SABER Significant Accomplishments 2020 - 2022

The prior TIMED Senior Review Proposal submitted to NASA in 2020 identified three Science Objectives (SO) for the Mission to pursue in the years covering government fiscal years 2021, 2022, and 2023 (October 1, 2020 through September 30, 2023). These three Objectives are:

SO#1: Understand the Causes for the Hemispheric and Longitudinal Variations in Storm-time Neutral Response

SO#2: Investigate how middle atmospheric meteorological disturbances influence the thermosphere.

SO#3: Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region.

The next several pages summarize nine key accomplishments related to these Science Objectives incorporating SABER data.

A listing of relevant peer-reviewed publications including reference reference citations for articles published and submitted in 2020, 2021, and 2022 are listed on the last two pages.

SABER O observations inform model representations of upper thermospheric and ionospheric intra-annual variations

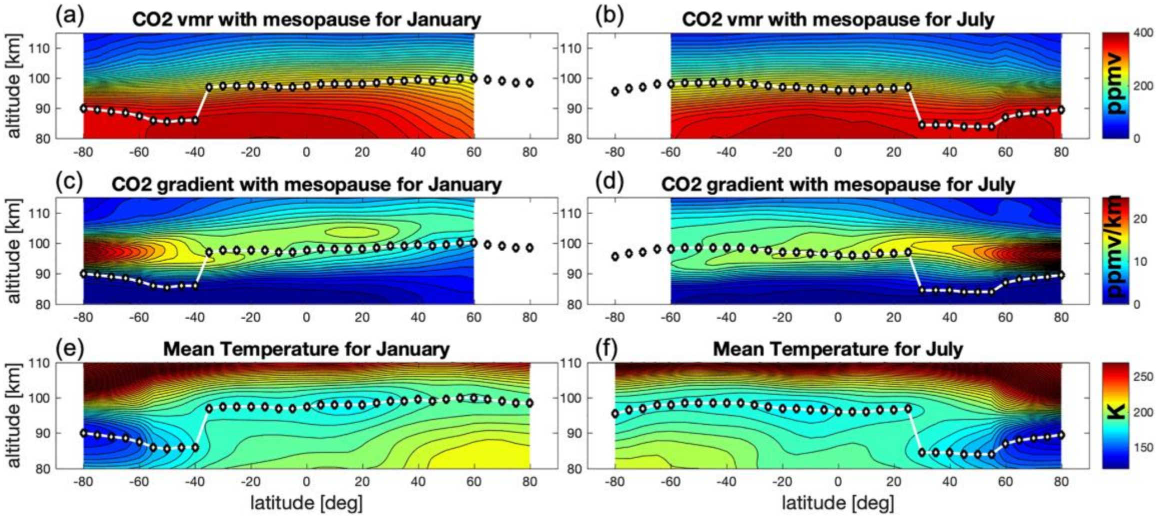
Subject title	Impacts of lower thermospheric atomic oxygen and dynamics on the thermospheric semiannual oscillation
Relevance	**2020 Science Objective (SO) #2:** Investigate how middle atmospheric meteorological disturbances influence the thermosphere.
Data/models used	NRLMSISE-00, TIMED/SABER, TIMED/GUVI, TIMED/TIDI, GNSS TEC, CHAMP, GRACE, GITM, WACCM-X
Findings Summary	The thermosphere-ionosphere (T-I) semiannual oscillation (SAO) is a large intra-annual density (mass and plasma) variation with maxima during equinoxes and minima during solstices. GITM's representation of the T-I SAO depends on the choice of composition, temperature, and dynamical lower boundary conditions (~95 km). It is demonstrated that GITM best reproduces the observed upper T-I SAO in mass and electron density using WACCM-X atomic oxygen (O) and dynamics at the GITM lower boundary, which are in good agreement with SABER O and TIDI winds.
Importance/ impact	This combined data modeling study demonstrates the connections between atomic oxygen in the MLT and upper T-I system.
Unanswered Questions and what next	The T-I SAO is a feature that has been observed for more than 70 years, however, the driving mechanisms and their relative contribution are still an active area of research. One of the main unanswered questions is how the T-I SAO is generated in different T-I general circulation models and how and why its amplitude increases with solar cycle.
References	Malhotra, G., Ridley, A. J., & Jones, M. (2022). Impacts of lower thermospheric atomic oxygen and dynamics on the thermospheric semiannual oscillation using GITM and WACCM-X. *Journal of Geophysical Research: Space Physics*, 127, e2021JA029320. https://doi.org/10.1029/2021JA029320

SABER CO_2 distribution is a proxy for the residual circulations in the MLT region

Subject title	Climatology of Mesosphere and Lower Thermosphere Residual Circulations and Mesopause Height Derived from SABER Observations
Relevance	**2020 Science Objective (SO) #2**: Investigate how middle atmospheric meteorological disturbances influence the thermosphere.
Data/models used	TIMED SABER CO2 and Temperature data
Findings Summary	Mesopause height strongly correlates with the CO2 VMR vertical gradient during solstices. Mesopause height has a discontinuity at midlatitude in the summer hemisphere, with a lower mesopause height at mid-to-high latitudes because of adiabatic cooling driven by strong upwelling. The residual circulations have strong seasonal variations at mid-to-high latitudes, but they are more uniform at low latitudes. The interannual variability of the residual circulations and mesopause height is larger in the Southern Hemisphere (SH; 4–5 km) than in the Northern Hemisphere (NH; 0.5–1 km).
Importance/ impact	The SABER CO2 measurements are the perfect tracer for the residual circulations in the MLT region. The data provide the opportunity to study the dynamical processes in the MLT region.
Unanswered Questions and what next	The interannual variations of the residual circulation pattern and the mesopause height are stronger in the SH than in the NH. In addition, the CO2 VMR vertical gradient belt becomes wider, and the peak CO2 VMR vertical gradient becomes smaller at high latitudes in the summer hemisphere from 2003 to 2020. Longer time series are needed in addition to successor missions and observations with more accurate CO2 and temperature data to obtain a better understanding of the hemispherical asymmetry of the circulations in the earth upper atmospheres.
References	Wang, N., et al., (2022). Climatology of mesosphere and lower thermosphere residual circulations and mesopause height derived from SABER observations. JGR-Atmospheres, 127, e2021JD035666. https://doi. org/10.1029/2021JD035666

See next page for relevant Figure

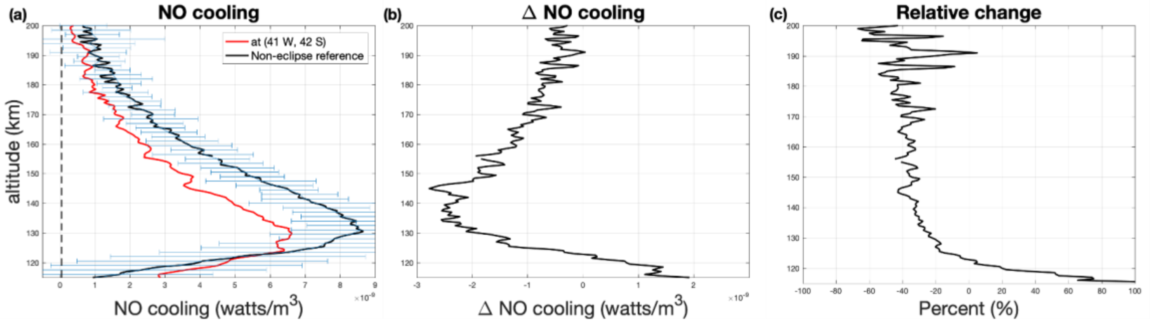
Variation of CO_2 volume mixing ratio from January to July



January (a, c, e) and July (b, d, f) monthly zonal averages of Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) CO_2 volume mixing ratio in ppmv (a, b), CO_2 vertical gradient in ppmv/km (c, d), and temperature in degrees K (e, f) using data from 2003 to 2020. The white line with black diamonds in each panel represents the mesopause location at each corresponding 5-degree latitude bin.

SABER NO Cooling Responses to The Transient Solar Event

Subject title	Thermospheric Nitric Oxide Cooling Responses to the December 14, 2020, Solar Eclipse
Relevance	Heliophysics-wide
Data/models used	TIMED SABER NO VER and WACCM-X
Findings Summary	SABER observed a decrease in radiative cooling by NO in the thermosphere during the solar eclipse on December 14, 2020. The eclipse-induced NO cooling rate decrease observed by SABER is consistent with the WACCM-X simulation. The eclipse-time decreases of the NO concentration and temperature are the major drivers of the NO cooling rate decrease during the eclipse.
Importance/ impact	The data is consistent with the WACCM-X simulations during the solar eclipse event. The results are also important to the studies of chemical and dynamical processes in the upper atmosphere during transient solar event.
Unanswered Questions and what next	During the December 14, 2020, solar eclipse, the SABER NO cooling change shows a good agreement to the WACCM-X, despite there are small differences in the vertical NO cooling rate profile between the data and model. Further effort such as statistical study is needed, which may require longer time series in addition to successor missions.
References	Wang, N., et al., (2022). Thermospheric Nitric Oxide Cooling Responses to the December 14, 2020, Solar Eclipse. JGR-Space Physics, in revision



(a) Vertical profile of the NO cooling rate in units of watts/m^3 during December 14, 2020 solar eclipse (red) at 17:58 UT at (41° W, 42° S) and non-eclipse reference (black), derived from the SABER measurements. The equivalent noise value for the cooling rate is shown as the black dashed line. The horizontal bars represent the second standard deviation ($2\text{-}\sigma$) of the non-eclipse means; (b) the difference of the NO cooling rate between the eclipse and the non-eclipse reference; (c) the relative change of the NO cooling during the eclipse with respect to the non-eclipse reference.

SABER observes atmospheric contraction due to CO_2 increase & declining solar activity

Subject title	Effects of solar cycle and increasing CO_2 on mesosphere and lower thermosphere temperature (MLT), geopotential height, and thickness
Relevance	**2020 Science Objective (SO) #3**: Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region.
Data/models used	TIMED SABER and TIMED SEE data
Findings Summary	The MLT are substantially colder in 2020 than during 2002 due to a combination of decreasing intensity of the 11-year solar cycle and continuously increasing CO_2. The thickness of the atmosphere between 1 hPa and 1e-04 hPa pressure surfaces (47 km to 105 km) decreased by nearly 1.5 km. MLT may be coldest in 2020 since the start of the industrial age.
Importance/ impact	The data highlight the ongoing effects of weaker solar cycle intensity and increasing CO_2 in determining the thermal structure and composition of the MLT. The results are also important to studies of density variability at satellite altitudes
Unanswered Questions and what next	At 105 km the decline of the solar cycle intensity is responsible for a substantial fraction of the cooling relative to increasing CO_2, complicating the ability to accurately derive the cooling trend in temperature due to increasing CO_2 at that altitude. Ultimately the cooling in this “heat sink” region will result is a ~ 40% decrease in density at low earth orbit satellite altitudes. Longer time series are needed in addition to successor missions and observations with more accurate temperature data and more accurate quantification of the effects of the solar cycle variability.
References	Mlynczak, M. G., et al., (2020). Global Warming *and* Global Cooling in 2020: The warmest surface *and* the coldest, thinnest mesosphere and lower thermosphere. JGR-Atmospheres, in revision.

SABER observes day-to-day variations in the diurnal non-migrating tidal spectrum

Subject title	Short-term variability of non-migrating tide DE3 from SABER, TIDI, and MIGHTI and its ionospheric impacts
Relevance	**2020 Science Objective (SO) #3**: Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region.
Data/models used	TIMED/SABER, TIMED/TIDI, and ICON/MIGHTI, TIME-GCM, NAVGEM-HA
Findings Summary	At solar minimum, lower atmospheric wave forcing is responsible for a substantial amount of variability on space weather time scales in the MLT and overlying thermosphere-ionosphere system (T-I). This study investigates DE3 variability from day to day to interannual scales utilizing data from three currently operational space-based instruments (TIDI, MIGHTI, and SABER), and its impact on ionosphere utilizing a combined data and modeling approach. We find that DE3 estimated with TIDI and SABER by fitting Hough expansion functions are consistent with each other as well as TIMEGCM/NAVGEM-HA and MIGHTI. All of them virtually capture similar DE3 features from day to day to seasonal time scales. The resemblances of these features from independent data sources suggest that these features have geophysical origin.
Importance/ impact	This combined data and modeling study demonstrates that with only 2 local solar time measurements per day, one can extract day-to-day variations in atmospheric tides (with some assumptions) free from aliasing. The results are also important for showing that day-to-day variations in the MLT drive day-to-day variations in the F-region ionosphere.
Unanswered Questions and what next	Understanding the day-to-day variations in other parts of the tidal spectrum including the semidiurnal tides using TIMED/SABER and TIMED/TIDI measurements. This would help to complement and validate tides measured by ICON/MIGHTI.
References	Dhadly, M., M. Jones Jr., et al. (2022). Short-term variability of Non-migrating Tide DE3 from SABER, TIDI, and MIGHTI and its ionospheric impacts. GRL, in preparation.

SABER and Nitric Oxide Cooling in the Thermosphere

Subject title	Radiative Cooling by Nitric Oxide in the Thermosphere
Relevance	**2020 Science Objective (SO) #3**: Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region.
Data/models used	TIMED/SABER data and MSIS 2.0 Model
Findings Summary	1. The thermosphere below 115 km is too cold for collisions by atomic oxygen to excite NO fundamental vibrational mode. Hence, emission observed by SABER below 115 km is not indicative of radiative cooling. The emission below 115 km is due to resonant scatter of solar radiation and upwelling 'earthshine' from the lower troposphere 2. There is a strong solar cycle dependence of the radiative cooling above 115 km driven non-linearly by temperature and linearly by atomic oxygen. 3. SABER radiative cooling currently overestimates the global infrared power due to nitric oxide emission by as much as 15%. This overestimation has a strong solar cycle dependence.
Importance/ impact	The SABER NO cooling rate data have been widely used to study the response of the thermosphere to geomagnetic storm events. The new results place new altitude ranges on the regions where NO emission can be interpreted as true cooling. This is critical to understanding the flow of energy through the ITM system during disturbed conditions. The new MSIS 2.0 model has been significantly updated with data from SABER and other satellites, making studies such as this possible.
Unanswered Questions and what next	Are there any trends discernable in the radiative cooling by NO in the thermosphere? Given the large (factor of 10) variation in cooling with solar cycle, more observations are needed to reduce (and to even deduce) the uncertainty in trends.
References	Mlynczak, M. G., et al., (2021). Spectroscopy, gas kinetics, and opacity of thermospheric nitric oxide and implications for analysis of SABER infrared emission measurements at 5.3 μm, *J. Quant. Spectrosc. Rad. Transfer,* https://doi.org/10.1016/j.jqsrt.2021.107609. Emmert, J. T., Drob, D. P., Picone, J. M., Siskind, D. E., Jones, M., Mlynczak, M. G., et al. (2021). NRLMSIS 2.0: A whole-atmosphere empirical model of temperature and neutral species densities. *Earth and Space Science*, 8, e2020EA001321. https://doi.org/10.1029/2020EA001321.

Long-term change in the ITM system and need for new observing systems

Subject title	Continuity of long-term observations of the ITM system
Relevance	**2020 Science Objective (SO) #3**: Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region.
Data/models used	TIMED, ACE, Aura, AIM, EnviSAT, ICON
Findings Summary	The ITM system, in large part due to TIMED, is now recognized as an integral component of the geospace system which is undergoing long term change due to increasing carbon dioxide. The current observing systems are aging (20+ years old) and have no identified replacements. Solar cycle variability imposes a large natural variability on the ITM system requiring extended observational data sets to accurately determine changes due to CO_2 increase.
Importance/ impact	Continued observations of the ITM system are crucial to enable prediction of the long-term changes in density at satellite altitudes so as to guide space policy and law and to inform the space insurance industry regarding orbital debris regulation and mitigation and space traffic management.
Unanswered Questions and what next	What are the consequences of long-term change in the ITM system for the habitability of low earth orbit?
References	Mlynczak, M. G.,Yue, J.,McCormack, J.,Liebermann, R. S., and Livesey, N. J. (2021), An observational gap at the edge of space, *Eos, 102*, https://doi.org/10.1029/2021EO155494**.**

Long-term trends in the diurnal vertically propagating tidal spectrum in the MLT region from both observations and models

Subject title	On the long-term trends in diurnal vertically propagating atmospheric tides within the mesosphere and lower thermosphere from 1980 to 2020
Relevance	**2020 Science Objective (SO) #2:** Investigate how middle atmospheric meteorological disturbances influence the thermosphere. **2020 Science Objective (SO) #3**: Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region.
Data/models used	TIMED/SABER, TIMED/TIDI, UARS/HRDI, WACCM-X
Findings Summary	The combined data-model results analyzed demonstrate that DW1 and DE3 amplitudes and phases from both the free-running and SD configurations of WACCM-X compare reasonably well with satellite observations from TIMED/SABER, TIMED/TIDI, and UARS/HRDI over the last ∼40 years. However, simulated and observed DW1 and DE3 amplitudes do not show a clear "long-term" trend over the last ∼40 or ∼20-30 years, respectively.
Importance/ impact	Our results indicate that a 40-year time series of tidal amplitudes (and phases) is not long enough to determine a statistically significant trend. Even if a trend in tidal amplitudes or phases were to exist, a much longer data record (either model or observational), i.e., on the order of ~100 years is necessary to recover any trend in diurnal tidal amplitudes that could be attributable to changing CO_2, for example.
Unanswered Questions and what next	Understanding and looking at the trends in other parts of the tidal spectrum including the semidiurnal tides using TIMED/SABER and TIMED/TIDI measurements.
References	Jones, M., Jr. et al. (2022) On the long-term trends in diurnal vertically propagating atmospheric tides within the mesosphere and lower thermosphere from 1980 to 2020. JGR-Space Physics, in preparation.

Water vapor trends in the middle atmosphere

Subject title	Water vapor trends in the middle atmosphere
Relevance	**2020 Science Objective (SO) #2:** Investigate how middle atmospheric meteorological disturbances influence the thermosphere. **2020 Science Objective (SO) #3**: Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region.
Data/models used	Satellite data from TIMED-SABER, Aura-MLS, UARS-HALOE, and model analysis using SD-WACCM
Findings Summary	Nearly three decades of middle atmosphere water vapor mixing ratio data observed by satellites were analyzed to search for trends. A slight trend in mesospheric water vapor is observed. However no significant trend was observed in stratospheric water vapor. Model results are consistent with the stratosphere observations, but the model does not contain any trend in water vapor. Model analysis suggests changes in lower atmosphere dynamics and methane as being responsible for water vapor variations observed in the satellite data.
Importance/ impact	Water vapor is a key radiatively active gas in the middle atmosphere relevant to both global warming and ozone depletion. It is also the source of hydrogen in high thermosphere to the exosphere. Understanding the evolution of middle atmosphere water vapor is critical to aeronomy and climate science.
Unanswered Questions and what next	Does the observed trend in mesospheric water vapor influence the occurrence and distribution of polar mesospheric clouds?
References	Yu, W., Garcia, R., Yue, J., Russell, J. III, & Mlynczak, M. (2022). Variability of water vapor in the tropical middle atmosphere observed from satellites and interpreted using SD-WACCM simulations. Journal of Geophysical Research: Atmospheres, 127, e2022JD036714. https://doi.org/10.1029/2022JD036714. Nossal, S. M., Qian, L., Solomon, S. C., Burns, A. G., and Wang, W. (2016). Thermospheric hydrogen response to increases in greenhouse gases, *J. Geophys. Res. Space Physics*, 121, 3545– 3554, doi:10.1002/2015JA022008.

Reference Citations for Peer-Reviewed Publications related to SO #2 and SO #3 using data from SABER

SO#2: Investigate how middle atmospheric meteorological disturbances influence the thermosphere.

Salinas, C. C. J. H., L. C. Chang, J. Yue, L. Qian, Q. Gan, J. Russell, and M. Mlynczak (2022). Estimating the Migrating Diurnal Tide Component of Mesospheric Water Vapor, *J. Geophys. Res.- Space Physics*, https://doi.org/10.1029/2021JA030187.

Swenson, G. R., Vargas, F., Jones, M., Zhu, Y., Kaufmann, M., Yee, J. H., & Mlynczak, M. (2021). Intra-annual variation of eddy diffusion (k_{zz}) in the MLT, from SABER and SCIAMACHY atomic oxygen climatologies. *Journal of Geophysical Research: Atmospheres*, 126, e2021JD035343. https://doi.org/10.1029/2021JD035343.

Jones, M., et al., (2020). Coupling from the middle atmosphere to the exobase: Dynamical disturbance effects on light chemical species, J*. Geophys. Res. – Space Physics*, https://doi.org/10.1029/2020JA028331.

Malhotra, G., Ridley, A. J., Marsh, D. R., Wu, C., Paxton, L. J., & Mlynczak, M. G. (2020). Impacts of lower thermospheric atomic oxygen on thermospheric dynamics and composition using the global ionosphere thermosphere model. Journal of Geophysical Research: Space Physics, 125, e2020JA027877. https://doi.org/10.1029/2020JA027877.

Salinas, J. C., et al., (2020). Local-time variabilities of SABER CO_2 in the mesosphere and lower thermosphere region. Journal of Geophysical Research-Space Physics, *Journal of Geophysical Research:Space Physics*, 125, e2019JA027039. https://doi.org/10.1029/2019JA027039

S. Mondal, M. Sivakandan, S. Sarkhel, M. V. Sunil Krishna, Martin G. Mlynczak, James M. Russell III, G. Bharti (2021). A case study of a thermally ducted undular mesospheric bore accompanied by ripples over the western Himalayan region, *Adv. Space Res*. https://doi.org/10.1016/j.asr.2021.03.026

Sarkhel, S., G. Stober, J. L. Chau, S. M. Smith, C. Jacobi, S. Mondal, M. G. Mlynczak, and J. M. Russell III, (2022). A case study of a ducted gravity wave event over northern Germany using simultaneous airglow imaging and wind filed observations, *Ann. Geophys., 40*. https://doi.org/10.5194/angeo-40-179-2022.

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SO#3: Determine the ongoing effect of weaker solar cycles on the thermal structure, composition, and dynamics of the ITM region.

Yu, W., Garcia, R., Yue, J., Russell, J. III, & Mlynczak, M. (2022). Variability of water vapor in the tropical middle atmosphere observed from satellites and interpreted using SD-WACCM simulations. Journal of Geophysical Research: Atmospheres, 127, e2022JD036714. https://doi.org/10.1029/2022JD036714

Ozaki, M., et al., (2022). Localized mesospheric ozone destruction corresponding to isolated proton aurora coming from Earth's radiation belt, *Nature Communications*, https://doi.org/10.1038/s41598-022-20548-2

Stevens, M., et al., (2022). Temperature Observations of the Upper Mesosphere and Lower Thermosphere from O_2 Atmospheric Band Emission by ICON/MIGHTI, *J. Geophys. Res. – Space Physics*, *revised*.

Bruinsma, S., C. Siemes, J. Emmert, W. Kent Tobiska, M. G. Mlynczak (2022). Description and comparison of 21st century thermosphere data. *Adv. Space Res.*, https://doi.org/10.1016/j.asr.2022.09.038

Mlynczak, M. G., L. A. Hunt, V. L. Harvey, and J. Yue, (2021). Global Warming *and* Global Cooling in 2020: The warmest surface *and* the coldest, thinnest mesosphere and lower thermosphere, *J. Geophys. Res. Atmospheres.*, *in press*.

Mlynczak, M. G., J. Yue, J. McCormack, R. S. Liebermann, and N. J. Livesey (2021), An observational gap at the edge of space, *Eos, 102,* https://doi.org/10.1029/2021EO155494.

Ern, M. M. Diallo, P. Preusse, M. G. Mlynczak, J. M. Russell III, M. J. Schwartz, Q. Wu, and M. Riese (2021). The semiannual oscillation (SAO) in the tropical middle atmosphere and its gravity wave driving in reanalyses and satellite observations, *Atmos. Chem. Phys.*, https://doi.org/10.5194/acp-21-13763-2021

Grandin, M., Palmroth, M., Whipps, G., Kalliokoski, M., Ferrier, M., Paxton, L. J., et al. (2021). Large-scale dune aurora event investigation combining Citizen Scientists' photographs and spacecraft observations. *AGU Advances*, 2, e2020AV000338. https://doi.org/10.1029/2020AV000338.

Mlynczak, M. G., et al., (2021). Spectroscopy, gas kinetics, and opacity of thermospheric nitric oxide and implications for analysis of SABER infrared emission measurements at 5.3 μm, *J. Quant. Spectrosc. Rad. Transfer,* https://doi.org/10.1016/j.jqsrt.2021.107609.

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Emmert, J. T., et al., (2020). NRLMSIS 2.0 – A whole atmosphere empirical model of temperature and neutral species densities, J*. Geophys. Res. – Space Physics*, https://doi.org/10.1029/2020EA001321