COMMENTARY

Key Points:
- Jupiter's dark belts exhibit cycles of plume activity and color changes over long timescales
- A jet stream outbreak in Jupiter's North Temperate Belt was captured shortly after Juno's arrival
- Juno may help to reveal the sources generating Jupiter's belt/zone variability

Correspondence to:
L. N. Fletcher,
leigh.fletcher@leicester.ac.uk

Cycles of activity in the Jovian atmosphere

L. N. Fletcher[1] (iD)

[1]Department of Physics and Astronomy, University of Leicester, Leicester, UK

Abstract Jupiter's banded appearance may appear unchanging to the casual observer, but closer inspection reveals a dynamic, ever-changing system of belts and zones with distinct cycles of activity. Identification of these long-term cycles requires access to data sets spanning multiple Jovian years, but explaining them requires multispectral characterization of the thermal, chemical, and aerosol changes associated with visible color variations. The Earth-based support campaign for Juno's exploration of Jupiter has already characterized two upheaval events in the equatorial and temperate belts that are part of long-term Jovian cycles, whose underlying sources could be revealed by Juno's exploration of Jupiter's deep atmosphere.

1. Introduction

Four decades of robotic planetary exploration, combined with an ever-expanding record of Earth-based remote observation, have revealed astounding insights into the atmospheric phenomena shaping the giant planet Jupiter but have also raised many unanswered questions [*Ingersoll et al.*, 2004; *Vasavada and Showman*, 2005]. NASA's Juno mission, in orbit around Jupiter since July 2016, is set to transform our understanding of Jovian processes that are largely inaccessible to Earth-based observers—in the polar regions, the magnetospheric environment, and the composition and structure of the planet hidden deep below the visible clouds. But compared to Jupiter's 11.9 year orbital cycle, Juno's orbital exploration will be comparatively short-lived. Long-term Earth-based records of atmospheric variability (Figure 1) therefore provide essential temporal context to Juno's new discoveries. In addition to monitoring Jupiter's ever-changing appearance, an international campaign of Earth-based professional and amateur support for Juno is providing both spatial context for Juno's close-in views and spectral support in wavelengths inaccessible from Juno's remote sensing experiments. This support campaign has both characterized Jupiter's atmospheric state (belt/zone structure, winds, and storms) at the start of Juno's mission and yielded discoveries in its own right, as reported in this Juno special collection for GRL.

2. Time Variability of Jupiter's Banded Structure

Jupiter's characteristic banded structure of bright white zones and darker belts can evolve over hours (convective storm eruptions), months, and years in response to poorly understood meteorological activity within (and potentially below) the main cloud decks. These "upheavals" in the banded structure appear to be most severe within the cyclonic, darker belts (Figure 1), with patterns of variability observed in both the Equatorial and Temperate Belts, albeit with ill-defined and irregular periodicities (Table 1). These profound changes encircle the whole planet and provide valuable insights into Jovian atmospheric dynamics and cloud and chemical structures. Notable modes of Jovian belt/zone variability in Table 1 can be subdivided into three broad categories: (a) gradual coloration episodes (reddening) that could be related to aerosol changes via photochemical processing of newly advected material, (b) gradual whitening caused by condensation/thickening of aerosol layers (known as fades) or darkening caused by evaporation/thinning of condensate aerosols (revivals), and (c) sudden outbreaks of convective plumes [*Stoker*, 1986; *Gierasch et al.*, 2000], both on jet streams and within major belts, leading to some revival events.

This latter category can be extreme, to the delight of Earth-bound astronomers—the South Equatorial Belt (SEB), the brown band immediately south of Jupiter's equator, undergoes significant whitening events (fades) over many months before vigorous convective activity "revives" the typical brown appearance [*Rogers*, 1995; *Sánchez-Lavega et al.*, 1996; *Sánchez-Lavega and Gómez*, 1996]. Such strong moist convective activity may be associated with Jovian lightning [*Little et al.*, 1999]. During these fade events, the SEB can appear hidden and almost indistinguishable from the Equatorial Zone (EZ) to the north and the South Tropical Zone to the south
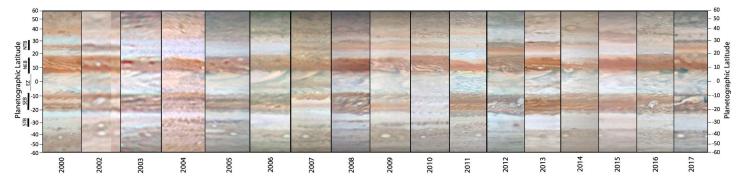
Figure 1. Jupiter's belt/zone variability observed between the 2000 Cassini flyby and the Juno observations in 2017. Representative longitude ranges were extracted from maps of amateur observations compiled by *Rogers* [2017] (see *Fletcher et al.* [2017b] for a complete list of observers and dates). Several examples of NTB revivals, NEB expansions, EZ coloration episodes, and SEB revivals can be seen during this 17 year (1.5 Jupiter year) time span. Exploring this variability with (i) a broad wavelength range extending into the infrared, (ii) higher frequency of observations within a particular apparition, and (iii) extended time coverage in the 20th century is a goal of future Jovian research.

(Figure 1). The last SEB fade and revival occurred between 2009 and 2011 [*Fletcher et al.*, 2011; *Pérez-Hoyos et al.*, 2012; *Fletcher et al.*, 2017a], and assessment of the historical record shows that these dramatic cycles sometimes occur at intervals of about 3 years, but periods between fades can be as long as 36 years, with many intervening years of "normal" SEB activity. If Juno had been observing Jupiter during one of these events, as Pioneer 10 and 11 did, we might expect aerosol distributions (measured by JunoCam and Jovian Infrared Auroral Mapper) and gaseous distributions (e.g., ammonia measured by the microwave radiometer) to be anomalous compared to the long-term record.

3. Jupiter's Belts in 2016

Variability within the other Jovian belts (Table 1) can be similarly dramatic, and the 2016–2017 campaign of Juno-supporting observations has witnessed events at two distinct locations that form part of this wider cycle of Jovian atmospheric variability. Jupiter's North Equatorial Belt (NEB), which typically resides between 7 and 17°N latitude, showed signs of expanding northward into the neighboring North Tropical Zone (NTrZ) during 2015–2016. *Fletcher et al.* [2017b] describe this as part of a 3 to 5 year cycle of NEB activity that has occurred since 1988, temporarily removing white aerosols from the NTrZ and giving the appearance of an expansion of the brown NEB. However, the NEB had receded to its normal latitudinal extent by the time of Juno's arrival, making the planet appear "normal" at the start of Juno's orbital exploration. What came next was even more spectacular—*Sánchez-Lavega et al.* [2017] report the eruption of four extraordinary plumes near Jupiter's fastest eastward jet at 23.9°N, characteristic of another cycle of atmospheric variability in the North Temperate Belt (NTB) [*Sánchez-Lavega et al.*, 1991, 2008]. The October 2016 NTB eruption was remarkable for several reasons: (i) Juno had just arrived in the Jovian system to observe the phenomenon; (ii) four plumes

Table 1. Characteristic Variability in Jupiter's Tropical and Midlatitude Belts (the Equatorial Zone Is Also Included)[a]

Band	Name	Latitude Range	Event(s)	Description
NTB	North Temperate Belt	24–31°N	Jet outbreaks and revival	Outburst of convective plumes on southern jet; reddening of southern part of belt (last in 2016 [*Sánchez-Lavega et al.*, 2017])
NEB	North Equatorial Belt	7–17°N	Expansion events	Narrowing and broadening into neighboring zone with 3–5 year cycle (last in 2015–2016 [*Fletcher et al.*, 2017b])
EZ	Equatorial Zone	7°S–7°N	EZ coloration episodes	Orange/yellow tint in EZ (last in 2012–2013)
SEB	South Equatorial Belt	7–20°S	Fade and revival cycles	Whitening then convective revival (last in 2010–2011). Smaller SEB outbreaks occur during "normal" state.
STB	South Temperate Belt	27–32°S	Fade and revival in discrete sectors	Outburst of spots on northern jet, but none as large as NTB outbreaks [*Rogers*, 1995]

[a]Latitude ranges are taken from Cassini-derived jet locations [e.g., *Porco et al.*, 2003]. Events in the NTB and NEB are discussed in this GRL special collection. For historical overviews of other events, the reader is referred to *Rogers* [1995].

at widely separated longitudes were identified; and (iii) the Earth-based support campaign was able to provide remarkable temporal coverage even though Jupiter was still relatively close to solar conjunction.

Unlike the less organized NEB expansion events, these NTB disturbances are likely powered by moist convective plumes rising from the depths of Jupiter's water cloud [*Sánchez-Lavega et al.*, 2008], bearing many similarities to the processes controlling SEB revivals. The rising plumes interact with the background zonal flows to form characteristic shapes [*Hueso et al.*, 2002], whereas SEB revivals take on an "S-shaped" form due to their location between an eastward jet to the north and a westward jet to the south [*Sánchez-Lavega and Gómez*, 1996], the NTB plumes moved eastward faster than the ambient zonal flows, generating wakes of bright and dark spots that went on to encircle the whole latitude band. The evolution of these disturbances is well reproduced in numerical simulations by injecting heat pulses or mass sources to represent convective plumes [*Sánchez-Lavega et al.*, 2017]. The 2016 plumes appeared to erupt from the anticyclonic region just to the south of the eastward zonal jet at 23.9°N. This is technically the northern edge of the NTrZ, but numerical simulations by Sánchez-Lavega and colleagues suggest that the disturbance morphology can only be correctly reproduced if the plumes originate from the cyclonic NTB north of the zonal jet. Intriguingly, this suggests that the plumes experience a significant tilt equatorward as they ascend, such that their cloud top appearance near 22.2–23.0°N does not represent their deep sources near 24.5–25.0°N.

Furthermore, the 2016 NTB eruption stands out in that four individual plumes were involved, at latitudes that were geographically separated from one another. What process could trigger plumes in these four different locations over a period of just 2–3 weeks? This hints at some connection between these plume sites at deeper unobserved levels below the visible clouds. Could some deep atmospheric wave pattern or instability be responsible? Or could multiple hidden meteorological features, propagating at depth, be responsible for destabilizing the weather layer to convective outbursts? SEB revival plumes appear to erupt within cyclonic circulation patterns known as barges [*Fletcher et al.*, 2017a], whose low-pressure centers may serve to raise isentropes in deeper layers and possibly cause the upward displacement near the water clouds necessary to initiate convection [*Dowling and Gierasch*, 1989]. These SEB barges were practically invisible at the time of the SEB plume eruptions in 2010 but were likely still present at deeper levels. No comparable cyclonic circulations were noted in the NTB jet prior to the eruption. However, it has been noted that the zonal jet at 23.9°N gradually accelerates prior to these disturbances [*Sánchez-Lavega et al.*, 2008; *Rogers et al.*, 2006], and the same was true in 2016 [*Hueso et al.*, 2017].

4. Cyclic Activity in the North Temperate Belt

The deep environmental changes responsible for this jet acceleration remain unclear, but by identifying these precursors, Jupiter researchers are able to provide crude predictions of when an NTB outbreak might be imminent. *Rogers* [1995] presents a historical overview of NTB outbreaks, and we note that the NTB has been through this cycle at least 6 times since spacecraft observations began—in 1975 [*Sánchez-Lavega and Quesada*, 1988], 1980, possibly 1985 during solar conjunction, 1990 [*Rogers*, 1995; *Sánchez-Lavega et al.*, 1991], 2007 [*Sánchez-Lavega et al.*, 2008], and in 2012 when Jupiter was in solar conjunction [*Rogers and Adamoli*, 2012]. Thus, successive NTB outbreaks can occur at intervals of 5 years or longer.

If the individual plumes themselves are hard to study because of their short lifetimes, the aftermath of these events is sometimes easier to characterize. The 2016 NTB disturbance produced a new, red band over the southern half of the NTB (22.8–26.7°N), whereas the northern half of the NTB became gray and turbulent up to the westward jet on its northern edge (near 32°N). This reddening of the southern NTB has been referred to as an NTB revival [*Rogers*, 1995], as this belt is often "faded" before the outbreak and dark gray at other times, as can be seen in Figure 1 after the 2007, 2012, and 2016 outbreaks. However, during both SEB revivals [*Fletcher et al.*, 2017a] and NEB expansion events [*Fletcher et al.*, 2017b], low-albedo red-brown regions are typically associated with high emission at 5 μm (and other thermal-infrared wavelengths), suggestive of a removal of aerosol opacity to allow radiance to escape from deeper, warmer levels of the atmosphere. The reddened NTB appears to be different, in both the vivid nature of the red color and the fact that it has no 5 μm bright counterpart. This combination of red color and high 5 μm opacity is also observed in Jupiter's Great Red Spot, raising the possibility of a photochemical explanation for this new band. For example, material dredged upward by the erupting plumes is exposed to solar ultraviolet radiation, which may lead to a chain of photochemical pathways [e.g., *Carlson et al.*, 2016] to produce a high-altitude haze

containing a red coloring agent. SEB revival events tend to take on an orange coloration during their latter stages [*Fletcher et al.*, 2017a], and the Equatorial Zone periodically takes on an orange/yellow appearance (Figure 1 and Table 1), and we speculate that similar photochemical modification of newly emplaced material could be at work. The existence of this reddened NTB band, which persists for some years before it narrows and fades away, could help to improve our understanding of the NTB life cycle. For example, the historical record of *Rogers* [1995] shows a 5 year activity cycle for this belt, consistent with recent events in 2007, 2012, and 2016.

5. Identifying the Causes of Jovian Variability

Several different processes appear to be at work during these cyclic events on Jupiter: eruption of moist convective plumes that interact with the ambient winds in the SEB and NTB, large-scale subsidence and cloud clearing in the SEB and NEB, and production of orange-red aerosols (potentially via photochemistry) following NTB outbreaks and SEB revivals. However, events at particular latitudes are rarely identical, and with only ~3 Jovian years of high-quality digital observations (since Pioneer in 1973–1974), we must be cautious about generalizations.

For each cycle discussed above, a combination of improved observations and numerical simulation is required to address some of the outstanding questions. What controls the time intervals between successive disturbances and expansion episodes? The small axial tilt of Jupiter (3°) means that seasonal oscillations are unlikely to play a role, but the 4.4 year cycle of Jupiter's quasi-quadrennial oscillation [*Leovy et al.*, 1991] that shapes the equatorial stratosphere will have secondary circulation patterns in the extratropics. Further work is needed to determine whether this could provide a cyclic influence on the upper tropospheric temperatures [e.g., *Simon-Miller et al.*, 2007] and, potentially, a connection to the aerosol changes observed in visible light. The next generation of numerical models, incorporating the active meteorology of Jovian water [e.g., *Sugiyama et al.*, 2014; *Li and Ingersoll*, 2015], might hold the key to the buildup of convective available potential energy preceding an outburst. What determines the longitude for the first plumes of an SEB revival or the first regions of the NEB to expand? Why does an NTB disturbance erupt on the peak of the prograde jet, and how can it erupt almost simultaneously from multiple, well-separated longitudes? Analysis of the first microwave observations from Juno, along with Earth-based observations in the millimeter and radio regimes [e.g., *de Pater et al.*, 2016], could reveal interesting insights into the deep atmospheric phenomena underlying these belts. What determines the lifetime of the convective plumes and the postplume evolution of the belts (e.g., the aerosol clearing of an SEB revival and the reddening of the NTB)?

Perhaps the most intriguing question of all: are any of these cyclic events in different Jovian domains somehow connected as part of an atmospheric cycle that is global in scale [*Rogers*, 1995]? And if so, what mechanism (waves, general circulation, etc.?) permits the transmission of energy and information between adjacent latitude bands? Or are the changes purely stochastic, governed by the unpredictable dynamical changes and instabilities at smaller scales? After all, correlation does not imply causation. Nevertheless, with continued improvements to our observing and image processing capabilities, as well as access to infrared observations to characterize the chemistry, temperatures, and cloud properties coinciding with these visible-light changes, the time series for studying Jupiter's cyclic variations is becoming ever more comprehensive.

References

Carlson, R. W., K. H. Baines, M. S. Anderson, G. Filacchione, and A. A. Simon (2016), Chromophores from photolyzed ammonia reacting with acetylene: Application to Jupiter's Great Red Spot, *Icarus*, *274*, 106–115.

de Pater, I., R. J. Sault, B. Butler, D. DeBoer, and M. H. Wong (2016), Peering through Jupiter's clouds with radio spectral imaging, *Science*, *352*, 1198–1201, doi:10.1126/science.aaf2210.

Dowling, T. E., and P. J. Gierasch (1989), Cyclones and moist convection on Jovian planets, *Bull. Am. Astron. Soc.*, *21*, 946.

Fletcher, L. N., G. S. Orton, J. H. Rogers, A. A. Simon-Miller, I. de Pater, M. H. Wong, O. Mousis, P. G. J. Irwin, M. Jacquesson, and P. A. Yanamandra-Fisher (2011), Jovian temperature and cloud variability during the 2009–2010 fade of the South Equatorial Belt, *Icarus*, *213*, 564–580, doi:10.1016/j.icarus.2011.03.007.

Fletcher, L. N., G. S. Orton, J. H. Rogers, R. S. Giles, A. V. Payne, P. G. J. Irwin, and M. Vedovato (2017a), Moist convection and the 2010–2011 revival of Jupiter's South Equatorial Belt, *Icarus*, *286*, 94–117, doi:10.1016/j.icarus.2017.01.001.

Fletcher, L. N., et al. (2017b), Jupiter's North Equatorial Belt expansion and thermal wave activity ahead of Juno's arrival, *Geophys. Res. Lett.*, *44*, 1–9, doi:10.1002/2017GL073383.

Gierasch, P. J., A. P. Ingersoll, D. Banfield, S. P. Ewald, P. Helfenstein, A. Simon-Miller, A. Vasavada, H. H. Breneman, D. A. Senske, and Galileo Imaging Team (2000), Observation of moist convection in Jupiter's atmosphere, *Nature*, *403*, 628–630, doi:10.1038/35001017.

Hueso, R., A. Sánchez-Lavega, T. Guillot (2002), A model for large-scale convective storms in Jupiter, *J. Geophys. Res.*, *107*(E10), 5075, doi:10.1029/2001JE001839

Hueso, R., et al. (2017), Jupiter cloud morphology and zonal winds from ground-based observations before and during Juno first perijove, *Geophys. Res. Lett.*, *44*, doi:10.1002/2017GL073444, in press.

Ingersoll, A. P., T. E. Dowling, P. J. Gierasch, G. S. Orton, P. L. Read, A. Sánchez-Lavega, A. P. Showman, A. A. Simon-Miller, and A. R. Vasavada (2004), Dynamics of Jupiter's atmosphere, in *Jupiter. The Planet, Satellites and Magnetosphere*, pp. 105–128, Cambridge Univ. Press, Cambridge.

Leovy, C. B., A. J. Friedson, and G. S. Orton (1991), The quasiquadrennial oscillation of Jupiter's equatorial stratosphere, *Nature*, *354*, 380–382.

Li, C., and A. P. Ingersoll (2015), Moist convection in hydrogen atmospheres and the frequency of Saturn's giant storms, *Nature Geosci.*, *8*, 398–403, doi:10.1038/ngeo2405.

Little, B., C. D. Anger, A. P. Ingersoll, A. R. Vasavada, D. A. Senske, H. H. Breneman, W. J. Borucki, and The Galileo SSI Team (1999), Galileo images of lightning on Jupiter, *Icarus*, *142*, 306–323, doi:10.1006/icar.1999.6195.

Pérez-Hoyos, S., J. F. Sanz-Requena, N. Barrado-Izagirre, J. F. Rojas, A. Sánchez-Lavega, and I. O. P. W. Team (2012), The 2009–2010 fade of Jupiter's South Equatorial Belt: Vertical cloud structure models and zonal winds from visible imaging, *Icarus*, *217*, 256–271, doi:10.1016/j.icarus.2011.11.008.

Porco, C. C., et al. (2003), Cassini imaging of Jupiter's atmosphere, satellites, and rings, *Science*, *299*, 1541–1547, doi:10.1126/science.1079462.

Rogers, J. H. (1995), *The Giant Planet Jupiter*, 418 pp., Cambridge Univ. Press, Cambridge, U. K.

Rogers, J. H. (2017), Jupiter's North Equatorial Belt and jet: I. Cyclic expansions and planetary waves, *Journal of the British Astronomical Association*, in press.

Rogers, J. H. and G. Adamoli (2012), Progress of Jupiter's great northern upheaval, 2012 July–August. Jupiter in 2012/13: Interim report no.3 (British Astronomical Association). [Available at http://www.britastro.org/jupiter/2012_13report03.htm.]

Rogers, J. H., H.-J. Mettig, and D. Peach (2006), Renewed acceleration of the 24°N jet on Jupiter, *Icarus*, *184*, 452–459.

Sánchez-Lavega, A., and J. M. Gómez (1996), The South Equatorial Belt of Jupiter. I: Its life cycle, *Icarus*, *121*, 1–17.

Sánchez-Lavega, A., and J. A. Quesada (1988), Ground-based imaging of Jovian cloud morphologies and motions. II. The northern hemisphere from 1975 to 1985, *Icarus*, *76*, 533–557.

Sánchez-Lavega, A., I. Miyazaki, D. Parker, P. Laques, and J. Lecacheux (1991), A disturbance in Jupiter's high-speed north temperate jet during 1990, *Icarus*, *94*, 92–97.

Sánchez-Lavega, A., J. M. Gomez, J. Lecacheux, F. Colas, I. Miyazaki, D. Parker, and J. Guarro (1996), The South Equatorial Belt of Jupiter. II: The onset and development of the 1993 disturbance, *Icarus*, *121*, 18–29, doi:10.1006/icar.1996.0068.

Sánchez-Lavega, A., et al. (2008), Depth of a strong Jovian jet from a planetary-scale disturbance driven by storms, *Nature*, *451*, 437–440.

Sánchez-Lavega, A., et al. (2017), A planetary-scale disturbance in the most intense Jovian atmospheric jet from JunoCam and ground-based observations, *Geophys. Res. Lett.*, *44*, doi:10.1002/2017GL073421, in press.

Simon-Miller, A. A., B. W. Poston, G. S. Orton, and B. Fisher (2007), Wind variations in Jupiter's equatorial atmosphere: A QQO counterpart?, *Icarus*, *186*, 192–203, doi:10.1016/j.icarus.2006.08.009.

Stoker, C. R. (1986), Moist convection—A mechanism for producing the vertical structure of the Jovian equatorial plumes, *Icarus*, *67*, 106–125, doi:10.1016/0019-1035(86)90179-X.

Sugiyama, K., K. Nakajima, M. Odaka, K. Kuramoto, and Y.-Y. Hayashi (2014), Numerical simulations of Jupiter's moist convection layer: Structure and dynamics in statistically steady states, *Icarus*, *229*, 71–91, doi:10.1016/j.icarus.2013.10.016.

Vasavada, A. R., and A. P. Showman (2005), Jovian atmospheric dynamics: An update after Galileo and Cassini, *Rep. Prog. Phys.*, *68*, 1935–1996, doi:10.1088/0034-4885/68/8/R06.