Long-Term Behavior of Tropospheric Temperatures in Jupiter: Evidence for Quasi-Seasonal and Non-Seasonal Variability

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Abstract

A four-decade study of ground-based mid-infrared observations of Jupiter covering three and a half of its solar orbits over $\pm 30^\circ$ of latitude has revealed unexpected variations of upper-tropospheric temperatures. Patterns of variability with 10-14 year periods at discrete latitudes were discovered, all within ± 2 years of Jupiter's 11.9-year orbital period. Their repeated pattern of temperature variations is strongly anticorrelated between conjugate latitudes at 16° , 22° and 30° from the equator, latitudes too low to be significantly influenced by seasonal solar forcing. A strong temperature periodicity of 8-9 years is limited to within 10° of the equator. Another periodicity of 7 years covers a wide range of latitudes. A weaker but significant 4-year period covers latitudes from 10°S to 30°N . The 4- and 8-9-year periods at 330 mbars appear to be correlated with those 60-70 km higher in the stratosphere near ~ 10 mbar, with a ~ 2 -year delay from the stratospheric to the tropospheric level, suggesting a top-down control of tropospheric temperatures by radiative processes in Jupiter's stratosphere. Correlations between temperature variability and changes in visible appearance of clouds were also detected in Jupiter's South Equatorial Belt (6°S - 17°S) and North Equatorial Belt (6° - 15°N). No variability was detected at periods longer than 14 years.

Full Text

Images of Jupiter's thermal emission at two wavelengths sensitive to its upper-tropospheric temperatures were acquired over a span of 40 years. The longitudinal-mean variability of the emission and the 330-mbar temperatures derived from these observations $\pm 30^\circ$ of latitude from the equator are shown in Figure 1, together with their associated power spectra. Several features are prominent in the power spectra. Variations at specific latitudes, shown in Figure 2, reveal correlations with changes Jupiter's visible appearance. An apparent anticorrelation of temperature variability in northern and southern hemispheres at specific latitudes in this figure is found to be true overall, as shown in Figure 3. Variability at 300 mbar appears to be correlated with temperature variations higher in the stratosphere, but with a 2-year delay, suggesting a top-down control of temperature variations. Further details on this correlation, as well as the data acquisition and processing are provided in the Supplementary Information.

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^{1,2,3,4}. Studies focused on Jupiter detected a stratospheric temperature oscillation^{5,6} which – like Saturn - results from the vertical propagation of waves⁷. The earliest study of Jupiter's tropospheric temperatures examined 1- and 2-dimensional scans of its disk over 1980-1990⁸, later extended in time to include 2-dimensional mid-infrared imaging through 2001⁹. Although snapshots of Jupiter's tropospheric temperatures have been investigated during epochs of visible change in Jupiter's banded features^{10,11,12} there has been no systematic assessment of long-term tropospheric temperature variations.

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 discrete filters at 17-25 μm , where the emission is sensitive to temperatures in the upper troposphere (100-400 mbar). In order to cover variability over such a long time frame, we chose a subset of these filters providing the longest continuous record, with central wavelengths of 18.72 and 20.50 μm . Some of the earliest observations that were made with only a broad filter near 18 μm between 1978 and 1983⁸ were analyzed independently, as discussed in the Supplementary Information.

Figure 1 shows the 1983-2019 longitudinal-mean brightness temperatures of both filters. Brightness temperatures were smoothed and interpolated from an irregular sampling to a 60-day time grid. In order to remove any systematic emission-angle dependences in the apparent brightness temperature, we derived physical temperatures over pressures of 100-400 mbar from an inversion of filtered radiances measured at 18.72 and 20.50 μm , using the NEMESIS atmospheric retrieval code¹³ following procedures for discrete-filtered observations¹⁴ (see Supplementary Information for details). Temperatures were allowed to vary at all altitudes in a constrained way; the retrieved temperatures near 330 mbar had the smallest uncertainties. To minimize any dependence on emission angle further, we limited our analysis to planetocentric latitudes within 30° of the equator, focusing on a region where planetary-scale changes in Jupiter's bands (its visibly dark 'belts' and bright 'zones') appear most frequently and where they are adequately resolved, even in our earliest data. Adding more filters to constrain the inversion better would have provided a more limited temporal sampling. Figure 1C shows the retrieved temperatures and Figure 1D the residual from a longitudinal mean. Figure 2 illustrates temperatures at specific latitudes.

Among the striking properties of the brightness-temperature time series (Fig. 1E and 1F) are apparent ~10-14 year periodicities of temperatures (the yellow, orange and red boxes in Fig. 1H), all intriguingly close to Jupiter's 11.9-year orbital period. To ensure that this quasi-annual behavior is not an artifact of the seasonal variations of the emission angle at a fixed latitude, we estimated the size of the brightness temperature change due solely to the change of emission angle: even at 30° from the equator, the change (0.3 K) is much smaller than the observed variations. Furthermore, the apparent warmest and coldest temperatures are not coincident with the solstices, $L_s = 90^\circ$ and 270° (see Figs. 2, S4 and S5), which would result from a purely geometric effect. In addition, the hemispheric temperature contrasts are consistent with those derived from independent studies of Voyager IRIS¹⁵ and Cassini CIRS¹⁶ observations (Fig. 2). The temperature variations are unlikely to result directly from radiative heating, as recent models¹⁹ 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 significantly offset in time from the measurements

(Fig. S4). Time-dependent oscillations do exist in other planetary atmospheres that are related to seasonal cadences, such as Saturn's semi-annual equatorial oscillation²⁰, or perhaps more loosely, the Earth's 28-29 month Quasi-Biennial Oscillation (QBO)²¹. Both are tied to narrow low-latitude regions, which might imply similar mechanisms for Jupiter, but they do not explain one other striking characteristic: the variability of these waves is anticorrelated between the northern and southern hemispheres. This can be seen at the discrete latitudes shown in Figure 2B and 2C. 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° and 30° from the equator (Fig. 3B). This suggests teleconnected patterns, such as the Earth's El Niño Southern Oscillation (ENSO)²² and the North Atlantic Oscillation (NAO)²³ 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 $\pm 16^\circ$ where the cylinders do not intersect with the inhibiting dynamics of a region of metallic hydrogen^{24,25}, 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 upward wave fluxes.

A prominent period near 8-9 years confined to $\pm 10^\circ$ of the equator, and a fainter period of ~ 4 years, are both detectable at 8°S-22°N (the green and white boxes, respectively, in Fig. 1G). These tropospheric periodicities are similar to and may be related to the ~ 4 -year equatorial stratospheric oscillation²⁶. Temperature oscillations at 330 mbar (Fig. 2A) appear to lag equatorial zonal-mean stratospheric temperature oscillations in 1980-2011²⁶ by ~ 2 years, consistent with the shorter study of 1978-2001 data⁹. This implies that the 330-mbar oscillation is compatible with "top-down" control of tropospheric temperatures by the dynamics of the stratosphere, similar to "sudden warming" events in the Earth's atmosphere²⁷. If both the ~ 4 - and 8-9-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-year and 7.6-year variabilities²⁸, both confined to within 5° of the equator; the latter is near our low-latitude 8-9 year periodicity. A period of ~ 7 years is also detectable over a wide range of latitudes (dark orange box in Fig 1H). Intriguingly, although apparently unrelated to variability in the major axisymmetric bands, a 7-year period is also detected in 5- μ m studies near the equator¹⁸, suggesting a possible correlation between temperature variability and condensate levels there.

We found several correlations between temperatures and the visual appearance of Jupiter's bands. We searched first for correlations with quasi-periodic changes in Jupiter's belts and zones. The red horizontal bars shown in Fig. 2B indicate the duration of South Equatorial Belt (SEB, 6°S-17°S) brightening and re-

darkening (“fade” and “revival”) episodes. 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. Blue horizontal bars in Fig. 2B denote epochs when the typically dark ~6-15°N North Equatorial Belt (NEB) expanded northward to cover 18.5°N^{10,16}. The periods of expansion in 2002, 2010 and 2018 appear to be coincident with prominent maxima of the NEB upper tropospheric temperatures at 16°-30° N, consistent with the removal of aerosols by heating and sublimation. Equatorial Zone (EZ) disturbances^{17,18} in 1992, 1999-2000 and 2006-2007 (denoted by the black horizontal bars in Fig. 2A) appear to be contemporaneous with decreases in 330-mbar temperatures, in general agreement with a detailed study of atmospheric properties for the 2006-2007 event²⁹. This cadence is also consistent with the 6-7 year period of these events¹², even though not all of the equatorial temperature changes are tied to full-scale cloud-disturbance events. On the other hand, periods when the prominent dark North Temperate Belt (NTB, ~22°-24°N) underwent lengthy brightening and re-darkening 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.

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 intriguingly close to Jupiter’s 11.9-year revolution, 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 SEB¹⁸. 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 cadence¹⁸. 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 gas-giant planets outside our solar system.

Declarations

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Author contributions: Orton wrote all of the main text and most of the Supplementary Information, was responsible for the general organization, led many of the observing runs and the initial reduction of the observations. Antuñano organized the observations from the original measurements, performed the calibrations, executed the temperature retrievals and wrote a part of the Supplementary Information. Fletcher guided the spectral retrieval methodology, led many of the observing runs and the initial reduction of the observations, and helped to draft the manuscript. Sinclair, Momary, Fujiyoshi, Yanamandra-Fisher and Donnelly constituted part of the teams making the observations since 2002. Greco, Payne, Boydstun and Wakefield were interns at the Jet Propulsion Laboratory, and 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. We acknowledge the work of those who made observations prior to 2002 and the authors of previous work^{5,9} that inspired this study.

Competing interests: None of the authors have competing interests involving this research.

Data and materials availability: Data are archived in DOI 10.5281/zenodo.5768657.

SUPPLEMENTARY INFORMATION

Materials and Methods

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Figures

Figure 1

Brightness temperature variations along Jupiter's central meridian for filters at $18.72 \mu\text{m}$ (Panel A), $20.50 \mu\text{m}$ (Panel B), the 330-mbar temperatures derived from them Panel C), and the residual 330-mbar temperatures from the zonal mean (Panel D). The power spectra corresponding to these panels are shown in corresponding Panels E-H. The spectra were derived using Lomb-Scargle periodogram analysis, showing all results exceeding a 1% false-alarm probability. Detection of important but fainter features in the power-spectra panels is enabled by raising them to the 0.7 power. The power spectra in panels G and H are identical, but in Panel H we identify period that are discussed in the text. The white box bounds the latitude and period range ~ 4 years, the dark orange box ~ 7 years, the green box $\sim 8-9$ years, the light orange boxes 9-12 years, the yellow boxes $\sim 10-14$ years, and the red box 11-14 years. There are no significant periods longer than 14 years.

Figure 2

Retrieved temperatures at 330 mbar, shown at (A) the equator, (B) 16° from the equator and (C) 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 $\sim 18.72\text{-}\mu\text{m}$ 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 likely due to contamination from the nearby brighter North and South Equatorial Belts. Asterisks denote corresponding 330-mbar temperature differences derived by the Voyager-1 IRIS instrument in 1978 (15) and the Cassini CIRS instrument in 2001 (16). The black horizontal bars shown with temperatures at the equator in Panel A denote the approximate duration of Equatorial Zone disturbances (17,18). The blue horizontal bars in Panel B indicate the approximate duration of North Equatorial Belt expansions (10,18). The red horizontal bars in Panel B indicate approximate duration of South Equatorial Belt fade and revival episodes (11,18). Total formal retrieval uncertainties are 2.2K at 330 mbar, but the relative changes in time mimic those of the brightness temperatures, which are on the order of 0.2K and only slightly larger than the filled circles in this figure. For this reason and for clarity they are not illustrated by error bars.

Figure 3

A. Correlation between temperatures on all dates of observation at 16°N vs. 16°S. Filled circles represent temperatures retrieved from 1983 to 2019. Open circles represent temperatures that include those from 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 2.2K, but the point-to-point relative uncertainty is close to that of the measured brightness temperatures themselves, which is ~0.2K. B. 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.

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