10 YEARS OF ENVIRONMENTAL SCIENCE IN GALE CRATER. S. D. Guzewich[1], G. Martínez[2], A. Innanen[3], J. Pla-García[4], M. Ruíz-Pérez[4], M. de la Torre Juárez[5], C. E. Newman[6], M. Lemmon[7], G. Bischof[3], M. I. Richardson[7], J. Moores[3], E. Mason[8,1], J. M. Battalio[9], Á. de Vicente-Retortillo[4], T. McConnochie[7], C. Hayes[3], A. A. Fraeman[5], A. Vasavada[5], and the MSL Environmental Science Theme Group, [1]NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771 (scott.d.guzewich@nasa.gov), [2]Lunar and Planetary Institute, Houston, TX, [3]York University, Toronto, Canada, [4]Centro de Astrobiología (CSIC-INTA), Madrid, Spain, [5]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [6]Aeolis Research, Pasadena, CA, [7]Space Science Institute, Boulder, CO, [8]University of Maryland Baltimore County, Catonsville, MD, [9]Yale University, New Haven, CT.

Introduction: The Mars Science Laboratory (MSL) Curiosity rover has collected the longest comprehensive *in situ* environmental science record on the Red Planet. Since the beginning of the mission, the Atmosphere and Environment science theme group has participated in operations on each planning day, to advocate for and coordinate the scheduling of environmental science activities within Curiosity's larger portfolio of science and engineering activities.

Curiosity's environmental science activities represent a varied suite of observations that have utilized nearly every instrument on the rover. These include, but are certainly not limited to: the pressure, temperature, wind, humidity, and UV radiation measurements by the Rover Environmental Monitoring Station (REMS), atmospheric cloud and dust lifting movies with the Navigation Cameras (Navcam), measurements of atmospheric opacity and aeolian activity with the Mast Camera (Mastcam), atmospheric gas and aerosol property spectroscopy with the Chemistry and Camera (ChemCam), atmospheric gas composition with the Sample Analysis at Mars (SAM), radiation environment measurements with the Radiation Assessment Detector (RAD), measurements of atmospheric argon with the Alpha Particle X-Ray Spectrometer (APXS), subsurface hydration with the Dynamic Albedo of Neutrons (DAN), imaging of triboelectric charging of saltating sand grains with the Mars Hands Lens Imager (MAHLI) and aeolian activity with both MAHLI and the Mars Descent Imager (MARDI). Many of these observations are taken at daily frequency or higher (e.g., REMS and RAD measurements), while others are typically taken multiple times per week (e.g., Navcam atmospheric movies and Mastcam opacity measurements), and the rest are less frequent or opportunistic.

In this presentation, we provide an overview of MSL's environmental science results, discuss recent results that are specifically due to the long spatial and temporal record of MSL's mission, and preview future work.

10 Years of Science: An incredibly diverse set of scientific results can be included under the broad umbrella of environmental science that we briefly summarize here. The 10-year (5 Mars year) baseline created by Curiosity's longevity has been uniquely valuable to understand variability driven by seasons, interannual variations, and even the Solar cycle. The radiation environment has been measured for nearly a full solar cycle, including a variety of flares and coronal mass ejections that provide a detailed record to predict the conditions for future astronauts [1,2]. Repeated measurements by SAM have not only measured the background atmospheric chemical and isotopic composition [3], ephemeral variations in CH_4 [4,5,6], but also found unexpected seasonal and interannual cycles of O_2 by comparison with ChemCam data [7]

A long temporal record, but also one acquired from a rover that has crossed surfaces with varied properties ranging from basaltic sand dunes to hard bedrock has presented a unique opportunity to understand the surface energy balance [8] and also how the atmosphere exchanges water with the surface [e.g, 9-10]. This traverse has also been incredibly useful for understanding how dust is lifted from the surface of the planet. Famously, the first ~1500 sols of the MSL mission saw no dust devils over the Gale Crater floor [11] despite numerous pressure vortices [12], but climbing toward the Bagnold Dunes and optimization of observation sequences found an abundance of both dust devils and wind-stress forced dust lifting events [e.g., 13], with greater vortex activity as Curiosity departed [14]. Curiosity also conducted an intensive environmental science campaign within the Bagnold Dune field (and near other major aeolian features such as the Sands of Forvie) to understand the aeolian physics and microscale meteorology of an active planetary dune field [e.g., 15].

Despite being in a deep crater, Curiosity has been able to measure global and regional phenomena. Using REMS, Curiosity has measured atmospheric tides (a global response to integrated solar and aerosol forcing) [16], baroclinic and barotropic traveling waves originating in the high latitudes of both hemispheres that still produce a distinct signal in the tropics (very different from Earth) [e.g., 17], and higher frequency gravity and inertia-gravity waves that are likely forced by terrain both within Gale Crater and in the larger surrounding region [18,19]. In 2018 (Mars Year 34), Curiosity provided the first *in situ* meteorological measurements of a martian global dust storm since the Viking landers [20] and the first ever in the martian tropics. With Curiosity's radioisotope power source, it was able to conduct a full observational campaign with a rich record of REMS meteorological measurements [21], atmospheric opacity studies [22], and studies of the dust particles themselves [23] despite the high atmospheric opacity that ultimately ended the solar-powered Opportunity mission. This long record has shown that Gale Crater is rarely, if ever, a source of wide-scale dust lifting, in stark contrast already to measurements by Perseverance in Jezero Crater [24].

Although Gale Crater does not appear to be a significant source of dust lifting to the atmosphere, REMS UV sensor measurements have shown how dust is lifted and deposited on timescales ranging from sols to years via periodic dust deposition and "cleaning" [25]. In a complementary measurement, routine images of the distant Gale Crater rim have shown how dust opacity (and hence dust lifting and deposition by proxy) varies within the crater boundary layer [e.g., 26].

Gale Crater sits beneath the seasonal Aphelion Cloud Belt (ACB) and now has 5 Mars years' worth of image sequences to study the opacity, morphologies, seasonal and diurnal cycling, and direction of motion of those clouds [27-29]. Curiosity has also observed high-altitude clouds prior to the annual ACB season. Increasingly sophisticated image sequences have produced estimates of ice cloud particle sizes and shapes [28] while a serendipitous discovery of cloud shadows moving across Mt. Sharp allows precise determination of cloud heights and speed of motion [29].

New Results and Ongoing Work: Curiosity has now traveled more than 10 km in straight-line distance from Bradbury Landing and nearly 700 m vertically, representing a long transect through the Gale Crater atmospheric boundary layer. Some meteorological changes have been expected and unsurprising. The mean daily pressure has declined with increasing elevation, closely following the hydrostatic effect. But other effects of increasing elevation have been unexpected. The "crater effect" on daily pressure variations, first noted by [30,31], is the result of lateral flow of mass needed to accomplish hydrostatic adjustment across the varied crater topography in response to diurnal air temperature variations [32] and can now be directly measured using REMS [33]. Climbing up the slopes of Mt. Sharp has exposed Curiosity to different thermal environments as well. While in the crater trench, Curiosity sat within a nocturnal "cold pool", but now has climbed above that region and nighttime minimum temperatures are as much as 10 K warmer than earlier in the mission [34]. Year-over-year comparisons in dust opacity have also shown intriguing declines, suggestive of a shallow Gale Crater boundary layer with little vertical mixing [33].

Having multiple landers on the martian surface with environmental sensor suites also affords something novel in planetary environmental research: network science. InSight's location at a near-identical longitude somewhat limited its utility in conjunction with MSL, but Perseverance's record in Jezero Crater is already providing unique joint science results [35]. Additional landers with environmental sensors could allow a truly global perspective on the *in situ* martian environment as Curiosity continues its uphill climb in the next 10 years.

Acknowledgments: MSL data is archived at https://pds-geosciences.wustl.edu/missions/msl/.

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