Jupiter in 2020, Report no.9;
Final numerical report: Northern hemisphere *[Short version]*

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Introduction & Acknowledgements

This report describes Jupiter's atmospheric activity in the 2020 apparition, concentrating on the period from July to December, as the earlier months were thoroughly covered in our 2020 report no.4. As usual, it is based entirely on amateur ground-based images apart from specific references to JunoCam or Hubble (HST) images.

A much more detailed version (including more background information) is available as **Supplement A**, with 32 figures including large galleries of images. Figures 1-3 are included here, along with Fig.28.

We use our usual conventions and abbreviations, as noted in **Supplement A**. Latitudes herein are planetographic.

Results are included from the JUPOS team (Gianluigi Adamoli, Rob Bullen, Michel Jacquesson, José Luis Pereira, Marco Vedovato & Hans-Jörg Mettig), who produced many maps and a comprehensive set of drift charts. **Supplement B** presents annotated copies of these charts. Also, the ALPO-Japan web site contains a comprehensive set of maps of the planet and detailed analysis of some phenomena, mostly due to Shinji Mizumoto, with some charts due to Kuniaki Horikawa. Their work has been very useful for this report and in some cases we simply refer to it.

We are very grateful to all the observers who contributed images, whether they are shown here or not; and especially to the observers in the southern hemisphere and the tropics (Australia, Brazil, the Philippines and South Africa), whose assiduous imaging was essential.

Figure 1 is our zonal drift profile (ZDP) from the NNTZ to the mid-NEB, from JUPOS data. Figure 2 presents slices from maps in 2020 to show changes in major belts and zones. The greatest changes were in the NTB, NTropZ and NEB, with great upheavals in those domains. Figure 3 is a map covering most of the planet on 2020 Sep.15.

N5 & N6 domains

In 2020 we have exceptionally good coverage of the high northern domains, showing interesting interactions between spots, many of which can be identified in maps from Hubble (OPAL: Aug.25) and JunoCam (esp. PJ29: Sep.16). We even recorded two spots at ~66°N, identified as small AWOs in the middle of the N6 domain (Bland Zone), rapidly prograding.

There has been one large and long-lived AWO in the N5 domain, tracked since 2019 March. It was fortuitously captured by JunoCam at several perijoves. There were interesting changes around this AWO in 2020 Aug-Sep., when we got an unusually detailed record of its coordinated changes in speed and latitude, apparently induced by interacting with adjacent features. In each case, a smaller spot passed north or south of the large AWO. It is remarkable that the large AWO, not the smaller spot, changes its speed during these events, but we believe that the smaller spots are representative of the slow current for the domain, which also governs the larger though less obvious features of the N5 domain, with typical speed DL2 ≈ +13 deg/30d.

The detailed coverage this year shows new details of the N5 AWO's latitude changes, which were often slower than its speed changes. When the oval had high speed, its latitude was sometimes even higher than indicated by the zonal wind profile (ZWP), perhaps due to the oval deflecting the N6 prograde jet around it. Conversely, when the oval had low speed, it would wander in latitude, consistent with the almost flat ZWP in this range.

N4 domain

Here too we obtained a hi-res ZDP, which is very close to the ZWP from spacecraft, showing only a slight cyclonic gradient across the southerly half of the domain. Several spots in this range drifted in latitude with little change of speed. Further north, N4 AWOs drifted much faster on the steep anticyclonic gradient with latitude.

N2 (N.N. Temperate) domain

NNTZ AWOs: Four major AWOs were tracked in 2020. Both LRS-1 and WS-4 were white from July to Nov., with a dark rim that may have faded in Nov. WS-6 & 7 were two bright white ovals, approaching each other, which met in late Oct. and merged around Oct.29-31. The merged oval remained large and bright and methane-bright in Dec.

NNTB: Overall, at most longitudes there was no distinct dark belt, but the NNTB was a collection of variable dark segments, pale ochre segments, and FFRs, with some of these interconverting during the year. Both dark and pale segments often appeared 'closed', i.e. with curved ends suggesting cyclonic circulation, and this was confirmed by some spectacular closeups from JunoCam. The NNTB was not evidently affected by the great NTBs jet outbreak, in contrast to previous such events.

NNTBs jet: The high abundance of small dark spots on this jet was undiminished by the NTBs jet outbreak. From late July onwards, the spots were mainly appearing downstream of a vigorous FFR, and tended to move south and decelerate along their course. Mean drift rates were DL2 = -83 deg/30d before deceleration and -72 deg/30d after deceleration. The ZDP is broader and faster than the Cassini ZWP, confirming that the jet's ZWP is variable.

North Temperate domain

The main feature of this domain was, of course, the great NTBs jet outbreak that started on August 18, creating three powerful plumes here named NTBO-1, -2, -3, with expanding turbulent 'wakes', leading to eventual revival of the NTB.

In July-August, before the outbreak, the NTB was still very faint at most longitudes, pale fawn in colour, but still with a long-lived rifted sector drifting with the N. Temperate Current A (NTC-A); and a dark grey NTB sector p. the rifted region, with tiny dark spots emanating from it in the N. Temperate Current B (NTC-B); and a weaker, narrower, variable NTB(N) tapering f. the rifted region. This appearance did not change until mid-Sep. Then, as the expanding 'wake' of NTBO-1 passed the rifted region, production of NTC-B spots was no longer observable. However the rifted region probably survived. Alongside its f. end, continuously from March to Dec., was a small bright AWO in the NTZ at 32°N. F. this AWO, dark spots were notable for their oscillations or other instability, and were eventually replaced by a wave pattern.

As the three plumes disappeared, from mid-Sep. to early Oct., the NTB evolved rapidly. The large-scale wave structure of the plume tails dissipated, leaving (from N to S):

--a narrow NTB(N), still pale at some longitudes but darkening at others (~30°N);
--a dark grey streaky NTB(S) without major features (~25°N);
--from Nov. onwards, a reddish southern fringe;
--a disturbed narrow NTropZ, still streaked with remnants of the plume wakes' wave structure entangled in the NEBn.
So by the end of the apparition, the NTB was generally quiescent. In Dec., it was a broad grey belt at most longitudes, with a reddish southern fringe. There was still a gap (probably representing the rifted sector) with the NTZ AWO still adjacent. At many other longitudes there was a wave pattern on the NTBn, which is a common appearance some time after a NTBs jet outbreak; the waves did not show significant drift relative to the NTB.

The NTBs jet outbreak

This great upheaval followed the same pattern as previous ones, but this was the best-observed ever. It was expected in 2021 but it started a year early. Previous outbreaks in this series occurred in 2007, 2012, and 2016, though only the first was observed thoroughly, as the 2012 and 2016 events took place largely during solar conjunction.

Before the outbreak, only a few inconspicuous little flecks indicated the presence of the super-fast jet, with DL1 = -3.6 deg/day. This was no faster than a year earlier, so did not predict the imminence of the outbreak.

The NTBs jet outbreak started on 2020 Aug.18. Following Shinji's Mizumoto's description, four elements can be distinguished:

1) The super-fast plumes at 23°N. Three of the these appeared at different longitudes, initiating all the other phenomena. Plume 1 appeared on Aug.18, plume 2 on Sep.1-2, & plume 3 on Sep.7-8. Each one was extremely bright in RGB & CH4 & UV images, indicating an extrusive phenomenon rising high above the main cloud deck. They moved with the full speed of the NTBs jet-stream, prograding in L1 at almost -5 deg/day. The detailed coverage in 2020 revealed that each plume accelerated in its first few days. Even so, the sustained speeds were slightly lower than in most previous such outbreaks (Figure 28).

2) The 'tail' or 'wake' that rapidly grew f. each plume, consisting mainly of large dark spots centred at ~24°N, with DL1 averaging ~-1 deg/day. Animations confirmed that these had anticyclonic circulation. On the N and S edges of the wake were streaks of methane-bright cloud from the plume, which became items 3 & 4 below.

These dark spots were produced f. plume 1 every 4-5 days, forming a regular chain on those dates, but on intervening dates the wake appeared more chaotic. This process continued until there were 6 distinct spots on Sep.11-13. (Thereafter, the whole wake became chaotic on a smaller scale.) The same process occurred f. plume 2, reaching 4 dark spots on Sep.21. The spacing of these dark spots, 12-20° longitude with mean ~14°, accords with their production about every 4-5 days. The relationship to waves of similar wavelength along the NEBn edge is discussed below.

3) NTBs white clouds (~25-26°N). These narrow streaks, sometimes methane-bright, seem to have flowed out of plumes along the wakes, with comparatively slow drift rates, close to System 1. Some of them became the westernmost features of the wakes, and seemed to be related to the weakening and disappearance of the next plume on the f. side (see below).

4) NTropZs white clouds (~20-22°N). They seem to have flowed out of the plumes. Vigorous interaction was observed between the white clouds and the NEBn (which was far north following the NEB expansion event) (see below). In a few cases, the dark spot(s) at the f. (W) end of the wake evolved into distinct dark anticyclonic rings with methane-bright cloud caps.

Weakening / Disappearance of Plumes

As predicted, each plume disappeared at about the time when it caught up with the turbulent wake of the next one p. it; plume 3 on Sep.19-22, plume 2 on Sep.25-28, and plume 1 on Oct.7-14. But this process was more complex than previously known. Mizumoto's summary states: "When plume 1 reached the end of outbreak 2 (NTBs white clouds; plume 2 had disappeared by this time), plume 1 weakened (decreased brightness) and then disappeared (not detected in CH4). Plumes 2 and 3 also disappeared through a similar process. The three elements other than the plume (dark spots, NTBs white clouds, & NTropZs white clouds) also weakened to become diffuse after the disappearance of the plume."

The 'NTBs white clouds' emanated from the f. end of each wake ~14 days after the plume arose, and trailed following the wake, with DL1 near zero. The westernmost (f.) such cloud became a very small methane-bright white spot 10-17° p. the following plume, accelerating to almost the same speed as the plume, and this near-contact signalled the sudden weakening of the plume within a few days. (The white cloud then faded along with the plume.)

Effects of the NTBs outbreak on the NTropZ & NEBn

There was dramatic interaction between the wakes of the NTBs outbreaks and the NEBn edge, which was very northerly following the NEB expansion event a few months earlier (see below). As Mizumoto reported: "The NTropZs white clouds invaded NEBn, and NEBn became disturbed (probably related to NEB expanding). The invasion of the NTropZs white clouds into NEBn may be related to NEB barges (cyclonic vortices)." Long sectors of the NEBn were deformed into waves with mean wavelength ~17°, lined with bright streaks of the 'NTropZs white clouds' which often intruded as oblique rifts into the belt. These waves often appeared aligned with the similarly periodic dark spots in the wake of plume 1 (and later, of plume 2), but had very different drift rates. The NEBn waves f. outbreak 1 were moving close to System 3, and were in a sector where there was already a series of cyclonic and anticyclonic ovals drifting with similar speed and spacing. It appears that the passage of the NTBs jet outbreak induced these waves to form around the pre-existing NEBn circulations. There may also have been feedback to mould the NTBs dark spots, which were most distinct when in phase with the NEBn waves.

NTBs & NTropZ in Oct-Dec.

The region evolved rapidly during Oct. following the disappearance of the three plumes. The southern NTB and NTropZ were initially filled with streaks and turbulence, which rapidly resolved into a narrow dark grey NTB(S) (24-25°N) and a very narrow, uneven NTropZ.

By mid-Nov., the NTBs had a narrow reddish fringe at most longitudes, alongside a very narrow NTropZ that was still 'warm' tinted, in contrast to the white NTZ. The aspect was similar though quieter in Dec. So by the end of the apparition, the region was generally quiescent.

In Nov., there were also several prograding reddish blobs in the NTropZ. The best-observed had an unusual drift rate of DL1 = +1.3 deg/day (DL3 = -6.1 deg/day), on the S flank of the NTBs jet. Fortuitously, it was captured in Juno's PJ30 images, and was revealed as a well-formed anticyclonic vortex. Two other such reddish blobs had a slightly faster drift, DL1 ~ +0.6 deg/day; one was last imaged on Dec.9. These red blobs could fit onto a plausible ZDP together with the dark spots seen during the outbreak, consistent with the idea that the jet at cloud-top level 'collapses' to lower speed during the outbreak.

Discussion:

Was this the last NTBs outbreak in the series?

Although a reddish fringe developed along the NTBs edge, it was much weaker than after previous such outbreaks – only a feeble copy of the "big red stripe" in 2016-17. Also, the 2020 outbreak did not suppress the NNTBs jet spot activity as previous outbreaks did. Both of these phenomena have resulted after all such NTBs outbreaks since 1970, except that of 1990 – which was the final one in a quinquennial series. This raises the possibility that 2020 will be the last in the present series. It could also be relevant that the speed of the super-fast plumes was slightly lower than in any previous outbreak (although this was not the case in 1990). Alternatively, all these signs of comparative weakness could be consequences of the short interval since the previous outbreak. We should get a firmer expectation in the next two years or so.

Is the 'great northern upheaval' a coherent phenomenon?

It is notable that the NTBs outbreak and the NEB expansion event occurred within a few months of each other, so by November, all latitudes from the NTB to the Equatorial Band were disturbed and largely reddish, as the NTB revival and NEB expansion resulted in turbulence and reddish colour that spanned the NTropZ, and the EZ coloration had re-intensified (conceivably, as a consequence of these upheavals). The picture resembled the 'great northern upheavals' of 2012 and 2016-17, which also comprised near-simultaneous NTB and NEB upheavals, although the relative timings differed by several months.

Whether this was just a coincidence, or a sign of a real hemispheric phenomenon, is difficult to judge. Throughout observational history, Jupiter has occasionally displayed 'global upheavals', which we now think consist essentially of near-simultaneous upheavals in the NTB, SEB, and EZ; the last of these was in 2007. The more recent groupings of the NTB and NEB upheavals and EZ coloration are obviously comparable, but with only three examples and a variable timeframe, it is too early to tell whether the correlation implies causation.

N. Tropical domain & the NEB Expansion Event (NEE)

The NEB Expansion Event (NEE)

The typical cyclic upheaval in the NEB is a NEB expansion event (NEE), in which the dark belt broadens to the north over several months. A new NEE developed in the first half of 2020, and was covered in our Reports nos.3&4.

Features in northern NEB: AWOs & barges

White spot Z (WSZ), the longest-lived AWO in this domain, was still a white oval up to Sep., and had become embedded in the expanded NEBn. Preceding WSZ, in June, there were several other AWOs; one (WS-a) had persisted since 2017, but others appeared more recently. But some of them shrank to become tiny spots, embedded in dark brown patches of expanded NEB. Unusual large cyclonic pale ovals also developed along this sector.

WSZ always turns dark and obscure during NTBs jet outbreaks, temporarily, and this process was observed in detail in 2020 Sep. NTBs plume 1 passed it on Sep.8, then over the next few days, as the wake passed it, a brilliant filament of NTropZs white cloud intruded into the NEB along the p. side of WSZ and wrapped anticyclonically around it. This happened again on Sep.18-20, just as plume 3 passed it and started fading; and again on Sep.23. Thereafter, WSZ was pale but had lost all its white cloud cap, appearing in hi-res images as an anticyclonic swirl, at least throughout Oct. and (at lower resolution) Nov. The other AWOs also disappeared; some shrunk to tiny spots within the expanded dark brown NEB.

However,WSZ and possibly others were reappearing in Dec., after the disturbances quietened down. WSZ and possibly other AWOs thus recapitulated the behaviour shown during the previous NTBs jet outbreaks from 2007 onwards. Most AWOs may not survive, but WSZ always loses its white cloud cover during the outbreak but later revives.

Before the NEB expansion was complete, the NEBn edge at 17-18°N had various dark projections and white bays, moving under the influence of the retrograde jet at 17°N; their DL2 ranged from +5 to +17 deg/30d. They apparently included waves along the jet, which may have been suffering interference with stationary (NTropC) features. We also tracked a single white spot with the peak jet speed (DL2 = +25).

Methane-dark patches in the NEB

During some previous NEB expansion events, notably in 2000-01 and 2015-17, a series of methane-dark waves appeared around most of the NEB. But in 2020 there was only a short-lived, incomplete wave-train in May, and a single very dark patch that developed later.

In May, a series of large diffuse methane-dark waves developed in the expanded sector of NEB. There were five such waves with a spacing of ~25-30º, overlying the retrograding NEBn jet. Wave no.2 was especially large and coincided with a dark brown patch of NEB around a shrunken AWO. These waves were short-lived, only appearing in mid-May and fading in mid-June as NEB rifts began to disrupt this sector.

Separately, in July & August, observers noticed a very methane-dark patch (MDP) on the NEB, which had appeared at the end of June. It coincided with a deeply brown patch at L3 ~ 240 (L2 ~ 160), with a small anticyclonic vortex within it. There was also a dark brown, methane-dark barge on the f. edge of the dark patch. But the MDP itself was more extended and did not correspond to any distinct circulation pattern, so its origin is a puzzle. It resembled the large reddish-brown anticyclonic bulges that have sometimes been especially methane-dark in those previous wave-trains, including wave no.2 in 2020 June – although it did not appear to be an organised circulation. But from mid-Sep. onwards it started to drift westwards. A possible cause for this was the passage of NTBs plume 1 on Sep.10, followed by its wake with consequent wave generation along the NEBn, which probably perturbed the NEBn retrograde jet. With this drift the MDP was crossing over the tropospheric circulations, and only faded away after it encountered the remnant of WSZ in Oct., just as that region was particularly disturbed. It disappeared by early Nov.

The NEB from July to Dec.

An expanding rift system affected the NEB throughout the apparition, having initiated the NEE in the spring. Extensive rifted sectors covered ≥180° by June-July, though by this time the turbulence was quite small-scale and low-contrast, without large bright rifts.

The NEB was fully expanded to 20.5°N from late July onwards, apart from a short sector which remained lighter until overtaken by a large rifted sector in early Sep. In Oct., with these turbulent sectors as well as rifting of the NEBn edge due to the NTBs jet outbreak, the largescale appearance of the NEB became rather pale and quiescent.

In Dec., the NEB was mostly rather pale, except for a narrow brown NEB(S), and barges were forming along a central line. Some bright NEB rifts were also reappearing.

The images in Dec. show many barges and white ovals (probable AWOs). The barges include some that were established in Sep. before or during the NTBs outbreak, plus some new ones. The AWOs include WSZ and possibly one or two others reappearing after their obscurity, plus several new ones as well.

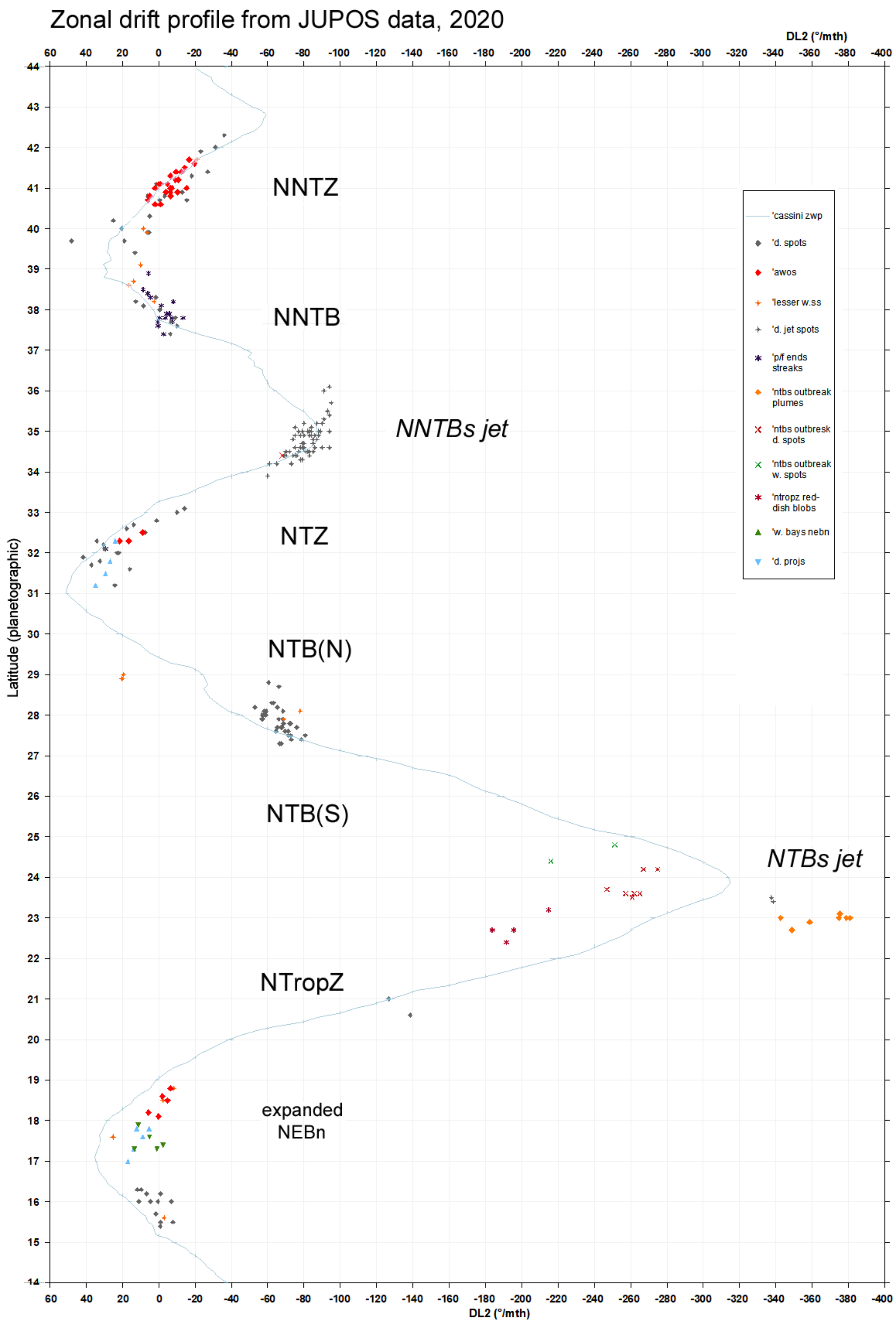

Figure 1. Zonal drift profile from JUPOS data from the NNTZ to the mid-NEB, compared with the zonal wind profile from Cassini [Porco et al., 2003; Science 299, 1541].

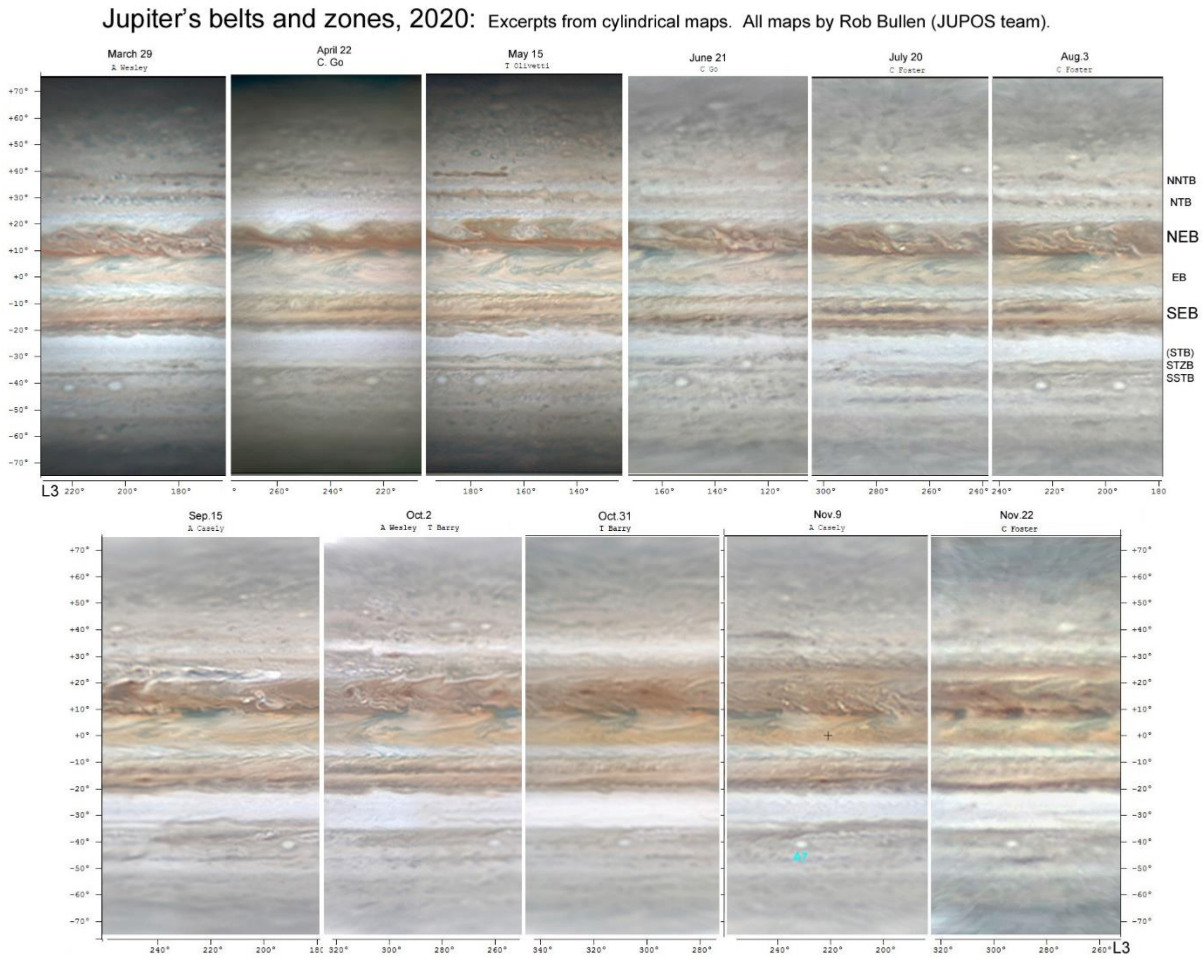

Figure 2. Slices from maps throughout 2020 to show changes in major belts and zones, notably the NTB upheaval, the NEB expansion event, and the EZ coloration. This follows on from a series presented in our 2019 report no.9.

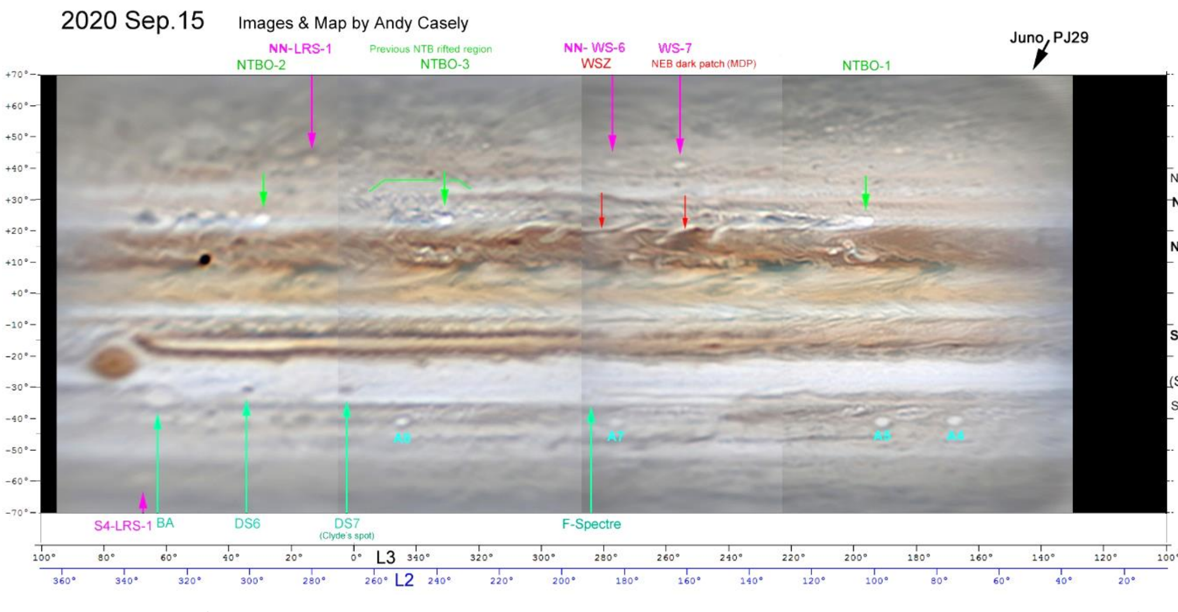

Figure 3. Map from Sep.15; images & map by Andy Casely, giving the best overview of the NTBs outbreak.

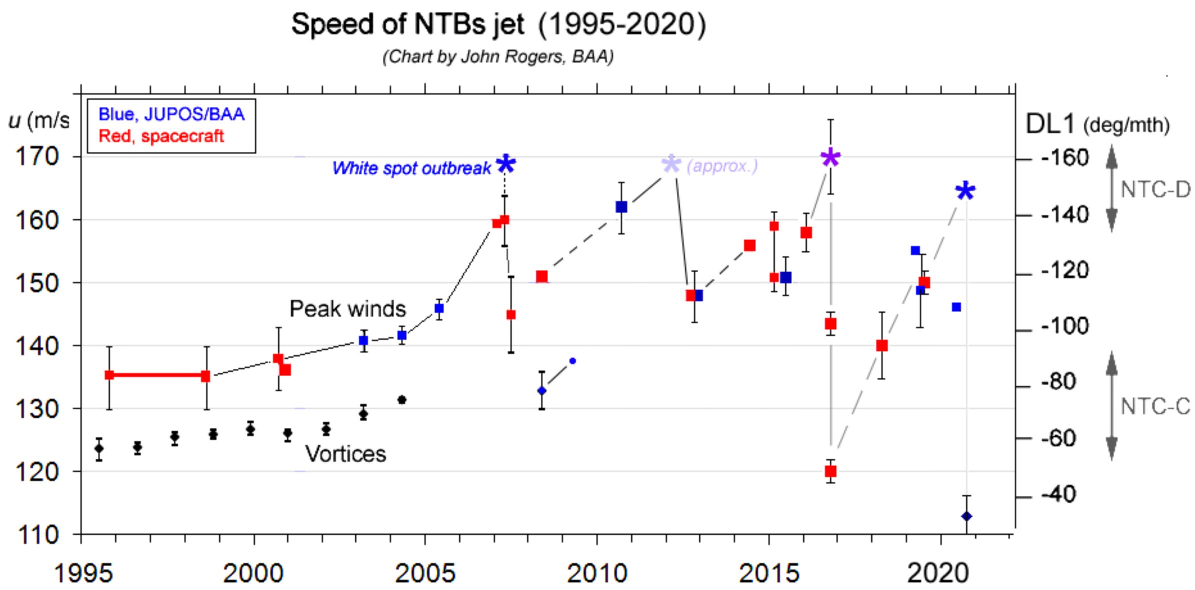

Figure 28. History of the NTBs jet from 1995 to 2020: chart showing its recorded speeds.