INTER-ANNUAL AND DIURNAL VARIABILITY IN CLOUDS OBSERVED FROM MSL OVER TWO MARTIAN YEARS Jacob L. Kloos[1*] and John E. Moores[1], [1]York University, Centre for Research in Earth and Space Sciences, Toronto, Ontario, Canada *(jlkloos@yorku.ca)

Introduction: The Mars Science Laboratory (MSL) rover Curiosity has been operational in Gale Crater (4.5° S, 137.4° E) for over two Martian years. From the onset of the mission, Curiosity has executed two separate cloud imaging observations that have captured tenuous, sub-optical water-ice and dust clouds in the skies of its landing site. Each observation consists of a sequence of images captured using a specific pointing of the rover's Navigation Cameras (Navcam): Zenith Movies (ZMs) use a vertical pointing while Supra-Horizon Movies (SHMs) use a lower elevation angle pointing. These observations have been conducted with a regular cadence, and in the first two Martian years of operations, Curiosity has returned 508 observations.

The equatorial latitude of Gale Crater has enabled consistent imaging of the aphelion cloud belt (ACB) during the aphelion seasons (centered around $L_S = 71°$) of Mars Year (MY) 32 and 33. The ACB is an annually recurring equatorial belt of water-ice clouds covering latitudes between 10° S and 30° N during the aphelion season of Mars [1, 2], and is now recognized as one of the two major seasonal cloud regimes that occur on Mars - the other being polar hood clouds. In contrast to the dusty perihelion season, which exhibits a high degree of inter-annual variability and is characterized by intermittent regional dust storms and semi-annual global dust storms, the aphelion season has shown little inter-annual variation in temporal and geographic distribution of water-ice clouds [2]. The ACB, however, has shown a diurnal pattern, as cloud activity appears enhanced either in the early morning [3] or late afternoon [4].

We report on MSL ZMs and SHMs over a two Martian year period between $L_S = 150°$ of MY 31 to $L_S = 160°$ of MY 33. We compare the inter-annual variation in cloud opacity between the aphelion seasons of MY 33 and 32, as well as the diurnal variability in MY 33.

Diurnal variability of ACB during MY 33: Figure 1 shows cloud opacity as a function of Local True Solar Time (LTST). Although the data gap in the late morning complicates the assessment, diurnal patterns are still evident. The data show enhanced cloud activity in the morning hours between 07:00-09:00, as many of the highest opacity clouds detected occur during this interval. Additionally, a steady enhancement of opacity is seen as the day progresses, with a minimum occurring in the late morning, which steadily builds until a second peak is reached in the late afternoon between 15:00-17:00. The afternoon peak in cloud opacity, however, is only 72% of its morning counterpart (between 07:00-09:00), indicating that the atmospheric conditions in the early morning hours are more favorable for the formation of thicker clouds.

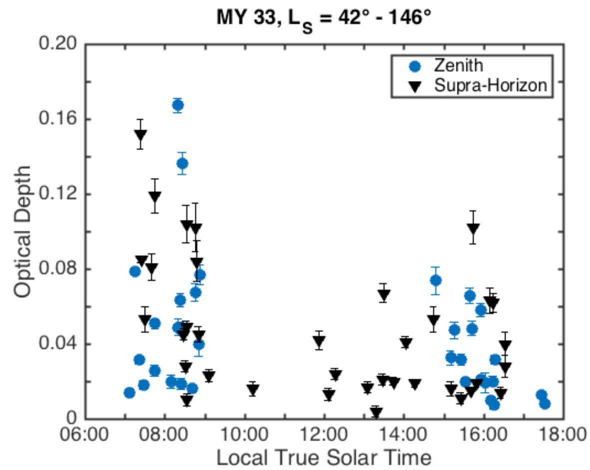

Figure 1. *Optical depth versus time of day for the ZMs and SHMs. The MSL data has good coverage between 07:00-09:00 and 12:00-18:00 LTST in MY 33. The lack of data between 09:00-12:00 is due to the timing of the uplink sequence, which occurs near 10:00 LTST.*

Inter-annual variability: Figure 2 shows cloud opacity with the 95% confidence interval as a function of season for MY 32 (top) and MY 33 (bottom). Compared to MY 32, an increased number of higher opacity clouds are observed in the ZMs and SHMs, as 11% of the movies acquired during $L_S = 42°\text{-}146°$ have an opacity > 0.1. The SHM data set exhibits a substantial increase (400%) in opacity in MY 33, which is attributed to the disproportionately low values seen during the aphelion season of MY 32, compared to the ZMs. While the reason for the disparity between the ZM and SHM optical depth MY 32 is unclear, this does appear consistent with the low quality of the SHM observations reported by Kloos et al. [5] during this time period. The consistency of the ZM observation therefore permits a more precise assessment of the inter-annual variation in cloud opacity. In MY 33, the ZM data set exhibits a 38% increase in average opacity.

Discussion: *Diurnal variability:* The structure and temporal evolution of water-ice clouds associated with the ACB was shown to be strongly influenced by tidal temperature variations [3], suggesting that diurnal trends in cloud activity are expected. The enhancement of cloud formation in the morning hours is not surprising, as saturation conditions are increased when the temperature is diminished with all other variables being equal. The trend of increasing clouds throughout the day, however, is unexpected as higher temperatures should decrease the probability of saturation. One explanation for the afternoon enhancement put forth by Tamppari et. al. [4] is that as atmospheric temperatures increase in the throughout the day, enhanced convection lifts water vapor to the saturation altitude, therefore increasing the likelihood of cloud formation. In addition to water vapor, dust could also be lifted, which act as condensation nuclei, allowing for more efficient cloud formation.

Inter-annual variability: The 38% increase in cloud opacity in MY 33 is significant as the aphelion season of Mars has shown a high degree of repeatability. This large inter-annual variation, however, is likely due to a statistical bias in the diurnal distribution of ZMs and SHMs in MY 32 and MY 33, given that substantially more early morning observations were acquired in MY 33 compared to MY 32. When this statistical bias is accounted for, there is < 5% difference in cloud opacity between the Mars years examined, which is expected given the low inter-annual variation observed from orbital data sets. For comparison, using thermal IR data from Viking (MY 12-14) and Mars Global Surveyor (MY 23-26) between L_S = 105°-130° Liu et al. [6] observed <10% difference in water-ice cloud opacity for the ACB between Mars years.

Conclusions: Diurnal variation in cloud is examined between L_S = 42°-146° of MY 33. Increased opacity is occurs the morning hours between 07:00-09:00. The opacity appears lowest near midday, although the diminished coverage between 09:00-13:00 limits the analysis that can be made. Cloud opacity is found to steadily increase as the day progresses, reaching another maximum in the late afternoon between 15:00-17:00.

Additionally, we observe higher opacity in MY 33, however we attribute this inter-annual variation to a statistical bias in the diurnal distribution of the ZMs and SHMs. When this bias is accounted for, <5% variation in cloud opacity is seen in the ZM data set between the two Mars years observed, which is expected given the highly repeatable aphelion season of Mars.

References: [1] R.T. Clancy (1996) *Icarus*, 122 (1):36–62. [2] M. D. Smith (2004) *Icarus*, 167(1):148–165. [3] D. P. Hinson and RJ Wilson (2004) *JGR:Planets*, 109(E1). [4] L. K Tamppari (2003) *JGR* 108(E7). [5] J.L Kloos (2016) *ASR*, 57 (5):1223–1240. [6] J. Liu (2003) *JGR:Planets 108*(E8)

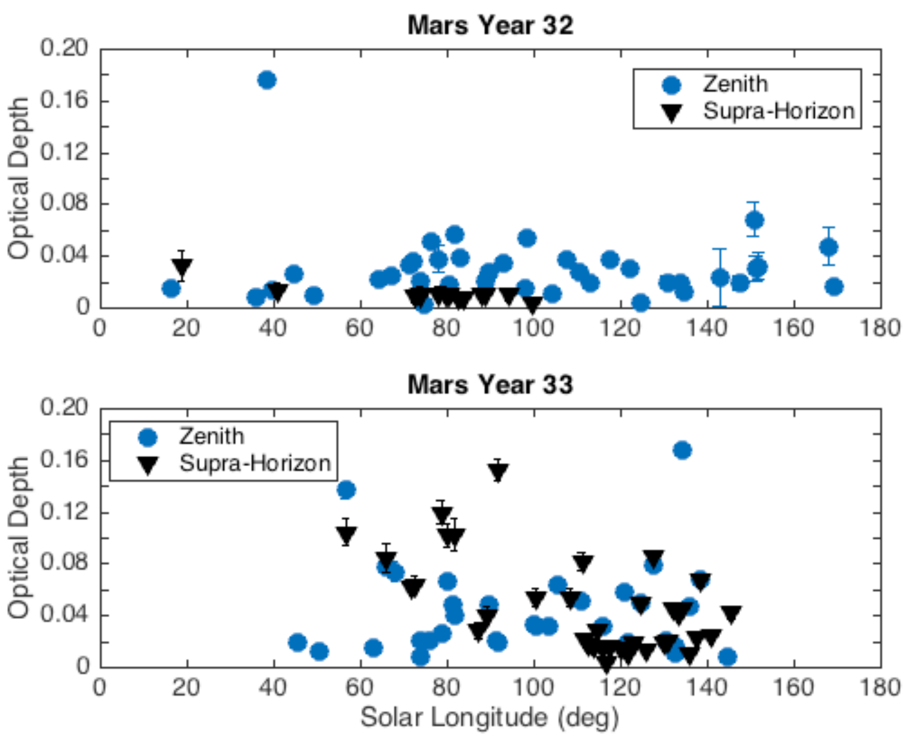

Figure 2. *Average cloud opacity and the 95% CI as a function of season for the aphelions seasons of MY 32 (top) and MY 33 (bottom).*