GLOBAL CIRCULATION OF THE THERMOSPHERE OF MARS AS REVEALED BY MAVEN/NGIMS MEASUREMENTS. S. W. Bougher¹, M. Benna², Y. Lee², K. J. Roeten¹, E. Yiğit³, P. R. Mahaffy², and B. Jakosky⁴,
¹University of Michigan, Ann Arbor, MI (bougher@umich.edu), ²NASA Goddard Space Flight Center, Greenbelt, MD, ³George Mason University, Fairfax, VA, ⁴LASP, University of Colorado, Boulder, CO.

Introduction: Global circulation in planetary thermospheres plays an important role in redistributing energy and momentum both locally and globally, it strongly affects neutral and ion composition distributions, and it drives a variety of electrodynamic processes. From initial studies, we report the results of the first mapping of the global circulation in the thermosphere of Mars that was made by the Mars Atmosphere and Volatile Evolution mission (MAVEN) spacecraft. The Neutral Gas and Ion Mass Spectrometer (NGIMS) instrument has collected observations of thermospheric winds organized in 33 campaigns that span 2 years (2016 – 2018) [1]. The measured neutral winds (cross track and along track components) reveal seasonally-stable equatorial and transpolar flow patterns, with stagnation and convergence regions on the day and night sides, respectively. However, striking short-term (orbit-to-orbit) variability of these winds is also observed on ~4.5 hour timescales [1, 2]. Lastly, these winds exhibit pronounced correlation with the underlying topography likely due to the impact of upward propagating orographic gravity waves.

NGIMS Wind Measurements and Campaigns: Since April 2016, a new observational technique has been implemented that enables the NGIMS instrument to take regular measurements of horizontal neutral winds [1]. During this sampling mode, the normal data collection of NGIMS is paused [3, 4] to allow for wind observations to be conducted. The new wind measurement technique relies on the ability of the MAVEN spacecraft to rapidly and continuously vary the boresight pointing by nodding the articulated payload platform (APP) on which NGIMS is mounted back and forth by ±8° off the spacecraft ram direction. Wind velocities were extracted from the observed modulations of neutral and ion fluxes as the instrument pointing direction changed. The data reduction procedure is detailed elsewhere [1]. The resulting wind measurements were retrieved over an altitude range of ~140 - 240 km. Measurements were separated by the 30 seconds it takes for the instrument boresight to complete a full APP motion cycle. Reconstructed along- and across-track wind magnitudes have a random uncertainty typical of 20 m/s and 6 m/s, respectively. These uncertainties are carefully evaluated and are mainly due to inherent errors in the reconstructed ephemeris of the spacecraft and the direction of the instrument boresight, in the energy resolution of the instrument’s mass filter, and in counting statistics. See [1] for details.

The resulting dataset of zonal and meridional wind measurements is now an MAVEN NGIMS Level 3 data product. Most wind measurements were collected in monthly campaigns, typically of two to three day duration. NGIMS conducted a set of consecutive 5-10 orbits of neutral wind observations over the same local time and latitude region (but different longitudes as the planet rotates). For the purpose of comparing to the M-GITM model [5], these 5-10 consecutive orbits can be averaged to produce a campaign-average profile. Campaign averaging is effectively also a longitudinal average, as the MAVEN periapsis traverses the planet in longitude approximately once every five orbits [6]. To help assess the orbit-to-orbit variability of the winds, a quantity called the coefficient of variation (COV) was also calculated [2, 7]. This quantity provides a dimensionless scalar measure of the orbit-to-orbit variability of the winds related to both variability in direction and magnitude.

M-GITM Corresponding Simulations: The Mars Global Ionosphere Thermosphere Model (M-GITM) [5], a primarily solar driven climate model, was run for sampling conditions corresponding to selected campaigns to create a suite of baseline predictions of neutral winds which were compared to the corresponding NGIMS wind measurements [1, 2]. Pre-MAVEN simulations are used in this specific study [5]. M-GITM wind vector maps at a constant altitude for a given season and solar EUV-UV flux conditions can be used for initial comparisons with the suite of NGIMS wind campaign measurements.

Global Thermospheric Flow Patterns: The current collection of all neutral winds (averaged wind vectors assessed for each campaign) that were measured is illustrated in Figure 1. These average neutral winds (whiskers) and the magnitude of their orbit-to-orbit variability (whisker’s color code) are plotted as observed by NGIMS during 33 monthly campaigns spanning April 2016 to July 2018. The orbit-to-orbit variability of the winds for a given location is captured by the COV (color scale). No variability is assessed for campaigns that involved a single orbit (black whiskers). The MAVEN ground tracks are shown by the black traces.
The location of the periapsis is depicted by the black dots. The relevant season of each campaign is indicated by the Solar Longitude (Ls).

An underlying neutral wind flow map generated by the M-GITM model is shown in gray for a general comparison [5]. This MGITM map represents the expected winds at 150 km for Ls = 180 (equinox) season and under moderate solar EUV conditions. These NGIMS average neutral wind observations provide the first global view of thermospheric circulation at Mars. However, the sampling coverage over latitude and solar local time is not complete. Continued measurements during MAVEN Extended Mission-4 will fill in many of these gaps, and provide sampling that spans multiple seasons for the same location.

Figure 1. Thermospheric wind vector map for NGIMS wind campaigns (C#1 to C#33). The color code indicates the COV index (described in the text). Taken from Benna et al. (2019).

Notice that: (a) the measured neutral wind vectors reveal seasonally-stable equatorial and transpolar flow patterns, with stagnation and convergence regions on the day and night sides, and (b) the COV scalar diagnostic identifies campaigns when orbit-to-orbit variability was minimal (blue colors) and campaigns when variability was significant (yellow-orange-red colors). Data-model comparisons of winds (magnitudes and directions) show agreement sometimes, and diverge at other times. These features have implications for the drivers of the mean global circulation and its significant short-term variations [2].

Correlation of Winds with Underlying Topography: Due to planetary rotation, the MAVEN spacecraft overflies distinct Martian terrains on successive orbits [1, 6]. The analysis of the orbit-to-orbit variations of the measured winds during campaigns C#17 and C#18 revealed a pronounced correlation between the observed wind variability and the underlying topography of the planet. These two campaigns are unique in two important aspects. First, they covered the latitudinal band of ±30° over which Mars exhibits its topographic transition between the southern highlands and the northern lowlands. This band encompasses also the pronounced elevated terrains of the Tharsis plateau (i.e. volcanoes). Second, these two campaigns captured the relatively strong and steady equatorial westward flows that advect thermospheric constituents from day to night. These steady flows exhibit the lowest orbit-to-orbit COV of all equatorial campaigns. We postulate that the intrinsic stability of the neutral flows in this region was key to revealing the faint (background) disturbances that are induced by the varying Martian topography. This topographic correlation represents the first detection of orographic gravity wave signatures in the upper atmosphere of a planet, including that of Earth. Measurements of additional topographic correlations at other seasons and locations are clearly needed. In the future, detailed wave modeling is also essential to demonstrate the causal mechanism impacting thermospheric winds involving vertical propagating orographic gravity waves [8, 9].

Summary: Observations from the MAVEN NGIMS instrument at Mars have provided the first mapping of the global circulation of a planetary thermosphere other than Earth. Studies are underway to determine the physical processes which play a significant role in driving mean thermospheric winds speeds and directions (and their variations) during these campaigns. Solar forcing appears to compete with gravity wave impacts resulting from coupling with the lower Martian atmosphere during specific seasons and at specific locations around the planet.

References: