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Evaluation of Space Traffic Effects in SBUV Polar Mesospheric Cloud Data

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Abstract

Water-rich rocket exhaust plumes, in particular those emitted by the National Aeronautics and Space Administration Space Shuttle, have been suggested to make a significant contribution to long-term trends in polar mesospheric cloud (PMC) ice water content. We investigate this claim using the combined Solar Backscatter Ultraviolet (SBUV) PMC data record from eight separate instruments, which includes 60 Shuttle launches during PMC seasons between 1985 and 2011. No statistically significant postlaunch signal in PMC total ice is observed based on superposed epoch analysis of the SBUV record. Only a few launches show individual peaks in total ice anomaly above the seasonal background that exceed an empirical threshold, and the maximum cumulative signature from these infrequent cases is typically less than 5% of the season total in ice mass. Other non-Shuttle launches show circumstantial evidence of possible PMC effects, although supporting evidence for plume transport is not available. We conclude that space traffic effects have been a negligible component of long-term PMC behavior.

1. Introduction

Polar mesospheric clouds (PMCs) are observed at very high altitudes (80–85 km) and relatively high latitudes (typically poleward of 50°) during summer months in both hemispheres. Formation of PMCs in the presence of very low water vapor abundances (<10 ppmv) requires temperatures below 155 K (Rapp and Thomas, 1996; Hervig et al., 2009). Formation and growth of PMC are very sensitive to mesospheric conditions, with temperature being the primary forcing mechanism (Hervig et al., 2016) over time scales of

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decades. However, water vapor may be the ultimate driver over still longer time scales (Lübken et al., 2018; Thomas, 1996; Thomas et al., 1989).

Both increases of CO₂ (leading to decreasing temperature) and of CH₄ (whose photodissociation products yield increased water vapor) should result in corresponding changes in PMC morphology over time. There have been numerous recent studies to evaluate this hypothesis. These include the Solar Backscatter Ultraviolet (SBUV) PMC database (DeLand & Thomas, 2015; Hervig et al., 2016; Hervig & Stevens, 2014), the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) lidar database (Fiedler et al., 2017), and the Mesospheric Ice Microphysics and Transport (MIMAS) atmospheric model (Berger & Lübken, 2015; Lübken et al., 2009). While the data sources and analysis techniques vary between these studies, they consistently report increasing trends in PMC occurrence frequency, brightness, and ice water content (IWC) over multiple decades. The analyses of Hervig and Stevens (2014) and Hervig et al. (2016) obtained separate sensitivities of PMC IWC to changes in temperature and water vapor, using data from the Solar Occultation for Ice Experiment (SOFIE) instrument on the Aeronomy of Ice in the Mesosphere (AIM) satellite. They applied these results to the long-term time series of IWC from SBUV (1979–2013) and showed that the observed Northern Hemisphere (NH) trend in IWC is consistent with a temperature trend of $-0.3(\pm 0.2)$ K/decade. The accompanying water vapor trend was $+0.05(\pm 0.03)$ ppmv/decade. The temperature trend was somewhat smaller in the Southern Hemisphere (SH), while the water vapor trend was also smaller and not statistically significant. The MIMAS model simulations (Berger & Lübken, 2015) are consistent with these empirical results, lending strong support to the reality of the trends. Their results showed that long-term changes in stratospheric ozone and cooling due to increasing CO₂ lead to a shrinking of the atmosphere and consequent cooling of the mesopause region. These latter results are directly relevant to the present study, since neither of these studies explicitly considered possible trends from space traffic as a forcing mechanism.

Stevens et al. (2002) demonstrated that the water-rich exhaust plume from the National Aeronautics and Space Administration (NASA) Space Shuttle could be transported to polar latitudes in a few days after launch and produce a significant enhancement in OH signal, a dissociation product of water vapor. Stevens et al. (2003) looked at a subsequent Shuttle launch during the NH PMC season and identified a distinct postlaunch enhancement in PMC occurrence frequency and calculated IWC, using National Oceanic and Atmospheric Administration (NOAA)-14 SBUV/2 PMC data. Shuttle-related signals in PMC data have since been reported for five additional launches during the period 1999–2011 (Collins et al., 2009; Kelley et al., 2010, 2009; Stevens et al., 2005; Stevens et al., 2005; Stevens et al., 2012). Table 1 briefly summarizes these published results.

The magnitude of the Shuttle-related PMC signal reported by Stevens et al. (2003; 22% of the season total ice mass at 65–70°N) led to the suggestion that Shuttle launch plume effects, although infrequent, could represent an important component of the long-term trends in PMC IWC derived from the seasonally averaged SBUV data set. This concept has continued to be advanced in subsequent papers (e.g., Siskind et al., 2013; Stevens et al., 2012; Stevens,

Englert, et al., 2005; Stevens, Meier, et al., 2005), despite the small number of launches and limited geographic regions for which PMC effects were claimed.

We do not consider the occasional cloud sightings that occur directly in the plumes of rocket launches (e.g., Gadsden & Schröder, 1989; Cable News Network, 2009) in this work. These events are generally (but not always) related to much smaller rockets than the Space Shuttle, with launch vehicles that are propelled by solid fuel (and thus do not produce a water-enriched exhaust plume). Most likely, such clouds are a result of direct injection of nonvolatile particles, since they often occur over nonpolar sites where the ambient air is normally well above ice sublimation temperature (Benech & Dessens, 1974; Meinel et al., 1963). These occurrences have been observed throughout the space flight era.

In this work, we present a comprehensive analysis of the SBUV PMC database to evaluate the potential impact of rocket launch plumes on PMC IWC. We focus on Shuttle launches as the largest individual events to maximize the possibility of demonstrating an effect in SBUV data. Table 2 lists all Shuttle launches that occurred during our nominal PMC season (30 days before solstice [days since solstice, DSS = -30] to 70 days after solstice [DSS = +70]), as well as all SBUV instruments that were operating during each postlaunch period. We note that most Shuttle launches were observed by multiple SBUV instruments concurrently. The superposed epoch analysis (SEA) method, which temporally aligns all post-launch data to enhance any regular response that may be present, is used to establish a framework for consistent intercomparison of results from all Shuttle launches during both NH and SH PMC seasons between 1982 and 2011. We also examine the NH 2011 season in more detail to evaluate possible effects from non-Shuttle space traffic.

2. SBUV PMC IWC Data and Total Ice Mass

The detection and characterization of PMCs in SBUV measurements was first presented by Thomas et al. (1991) and has been refined in subsequent publications (DeLand et al., 2003, 2006, 2007; DeLand & Thomas, 2015; Shettle et al., 2009). We note that SBUV measurements have a relatively coarse spatial resolution ($\sim 150 \text{ km} \times 150 \text{ km}$ at PMC altitudes) and that the nadir-viewing SBUV observations only detect the brightest fraction (approximately 10–15%) of the overall PMC population. We use the term *ascending node* to identify the portion of the orbit when the SBUV instrument is traveling northward and *descending node* for the portion of the orbit when it is traveling southward.

We use IWC as our initial parameter to evaluate possible Shuttle plume effects in SBUV PMC data. Other studies have examined changes in frequency of occurrence following a Shuttle launch, although in some cases (e.g., Siskind et al., 2013) the high IWC clouds most easily observed by SBUV instruments are a key element of their analysis. We derive IWC from cloud albedo by using the method described by DeLand and Thomas (2015) and Thomas et al. (2019) to represent the strength of each detected PMC. This approach yields a minimum observable PMC column mass density of approximately 40 gm/km^2 , which dictated the IWC threshold result chosen by Hervig and Stevens (2014) using a more sensitive technique. DeLand and Thomas (2015) derived a diurnal local time variation in order to combine the absolute IWC data from multiple SBUV instruments during any given

season for trend analysis. Since we are studying relative IWC variations within each season in this work (as described below), we do not apply their function here. The total ice mass for each PMC is then calculated by multiplying the IWC value (which is proportional to column mass density) by the size of the SBUV field of view (area viewed) at 80 km. We initially calculate the total ice mass by summing individual values for all clouds over the latitude range 65–75° to correspond to published reports of Shuttle plume effects as listed in Table 1. However, we do evaluate other latitude ranges as well. Since SBUV instruments collect both ascending node and descending node data (separated by 7–8 hr in local time) during summer months at high latitudes, we analyze these measurements separately for each Shuttle launch.

SBUV PMC daily total ice mass (M_{tot}) shows significant variability throughout a typical PMC season, as well as on day-to-day time scales. This variability represents the time-varying PMC evolution (i.e., growth and decay) within the selected latitude range, as well as transport into or out of this range. Two SBUV instruments observing during the same season can also derive different short-term ice mass behavior because of changes in sampling location and conditions within a latitude range. In order to provide a basis for comparison of possible Shuttle effects, we normalized the time series of M_{tot} for each combination of instrument, year, latitude band, and orbit node to the maximum daily value observed during that season. Figure 1 shows an example of the normalized total ice (M_{norm}) data from NOAA-11 SBUV/2 at 65–75°N for the NH 2000 PMC season, in which no Shuttle launch occurred. We note that the date of the maximum total ice value can vary significantly from year to year.

2.1. Analysis for Launch Plume Effects

In order to construct a reference baseline, we identified all seasons for which no Shuttle launch occurred. Since some such years have multiple active SBUV instruments, there are a total of 23 such seasons available in both NH and SH data. We then averaged together the M_{norm} time series for all seasons in a given latitude band and orbit node. Figure 2 shows a sample of this result for 65–75°N ascending node data. The daily standard deviation is approximately 0.25–0.30 normalized units during the core of the season (DSS = 0–30), decreasing at earlier and later times.

While the seasonal variation of the averaged non-Shuttle M_{norm} data is reasonably smooth, the remaining day-to-day structure could nevertheless introduce unintended behavior if used directly as a reference data set. To define a smooth “background reference,” we used a fit to the averaged data, using a Gaussian function of the following form:

$$f(x) = A_0 \exp(-z^2/2) + A_3 \quad (1)$$

$$z = (x - A_1)/A_2 \quad (2)$$

where A_0 is the height, A_1 is the center, A_2 is the width (standard deviation), and A_3 is a constant. The dash-dotted line in Figure 2 shows the Gaussian fit overplotted with the M_{norm} data at 65–75°N.

Figure 3a shows the Gaussian fit results for NH cases in three latitude bands (55–65°, 65–75°, and 75–82°) and both orbit nodes. We did not create a 55–65° descending node fit because many seasons do not have such measurements. Figure 3b shows the corresponding fits for SH cases. Some observations can be made regarding the characteristics of these fits.

1. Ascending node and descending node fits are very similar for all latitude bands.
2. The largest peak values are found at higher latitudes, indicating that the brightest PMCs (with largest ice mass) are more likely to be found near the center of the season for those latitudes.
3. SH peak values are lower than the corresponding NH fit for the same latitude band, and the date of the fit center is approximately 5 days earlier.
4. The earlier peak in the SH season can be compared to the results of Benze et al. (2012), who find a comparable starting date in each hemisphere at 75–82° latitude: SH onset = $-12(\pm 12)$ DSS and NH onset = $-15(\pm 6)$ DSS.

Table 3 lists the Gaussian fit parameters for each case (note that a three-term fit was used for the 55–65° latitude band).

These fits were then used to calculate anomaly values ($M_{\text{norm}} - M_{\text{fit}}$) for each season containing a Shuttle launch. Figure 4 shows an example for NOAA-14 SBUV/2 data during the NH 1999 season at 65–75°N. Figure 4a shows the M_{norm} data and reference fit (M_{fit}), with the dates of the STS-96 and STS-93 launches identified. Figure 4b shows the anomaly values, where the minimum value of M_{fit} is set to 0 at the start and end of the season. Note that each season will have at least one anomaly value of +0.4 or more, given the maximum background values shown in Figure 3 and the requirement that $M_{\text{norm}} = 1.0$ on the normalization date. Since we are using a previously defined background function rather than a fit to each season, the cumulative anomaly for any season is not required to equal 0.0. We note also that the anomaly signature for a specific amount of total ice (e.g., 20 t) will depend on the activity level of that season and the timing of the event within the season.

Figure 4, which uses descending node measurements, shows an increase in M_{norm} beginning approximately 3 days after the launch of STS-96 ($L + 3$ days) and lasting for several days. Figure 5 shows the NOAA-14 ascending node data for the same latitude band and season. These data do not show any significant increase in M_{norm} following either Shuttle launch. This difference between ascending and descending node results from the same satellite is observed in many other cases, even though both results are based on zonal average data. Since these measurements sample significantly different local times, there will be diurnal temperature differences between them due to tidal variations (Stevens et al., 2017). This suggests that Shuttle plume effects on PMCs are more likely to be a geographically localized occurrence that may be seen by some SBUV measurements, but not others, because of the separation between satellite orbit tracks. Similar anomaly plots for every SBUV season are available online.

We have also examined the SBUV PMC data record for exhaust plume effects in the latitude range 55–65°N, which is closer to the Shuttle launch site. SBUV PMC detections are typically more difficult in this region due to higher sky background albedo, lower solar

zenith angle, and weaker PMCs (see also the Cloud Imaging and Particle Size [CIPS] sensitivity analysis of Lumpe et al., 2013). The day-to-day total ice variability at 55–65°N is quite large throughout the PMC season, which leads to the relatively low maximum value for the M_{norm} Gaussian fits shown in Figure 3. The low PMC occurrence frequency in this latitude range means that a noticeable step in total ice (as described further in section 2.3) may only represent the addition of one or two bright clouds. It is very difficult to confidently claim that such a small number of clouds has a specific origin. We therefore do not present further quantitative results for the 55–65° latitude region in this paper.

2.2. Seasonal Average Results

The transport time of a Shuttle plume from its injection location at 31–37°N and 100–115 km to polar regions has been reported to be 1 to 3 days for launches with observed PMC effects (e.g., Stevens et al., 2003, 2012), while the effective residence time has been reported to be up to 6 days based on Lyman alpha images from the Global Ultraviolet Imager (GUVI) on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite (Meier et al., 2011). We therefore examine the ice mass anomaly values for 20 days following each Shuttle launch to evaluate both the potential PMC response period and a nominal “control” period when no persistent effects would be expected.

The SEA approach (Chree, 1912; Robert et al., 2010; Thomas et al., 2015; von Savigny et al., 2017) is used to combine and average these anomaly data to determine the nature of any systematic postlaunch behavior in PMC ice mass. The presence of multiple SBUV instruments in many seasons gives us a total of 56 Shuttle launch events for NH PMC seasons and 50 events for SH PMC seasons. For each event, we extract a 20-day time series of anomaly values beginning with the launch date and then normalize to that date to help identify postlaunch changes. The normalized time series for all events are then averaged to create a postlaunch SEA response data set for a selected latitude band and orbit node. The typical standard deviation of such a data set is approximately 0.20–0.25 normalized units, which is similar to the variability shown in Figure 2 for normalized IWC values in non-Shuttle seasons.

We also use the SEA method in a Monte Carlo approach to determine a typical level of natural variability for this analysis. For each of the 23 non-Shuttle PMC seasons described in section 2.1, a randomly chosen “launch” date is used to select a 20-day anomaly time series. These time series are averaged together to create a SEA data set, and this process is repeated 50 times to correspond to the approximate number of Shuttle events. Averaging these data sets together then gives a daily standard deviation time series that represents the 1σ “noise” level.

Figure 6 shows the SEA results for all NH latitude bands. No peak exceeds the 95% significance level indicated by the standard deviation of the non-Shuttle data. For comparison, the individual non-Shuttle seasons do show some peaks above the $+2\sigma$ noise level but only at the 5% or less frequency expected from statistics.

Figure 7 shows a similar null result for SH latitude bands. If there is a significant Shuttle plume effect, we would expect a cluster of larger anomalies peaking at the mean meridional

transport time. We conclude that there is no characteristic or persistent time scale for which a significant fraction of Shuttle plumes are transported to polar regions to create observable effects in SBUV PMC data.

While separating SBUV data into ascending and descending node observations yields a unique local time for each satellite and PMC season, a combined calculation such as that in Figure 6 nevertheless results in a combination of multiple local times for each latitude band and node over the full SBUV record, due to the orbit drift of the NOAA polar orbiter spacecraft (see Figure 2 in DeLand et al., 2007). As a result, any signature of a local time dependence in the transport of Shuttle launch plumes (e.g., Siskind et al., 2013; Stevens et al., 2014) would be weakened in this analysis. We discuss this issue further in section 2.4.

2.3. Individual Shuttle Launches

We next examined our PMC database for evidence of total ice effects following any Shuttle launch. Proposed Shuttle effects in PMC total ice could last for multiple days following the arrival of the rocket exhaust plume at high latitudes. We therefore create a cumulative anomaly time series for each event by summing the post-launch M_{norm} anomaly values at each date from 1 day after launch ($L + 1$) to 10 days after launch ($L + 10$). Figure 8 shows examples of these results for NOAA-11 and NOAA-14 descending node and ascending node data at 65–75°N following the STS-93 launch in July 1999. Consistent with the M_{norm} time series data shown in Figures 4 and 5, there is a distinct step in the NOAA-14 descending node cumulative time series at $L + 3$ days, while the concurrent NOAA-14 ascending node data do not show any increase. NOAA-11 time series do not show a significant postlaunch step in either descending or ascending node data. Similar plots are available online for every Shuttle launch during a PMC season.

Assessing whether a given change in M_{norm} actually represents an infusion event of water vapor from a rocket plume is difficult to establish quantitatively. Based on inspection of numerous cumulative anomaly plots such as Figure 8, we chose a day-to-day step of +0.5 units as a nominal threshold for potentially significant events. Table 4 lists all of the cases where this threshold was exceeded between $L + 1$ and $L + 10$ days following a Shuttle launch. Figure 9 shows the distribution of these events within the 10-day postlaunch window. There is no preferred time lag, consistent with the results of the SEA study. We first consider the published cases listed in Table 1. For STS-93 and STS-107, where the published evidence included SBUV data, there are multiple steps identified. STS-135 has a step at $L + 7$ days, whereas the patches of bright PMCs in CIPS instrument data reported by Stevens et al. (2012) occurred at $L + 1$ days. Three other cases (STS-95, STS-114, and STS-118) cite geographically local evidence for PMC effects but do not show any steps in the cumulative anomaly analysis. This suggests that a local increase in PMC brightness will generally be diluted when zonal mean averages are considered.

The number of identified events in each band of latitude ranges from 15 to 23 out of 50+ launch events. The analysis of some events (e.g., Stevens et al., 2012; Stevens et al., 2014; Stevens, Meier, et al., 2005) includes supporting information that illustrates the meridional transport of the Shuttle plume. For many others, though, there is no additional information available to evaluate possible exhaust plume transport for these events. For comparison, the

23 non-Shuttle PMC seasons available in each hemisphere have between 51 and 60 total steps of +0.5 units or greater, depending on the choice of latitude band. Figure 10 shows the distribution of these results as a function of step size for each latitude band. The requirement of $M_{\text{norm}} = 1.0$ for normalization can introduce a large step in the anomaly time series, as noted in section 2.1, so the totals listed for non-Shuttle seasons exclude dates where a large step coincides with $M_{\text{norm}} = 1.0$. The general shape of the distribution in each band is similar for post-Shuttle and non-Shuttle cases, although the number of non-Shuttle events is greater. We conclude that the magnitude of the potentially significant post-Shuttle launch events is thus consistent with normal geophysical variability in PMC total ice mass.

We have also evaluated the magnitude of post-Shuttle launch events on changes in absolute total ice mass. For each event listed in Table 4, we take the cumulative anomaly value 5 days after the step date, subtract the cumulative anomaly value on the day prior to the step, and then convert this difference to total ice mass using the normalization value for that season. For example, the NOAA-14 65–75°N descending node time series shown in Figure 8a has a total change of 1.54 units during the 5 days that include the step that occurred 5 days after launch (DsL = 5). The maximum daily total ice value for this season was 51.9 t, so the corresponding change in total ice is calculated to be 79.7 t. These values, and their relative contribution to the corresponding season total, are also listed in Table 4. The 5-day changes in total ice mass are almost all less than 10% of the season total, although some cases are larger. We suggest that these results should probably be considered as a maximum contribution from Shuttle plume effects, since other processes that affect PMCs (e.g., transport and natural formation/destruction) are happening concurrently. It should be noted that Siskind et al. (2013), using a 30-day average of SOFIE IWC that encompassed the STS-135 launch, estimated an IWC increase of 47% over the average value predicted by analyzing stratospheric temperature deviations. Further investigation of such differences is a topic for future research.

We note also that our PMC trend analysis method combines ascending node and descending node data from each instrument for each season, as well as multiple instruments when available. The total ice effect from any launch that only appears once in Table 4 will therefore be diluted in the trend analysis. Some Shuttle launches not listed in Table 1 do show anomaly steps that were detected by multiple instruments at approximately the same time (e.g., STS-61C, STS-32, STS-44, and STS-78). These isolated cases do not represent a contribution that would systematically affect long-term trends in PMC ice mass. Figure 11 shows the time series of all fractional total ice mass changes (last column in Table 4) for both NH and SH observations. A linear regression fit to these data gives a slope that is not statistically different from a zero trend in each hemisphere.

2.4. Role of Local Time on Plume Transport

Siskind et al. (2003) described the observation of Shuttle exhaust plumes using radiance measurements from the Sounding of the Atmosphere with Broadband Emission Radiometry (SABER) instrument on the TIMED satellite. They suggested that differences in meridional location of these plumes were controlled by diurnal variations in the direction and speed of the meridional wind, based on results from the Upper Atmospheric Research Satellite

(UARS) High Resolution Doppler Interferometer (HRDI) instrument. The most significant northward transport occurred at 10–13 hr LT (= 1400–1700 UT at Cape Canaveral during the NH PMC season), while the largest southward velocities corresponded to 6–8 hr and 16–18 hr LT (= 1100–1300 and 2100–2300 UT during the SH PMC season). For the Shuttle launches during PMC seasons listed in Table 2, eight launches took place within the best window for northward plume transport, while five launches took place during the best window for southward transport. Three such launches (STS-4, STS-50, and STS-78) had multiple SBUV PMC total ice anomaly steps that exceeded the +0.5 unit threshold for NH cases, while two launches (STS-61C and STS-32) had multiple steps for SH cases. So the local time of Shuttle launch is not a consistent predictor of subsequent PMC effects.

Meier et al. (2011) extended the analysis of Shuttle plume transport using far-ultraviolet (FUV) measurements from the GUVI instrument on TIMED. Their results for eight Shuttle launches between 2002 and 2007 showed significant variability in transport speed for both meridional and zonal components. Stevens et al. (2014) expanded the analysis of SABER data to consider 27 Shuttle launches during all seasons between 2002 and 2011 and also included observations from the Sub-Millimeter Radiometer (SMR) instrument on the Odin satellite. They found that launches between 13 and 22 hr LT were most likely to experience southward advection of the plume, with a wide range of initial meridional speeds indicated for observations between 6 and 18 hr after launch. Other launch times were more likely to experience northward transport. However, they also show multiple pieces of evidence for northward transport of the STS-118 launch plume in August 2007, despite a launch time (2236 UT = 1736 LT) that would be predicted to be favorable to southward transport. They conclude that fully characterizing the postlaunch transport of Shuttle plumes (and presumably other rocket exhaust plumes as well) requires case-by-case meteorological information. This result clearly limits the ability to define any systematic contribution of such exhaust plumes to long-term trends in PMC behavior.

2.5. All Space Traffic During NH 2011 Season

While the Space Shuttle provides a particularly strong example of a water-rich rocket exhaust plume, there are many other rocket launches that represent potential contributions to PMC behavior. We focus on the NH 2011 season to make use of the valuable compilation created by Stevens et al. (2012). The complete list of launches given in their Table 3 includes dates with multiple launches that cannot be separated with the SEA method, as well as numerous cases with 1-day separation that would be difficult to distinguish in our analysis in terms of postlaunch effects. We therefore selected a reduced set of launches with at least 3 days of separation, as listed in Table 5, for further evaluation. Three SBUV/2 instruments (NOAA-17, NOAA-18, and NOAA-19) were operational during this season.

Figure 12 shows the total ice mass time series and anomaly time series for NOAA-18 ascending node data at 65–75°N for the NH 2011 season. All of the launches listed in Table 5 are identified, using the same method as in Figure 4. We performed the same analysis for step changes in normalized cumulative anomaly as was done in section 2.3 for Shuttle launches. Table 6 lists the results of this analysis. Note that for some events (e.g., Long March 3A launched on 2011/207), the 5-day total ice calculation includes an additional

launch that occurs a few days later. As noted in section 2.3 for the analysis of Shuttle launches, it is difficult to know how to apportion any change in total ice between possible plume effects and natural variability.

Since some of the launch sites listed in Table 4 are located closer to the PMC detection region than is the Shuttle launch site, we can examine whether specific cloud detections might be associated with an individual launch. Likely requirements for such an occurrence would be a relatively short time after launch (to maintain exhaust plume integrity), spatial coherence of the detections, and relatively bright clouds. Figure 13 shows a map of all PMC detections and brightness for NOAA-19 data on 2011 day 188 (7 July), 1 day after a Long March 2C launch. There is a cluster of brighter PMCs (yellow and orange), representing four consecutive measurements, located at approximately 65–70°N and –100°E. These measurements were made at 9.5 hr UT on day 188. Similar bright clouds are observed in concurrent NOAA-18 data at approximately the same location. Transporting the Long March 2C launch plume to this location would require an average transport velocity of ~70–80 m/s over 29 hr following a direct path through polar regions. This velocity is at the upper edge of results suggested in previous work (e.g., Meier et al., 2011).

The evidence for PMC effects due to rocket exhaust plumes from this map is circumstantial and would require supporting meteorological information to be more convincing. However, we note that this Long March 2C launch occurred at 41.3°N latitude, which reduces the exhaust plume transport time and distance required to reach typical PMC regions compared with a Shuttle launch. The launch also occurred at 11.2 hr LT, which avoids the range of times for predominantly southward postlaunch transport (~13–22 hr LT) proposed by Stevens et al. (2014). So the combination of higher injection latitude and appropriate launch time may increase the possibility of observable PMC effects. A comprehensive evaluation of all launches during the SBUV PMC record is beyond the scope of this paper.

3. Summary and Conclusions

It is well established that long-term variations in PMC IWC are sensitive to upper mesospheric temperature and water vapor concentrations. We have investigated the suggestion that anthropogenic contributions to PMC ice mass, in the form of water-rich exhaust plumes from rockets such as the Space Shuttle, represent a significant component of observed long-term PMC behavior. The SBUV PMC data record includes 60 Shuttle launches during PMC seasons in both hemispheres between 1985 and 2011. We find no evidence for a systematic contribution to PMC IWC from Shuttle launches, although they may provide locally significant short-term effects. Increases above an empirically determined threshold for a single launch are often not registered equally in concurrent ascending node and descending node measurements by multiple active instruments, confirming the localized nature of any changes. Postlaunch changes in total ice mass for a single instrument/latitude/node combination typically do not exceed 5–7% of the season total for a 5-day period, and there is no direct way to ascertain what fraction of these changes might be due to launch plume effects. Our results support the assumption of Hervig et al. (2016) that space traffic increases do not affect the long-term record of PMC activity. Future work could consider the possible effects on the PMC record from the larger number

of smaller rocket launches, which would require evaluation of the supporting meteorological information needed to confidently attribute PMC changes to a specific launch.

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References

- Benech B, & Dessens J (1974). Mid-latitude artificial noctilucent clouds initiated by high-altitude rockets. *Journal of Geophysical Research*, 79(9), 1299–1301. 10.1029/JC079i009p01299
- Benze S, Randall CE, Karlsson B, Harvey VL, DeLand MT, Thomas GE, & Shettle EP (2012). On the onset of polar mesospheric cloud seasons as observed by SBUV. *Journal of Geophysical Research*, 117, D07104. 10.1029/2011JD017350
- Berger U, & Lübken F-J (2015). Trends in mesospheric ice layers in the Northern Hemisphere during 1961–2013. *Journal of Geophysical Research: Atmospheres*, 120, 11,277–11,298. 10.1002/2015JD023355
- Cable News Network (2009). Rocket launch prompts calls of strange lights in sky, 2009-09-20. Retrieved from <http://www.cnn.com/2009/US/09/20/strange.lights/index.html>
- Chree C (1912). Some phenomena of sunspots and of terrestrial magnetism at Kew Observatory. *Philosophical Transactions Royal Society, Series A*, 212, 75–116.
- Collins RL, Taylor MJ, Nielsen K, Mizutani K, Murayama Y, Sakanoi K, & DeLand MT (2009). Noctilucent cloud in the Western Arctic in 2005: Simultaneous lidar and camera observations and analysis. *Journal of Atmospheric and Solar-Terrestrial Physics*, 71(3-4), 446–452. 10.1016/j.jastp.2008.09.044
- DeLand MT, Shettle EP, Thomas GE, & Olivero JJ (2003). Solar backscattered ultraviolet (SBUV) observations of polar mesospheric clouds (PMCs) over two solar cycles. *Journal of Geophysical Research*, 108(D8), 8445. 10.1029/2002JD002398
- DeLand MT, Shettle EP, Thomas GE, & Olivero JJ (2006). A quarter-century of satellite PMC observations. *Journal of Atmospheric and Solar-Terrestrial Physics*, 68(1), 9–29. 10.1016/j.jastp.2005.08.003
- DeLand MT, Shettle EP, Thomas GE, & Olivero JJ (2007). Latitude-dependent long-term variations in polar mesospheric clouds from SBUV version 3 PMC data. *Journal of Geophysical Research*, 112, D10315. 10.1029/2006JD007857
- DeLand MT, & Thomas GE (2015). Updated PMC trends derived from SBUV data. *Journal of Geophysical Research: Atmospheres*, 120, 2140–2166. 10.1002/2014JD022253
- Fiedler J, Baumgarten G, Berger U, & Lübken F-J (2017). Long-term variations of noctilucent clouds at ALOMAR. *Journal of Atmospheric and Solar-Terrestrial Physics*, 162, 79–89. 10.1016/j.jastp.2016.08.006
- Gadsden M, & Schröder W (1989). Noctilucent clouds (pp. 105–106). Berlin: Springer-Verlag 10.1007/978-3-642-48626-5
- Hervig ME, Berger U, & Siskind DE (2016). Decadal variability in PMCs and implications for changing temperature and water vapor in the upper mesosphere. *Journal of Geophysical Research: Atmospheres*, 121, 2383–2392. 10.1002/2015JD024439
- Hervig ME, & Stevens MH (2014). Interpreting the 35-year SBUV PMC record with SOFIE observations. *Journal of Geophysical Research: Atmospheres*, 119, 12,689–12,705. 10.1002/2014JD021923

- Hervig ME, Stevens MH, Gordley LL, Deaver LE, Russell JM III, & Bailey SM (2009). Relationships between polar mesospheric clouds, temperature, and water vapor from Solar Occultation for Ice Experiment (SOFIE) observations. *Journal of Geophysical Research*, 114, D20203. 10.1029/2009JD012302
- Kelley MC, Nicolls MJ, Varney RH, Collins RL, Doe R, Plane JMC, et al. (2010). Radar, lidar, and optical observations in the polar summer mesosphere shortly after a space shuttle launch. *Journal of Geophysical Research*, 115, A05304. 10.1029/2009JA014938
- Kelley MC, Seyler CE, & Larsen MF (2009). Two-dimensional turbulence, space shuttle plume transport in the thermosphere, and a possible relation to the Great Siberian Impact Event. *Geophysical Research Letters*, 36, L14103. 10.1029/2009GL038362
- Lübken F-J, Berger U, & Baumgarten G (2009). Stratospheric and solar cycle effects on long-term variability of mesospheric ice clouds. *Journal of Geophysical Research*, 114, D00I06. 10.1029/2009JD012377
- Lübken F-J, Berger U, & Baumgarten G (2018). On the anthropogenic impact on long-term evolution of noctilucent clouds. *Geophysical Research Letters*, 45, 6681–6689. 10.1029/2018GL077719
- Lumpe JD, Bailey SM, Carstens JN, Randall CE, Rusch DW, Thomas GE, et al. (2013). Retrieval of polar mesospheric cloud properties from CIPS: Algorithm description, error analysis and cloud detection sensitivity. *Journal of Atmospheric and Solar-Terrestrial Physics*, 104, 167–196. 10.1016/j.jastp.2013.06.007
- Meier RR, Stevens MH, Plane JMC, Emmert JT, Crowley G, Azeem I, et al. (2011). A study of space shuttle plumes in the lower thermosphere. *Journal of Geophysical Research*, 116, A12322. 10.1029/2011JA016987
- Meinel AB, Middlehurst B, & Whitaker E (1963). Low-latitude noctilucent cloud of 15 June 1963. *Science*, 141(3586), 1176–1178. 10.1126/science.141.3586.1176 [PubMed: 17751795]
- Robert CE, von Savigny C, Rahpoe N, Bovensmann H, Burrows JP, & DeLand MT (2010). Evidence of a 27-day signature in noctilucent cloud occurrence frequency. *Journal of Geophysical Research*, 115, D00I12. 10.1029/2009JD012359
- Shettle EP, DeLand MT, Thomas GE, & Olivero JJ (2009). Long term variations in the frequency of polar mesospheric clouds in the Northern Hemisphere from SBUV. *Geophysical Research Letters*, 36, L02803. 10.1029/2008GL036048
- Siskind DE, Stevens MH, Emmert JT, Drob DP, Kochenash AJ, Russell JM III, et al. (2003). Signatures of shuttle and rocket exhaust plumes in TIMED/SABER radiance data. *Geophysical Research Letters*, 30(15), 1819. 10.1029/2003GL017627
- Siskind DE, Stevens MH, Hervig ME, & Randall CE (2013). Recent observations of high mass density polar mesospheric clouds: A link to space traffic? *Geophysical Research Letters*, 40, 2813–2817. 10.1002/grl.50540
- Stevens MH, Englert CR, DeLand MT, & Hervig M (2005). The polar mesospheric cloud mass in the Arctic summer. *Journal of Geophysical Research*, 110, A02306. 10.1029/2004JA010566
- Stevens MH, Englert CR, & Gumbel J (2002). OH observations of space shuttle exhaust. *Geophysical Research Letters*, 29(10), 1378. 10.1029/2002GL015079
- Stevens MH, Gumbel J, Englert CR, Grossmann KU, Rapp M, & Hartogh P (2003). Polar mesospheric clouds formed from space shuttle exhaust. *Geophysical Research Letters*, 30(10), 1546. 10.1029/2003GL017249
- Stevens MH, Lieberman RS, Siskind DE, McCormack JP, Hervig ME, & Englert CR (2017). Periodicities of polar mesospheric clouds inferred from a meteorological analysis and forecast system. *Journal of Geophysical Research: Atmospheres*, 122, 4508–4527. 10.1002/2016JD025349
- Stevens MH, Lossow S, Fiedler J, Baumgarten G, Lübken F-J, Hallgren K, et al. (2012). Bright polar mesospheric clouds formed by main engine exhaust from the space shuttle's final launch. *Journal of Geophysical Research*, 117, D19206. 10.1029/2012JD017638
- Stevens MH, Lossow S, Siskind DE, Meier RR, Randall CE, Russell JM III, et al. (2014). Space shuttle exhaust plumes in the lower thermosphere: Advective transport and diffusive spreading. *Journal of Atmospheric and Solar-Terrestrial Physics*, 108, 50–60. 10.1016/j.jastp.2013.12.004

- Stevens MH, Meier RR, Chu X, DeLand MT, & Plane JMC (2005). Antarctic mesospheric clouds formed from space shuttle exhaust. *Geophysical Research Letters*, 32, L13810. 10.1029/2005GL023054
- Thomas GE (1996). Global change in the mesosphere-lower thermosphere region: Has it already arrived? *Journal of Atmospheric and Solar-Terrestrial Physics*, 58(14), 1629–1656. 10.1016/021-9169(96)00008-6
- Thomas GE, Lumpe J, Bardeen C, & Randall CE (2019). Albedo-ice regression method for determining ice water content of polar mesospheric clouds using ultraviolet observations from space. *Atmospheric Measurement Techniques*, 12, 1755–1766. 10.5194/amt-12-1755-2019
- Thomas GE, McPeters RD, & Jensen EJ (1991). Satellite observations of polar mesospheric clouds by the Solar Backscattered Ultraviolet radiometer: Evidence of a solar cycle dependence. *Journal of Geophysical Research*, 96(D1), 927–939. 10.1029/90JD02312
- Thomas GE, Olivero JJ, Jensen EJ, Schröder W, & Toon OB (1989). Relation between increasing methane and the presence of ice clouds at the mesopause. *Nature*, 338(6215), 490–492. 10.1038/338490a0
- Thomas GE, Thurairajah B, Hervig ME, von Savigny C, & Snow M (2015). Solar-induced 27-day variations of mesospheric temperature and water vapor from the AIM SOFIE experiment: Drivers of polar mesospheric cloud variability. *Journal of Atmospheric and Solar-Terrestrial Physics*, 134, 56–68. 10.1016/j.jastp.2015.09.015
- von Savigny C, DeLand MT, & Schwartz MJ (2017). First identification of lunar tides in satellite observations of noctilucent clouds. *Journal of Atmospheric and Solar-Terrestrial Physics*, 162, 116–121. 10.1016/j.jastp.2016.07.002

Key Points:

- Evaluation of SBUV PMC database for effects from Shuttle exhaust plumes is presented
- No evidence for contribution to long-term trends in PMC behavior is found
- Possible short-term PMC effects from other launches require further support to confirm

Figure 1.

Daily zonal mean values of PMC total ice, normalized to the maximum single-day value observed by NOAA-11 SBUV/2 for ascending node measurements at 65–75°N during the NH 2000 PMC season.

Figure 2.

Averaged normalized PMC total ice for all seasons with no Shuttle launch. Ascending node measurements at 65–75°N are shown. Dotted line = $\pm 1\sigma$ daily variation. Dash-dotted line = Gaussian fit to the averaged data.

Figure 3.

(a) Gaussian fits to Northern Hemisphere averaged normalized total ice mass data for non-Shuttle seasons. Green = 55–65°N; red = 65–75°N; blue = 75–82°N. Solid = ascending node; dotted = descending node. (b) Gaussian fits to Southern Hemisphere averaged normalized total ice mass data for non-Shuttle seasons. Identifications are as in panel (a).

Figure 4.

(a) NOAA-14 descending node normalized total ice data (blue) at 65–75°N for the NH 1999 season. The Gaussian reference fit for this latitude band is also shown (green). The launch dates for STS-96 and STS-93 are marked (red). (b) The normalized total ice anomaly ($M_{\text{norm}} - M_{\text{fit}}$) for this season.

Figure 5.

(a) NOAA-14 ascending node normalized total ice data (blue) at 65–75°N for the NH 1999 season. Identifications are as in Figure 4. (b) The normalized total ice anomaly ($M_{\text{norm}} - M_{\text{fit}}$) for this season.

Figure 6.

Results of a superposed epoch analysis for Northern Hemisphere SBUV PMC data. (a) Solid = average normalized PMC total ice anomaly as a function of days since Shuttle launch for all SBUV ascending node measurements at 65–75°N. Dashed = 2 * standard deviation of Monte Carlo SEA analysis for non-Shuttle seasons, as described in the text. The dash-dotted line shows the zero anomaly level for reference. (b) SEA results for 65–75°N descending node measurements. Identifications are as in panel (a). (c) SEA results for 75–82°N ascending node measurements. Identifications are as in panel (a). (d) SEA results for 75–82°N descending node measurements. Identifications are as in panel (a).

Figure 7.
Results of a superposed epoch analysis for Southern Hemisphere SBUV PMC data.
Identifications are as in Figure 6.

Figure 8.

(a) Cumulative normalized total ice anomaly for descending node measurements at 65–75°N following the STS-93 launch. Blue = NOAA-11 data; green = NOAA-14 data. The triangle indicates a day-to-day step greater than +0.5 units. (b) Cumulative normalized total ice anomaly for ascending node measurements at 65–75°N following the STS-93 launch. Identifications are as in panel (a).

Figure 9. Distribution of possible post-Shuttle launch total ice anomaly events listed in Table 4 as a function of days since launch (DsL).

Figure 10.

Distribution of large total ice anomaly steps (>0.5 units) as a function of step size for post-Shuttle events (solid) and non-Shuttle season events (dashed). Dates with $M_{\text{norm}} = 1.0$ have been excluded, as described in the text. (a) Data for 65–75°N. (b) Data for 65–75°S. (c) Data for 75–82°N. (d) Data for 75–82°S.

Figure 11.

Time series of cumulative total ice increase following a postlaunch total ice anomaly step (expressed as fraction of season total) as a function of time, as listed in the last column of Table 4. Each latitude band is identified. The result of a linear regression fit to the combined data set in each hemisphere is also shown. (a) Northern Hemisphere. (b) Southern Hemisphere.

Figure 12.

(a) NOAA-18 ascending node normalized total ice data (blue) at 65–75°N for the NH 2011 season. The launch dates for all rocket launches listed in Table 4 are marked (red). (b) The normalized total ice anomaly ($M_{\text{norm}} - M_{\text{fit}}$) time series for this season.

NOAA-19 SBUV/2 PMC Detections for 2011 day 188

Figure 13.

Map of PMC detections for NOAA-19 SBUV/2 measurements on 2011 day 188 (7 July).

The location of the Long March 2C launch site is shown. The arrow points to a cluster of bright PMCs that could represent a launch plume signature.

Table 1

Published Observations of Shuttle Exhaust Plume Effects in PMC Observations

Shuttle flight	Launch date	Observational evidence	Reference
STS-85	7 August 1997	PMC detection by MAHRSI and CRISTA at 65–72°N on 13–14 August.	Stevens et al. (2003)
STS-93	23 July 1999	Eight-day average of NOAA-14 descending node data between 65°N and 75°N on 23–31 July yields 22% of season total in PMC ice mass.	Stevens, Englert, et al. (2005)
STS-107	16 January 2003	PMC enhancement in SBUV data at 65–79°S on 18–28 January.	Stevens, Meier, et al. (2005)
STS-114	26 July 2005	Average of NOAA-16 ascending node and NOAA-17 descending node data gives 10–20% of season total ice mass due to Shuttle. Lidar and visual NLC observations at 65°N on 9–10 August. NOAA-18 PMC frequency peak with spike on 10 August.	Collins et al. (2009)
STS-118	8 August 2007	Visual NLC and lidar Fe layer at 65°N on 11 August. CIPS detection of bright PMCs at 75°–85°N on 9 August.	Kelley et al. (2009) Stevens et al. (2014)
STS-135	8 July 2011	Bright PMCs in CIPS data (patches) at 71°N on 9 July.	Stevens et al. (2012)

Note. PMC = polar mesospheric cloud; MAHRSI = Middle Atmosphere High Resolution Spectrograph Investigation; CRISTA = Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere; NOAA = National Oceanic and Atmospheric Administration; SBUV = Solar Backscatter Ultraviolet; NLC = noctilucent cloud; CIPS = Cloud Imaging and Particle Size.

Table 2

Shuttle Launches Within PMC Season During SBUV Data Record

Shuttle flight	Launch date	DSS	Launch time (UT)	SBUV instruments
STS-4	27 Jun 1982	6	1500	7
STS-7	18 Jun 1983	−3	1133	7
STS-9	28 Nov 1983	−23	1600	7
STS-41B	3 Feb 1984	44	1300	7
STS-51G	17 Jun 1985	−4	1133	7, 9
STS-51F	29 Jul 1985	38	2100	7, 9
STS-61B	27 Nov 1985	−24	0029	7, 9
STS-61C	12 Jan 1986	22	1155	7, 9
STS-27	2 Dec 1988	−18	1430	9, 11
STS-28	8 Aug 1989	48	1237	9, 11
STS-33	23 Nov 1989	−28	0023	9, 11
STS-32	9 Jan 1990	19	1235	9, 11
STS-35	2 Dec 1990	−19	0649	11
STS-40	5 Jun 1991	−16	1324	11
STS-43	2 Aug 1991	42	1502	11
STS-44	24 Nov 1991	−27	2344	9, 11
STS-42	22 Jan 1992	32	1452	9, 11
STS-50	25 Jun 1992	5	1612	9, 11
STS-46	31 Jul 1992	41	1356	9, 11
STS-53	2 Dec 1992	−19	1324	9, 11
STS-54	13 Jan 1993	23	1359	9, 11
STS-57	21 Jun 1993	0	1307	9, 11
STS-61	2 Dec 1993	−19	0927	9, 11
STS-60	3 Feb 1994	44	1210	9, 11
STS-65	8 Jul 1994	17	1643	9, 11
STS-63	3 Feb 1995	44	0522	9, 11
STS-71	27 Jun 1995	6	1932	9, 14
STS-70	13 Jul 1995	22	1341	9, 14
STS-72	11 Jan 1996	21	0941	9, 14
STS-75	22 Feb 1996	63	2018	9, 14
STS-78	20 Jun 1996	0	1449	9, 14
STS-82	11 Feb 1997	52	0855	9, 14
STS-94	1 Jul 1997	10	1802	9, 14
STS-85	7 Aug 1997	47	1441	9, 14
STS-89	23 Jan 1998	33	0248	11, 14
STS-91	2 Jun 1998	−19	2206	11, 14
STS-88	4 Dec 1998	−17	0835	11, 14
STS-96	27 May 1999	−25	1049	11, 14
STS-93	23 Jul 1999	32	0431	11, 14

Shuttle flight	Launch date	DSS	Launch time (UT)	SBUV instruments
STS-103	20 Dec 1999	−1	0050	11, 14
STS-99	11 Dec 2000	52	1743	11, 14
STS-97	1 Dec 2000	−19	0306	11, 14, 16
STS-98	7 Feb 2001	48	2313	11, 14, 16
STS-104	12 Jul 2001	22	0903	16
STS-105	10 Aug 2001	50	2110	16
STS-108	5 Dec 2001	−16	2219	16
STS-111	5 Jun 2002	−16	2123	16
STS-113	24 Nov 2002	−27	0049	16, 17
STS-107	16 Jan 2003	26	1539	16, 17
STS-114	26 Jul 2005	35	1439	14, 16, 17, 18
STS-121	4 Jul 2006	13	0033	14, 16, 17, 18
STS-116	10 Dec 2006	−11	0147	16, 17, 18
STS-117	8 Jun 2007	−13	2238	16, 17, 18
STS-118	8 Aug 2007	48	2236	16, 17, 18
STS-122	7 Feb 2008	48	1945	16, 17, 18
STS-124	11 May 2008	−20	2102	17
STS-127	15 Jul 2009	24	2203	17, 18, 19
STS-130	8 Feb 2010	49	0914	17, 18, 19
STS-133	24 Feb 2011	65	2153	16, 17, 18, 19
S STS-135	8 Jul 2011	17	1529	17, 18, 19

Note. PMC = polar mesospheric cloud; SBUV = Solar Backscatter Ultraviolet; DSS = days since solstice.

^a₇ = Nimbus-7 SBUV; 9, 11, 14, 16, 17, 18, 19 = NOAA-*x* SBUV/2.

Table 3

Gaussian Fit Parameters for Normalized Daily PMC Total Ice in Non-Shuttle Seasons

Latitude	Node	A_0	A_1	A_2	A_3
55–65°N	Ascending	0.191	15.536	20.745	—
65–75°N	Ascending	0.439	17.627	20.391	0.004
65–75°N	Descending	0.455	18.561	19.314	0.009
75–82°N	Ascending	0.581	19.751	21.076	−0.024
75–82°N	Descending	0.585	20.697	22.598	−0.028
55–65°S	Ascending	0.093	10.091	23.721	—
65–75°S	Ascending	0.256	12.207	15.348	−0.044
65–75°S	Descending	0.281	11.088	15.109	−0.035
75–82°S	Ascending	0.436	14.192	19.771	−0.056
75–82°S	Descending	0.451	15.437	19.974	−0.082

Note. A_0 = height of fit (normalized units); A_1 = center of fit (days since solstice); A_2 = width of fit (days); A_3 = constant (normalized units).

Table 4:

Potential Shuttle Plume Signatures in Cumulative Anomaly Plots

Latitude	Node	Flt	Year/day	Inst	DsL	Step [nrm]	Step [ice]	5-day ice	Season ice	Frac [pct]
65–75°N	asc	4	1982/178	7	3	0.53	13.4	26.9	395.5	6.80
65–75°N	asc	4	1982/178	7	7	0.52	13.3	20.2	395.5	5.11
65–75°N	asc	51G	1985/168	7	4	0.60	23.8	18.6	757.3	2.46
65–75°N	asc	51G	1985/168	7	10	0.67	26.4	63.6	757.3	8.40
65–75°N	asc	50	1992/177	11	10	0.61	10.1	6.9	195.5	3.53
65–75°N	asc	78	1996/172	14	4	0.69	31.8	56.0	904.3	6.19
65–75°N	asc	105	2001/222	16	2	0.51	11.0	19.4	405.3	4.79
65–75°N	asc	127	2009/196	18	6	0.66	29.5	16.4	920.5	1.78
65–75°N	desc	4	1982/178	7	8	0.58	12.0	–9.0	225.1	–4.00
65–75°N	desc	65	1994/189	9	2	0.58	36.9	9.4	1,216.0	0.77
65–75°N	desc	70	1995/194	14	8	0.65	26.1	29.8	691.6	4.31
65–75°N	desc	78	1996/172	9	5	0.68	39.0	92.5	1,101.5	8.40
65–75°N	desc	78	1996/172	14	5	0.68	51.7	65.3	1,308.6	4.99
65–75°N	desc	94	1997/182	14	4	0.53	35.7	35.8	1,669.9	2.14
65–75°N	desc	93	1999/204	14	5	0.75	38.9	79.7	755.7	10.55
65–75°N	desc	135	2011/189	18	7	0.60	35.9	70.6	1,260.6	5.60
65–75°S	asc	61C	1986/012	7	5	0.83	19.0	30.0	314.4	9.54
65–75°S	asc	32	1990/009	9	1	0.59	4.8	5.9	98.8	5.97
65–75°S	asc	32	1990/009	9	3	0.56	4.5	4.2	98.8	4.25
65–75°S	asc	32	1990/009	9	9	0.81	6.5	2.3	98.8	2.33
65–75°S	asc	44	1991/328	9	3	0.75	7.0	18.0	139.7	12.88
65–75°S	asc	44	1991/328	9	4	0.58	5.4	12.4	139.7	8.88
65–75°S	asc	44	1991/328	11	4	0.51	7.4	16.1	147.7	10.90
65–75°S	asc	44	1991/328	11	5	0.70	10.1	9.8	147.7	6.69
65–75°S	asc	72	1996/011	9	3	0.81	18.9	25.9	245.1	10.57
65–75°S	asc	89	1998/023	14	10	0.53	8.2	9.2	229.8	4.00
65–75°S	desc	61C	1986/012	7	3	0.81	19.7	45.3	262.1	17.28
65–75°S	desc	61C	1986/012	7	5	0.60	14.6	23.6	262.1	9.00

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Latitude	Node	Flt	Year/day	Inst	DsL	Step [nrm]	Step [icc]	5-day ice	Season ice	Frac [pet]
65–75°S	dsc	61C	1986/012	9	5	0.64	12.8	11.5	177.5	6.48
65–75°S	dsc	32	1990/009	9	1	0.75	13.1	11.5	261.4	4.40
65–75°S	dsc	44	1991/328	9	2	0.51	7.0	19.0	234.0	8.12
65–75°S	dsc	44	1991/328	9	5	0.72	9.9	21.0	234.0	8.97
65–75°S	dsc	44	1991/328	9	7	0.51	7.0	10.6	234.0	4.53
65–75°S	dsc	42	1992/022	9	3	0.56	7.7	3.8	234.0	1.62
65–75°S	dsc	61	1993/336	11	7	0.90	26.3	41.6	434.5	9.57
65–75°S	dsc	72	1996/011	9	9	0.86	31.5	90.3	566.5	15.94
65–75°S	dsc	107	2003/016	17	9	0.60	12.1	18.4	320.0	5.75
65–75°S	dsc	116	2006/344	16	10	0.77	20.3	21.3	289.5	7.36
75–82°N	asc	51G	1985/168	7	5	0.67	52.1	143.2	2,362.0	6.06
75–82°N	asc	50	1992/177	9	1	0.54	23.8	30.1	796.1	3.78
75–82°N	asc	50	1992/177	11	1	0.59	46.4	7.0	1,373.9	0.51
75–82°N	asc	65	1994/189	9	10	0.51	49.2	48.6	3,445.0	1.41
75–82°N	asc	78	1996/172	9	7	0.57	68.0	97.3	3,344.0	2.91
75–82°N	asc	93	1999/204	11	1	0.58	61.7	115.4	2,200.5	5.24
75–82°N	asc	93	1999/204	14	4	0.62	46.9	109.4	2,138.9	5.11
75–82°N	asc	104	2001/194	16	9	0.55	42.1	48.4	2,220.0	2.18
75–82°N	asc	127	2009/196	18	2	0.50	60.6	67.4	3,898.4	1.73
75–82°N	dsc	50	1992/177	9	1	0.61	34.3	17.2	1,027.9	1.67
75–82°N	dsc	70	1995/194	14	4	0.54	50.8	27.6	1,572.5	1.76
75–82°N	dsc	70	1995/194	9	10	0.57	57.6	61.1	2,373.7	2.57
75–82°N	dsc	78	1996/172	14	2	0.67	70.2	175.2	2,523.8	6.94
75–82°N	dsc	93	1999/204	14	1	0.58	56.4	86.0	2,147.1	4.01
75–82°N	dsc	127	2009/196	18	10	0.57	52.6	172.7	2,842.9	6.07
75–82°S	asc	61C	1986/012	7	4	0.57	36.8	146.1	1,111.2	13.15
75–82°S	asc	61C	1986/012	7	5	0.67	43.1	123.1	1,111.2	11.08
75–82°S	asc	61C	1986/012	7	8	0.59	37.9	72.6	1,111.2	6.53
75–82°S	asc	61C	1986/012	9	1	0.51	14.0	19.2	469.2	4.09
75–82°S	asc	61C	1986/012	9	8	0.71	19.5	6.1	469.2	1.30
75–82°S	asc	32	1990/009	9	1	0.61	29.4	63.8	869.8	7.33

Latitude	Node	Flt	Year/day	Inst	DsL	Step [nrm]	Step [ice]	5-day ice	Season ice	Frac [pct]
75–82°S	asc	32	1990/009	9	5	0.54	24.2	48.3	869.8	5.55
75–82°S	asc	32	1990/009	11	1	0.61	27.3	63.9	845.1	7.56
75–82°S	asc	42	1992/022	9	3	0.53	33.5	–4.3	1,272.5	–0.34
75–82°S	asc	61	1993/336	11	9	0.57	25.3	77.1	1,170.3	6.59
75–82°S	asc	99	2000/042	11	2	0.62	10.9	19.1	233.6	8.18
75–82°S	asc	99	2000/042	11	3	0.52	9.2	8.1	233.6	3.47
75–82°S	asc	113	2002/328	16	4	0.51	21.8	22.4	821.6	2.73
75–82°S	asc	107	2003/016	16	5	0.72	30.6	80.2	821.6	9.76
75–82°S	asc	107	2003/016	16	7	0.57	24.4	57.8	821.6	7.04
75–82°S	asc	107	2003/016	17	7	0.61	31.9	53.9	1,097.1	4.91
75–82°S	desc	61C	1986/012	9	5	0.54	41.8	20.7	866.2	2.39
75–82°S	desc	32	1990/009	11	1	0.59	46.4	39.4	1,207.1	3.26
75–82°S	desc	32	1990/009	9	5	0.62	62.7	145.1	1,857.4	7.81
75–82°S	desc	44	1991/328	9	3	0.53	45.0	109.8	1,996.4	5.50
75–82°S	desc	107	2003/016	16	7	0.72	34.9	86.8	1,170.1	7.42
75–82°S	desc	107	2003/016	17	7	0.51	45.8	126.8	1,840.7	6.89
75–82°S	desc	107	2003/016	17	10	0.51	45.4	47.0	1,840.7	2.55

Note. Minimum normalized step size = +0.5 units; Node = ascending (asc) or descending (desc) orbit node; Flt = Shuttle flight number; Year/day = days of launch; Inst = SBUV instrument (see Table 1); DsL = days since launch; Step [nrm] = total ice anomaly step in normalized units; Step [ice] = total ice anomaly step (°); 5-day ice = change in total ice from step date to 5 days after step (t); Season ice = PMC total ice for season (t); Frac [pct] = percentage of season total represented by 5-day ice. PMC = polar mesospheric cloud; SBUV = Solar Backscatter Ultraviolet.

Table 5:

Selected Rocket Launches During the NH 2011 Summer Season

Date	Day of year	DSS	Vehicle	Latitude (north)	Longitude (east)	Time (UT)	Prop. mass (t)
7 Jun	158	-14	Soyuz	45.6°	63.4°	2013	120
10 Jun	161	-11	Delta 2	34.7°	-120.6°	1420	100
20 Jun	171	-1	Long March 3B	28.2°	102.0°	1613	220
27 Jun	178	6	Soyuz	62.9°	46.8°	1600	120
6 Jul	187	15	Long March 2C	41.3°	100.3°	0428	180
11 Jul	192	20	Long March 3C	28.2°	102.0°	1541	220
15 Jul	196	24	Proton	45.6°	63.4°	2316	640
18 Jul	199	27	Zenit 3F	45.6°	63.4°	0231	420
26 Jul	207	35	Long March 3A	28.2°	102.0°	2144	220
29 Jul	210	38	Long March 2C	41.3°	100.3°	0742	180
5 Aug	217	45	Atlas 5	28.5°	-81.5°	1625	280
11 Aug	223	51	Long March 3B	28.2°	102.0°	1615	220
15 Aug	227	55	Long March 4B	37.8°	111.5°	2057	230

Note. Adapted from Stevens et al. (2012). DSS = days since solstice; Prop. mass = total propellant mass (t); NH = Northern Hemisphere.

Table 6:

Potential Launch Plume Signatures in Cumulative Anomaly Plots for NH 2011 at 65–75°N

Dnum	Node	Launch	Inst	DsL	Step [nrm]	Step [ice]	5-day ice	Season ice	Frac [pct]
178	asc	Soyuz	18	5	0.63	19.8	38.7	755.4	5.12
187	asc	Long March 2C	19	1	0.61	32.2	22.5	977.4	2.30
207	asc	Long March 3A	18	1	0.50	15.8	71.1	755.4	9.41
207	asc	Long March 3A	17	4	0.79	31.5	22.1	541.6	4.08
187	desc	Long March 2C	17	1	0.58	27.5	8.9	1,016.8	0.88
187	desc	Long March 2C	18	1	0.54	32.4	59.2	1,260.6	4.70
187	desc	Long March 2C	19	1	0.58	44.4	51.7	1,260.9	4.10
192	desc	Long March 3C	18	4	0.60	35.9	70.6	1,260.6	5.60
207	desc	Long March 3A	17	2	0.66	30.9	85.3	1,016.8	8.39
207	desc	Long March 2C	18	3	0.51	30.5	53.4	1,260.6	4.24
210	desc	Long March 2C	17	2	0.75	35.2	32.7	1,016.8	3.22

Note. Minimum normalized step size = +0.5 units; Dnum = day number of launch; Node = ascending (asc) or descending (desc) orbit node; Launch = name of launch vehicle; Inst = SBUV instrument (see Table 1; DsL = days since launch; Step [nrm] = total ice anomaly step in normalized units; Step [ice] = total ice anomaly step (t); 5-day ice = change in total ice from step date to 5 days after step (t); Season ice = PMC total ice for season (t); Frac [pct] = percentage of season total represented by 5-day ice. NH = Northern Hemisphere; PMC = polar mesospheric cloud; SBUV = Solar Backscatter Ultraviolet.