Polar Mesospheric Clouds: A correlative analysis of latitudinal zonal cloud frequency with seasonal mesospheric temperature and water vapor cycles

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Polar Mesospheric Clouds: A correlative analysis of latitudinal zonal cloud frequency with seasonal mesospheric temperature and water vapor cycles

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A thesis submitted to the
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Abstract

This paper examines to what extent polar mesospheric clouds are dependent on temperature and water vapor. The most recent versions of Cloud Imaging and Particle Size instrument (CIPS) v5.10 and Microwave Limb Sounder (MLS) v4.2 Northern Hemisphere 2007 and 2011 data are used to analyze clouds in a lower latitude bin than has previously been researched (50°N-65°N). In each season, this data is compared to results from a higher latitude bin (75°N-80°N) in order to assess the applicability of low latitude results to high latitude clouds, and vice versa. This study finds that though temperature does seem to be the greatest driver of cloud frequency in both latitude bins, the strength of this anti-correlation varies across and between the seasons and latitudes.
Preface

At age two, my parents had to scoop me off of the sidewalk as a thunderstorm rolled across the northern Colorado horizon towards our house. Unfazed by the approaching storm, I resisted extensively; I wanted to watch the lightning and feel the thunder shake the ground. I had to settle for watching from the window that day, but haven’t missed an opportunity to have my head in the clouds since.

Studying polar mesospheric clouds allowed me to continue to pursue my love for the weather in an applied manner that exposed me to research and analysis of data from the middle atmosphere. As a student, my interests have always aligned directly in between the topics covered in Environmental Studies and Atmospheric and Oceanic Science. I initially focused this thesis on examining how anthropogenic impacts on the troposphere might influence the instance of low latitudinal clouds, however that approach required too many leaps in logic for too unsound a conclusion. Hence, I focused on a pet peeve of mine: lack of available data. This thesis examines to what extent polar mesospheric clouds can be used as an indicator of temperature in the mesosphere by comparing their temperature dependence to their water vapor dependence, through this hoping to improve the vertical resolution of temperature measurements in the mesosphere.

I would like to acknowledge Dr. Cora Randall for her infinite patience and enthusiasm as she taught me the very basics of computer programming, searching through dozens of lines of code only to realize that I simply forgot to “End” the program. Without these hours of meetings and her guidance, I would not have been able to progress quickly enough to complete this thesis, or work with code of any kind of complexity. I also would like to convey my utmost appreciation of Dr. Lynn Harvey’s computer trouble shooting ability, as well as her code that organized the complex and oddly sorted data from the Microwave Limb Sounder instrument into a format I was able to easily manipulate and analyze. Additionally, I would like to acknowledge Dale Miller for keeping me up to date on deadlines and supporting me throughout the thesis writing process, despite my scheduling conflict with the thesis course. The assistance, persistence, and reassurance of all of my advisors made this otherwise daunting project a smooth, manageable undertaking.
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Introduction

Polar mesospheric clouds (PMCs), also called noctilucent or ‘night shining’ clouds when viewed from the ground, are clouds that form around the polar latitudes in each respective hemisphere’s summer season. Research conducted on PMCs at high latitudes (75°N and S -- 90°N and S) has shown these clouds to be highly temperature and water concentration dependent; the mesosphere must be extremely cold and have enough water vapor concentrated in a region for them to form. Of these two factors, temperature is believed in current research to be a greater driver. My thesis project examines to what extent the lower latitudinal (50°N-65°N) polar mesospheric clouds, for which data has only recently become available, can be used as an accurate indicator of seasonally anomalous mesospheric temperature change. I will be examining satellite data from the Aeronomy of Ice in the Mesosphere (AIM) satellite mission, which was launched in 2007, and working with the Northern Hemisphere 2007 and 2011 cloud seasons (May 25th - August 30th and May 1st - August 25th respectively). I will overlay satellite temperature data that is available from the Microwave Limb Sounder on the Aura satellite for this same season on top of the true cloud signals, and determine what level of correlation may be viewed to occur. This process will be repeated with water vapor mixing ratio data, also retrieved by the Aura satellite. All three seasonal tendency lines will be processed to also show anomalies, from which an anti-correlation between seasonal temperature progression anomalies and cloud frequency anomalies is expected, and to a lesser extent a correlation between seasonal water
vapor availability anomalies and cloud frequency anomalies is expected. This data is not flawless, so I compare the outputs of computer codes indicating the minimum cloud latitudes observed with visual examination of the images captured from the satellite on days that appear to have outlier data, such as reporting high temperature and high cloud frequency simultaneously, in order to distinguish between true clouds and false positives. This manual analysis of images will evaluate the structure and shape of the reflected images, which may be more consistently and accurately indicative of clouds.

Polar mesospheric clouds are a relatively new area of upper atmospheric research; the first mission with instruments dedicated to studying them was not launched until just under a decade ago. Because of the relative dimness of clouds at low latitudes compared to those at higher latitudes, little is known about the occurrence and frequency of PMCs below 60°N and S. This was fixed to an extent by the new retrieval algorithm, which is able to more effectively subtract the atmospheric background albedo than the previous algorithm was. My research attempts to inform the conversation regarding the accuracy of the current retrieval algorithms for lower latitude PMCs, and if the majority of the data...
is found to be viable, to use the cloud trends to examine temperature fluctuations in the mesosphere.

Low latitude PMCs are of special interest due to their theoretically strong temperature dependence. Around the polar region, specifically above 80° N, they occur fairly predictably in response to the extremely cold temperatures at the mesopause in that region around the hemispheric summer solstice. However, the lower in latitude and thus farther away from the poles that satellites look, a much more dynamic and seemingly sporadic pattern of clouds has been observed. Because of data and instrument limitations that have existed until recently, far less research has been done on the temperature dependence of PMCs in my latitudes of interest than in the polar regions above 80° in latitude. The vertical resolution of the MLS instrument on the Aura satellite, which measures mesospheric temperature and water vapor among other things, becomes increasingly coarser at higher altitudes particularly in the region where the clouds occur (82 km – 85 km). If the frequency of the seasonally anomalous occurrence of PMCs at lower latitudes can be shown to correspond to temperature anomalies in the same region of the mesosphere to a much greater extent than the availability of water vapor, this could potentially indicate an ability to use the occurrence of the clouds to examine mesospheric temperature at a higher vertical resolution in the upper altitudes (the 82 km – 85 km region) than the current instruments are able to.

The predicted mesospheric response to anthropogenic warming of the atmosphere is uncertain. It is generally expected a greater amount of carbon dioxide (such as that from anthropogenic emissions) should result in a cooler mesosphere,
which would allow for PMC formation at lower latitudes than seen previously. This information could also potentially inform a discussion about why ground sightings of noctilucent clouds seem to have occurred with notable frequency only in the last century and a half, where most other visual anomalies such as the aurora borealis are well documented in historical writings. Though my research does not specifically examine the potential for anthropogenic tropospheric influence on mesospheric cloud formation, my analysis provides a starting point for future research into this phenomenon through my 2007 and 2011 northern hemisphere PMC season conclusions and their potential application to all seasons for which there is data. My research will involve the construction of a new computer code that will correlate AIM cloud data and Aura water vapor and temperature in a unique and accessible manner, using an updated version of data that has only recently become available, and thus has the potential to draw conclusions about clouds at lower latitudes than prior research.
Background

**Vertical Structure of the Atmosphere**

The mesosphere is the layer of the atmosphere generally defined to exist between approximately 50km and 85km above the surface of the earth, above both the stratosphere and the troposphere. In this region of the atmosphere, temperature decreases with height, reaching a minimum near the mesopause (approximately 87 km). PMCs generally occur in between 82-85 km near where this temperature is at its minimum, as they require extremely cold temperatures to form [Oklahoma Climatological Survey n.d., Dieminger et al 1996]. These low temperatures occur over the poles in the northern and southern hemisphere’s respective summer seasons [Laboratory for Atmospheric and Space Physics (LASP), 2013.]. Because of maximum altitude limitations of many direct data collection tools, such as weather balloons and airplanes, gathering accurate and detailed information from the mesosphere is not easy [UCAR n.d.]. PMCs are one of the many relatively unexplored and lesser-understood fields of middle atmosphere research, due in part to the difficulty gathering information and in part to their fairly recently increased incidence that has in the last few decades piqued the interest of atmospheric scientists.

**Clouds**

In general, when a parcel of air is lifted, it cools. This is due to the ideal gas law, which equates a drop in pressure to cooling. Pressure declines exponentially with height in the atmosphere, with more than 99% of the molecules in Earth’s atmosphere residing below the stratopause (boundary region where temperature is
constant as height increases between the stratosphere and the mesosphere). This decrease in pressure and density of the molecules results in a much cooler environment [Oklahoma Climatological Survey, n.d.]. The polar areas of extremely low temperatures that are necessary for PMCs to develop occur in response to an area of rising air in the mesosphere above the polar region [Karlsson et al., 2011].

Polar Mesospheric Clouds, as indicated by their name, form and reside in the upper mesosphere around the polar latitudes. Clouds in the troposphere generally composed of both condensed liquid water and ice particles, depending on the ambient temperature. In the mesosphere, the temperatures are so low that PMCs are composed exclusively of tiny ice crystals, rather than a mix of liquid water and ice particles as is seen in the troposphere [Hervig et al., 2001]. Though it was proposed as early as 1912 by Alfred Wegener that “water ice” is the primary component of PMCs, this theory wasn’t confirmed until the Halogen Occultation Experiment (HALOE) provided infrared measurements of the clouds that agreed with the distinct signature of ice particle extinction that models had produced [Hervig et al., 2001]. The confirmation of the composition of ice particles made by researchers as a result of the data gathered by HALOE also suggests accuracy of the previously determined exponential growth function of PMCs with respect to temperature [Hervig et al., 2001].

Variability

High day-to-day variability is demonstrated in PMCs, as well as inter-annual and inter-hemispheric variability; PMCs in the southern hemisphere tend to have greater variability and lower brightness than PMCs in the northern hemisphere
Hervig and coauthors reflect that the “seasonal dependence of ice abundance is generally controlled by temperature and that in a broad sense, changes in water vapor are a result of changes in ice” [Hervig et al 2009]. They indicate that results showing the association of higher ice mass density with lower temperatures and “smaller particle radii” demonstrate that density of the ice mass is not due to continued growth of ice particles that have already nucleated, rather is a result of increased nucleation of ice particles, and cite this as a key factor in PMC variability [Hervig et al., 2009]. PMC variations on a decadal scale are concluded by Hervig and coauthors to result from solar variability [Hervig et al., 2016].

**Cloud Structures**

There are four main structures that have been identified in PMCs; type I-Veil, type II-band, type III-billow, and type IV-whirl. There are also three broadly identifiable absence-of-ice patterns, classified as voids I through III [Thurairajah et al., 2013]. These structures often correlate with structures commonly seen in tropospheric clouds [Thurairajah et al., 2013], about which much more research has been done, and thus could potentially provide an avenue of understanding of the dynamics of PMC formation and movement.
Aeronomy of Ice in the Mesosphere

The AIM mission was launched in 2007 with the goal of “measuring the [polar mesospheric] clouds and their environment to better understand the underlying chemistry and physics, and the forces that cause them to vary”, and seeks to understand the potential correlations between anthropogenic effects on the atmosphere and observed PMC changes [LASP, 2013]. The AIM satellite is on a polar orbit, an orbit in which the satellite “moves in a near-circle about 1000 km (600 miles) above ground,” covering the entire surface of the Earth every day with each orbit spanning 90-100 minutes [NASA, n.d.]. The Cloud Imaging and Particle Size (CIPS) instrument aboard the AIM satellite provides images with a range from between approximately 40°N-90°N and 40°S-90°S on the daylight side of the orbit, with images starting at the terminator on the ascending node. The terminator is the line between night and day, where the sun’s light reaches the Earth’s surface. At the solstice, this line is at a 23.5° angle, where at the equinoxes, it is approximately parallel to lines of longitude between the poles. Because the CIPS instrument measures ultraviolet radiation scattering, not infrared, it does not provide measurements for areas on the night side of the planet. [NOAA, n.d.; LASP, 2013].
Mesospheric Temperature Dynamics

As Karlsson and coauthors describe concisely in their paper “On the seasonal onset of polar mesospheric clouds and the breakdown of the stratospheric polar vortex in the Southern Hemisphere”,

“The low temperatures necessary for [PMCs] to form are linked to the meridional circulation of the mesosphere, which in the summer hemisphere is directed toward the equator. By mass continuity, upwelling occurs at high latitudes, and the ascending air is cooled adiabatically to temperatures lower than 150 K [e.g., Lübken, 1999]. In addition to lowering the temperatures, this upward flow transports water vapor to the summer polar mesopause region, and also causes PMCs, that are mostly composed of water ice [Hervig et al., 2001], to remain in the super saturated altitude range longer so that they can grow larger. Because all three effects act in the same direction, PMCs are excellent indicators of the strength of the mesospheric upwelling above the summer pole” [Karlsson et al., 2011].

Measurements of temperature and temperature changes in the mesosphere are difficult to this day. Beig and coauthors emphasize that “our knowledge of systematic changes and trends in the temperature e of the mesosphere...is relatively limited compared to the Earth’s lower atmosphere” [2003]. Before more recent satellites had been launched, the most reliable and commonly used datasets for studying mesospheric temperatures are hydroxyl airglow measurements [Beig et al 2003]. Hydroxyl (with the chemical symbol OH) is formed through an exothermic chemical reaction; it releases heat in the form of an excited state of the OH molecule, which emits photons across a spectrum of wavelengths, with “lines” of intensity exhibited at some wavelengths. Atmospheric temperature was calculated by examining “[the] ratio of intensities of one [P-branch] line to another, coupled with
known line parameters and constants” [Department of Energy and the Environment, n.d.]. Now, instruments such as the Microwave Limb Sounder instrument on the Aura satellite, launched in 2004, are able to make continuous measurements using “thermal emission from the atmospheric limb in broad spectral regions centered near 118, 190, 240, and 640 GHz, and 2.5 THz” [Waters et al., 2006]. Though this instrument greatly increases the accuracy of temperature measurements in the mesosphere, it has poor vertical resolution as it nears the mesopause and the region where PMCs form due in part to the low density of molecules with measurable temperature and in part to the atmospheric distortion experienced by the instrument’s line of sight as it looks higher up in the atmosphere.
Methods

Overview

My first step in analyzing cloud data was to manually examine series of orbit strips from the publicly available level 4 data retrieved by the polar-orbiting AIM satellite. This data is presented visually in two forms, daily daisies and orbit strips. An orbit strip is a series of images taken by satellite instruments as it passes over the polar region combined into one “strip”; a daily daisy is a combined image of all orbit strips from one calendar day. Due to the nature of a polar orbit, these images when combined appear to form a daisy-like shape, with the center of the flower being the data-less area around the poles necessitated by the nature of polar orbiting satellites.

Because PMCs form only in the hemispheric summer season, I begin my analysis by looking at images from June-July 2015 to familiarize myself with what patterns and intensities indicate the presence of an actual cloud, and what is simply noise or edge effects caused by the retrieval algorithms used. The 2015 season is known to have many issues in the
retrieval algorithm, making it an ideal season with which to familiarize myself, as any error types that may be seen in other seasons will likely be encountered in this season.

I created a spreadsheet in Microsoft Excel that contained the orbit number of each orbit strip as well as the minimum latitude reached by clouds seen on that strip on the ascending and descending nodes. Initially it was my intent to analyze all seasons in this manner; however, the sheer number of orbit strips that have been captured and the amount of time spent analyzing each one quickly made it clear that in order to identify days with notably low latitude clouds, a computerized approach would be needed.

The computer programs used in this research were written and edited in Interactive Data Language (IDL). As I had no prior experience computer programming before this research, the first stage of my thesis project included learning the basics of the language and becoming comfortable using and editing codes written by other people. Throughout the data analysis process, I collaborated with Dr. Cora Randall and Dr. Lynn Harvey to initiate and confirm the accuracy of my code writing process. Because I had little experience coding prior to this research, Drs. Randall and Harvey were kind enough to provide me with the basic outline of much of the difficult coding for data organization and retrieval, which I was then able to modify, build on, and plot results from.
The cloud data used for analysis in this thesis is gathered by the Cloud Imaging and Particle Size (CIPS) instrument on the Aeronomy of Ice in the Mesosphere (AIM) satellite [LASP 2013]. Though there are many levels and versions of data available, my analysis focuses on Version 5 Level 3c data. The changes made to the retrieval algorithm for version 5 data were necessitated by manipulations of the position of the satellite and the precession of the satellite’s orbit over time. In the process of adjusting the retrieval algorithm to account for these changes, a better subtraction of the background albedo of the atmosphere was developed, allowing dimmer clouds at lower latitudes to be visible. The retrieval algorithm used for the version 5 data has not yet been verified. This could be a potential source of error in my findings, which I am attempting to mitigate through visual review of the low latitude clouds that seem to occur outside of the logical date, water vapor, and temperature range, in addition to examining the frequency of cloud occurrence relative to the number of observations at this level, rather than simply whether or not a cloud is present within a specific bin.

Because 2011 is generally regarded as a stable data year that the most recent version of data has been released for, and 2007 has previously demonstrated strong temperature and PMC frequency anti-correlations at high latitudes, I constrained my analysis to the 2007 and 2011 northern hemispheric cloud seasons. This analysis could in the future be conducted on other years and on the southern hemispheric cloud seasons, however due to the sheer size of the total data for the seasons when cloud, temperature, and water data all need to be processed in addition to my
limited computing power, I decided to conduct an in depth analysis of these two seasons only.

**Description of Data**

The mesospheric zonal average temperature data used and discussed in this analysis is retrieved from the Microwave Limb Sounder (MLS) instrument on the Aura satellite. This data is overlaid onto cloud data in order to examine at what temperatures PMCs tend to occur with high or low frequency relative to the number of available observations, with examinations of the maximum temperature at which clouds consistently form, the locations of warm and cold pools within the mesosphere in relation to the locations of the clouds, and whether or not the clouds that occur at the lowest latitudes consistently occur in abnormally cool regions as opposed to regions with higher water vapor availability, or where both elements are or are not present. This analysis is somewhat limited due to the temporal and spatial inconsistencies between the two satellites (their orbits do not coincide with one another exactly); as such the results of this research may provide insight into the extent to which data from these satellites is compatible when studying low latitudinal cloud occurrence. My analysis calculates zonal averages of the data from both satellites in order to minimize the spatial and temporal inconsistencies.

The retrieval algorithms for the version 4 data tends to struggle with determining the presence of clouds below 60°N and 60°S latitude. Initial runs of the programs used in this analysis that simply plot the orbit strip number against the lowest latitudes of clouds seen on the ascending and descending nodes of each orbit strip quickly demonstrated this difficulty. Data from orbits that occurred at the
genesis of the northern hemisphere PMC season (which usually occurs around late May) seemed to indicate clouds occurring below 40° N, far before the mesospheric temperature has dropped enough to support clouds anywhere except the immediate polar region—thus, these cloud indications were false positives. To ensure that results are not skewed by false positive cloud indicators, a combination of logical exclusion, i.e. disregarding positives below a certain latitude if the DFS absolute value is too high, and manual image analysis of version 5 Level 3c data of questionable borderline clouds to confirm the positive will be used.

Though both versions 4 and 5 of the CIPS data were used in this analysis for comparative purposes, my main correlation analysis uses version 5.10 CIPS data and version 4.2 MLS data. The ALL files of CIPS data used in this analysis include information about every albedo retrieved on that orbit strip, where the CLOUD files only have data for the locations where an albedo over 2 indicates cloud presence. Imbedded in this data is a time and location of each retrieved albedo, where location is determined by a 1 degree averaged bin of latitude and non-integer longitudes. The latitude data is pre-gridded into 110 1° latitude bins, 55 each on the ascending and descending nodes. This would allow an examination of clouds as low as 35°N or S, but due to known retrieval algorithm inaccuracies at the extreme low latitudes in addition to extremely low observed cloud frequencies below 50°N in the 2007 and 2011 seasons, I have restricted my low latitude analysis to the swath between 50°N and 65°N.
Coding

As seen in Appendices A, B, and C, I used several codes to isolate specific interesting elements of low latitudinal cloud data. These included looking at which latitude and longitudes these clouds occurred, the albedo of the lowest latitude cloud in each orbit strip, and the seasonal progression of clouds from higher to lower latitudes as temperatures fall in the mesosphere around the hemispheric summer solstice. My main analysis in coding, however, centered on determining the cloud frequency in varied latitude bins, and comparing the anomalies of these frequencies from the seasonal curve to the anomalies from the seasonal curves of the water vapor mixing ratio and temperature. From the MLS temperature data, I calculate zonal averages in the given latitude bins (50°N-65°N and 75°N-80°N), as well as in 5° increments within the low latitude bin. The two satellites that the data I am using is received from do not follow the same orbital path, though they do use the same type of orbit and cover approximately the same total area on the same day. In instances where there is cloud data but not temperature or water vapor data or vice versa, which happens more frequently at lower latitudes due to the nature of the polar orbits, I still plot the data but do not include the points in my anomaly analysis.

In order to extract cloud correlation with temperature and water vapor from the seasonal tendencies of the data, I smooth each of the seasonal curves on an 8-day loop, in which I average the temperature, cloud frequency, or water vapor mixing ratio of the first eight days of the season, then repeat the process with days two through nine, and three through 10, and so on, looping through until I have an
average smoothed curve of best fit for the entire season. I then subtract each respective smoothed curve from the correspondent original curve, creating a measure of the anomalies. The anomaly curves for each of these three variables is then over-plotted in order to provide a visual representation of the correlations or anti-correlations present in the data. I use IDL to calculate a correlation coefficient between the smoothed cloud frequency and temperature anomaly curves as well as the smoothed cloud frequency and water vapor mixing ratio anomaly curves to further inform the visual analysis of the data.
Results and Analysis

This section discusses the results of the computer programs run and examines the extent to which cloud frequency, temperature, and water vapor are correlated.

Figure 1

This graph demonstrates the daily frequency of clouds observed (number of observations with positive cloud readings divided by the total number of observations with good data) between 75°N and 80°N. Superimposed on this line in red is the smoothing curve, which is used to identify the seasonal cloud frequency trend and is subtracted from the frequency curve to present the cloud anomalies. The x-axis is Days From Solstice (DFS), or in this case days from June 21st (the northern hemisphere’s summer solstice).
In Figure 1, the peak of PMC season is clearly visible between approximately 7 and 20 DFS through the cloud frequencies reaching over 80%. This run was conducted in order to validate the accuracy of the code because similar code and research exists for only high latitude clouds, where my code leaves the latitude bin able to be manipulated so that it works for both high and low latitudes, as well as varying latitude bin sizes. Figure 2 shows a graph created by the same code, run for a bin in this paper’s focus region of 50°N to 65°N.

Figure 2
This graph is similar to Figure 1, showing daily frequency of clouds and the seasonal mean of cloud frequencies, but run for the 50°N-65°N latitudes.
This run also clearly demonstrates a peak in PMC frequency between DFS 7 and 20. At the lower latitude, the frequency was lower at the peak of the season than between 75°N and 80°N by a factor of nearly 10. This is consistent with predictions, as the polar regions are significantly colder than the lower latitudes, and thus in general should form more clouds.

For both Figures 1 and 2, the smoothed curve is subtracted from the frequency curve to get an anomaly curve. This process is repeated for temperature data and water vapor data from the 2007 and 2011 northern hemisphere seasons. The anomaly curves smoothed over five days for the high and low latitude bins are presented below. Unsmoothed versions of these plots can be found in Appendix E as they are scientifically valuable and identify individual days of interest more clearly than smoothed curves, but are more difficult to use to analyze seasonal correlation patterns. The same plots for the 2007 season are found in Figures 3 and 4.
Figure 3

Daily cloud frequency (black) versus seasonal mean cloud frequency (red) for the northern hemisphere 2007 season at 75°N-80°N.
Daily cloud frequency (black) versus seasonal mean cloud frequency (red) for the northern hemisphere 2007 season at 50°N-65°N.
Seasonal Residuals

The following are graphs of the smoothed anomaly curves for cloud frequency, water vapor mixing ratio, and temperature over plotted in order to demonstrate correlation or lack thereof.

Figure 5

A plot of the anomaly curves calculated by subtracting the daily (cloud, temperature, or water vapor) curves from the respective seasonal means for the Northern Hemisphere 2007 season at 50°N-65°N
The anomaly curves have been shown in previous research using older CIPS data versions for high latitude clouds to demonstrate a strong anti-correlation between temperature and cloud frequency, i.e. when cloud frequency is anomalously high, temperature is expected to be anomalously low relative to the seasonal curve. A strong example of this anti-correlation in the lower latitude bin is seen between DFS 3 and 15 in NH07, as well as DFS -10 and -1 in NH11. However, in
time frames such as DFS 20 to 25 in NH07 and DFS 23 to 28 in NH11, this expected anti-correlation is not seen, with both temperature and cloud frequency presenting at anomalously high values for those points in the season¹. It is interesting to note in this instance as well that the water vapor mixing ratio value is at least initially in the high cloud frequency event below its seasonal curve; this is in accordance with Hervig et al. [2009] findings that water vapor concentrations may be observed to decrease as the result of new nucleation of ice particles increasing cloud frequency, but decreasing the water vapor mixing ratio. The anomaly curves for the higher latitude bin of 75˚N to 80˚N for both seasons (NH07 and NH11) are presented below for sake of comparison to the lower latitudes². When broken down into separate variables, the correlations become more easily recognizable, so the rest of the analysis will be discussed using these graphs, with reference to the combined graphs of all three variables. Figures 9-16 are graphs of 50˚N-55˚N and 75˚-80˚N temperature imposed on cloud frequency anomalies for 2007 followed by 2011, 50˚N-55˚N and 75˚-80˚N water vapor mixing ratio imposed on cloud frequency anomalies for 2007 and 2011.³

¹ For ease of visual comparison, in the low latitude bin graphs the water vapor saturation anomalies have been increased in scale.
² For ease of visual comparison, in the high latitude bin graphs the temperature anomalies and water vapor anomalies have both been modified in scale.
³ The 50°-55° latitude is used as representative of the low latitude bin (50°N-65°N) due to lack of water vapor mixing ratio data from the MLS between 56° and 65°N. Graphs broken into 5° latitude bins from 55° to 65° are in Appendix D.
Figure 7

A plot of the anomaly curves calculated by subtracting the daily (cloud, temperature, or water vapor) curves from the respective seasonal means for the Northern Hemisphere 2007 season at 75°N-80°N
Figure 8
A plot of the anomaly curves calculated by subtracting the daily (cloud, temperature, or water vapor) curves from the respective seasonal means for the Northern Hemisphere 2011 season at 75°N-80°N
Temperature Anti-Correlation

Figure 9

This plot compares temperature and cloud frequency residuals from the respective seasonal means for the Northern Hemisphere 2007 season at 51°N-55°N. Note that the cloud variability for this latitude and season is extremely low.

In Figure 9 there are several identifiable areas of interest. Strong graphical temperature anti-correlation with cloud frequency is demonstrated between DFS 2 and 11. However, there are some visible contraindications of an anti-correlation, namely those at DFS -18 through -9 and 24 through 30, where an increase in temperature is not associated with a decrease or stagnation of cloud frequency, but rather with an increase in cloud frequency. Both of these occur outside of the peak
of the season, which could increase variability with of correlation at the lower latitudes. The correlation coefficient comparing cloud frequency anomaly and temperature for the DFS -20 to 0 period is 0.44, which is indicative of a weak positive correlation with temperature. The 0 to 30 DFS period has a correlation coefficient of -0.06, demonstrating neither correlation nor anti-correlation definitively. The weak or non-definitive correlations seen in the low latitude bin, even around the peak of PMC season, do not reflect the anti-correlation demonstrated in previous research at higher latitudes in the 2007 northern hemisphere season.

**Figure 10**

This plot compares temperature and cloud frequency residuals from the respective seasonal means for the Northern Hemisphere 2007 season at 75°N-80°N.
The 2007 season’s higher latitude [Figure 10] was initially run as a quality check for the data retrieval and coding used in this research due to the availability of results from a similar code that successfully negatively correlates temperature to cloud frequency. It also becomes an interesting study in the seasonal variability expected of PMCs, as clear differences between NH07 and NH11 are presented in this data. However, while temperature is both hypothesized and previously shown to be exponentially negatively correlated to cloud frequency, this study finds that even in a latitude bin of 75°N-80°N, a positive correlation coefficient of 0.69 between DFS -20 and 0 and an indeterminate coefficient of 0.11 between DFS 0 and 30 is present. This surprising positive correlation between temperature and cloud frequency at high latitudes could be a result of movement of clouds from their initial location of formation in a potentially cooler location, differences in CIPS data versions used, or as a result of another external driver of PMCs outside the bounds of this study.
In the NH11 season, plots of cloud frequency anomalies at the lower latitudes [Figure 11] indicate a beginning-of-season anti-correlation with temperature anomalies that is more in line with what previous research has suggested: a demonstrable anti-correlation at the beginning of the PMC season that decreases slightly as the season progresses and temperatures are consistently low. The correlation coefficient of cloud frequency anomalies with temperature anomalies is -0.04 between DFS-20 and 0 and -0.19 between DFS 0 and 30, which suggests no significant anti-correlation. However, visual analysis does indicate a more consistent matching of anomalously high temperature with anomalously low cloud frequency and vice versa fairly consistently across the season at this latitude.

Figure 11
This plot compares temperature and cloud frequency residuals from the respective seasonal means for the Northern Hemisphere 2011 season at 51°N-55°N.
In the higher latitude bin seen in Figure 12, similarly insignificant correlation coefficients are found between cloud frequency anomalies and temperature anomalies (-0.29 between DFS -20 and 0 and -0.19 between DFS 0 and 30). After DFS 20, the temperature anomaly curve appears to correlate with the cloud frequency anomaly curve, however this is within the bounds of the theory that at high latitudes as the PMC season progresses, cloud formation becomes temperature dependent to a lesser extent than in the beginning of the season.
Water Vapor Mixing Ratio Correlation

The following graphs and analysis examine the correlation of water vapor mixing ratio anomalies to the frequency of polar mesospheric clouds observed in the latitude bands of interest.

![Residuals at 51-55 NH07](image)

**Figure 13**

This plot compares water vapor mixing ratio and cloud frequency residuals from the respective seasonal means for the Northern Hemisphere 2007 season at 51°N-55°N.

In the low latitude bin of the NH 07 season shown in Figure 13, a correlation coefficient of -0.54 is seen between the smoothed water vapor mixing ratio anomaly and cloud frequency anomaly curves between DFS -20 and 0, and a coefficient of -
0.34 is seen between DFS 0 and 30. Very low cloud frequency anomalies are seen here, so it is interesting that temperature appears to have a weak correlation (0.44) and water vapor mixing ratio has a slightly stronger anti correlation in DFS -20 to 0.

The high latitude bins of NH 07 support previous research. Though the temperature is positively correlated with cloud frequency (0.69) between DFS -20 and 0, water vapor mixing ratio anomalies are positively correlated with a
coefficient of 0.49, suggesting there was enough water vapor available to form clouds despite the higher temperature. Not enough water vapor data points were available between DFS 0 and 30 to correlate them with cloud frequency.

In this study it is graphically clear in Figure 15 that in the low latitude bins for the 2011 Northern Hemisphere season, the correlation is not as strong between water vapor saturation and cloud frequency as it is between temperature and cloud frequency. For both DFS periods -20 to 0 and 0 to 30, the correlation coefficients
between water vapor mixing ratio anomalies and cloud frequency anomalies are insignificant (-20 to 0 is 0.04 and 0 to 30 is 0.09).

At the higher latitudes in NH11, both temperature and water vapor mixing ratio correlation coefficients are insignificant. The water vapor to cloud frequency coefficient between DFS -20 and 0 is 0.23, and between DFS 0 to 30 is 0.27.

Graphically, a delayed correlation is seen in Figure 16 after approximately DFS 8
through the end of the season, however fluctuations in water vapor anomalies at this latitude in this season were very small, particularly towards the beginning of the PMC season.
Conclusion

The results of this study do not conclusively indicate that lower or higher latitudinal PMCs respond to temperature in a way that is somewhat consistent with research that has been conducted on higher latitudinal PMCs. That is, from the correlation coefficient results, it cannot be said that PMCs are more highly temperature dependent than water vapor mixing ratio dependent.

Though correlation coefficients indicate some peaks in water vapor concentration anomalies that do accompany or precede some of the high cloud frequency anomaly periods, such as at 75°N-80°N in the NH 07 PMC season, the visual cloud frequency anomaly correlation across all latitudes in the study with water vapor mixing ratio anomalies is not as consistent or widespread as the visual temperature anti-correlation.

Notable periods where cloud frequency, temperature, and water vapor appear to be in opposition to the hypothesis include DFS -20 to 0 in the NH 07 low latitude bins, indicating a potential external influence on PMC formation from the two main drivers. This lack of apparent correlation could also be a Daily daisy for June 22nd, 2011, a day which experiences anomalously high temperature, anomalously low water vapor mixing ratio, and anomalously high cloud frequency [LASP, 2011].
manifestation of cloud formation taking up water vapor from the atmosphere; that is, forming more clouds requires more water vapor to freeze, so the amount of water vapor remaining in the atmosphere is reduced. This finding may also suggest that there is an additional factor that is able to override both of the factors that are considered to be the main drivers of cloud formation, or to allow existing clouds from previous days or other locations to continue to exist and grow. As is demonstrated in a daily daisy from a sample day where temperature is high, cloud frequency is high, and water vapor is low (easily visible in the first graph of Appendix E). Clouds in this seemingly contradictory occurrence hold the structure of true clouds, and thus are not false positives created by the retrieval algorithm, and must be externally influenced.

Though visual analysis of the data supports the theory that clouds are generally more dependent on temperature than water vapor at both high and low latitudes, uncertainty is raised by the either insignificant or counterintuitive correlation coefficients, in addition to the demonstrated water vapor dependence in periods where temperature anti-correlation does not appear to be a driving factor. These uncertainties indications that this is not a sufficiently reliable trait to apply to using clouds as proxy indicators for upper mesospheric temperatures. No clear examples of strong anti-correlation between temperature anomalies and cloud frequency anomalies were found in this study through correlation coefficient calculation. Because of the greater success of visual analysis in determining areas of anti-correlation, this may suggest that a correlation coefficient is not the best way to analyze relationships between the CIPS and MLS data. However, as the correlation
between clouds and temperature sought to provide proxy data cannot be validated simply on visual comparison of graphs, unless a subsequent study is able to numerically and consistently demonstrate strong anti-correlation between temperature and cloud frequency anomalies, this study cannot conclude that the presence or absence of PMCs is sufficient to indicate a temperature occurrence of at or below a certain threshold.
Recommendations

This study was limited in the scope of its evaluation to two seasons. It would benefit future research to have a similar study conducted across the best data available for all available seasons from 2007 onwards, in order to have a greater breadth of information and data from which to draw conclusions. Additionally, this study was conducted using zonal averages in order to expedite the process of analysis and to accommodate the coding abilities of the researcher. It could potentially yield more and finer scale local results if this study were conducted in the future using bins of longitude rather than zonal averages by matching data points from the Aura satellite to cloud observations from the AIM satellite within a reasonable longitude bin (of 5° for example) that occurred on the same day. This study should also be rerun once the verification of the retrieval algorithm used to process CIPS v5.10 data is completed and fully vetted, as there are potential data retrieval anomalies that could be impacting the results of this study. These anomalies were validated via manual image analysis in this study, however that methodology leaves room for human error to occur, and faces the downside of being extremely time inefficient to visually examine each individual daily daisy in a month, let alone a full season’s worth of daisies.

This research used data from both the ascending and descending nodes of the CIPS orbit strips. Due to the effect of the terminator limiting the low latitudinal visibility on the ascending nodes of the orbit strips, this may have inserted an analytical bias at the lower latitude analysis, which has not had to be accounted for at high latitudes that occur consistently above the terminator. Further research
could examine the extent of this bias, and provide suggestions for limiting or mitigating the bias for research conducted on low latitude PMCs. This could be as simple as analyzing only the descending node in the northern hemisphere at both high and low latitudes in order to achieve consistency across all latitudes of data.

In continuing research, use of other satellite retrievals of water data that are able to distinguish between ice water and water vapor, such as the Solar Occultation for Ice (SOFIE) instrument available on the AIM satellite could be compared to pure water vapor mixing ratio results from the MLS instrument on the Aura satellite, and this comparison could be used to increase the understanding of water vapor correlation to cloud formation.


Appendices

Appendix A: MLS Data Retrieval and Organization Code

mdir=’/Volumes/atmos/aura6/data/MLS_data/Datfiles_SOSST/’ ;;; might be atmos-1, might not need /Volumes

PATH = ’/users/Ekirby/Thesis_IDL/CIPS_data/’
FNAME = ’cips_3c_north_11_v05.10_r01_02G_all.sav’ ;Name of file to be restored
RESTORE,PATH+FNAME
VERSION = STRMID(FNAME,19,4) ;Extracts the version number from FNAME and calls it ”VERSION”
;; 14 IS THE INDEX OF THE START OF THE STRING, AND THE STRING IS 10 CHARACTERS LONG
HEM = STRMID(FNAME,8,1) ;EXTRACTS ”n” OR ”s”
HEM = STRUPCASE(HEM)+’H’ ;CONVERTS ”n” OR ”s” TO ”N” OR ”S” AND ADDS H FOR NH OR SH
;; WE COULD HAVE COMBINED THE TWO LINES ABOVE INTO A SINGLE LINE.
SEASON = STRMID(FNAME,14,2) ;EXTRACTS THE YEAR (YY)

DT=DATE
DFS=YYYYMDD_TO_DFS_NH(DATE)

LAT=(LATHI + LATLO)/2.0
nlat=n_elements(lat)
LATA = LAT(0:NLAT/2-1) ;ASCENDING NODE LATITUDES
LATD = LAT(NLAT/2:*); DESCENDING NODE LATITUDES
ALBA = ALB(*,0:NLAT/2-1) ;ASCENDING NODE ALBEDOS
ALBD = ALB(*,NLAT/2:*); DESCENDING NODE ALBEDOS
LONA = LON(*,0:NLAT/2-1) ;ASCENDING NODE LONGITUDES
LOND = LON(*,NLAT/2:*); DESCENDING NODE LONGITUDES
Fill=-99

LAT=(LATHI + LATLO)/2.0
nlat=n_elements(lat)
dfsmin=min(dfs)
dfsmax=max(dfs)
ndays=dfsmax-dfsmin+1
DAYS=indgen(ndays) + min(dfs)
latbot=40
lattop=65
ncloudbins=360

;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

; define matrix that serves as the bin
; CLOUDBIN(i,j) is day i(column i) by binj (row j). dimensions should equal ndays (#columns - across top)
; and ncloudbins (360, one for each degree lon)
; CLOUDBIN value = 0 if no cloud, value=1 if cloud

cloudbinA = fltarr(ndays,ncloudbins)
; LOOP OVER DAYS: this works for cips 3c data because dfs and date are the same size and 1-to-1
;
for i=0,ndays-1 do begin
  x=where (dfs eq Days(i),nx) ;vector of indicies of orbits on day i
  if nx gt 0 then begin ;loops over orbits on this day i using index
    date_today=DT(x(0)) ; get the YYYYMMDD that corresponds to the DFS today
    sdate_today=strcompress(date_today,/r)

    for index= 0, nx-1 do begin
      ;index is pulling information from individual orbit strips, separates them by day (x)
      orb_albedoa= reform(ALBA(x(index),*))
      orb_latA=LATA
      orb_lonA= reform(LONA(x(index),*))
      for m = 0,54 do begin
        ; loop over all measurements (points) in orbit (long, alb)
        if (orb_albedoa(m) gt 2) and (orb_latA(m) ge latbot) and (orb_latA(m) le lattop) then begin
          ; The above says: Are you a cloud in the band of interest?
          ; gets us in right lat strip
          ; gets us in right longitude strip
          ; abl greater than x is a cloud, so are you a cloud.
          j= floor(orb_lonA(m))
          cloudbinA(i,j)=1
        endif
      endfor
    endfor
  endif
endfor
;
; READ MLS TEMPERATURE and WATER
; NOTE, there is a DATE variable in MLS that will overwrite the existing "DATE" variable
;
dum=findfile(mdir+"cat_mls_v4.2_"+sdate_today+".sav")
print,dum
if dum(0) ne '' then begin ; if there is temperature data today then read it
  restore,mdir+"cat_mls_v4.2_"+sdate_today+".sav"
  restore,mdir+"h2o_mls_v4.2_"+sdate_today+".sav"
  restore,mdir+"tpd_mls_v4.2_"+sdate_today+".sav"
  print,'restored file'
  ;
  ; check
  ;
  ;map_set,0,0,0,/contin
  ;oplot,longitude,latitude,psym=1
  ;
  ; set bad data to fill value
  ;
  index=where(mask eq -99.)
  if index(0) ne -1L then mix(index)=-99.
  h2o=mix
good = where(h2o ne -99.)
h2o(good) = h2o(good)*1.e6
index = where(temperature_mask eq -99.)
if index(0) ne -1L then temperature(index) = -99.

; only save NH and only between latbot and lattop
; good = where(latitude gt 0.)
good = where(latitude ge latbot and latitude le lattop)
if good(0) ne -1L then begin
   id = id(good)
lngitude = longitude(good)
latitude = latitude(good)
fdoy = fdoy(good)
pressure = reform(pressure(good,*))
temperature = reform(temperature(good,*))
temperature_error = reform(temperature_error(good,*))
h2o = reform(h2o(good,*))
endif

; on the first day, declare the arrays in which to hold all of the data
if i eq 0L then begin
   date_all = date_today + lonarr(n_elements(id))
   fdoy_all = fdoy
   longitude_all = longitude
   latitude_all = latitude
   temperature_all = temperature
   temperature_error_all = temperature_error
   h2o_all = h2o
endif

; on all subsequent days, concatenate the data and retain it all.
if i gt 0L then begin
   date_all = [date_all, date_today + lonarr(n_elements(id))]
   fdoy_all = [fdoy_all, fdoy]
   longitude_all = [longitude_all, longitude]
   latitude_all = [latitude_all, latitude]
   temperature_all = [temperature_all, temperature]
   temperature_error_all = [temperature_error_all, temperature_error]
   h2o_all = [h2o_all, h2o]
endif
help, date_all, fdoy_all, temperature_all
stop
endif
print, date_today
endfor

save, filename='mls_2011_all.sav', date_all, fdoy_all, h2o_all, latitude_all, longitude_all, temperature_all, temperature_error_all
Appendix B: Seasonal Cloud Frequency and Smoothing Code

PATH = '/users/Ekirby/Thesis_IDL/CIPS_data/'
FNAME = 'cips_3c_north_11_v05.10_r01_02G_all.sav' ;Name of file to be restored
RESTORE,PATH+FNAME ;Loads the data into IDL
VERSION = STRMID(FNAME,19,4) ;Extracts the version number from FNAME and calls it "VERSION"
; 14 IS THE INDEX OF THE START OF THE STRING, AND THE STRING IS 10 CHARACTERS LONG
HEM = STRMID(FNAME,8,1) ;EXTRACTS "n" OR "s"
HEM = STRUPCASE(HEM)+'H' ;CONVERTS "n" OR "s" TO "N" OR "S" AND ADDS H FOR NH OR SH
; WE COULD HAVE COMBINED THE TWO LINES ABOVE INTO A SINGLE LINE.
SEASON = STRMID(FNAME,14,2) ;EXTRACTS THE YEAR (YY)

DFS=YYYYMMDD_TO_DFS_NH(DATE)

lattop=80
latbot=75
Fill=-999

LAT=(LATHI + LATLO)/2.0
nlat=n_elements(lat)
dfsmmin=min(dfs)
dfsmmax=max(dfs)
ndays=dfsmmax-dfsmmin+1
DAYS=indgen(ndays) + min(dfs)

for i=0,nlat-1 do lat(i)=((lathi(i)+latlo(i))/2.0)
ndays=max(dfs)-min(dfs)+1
ddd = indgen(ndays)+min(dfs)
array=fltarr(ndays,nlat)-99
totclouds=array
totobs=array

for i=0,ndays-1 do begin
  x=where(dfs eq ddd(i),nx)
  if nx gt 0 then begin
    cld=num_cld(x,*) & obs=num_obs(x,*)
    for j=0,nlat-1 do begin
      good=where(cld(*,j) ne fill and obs(*,j) gt 0,ngood)
      if ngood gt 0 then begin
        totclouds(i,j)=total(cld(good,j))
        totobs(i,j)=total(obs(good,j))
        array(i,j)=total(cld(good,j))/total(obs(good,j))
      endif
    endfor
  endif
endfor

bad=where(array eq -99)
array(bad)=0./0
binarray=fltarr(ndays)-99
for i=0, ndays-1 do begin
    good=where(lat ge latbot and lat le lattop, ngood)
    if ngood gt 0 then begin
        temp=reform(array(i,good))
        good2=where(finite(temp) eq 1, ngood2)
        if ngood2 gt 0 then begin
            binarray(i)=mean(temp(good2))
        endif
    endif
endfor

bad=where(binarray eq -99)
binarray(bad)=0./0

print, binarray
plot, days, 100.*binarray, /ynoz

set_plot, 'PS'
DEVICE, /COLOR,BITS_PER_PIXEL=8
DEVICE, SET_FONT='TIMES BOLD', /TT_FONT ;MAKES NICE-LOOKING FONTS.
!P.FONT=1 ;REQUIRED FOR THE ABOVE COMMAND TO TAKE EFFECT
DEVICE, FILENAME = 'Cloudfreq_'+HEM+SEASON+'_v'+VERSION+'.ps'

!P.CHARSIZE=2 ;CHARACTER SIZES WILL BE TWICE AS LARGE AS DEFAULT
!P.THICK=4 ;SOME LINES/TEXT WILL BE THICKER THAN NORMAL
!X.THICK=4 ;X AXIS LINE WILL BE THICKER THAN NORMAL
!Y.THICK=4 ;Y AXIS LINE WILL BE THICKER THAN NORMAL
LOADCT,39
binarray=100.*binarray
YMIN = MIN(binarray,/NAN) & YMAX=MAX(binarray,/NAN)
PLOT,days, BINArray,thick=10,XTITLE='Days From Solstice',YTITLE='Cloud Frequency (%)', $
    $YRANGE=[YMIN,YMAX], TITLE='Seasonal Cloud Variance at 50-65 ' + HEM + SEASON, $
    $SUBTITLE='CIPS v'+version, XSTYLE=1
OPLOT,days,smooth(Binarray,8,/nan),thick=10, color=240
xyouts,0.28,0.75,'Cloud Frequency',/normal,charsize=1.5,color=0
xyouts,0.28,0.70,'Seasonal Mean',/normal,charsize=1.5,color=240

Device,/close
set_plot, 'x'

END
Appendix C: Data Analysis and Plotting Code

PATH1 = '/users/Ekirby/
PATH2 = '/users/Ekirby/Thesis_IDL/CIPS_data/
FNAME1 = 'mls_2007_5065_all.sav'
fname2 = 'cips_3c_north_07_v05.10_r01_02G_all.sav'
restore, path1+fname1
restore, path2+fname2

latitude=indgen(121) ; should have put in save file but need to define because I didn’t

lattop=65
latbot=50
Fill=-999

LAT=(LATHI + LATLO)/2.0
nlat=n_elements(lat)

DFS_MLS=YYYYMMDD_TO_DFS_NH_MLS(DATE_all)

dfsMLS_min=min(dfs_MLS)
dfsMLS_max=max(dfs_MLS)
ndays=dfsMLS_max-dfsMLS_min+1
MLS_DAYS=indgen(ndays) + min(dfs_MLS)

fill=-99

MLS_T = fltarr(ndays)-99
T = reform(temperature_all(*,87)) ;;; 87 is the altitude HARDWIRED IN
for dayi = 0,ndays-1 do begin
    good = where(dfs_mls eq mls_days(dayi) and t ne -99,ngood)
    if ngood gt 10 then begin
        mls_t(dayi)=mean(t(good))
    endif
endfor

bad=where(mls_t eq -99)
mls_t(bad)=0./0

;plot,dfs_mls,temperature_all(*,83),psym=3
;oplot,mls_days,mls_t,thick=4

MLS_w = fltarr(ndays)-99
w = reform(h2o_all(*,87)) ;;; 87 is the altitude HARDWIRED IN: MANIPULATE THIS FOR OTHER ALTITUDES
for dayi = 0,ndays-1 do begin
    good = where(dfs_mls eq mls_days(dayi) and w ne -99,ngood)
    if ngood gt 10 then begin
        mls_w(dayi)=mean(w(good))
    endif
endfor
bad = where(mls_w eq -99)
mls_w(bad) = 0./0

; screen plots to use to check code run
; oplot, mls_days, h2o_all(*, 83), psym=3, color=240
; oplot, mls_days, mls_w, thick=4, color=240
; plot, mls_days, mls_t, thick=4, /ynoz
; oplot, mls_days, smooth(mls_t, 8, /nan), color=240, thick=5
; plot, mls_days, mls_t-smooth(mls_t, 10, /nan), thick=2, /ynoz
; oplot, mls_days, smooth_w(mls_w, 10, /nan), thick=2, color=700000, thick=5

plot, mls_days, smooth(1*(binarray-smooth(binarray,10, /nan)), 5, /nan), thick=1, xrange=[-20, 30]
oplots, mls_days, 4*smooth(1*(mls_t-smooth(mls_t, 10, /nan)), 5, /nan), color=240, thick=1
oplots, mls_days, 8*smooth((mls_w-smooth(mls_w, 10, /nan)), 5, /nan), color=700000, thick=1

;;; PLOTTING SECTION ;;

set_plot, 'PS'
device, /color, bits_per_pixel=8
device, set_font='TIMES BOLD', /tt_font ; makes nice-looking fonts.
!P.FONT=1 ; required for the above command to take effect
device, filename = '07NH_5065.ps'

!P.CHAR_SIZE=2 ; character sizes will be twice as large as default
!P.THICK=4 ; some lines/text will be thicker than normal
!X.THICK=4 ; x axis line will be thicker than normal
!Y.THICK=4 ; y axis line will be thicker than normal
loadct, 39

; ; all variables ;
; YMIN = MIN(binarray, /NAN) & YMAX=MAX(binarray, /NAN)
plot, mls_days, 8*smooth((binarray-smooth(binarray, 8, /nan)), 5, /nan), thick=10,
xrange=[-15, 30], yrange=[-1.5, 2.0], xtitle='Days From Solstice', ytitle='Anomaly', $ 
  title='Residuals at 50-65 ' + hem + season, $
  subtitle='CIPS v5.10, MLS v4.2', xstyle=1
oplots, mls_days, 4*smooth((mls_t-smooth(mls_t, 8, /nan)), 5, /nan), color=240, thick=10
oplots, mls_days, 3*smooth((mls_w-smooth(mls_w, 8, /nan)), 5, /nan), color=70, thick=10
xyouts, 0.3, 0.82, 'Cloud Frequency', /normal, charsize=1.5, color=0
xyouts, 0.3, 0.78, 'Temperature', /normal, charsize=1.5, color=240
xyouts, 0.3, 0.74, 'H2O Mixing Ratio', /normal, charsize=1.5, color=70

;;; Clouds vs. H2O ;
PLOT, MLS_days, 8*smooth((binarray-smooth(binarray,8,/nan)),5,/nan), thick=10, xrange=[-15,30],/yloz, XTITLE='Days From Solstice', YTITLE='Anomaly', $ TITL E='Residuals at 50-65 ' + HEM + SEASON, $ SUBTITLE='CIPS v5.10, MLS v4.2', XSTYLE=1
opl ot, mls_days, 3*smooth((mls_w-smooth(mls_w,8,/nan)),5,/nan), color=70, thick=10
xyoute s, 0.3, 0.8, 'Cloud Frequency', /normal, charsize=1.5, color=0
xyouts, 0.3, 0.76, 'H2O Mixing Ratio', /normal, charsize=1.5, color=70

;;; Clouds vs. Temp;;;

PLOT, MLS_days, 8*smooth((binarray-smooth(binarray,8,/nan)),5,/nan), thick=10, xrange=[-15,30], yrange=[-1.5,2.0], XTITLE='Days From Solstice', YTITLE='Anomaly', $ TITL E='Residuals at 50-65 ' + HEM + SEASON, $ SUBTITLE='CIPS v5.10, MLS v4.2', XSTYLE=1
opl ot, mls_days, 4*smooth((mls_t-smooth(mls_t,8,/nan)),5,/nan), color=240, thick=10
xyoute s, 0.3, 0.8, 'Cloud Frequency', /normal, charsize=1.5, color=0
xyouts, 0.3, 0.76, 'Temperature', /normal, charsize=1.5, color=240

Device, /close
set_plot, 'x'

END
Appendix D: Other Latitude Bins

Residuals at 56-60 NH07

Cloud Frequency
Temperature
H2O Mixing Ratio

Days From Solstice
CIPS v5.10, MLS v4.2

Residuals at 61-65 NH07

Cloud Frequency
Temperature
H2O Mixing Ratio

Days From Solstice
CIPS v5.10, MLS v4.2
Residuals at 56-60 NH11

![Graph showing residuals at 56-60 NH11 with axes for days from solstice and anomaly, showing data points for cloud frequency, temperature, and H2O mixing ratio.]

Residuals at 61-65 NH11

![Graph showing residuals at 61-65 NH11 with axes for days from solstice and anomaly, showing data points for cloud frequency, temperature, and H2O mixing ratio.]

CIPS v5.10, MLS v4.2
Appendix E: Unsmoothed NH11 Anomalies

40°N-65°N NH11