Unexpected long-term variability in Jupiter’s tropospheric temperatures

An essential component of planetary climatology is knowledge of the tropospheric temperature field and its variability. Previous studies of Jupiter hinted at non-seasonal periodic behaviour, as well as the presence of a dynamical relationship between tropospheric and stratospheric temperatures. However, these observations were made over time frames shorter than Jupiter’s orbit or they used sparse sampling. Here we derive upper-tropospheric (330-mbar) temperatures over 40 years, covering several orbits of Jupiter. Periodicities of 4, 7–9 and 10–14 years were discovered that involve different latitude bands and seem disconnected from seasonal changes in solar heating. Anticorrelations of variability in opposite hemispheres were particularly striking at 16°, 22° and 30° from the equator. Equatorial temperature variations are also anticorrelated with those observed 60–70 km above. Such behaviour suggests a top-down control of equatorial tropospheric temperatures from stratospheric dynamics. Realistic future global climate models must address the origins of these variations in preparation for their extension to a wider array of gas giant exoplanets.

Temperature and its variability constitute an essential element of the climatology of a planetary atmosphere, inextricably linked to planetary dynamics and chemistry. Initial studies of long-term variability of outer-planet temperatures focused on the stratosphere of Saturn. Studies focused on Jupiter detected a stratospheric temperature oscillation that—like Saturn—results from the vertical propagation of waves. The earliest study of Jupiter’s tropospheric temperatures examined one- and two-dimensional scans of its disc over 1980–1990, later extended in time to include two-dimensional mid-infrared imaging through 2001. Although snapshots of Jupiter’s tropospheric temperatures have been investigated during epochs of visible change in Jupiter’s banded features, there has been no systematic assessment of long-term tropospheric temperature variations.

Observations

Here, we extend the record of Jupiter’s infrared variability to cover 1978–2019, allowing us to diagnose Jupiter’s upper-tropospheric temperature field for three and a half of its 11.9-year solar orbits, separating seasonal and non-seasonal variability unambiguously. The images were obtained using mid-infrared instruments mounted on NASA’s Infrared Telescope Facility, the Subaru Telescope and the Very Large Telescope (VLT), as described in Methods section, the materials section in Supplementary.
Periodicities

Among the striking properties of the brightness-temperature time series (Fig. 1e–f) are apparent roughly 10–14-year periodicities of temperatures at 20.50 µm. Some of the earliest observations that were made with only a broad filter near 18 µm between 1978 and 1983 (ref. 8) were analysed for two filters. Information and detailed individually in Supplementary Table 1. These observations were made using mid-infrared instruments with discrete filters at 17–25 µm, where the emission is sensitive to temperatures in the upper troposphere (100–400 mbar). To cover variability over a broad range of latitudes, the largest at 16° (Fig. 3a), as well as 22° latitudes shown in Fig. 2b,c. Examining the Pearson correlation coefficients associated with conjugate latitudes yielded negative correlations variations. Furthermore, the apparent warmest and coldest temperatures are not coincident with the solstices, L = 90° and 270° (Fig. 2 and Supplementary Figs. 1 and 3), which would result from a purely geometric effect. In addition, the hemispheric temperature contrasts are consistent with those derived from independent studies of Voyager IRIS13 and Cassini CIRS14 observations (Fig. 2). The temperature variations are unlikely to result directly from radiative heating, as recent models15 predict peak-to-peak tropospheric temperature seasonal variability of only 0.4 K or less, given Jupiter’s small axial tilt. The models are also offset in time from the measurements (Supplementary Fig. 1). Time-dependent oscillations do exist in other planetary atmospheres that are related to seasonal cadences, such as Saturn’s semi-annual equatorial oscillation15, or perhaps more loosely, the Earth’s 28–29-month quasi-biennial oscillation16. Both phenomena are tied to narrow low-latitude regions, which might indicate similar mechanisms for Jupiter.

Hemispherical asymmetries

However, such mechanisms do not explain one other striking characteristic: the variability of these temperatures is anticorrelated between the northern and southern hemispheres. This can be seen at the discrete latitudes shown in Fig. 2b,c. Examining the Pearson correlation coefficient associated with conjugate latitudes yielded negative correlations over a broad range of latitudes, the largest at 16° (Fig. 3a), as well as 22° latitudes.
Fig. 2 | Retrieved temperatures at 330 mbar. **a.** The temperatures at the equator. **b.** The temperatures 16° from the equator. **c.** The temperatures 30° from the equator. Away from the equator, temperatures are shown at conjugate latitudes. Filled circles show the temperatures derived at each date of measurement and solid lines indicate temperatures retrieved from 18.72- and 20.50-µm radiances interpolated on a 60-day grid. For 1978–1983, temperatures were retrieved by scaling a fixed temperature profile to match the radiance from one roughly 18.72-µm filter, shown by filled circles without interpolated solid lines. Open circles at the equator denote the poorer spatial resolution of these data, because their relatively high values are most probably due to contamination from the nearby brighter NEB and SEB. Asterisks denote corresponding 330-mbar temperature differences derived by the Voyager-1 IRIS instrument in 1978 (ref. 13) and the Cassini CIRS instrument in 2001 (ref. 14). The black horizontal bars shown with temperatures at the equator in **a** denote the approximate duration of equatorial zone disturbances 25,26. The blue horizontal bars in **b** indicate the approximate duration of NEB expansions 10,17. The red horizontal bars in **b** indicate approximate duration of SEB fade and revival episodes 11,12. Total formal retrieval uncertainties are 2.2 K at 330 mbar, but the relative changes in time mimic those of the brightness temperatures, which are on the order of 0.2 K and only slightly larger than the filled circles in this figure. For this reason and for clarity, they are not illustrated by error bars.

Fig. 3 | Interhemispheric correlations. **a.** The correlation between temperatures on all dates of observation at 16° N versus 16° S. Filled circles represent temperatures retrieved from 1983 to 2019. Open circles represent temperatures that include those from the period 1978–1982, which were scaled from single-filter lower-resolution observations. The Pearson correlation coefficient is shown for both cases. As noted in Fig. 2, the formal retrieval uncertainty is 2.2 K, but the point-to-point relative uncertainty is close to that of the measured brightness temperatures themselves, which is roughly 0.2 K. **b.** A plot of the Pearson correlation coefficient for each latitude sampled. The highest negative values are at 16°, 22° and 30° from the equator. The strong positive values within 5° of the equator are the result of overlapping instrumental fields of view.
and 30° from the equator (Fig. 3b). This suggests teleconnected patterns of variability between the two hemispheres, such as the Earth's El Niño southern oscillation and the North Atlantic oscillation that are not well understood, and may well be related to one another. If Jupiter’s quasi-annual tropospheric oscillations are driven from great depth, we would have expected that any anticorrelated patterns arising from connections via cylinders parallel to the rotation axis would be most effective equatorward of ±16° where the cylinders do not intersect with the inhibiting dynamics of a region of metallic hydrogen, but we observe exceptions to this at 22° and 30°. The anticorrelated variations could possibly be the result of seasonal variations of hazes that contribute substantially to upper-tropospheric radiative balance. Stratospheric oscillations could also be modulating dynamic heating of the upper troposphere, possibly by controlling upwards wave fluxes.

**Relation to stratospheric temperatures**

A prominent period of 8.3 ± 1.0 years, confined to ±10° of the equator, and a fainter period of 4.5 ± 0.5 years are both detectable at 8° S–22° N (the blue and white boxes, respectively, in Fig. 1g). These tropospheric periodicities are similar to and may be related to the roughly 4-year equatorial stratospheric oscillation. Temperature oscillations at 330 mbar (Fig. 2a) appear to be anticorrelated with equatorial zonal-mean stratospheric temperature oscillations in 1980–2011 (ref. 27), which are consistent with the presence of the descending pattern of temperature anomalies detected in a study of the evolution of stratospheric temperatures at high vertical resolution, as shown in Fig. 3 of ref. 28. This implies a ‘top-down’ control of tropospheric temperatures by the dynamics of the stratosphere, similar to ‘sudden warming’ events in the Earth’s atmosphere. If both the 4.5- and 8.3-year periodicities are related to the equatorial stratospheric oscillation, the cause of the major difference in their latitudinal extent remains unresolved. Jupiter’s zonal-mean winds have 13.8- and 7.6-year variabilities, both confined to within 5° of the equator; the latter is near our low-latitude 8.3-year periodicity. A period of 7.4 ± 0.5 years is also detectable over a wide range of latitudes (dark orange box in Fig. 1b). Although apparently unrelated to variability in the major axisymmetric bands, a 7-year period is also detected in 5-µm studies near the equator29, suggesting a possible correlation between temperature variability and the condensation of clouds in the 1–4 bar range.

**Comparison with other atmospheric properties**

We found several correlations between temperatures and the visual appearance of Jupiter’s prominent bands, looking particularly for correlations with dramatic quasi-periodic changes involving all longitudes of Jupiter’s visibly dark belts and bright zones. Blue horizontal bars in Fig. 2b denote when the typically dark roughly 6° N–15° N north equatorial belt (NEB) expanded northwards to cover 18.5° N (refs. 10,14), as illustrated in Supplementary Fig. 3a. The periods of expansion in 2002, 2010 and 2018 appear to be coincident with prominent maxima of the NEB upper-tropospheric temperatures at 16° N–30° N, consistent with the removal of aerosols by heating and sublimation. Equatorial zone disturbances in 1992, 1999–2000 and 2006–2007, denoted by the black horizontal bars in Fig. 2a and illustrated by Supplementary Fig. 3b, appear to be contemporaneous with decreases in 330-mbar temperatures, in general agreement with a detailed study of atmospheric features for the 2006–2007 event30. This cadence is also consistent with the 6–7-year period of these events, even though not all of the equatorial temperature changes are tied to full-scale cloud-disturbance episodes. The red horizontal bars shown in Fig. 2b indicate the duration of south equatorial belt (SEB) (6° S–17° S) brightening and redarkening (‘fade’ and ‘revival’) episodes, one of which is illustrated in Supplementary Fig. 3c. All except a very brief sequence in the first half of 2007 coincide with the coldest periods at 16° S, which would be consistent with more aerosol condensation and visible whitening. On the other hand, periods when the prominent dark north temperate belt (roughly 22° N–24° N, also identified in Supplementary Fig. 3) underwent lengthy brightness and redarkening episodes related to spectacular plume activity (not shown in Fig. 2) appear to have no correlation with temperatures or their variability, at least at the resolution of our observations. We found no robust evidence for anticorrelations at conjugate latitudes north and south of the equator in the visible record that mirror those for 330-mbar temperatures shown in Fig. 2b. We note that previous investigations suggest that changes in temperatures and aerosols within a band do not occur at all longitudes simultaneously, but rather start in localized domains and spread with longitude over a finite time period, in the order of weeks31. For the purposes of this study, which probes time scales of years, we assume that the observations on individual dates are representative of the mean within a band at a certain time, but we note that this will lead to uncertainties in brightness temperature of ±1–2 K, as shown in Fig. 4 for the individual measurements. Figure 5 compares the 330-mbar zonal-mean temperatures with brightness temperatures at 7.9 µm, corresponding to stratospheric emission, which serve as a proxy for temperatures in Jupiter’s stratosphere near 1–10 mbar of pressure, some 60–70 km higher in the atmosphere. We note that the anticorrelation...
The presence of 4- and 8–9-year periodicities suggests a presence of an opacity detected by 5-µm imaging, most prominently between the NEB at 22° and 30° from the equator. Such an asymmetry is mirrored in cloud temperature distributions, with Jupiter's weak seasons, particularly given the distinct 10–14-year periodicities are unlikely to be the direct result of Jupiter's equatorial stratospheric oscillation\(^2\). Although close to Jupiter's 11.9-year orbit, the quasi-seasonal periodicities at temperate to tropical latitudes along with Jupiter's equatorial stratospheric oscillation\(^2\) have yielded evidence for both non-seasonal and seasonal periodicities on a virtually aseasonal gas giant in preparation for their eventual extension to a wider array of brown dwarfs and gas giant planets outside our solar system. Jupiter has been used as a basis for assessing longitudinal variability in exoplanets on the basis of rotational variability\(^2\), and variabilities have been detected on short time scales for a close-in gas giant\(^2\) and on longer time scales for a brown dwarf\(^2\). The challenge of differentiating between changes arising from local meteorology, latitude-dependent dependence variations and global-scale phenomena will require time-series analyses probing time scales of days, weeks and years to unravel.

**Methods**

**Basic reduction**

All observations were reduced and mapped following the same procedure used by Fletcher et al.\(^3\). We subtracted background emission by both rapid chopping and slower nodding between Jupiter and the adjacent sky that were obtained as a part of the standard observing routine. We then applied flat-fielding corrections and geometrically calibrated the images. For the images, we projected the data onto cylindrical maps. For the VLT imager and spectrometer for mid-infrared (VISIR), due to the maximum chopping amplitude of 25 arc seconds of the VLT and the small 32 × 32-arc second field of view of the instrument, the chopping–nodding technique used to remove the sky emission from the VISIR data led 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. We avoided the obscured regions from the VISIR data, resulting in only one hemisphere being available per image, which led to missing latitudes at dates where only one image was acquired.

**Filter consolidation**

A wide range of instruments were used in this study, starting with scanning by single-element detectors, followed by two-dimensional imaging using MIRAC\(^3\), MIRLIN\(^3\), MIRSI\(^3\), COMICS\(^3\) and VISIR\(^3\), as described in more detail in Supplementary Information. This diversity led to images being captured by slightly different filters (as shown in Supplementary Table 1). In this study, we shifted in wavelength images captured by the different instruments to match the central wavelength of the filters in VISIR and COMICS (this is 18.72 and 20.50 µm) as if they were obtained using the 18.72-µm VISIR near 18 and 20 µm as if they were obtained using the 18.72-µm VISIR and 20.50-µm COMICS filters, respectively, during the radiometric calibration step described below, enabling us to treat the different filters equally over the entire time series. Additionally, due to the higher diffraction-limited spatial resolutions of VISIR and COMICS observations compared to those acquired with the 3-m Infrared Telescope Facility, we smoothed VISIR and COMICS images before the calibration to match the spatial resolution of MIRAC, MIRLIN and MIRSI observations, which is used throughout the subsequent analysis.

**Radiometric calibration**

Each image was radiometrically calibrated using its cylindrical-map representation by scaling the 18.72- and 20.50-µm radiances to match with the 330-µbar temperatures at the equator is consistent with a top-down control of upper-tropospheric temperature variations: that is, the downwards propagation of temperature anomalies associated with Jupiter's equatorial stratospheric oscillation\(^3\).

**Conclusions**

Our study of long-term zonal-mean tropospheric temperature variability in Jupiter has yielded evidence for both non-seasonal and quasi-seasonal periodicities at temperate to tropical latitudes along with associated puzzles. Although close to Jupiter’s 11.9-year orbit, the distinct 10–14-year periodicities are unlikely to be the direct result of radiative forcing in view of Jupiter’s weak seasons, particularly given the pronounced hemispherical asymmetry of temperatures peaking at 16°, 22° and 30° from the equator. Such an asymmetry is mirrored in cloud opacity detected by 5-µm imaging, most prominently between the NEB and SEB\(^3\). The presence of 4- and 8–9-year periodicities suggests a relationship with stratospheric temperature variability. More detailed correlation between their periodicity and phase is needed to validate that connection, particularly to test the suggestion of 'top-down' mechanisms, such as descending waves. The 7-year periodicity over a broad latitude range may also be related to the quasi-periodic equatorial disruption with the same cadence\(^3\). Although we found no straightforward correlations between periods and the latitudes of Jupiter’s belts and zones, correlations with known global-scale changes of cloud morphology suggest at least some thermal modulation of aerosol condensation and sublimation cycles, which deserves more detailed quantitative scrutiny. Realistic global climate models for Jupiter must address the origins of these unexpected seasonal and non-seasonal periodicities on a virtually aseasonal gas giant in preparation for their eventual extension to a wider array of brown dwarfs and gas giant planets outside our solar system.

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**Fig. 5** (Comparison between variability of zonal-mean temperatures at 330 mbar (green lines and filled circles) and 7.9-µm brightness temperatures (orange lines and filled circles). a. This comparison at 30° N. b. At the equator. c. At 30° S. The 7.9-µm brightness temperatures are smoothed versions of those described by Antuñano et al.\(^3\).)**

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Voyager IRIS observations at latitudes spanning 50° S to 50° N. This was done by comparing the averaged radiance between these latitudes in each image to the averaged radiance for the same latitudes of the Voyager IRIS profile. Observations with these filters were scaled to Voyager IRIS observations because, although this wavelength range was also covered by Cassini CIRS observations in its focal plane 1, Cassini provided only hemispheric averages in this spectral region. This scaling approach was judged to be far more reliable than referencing observations of a ‘standard’ star whose flux spectrum is known 36. First, we made several observations on partially cloudy nights when images were acquired in transparent gaps between clouds, but observations of a stellar flux standard were not possible. Second, and more generally, our tests of this calibration approach in ostensibly clear skies yielded inconsistencies on the order of ± 30%, due to variable transparency through parcels of invisible humid air in the optical path, to which these wavelengths are particularly susceptible.

Zonally averaged radiances
Our study examined the variability of zonal (longitudinal) mean temperatures. To achieve this, the observed radiances were averaged zonally using the mean of radiances within 30° longitude of the minimum emission angle at each latitude in 1° latitudinal bins, that is along the central meridian. In our long term 5-µm radiance variability study 36, we showed that there were no substantial differences between the zonally averaged radiance using (1) this technique and (2) a second-order polynomial fitting to the emission angle. Smoothened radiance profiles
We first linearly interpolated radiance profiles onto a 60-day regular grid in 1° latitude bins. We then convolved the interpolated radiance with a Savitzky–Golay smoothing filter, which fits sets of adjacent data points in a regular grid with a polynomial using a linear least-square method (https://www.l3harrisgeospatial.com/docs/SAVGOL.html). This allowed us to complete the radiance sequence when instruments were unavailable, developing radiance profiles that better represent the full data set. This convolution was performed by linearly interpolating our radiance profiles onto a 60-day regular grid and then convolving the interpolated radiances with a 24-point wide fourth-order polynomial. Different window sizes, interpolations and polynomials were tested. Larger window sizes resulted in excessively smoothed profiles, while smaller windows and higher-order polynomials showed an artificially wavy profile. The smoothing was repeated 200 times for each latitude and wavelength, taking each time different random values of radiance within the estimated errors to consider the uncertainties of the zonally averaged radiance. Finally, the 200 smoothed profiles were averaged together at each date to obtain an averaged smoothed radiance profile for each latitude and wavelength (see Fig. 4 for an example of the radiance smoothing performed, represented by the equivalent brightness temperature). The same smoothing process was also applied to the 7.9-µm brightness temperatures shown in Fig. 1g of ref. 21 that are shown in Fig. 4.

Temperature retrievals
Temperatures were retrieved using the NEMESIS retrieval code 37 using only the 18-µm (calibrated to 18.72 µm) and 20-µm (calibrated to 20.50 µm) data interpolated onto the 60-day grid, as shown in the top and middle panels of Fig. 1, respectively. Only temperatures were allowed to vary. The chosen aerosol profile is based on an NH₃ ice cloud with a 10 ± 5 µm radius size distribution, a base at 800 mbar and top at 400 mbar, with a fractional scale height of 0.4. These values were chosen as they resulted in optimal fits to observations in a smaller data set that uses eight filters, including those in the 7–14 µm region that are sensitive to absorption by NH₃ gas and aerosols. If a size distribution of aerosols with a radius of 1 ± 0.5 µm is assumed, the retrieved temperatures are only 0.1 K lower than for the 10-µm case on average and the temporal behaviour is the same in both cases. A comparison between the temperatures retrieved from the images in all eight filters (which includes solving for the aerosol opacity as a function of latitude and time) versus the 18.72- and 20.50-µm images alone show differences ranging only from +1.6 to −1.0 K, well within our stated uncertainty. We note further that differences associated with variability in time, which are independent of the systematic offsets included in the differences cited above, are even smaller.

We formally derived temperatures at pressures of 100, 220 and 330 mbar, but we found that the 330-mbar temperatures were associated with the smallest uncertainties, and so we concentrated on those retrieved temperatures. The variability from a temporal mean is very similar at each pressure. Temperatures from the less frequent 1978–1982 data shown in Fig. 2 were derived from a single roughly 18-µm filter using a simple uniform increase or decrease of temperatures for a ‘standard’ vertical profile. As described in ref. 39 and shown in their Fig. 2, this standard profile was derived from a smoothed average of the Voyager-1 radio-occultation results 39, with a cooler overlying stratosphere that provided a better fit to radiance observed across Jupiter’s disc at all emission angles. Derived temperatures from the Voyager IRIS experiment were taken from the repository of L.N.F. at https://github.com/leighfletcher/Voyager, and from the Cassini CIRS experiment from a similar repository: https://github.com/leighfletcher/CassiniCIRS.

We found that using their temperatures at a pressure of 330 mbar in place of their choice of 250 mbar provided a reasonable match to the temperatures we derived for the 1983 and later, and that is what is shown in Fig. 2. A comparison of this simple approach to the derivation of 330-mbar temperatures with those resulting from the eight-filter retrievals yielded differences on the same order as our two-filter retrievals (+1.6 to −1.0 K), also well within our stated uncertainty. One latitude region that did not appear to match well was immediately around the equator, which was much brighter (see the open circles in the upper panel of Fig. 2). We attribute this to the factor of two poorer angular resolution of the 1978–1982 scans and maps that would be ‘contaminated’ by the much warmer nearby NEB and SEB regions.

Power spectra
The power spectra shown in Fig. 1 were derived from Lomb–Scargle periodograms using the IDL routine scargle and displayed with the IDL routine contour.

Correlation analysis
The Pearson coefficients shown in Fig. 3 were derived using the IDL function c_correlate (https://www.l3harrisgeospatial.com/docs/c_correlate.html).

Data availability
Data are archived in: https://zenodo.org/record/7336240#.Y36gUcHMLqo.

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Author contributions
G.S.O. wrote most of the main text and Supplementary Information, was responsible for the general organization and led many of
the observing runs and the initial reduction of the observations. A.A. organized the observations from the original measurements, performed the calibrations, executed the temperature retrievals and wrote a part of the main text and Supplementary Information. L.N.F. guided the spectral retrieval methodology, led many of the observing runs and the initial reduction of the observations and helped to draft the manuscript. J.A.S., T.W.M., T.F., P.Y.-F. and P.T.D. constituted part of the teams making the observations since 2002. J.J.G., A.V.P., K.A.B. and L.E.W. were responsible for examining the consistency of the calibrations, testing stellar calibrations and testing retrieval approaches on subsets of the data addressed here. All authors reviewed and commented on the manuscript.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Glenn S. Orton.

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