time period.**

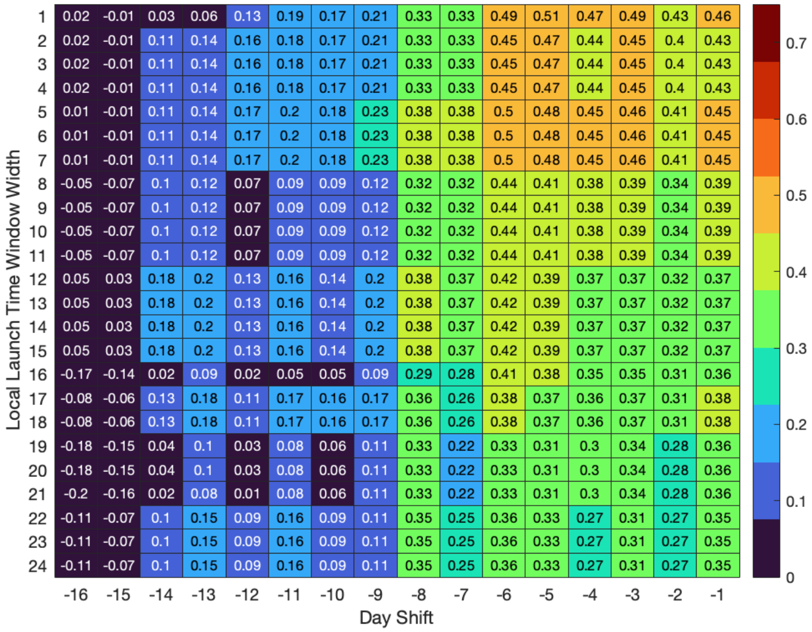


(a) 56-60° N



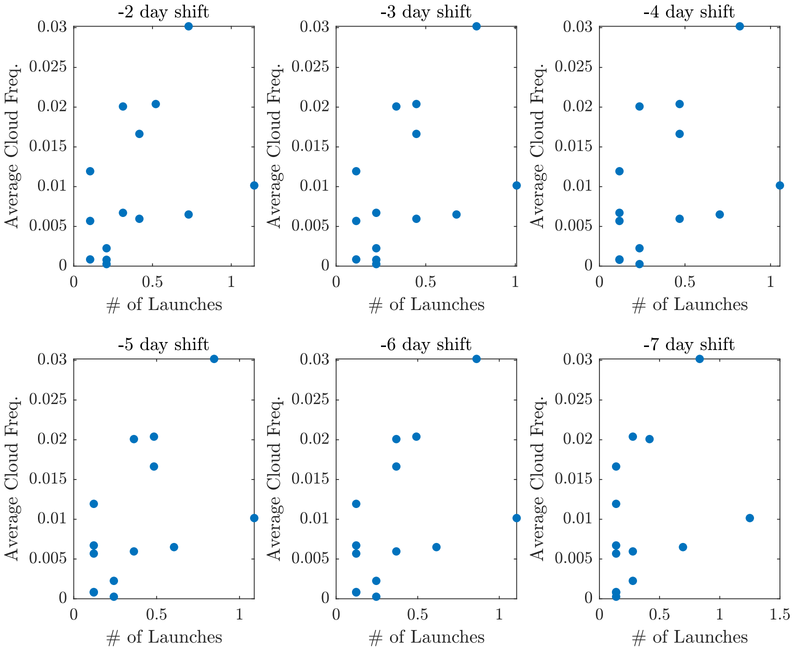
(b) 80° N

Fig. 4 **Average cloud frequency for varying shifts showing the difference in magnitude from mid to high latitudes. At mid-latitudes, the cloud frequency ranges from 0 to 3% and at high latitudes, the cloud frequency ranges from 55 to 75 %.**



Local Launch Time Window Width	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1
1	0.02	-0.01	0.03	0.06	0.13	0.19	0.17	0.21	0.33	0.33	0.49	0.51	0.47	0.49	0.43	0.46
2	0.02	-0.01	0.11	0.14	0.16	0.18	0.17	0.21	0.33	0.33	0.45	0.47	0.44	0.45	0.4	0.43
3	0.02	-0.01	0.11	0.14	0.16	0.18	0.17	0.21	0.33	0.33	0.45	0.47	0.44	0.45	0.4	0.43
4	0.02	-0.01	0.11	0.14	0.16	0.18	0.17	0.21	0.33	0.33	0.45	0.47	0.44	0.45	0.4	0.43
5	0.01	-0.01	0.11	0.14	0.17	0.2	0.18	0.23	0.38	0.38	0.5	0.48	0.45	0.46	0.41	0.45
6	0.01	-0.01	0.11	0.14	0.17	0.2	0.18	0.23	0.38	0.38	0.5	0.48	0.45	0.46	0.41	0.45
7	0.01	-0.01	0.11	0.14	0.17	0.2	0.18	0.23	0.38	0.38	0.5	0.48	0.45	0.46	0.41	0.45
8	-0.05	-0.07	0.1	0.12	0.07	0.09	0.09	0.12	0.32	0.32	0.44	0.41	0.38	0.39	0.34	0.39
9	-0.05	-0.07	0.1	0.12	0.07	0.09	0.09	0.12	0.32	0.32	0.44	0.41	0.38	0.39	0.34	0.39
10	-0.05	-0.07	0.1	0.12	0.07	0.09	0.09	0.12	0.32	0.32	0.44	0.41	0.38	0.39	0.34	0.39
11	-0.05	-0.07	0.1	0.12	0.07	0.09	0.09	0.12	0.32	0.32	0.44	0.41	0.38	0.39	0.34	0.39
12	0.05	0.03	0.18	0.2	0.13	0.16	0.14	0.2	0.38	0.37	0.42	0.39	0.37	0.37	0.32	0.37
13	0.05	0.03	0.18	0.2	0.13	0.16	0.14	0.2	0.38	0.37	0.42	0.39	0.37	0.37	0.32	0.37
14	0.05	0.03	0.18	0.2	0.13	0.16	0.14	0.2	0.38	0.37	0.42	0.39	0.37	0.37	0.32	0.37
15	0.05	0.03	0.18	0.2	0.13	0.16	0.14	0.2	0.38	0.37	0.42	0.39	0.37	0.37	0.32	0.37
16	-0.17	-0.14	0.02	0.09	0.02	0.05	0.05	0.09	0.29	0.28	0.41	0.38	0.35	0.35	0.31	0.36
17	-0.08	-0.06	0.13	0.18	0.11	0.17	0.16	0.17	0.36	0.26	0.38	0.37	0.36	0.37	0.31	0.38
18	-0.08	-0.06	0.13	0.18	0.11	0.17	0.16	0.17	0.36	0.26	0.38	0.37	0.36	0.37	0.31	0.38
19	-0.18	-0.15	0.04	0.1	0.03	0.08	0.06	0.11	0.33	0.22	0.33	0.31	0.3	0.34	0.28	0.36
20	-0.18	-0.15	0.04	0.1	0.03	0.08	0.06	0.11	0.33	0.22	0.33	0.31	0.3	0.34	0.28	0.36
21	-0.2	-0.16	0.02	0.08	0.01	0.08	0.06	0.11	0.33	0.22	0.33	0.31	0.3	0.34	0.28	0.36
22	-0.11	-0.07	0.1	0.15	0.09	0.16	0.09	0.11	0.35	0.25	0.36	0.33	0.27	0.31	0.27	0.35
23	-0.11	-0.07	0.1	0.15	0.09	0.16	0.09	0.11	0.35	0.25	0.36	0.33	0.27	0.31	0.27	0.35
24	-0.11	-0.07	0.1	0.15	0.09	0.16	0.09	0.11	0.35	0.25	0.36	0.33	0.27	0.31	0.27	0.35

(a) Correlation coefficients.



(b) Shifts for 1 hour local time width.

Fig. 5 56-60° N correlation coefficients and trends for cloud frequency versus rocket launches without the 2022 data point.

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