Clouds will Likely Prevent the Detection of Water Vapor in JWST Transmission Spectra of Terrestrial Exoplanets

Thaddeus D. Komacek1, Thomas J. Fauchez2,3,4, Eric T. Wolf5,6, and Dorian S. Abbot1

1Department of the Geophysical Sciences, The University of Chicago, Chicago, IL, 60637, USA; tkomacek@uchicago.edu
2Goddard Earth Sciences Technology and Research (GESTAR), Universities Space Research Association, Columbia, MD, USA
3NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA
4GSCF Sellers Exoplanet Environments Collaboration, USA
5Laboratory for Atmospheric and Space Physics, Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, CO 80309, USA
6NASA Astrobiology Institute’s Virtual Planetary Laboratory, P.O. Box 351580, Seattle, WA 98195, USA

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Abstract

We are on the verge of characterizing the atmospheres of terrestrial exoplanets in the habitable zones of M dwarf stars. Due to their large planet-to-star radius ratios and higher frequency of transits, terrestrial exoplanets orbiting M dwarf stars are favorable for transmission spectroscopy. In this work, we quantify the effect that water clouds have on the amplitude of water vapor transmission spectral features of terrestrial exoplanets orbiting M dwarf stars. To do so, we make synthetic transmission spectra from general circulation model (GCM) experiments of tidally locked planets. We improve upon previous work by considering how varying a broad range of planetary parameters affects transmission spectra. We find that clouds lead to a 10–100 times increase in the number of transits required to detect water features with the James Webb Space Telescope (JWST) with varying rotation period, incident stellar flux, surface pressure, planetary radius, and surface gravity. We also find that there is a strong increase in the dayside cloud coverage in our GCM simulations with rotation periods \( \geq 12 \) days for planets with Earth’s radius. This increase in cloud coverage leads to even stronger muting of spectral features for slowly rotating exoplanets orbiting M dwarf stars. We predict that it will be extremely challenging to detect water transmission features in the atmospheres of terrestrial exoplanets in the habitable zone of M dwarf stars with JWST. However, species that are well-mixed above the cloud deck (e.g., CO\(_2\) and CH\(_4\)) may still be detectable on these planets with JWST.

Unified Astronomy Thesaurus concepts: Exoplanet atmospheres (487); Exoplanet atmospheric composition (201); Extrasolar rocky planets (511); Habitable planets (695); Planetary atmospheres (1244); Water vapor (1791)

1. Introduction

The upcoming launch of James Webb Space Telescope (JWST) and the future space mission concepts LUVOIR/HabEx/OST promise the characterization of terrestrial exoplanet atmospheres. Previous 1D simulations, which cannot properly account for clouds, have indicated that JWST will be able to observe the atmospheres of potentially habitable exoplanets orbiting M dwarf stars and detect molecular signatures of life in these atmospheres (Barstow & Irwin 2016; Morley et al. 2017; Lincowski et al. 2018, 2019; Lustig-Yaeger et al. 2019). However, clouds and hazes have affected observations of exoplanet atmospheres with the Hubble and Spitzer space telescopes by muting signatures of molecular features in transmission (Kreidberg et al. 2014; Sing et al. 2016; Crossfield & Kreidberg 2017). If clouds or hazes are present at the planetary limb, they pose a problem for transmission spectra of terrestrial exoplanets because of long path lengths through the atmosphere (Moran et al. 2018; Afrin Badhan et al. 2019; Fauchez et al. 2019; Lustig-Yaeger et al. 2019).

Surface liquid water is considered a necessary constituent of a habitable world (Kasting et al. 1993), and ideally we would like to detect water vapor spectral signatures as an indicator of the habitability of a terrestrial exoplanet. Given the narrow thermodynamic range of liquid water stability, and typical lapse rates in planetary atmospheres, any planet with abundant liquid surface water will also have clouds condensing in its atmosphere. This suggests that hunting for water spectral signatures will be confounded by clouds in terrestrial planet atmospheres. On tidally locked planets with hot daysides and cold nightsides, upwelling on the dayside carries moist air to low pressures. This moist air condenses as it is lifted, leading to strong dayside cloud cover on tidally locked terrestrial planets that have surface water (Yang et al. 2013, 2019a; Kopparapu et al. 2017; Haqq-Misra et al. 2018; Fauchez et al. 2019; Komacek & Abbot 2019; Suissa et al. 2019). If this dayside cloud cover extends to the terminator, it could significantly hinder the detection of molecular features in transmission.

Recent climate modeling has begun to explore how clouds affect the detection of transmission spectral features with JWST. Using the 1D climate and photochemical models of Lincowski et al. (2018), Lustig-Yaeger et al. (2019) found that clouds inhibit the detection of water features on TRAPPIST-1e. However, 3D simulations are necessary to accurately simulate cloud and water vapor mixing ratios. By post-processing 3D general circulation model (GCM) experiments, Fauchez et al. (2019) and Suissa et al. (2019) found that water vapor is challenging to detect in the atmospheres of terrestrial planets in the habitable zone due to the presence of clouds. However, Fauchez et al. (2019) analyzed simulations only varying the atmospheric composition for individual planets in the TRAPPIST-1 system, and Suissa et al. (2019) considered only the joint effects of varying incident stellar flux and rotation period.

In this work, we consider how a much broader range of possible planetary parameters affects transmission spectra. To do so, we post-process the 3D GCM output of Komacek &
Abbot (2019) to make simulated JWST observations of transmission spectra for planets orbiting late-type M dwarf stars. We find that clouds make water vapor transmission spectral features challenging to detect with JWST over a wide range of planetary parameters. We study the difference in transmission spectra when including and not including clouds, along with the effects of varying rotation rate, incident stellar flux, surface pressure, planetary radius, surface gravity, and cloud particle size. In Section 2, we describe our GCM experiments and how we post-process our GCM results to simulate transmission spectra. We show how clouds and varying planetary parameters impact transmission spectra in Section 3, along with estimating the number of transits needed to detect water vapor transmission features with JWST. We discuss our results and conclude in Section 4.

2. Methods

2.1. GCM Setup

To simulate the atmospheres of tidally locked terrestrial exoplanets, we use the ExoCAM GCM7 (Wolf & Toon 2015). ExoCAM is a version of the Community Atmosphere Model version 4 with updated correlated-k radiative transfer and water vapor continuum absorption, with spectral coefficients from HITRAN 2012. ExoCAM has been used in a wide range of studies of the atmospheres of terrestrial exoplanets (Kopparapu et al. 2016, 2017; Wolf et al. 2017, 2019; Wolf 2017; Haqq-Misra et al. 2018; Komacek & Abbot 2019; Yang et al. 2019a). We vary the rotation period, surface pressure, incident stellar flux, planetary radius, surface gravity, and cloud particle size over a wide range relevant for terrestrial exoplanets. The first column of Table 1 shows our considered variations in planetary parameters. Specifically, we use the GCM results for planets orbiting a late-type M dwarf star with $T_{\text{eff}} = 2600$ K from Komacek & Abbot (2019, see their Table 3). We conduct additional simulations to cover a range of dynamical regimes, including fast, intermediate, and slow rotators. If it is not explicitly stated in Table 1 that a parameter is varied, we keep its value fixed to that of Earth. As a result, this suite of GCM experiments varies planetary parameters individually, and includes some combinations of rotation period and incident stellar flux that are inconsistent with Kepler’s laws. We analyze these simulations in order to examine how each of these factors individually affect transmission spectra.

We consider an atmosphere consisting of only $N_2$ and $H_2O$ on a tidally locked aquaplanet with a 50 m deep slab ocean and zero obliquity. As a result, in this work we focus on how clouds and varying planetary parameters affect transmission spectra. We conducted additional GCM experiments including Earth-like abundances of $CO_2$ and $CH_4$ in order to test the sensitivity of our results to additional greenhouse gases. To determine if the parameterized ice cloud particle size in ExoCAM affects our results, we also include a suite of sensitivity tests with varying ice cloud particle size. Our range of considered ice cloud particle size is 20–200 μm (see Table 2), chosen to cover the range of ice cloud particle size in the parameterization of Rasch & Kristjánsson (1998) used in ExoCAM. All simulations use a horizontal resolution of $4^\circ \times 5^\circ$ with 40 vertical levels and a timestep of 30 minutes. The GCM results presented in this work are averaged over the last 10 yr of simulation time.

Table 1

| Simulation Parameters | Number of Transits with Clouds | Number of Transits Ignoring Clouds |
|-----------------------|-------------------------------|-----------------------------------|
| **Rotation Period**   |                               |                                   |
| 1 day                 | >1000                         | 71                                |
| 2 days                | 658                           | 18                                |
| 4 days                | 180                           | 10                                |
| 8 days                | 63                            | 4                                 |
| 16 days               | 189                           | 2                                 |
| **Surface Pressure**  |                               |                                   |
| 1 day rotation period |                               |                                   |
| 0.5 bars              | >1000                         | 52                                |
| 1 bar                 | >1000                         | 71                                |
| 2 bars                | >1000                         | 67                                |
| 4 bars                | >1000                         | 174                               |
| 8 day rotation period |                               |                                   |
| 0.5 bars              | 24                            | 2                                 |
| 4 bars                | 54                            | 2                                 |
| 16 day rotation period|                               |                                   |
| 0.5 bars              | 68                            | 1                                 |
| 4 bars                | 12                            | 1                                 |
| **Planetary Radius**  |                               |                                   |
| 1 day rotation period |                               |                                   |
| 0.5 $R_\oplus$       | >1000                         | 535                               |
| 0.707 $R_\oplus$     | >1000                         | 202                               |
| 1 $R_\oplus$         | >1000                         | 71                                |
| 1.414 $R_\oplus$     | >1000                         | 32                                |
| 2 $R_\oplus$         | 250                           | 6                                 |
| 8 day rotation period |                               |                                   |
| 0.5 $R_\oplus$       | >1000                         | 11                                |
| 2 $R_\oplus$         | >1000                         | 1                                 |
| 16 day rotation period|                               |                                   |
| 0.5 $R_\oplus$       | 904                           | 5                                 |
| 2 $R_\oplus$         | 10                            | 1                                 |
| **Surface Gravity**   |                               |                                   |
| 1 day rotation period |                               |                                   |
| 0.707 $g_\oplus$     | >1000                         | 28                                |
| 1 $g_\oplus$         | >1000                         | 71                                |
| 1.414 $g_\oplus$     | >1000                         | 149                               |
| 8 day rotation period |                               |                                   |
| 0.707 $g_\oplus$     | 479                           | 1                                 |
| 1.414 $g_\oplus$     | 187                           | 4                                 |
| 16 day rotation period|                               |                                   |
| 0.707 $g_\oplus$     | 27                            | 1                                 |
| 1.414 $g_\oplus$     | 299                           | 2                                 |
| **Incident Stellar Flux and Rotation Period** | | |
| 0.544 $F_{\odot}$    | 6.49 days                     | 616                               |
| 0.667 $F_{\odot}$    | 5.57 days                     | >1000                             |
| 0.816 $F_{\odot}$    | 4.79 days                     | 709                               |
| 1 $F_{\odot}$        | 4.11 days                     | 320                               |

Note. Shown are the number of transits needed to detect water features at an $S/N > 5$ with and without clouds for planets orbiting a late-type M dwarf star with $T_{\text{eff}} = 2600$ K using JWST NIRSpec/Prism.

2.2. Simulated Observables

To simulate transmission spectra from our GCM output, we use the Planetary Spectrum Generator8 (PSG; Villanueva et al.
Shown are the number of transits needed to detect water features at an S/N > 5 with ice clouds of varying particle size. These experiments have a rotation period of 16 days and all other parameters are fixed to that of Earth. We use the moderate spectral resolution mode of PSG, which employs the correlated-k technique for radiative transfer, while multiple scattering from aerosols is performed using the discrete ordinates method. The molecular spectroscopy is based on the HITRAN 2016 database (Gordon et al. 2017), which is complemented by ultraviolet (UV)/optical data from the MPI-Mainz database (Keller-Rudek et al. 2013). We take the temperature, molecular abundance, and liquid and ice cloud profiles from the GCM at each latitude point on the limb as input for PSG. We then use PSG to make a simulated transmission spectrum at every GCM grid point along the terminator, each of which comprises 4° of latitude. To make the planetary transmission spectrum, we average the spectra over all latitudinal grid points along the terminator with equal weighting of each spectrum, the same method as used in Fauchez et al. (2019) and Süssa et al. (2019). Note that this method only takes into account transmission through the limb, but transmission through the cloudier dayside may further reduce the amplitude of transmission spectral features (Caldas et al. 2019).

We simulate the transmission spectra for R = 300 from 0.6 to 5.3 μm relevant for the Near-Infrared Spectrograph (NIRSpec)/PRISM instrument on JWST, which has been shown to be the ideal instrument for JWST characterization of terrestrial exoplanets (Batalha et al. 2018; Fauchez et al. 2019; Lincowski et al. 2019; Lustig-Yaeger et al. 2019). We use the PSG imager noise model and do not include a noise floor in our simulated spectra. As a result, our results can be considered lower limits on the number of required transits to detect water vapor. Note that Süssa et al. (2019) showed that including a noise floor greatly affects the detectability of water features, finding that water vapor is not detectable if the JWST noise floor is >5 ppm.

### 3. The Dependence of Transmission Spectra on Planetary Parameters

#### 3.1. Transmission Spectra with and without Clouds

Our simulated transmission spectra depend strongly on whether we include clouds. Figure 1 shows simulated transmission spectra from 30 transits with JWST NIRSpec/PRISM. We show results from two GCM experiments with rotation periods of 8 and 16 days, simulating the transmission spectra both including and not including the effects of clouds. We find that when we do not include the effects of clouds in our simulated transmission spectra, transmission spectral features are deep and well above the level of the noise. However, when we include the effects of clouds, the transmission spectral features are strongly muted, with a maximum depth of ~20 ppm that is comparable to the expected noise floor of JWST NIRSpec (Greene et al. 2016).

Cloud muting of transmission spectral features is particularly strong for slowly rotating planets. In Figure 1, spectral features for the case with a rotation period of 16 days have an amplitude less than half that of the 8 day rotation period case. In Figure 2, we show transmission features are strongly muted, with a maximum depth of ~20 ppm that is comparable to the expected noise floor of JWST NIRSpec (Greene et al. 2016).

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### Table 2

Transmission Spectral Features of Water are Challenging to Detect over a Wide Range of Cloud Particle Size

| Ice Cloud Particle Radius | Number of Transits |
|---------------------------|--------------------|
| 20 μm                     | 126                |
| 50 μm                     | 378                |
| 80 μm                     | 377                |
| 110 μm                    | 434                |
| 140 μm                    | 327                |
| 170 μm                    | 297                |
| 200 μm                    | 222                |

Note. Shown are the number of transits needed to detect water features at an S/N > 5 with ice clouds of varying particle size. These experiments have a rotation period of 16 days and all other parameters are fixed to that of Earth.
weaker water vapor absorption features. High ice cloud cover between rotation periods of 8 and 16 days, leading to Earth. Pro orbiting a late-type M dwarf star, with all other parameters (Earth) detect water vapor if its surface pressure is equal to that of Earth. The number of transits of a planet with a rotation period of 8 days (orange) and 16 days (blue) would decrease to 31 for a planet with an orbital period of 16 days. Note that this is the maximum observable number of transits needed to detect water vapor in the atmosphere of a terrestrial exoplanet that orbits a late-type M dwarf star and receives an extended mission lifetime, lowered S/N threshold for detection, or the discovery of a habitable planet that is continuously visible to JWST may allow for a detection of water vapor.

3.3. Dependence of Water Vapor Detection on Planetary and Atmospheric Properties

Table 1 shows that the number of transits needed to detect water vapor is extremely sensitive to planetary parameters. We find that rotation period is a key controlling parameter. This is because planets that rotate quickly have reduced transport of water vapor to high altitudes, while planets that rotate slowly have significant high-altitude cloud cover at the terminator. When varying incident stellar flux and rotation period together, we find that there is a maximum in the number of transits needed to detect water vapor at an intermediate rotation period of 5.57 days. This is because there is a dynamical transition leading to decreased cloud cover for planets that are closer to their host star and more rapidly rotating (Komacek & Abbot 2019), reducing the number of transits needed to detect water vapor. When varying surface pressure alone in the rapidly rotating regime and ignoring the effect of clouds, we find that the number of transits required to detect water vapor sharply increases with increasing surface pressure from 2 to 4 bars. This is because Rayleigh scattering from atmospheric N₂ increases with increasing surface pressure (Kopparapu et al. 2014), leading to a cooler climate and reduced atmospheric water vapor content (Komacek & Abbot 2019).

In our simulations with a rotation period of 16 days, planets have ubiquitous high ice cloud coverage over a wide range of planetary parameters. Within this slowly rotating regime, we
find that planets that have larger radii, have lower gravities, and/or have higher surface pressures require fewer transits to detect water features. This is because, for fixed gravity, larger planets have a larger total transit signal, making deviations from the total signal larger. For fixed radius, lower-gravity planets have larger scale heights, leading to larger transmission features. Increasing the surface pressure leads to an increase in global-mean temperature and water vapor content of the air, leading to larger transmission features. The combination of large radius, high surface pressure, and low gravity enhances the detectability of water. Our results hence point toward sub-Neptunes (e.g., K2-18b, Benneke et al. 2019; Tsiaras et al. 2019) as viable targets to search for water vapor in transmission.

In simulations with an intermediate rotation period of 8 days, we find that the cloud coverage is itself strongly affected by planetary parameters. The resulting trends in the number of transits needed to detect water are non-monotonic with increasing surface pressure, radius, and gravity. Higher surface pressure leads to a cloudier dayside (Komacek & Abbot 2019), which increases the number of transits needed to detect water. However, at high surface pressures the increased amount of water vapor in the atmosphere makes it easier to detect. Larger radius leads to an increase in the size of transmission features, but at 2 $R_\oplus$ we find a transition to a more rapidly rotating dynamical regime (Yang et al. 2019a) that increases high-altitude ice cloud coverage and diminishes spectral features. Increased surface gravity makes the atmosphere clearer by causing the settling rate of cloud particles to increase. This is counteracted by the reduced atmospheric scale height of planets with larger gravity, making water hard to detect on high-gravity planets.

Our results are robust over a wide range in cloud particle size. Table 2 shows how the number of transits needed to detect water vapor on slowly rotating terrestrial exoplanets orbiting late-type M dwarf stars depends on the ice cloud particle size. We find that for slowly rotating planets with otherwise Earth-like planetary parameters, no cloud particle size that we consider allows detection of water vapor in fewer than 100 transits, over a factor of 10 variation in ice cloud particle size. Still, our results underly the importance of accurate microphysical modeling of cloud particle sizes, as plausible changes in ice cloud particle size can change the number of transits required for water detection by more than a factor of three. Additionally, we performed sensitivity tests including 400 ppm of CO$_2$ and 1.7 ppm of CH$_4$ in our GCM simulations. We found that the number of transits needed to detect water vapor when including CO$_2$ and CH$_4$ is comparable to or greater than that in simulations without CO$_2$ and CH$_4$.

4. Discussion and Conclusions

Our results are consistent with Lustig-Yaeger et al. (2019), Fauchez et al. (2019), and Süssa et al. (2019), who also found that clouds will probably prevent the detection of water features on terrestrial planets via transit spectroscopy with JWST. These results are also consistent with the non-detection of molecular features in the atmospheres of TRAPPIST-1d, e, and f with the Hubble Space Telescope (de Wit et al. 2018). However, water clouds only affect features originating from below the cloud deck, so well-mixed species that have strong spectral features (e.g., CO$_2$, CH$_4$) may still be detectable in the presence of water clouds (Fauchez et al. 2019). As a result, searching for chemical disequilibrium as an exoplanet biosignature (Krisansen-Totton et al. 2018a, 2018b) would likely not be significantly impacted by the presence of clouds. Similarly, a statistical search for variations in CO$_2$ as a function of position in the habitable zone might still be possible (Bean et al. 2017).

In this work, we did not consider atmospheres of planets that have significant amounts of water in the stratosphere or that are too hot to have surface liquid water. Fujii et al. (2017) showed that atmospheres in a moist greenhouse state have strong water vapor spectral features. Further, Chen et al. (2019) found that transmission spectral features of water vapor in these atmospheres could be detectable with JWST. Due to the increased scale height of runaway greenhouse atmospheres (Turbet et al. 2019), observations of the atmospheres of terrestrial exoplanets orbiting M dwarfs that are interior to the habitable zone should find stronger molecular signatures.

Though we post-processed a complex GCM to simulate transmission spectra over a wide range of planetary parameters, there are a variety of limitations to our model setup. We did not consider all atmospheric constituents relevant for Earth-like planets, including O$_3$ and O$_7$. Additionally, we did not perform a retrieval on simulated spectra to quantify the effects of band overlap between molecular species on detectability. We did not include a dynamic ocean, which would affect the surface temperature distribution and location of dayside cloud cover (Hu & Yang 2014; Del Genio et al. 2019; Way et al. 2018; Yang et al. 2019b). We did not include continents, which could reduce the amount of water vapor available to form clouds (Lewis et al. 2018). Lastly, we assumed that water is plentiful on the surfaces of planets orbiting M dwarf stars. It is possible that planets orbiting M dwarf stars lose their entire surface complement of water, leading to high amounts of O$_2$ that could act as a false-positive biosignature (Ramirez & Kälenegger 2014; Luger & Barnes 2015; Raff 2015; Schaefer et al. 2016).

In this work, we quantified the effect of water clouds on transmission spectra of tidally locked terrestrial exoplanets with a range of planetary parameters in the habitable zone of M dwarf stars. We find that transmission spectral features of water are significantly muted due to clouds on terrestrial exoplanets orbiting M dwarf stars. The decrease in transit depth due to clouds is especially strong for slowly rotating planets with rotation periods $>_{\sim}12$ days, which have large dayside cloud decks. Due to cloud coverage, water transmission features of Earth-sized planets orbiting M dwarf stars will be challenging to detect with JWST.

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**ORCID iDs**

Thaddeus D. Komacek @ https://orcid.org/0000-0002-9258-5311

Thomas J. Fauchez @ https://orcid.org/0000-0002-5967-9631

Eric T. Wolf @ https://orcid.org/0000-0002-7188-1648

Dorian S. Abbot @ https://orcid.org/0000-0001-8335-6560
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