Characterizing Temperature and Aerosol Variability During Jupiter’s 2006–2007 Equatorial Zone Disturbance

Arrate Antuñano, Leigh N. Fletcher, Glenn S. Orton, Daniel Toledo, Henrik Melin, Michael T. Roman, James A. Sinclair, Padraig T. Donnelly, Eleanor K. Morton, and Peter Selves

1School of Physics & Astronomy, University of Leicester, Leicester, UK, 2Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, 3National Institute for Aerospace Technology (INTA), Torrejón de Ardoz, Spain

Abstract We use ground-based mid-infrared (8–20 μm) data acquired by three different instruments between 2005 and 2008 to characterize the variability of tropospheric temperature and aerosol opacity during the 2006–2007 Equatorial Zone disturbance. This disturbance is part of a repeating pattern of cloud-clearing events at Jupiter’s equator, observed as a significant brightening at 5 μm (sensing the 2- to 7-bar region) and darkening at visible wavelengths (sensing the ~0.7-bar pressure level). The data reveal a brightness temperature increase of ~3.1 K between 2005 and February 2007 at 8.6-μm sensing tropospheric aerosol opacity and temperature near 0.6–0.8 bar. At wavelengths sensing tropospheric ammonia and temperatures between 150 and 600 mbar, the brightness temperature remains largely invariant between 2005 and 2008. The tropospheric vertical temperature profile and the tropospheric aerosol opacity were derived from images captured in different filters on four different dates, one for each year. The retrieved aerosol opacity at ~0.6–0.8 bar shows a decrease at 2–5°S of ~45% in 2006 and ~65% in 2007, with respect to 2008. This is consistent with cloud clearing/thinning during the coloration of the Equatorial Zone at visible wavelengths. This brightening at 8.6 μm started in 2005 and preceded the brightening at 5 μm, which started in April 2006. The results also suggest that cloud clearing during the Equatorial Zone disturbances is not simply the result of tropospheric warming, at least at p < 0.7 bar. We propose that cloud clearing occurs due to a decrease in the ammonia gas upwelling at the equator.

Plain Language Summary Jupiter's equatorial latitudes between ~7°, known as the Equatorial Zone (EZ), undergo dramatic planetary-scale disturbances that completely alter its appearance at different altitudes of the troposphere between 0.7 and 4 bar. Here we characterize the last EZ disturbance, observed in 2006–2007, to investigate what atmospheric conditions vary during these disturbances. Retrieved aerosol opacity at ~0.6 bar shows a decrease at 2–5°S of ~45% in 2006 and ~65% in 2007, with respect to 2008, consistent with cloud clearing/thinning during these events. This removal of aerosol opacity is observed to start in 2005, a year before the deeper clouds are cleared. These results indicate that the EZ disturbance involves the clearing of both the ammonia ice cloud near 0.7 bar and the deeper NH4SH clouds with each cloud deck responding at different times. Results also suggest that cloud clearing during the EZ disturbances is not simply the result of tropospheric warming in the middle- to high troposphere. We propose that cloud clearing occurs due to a decrease in the ammonia gas upwelling from deeper levels.

1. Introduction

Jupiter’s banded atmosphere is controlled by a wide variety of complex physical processes leading to dramatic planetary-scale disturbances and a range of colorful cloud morphologies. In particular, Jupiter’s Equatorial Zone (EZ) displays uniquely interesting atmospheric phenomena (e.g., Choi et al., 2013; Rogers, 1995). In visible light, the EZ is a whitish zone extending between ±7° latitude (all latitudes in this study are planetocentric) around the equator and is flanked by the brownish colored North Equatorial Belt (NEB) at its northern edge and South Equatorial Belt (SEB) at its southern edge. At visible wavelengths, where the top of the putative ammonia ice clouds are observed (~500–700 mbar), the northern and southern boundaries...
of the EZ display completely different cloud morphologies. The northern EZ features a quasi-periodic pattern of white plumes (ammonia ice-rich regions) and dark formations, which are bright at 5 μm and hence termed 5-μm “hot spots” (Keay et al., 1973; Terrile & Westphal, 1977). These features have been observed to be confined to pressures less than approximately 8 bar (de Pater et al., 2016, 2019; Fletcher et al., 2020). At the southern edge of the EZ, periodic chevron-like features have been observed (Simon-Miller et al., 2012). At 5 μm, where the thermal emission from Jupiter’s 2- to 7-bar pressure level is detected in the absence of clouds (Bjøraker et al., 2015; Giles et al., 2015), the EZ usually displays a uniformly dark appearance, due to thick NH₃ ice clouds covering this region, with bright hot spots at its northern boundary where aerosols and volatiles are observed to be depleted (de Pater et al., 2016, 2019; Fletcher et al., 2016; Wong et al., 2004). Juno’s microwave observations revealed a high concentration of NH₃ gas below the EZ extending to ∼100-bar pressure (Bolton et al., 2017; Ingersoll et al., 2017; Li et al., 2017). This was interpreted as a deep-seated global NH₃ upwelling within the EZ that could potentially be related to, or influenced by, the disturbances described below.

Studies of the long-term variability of Jupiter’s EZ at 5 μm (Antuñano et al., 2018, 2019) have revealed that the EZ displays a quasi-periodic planetary-scale disturbance that completely changes its appearance at infrared and visible wavelengths every ∼7 years (Antuñano et al., 2019). During the disturbed periods, the usually cloudy and 5-μm-dark EZ appears highly unusual: (i) a narrow 5-μm-bright band develops between 2°S and 5°S, and (ii) a rare wave-like pattern with 5-μm-bright narrow filaments (festoons) becomes visible, connecting the NEB and the newly brightened band south of the equator. These 5-μm disturbances last around 1–1.5 years and are observed to start around 18 months after the coloration of the EZ changes at visible wavelengths (Antuñano et al., 2018). So far, five of these EZ infrared disturbances have been observed since 1973, with two missing events in 1984–1986 and 2012–2013 where the EZ underwent strong coloration changes at visible wavelengths but did not brighten at 5 μm. A new EZ infrared disturbance developed between later 2018 and mid-2019, as expected by Antuñano et al. (2018), so this study looks back at past mid-infrared data to make predictions about the temperature and aerosols perturbations that might be apparent in the recent and future EZ disturbances.

The last infrared EZ disturbance occurred between April 2006 and October 2007, reaching its maximum 5-μm brightness in February 2007. During this event, the EZ had already altered from its usual whitish color to a brownish tone at visible wavelengths (similar to the NEB and SEB) in mid-2005 and continued to appear perturbed until the end of 2008. It also coincided with a period of decreased ultraviolet reflectivity at 410 nm (Simon-Miller & Gierasch, 2010), suggesting a removal of tropospheric hazes, and with an apparent increase in the velocity of the zonal equatorial winds derived from cloud tracking (Tollefson et al., 2017), in agreement with cloud clearing during these events. This allowed us to track winds at deeper atmospheric levels. All the changes observed in 2006–2007 suggest that the EZ undergoes a quasi-periodic thinning/removing of the white ammonia ice cloud, revealing aerosols with a red-brown chromophore and dynamic structure (e.g., the festoons) at higher pressures. However, the cause of this change is not yet understood—are these disturbances related to some deep moist convective processes releasing accumulated potential energy at ∼7-year intervals? Are they due to vertically propagating waves moving downward from higher altitudes? Or are they a manifestation of deep-seated changes of ammonia? In an effort to distinguish between these possibilities, we must extend our understanding of the vertical structure of these disturbances.

In this study we use ground-based 7- to 20-μm images captured by three different telescopes between 2005 and 2008 to determine how environmental conditions changed during the last infrared EZ disturbance event between April 2006 and October 2007. A description of the observations and data reduction techniques is given in section 2. In section 3, we analyze the variability of the brightness temperature at different wavelengths. We combine multiple filters in the infrared to measure the two-dimensional (pressure-latitude) temperatures and aerosol distributions at Jupiter’s troposphere during and after the EZ disturbance in section 4. Finally, we discuss the nature of these EZ disturbances and investigate the 2012–2013 coloration event in section 5.

2. Ground-Based Observations and Data Reduction

2.1. VISIR Observations

The VLT Imager and Spectrometer for mid-infrared wavelengths (VISIR, Lagage et al., 2004), installed on the 8.2-m Very Large Telescope (VLT) in Chile since 2004, provides diffraction-limited imaging in the N band.
Table 1
Summary of the Data Set Used in This Study Describing the Dates, Instruments, ID Codes, Wavelengths, and Central Meridian Longitude Coverage for Each Date

| Instrument | Date       | CMLIII (°) | Wavelengths (μm) | Program ID |
|------------|------------|------------|------------------|------------|
| IRTF/MIRSI | 2005-01-30 | 17–22      | 17.65            | 038        |
| IRTF/MIRSI | 2005-01-31 | 150        | 17.65            | 038        |
| IRTF/MIRSI | 2005-05-06 | 144        | 8.6, 13.0, 17.2, 18.4 | 004        |
| IRTF/MIRSI | 2005-05-23 | 204–231    | 8.6, 13.0, 17.2, 18.4 | 004        |
| IRTF/MIRSI | 2005-05-24 | 331–16     | 8.6, 13.0, 17.2, 18.4 | 004        |
| IRTF/MIRSI | 2006-01-29 | 170–256    | 8.6, 9.8, 13.0, 17.2, 18.4 | 006        |
| IRTF/MIRSI | 2006-01-30 | 282–57     | 8.6, 9.8, 13.0, 17.2, 18.4 | 006        |
| IRTF/MIRSI | 2006-02-16 | 204        | 17.2            | 006        |
| IRTF/MIRSI | 2006-04-09 | 250–261    | 10.7, 13.0, 17.6, 18.7, 19.5 | 006        |
| IRTF/MIRSI | 2006-04-10 | 261–269    | 10.7, 13.0, 17.6, 18.7 | 006        |
| IRTF/MIRSI | 2006-04-16 | 266–285    | 8.6, 10.7, 13.0, 17.2, 18.7 | 006        |
| IRTF/MIRSI | 2006-05-25 | 271–272    | 17.2, 18.4      | 006        |
| IRTF/MIRSI | 2006-06-20 | 252–69     | 8.6, 13.2, 17.2, 18.4 | 006        |
| IRTF/MIRSI | 2006-08-01 | 350–5      | 8.6, 17.2, 18.4  | 006        |
| IRTF/MIRSI | 2006-08-10 | 282–310    | 9.8, 13.2, 17.2, 18.4 | 098        |
| IRTF/MIRSI | 2006-08-12 | 232–249    | 8.6, 13.2, 17.2  | 098        |
| IRTF/MIRSI | 2006-08-24 | 268–284    | 8.6, 13.0, 18.4  | 016        |
| IRTF/MIRSI | 2007-02-24 | 26–41      | 13.2, 18.4      | 020        |
| IRTF/MIRSI | 2007-03-18 | 326–343    | 13.2, 17.2, 18.4 | 020        |
| IRTF/MIRSI | 2007-03-19 | 145–162    | 8.6, 13.2, 17.2, 18.4 | 020        |
| IRTF/MIRSI | 2007-04-05 | 224–244    | 9.8, 17.2, 18.4  | 020        |
| IRTF/MIRSI | 2007-05-29 | 256        | 18.4            | 020        |
| IRTF/MIRSI | 2007-05-30 | 24–53      | 9.8, 13.2, 17.2, 18.4 | 020        |
| IRTF/MIRSI | 2007-09-07 | 11–41      | 8.6, 9.8, 13.2, 17.2, 18.4 | 093        |
| IRTF/MIRSI | 2007-09-08 | 167–190    | 9.8, 13.2, 17.2, 18.4 | 093        |
| IRTF/MIRSI | 2008-06-16 | 166–181    | 9.8, 17.2, 18.4  | 062        |
| IRTF/MIRSI | 2008-06-17 | 320–69     | 9.8, 13.2, 17.2, 18.4 | 062        |
| IRTF/MIRSI | 2008-07-10 | 357–36     | 8.6, 13.2, 17.2, 18.4 | 062, 064   |
| IRTF/MIRSI | 2008-07-11 | 83–100     | 8.6, 13.2, 17.2, 18.4 | 062, 064   |
| IRTF/MIRSI | 2008-08-07 | 85–217     | 9.8, 13.0, 17.2, 18.4 | 002        |
| IRTF/MIRSI | 2008-08-08 | 350–16     | 8.6, 13.2, 17.2, 18.4 | 002        |
| IRTF/MIRSI | 2008-10-23 | 31–86      | 8.6, 13.2, 17.2, 18.4 | 002        |
| Subaru/COMICS | 2005-04-30 | 58–80  | 8.7, 10.3, 17.6, 18.7 | 05108      |
| Subaru/COMICS | 2005-05-24 | 349–101  | 8.7, 10.3, 17.6, 18.7, 20.5 | 05108      |
| VLT/VISIR   | 2006-04-09 | 250–261    | 10.7, 13.0, 17.6, 18.7, 19.5 | 276.C-5055 |
| VLT/VISIR   | 2006-04-10 | 261–269    | 10.7, 13.0, 17.6, 18.7, 19.5 | 276.C-5055 |
| VLT/VISIR   | 2006-04-16 | 274–282    | 10.7, 13.0, 18.7  | 276.C-5055 |
| VLT/VISIR   | 2007-02-27 | 54–66      | 10.7, 13.0, 17.6, 18.7, 19.5 | 278.C-5023 |
| VLT/VISIR   | 2007-02-28 | 180–226    | 13.0, 17.6, 18.7, 19.5 | 278.C-5023 |
| VLT/VISIR   | 2007-03-01 | 341–25     | 13.0, 17.6, 18.7  | 278.C-5023 |
| VLT/VISIR   | 2007-08-14 | 16         | 10.7            | 279.C-5043 |
| VLT/VISIR   | 2007-08-15 | 19–143     | 10.7, 13.0, 17.6, 18.7 | 279.C-5043 |
| VLT/VISIR   | 2007-08-16 | 192–329    | 10.7, 13.0, 17.6, 18.7 | 279.C-5043 |
| VLT/VISIR   | 2007-10-06 | 58–62      | 13.0, 17.6, 18.7  | 279.C-5043 |
| VLT/VISIR   | 2007-10-10 | 293–301    | 13.0, 17.6, 18.7  | 279.C-5043 |
| VLT/VISIR   | 2008-05-17 | 136–138    | 10.7            | 081.C-0134 |
Table 1  
(continued)

| Instrument | Date   | CMLIH (°) | Wavelengths (μm)                     | Program ID |
|------------|--------|-----------|-------------------------------------|------------|
| VLT/VISIR  | 2008-05-18 | 115–180  | 10.7, 13.0, 17.6, 18.7               | 081.C-0134 |
| VLT/VISIR  | 2008-05-19 | 45–71     | 10.7, 13.0, 18.7                     | 081.C-0134 |
| VLT/VISIR  | 2008-05-20 | 121–133   | 10.7, 13.0, 17.6, 18.7               | 081.C-0134 |
| VLT/VISIR  | 2008-05-22 | 54        | 10.7                                 | 081.C-0134 |
| VLT/VISIR  | 2008-05-26 | 228–237   | 10.7, 13.0, 17.6, 18.7               | 081.C-0134 |
| VLT/VISIR  | 2008-05-27 | 28–37     | 13.0, 18.7                           | 081.C-0134 |
| VLT/VISIR  | 2008-06-27 | 144–147   | 10.7, 13.0                           | 081.C-0137 |
| VLT/VISIR  | 2008-07-04 | 110–114   | 10.7, 13.0                           | 081.C-0137 |
| VLT/VISIR  | 2008-07-09 | 295–320   | 10.7, 13.0                           | 081.C-0137 |
| VLT/VISIR  | 2008-07-13 | 92–102    | 10.7, 13.0, 18.7                     | 081.C-0137 |
| VLT/VISIR  | 2008-07-19 | 88–93     | 10.7, 13.0                           | 081.C-0137 |
| VLT/VISIR  | 2008-07-29 | 105–109   | 10.7, 13.0                           | 081.C-0137 |
| VLT/VISIR  | 2008-07-30 | 126–130   | 10.7, 13.0                           | 081.C-0137 |
| VLT/VISIR  | 2008-08-10 | 134–161   | 10.7, 13.0, 17.6, 18.7, 19.5         | 081.C-0141 |
| VLT/VISIR  | 2008-08-31 | 307–312   | 10.7, 13.0                           | 081.C-0137 |
| VLT/VISIR  | 2008-09-01 | 92–120    | 10.7, 13.0, 17.6                     | 081.C-0137 |
| VLT/VISIR  | 2008-09-02 | 264–267   | 10.7, 13.0                           | 081.C-0137 |
| VLT/VISIR  | 2008-09-03 | 89–138    | 10.7, 13.0, 17.6, 18.7               | 081.C-0137 |
| VLT/VISIR  | 2008-09-18 | 186–196   | 10.7, 13.0, 17.6, 18.7               | 081.C-0137 |

**Note.** Dates are formatted as YYYY-MM-DD.

(8 to 13 μm) and Q band (17 to 20 μm) with a pixel field of view of 0.127′′, a total field of view of 32 × 32′′, and a spatial resolution of 0.3′′ in the N band and 0.6′′ in the Q band. In 2015, after a 3-year refurbishment, an M-band filter was installed with a new burst mode allowing us to capture diffraction-limited imaging at 5 μm with a spatial resolution of 0.15 ′′. However, as described below we do not use VISIR 5-μm data in this study. As the field of view is smaller than Jupiter’s disk at opposition and VISIR is not set up to perform traditional mosaicing (where multiple tiles are placed on the scene, like COMICS instrument described below), the observations are designed to target one hemisphere at a time chopping in the appropriate direction so as not to obscure the hemisphere of interest, given the limited chopping amplitude of 25 ′′. To remove the thermal background from the atmosphere and the telescope, the observations are designed to chop 25 ′′ away from Jupiter for each of the nodding cycles during a single observation night (Fletcher, Melin, et al., 2018). In this study we use VISIR data captured between April 2006 and September 2008 using six different filters (i.e., 8.6, 10.7, 13, 17.6, 18.7, and 19.5 μm) sensing the troposphere in the 150- to 600-mbar pressure range. Further details of these specific observations can be found in Fletcher et al. (2010), where they were used to study the temperature and composition of the Great Red Spot. A list of the exact dates, instruments, and their corresponding program IDs are given in Table 1. A summary of the spatial resolution of each instrument and wavelength is shown in Table S1 in the supporting information.

### 2.2. COMICS Observations

The Cooled Mid-Infrared Camera and Spectrometer (COMICS, Kataza et al., 2000) mounted at the Cassegrain focus of the 8.2-m Subaru Telescope at the summit of Maunakea, Hawaii, provides imaging and spectroscopy in the mid-infrared between 7.5 and 25 μm. The camera uses a plate scale of 0.13′′ and provides a total field of view of 42 × 32′′ which is mosaicked across Jupiter’s disk. In this study, a set of five filters centered at 8.7, 10.3, 17.6, 18.7, and 19.5 μm) sensing the troposphere in the 150- to 600-mbar pressure range. Further details of these specific observations can be found in Fletcher et al. (2010), where they were used to study the temperature and composition of the Great Red Spot. A list of the exact dates, instruments, and their corresponding program IDs are given in Table 1. A summary of the spatial resolution of each instrument and wavelength is shown in Table S1 in the supporting information.

### 2.3. MIRSI Observations

The Mid-Infrared Imager and Spectrometer (MIRSI, Deutsch et al., 2003), mounted on the 3-m Infrared Telescope Facility (IRTF) on Maunakea, Hawaii, provides diffraction-limited spatial resolution imaging and
Figure 1. Scaled cylindrical maps of Jupiter for ±30° latitude showing the 8.59 μm (a), 10.7 μm (b), 13.0 μm (c), and 17.6 μm (d) radiances before (24 May 2005), during (9 April 2006 and 27 February 2007), and after (10 August 2008) the EZ disturbance. A clear increase of the radiance is observed at the equatorial latitudes at 8.59 μm. Gray areas correspond to obscured regions artificially introduced during the sky emission correction process and are not taken into account in our analysis (see section 2.4). The difference in the brightness of the 2005 COMICS image at 17.6 μm, compared to 2006–2008, might be due to differences in the filter between instruments. Dark spots correspond to moon silhouettes and are ignored in our analysis.
spectroscopy between 5 and 25 μm with a field of view of 85 × 64′′, larger than Jupiter's full disk at opposition. In this study, images captured at 8.6, 9.8, 13.2, 17.9, and 18.4 μm between 2005 and 2008 are used, together with COMICS and VISIR data, to analyze potential spectral radiance changes in these filters during the EZ disturbance. As for COMICS, we omit the 24.8-μm MIRSI data. Due to the lower spatial resolution of the MIRSI data (0.6′′ and 1.42′′ at 8.6 and 20.6 μm, respectively), these are not used in the NEMESIS retrievals (see section 3).

2.4. Data Reduction

Data from all three instruments are reduced following the steps in Fletcher, Orton, Yanamandra-Fisher, et al. (2009), by subtracting the sky emission using the chop-nodded images, removing corrupted pixels by applying a flat-field and bad pixel map that corrects the non-uniformities in the detector response, and coadding multiple corrected images to increase the signal-to-noise ratio. The corrected and coadded images are geometrically calibrated by visually fitting the limb to assign latitudes, longitudes, and emission angles to each pixel and then are projected into cylindrical maps with 0.5° spatial resolution. Due to the maximum chopping amplitude of 25° of the VLT and the small (32 × 32′′) field of view of the VISIR instrument, the chopping-nodding technique used to remove the sky emission from the VISIR data leads to a region of Jupiter being artificially obscured. This is due to part of Jupiter's thermal emission being subtracted together with the sky emission. In this study, the obscured regions of the images are corrected, before geometrically calibrating the data, by adding back the region of the planet that was previously subtracted. Any uncorrected or spurious pixels added by this technique (e.g., adding back part of the sky and artificially brightening some pixels and/or obscured pixels, see Figure 1) are ignored in our retrievals. These pixels are manually removed and are easily identified as large spikes in the radiance images.

Each cylindrical map is radiometrically calibrated by scaling the N-band and Q-band radiances to match Cassini CIRS and Voyager IRIS observations, respectively, at latitudes away from the equator and poles (i.e., mainly spanning from 15° to 60° north and south). The choice for scaling the Q-band data to IRIS is due to the very low spatial resolution of the CIRS Q-band observations (these were acquired by CIRS focal plane one, which only provided hemispheric averages in the λ > 16 μm region). In performing this radiometric scaling, we are assuming that Jupiter's averaged brightness has not altered significantly with time, despite Jupiter's intrinsic atmospheric variability. If Jupiter has warmed or cooled in a global sense, this assumption might introduce a systematic offset to the final retrieved temperatures (see Table 2). Though we deem this unlikely (and a comparison between Voyager and SOFIA/FORCAST by Fletcher, de Pater, et al., 2017, suggested temperature changes smaller than 5 K in the Q band over the 35-year period), we have no source of independently calibrated observations during the Voyager/Cassini encounters to refute this possibility.

We have attempted to ensure that all images and cylindrical maps have been corrected for radiance offsets introduced by small radiometric calibration differences from date to date. This is done by scaling the radiance to the temporal mean radiance of 50–70° north and south over 2005–2008, where it is assumed to remain largely invariant. Finally, scaled cylindrical maps from the different filters mentioned above are stacked together on 9 April 2006, 27 February 2007, and 10 August 2008 (VISIR data) and 24 May 2005 (COMICS data) to form four image cubes (one for each date). Each cube contains six spectral points (five in the case of COMICS) to retrieve tropospheric temperatures in the 100- to 600-mbar range from observations of the H₂-He collision-induced continuum at 13–20 μm and aerosols opacity near 600–700 mbar from the 8.6-μm observations. Aerosol scattering is assumed to have a negligible effect in the 13- to 20-μm continuum, and therefore, only gas opacity is included in these calculations.

2.5. Measurement Uncertainties

Ground-based mid-infrared imaging can be subject to uncertainties from a range of sources, some random, and some systematic. The most important errors are being introduced via the radiometric calibration process and include the (i) absolute calibration uncertainties from assuming Jupiter has not changed since the Voyager and Cassini flybys, (ii) difficulties in scaling the observed flux to the Voyager/Cassini profiles due to differences in the latitudinal distribution of the radiance from observation to observation, and (iii) the assumption that the 50–70° north and south latitudes remain invariant between 2005 and 2008. We note that errors introduced by these three sources cannot be considered as independent. Nevertheless, they may combine to produce systematic radiance offsets and therefore uncertainties in the absolute values of the retrieved
### Table 2

**Summary of the Standard Deviation of the Random Sky Background and the Uncertainties Introduced During the Calibration Process**

| Wavelength (μm) | Random sky (K) | Absolute calibration (K) | Radiometric scaling (K) |
|----------------|----------------|--------------------------|-------------------------|
| 8.6            | 0.4–0.6        | 0.3                      | 0.5                     |
| 10.3–10.7      | 0.4–0.5        | 0.9                      | 0.3                     |
| 13.2           | 0.5–0.7        | 1.6                      | 0.3                     |
| 17.2–17.7      | 0.5–0.7        | 2.0                      | 0.2                     |
| 18.4–18.7      | 0.5–0.6        | 2.2                      | 0.3                     |
| 19.5           | 0.6–0.9        | 2.7                      | 0.2                     |

*Note.* The absolute calibration uncertainty corresponds to differences between the CIRS and IRIS profiles. The radiometric scaling uncertainty shown here corresponds to the temporal average over the entire 2005–2008 period. The ranges in the random sky background uncertainties represent differences over the four different dates used in the NEMESIS retrievals.

atmospheric parameters (temperatures and aerosols). However, a systematic radiance offset (affecting all locations equally) still permits us to explore relative temperature and aerosol variability.

#### 2.5.1. Random Uncertainties

Random releases of electrons due to thermal fluctuations in the detector from observation to observation (i.e., dark current) and the variability of Earth’s atmosphere, among others, introduce random noise to our images. Here we estimate these random uncertainties introduced by these sources by computing the standard deviation of the sky background of each of the images used in the NEMESIS retrievals. For each of these images, a threshold is manually set to distinguish the sky background emission from Jupiter’s emission. The estimated random uncertainties are shown in Table 2, where the best and worst cases are shown.

#### 2.5.2. Absolute Calibration

The scaling of the data to the CIRS observations (or IRIS for the Q band) assumes that the radiometric calibration of these space-borne Fourier transform spectrometers provides a near-perfect measurement. However, we recognize that there was no independent confirmation possible at the same time as those observations. For this reason, we estimate the absolute calibration error by comparing the differences between the CIRS and IRIS global radiances. These global radiances were computed by averaging the CIRS and IRIS profiles independently between ±60° latitudes. Higher latitudes were ignored to avoid issues at high emission angles. As IRIS observations at wavelengths smaller than 16 μm have around 5–6 times lower spatial resolution than CIRS observations (around 14° latitude compared to 2.5°, Fletcher, de Pater, et al., 2017), the latter was smoothed before the comparison. The estimated uncertainties are shown in Table 2. The global differences shown in Table 2 not only account for potential calibration differences between the CIRS and IRIS instruments but also for real temporal variability of Jupiter’s atmosphere between 1979 and 2000 and for differences in the wavelengths used by the two instruments. However, we believe the global errors shown here are good indicators of the potential absolute calibration errors. It is worth noting that CIRS and IRIS profiles can differ locally by a much larger value as a result of temporal variability of the atmosphere.

#### 2.5.3. Scaling Uncertainties

Sometimes, multiple observations in a single filter during the same night can show slightly different latitudinal radiance profiles, given the sampling of different jovian latitudes and variable telluric conditions during the night. This can lead to slight differences in the radiometric scaling to the CIRS/IRIS profiles from observation to observation. This is not only true at wavelengths where a large longitudinal variability is observed (i.e., 8.6 μm) but also in 10.0- to 17.7-μm images where the presence of the Great Red Spot (GRS) close to the central meridian, for example, would result in lower brightness temperatures within the SEB. To estimate these radiometric scaling errors, we measure how much individual latitudinal radiance profiles differ from a 2-week temporal mean radiance profile. The 2-week interval is chosen as it is long enough to account for differences in weather conditions between observing runs and short enough to avoid real temporal changes occurring during the EZ disturbance (Antuñano et al., 2018). These “radiometric scaling” uncertainties are shown in Table 2, where we provide an average over the entire 2005–2008 period. Note from
Figure 2. Cylindrical map of Jupiter for ±10° latitude showing the 8.59-μm radiance on 9 April 2006 with the EZ already disturbed. This shows a bright and dark pattern at the northern region of the EZ and a continuous bright band at the southern region. Gray areas correspond to obscured regions artificially introduced during the sky emission correction process and are not taken into account in our analysis (see section 2.4).

Table 2 that the largest uncertainty is found at 8.6 μm, where greater longitudinal and temporal variability is observed.

2.5.4. Model Uncertainties

NEMESIS spectral retrievals (Irwin et al., 2008) seek to balance the closeness of the model fits to the data with the realism of the retrieved atmospheric profiles, as described in section 4. The model itself introduces “forward-modeling” uncertainties (associated with line data uncertainties, the production and sampling of \( k \) distributions for opacity, parameterized vertical profiles, uncertainties in the aerosol opacity, etc.), which are usually added in quadrature to the measurement uncertainties described above. In this study, we combine the measurement and modeling uncertainties into a single value, equivalent to 3 times the standard deviation of the sky background in each filter. This value was found after experimentation and allows us to fit all our observations within a \( \chi^2 < 1 \). These combined errors are of the same order of the absolute calibration errors for the Q band, but much larger than those of the N band (i.e., we are being over-conservative). Alternatively, if we only assume the radiometric scaling uncertainty (or the absolute calibration uncertainty) as a smaller measurement error without accounting for the additional modeling error, then we cannot achieve an adequate fit to the data (i.e., \( \chi^2 > 1 \)). Furthermore, those retrievals were too tightly constrained to the data, requiring non-realistic vertical temperature profiles. The measurement errors (random and systematic), the modeling errors, and further potential errors associated with the gaseous NH₃ profiles (section 4) are all accounted for in our spectral retrievals.

3. EZ Disturbance in the Mid-Infrared

In Figure 1 we show examples of the reduced cylindrical maps of Jupiter between ±30° latitude depicting the cycle of the EZ from normal state (2005), to onset (2006), to peak (2007), and back to normal state (2008) at four of the six wavelengths analyzed in this study. The gray regions are not real and correspond to obscured regions artificially introduced during the sky emission correction process (see section 2.4).

This series of images shows a significant change in the appearance of Jupiter’s EZ at 8.6 μm, where tropospheric aerosols and temperatures at 600–800 mbar are sensed (Fletcher, Orton, Teanby, et al., 2009), between 2005 and 2008. At this wavelength, the EZ is observed to be brighter during 2006 and 2007 (i.e., the tropospheric aerosol opacity decreases or the temperature at this level increases), displaying a similar appearance to that observed at 5 μm—a bright band south of the equator encircling the planet at 2–5° south and a pattern of alternating bright and dark regions (corresponding to the 5-μm-bright festoons and 5-μm-dark ammonia enriched plumes, see Figure 2) between 2° south and 7° north (Antuñano et al., 2018). A comparison of Jupiter’s EZ appearance at 8.6 μm, 5 μm, and visible wavelengths is shown in Figure 3 for two different epochs showing that the EZ already appeared disturbed in 2005 in the visible and at 8.6 μm, while it remained undisturbed at 5 μm, suggesting that the disturbance started at higher altitudes and moved downward. By 2007, when the peak of the EZ disturbance was reached at 5 μm, the entire EZ had brightened at 8.6 μm (except for the dark plumes found at the northern edge), displaying a broader brightened region compared to 5 μm.

At 10.7 μm, sensing tropospheric ammonia gas and temperature near 500 mbar (Fletcher, Orton, Teanby, et al., 2009), COMICS images from 2005 show a slight bright band at the equator, which continues to be observable, although less clearly, in the 2006 VISIR images. At 13.0-μm wavelength, sensing tropospheric...
temperatures at \( \sim 500 \text{ mbar} \) via the \( \text{H}_2\text{-He} \) collision-induced absorption (Fletcher, Orton, Teanby, et al., 2009), the EZ looks mainly undisturbed between 2005 and 2008, with a very subtle brightness increase in 2006. The lack of Jupiter data at this wavelength from 2005 does not allow us to determine whether a brightness increase was observable in 2005. The brightness increase at 10.7 \( \mu \text{m} \) in 2005–2006 would suggest either a potential decrease in the ammonia gas abundance at the equatorial latitudes or, alternatively, an increase in the 500-mbar equatorial temperatures. The contemporaneous brightness increase at 10.7 and 13.0 \( \mu \text{m} \) hints at a subtle temperature change in 2006, rather than a change in ammonia. Finally, at 17.6-\( \mu \text{m} \) wavelengths, sensing upper tropospheric temperatures near 200-mbar pressure (Fletcher, Orton, Teanby, et al., 2009), the EZ looks undisturbed between 2005 and 2008, implying that this event does not reach the \( \sim 200\text{-mbar} \) region sounded by this filter.

To better constrain the brightness changes observed in Figure 1, we compute zonal-mean brightness temperatures at 2\(^\circ\)S for the same four wavelengths. These are shown in Figure 4 together with the normalized brightness at 5-\( \mu \text{m} \). The 2\(^\circ\)S latitude is chosen because it corresponds to the maximum brightness increase at 5-\( \mu \text{m} \) during EZ disturbances (Antuñano et al., 2018). The zonal-mean brightnesses are computed by averaging the brightness temperature within 20\(^\circ\) around the central meridian for each latitude and date. In the cases where the obscured region in VISIR data (gray regions in Figure 1, see section 2) falls within the Equatorial Zone and within 20\(^\circ\) around the central meridian, we compute the zonal-mean brightnesses by averaging the brightness temperatures at other longitudes, trying to avoid as much as possible high emission angles. This can lead to differences in the zonal-mean brightnesses between observations. However, the radiometric scaling uncertainty shown in Table 2 includes any potential errors that might be introduced by this technique. At 5-\( \mu \text{m} \), the normalized brightness temperatures are computed by normalizing the maximum brightness value of the entire time series to 1.0, following Antuñano et al. (2018, 2019). The black error bars in this figure represent the standard deviation of the average of the zonal-mean brightness at 2\(^\circ\)S from different images taken on the same date and wavelength. In the case where only one image is available during the same observing night, these error bars represent the longitudinal variability at 2\(^\circ\)S at each wavelength. However, in the case where more than one image is available on a single observing night, the standard deviation includes not only the contribution from the longitudinal variability but also small radiometric scaling uncertainties introduced in different images captured during the same observing night. The absolute calibration error (see section 2.5) is represented by gray error bars.
Figure 4. Zonal-mean brightness temperatures at 2°S between 2005 and 2009 at (a) 8.6-μm, (b) 10.7-μm, (c) 13.04-μm, (d) 17.65-μm, and (e) 5-μm wavelengths. Orange, red, blue, and green dots in (a)–(d) represent the data used for the NEMESIS retrievals (see section 4) and correspond to 24 May 2005, 9 April 2006, 27 February 2007, and 10 August 2008, respectively. Data in (a) and (d) correspond to COMICS (2005), MIRSI (2005–2008), and VISIR (2006–2008) images. COMICS (2005) and VISIR (2006–2008) images were used in (b). MIRSI (2005–2008) and VISIR (2006–2008) images were used in (c). NSFCam2, MIRSI, and VISIR data were used in (e). Black error bars represent the standard deviation of the average of zonal-mean brightnesses at 2°S from the same date. Gray error bars in (a)–(d) represent the absolute calibration uncertainty (see section 2.5 and Table 2). Note the later onset in the disturbance observed at 5 μm compared to the 8.6-μm filter, the latter sensing higher in the troposphere.
Figure 4a shows a gradual increase of the brightness temperature at 8.6 μm between 2005 and 2007, reaching the maximum temperature in February 2007, coinciding with the brightness maximum at 5 μm (Figure 4e). Between April–May 2005 and February 2007, the brightness temperature increased by 3.1 ± 0.6 K, where the error represents the 1σ uncertainty of the linear fit between 2005 and February 2007. After this date, the brightness temperature decreased until the normal state of the EZ was reached sometime before July 2008, but the lack of data between November 2007 and July 2008 does not allow us to precisely determine the date. During 2005 the brightness temperature was 1.0 ± 0.9 K higher than in 2008 at this wavelength, suggesting that by 2005 (around a year before the disturbance started to be observable at 5 μm) the EZ was already undergoing a change at 600–800 mbar. This was also observed at visible wavelengths, where the EZ started to display a change in its color in mid-2005, around a year before any change started to be observed at 5 μm (i.e., April 2006, see Figure 4e). These are clearly observed in Figures 3a–3c, where the 8.6-μm image of 2005 shows a bright equator compared to the undisturbed 5-μm-dark EZ and at visible wavelengths a slight coloration is observable. These suggest that the aerosol opacity at 600–800 mbar would decrease contemporaneously to the change in the coloration of the EZ at visible wavelengths, but months before the dissipation of clouds in the 2- to 7-bar range.

At 2°S, the 10.77-μm brightness temperature is 1.0 ± 0.4 K cooler in 2006 compared to 2005 (Figure 4b). However, it is unclear whether this variability is related to the EZ disturbance due to the small number of dates available at this wavelength between 2006 and 2007, and the observed change being close to the absolute calibration error (i.e., 0.9 K). At 13 and 17.6 μm (Figures 4c and 4d) the temporal variability of the brightness temperature between 2005 and 2008 lies within the estimated absolute calibration errors of 1.6 and 2.0 K, respectively. These suggest that the upper tropospheric temperatures do not significantly vary during the EZ disturbances in the 100- to 500-mbar range and that the observed faint bright bands in Figure 1 at 10.7 μm correspond to changes in the brightness temperatures smaller than 1.0 K. This lack of significant change in the brightness temperatures at 10.7 and 13.0 μm, compared to the much larger change at 8.6 μm, suggests that the increase at 8.6 μm is most probably due to a decrease of the aerosol opacity at 600–800 mbar. We note, however, that a temperature rise remains a plausible explanation, provided it is restricted to p > 800 mbar (below or at the base of the ammonia ice clouds), the level at which it would not be visible in the 10.7- and 13.0-μm filters; see Figure S1. In the next section, we use the observations marked as orange, red, blue, and green dots in Figure 4 to quantify the change of the tropospheric aerosol opacity during the EZ disturbances.

4. Tropospheric Temperatures and Aerosol Opacity

4.1. Mid-Infrared Retrievals

Fully reduced cylindrical maps of Jupiter in six VISIR filters (8.6, 10.7, 13, 17.6, 18.7, and 19.5 μm) and five COMICS filters (8.7, 10.3, 17.6, 18.7, and 20.5 μm) are stacked together to form spectral image cubes to derive the vertical profile of temperature and aerosols for 24 May 2005, 9 April 2006, 27 February 2007, and 10 August 2008 (represented by orange, red, blue, and green dots in Figure 4). These dates show the highest-quality data for each of the years in this study, with the largest number of filters available and the best spatial coverage of the planet. The large brightness temperature at 8.6, 13.0, and 17.65 μm observed on 27 February 2007 (see Figure 4) corresponds to a rare occasion where the EZ disturbance was more prominent than usual, with an extremely bright equator compared to the rest of the dates of the 2006–2007 disturbance. Here, we use these data points because they represent the maximum change in brightness of the EZ observed in this data set.

The spectra represented by these image cubes can be inverted to provide crude estimates of the temperature and aerosol opacity using the suite of radiative-transfer and retrieval codes known as NEMESIS (Irwin et al., 2008). The forward model uses pre-tabulated k distributions and opacity sources (collision-induced absorption, aerosol cross sections) to generate synthetic spectra (convolved with the relevant filter functions) for an atmospheric path. For the a priori atmospheric model we followed Fletcher, Orton, Yanamandra-Fisher, et al. (2009): Stratospheric hydrocarbons (methane, ethane, and acetylene) come from a low-latitude average of the results of Nixon et al. (2007); tropospheric ammonia, phosphine, and the vertical T(p) are obtained from Fletcher, Orton, Teanby, et al. (2009). The para-hydrogen is held fixed at equilibrium, and the collision-induced absorption for H2-He come from Fletcher, Gustafsson, et al. (2018), with the H2–He contribution from Borysow et al. (1988), and H2–CH4 and CH3–CH4 contributions from
Figure 5. Comparison of the zonal-mean radiances (points) and synthetic 6-point spectra (lines, 5-point spectra for the 2005 COMICS due to the lack of the 13.0-μm filter) at 2–3° S from four different dates: 24 May 2005 (before the infrared disturbance started), 9 April 2006 (beginning of the disturbance), 27 February 2007 (peak of the disturbance), and 10 August 2008 (once the disturbance disappeared and the EZ returned to normal). The radiances in (a) are converted to brightness temperatures in (b). The filters used to obtain the synthetic spectra from 2005 (COMICS) and 2006–2008 (VISIR) are different. The error bars represent the measurement errors used in the retrievals and correspond to 3 times the standard deviation of the random sky background.

Borysow and Frommhold (1986, 1987). The a priori aerosol profile used is the same as that in Fletcher et al. (2016)—a gray absorber at 800-mbar pressure level with the same cross section at all wavelengths and with a scale height 0.2 times the gas scale height. This choice is made because of the unknown optical properties of the aerosols in the 600- to 800-mbar range. The sources of spectral line data are those listed in supporting information Table S1 of Fletcher, Orton, et al. (2018).

The inverse model performs a nonlinear Levenburg-Marquardt fit to the measurements, evaluating a cost function to ensure a high-quality fit to the data without significantly deviating from the prior (which can lead to non-physical oscillations in the derived solutions). As described in section 2, the data errors are a combination of measurement uncertainties and forward model uncertainties, tuned to permit realistic vertical profiles and goodness-of-fit $\chi^2 < 1$. Our fits allow the vertical temperature profile to vary, while also scaling (i) the vertical ammonia distribution to fit radiances at 10.3 and 10.7 μm and (ii) the vertical distribution of aerosols to fit radiances at 8.6–8.7 μm.
The radiance at each wavelength and date are calculated by fitting a second-order polynomial to the radiance of each latitude as a function of the emission angle and averaging the fitted radiance within 5° of the central meridian. Radiances at emission angles greater than 70° are ignored for the fitting to avoid limb darkening/brightening. The artificially obscured regions in the VISIR data, introduced during the sky emission subtraction process (see section 2.4), are also ignored for the fitting. This results in incomplete latitudinal radiance profiles, with missing points at the latitudes where the obscured region covered the longitudinal region within 5° of the central meridian.

The spectra used in this study are primarily sensitive to tropospheric temperatures, ammonia gas, and aerosol opacities at the 150- to 600-mbar pressure levels. Due to the degeneracies between temperatures and ammonia inherent in retrievals from such a small number of spectral points, we first try to fit the observations by only allowing temperature and aerosol opacity to vary in our retrievals, assuming the gaseous ammonia remains invariant from the a priori profile. However, simultaneous retrievals of only temperature and aerosol opacity cannot fit the observations at any of the four dates chosen in this study. This could be due to (i) the ammonia gas profile used not being correct, (ii) the variability of ammonia gas not being accounted for in these retrievals, and (iii) relative offsets in the radiances due to calibration errors. In order to fit the observations we thus retrieve temperatures, ammonia gas abundance, and aerosol opacities simultaneously at each latitude for the four different dates by allowing the vertical temperature profile to vary at the same time as scaling the vertical ammonia gas distribution and the vertical aerosol distribution. This allows us to obtain a more suitable profile of the ammonia gas that allows us to achieve an adequate fit to the data. However, this does not provide a good constraint on spatial variability of ammonia. Indeed, tropospheric temperatures and aerosol retrievals show no difference in the fitting quality between allowing the new NH₃ profile to vary and simply using a latitudinally uniform NH₃ based on the new prior. Therefore, we fix the new ammonia gas profile to be the same at all latitudes and retrieve temperature and aerosol opacities simultaneously to study the latitudinal and temporal variations of these two atmospheric parameters before, during, and after the EZ disturbance.

Figure 5 shows both the spectral radiance fits and the brightness temperature fits at 2–3°S. The error bars in Figure 5a represent 3 times the standard deviation of the random sky background (see section 2.5). The modeled spectra fit the observed radiances reasonably well and show the radiance increase at 8.6 μm during 2006 and 2007. Note that the image cubes were built by using different filters in VISIR (red, blue, and green lines and dots) and COMICS data (orange line and dots in Figure 5, missing a filter near 13 μm).

4.2. Retrieved Temperatures and Aerosol Opacities

Variations in the retrieved tropospheric temperatures and aerosol opacity are shown in Figure 6. The vertical colored lines represent a latitudinal mean of the formal retrieval uncertainties on the absolute quantities and do not account for systematic offsets in the absolute calibration. Due to degeneracies inherent in imaging retrievals, the absolute values are highly uncertain, but relative variability of the temperatures and aerosols from latitude to latitude can be considered to be robust (as evidenced by the strong gradients in radiance in the raw images). Retrieved tropospheric temperatures at 200 mbar (primarily constrained by 17.6-, 18.7-, 19.5-, and 20.5-μm filters) are found to be 2–3 K warmer in 2005 and 2006 within 5° and 2° of the equator. At 500 mbar the temperature (constrained by 10.3-, 10.7-, and 13.0-μm filters) is observed to be around 1 K warmer in 2006 compared to the rest of the years. The warming of the upper troposphere of the EZ disturbance could explain the visible darkening and the later 5-μm brightening of the EZ due to sublimation of the ammonia ice. However, 17.6-, 13.0-, and 10.7-μm filter images sensing 150- to 300-mbar pressures shown in Figure 1 and the spectral fits at this wavelength shown in Figure 5 do not show significant changes between 2005 and 2008, with overall brightness temperature changes smaller than 1.5 K during these dates (see Figure 4), in disagreement with the retrieved temperature differences at the equator. This is due to the limitations of constraining the vertical atmospheric profiles with the limited available filters, where small uncertainties in the data can be magnified to large changes in the retrieved profiles. Therefore, one must remain cautious when interpreting the retrieved tropospheric temperatures.

Usually, tropospheric aerosol opacity profiles at the equatorial and off-equatorial latitudes show minima at the NEB and SEB and a maximum at the EZ (e.g., Fletcher et al., 2016). However, the 8.6-μm data shown in Figure 4a display a large increase of the brightness temperature between 2005 and 2007 at the equator, indicative of a reduction of the tropospheric aerosol opacity at 600–800 mbar or a temperature increase at p > 800 mbar, followed by a strong decrease of the brightness temperature in the following year. The retrieved
Figure 6. Zonal-mean temperature profiles at tropospheric pressure levels (a–c) and the aerosol opacity (d) for four different dates. The filters used to obtain the synthetic spectra from 2005 (COMICS) and 2006–2008 (VISIR) are different, with the former missing a 13-μm filter. The vertical colored lines represent the latitudinal-mean error bars from formal retrieval uncertainties and do not account for systematic offsets in the absolute calibration. Due to degeneracies inherent in imaging retrievals, these formal uncertainties on the absolute values appear large. However, relative latitudinal variability of the temperatures and aerosols (as evidenced by the raw images) are robust.

tropospheric aerosol opacity profiles presented in Figure 6d show a clear decrease in 2005, 2006, and 2007 at latitudes south of the equator, where the aerosol opacity is ∼25%, ∼45%, and ∼65% smaller than in 2008, respectively, reaching their minima at 3°S. At the northern equatorial latitudes, the aerosol opacity displays a smaller decrease of around 10% in 2005, 25% in 2006, and 37% in 2007. These results are in agreement with the picture of the EZ disturbance at 5 μm, where the northern latitudes (0–7°N) display a dark and bright pattern of cloudy and cloud-free regions, whereas the southern equatorial latitudes (i.e., 2–5°S) display a uniformly bright (cloud-free) band encircling the entire planet. This confirms that the cloud-clearing events of the middle troposphere (2–7 bars, seen at 5 μm) are also being observed in the upper tropospheric cloud (∼600 mbar) but that there is no significant change in temperature at the same time.

5. Discussion and Conclusions
In this study, MIRSI, VISIR, and COMICS images captured between 2005 and 2008 at wavelengths between 8.6 and 20 μm have been analyzed to study how atmospheric parameters changed during the EZ disturbance of 2006–2007. Observations between 2005 and 2008 at 10.7 and 17.6 μm showed variations within or close to the estimated absolute calibration errors (0.9 and 2.0 K, respectively), suggesting that the disturbance is potentially not associated with measurable tropospheric temperature changes in the 100- to 500-mbar range. Images captured in 2006 at 13.0 μm (primarily sensing tropospheric temperatures near 500 mbar) showed a very slight brightening of the EZ, which could suggest a small warming. However, the temporal variation of the retrieved zonal-mean brightness temperatures at this filter lies within the estimated absolute calibration error (i.e., 1.6 K). Finally, a significant brightening of the EZ was observed in 2005–2007 at 8.6 μm (sensing tropospheric aerosol opacity and temperatures at 600–800 mbar), indicative most probably of a
drop in the aerosol opacity at this level. However, due to the limited filters available, we are unable to rule out a possible temperature change at \( p > 800 \) mbar as the source of the 8.6-\( \mu \text{m} \) brightening (temperatures cannot be uniquely derived at deeper pressures by any of the filters used in this study). However, this deep warming would have to generate a substantial increase in the lapse rate (i.e., larger than \( \sim 0.6 \text{ K km}^{-1} \)) to explain the change in brightness temperature. Such a large “kink” in the thermal profile has not been previously revealed in Galileo (Magalhães et al., 2002; Seiff et al., 1998), Cassini, or ground-based spectroscopic observations (Fletcher et al., 2016).

Retrieval of tropospheric temperature and aerosol opacity from VISIR and COMICS imaging have revealed that the 5-\( \mu \text{m} \) brightening and coloration of the EZ during the disturbances are accompanied by a strong decrease of the 600- to 800-mbar aerosol opacity at latitudes between 2°N and 4°S, but not by a change of the tropospheric temperatures at \( p < 500 \) mbar. The decrease of the aerosol opacity at the latitudes where 5-\( \mu \text{m} \) brightening is observed supports the hypothesis of ammonia cloud thinning/clearing during the EZ disturbances (Antuñano et al., 2018). The contemporaneous decrease of the 8.6-\( \mu \text{m} \) aerosol opacity and coloration at visible wavelengths suggests that the clearing of tropospheric aerosol opacity is responsible for revealing a red chromophore. However, we note that our observations do not constrain the altitude of the chromophore—the decline in opacity at 600–800 mbar could be revealing chromophores at deeper levels, or condensation nuclei at the \( \sim 600 \)–800-mbar altitude of \( \text{NH}_3 \) condensation (Braude et al., 2020; Simon-Miller et al., 2001), or possibly even at higher altitudes by increasing the path length through upper tropospheric hazes (Sromovsky et al., 2017), although visually the chromophore appears to be similar to that present in the NEB and SEB under normal conditions. The discrepancy between the results of the aforementioned studies clearly shows that the properties and location of this chromophore are still an open question, and it is likely that there is more than one family of chromophores present on Jupiter—those resulting from photochemical processing of materials lofted from depth (e.g., by storms and vortices), and those that provide the coloration of the belts.

The observations also show that the decrease of the 8.6-\( \mu \text{m} \) aerosol opacity and coloration at visible wavelengths begins around a year before the 5-\( \mu \text{m} \) brightening starts. This suggests that changes begin in the topmost cloud deck and propagate downward to higher pressures. The absence of changes in the upper tropospheric temperatures \( p < 500 \) mbar rejects the hypothesis of cloud clearing via warming due to wave phenomena propagating downward from higher altitudes. This confirms that the EZ disturbances are not driven by the periodic warming and cooling produced by the Quasi-Quadrennial Oscillation in the lower stratosphere (e.g., Cosentino et al., 2017; Leovy et al., 1991). However, further analysis and observations would be needed to understand whether the EZ disturbance affects the wave phenomena that are thought to be driving the Quasi-Quadrennial Oscillation.

At \( p < 500 \) mbar, our interpretation of the retrieved solutions suggests that the cloud clearing is not due to warming-induced sublimation/evaporation. We explore other potential scenarios that could explain the EZ disturbances, such as cloud clearing via (i) subsidence and (ii) change in the ammonia gas upwelling. Fletcher, Orton, et al. (2017) reported that during SEB revivals a series of convective plumes rising up through quiescent atmospheric layers results in the removal of the aerosols responsible for the unique “faded state” of the SEB. The darker cloud-free regions surrounding the bright white plumes were redistributed by the winds and eddies in the SEB, eventually revealing the usual red-brown coloration of the belt. One could speculate that the same processes are at work at the equator, where vigorous ammonia ice plumes could clear the \( \sim 600 \)-mbar level of aerosol opacity (sensed at 8.6-\( \mu \text{m} \)) surrounding the plumes via subsidence, revealing the red-brown chromophores beneath. The interaction of aerosol-free regions with the horizontal wind shear could lead to a darkening of the EZ at visible wavelengths sensing the top of the ammonia clouds. However, unlike the SEB revival that started at one longitude and spread to the east and west, the EZ disturbance appears at all longitudes at the same time. This may be related to the equatorially trapped Rossby wave that spans the whole planet at this latitude, suggesting that the vigor of the plumes increases everywhere in connection with this wave. Previous studies by Del Genio and McGrattan (1990) and Palotai and Dowling (2008) showed that subsidence around moist upward equatorial plumes alone could only dry the atmospheres by small amounts due to the re-evaporation of the precipitation below the cloud base, suggesting that subsidence alone would not clear the equatorial ammonia clouds. However, a recent study by Guillot et al. (2020) reported that the formation of ammonia-water hail-like particles (called “mushballs”) at the 1- to 1.5-bar pressure level could allow the removal of ammonia at much deeper levels (i.e., 7–25 bar).
But what defines the timescale of 1–1.5 years for the cloud clearances at 5 μm? What ultimately restores the white and cool appearance of the EZ?

Using a one-dimensional cloud microphysical model, developed originally for Mars (Montmessin, 2002) and Titan (Rannou et al., 2006) (which includes the processes of nucleation, condensation, coagulation, evaporation, precipitation, and coalescence) and adapted for Jupiter, we have seen that the ammonia upwelling plays a key role in the tropospheric cloud clearing of Jupiter’s equatorial region via precipitation. In this simplified model, the transport of ammonia gas is parameterized using an eddy diffusion profile $K$ that...
controls the supply of gas for cloud nucleation and particle growth (Barth & Toon, 2003, 2006). Different eddy diffusion profiles were tested in this study, to understand whether ammonia precipitation alone could clear the 0.7-bar and 2- to 7-bar clouds. In Figure 7 we show three examples. We found that an eddy diffusion of 4 $m^2 s^{-1}$ is enough to form a significant opaque ammonia cloud. Figure 7a shows that when the eddy diffusion is kept constant at this value for 400 days (i.e., 4 $m^2 s^{-1}$, Model 1), the optical depth of the cloud deck does not reduce by large amounts, independent of the ammonia plumes injecting more ammonia into that pressure level. However, if the ammonia gas upwelling stops locally (Model 2) or reduces linearly from 4 to 0.4 $m^2 s^{-1}$ (Model 3), the results show an optical depth that decreases abruptly as soon as the upwelling is stopped (Model 2) or decreases with time (Model 3), revealing that a decrease of the ammonia gas upwelling could explain the cloud clearing observed during the EZ disturbances both at the cloud tops and at the 2- to 7-bar level. The magnitude of the EZ disturbances (i.e., coloration and 8.6- and 5-$\mu m$ brightening like in 2006–2008, or just coloration and/or 8.6-$\mu m$ brightening like in 2012–2013, see Figure 7) would then depend on the magnitude of decrease of the ammonia upwelling.

Recent observations from the Juno Microwave Radiometer (MWR) revealed a column of concentrated ammonia gas at the northern latitudes of the EZ (Bolton et al., 2017; Ingersoll et al., 2017; Li et al., 2017). A decrease in the deep ammonia column at the equator could then be responsible for the EZ disturbances; however, no changes have been reported so far. On Earth, studies of periodic and quasi-periodic atmospheric events have shown that large convection and precipitation events dry out the atmosphere in those places by suppressing the convection from below (e.g., Zhang, 2005). Here, we speculate that something similar could also happen in Jupiter, with strong precipitation surrounding vigorous white plumes locally suppressing the ammonia upwelling and carrying ammonia downward. Once the precipitation stops, ammonia upwelling could be restored, causing the EZ to whiten once again. Renewed vigor of the white plumes, maybe due to periodic releases of accumulated convective available potential energy (CAPE), could restart the process again. In the latter scenario, strong events with large and substantial white plumes, accompanied by strong regions of precipitation, could more easily suppress the upwelling and lead to cloud clearance at both the top of the ammonia cloud and the deeper levels (e.g., the 2006–2007 event). In contrast, weaker events with fewer substantial plumes, thus weaker precipitation, would only clear aerosol opacity at the ~600-mbar level but would not be strong enough to propagate downward and suppress upwelling in the deeper pressures sensed at 5 $\mu m$ (e.g., the “missing” event in the 5-$\mu m$ record in 2012–2013).

The recent EZ disturbance (2018–2019) seems to fall somewhere between these two cases. Observations at visible wavelengths showed that the EZ started to redden in 2017 and continued to darken in 2018–2019 (see Figure 8 in Wong et al., 2020) as expected from the ~7-year period reported by Antuñano et al. (2018).
and Antuñano et al. (2019). At 5 μm, images from late 2018 showed that, for the first time in 13 years, the EZ started to display bright patches at 2–5°S. However, 5-μm images from mid-2019 showed that the unfolding disturbance was not behaving like previous ones, with only some regions of the EZ becoming bright at 5 μm as if the disturbance stopped half way through, making this disturbance quite unique (see Figure 8 and Figure 8 in Wong et al., 2020). A recent study by Wong et al. (2020) showed that the previously reported 6- to 8-year periodic signal in the equatorial zonal wind (Tollefson et al., 2017) becomes weaker when 2019 data are included and stronger when only up to 2018 data are taken into account in agreement with the odd behavior of the EZ disturbance observed at 5 μm.

The key to distinguishing between these different scenarios would be to understand how ammonia is varying with time. The photometric imaging retrievals shown here exhibit severe degeneracies between temperatures and ammonia, although there are tantalizing hints that the faint bright equatorial band at 10.7 μm could be driven by a drop in NH₃ gas abundance. Further retrievals using spectroscopy, rather than photometry, of the recent EZ disturbance will enable us to better separate the atmospheric parameters during these disturbances for the first time as no spectroscopic observations from 2005 to 2007 are available. These, together with close-in observations of the EZ in 2018–2020 from Juno’s remote-sensing instruments JunoCam (visible wavelengths), JIRAM (near-infrared), and Microwave Radiometer (MWR), and corresponding Earth-based supporting observations (e.g., Bjoraker et al., 2018; Fletcher et al., 2020; Orton et al., 2017; Wong et al., 2020) will be essential to further our understanding of the connections of these rare events to Jupiter’s deep equatorial NH₃ column.

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References
Antuñano, A. (2020). ArrateAntuñano/Repository-for-the-Characterization-of-Jupiters-Equatorial-Zone-Disturbance V1 (Version V1). Zenodo, https://doi.org/10.5281/zenodo.3820468
Antuñano, A., Fletcher, L. N., Orton, G. S., Melin, H., Milan, S., Rogers, J., et al. (2019). Jupiter’s atmospheric variability from long-term ground-based observations at 5 μm. The Astronomical Journal, 158(3), 130.
Antuñano, A., Fletcher, L. N., Orton, G. S., Melin, H., Rogers, J. H., Harrington, J., et al. (2018). Infrared characterization of Jupiter’s equatorial disturbance cycle. Geophysical Research Letters, 45, 10,987–10,995. https://doi.org/10.1029/2018GL080382
Barth, E. L., & Toon, O. B. (2003). Microphysical modeling of ethane ice clouds in Titan’s atmosphere. Icarus, 162(1), 94–113.
Barth, E. L., & Toon, O. B. (2006). Methane, ethane, and mixed clouds in Titan’s atmosphere: Properties derived from microphysical modeling. Icarus, 182(1), 230–250.
Bjoraker, G. L., Wong, M. H., De Pater, I., & Adámkovics, M. (2015). Jupiter’s deep cloud structure revealed using Keck observations of spectrally resolved line shapes. The Astrophysical Journal, 816(2), 122.
Bjoraker, G. L., Wong, M. H., De Pater, I., Adámkovics, M., Hewagama, T., & Orton, G. (2018). Ammonia, water vapor, and clouds in Jupiter’s Equatorial Zone. American Geophysical Union, Fall Meeting 2018, abstract P33F-3885.
Bolton, S. J., Adriani, A., Adumitroaie, V., Allison, M., Anderson, J., Atreya, S., et al. (2017). Jupiter’s interior and deep atmosphere: The initial pole-to-pole passes with the Juno spacecraft. Science, 356(6340), 821–825.
Borysow, A., & Fromhold, L. (1986). Theoretical collision-induced rototranslational absorption spectra for the outer planets—H₂–CH₄ pairs. The Astrophysical Journal, 304, 849.
Borysow, A., & Fromhold, L. (1987). Collision-induced rototranslational absorption spectra of CH₄–CH₄ pairs at temperatures from 50 to 300 K. The Astrophysical Journal, 318, 1–940.
Borysow, J., Fromhold, L., & Birnbaum, G. (1988). Collision-induced rototranslational absorption spectra of H₂–He pairs at temperatures from 40 to 3000 K. The Astrophysical Journal, 326, 509.
Braude, A. S., Irwin, P. G. J., Orton, G. S., & Fletcher, L. N. (2020). Colour and tropospheric cloud structure of Jupiter from MUSE/VLT: Retrieving a universal chromophore. Icarus, 338(115589).
Choi, D. S., Showman, A. P., Vasavada, A. R., & Simon-Miller, A. A. (2013). Meteorology of Jupiter’s equatorial hot spots and plumes from Cassini. Icarus, 222(2), 832–843.
Cosentino, R. G., Butler, B., Sault, B., Morales-Juberias, R., Simon, A., & de Pater, I. (2017). Atmospheric waves and dynamics beneath Jupiter’s clouds from radio wavelength observations. Icarus, 292, 168–181.
de Pater, I., Sault, R. J., Butler, B., DeBoer, D., & Wong, M. H. (2016). Peering through Jupiter’s clouds with radio spectral imaging. Science, 352(6299), 1198–1201.
de Pater, I., Sault, R., Wong, M. H., Fletcher, L. N., DeBoer, D., & Butler, B. (2019). Jupiter’s ammonia distribution derived from VLA maps at J–17 GHz. Icarus, 322, 168–191.
Del Genio, A. D., & McGrattan, K. B. (2006). Moist convection and the vertical structure and water abundance of Jupiter’s atmosphere. Icarus, 84(1), 29–53.
Deutsch, L. K., Hora, J. L., & Adams, J. D. (2003). MIRS: A Mid-Infrared Spectrometer and Imager. Instrument Design and Performance for Optical/Infrared Ground-based Telescopes.
Fletcher, L. N., de Pater, I., Reach, W., Wong, M., Orton, G., Irwin, P., & Gehrz, R. D. (2017). Jupiter’s para-H₂ distribution from SOFIA/POCRAFT and Voyager/IRIS 17–37 μm spectroscopy. Icarus, 286, 223–240.
Fletcher, L. N., Grathew, T., Orton, G., Sinclair, J., Giles, R., Irwin, P., & Encraven, T. (2016). Mid-infrared mapping of Jupiter’s temperatures, aerosol opacity and chemical distributions with IRFT/TEXES. Icarus, 278, 128–161.
Fletcher, L. N., Gustafsson, M., & Orton, G. S. (2018). Hydrogen dimers in giant-planet infrared spectra. The Astrophysical Journal Supplement Series, 235(1), 24.
Fletcher, L. N., Melin, H., Adriani, A., Simon, A., Sanchez-Lavega, A., Donnelly, P., et al. (2018). Jupiter’s mesoscale waves observed at 5 μm by ground-based observations and Juno JIRAM. The Astronomical Journal, 156(2), 67.
Fletcher, L. N., Orton, G. S., Greathouse, T. K., Rogers, J. H., Zhang, Z., Oyafuso, F. A., et al. (2020). Jupiter’s equatorial plumes and hot spots: Spectral mapping from Gemini/TEXES and Juno/MWR. *Journal of Geophysical Research: Planets*, e2020JE006399. https://doi.org/10.1029/2020JE006399

Fletcher, L. N., Orton, G., Mousis, O., Yanamandra-Fisher, P., Parrish, F., Irwin, P., et al. (2010). Thermal structure and composition of Jupiter’s Great Red Spot from high-resolution thermal imaging. *Icarus*, 208(1), 306–328.

Fletcher, L. N., Orton, G., Rogers, J., Giles, R., Payne, A., Irwin, P., & Vedovato, M. (2017). Moist convection and the 2010–2011 revival of Jupiter’s South Equatorial Belt. *Icarus*, 286, 94–117.

Fletcher, L. N., Orton, G. S., Sinclair, J. A., Guerlet, S., Read, P. L., Antuñano, A., et al. (2018). A hexagon in Saturn’s northern stratosphere surrounding the emerging summertime polar vortex. *Nature Communications*, 9(1), 3564.

Fletcher, L. N., Orton, G., Teanby, N., & Irwin, P. (2009). Phosphine on Jupiter and Saturn from Cassini/CIRS. *Icarus*, 202(2), 543–564.

Fletcher, L. N., Orton, G., Yanamandra-Fisher, P., Fisher, B., Parrish, F., & Irwin, P. (2009). Retrievals of atmospheric variables on the gas giants from ground-based mid-infrared imaging. *Icarus*, 200(1), 154–175.

Giles, R. S., Fletcher, L. N., & Irwin, P. G. I. (2015). Cloud structure and composition of Jupiter’s troposphere from 0.5-μm Cassini VIMS spectroscopy. *Icarus*, 257, 477–490.

Guillot, T., Stevenson, D. J., Atreya, S. K., Bolton, S. J., & Becker, H. (2020). Storms and the depletion of ammonia in Jupiter: I. Microphysics of “mushballs”. *Earth and Space Science Open Archive*, 23.

Ingersoll, A. P., Adumitroaie, V., Allison, M. D., Atreya, S., Bellotti, A. A., Bolton, S. J., et al. (2017). Implications of the ammonia distribution on Jupiter from 1 to 100 bars as measured by the Juno microwave radiometer. *Geophysical Research Letters*, 44, 7676–7685. https://doi.org/10.1002/2017GL074277

Irwin, P., Teanby, N., de Kok, R., Fletcher, L., Howett, C., Tsang, C., et al. (2008). The NEAR planetary atmosphere radiative transfer and retrieval tool. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 109(6), 1136–1150. Spectroscopy and Radiative Transfer in Planetary Atmospheres.

Kataza, H., Okamoto, Y., Takubo, S., Onaka, T., Sako, N., Nakamura, K., et al. (2000). COMICS: The cooled mid-infrared camera and spectrometer for the Subaru telescope. *Optical and IR Telescope Instrumentation and Detectors*.

Keay, J., Low, F., Rieke, G., & Minton, R. (1973). High-resolution maps of Jupiter at 5 microns. *The Astrophysical Journal*, 183, 1063–1074.

Lagage, P., Pel, J., Authier, M., Belorgey, J., Claret, A., Doucet, C., et al. (2004). Successful commissioning of VISIR: The mid-infrared VLTI instrument. *The Messenger*, 117, 12.

Leovy, C. B., Friedson, A. J., & Orton, G. S. (1991). The quasi-quadrennial oscillation of Jupiter’s equatorial stratosphere. *Nature*, 354(6352), 380.

Li, C., Ingersoll, A., Janssen, M., Levin, S., Bolton, S., Adumitroaie, V., et al. (2017). The distribution of ammonia on Jupiter from a preliminary inversion of Juno microwave radiometer data. *Geophysical Research Letters*, 44, 5317–5325. https://doi.org/10.1002/2017GL073159

Magalhães, J. A., Seiff, A., & Becker, H. (2020). Storms and the depletion of ammonia in Jupiter: I. Microphysics of “mushballs”. *Earth and Space Science Open Archive*, 23.

Montmessin, F. (2002). New insights into Martian dust distribution and water-ice cloud microphysics. *Journal of Geophysical Research*, 107(E6), https://doi.org/10.1029/2001JE001520

Nixon, C., Achterberg, K., Conrath, B., Irwin, P., Teanby, N., Fouchet, T., et al. (2007). Meridional variations of C2H2 and C2H6 in Jupiter’s atmosphere from Cassini CIRS infrared spectra. *Icarus*, 188(1), 47–71.

Orton, G. S., Mommert, T., Ingersoll, A. P., Adriani, A., Hansen, C. J., Janssen, M., et al. (2017). Multiple-wavelength sensing of Jupiter during the Juno mission’s first perijove passage. *Geophysical Research Letters*, 44, 4607–4614. https://doi.org/10.1002/2017GL073019

Palotai, C., & Dowling, T. E. (2008). Addition of water and ammonia cloud microphysics to the epic model. *Icarus*, 194(1), 303–326.

Rannou, F., Montmessin, F., Hourdin, F., & Lebonnois, S. (2006). The latitudinal distribution of clouds on Titan. *Science*, 311(5758), 201–205.

Rogers, J. H. (1995). *The giant planet Jupiter*. Cambridge: Cambridge University Press (CUP).

Seiff, A., Kirk, D. B., Knight, T. C., Young, R. E., Mihalov, J. D., Young, L. A., et al. (1998). Thermal structure of Jupiter’s atmosphere near the edge of a 5-μm hot spot in the north equatorial belt. *Journal of Geophysical Research*, 103(E10), 22857–22889.

Simon-Miller, A. A., Banfield, D., & Gierasch, P. J. (2001). Color and the vertical structure in Jupiter’s belts, zones, and weather systems. *Icarus*, 154(2), 459–474.

Simon-Miller, A. A., & Gierasch, P. J. (2010). On the long-term variability of Jupiter’s winds and brightness as observed from Hubble. *Icarus*, 210(1), 258–269.

Simon-Miller, A. A., Rogers, J. H., Gierasch, P. J., Choi, D., Allison, M. D., Adamoli, G., & Mettig, H.-J. (2012). Longitudinal variation and waves in Jupiter’s south equatorial wind jet. *Icarus*, 218(2), 817–830.

Sromovsky, L. A., Baines, K. H., Fry, P. M., & Carlson, R. W. (2017). A possibly universal red chromophore for modeling color variations on Jupiter. *Icarus*, 291, 232–244.

Tollefson, J. W., de Pater, I., Barnett, M. N., Hsu, A. J., et al. (2020). High-resolution UV/Optical/IR Imaging of Jupiter in 2016–2019. *The Astrophysical Journal Supplement Series*, 247(2), 58.

Zhang, C. (2005). Madden-Julian oscillation. *Reviews of Geophysics*, 43, RG2003. https://doi.org/10.1029/2004RG000158