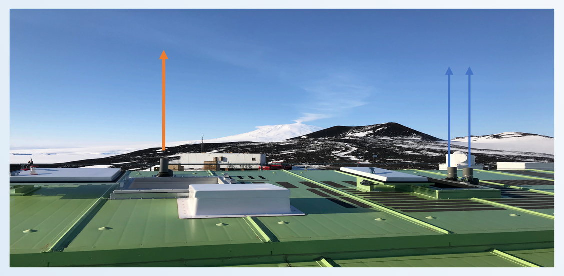

Nine-Year Survey (2010 - 2019) of Polar Mesospheric Clouds over McMurdo, Antarctica

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ABSTRACT

The Polar Mesospheric Clouds (PMC) measurements can help us understand better how the solar cycle can impact our upper and middle atmosphere. It also provides a tracer to monitor the climate change in this region, and study atmospheric dynamics. This project aims to analyze the PMC data collected from an Fe Boltzmann temperature lidar, located at Arrival Heights (77.84S, 166.67E) near McMurdo, Antarctica and operated by the University of Colorado at Boulder. The lidar team has managed to collect data continuously for 9 seasons, beginning in December 2010. These consecutive years of data allows us to register the main characteristics of Polar Mesospheric Clouds, as well as their occurrence in this latitude. The aim of this endeavor is to analyze the data from December 2010 to February 2019. The months registered will include November, December, January, and February. The main aspects to be studied under these conditions include inter-annual, seasonal, diurnal variations to PMC conditions and, afterwards, extrapolate significant behavior. It will try to build upon Chu et al. [2003], [2006], and [2011] to consolidate data and identity some possible Solar Cycle relationship. It is also important to note the mounting evidence for the anti-correlation between PMC brightness and centroid altitude supporting *Chu et al. [2006].* Both the seasonal averages and non-averaged data points have a statistically significant anti-correlation. In addition, the solar cycle analysis had interesting results. There was no clear signature of anti-correlation between Lyman-alpha irradiance at 121.5nm and total backscatter coefficient. These findings support Hervig et al. [2016], where water anomaly is greatly diminished after 2005. Solar cycle response isn't nearly as strong as previous cycles. There might be some inter-atmospheric coupling effects, such as QBOs and Polar vortexes.

Data Overview

The data was obtained using an Fe Boltzmann lidar operated and refurbished by University of Colorado Chu lidar group, and located at McMurdo Station, Antarctica. The raw data profiles were recorded at spatial resolution of 48 m and temporal resolution of 1 minute. The total observational hours were determined by the data's SNR, and every season's length is 4 months, from November to February. The PMC parameters were primarily derived from the 374 nm data where contamination from the weaker Fe line in minimum, by *Chu et al. [2003]*.

	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	Overall
Total Observational Hours	284	356	265	274	342	308	270	201	497	2797
Light-Medium-Strong PMC observation hours	76	189	138	136	166	159	166	81	237	1348
Medium-Strong PMC observation hours	73	122	96	95	76	107	130	47	183	929

Table 1 – Observational and PMC hours

Analysis Procedure

CASE EXAMPLE - January 11 2013

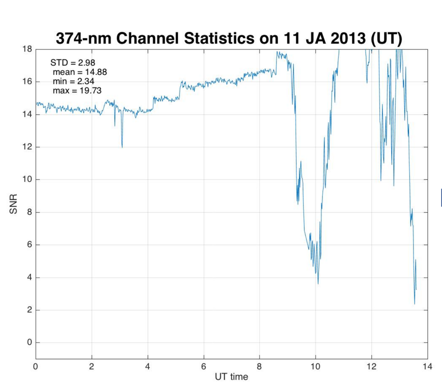

Figure 1 – SNR vs UT Time

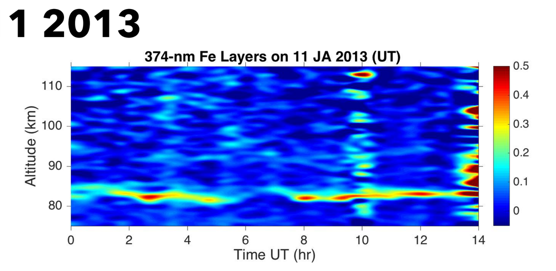

Figure 2 – 374nm contour before SNR cutoff

It can be seen during the times where SNR falls below 8 the quality of the data is not very good and, thus, no reliable results can be extrapolated.

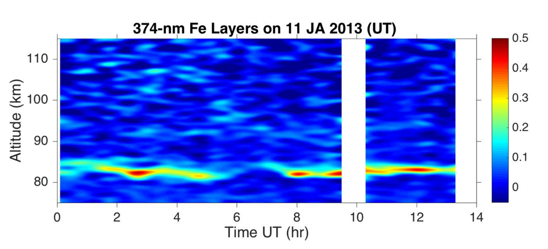

Figure 3 – 374nm contour after SNR=8 cutoff

During the UT time where the SNR falls below 8 there layer contour is cutoff, and it is considered anymore as observational time.

1. Screening of the data using limits for signal to Noise Ratio (SNR). The 372 nm channel the cutoff SNR was 2.8, while 374 nm channel had a cutoff of 8.2.
2. The 374 nm layer plots used to recognize PMC signatures take advantage of a smooth normalized signal in time with a resolution time of 6 min, and FW of 1 hour. The time smoothed signal in altitude was smoothed using FW = 2km, and resolution altitude of 0.1km.
3. Once this was completed, there were three criteria used to identify PMC as a distinct peak or peaks in the lidar data described by *Chu et al. [2006]*.
    1. The volume backscatter coefficient ($\beta(z)$)must be larger than 1.2/1.05 times the corresponding photon error $\Delta\beta(z)$ in each bin within the full width at half maximum (FWHM) range of the peak: i.e. $\beta_{PMC}(z) > 1.5\Delta\beta(z)$
    2. The peak volume backscatter coefficient, B_{max}, at altitude Z_{max}, must be at least twice as large as the photon counting error at the peak: $\beta_{max} > 2\Delta\beta(z_{max})$
    3. The peak volume backscatter coefficient must be larger than 1.5 times the standard deviation of the background noise : $\beta_{max} > 1.5 std noise$
4. Generate plots of pure PMC signal vs time:
    1. Compute $R(z)$, $B_{PMC}(z)$, B_{total}, Z_c, σ_{RMS} using procedure described by *Chu et al [2003]* .

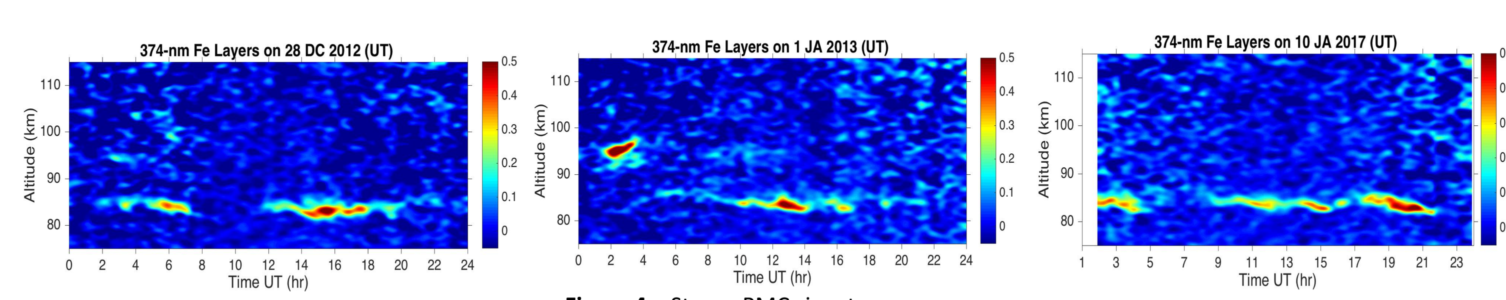

Figure 4 – Strong PMC signature

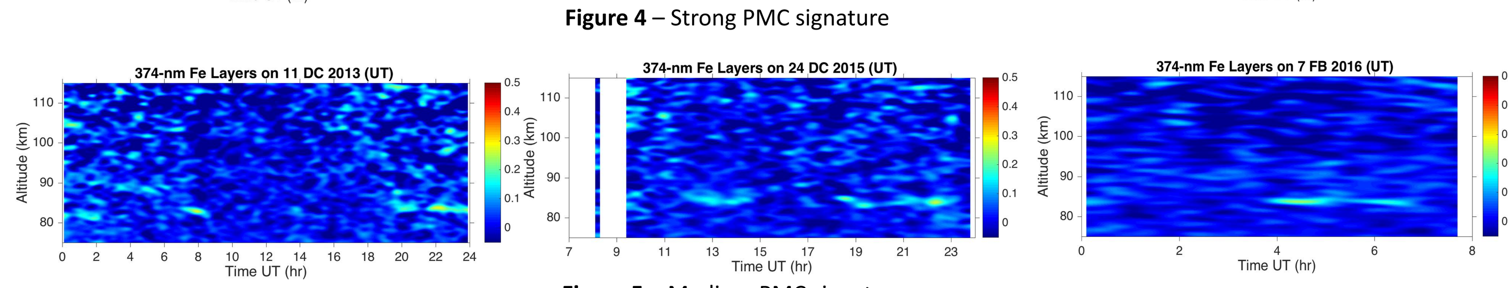

Figure 5 – Medium PMC signature

Conclusions

1. The interannual variations show a symmetric distribution for PMC altitude over the 9 seasons. For diurnal variations , β_{total} has an out-of-phase relationship with Z_c over a 24 h period. The overall occurrence frequency is as high as 50% for light-medium-strong PMC.
2. The mean statistics are consistent with Chu et al. [2011]. The 9 years of data show anti-correlation between brightness and centroid altitude. New findings include the abnormal behaviors of the first 2-3 PMC seasons of data.
3. The data indicates weak anti-correlation of PMC brightness with solar flux, i.e., PMC reach weakest when the solar flux is maximum. Under the most recent weak solar cycle (2010- 2019), we might see the influence from QBO or other possible factors.
4. The long-term goal of this endeavor is to use the PMC data to see if some patterns match up among the PMC, solar cycle, and the QBO data. For this, we need more years of data, which will encapsulate the entirety of a full solar cycle. It usually last 11 years.

Mean Characteristics

	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	Overall Mean
R_{max}	30.80±1.5	35.99±1.7	35.11±1.6	29.90±1.5	29.81±1.7	28.46±1.2	30.50±1.4	31.73±1.7	30.65±1.1	31.44±0.5
$B_{max}x10^{-9}m^{-1}sr^{-1}$	1.66±0.1	1.91±0.1	2.44±0.1	1.85±0.1	1.52±0.1	1.67±0.1	2.16±0.1	1.71±0.1	1.79±0.1	1.85±0.03
$B_{tot}x10^{-6}sr^{-1}$	3.30±0.2	4.34±0.2	5.02±0.3	3.56±0.2	2.88±0.2	3.19±0.2	4.28±0.3	3.21±0.3	3.58±0.2	3.71±0.11
$Z_c(km)$	84.59±0.2	84.77±0.2	84.28±0.2	84.65±0.2	84.81±0.2	84.78±0.2	84.14±0.1	84.89 ±0.3	84.72±0.1	84.62±0.05
$\sigma_{RMS}(km)$	0.87±0.04	0.99±0.02	0.80±0.02	0.82±0.02	0.79±0.02	0.78±0.02	0.80±0.02	0.84±0.03	0.83±0.02	0.84±0.01
Occurrence Probability	29.9%	53.03%	51.97%	49.70%	48.53%	51.72%	61.49%	39.92%	47.78%	48.23%
PMC Period	21DC to 15FB	17NV to 24FB	5 NV to 26FB	14NV to 27FB	1NV to 28FB	8NV to 27FB	3DC to 20FB	4NV to 14FB	7NV to 28FB	

Table 2 – Light-Medium-Strong Mean PMC characteristics

	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	Overall Mean
R_{max}	30.80 ±1.5	38.29±1.6	38.31±1.7	31.01±1.7	32.82±2.5	31.82±1.6	33.58±1.6	33.07±2.0	32.45±1.1	33.57±0.6
$B_{max}x10^{-9}m^{-1}sr^{-1}$	1.66±0.1	2.12±0.1	2.86±0.1	2.07±0.1	1.73±0.1	1.97±0.1	2.47±0.1	2.00±0.1	2.01±0.1	2.10±0.03
$B_{tot}x10^{-6}sr^{-1}$	3.30±0.2	4.88±0.2	6.13±0.4	4.11±0.2	3.21±0.3	3.85±0.3	4.96±0.3	3.78±0.3	4.08±0.2	4.25±0.06
$Z_c(km)$	84.59±0.2	84.93±0.2	84.26±0.2	84.45±0.2	85.15±0.2	84.63±0.3	84.19±0.1	84.61±0.3	84.72±0.1	84.61±0.04
$\sigma_{RMS}(km)$	0.87±0.04	1.00±0.03	0.83±0.03	0.84±0.03	0.76±0.03	0.81±0.03	0.84±0.02	0.85±0.04	0.85±0.02	0.85±0.01
Occurrence Probability	25.70%	34.27%	36.23%	34.67%	22.22%	34.74%	48.15%	23.38%	36.82%	32.90%
PMC Period	21DC o 15FB	17NV to 24FB	5 NV to 24FB	18NV to 27FB	1NV to 26FB	8NV to 27FB	3DC to 18FB	4NV to 14FB	7NV to 28FB	

Table 3 – Light-Medium-Strong Mean PMC characteristics

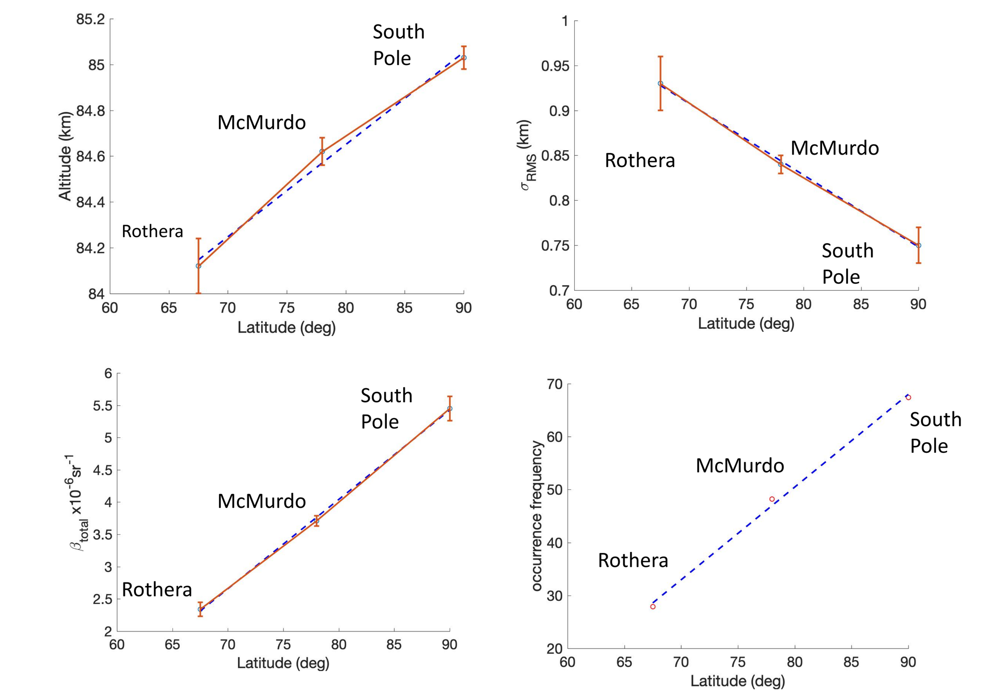

Figure 6 - Comparison of mean altitudes of PMCs, total backscatter, layer RMS width, and occurrence frequency versus latitude for South Pole (90°S), McMurdo(78°S), and Rothera (67.5 °S) confirming the findings in *Chu et al. [2011]*.

Results of Interannual, Seasonal, Diurnal, Solar Cycle Analysis

INTERTANNUAL VARIATIONS

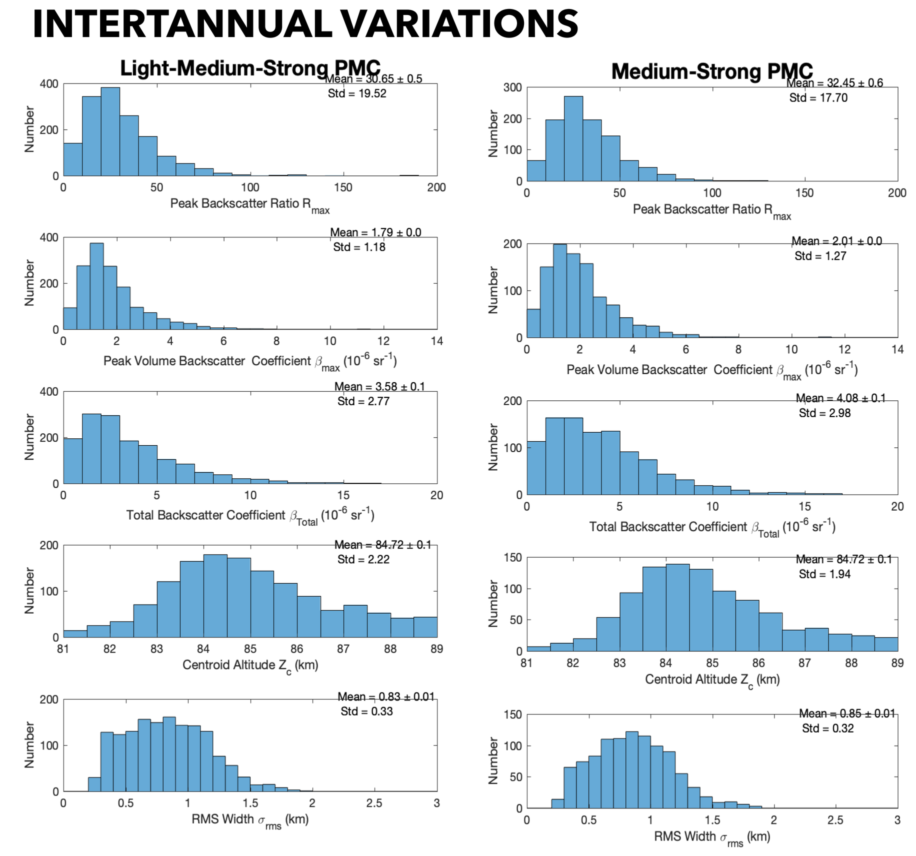

Figure 7 – Histogram of 9 seasons of light-medium-strong, and medium-strong PMC. There is a symmetric Gaussian of PMC centroid altitude, which reflects the variations of the saturation region around a mean altitude through the season *Chu et al. [2006].* The PMC brightness has a log normal behavior..

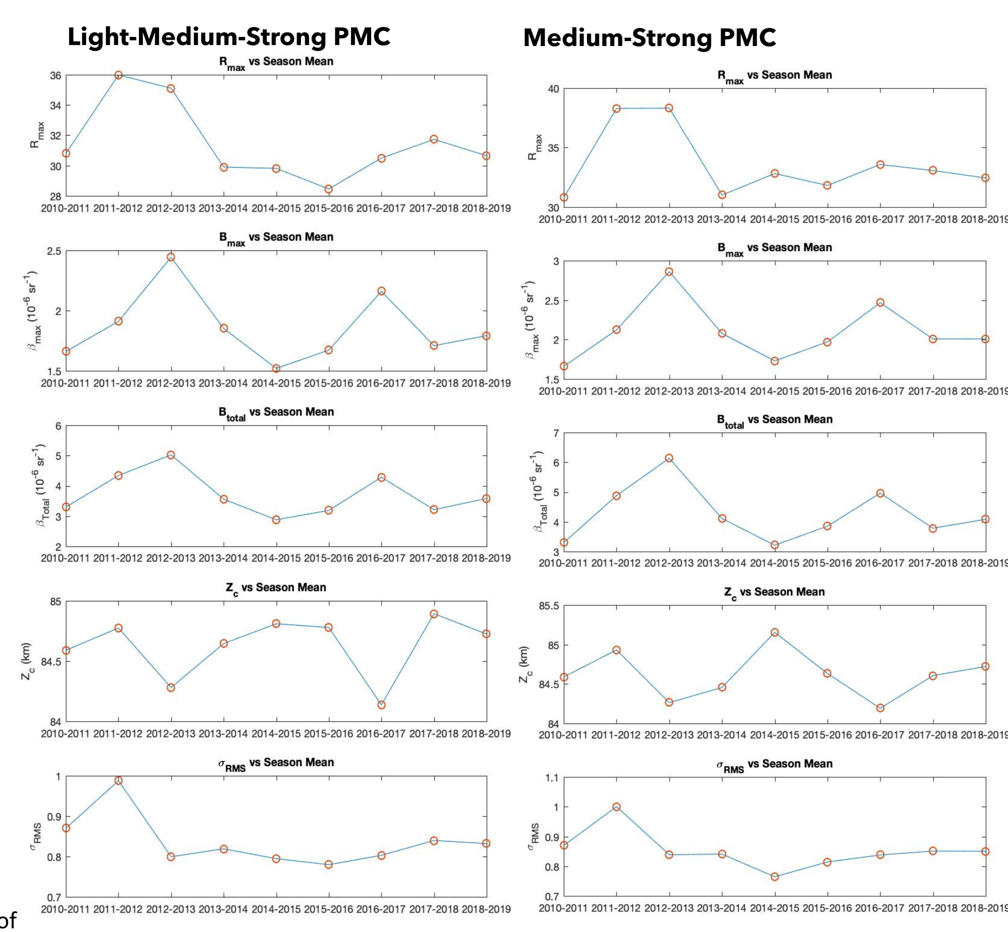

Figure 8 –PMC Mean characteristics for Light-Medium-Strong and Medium-Strong PMC

Anti-correlation between Z_c and β_{total}

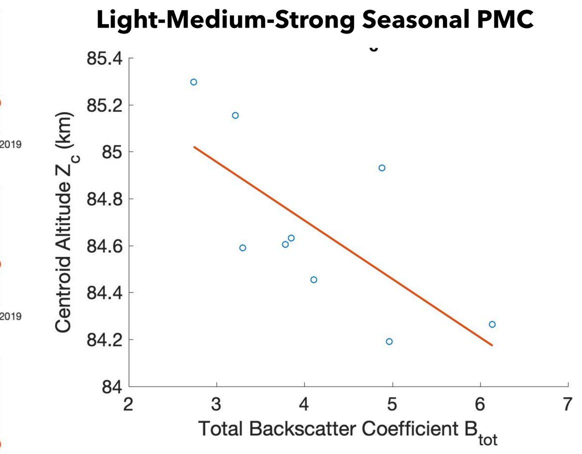

Figure 9 - Anti-correlation of around -70.98% between the mean centroid altitude and the mean total backscatter coefficient for the 9 seasons. The Pval is 0.03 which means the correlation is statistically significant.

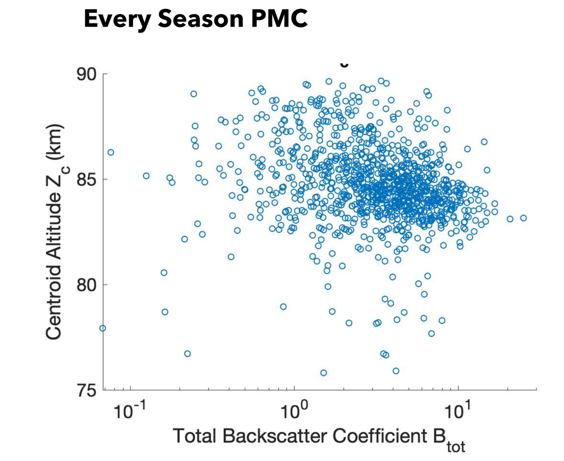

Figure 10 - Anti-correlation of around -22.92% between the mean centroid altitude and the total backscatter coefficient for every data point of the 9 seasons.

i. As it was mentioned in *Chu et al. [2006]* this anti-correlation means the PMC occurring **at higher altitude tend to have lower brightness**, just as predicted by the growth-sedimentation-sublimation model presented by the *Jensen and Thomas et al. [1988]*, and *Rapp and Thomas [2006]*.

ii. According to *Chu et al. [2006]*, **the strongest PMC occur at nearly constant altitude**, approximately 84km, in the middle of the PMC altitude distribution, **rather than at the lowest altitude.**

SOLAR CYCLE ANALYSIS

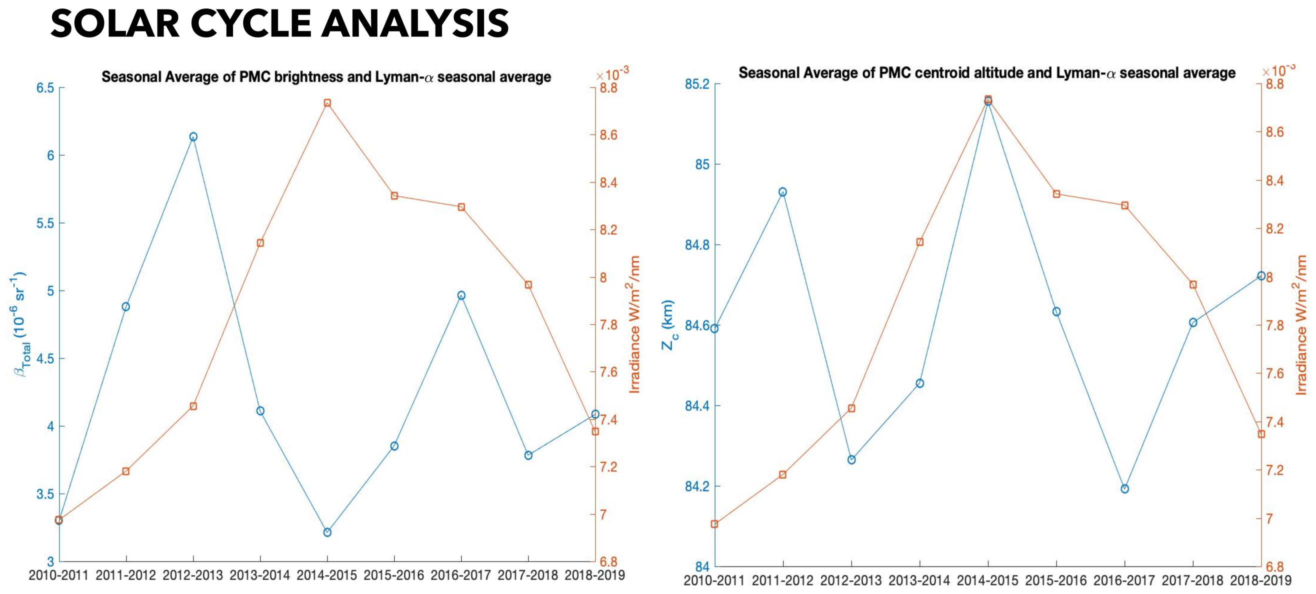

Figure 11 – Total Backscatter coefficient for every season versus Lyman alpha series averages for November, December, January and February. There is an anti-correlation of -25.4% between irradiance and total backscatter coefficient. Also, there is a positive correlation of 9.9% between irradiance and centroid altitude, but they are not statistically significant. Solar cycle response isn't nearly as strong as previous cycles. There might be some inter-atmospheric coupling effects in play.

SEASONAL VARIATIONS

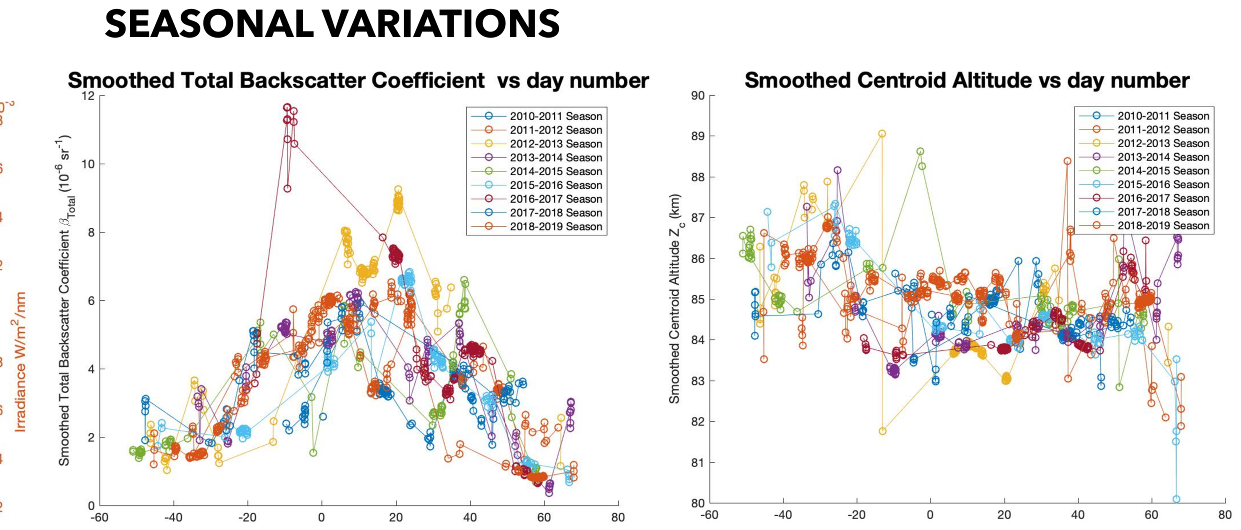

Figure 12 - Eleven-day Smoothed PMC Parameters vs Day Number Relative to Summer Solstice.

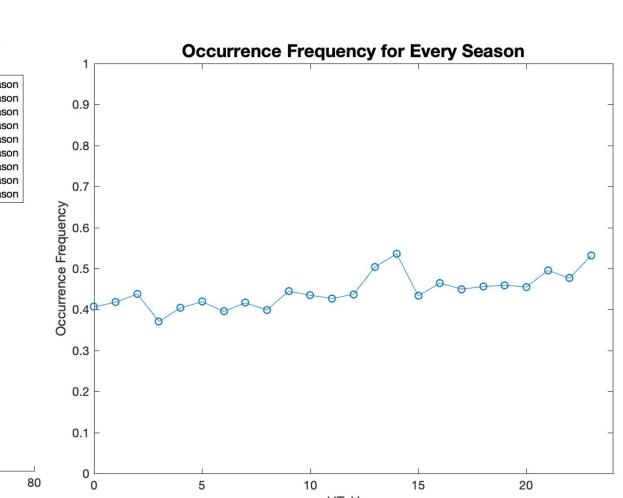

Figure 13 – Occurrence Frequency for every season's data versus UT time. There is a peak around 13-14 UT hours

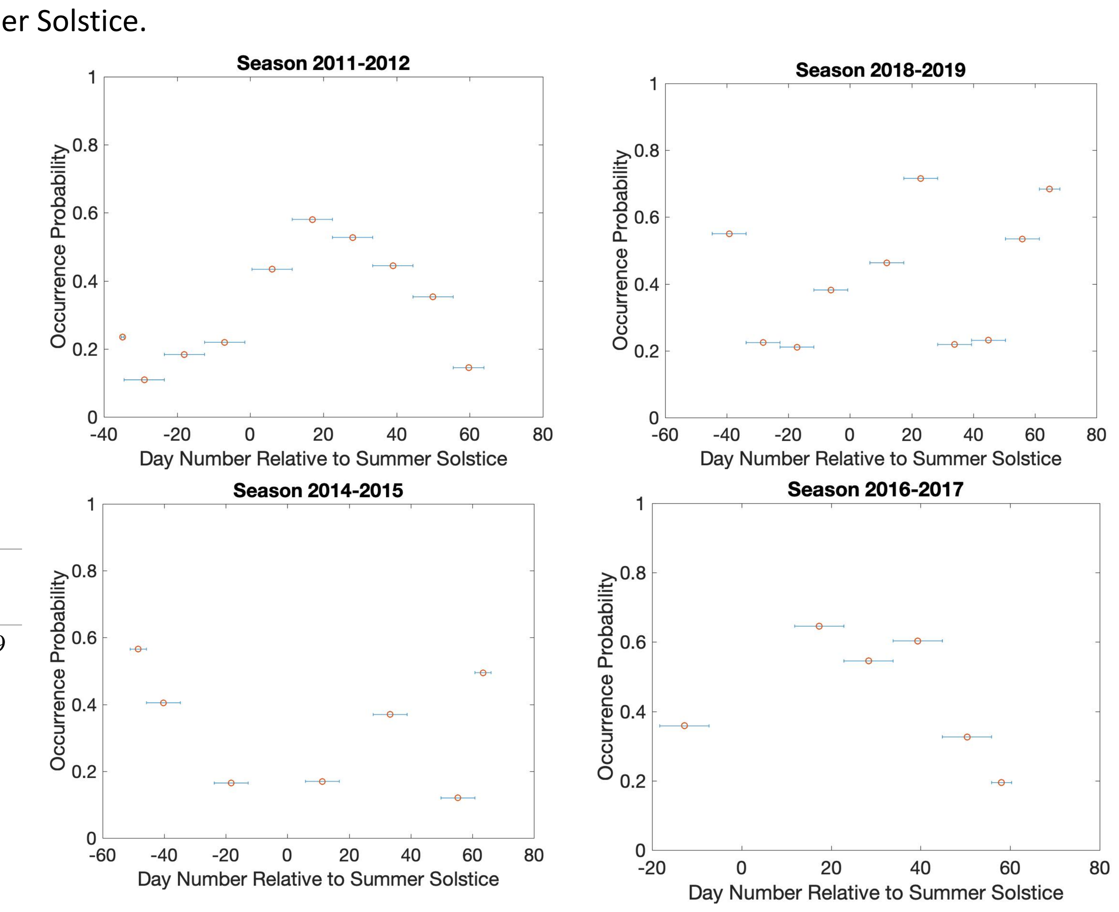

Figure 15 - Peak between the 20th and the 40th day after solstice. These 4 seasons were selected because they have the highest amount of PMC hours.

According to *Chu et al. [2006]*, β_{total} has an out-of-phase relationship with Z_c over a 24 h period and reaches as high as 12 hours. *Chu et al.[2003]* and *Vin Zahn et al. [1998]* attributed this behavior to the **changes in size of the PMC particles that form at higher altitudes and then begin falling as their size and weight increases.**

DIURNAL VARIATIONS

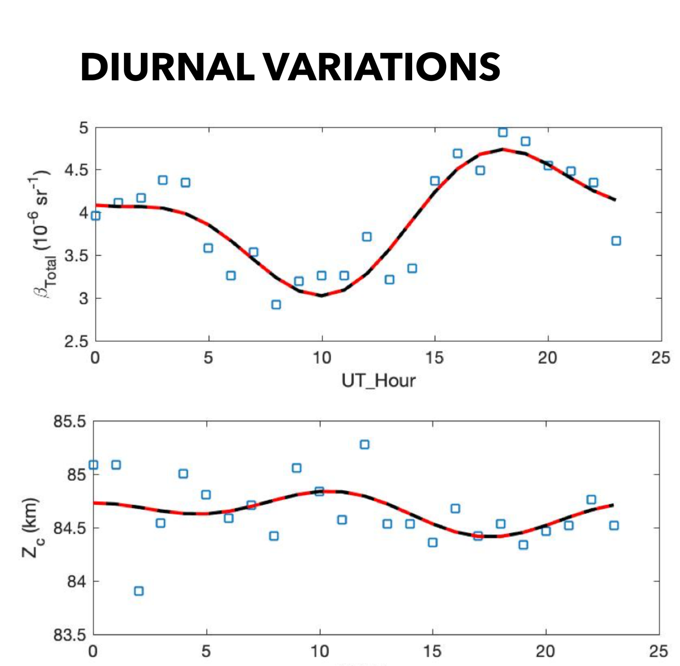

Figure 14 – PMC parameters diurnal variation with UT time. Local time = UT time + 11.11 hours.

The oscillations are consistent with what was observed at the South Pole by *Chu et al [2001].*

	R_{max}	β_{max} $x10^{-9}m^{-1}sr^{-1}$	β_{total} $x10^{-6}sr^{-1}$	Z_c/km
A_0	32.51±1.20	1.94±0.12	3.94±0.14	84.65±0.19
A_{12}	1.40±1.70	0.16±0.21	0.33±0.23	0.13±0.22
A_{24}	5.65±1.11	0.30±0.15	0.67±0.32	0.12±0.15
UT_{12}	4.16±3.12	5.10±1.43	4.74±1.21	0.83±0.94
UT_{24}	-1.90±1.50	-3.98±1.23	-3.54±1.92	7.02±2.32
Correlation Coefficient	82.69%	90.53%	89.11%	41.76%

Table 4 - Parameters for Harmonic Fits to the PMC Data