HABITABLE MOIST-GREENHOUSE ATMOSPHERES AROUND M-DWARF STARS. R. K. Kopparapu[1], E. T. Wolf[2], J. Haqq-Misra[3], S. L. Grimm[4], G. Arney[1], Heng, K[4] [1]Affiliation (NASA Goddard/UMD, ravikumar.kopparapu@nasa.gov), [2]U. Colorado, Boulder, [3]Blue Marble Space Institute of Science, [4] Center for Space Habitability, University of Bern, Switzerland

Summary: Determining potential habitability of planets near the inner edge of the HZ around M-dwarf stars is most crucial and timely for interpreting spectral data and aiding the selection of JWST targets. Our goal is to study the inner edge of the habitable zone (HZ) of M-dwarf stars, in a more realistic, cloudy, 3-D model.We have updated the water-vapor coefficients in Community Atmosphere Model (CAM) version 4 and also in an idealized version of Flexible Modeling System (FMS) with HITRAN2012 database, and with continuum absorption. Our results show that, even for synchronously rotating planets, the inner edge of the HZ around M-dwarfs is significantly further out from the star, and in some cases approach the inner edge limit for rapidly rotating planets. Even more interesting is that several simulated planets have water-rich atmospheres (mixing ratios ~> 10^{-3}) that are within the classic "moist-greenhouse" regime, but maintain mild surface temperatures (~ 280 K). In comparison, a moist-greenhouse in a 1-D climate model occurs at a surface temperature of ~ 340 K which is too hot for life similar to our's. Depending upon the amount of waterloss, it is possible that some planets can smoothly transition to water-poor or dry planets, while maintaining habitable conditions all along (Abe et al. 2011; Leconte et al. 2013a).

Both 1-D and 3-D models show that, for a water-rich planet, as the surface temperature increases due to increased stellar radiation, water vapor becomes a significant fraction of both the troposphere and stratosphere (Wolf & Toon. 2015). H_2O has absorption bands in the near-IR, so this leads to increased absorption of incoming solar radiation, thereby lowering a planet's albedo. This effect is accentuated on M-star planets because the radiation from M stars peak in the near-infrared.

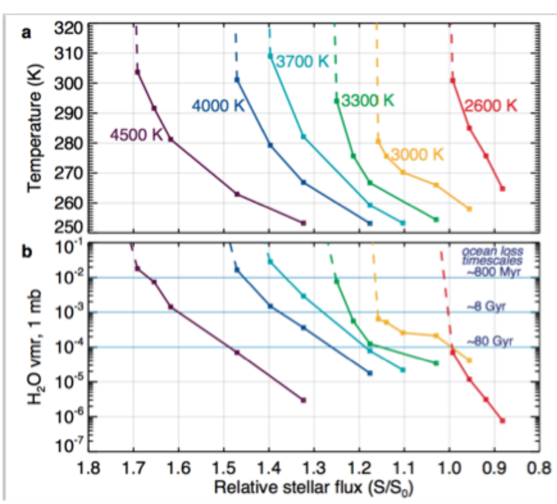

Fig. 1 shows the mean surface temperature (T_S) and top of the atmosphere (1 mb) water-vapor mixing ratio as a function of incident stellar flux. We note that the Earth has a water vapor volume mixing ratios of about 10^{-6} at 1 mb presently, with T_S ~ 288 K. Thus, here we have found a general result that there is significantly more water vapor in the atmospheres of planets around M-dwarfs, for all stellar T_{eff} and over a wide range of surface temperatures. As the stellar flux increases, surface temperature, and hence the water-vapor mixing ratio, increase for all the cases. This is expected, as there is more near-IR stellar flux at lower stellar T_{eff}, which rapidly warms water-rich planets around late M-dwarfs. Furthermore, the **classical "moist-greenhouse" or water-loss regime (water-vapor mixing ratio > 10^{-3}) occurs at significantly lower T_S (~280 K) compared with 1-D climate models (~ 340 K) for stars with 3000 K < Teff ≤ 4500 K**. Thus, habitable moist greenhouse planets are possible. This is the result of strong convection occurring at the substellar point, which is a basic property of slow and synchronous rotators (Yang et al. 2013, Kopparapu et al. 2016). Consequently, this strong substellar convection is also responsible for forming the thick cloud deck which increases the planetary albedo, keeping clement temperatures at the surface, despite a water-vapor dominated atmosphere. The complicated interplay between moist convection, relative humidity, clouds, atmospheric circulation, and radiative transfer that occurs for slow rotating planets fundamentally cannot be taken into account in 1-D climate models, which overestimated T_S in the moist-greenhouse state.

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Acknowledgments: We gratefully acknowledge funding from NASA Habitable Worlds grant NNX16AB61G and NASA Astrobiology Institute's Virtual Planetary Laboratory lead team, supported by NASA under cooperative agreement NNH05ZDA001C.