The Prospect of Detecting Volcanism on an ExoEarth Using Direct Imaging

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The Prospect of Detecting Volcanic Signatures on an ExoEarth Using Direct Imaging

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Abstract

The James Webb Space Telescope (JWST) has provided the first opportunity of studying the atmospheres of terrestrial exoplanets and estimating their surface conditions. Earth-sized planets around Sun-like stars are currently inaccessible with JWST, however, and will have to be observed using the next generation of telescopes with direct-imaging capabilities. Detecting active volcanism on an Earth-like planet would be particularly valuable as it would provide insight into its interior and provide context for the commonality of the interior states of Earth and Venus. In this work, we used a climate model to simulate four exoEarths over eight years with ongoing large igneous province eruptions with outputs ranging from 1.8 to 60 Gt of sulfur dioxide. The atmospheric data from the simulations were used to model direct-imaging observations between 0.2 and 2.0 μm, producing reflectance spectra for every month of each exoEarth simulation. We calculated the amount of observation time required to detect each of the major absorption features in the spectra, and we identified the most prominent effects that volcanism had on the reflectance spectra. These effects include changes in the size of the O_3, O_2, and H_2O absorption features and changes in the slope of the spectrum. Of these changes, we conclude that the most detectable and least ambiguous evidence of volcanism are changes in both O_3 absorption and the slope of the spectrum.

Unified Astronomy Thesaurus concepts: Exoplanet atmospheres (487); Exoplanet astronomy (486); Exoplanet detection methods (489); Exoplanets (498); Volcanism (2174); Direct imaging (387); Spectroscopy (1558)

Introduction

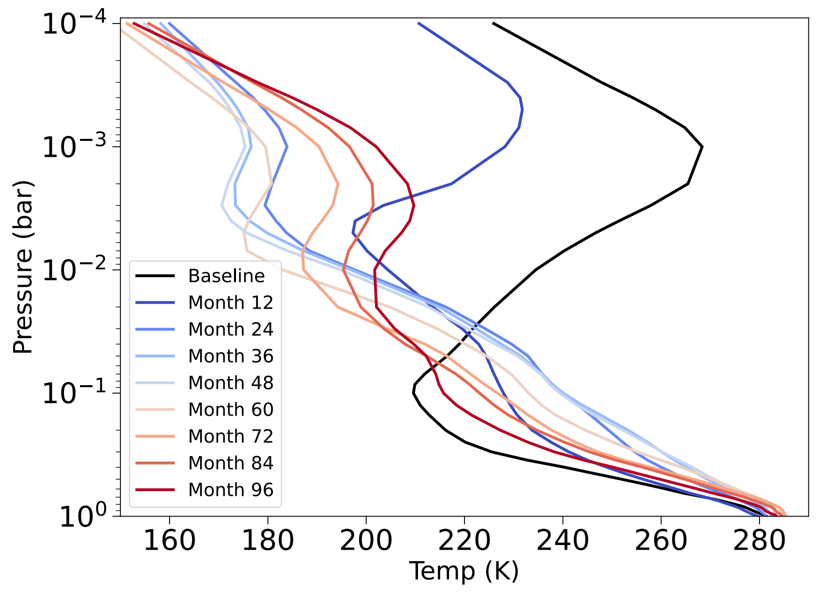
- Studying volcanism on exoplanets will give insight into their geological properties
- Provide context for the interior states of Earth and Venus
- Volcanic activity on exoplanets will need to be inferred from observations of their atmospheres
- Earth-sized planets around Sun-like stars will require future missions like the Habitable Worlds Observatory (HWO)

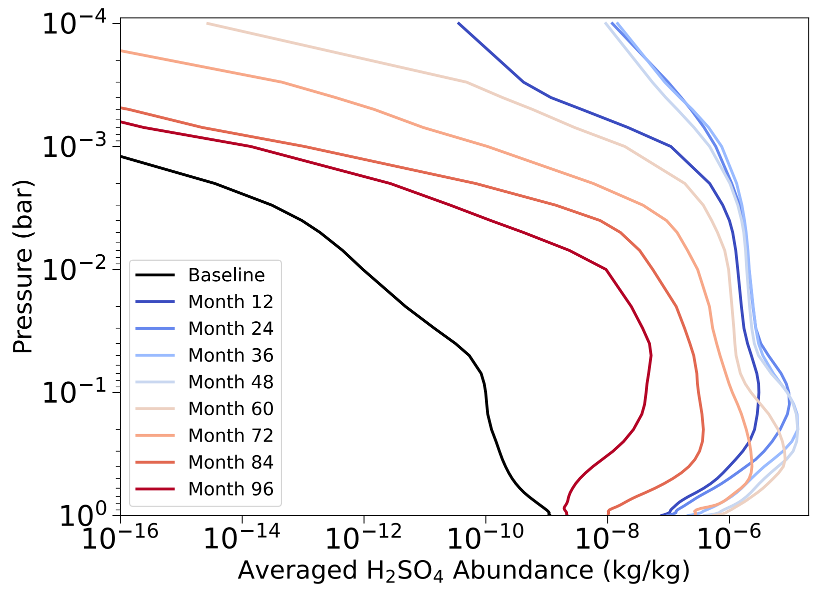
How can we tell if an exoplanet is volcanically active?

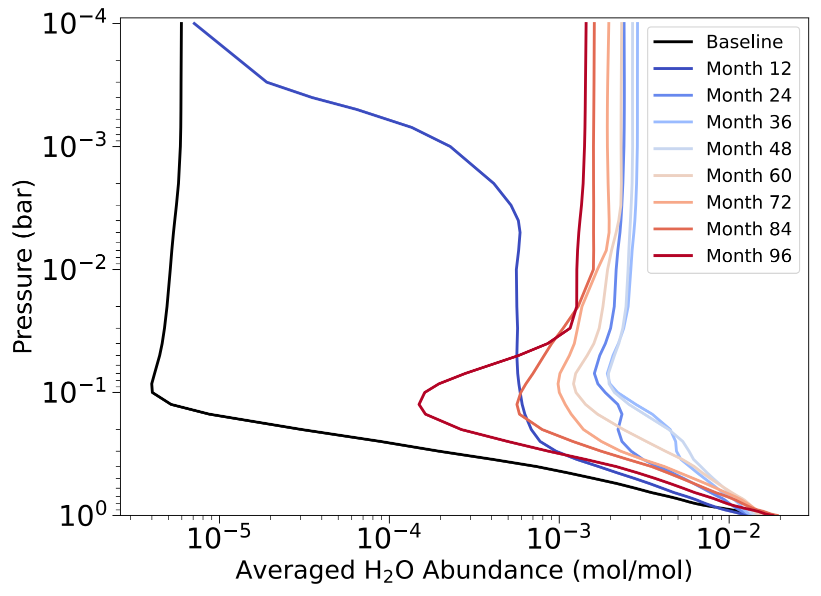
Modelling Volcanic Eruptions on Earth

- GEOSCCM Earth-based 3D GCM
- Resolution = 1 x 1 degrees, 72 vertical layers to 80 km
- 4 Large igneous province (LIP) eruptions:
  - Injecting SO_2 in upper troposphere and lower stratosphere
  - 1.8 – 60 Gt of SO_2 + Baseline no SO_2 case
- Each simulation = 4 years of eruptions + 4 years of no eruptions
- Output monthly averaged atmospheres

Effects of the Eruptions







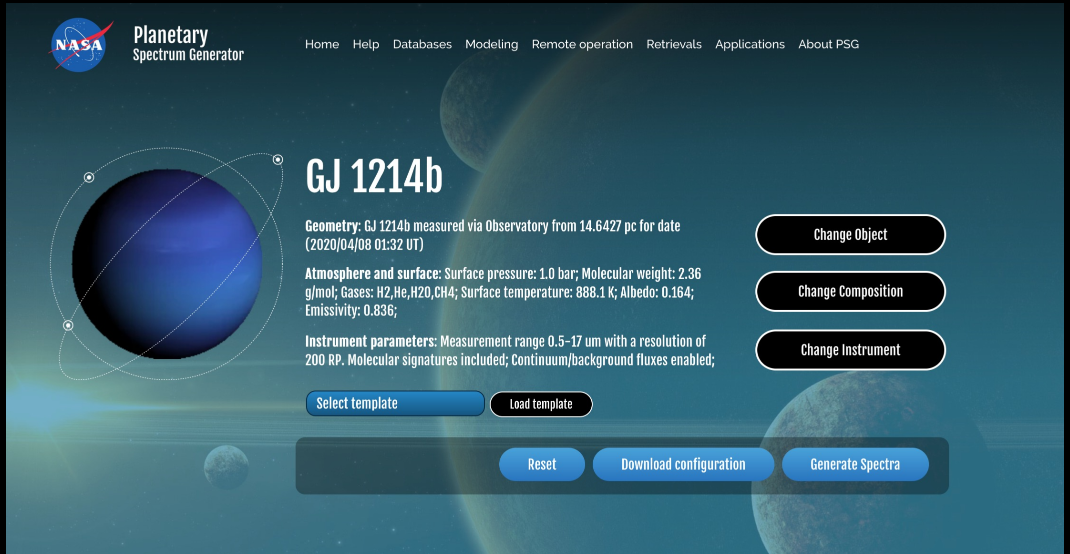
Loss of the tropopause

Increasing then decreasing H2SO4 haze

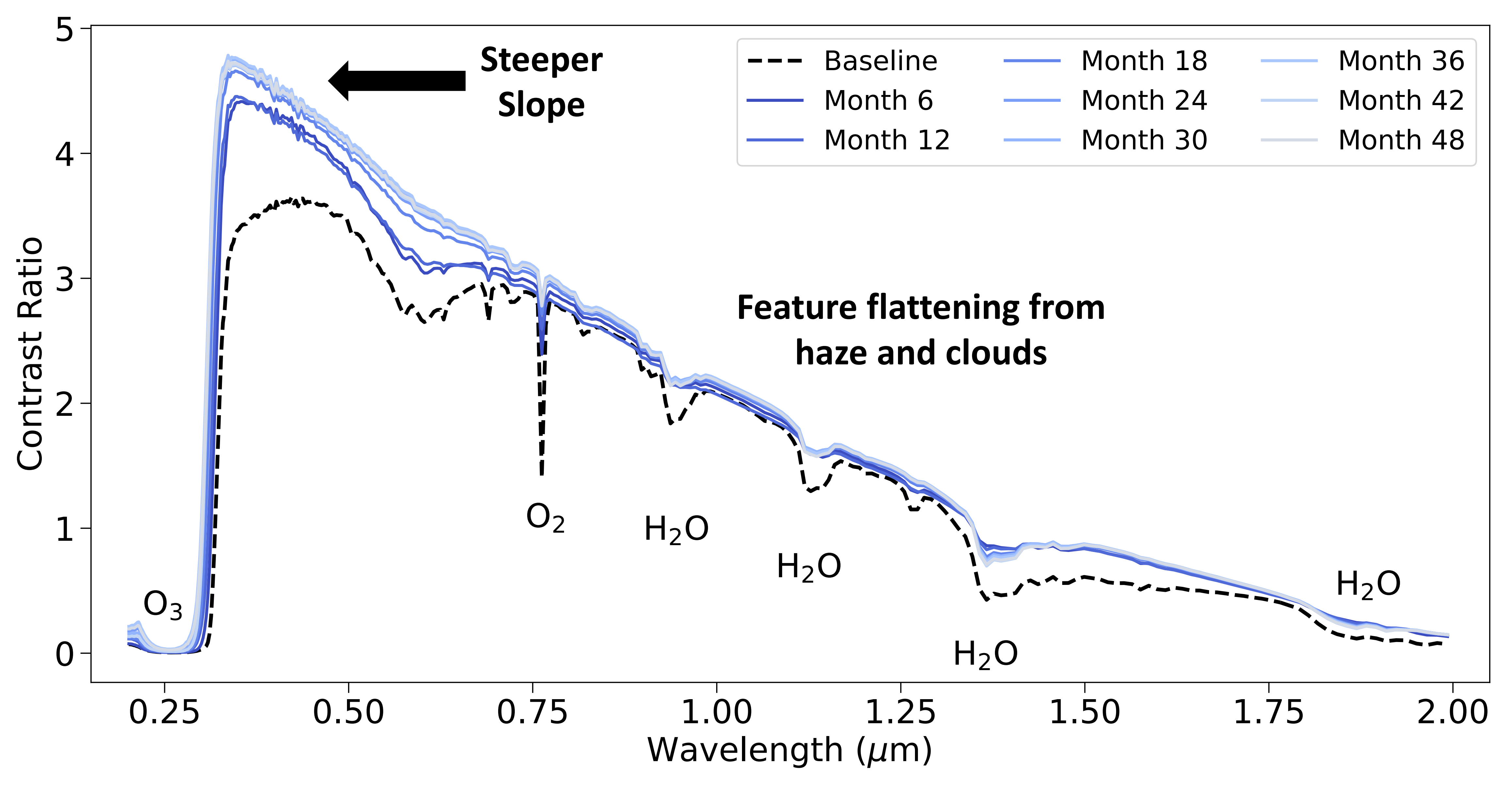
Movement of H2O to the upper atmosphere

Modelling Reflectance Spectra with GCM Data

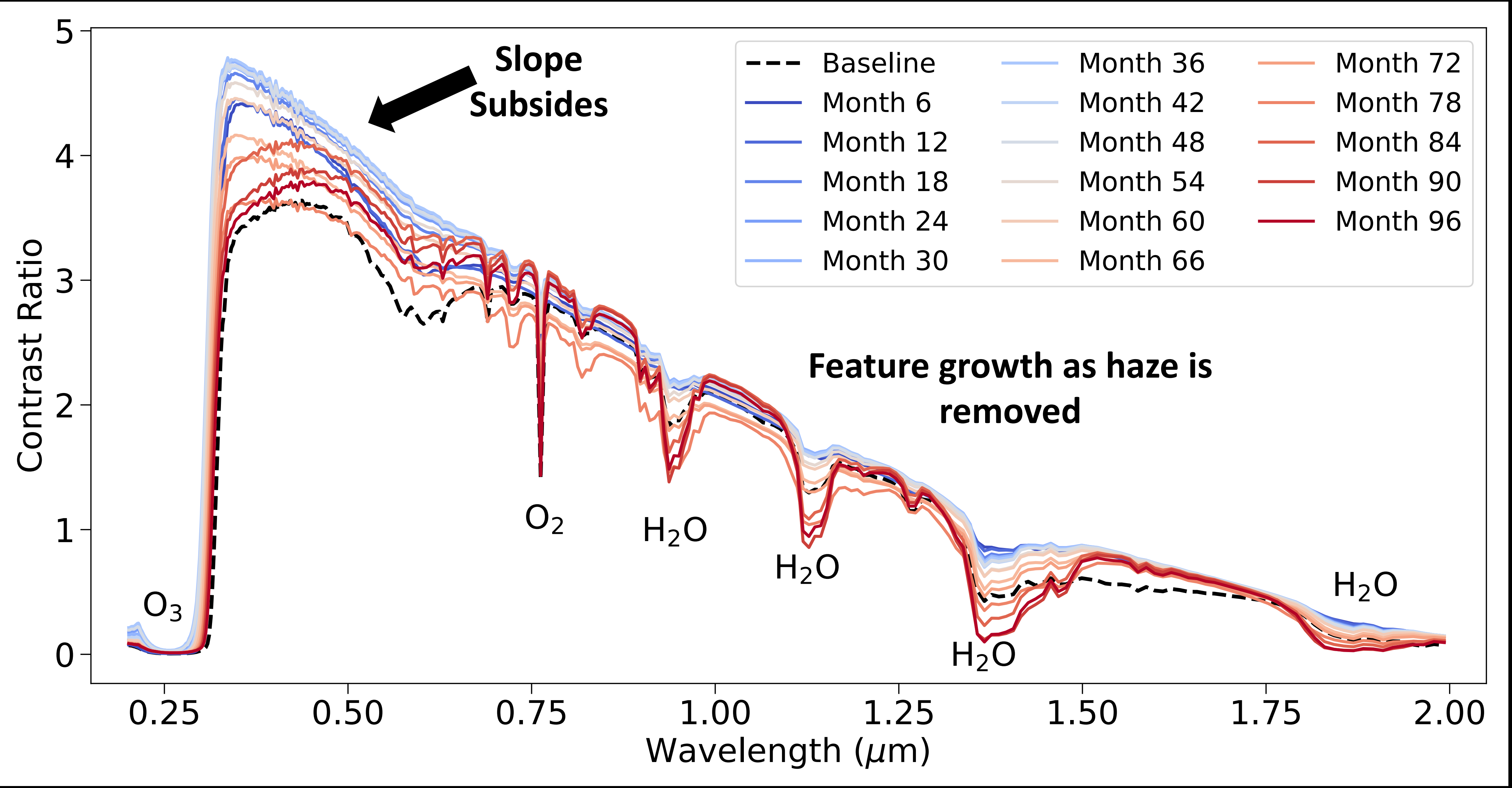
- Planetary Spectrum Generator (GlobES Application)
- Earth-analog around Sun-like star, 10 pc away
- LUVOIR-like telescope with coronagraph (6 meter)
- UV, Visible, and NIR bandpasses (0.2 - 2.0 microns)
- 90-degree planet phase angle
- Monthly averaged GCM data to define exoplanet atmosphere
- 96 Spectra per simulation



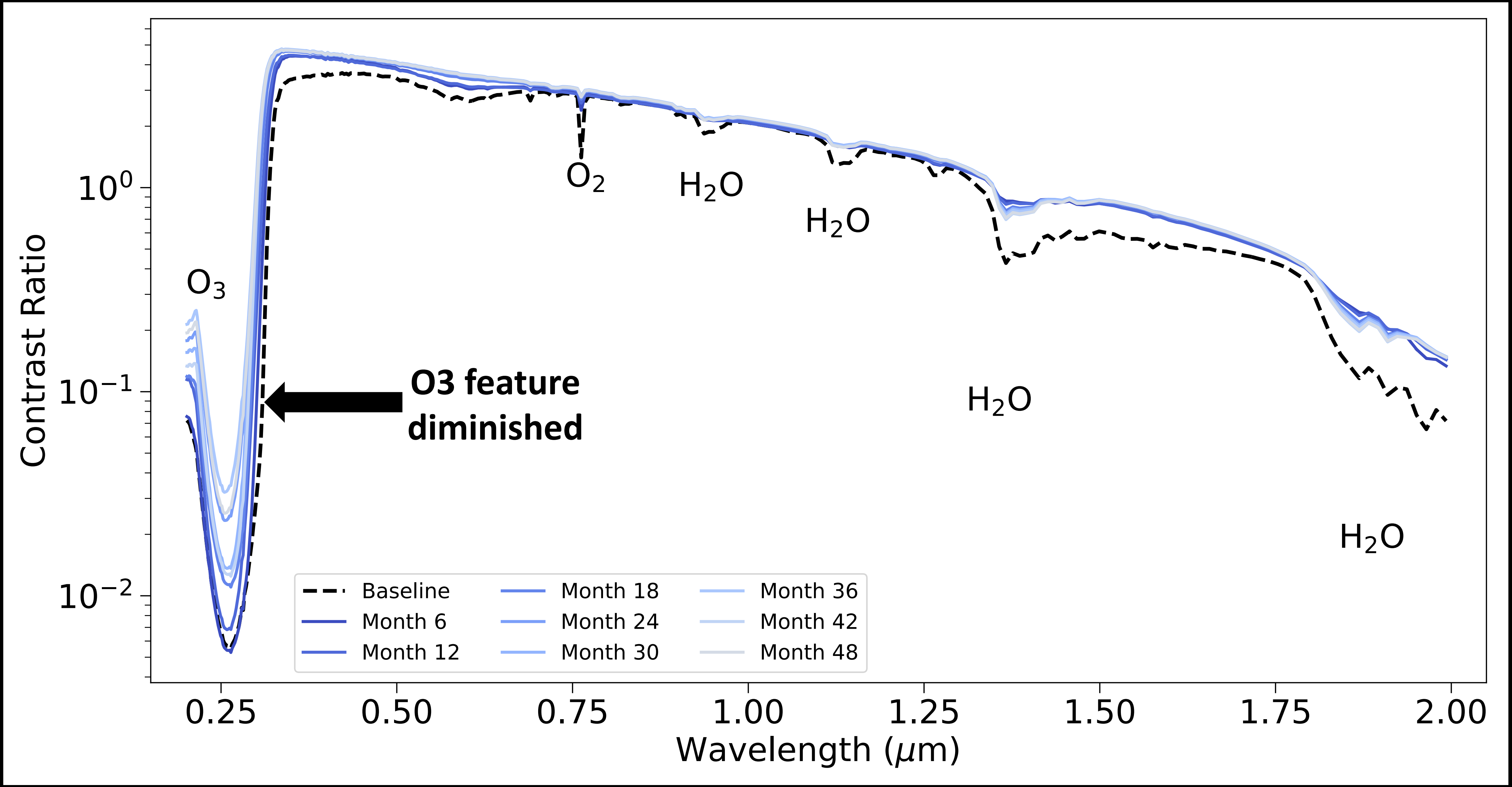
30 Gt Eruption (1st 4 Years)



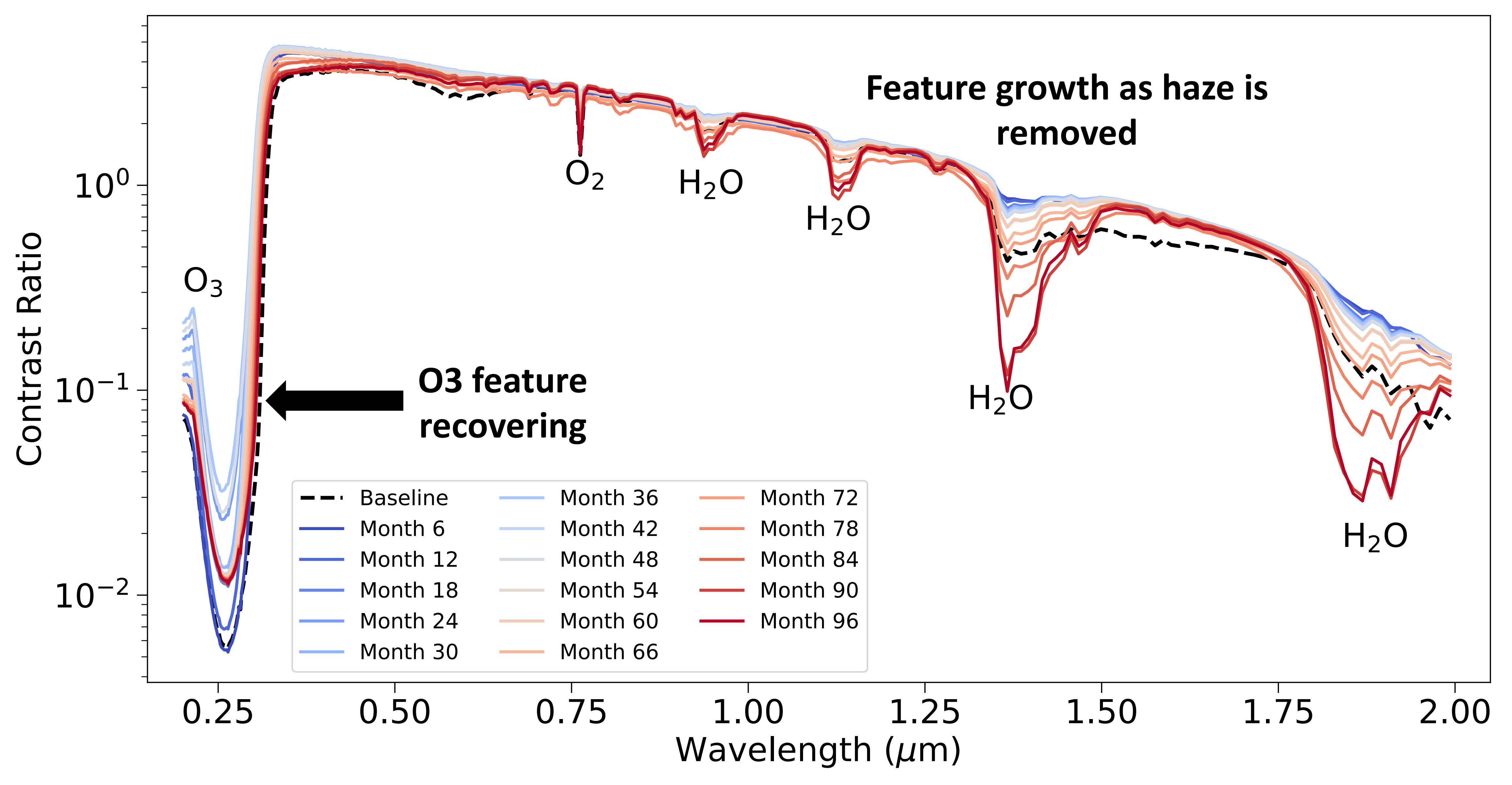
30 Gt Eruption (Entire Simulation)



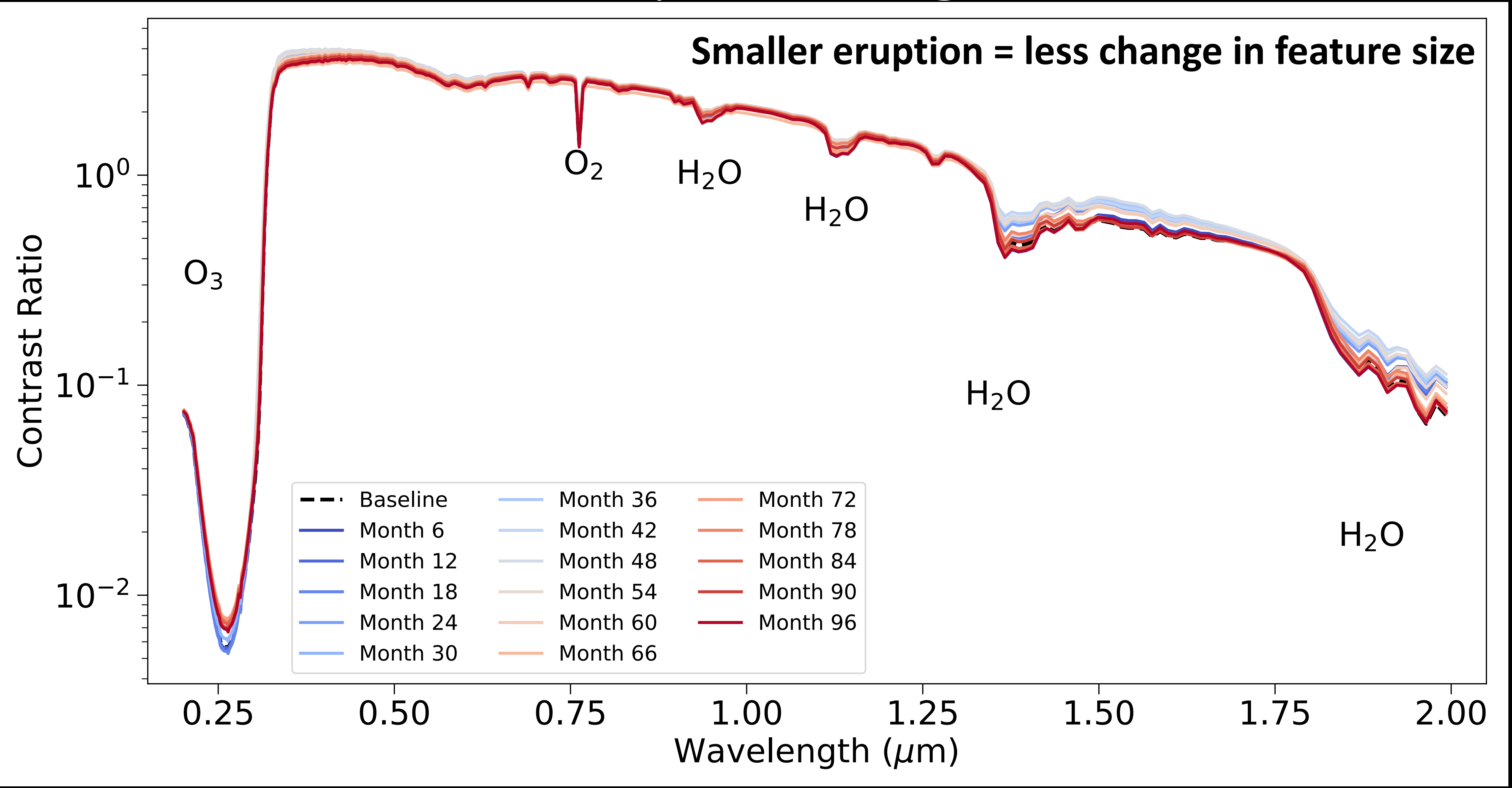
30 Gt Eruption (log-scale)



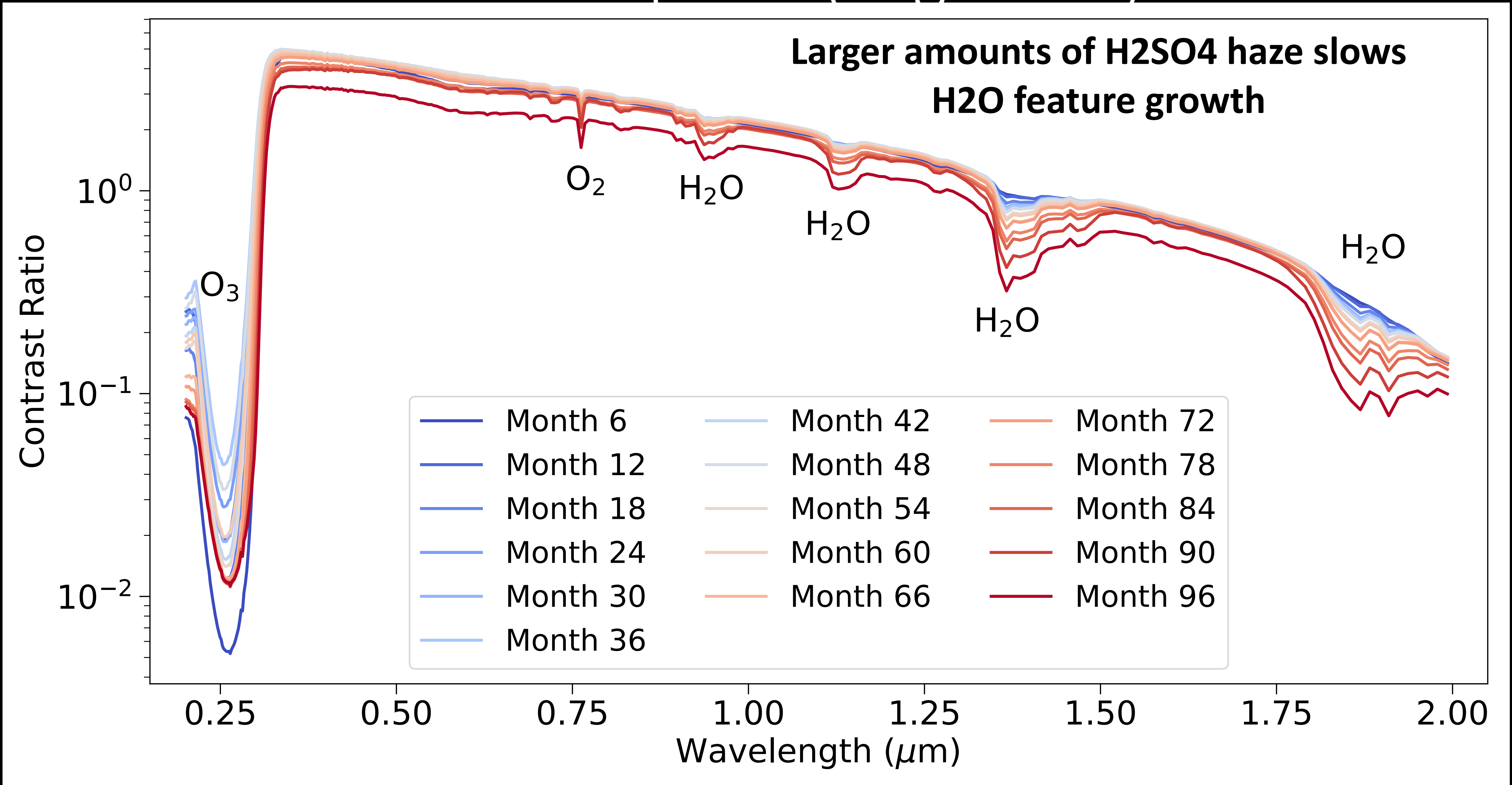
30 Gt Eruption (Log-scale)



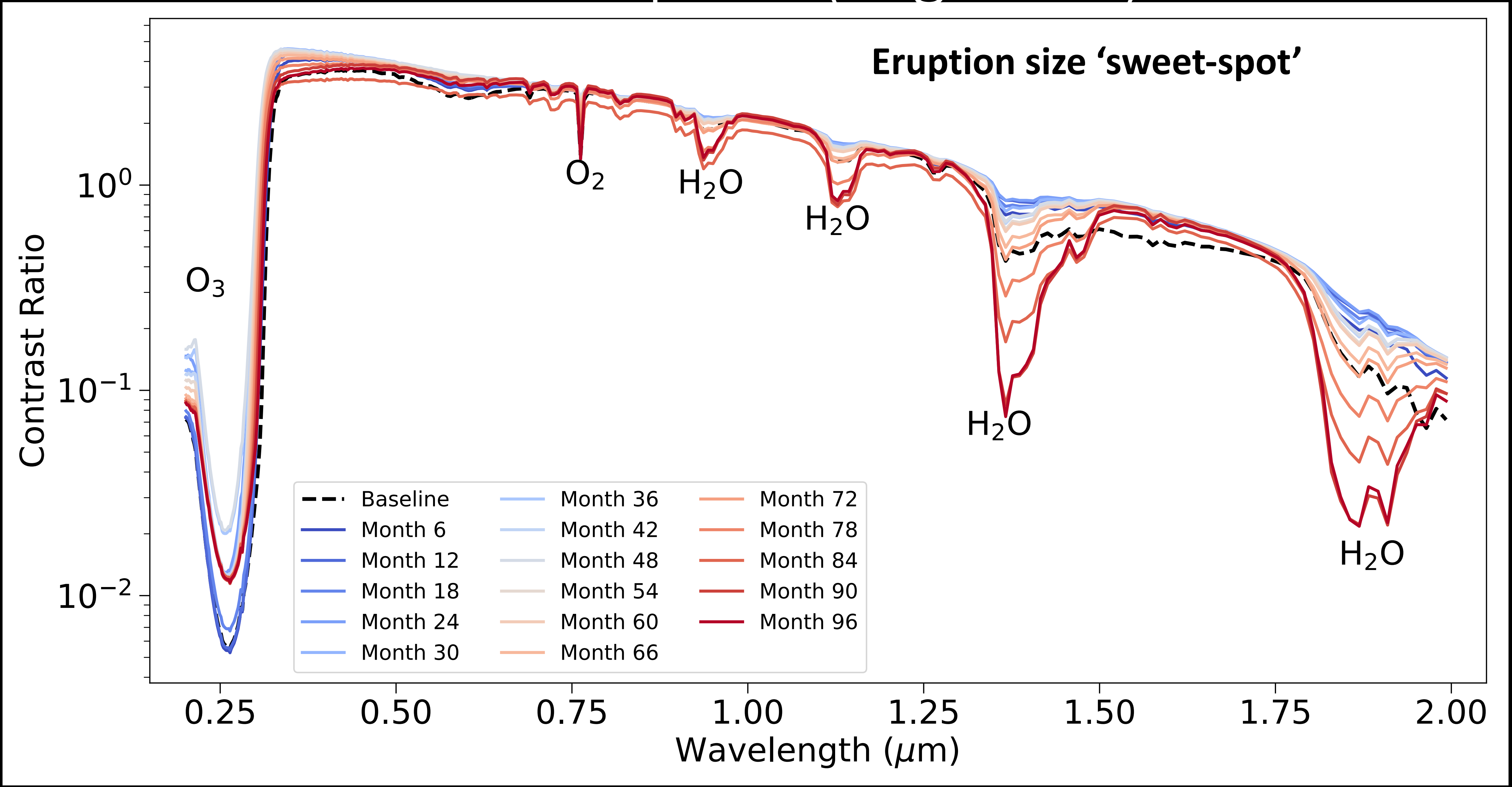
1.8 Gt Eruption (Log-Scale)



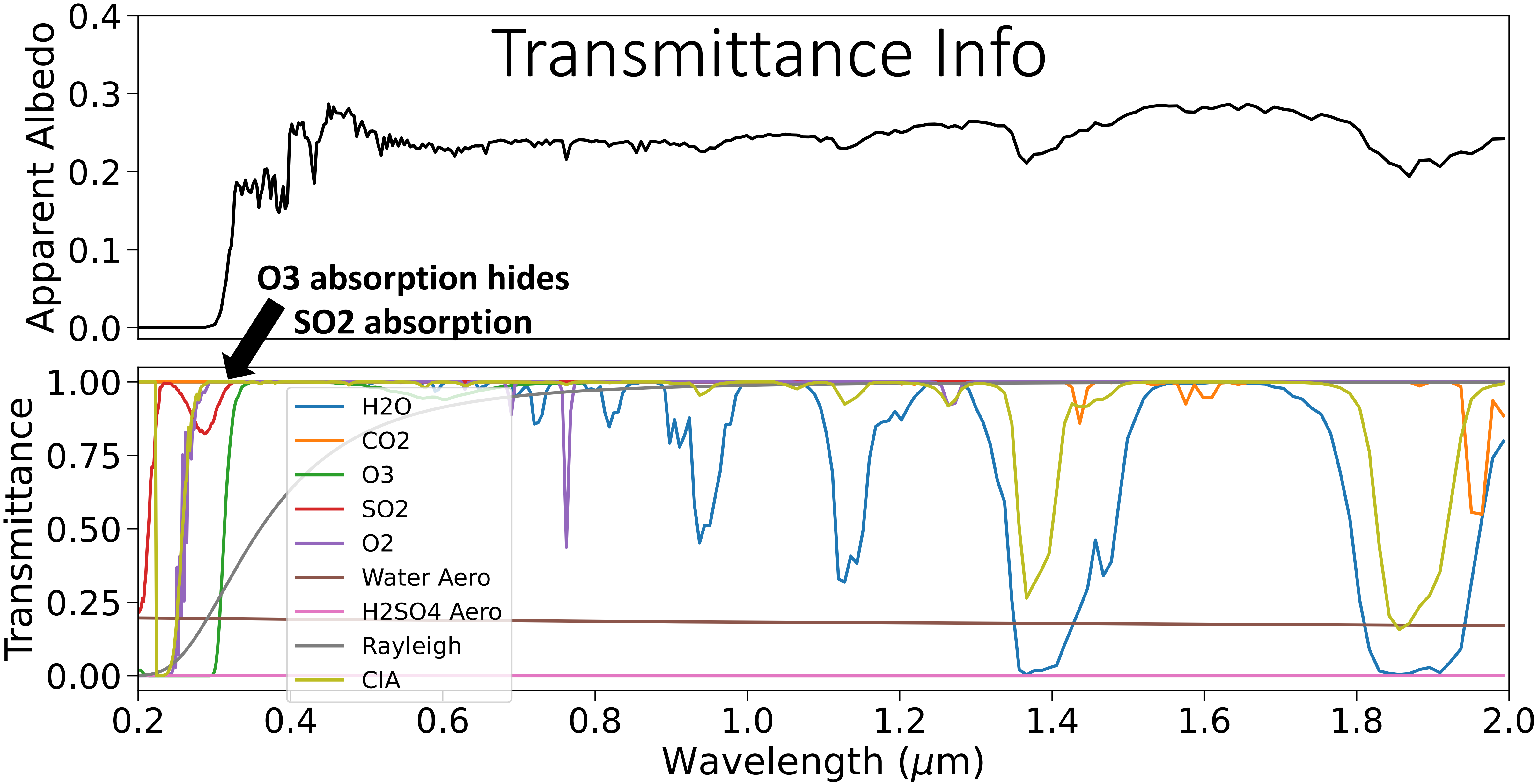
60 Gt Eruption (Log-Scale)



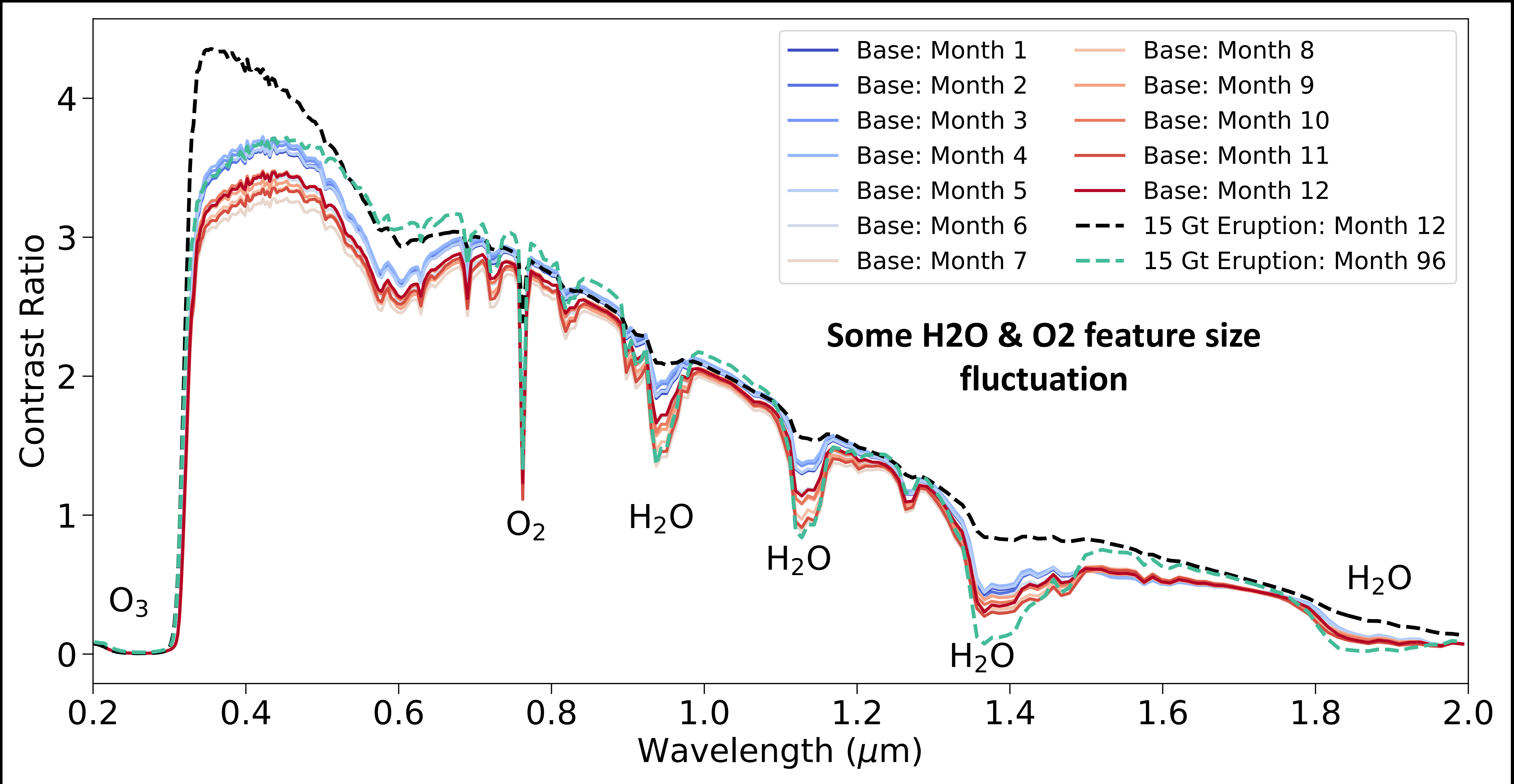
15 Gt Eruption (Log-Scale)



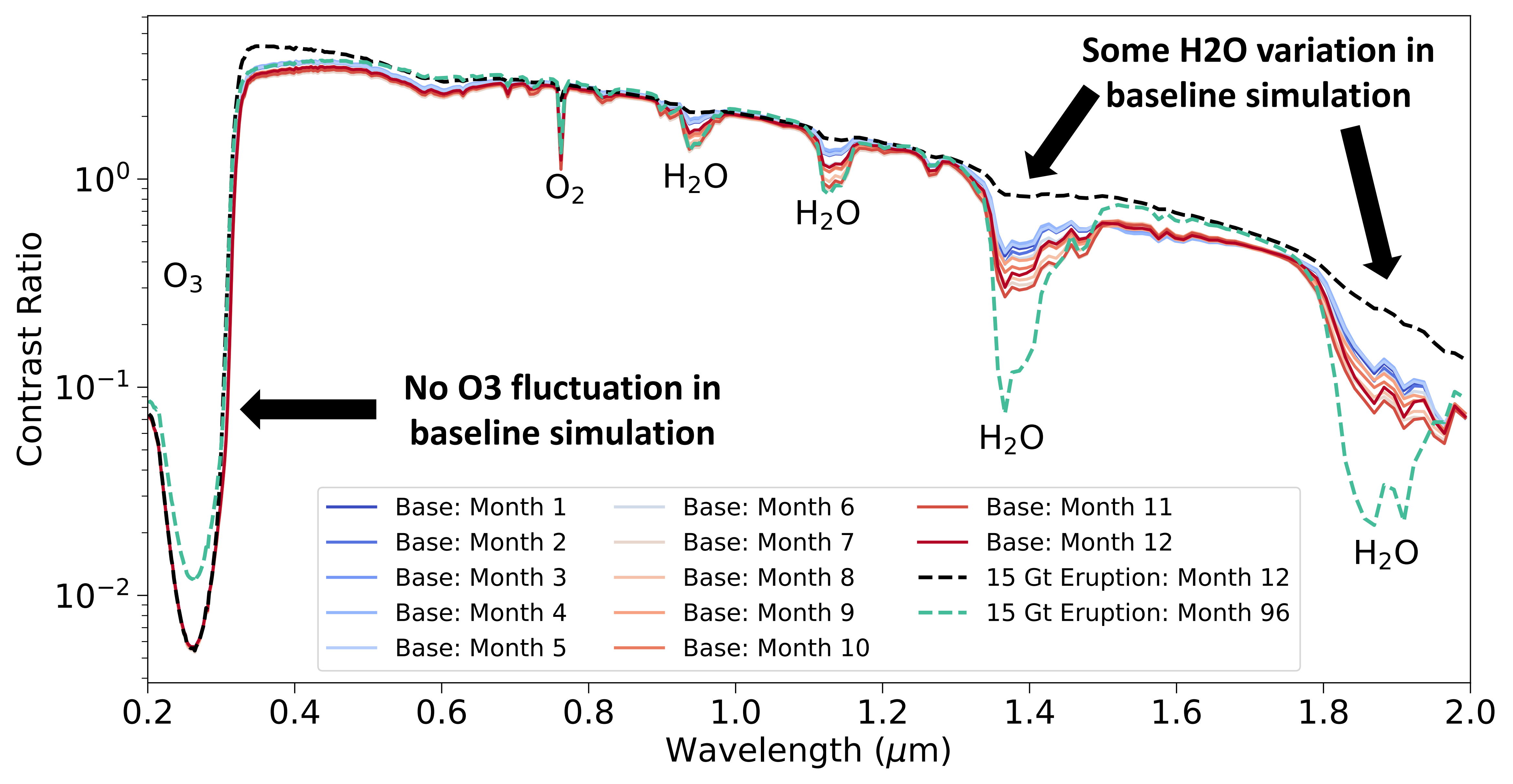
Transmittance Info



Baseline Simulation Variation



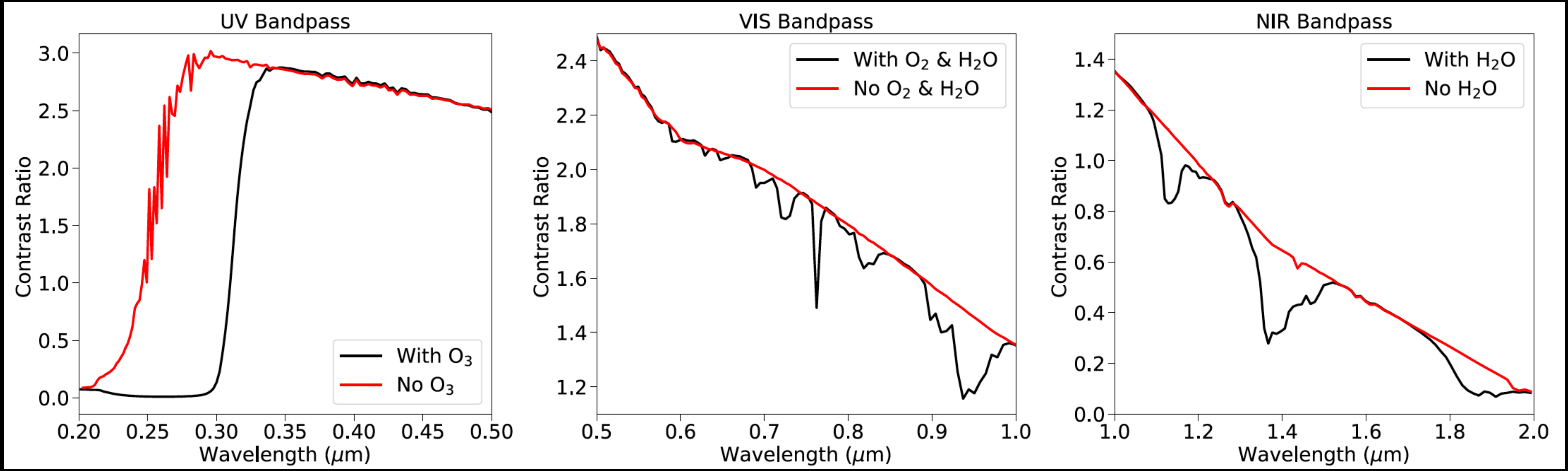
Eruption Variation vs Baseline Variation



Calculating S/N

- Spectrum with molecule absorption – spectrum without
- Simulated instrumental noise with PSG
- Quantified the detectability of all features (S/N > 5)
- Need to determine sensitivity to feature variation

$$\mathrm{S/N} = \sqrt{\sum_{i}^{N_{\lambda_i}} \left(\frac{y_i - y_{\mathrm{cont}}}{\sigma_i} \right)^2}\,.$$



Time Needed to Detect Features

- UV Bandpass (0.2 – 0.5 microns)
  - O_3 feature can be detected in 2-5 hours for all eruptions
- Visible Bandpass (0.5 – 1.0 microns)
  - H_2O and O_2 features range from 3-2000 hours to detect
- NIR Bandpass (1.0 – 2.0 microns)
  - H_2O features detected in 9-2000 hours

H_2O features can be detected relatively quickly or be undetectable depending on haze

O_3 is the most consistently detectable feature

Main Takeaways

- SO_2 would be ideal indicator but is hidden by O_3 absorption
- Main indicators of volcanic activity
  - Changes in O_3, H_2O, and O_2 feature
  - Steepened slope at 0.4 micron from haze scattering
- O_3 can be detected in 2-5 hours, H_2O & O_2 detectability varies drastically

Future Work

- If star is > 10 pc away, what changes?
- Possible with no coronograph and/or with HWO?
- Can weather changes on shorter timescales cause similar fluctuations in absorption feature size?
- Can the haze scatter slope be caused by other mechanisms/haze types?
- Different eruption types