WATER VAPOR IN THE UPPER ATMOSPHERES OF SYNCHRONOUSLY ROTATING TEMPERATE TERRESTRIAL EXOPLANETS. Yuka Fujii[1,2], Anthony D. Del Genio[2], and David S. Amundsen[2,3], [1]Earth-Life Science Institute, Tokyo Institute of Technology (2-12-1 Ookayama, Meguro, Tokyo 152-8550 Japan; yuka.fujii.ebihara@gmail.com), [2]NASA Goddard Institute for Space Studies (2880 Broadway, New York, NY 10025 USA), [3]Department of Applied Physics and Applied Mathematics, Columbia University (New York, NY 10025 USA)

Background and Aims: H_2O is a key molecule in characterizing atmospheres of temperate terrestrial planets, both as a tracer of habitable conditions and as a clue to the birthplaces and evolutional pathways of the planets. Its spectral signatures may be targeted in the near future transmission spectroscopy using JWST or next-generation ground-based telescopes. Several studies modeling transmission spectra of the Earth (e.g., [1]) found modest signatures of water vapor. Such modest features of water vapor are related to the efficient "cold trap"; water vapor evaporated from the surface is transported upward, but condenses as air rises and cools, and most of it precipitates, leaving the stratosphere—where transmission spectroscopy typically probes—fairly dry. However, the effciency of the cold trap depends on various conditions.

The abundance of water vapor in the upper atmosphere is also closely related to the rate of planetary water loss, which impacts planetary habitability. This motivated the earlier works to study the reponse of upper humidity to the varying irradiation and atmospheric properties (e.g., [2][3]). Most of these investigations were, however, limited to 1D models.

Here we study the effect of irradiation on realistic 3D water vapor structures, using a general circulation model (GCM). We are particularly interested in synchronously rotating planets due to their relevance to transmission spectroscopy, as its primary targets are planets around low-mass stars, which are likely to be synchronously rotating. Indeed, the permanent dayside and nightside of synchronously rotating planets question the validity of 1D models, calling for 3D studies.

Method: We use the ROCKE-3D GCM [4] to obtain 3D atmospheric structures of temperate terrestrial planets with surface water. ROCKE-3D GCM is a generalization of the ModelE2 GCM [5], which has been developed for the Earth at NASA's Goddard Institute for Space Studies. We consider synchronously rotating Earth-size planets wholly covered with ocean, and assume a 1 bar atmosphere composed mainly of N_2, analogous to the Earth. We change the total incident flux with 4 representative stellar spectra ranging from M-type to G-type, and see how the atmospheric structures respond to it. We also simulate transmission spectra based on our GCM outputs.

Results: We observe a more gentle increase of the water vapor mixing ratio in the upper atmosphere in response to increased incident flux than 1D models suggest. This is in qualitative agreement with the climate-stabilizing effect of dayside clouds previously observed in GCMs applied to synchronously rotating planets (e.g., [8]). However, the water vapor mixing ratio in the upper atmosphere starts to increase while the surface temperature is still moderate. This is explained by the large-scale circulation in the upper atmosphere, which is seen in the runs with high incident flux, causing efficient vertical transport of water vapor. This circulation is driven by the radiative heating due to absorption by water vapor and cloud particles in the upper atmosphere. Consistently, the water vapor mixing ratio in the upper atmosphere is found to be well correlated with the near-infrared portion of the incident flux, regardless of the stellar spectral type [6] (Fig. 1).

We also show that for the highly irradiated planets the H_2O signatures may be strengthened by a factor of a few or larger, compared with the standard model assuming an Earth-like atmospheric profile [6]. The larger features would considerably loosen the observational demands for a H_2O detection.

References: [1] Ehrenreich, D., et al. (2006) *A&A*, 448, 379 [2] Kasting, J. F., et al. (1993) *Icarus*, 101, 108 [3] Wardsworth, R. D., Pierrehumbert, R. T., (2013) *ApJ*, 778, 154 [4] Way, M. J., et al. (2017) *ApJS*, 231, 12 [5] Schmidt, G. A., et al. (2014), *JAMS*, 6, 141 [6] Fujii, Y., Del Genio, A. D., Amundsen, D. S. (2017) under review at *ApJ* [7] Yang, J., et al. (2013) *ApJL*, 771, L45 [8] Kopparapu, R. K., et al. (2013) *ApJ*, 765, 131

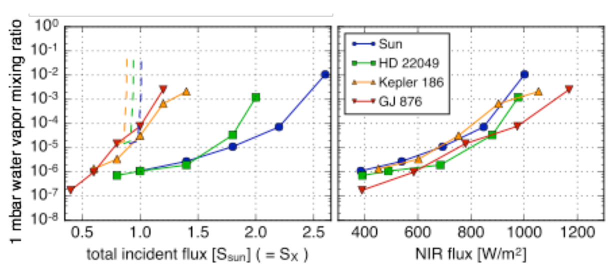

Fig 1.—Water vapor mixing ratio at 1.39 mbar as a function of total incident flux (left) and the near-infrared portion of the incident flux integrated between 0.9 and 3.0 μm (right) [6]. Dashed lines are adapted from the 1D model of [8] for varying stellar effective temperatures: 5800 K (navy), 4800 K (green), and 3800 K (orange).