Jupiter in 2020, Report no.9, Supplement A:
Final numerical report: Northern hemisphere *[Full version]*

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Introduction & Acknowledgements

This report describes Jupiter's atmospheric activity in the 2020 apparition, concentrating on the period from July (opposition was on July 14) to December (prior to solar conjunction on 2021 Jan.29); 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. The recent Juno perijoves were PJ27 (2020 June 2), PJ28 (July 25), PJ29 (Sep.16), PJ30 (Nov.8), PJ31 (Dec.30), & PJ32 (2021 Feb.21). More detail on the JunoCam images is in our reports on each perijove (PJ), on this site at: https://www.britastro.org/node/17650.
We also refer to the hi-res map from Hubble images (the OPAL project) made on 2020 Aug.25.*

Results are included from the JUPOS team (Gianluigi Adamoli, Rob Bullen, Michel Jacquesson, José Luis Pereira, Marco Vedovato & Hans-Jörg Mettig), who produced a comprehensive set of drift charts. **Supplement B** presents annotated copies of these charts. (Note that they are oriented with longitudes increasing to the right, for alignment with maps with south up, and thus inverted relative to the illustrations in this report, which all have north up.) The JUPOS team made 63933 measurements in the 2020 apparition, including 112 made by co-author G.A after the main database was completed.

Also, the ALPO-Japan web site (http://alpo-j.sakura.ne.jp/Latest/Jupiter.htm) contains not only all the original images as usual, but also 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.

Table 1 gives mean drift rates and latitudes for the main currents and the most important spots. We also measured tracks of many other spots, with smaller sizes, shorter tracks, and/or more diverse drift rates, that can be seen on the JUPOS charts (**Supplement B**) and Zonal Drift Profiles (e.g. Figure 1).

As usual, this report mostly uses System 2 longitude (L2), although L3 scales are given on maps, and L1 is used for the NTBs jet outbreak and the equatorial region. Drift rates in L1 or L2 (DL1, DL2) are given in degrees per 30 days (deg/mth) unless otherwise stated. DL3 = DL2 + 8.0 deg/mth.
P. = preceding (east), f. = following (west). Latitudes are planetographic. North is up in images.
We use the standard BAA abbreviations for the belts and zones and zonal slow currents.
Other abbreviations include:
AWO, anticyclonic white oval; FFR, folded filamentary region (chaotic cyclonic region);
ZSC, zonal slow current (mean drift for large features in a domain);
ZDP, zonal drift profile (relationship of drift rate to latitude for tracked spots);
ZWP, zonal wind profile ((relationship of drift rate to latitude for smallest cloud textures).

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. The list of observers has been posted separately under 'Jupiter in 2020' on this web site, and there is also a list on the JUPOS web site. Useful imaging began in late January, 2020, and continued until early January, 2021.

*The Hubble OPAL maps are due to A. Simon, M. Wong & G.S. Orton, downloaded from https://archive.stsci.edu/prepds/opal/. Acknowledgement: "This work used data acquired from the NASA/ESA HST Space Telescope, associated with OPAL program (PI: Simon, GO13937), and archived by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. All maps are available at http://dx.doi.org/10.17909/T9G593."

Table 1: Mean drifts and latitudes from JUPOS data: N. hemisphere, 2020							
Average values in this table represent the mean motions of major spots and/or the major flows visible on the JUPOS charts. Thus, short tracks and outliers are not included. All measured features can be seen in the JUPOS charts and the ZDPs.							
			No. of spots	*Mean DL2*		*Mean Lat.*	
			(tracks)	*(deg/mth)*	*SD*	*('graphic)*	*SD*
N5TC	Small dark & bright spots		5(7)	12.3	6.9	60.4	1.1
N4TC	Small dark & bright spots		24	7.2	3.2	51.6	0.9
N3TC	Small dark & bright spots		11	-18	(estimated)	(nd)	
NNTC	AWOs:	*Note: Track segments with steady drift over 2 months or more.*					
		WS-4 was decelerating. WS-7 & LRS-1 were oscillating.					
		WS-4 (Feb-Aug)	1	-14 --> -4		(nd)	
		WS-4 (Sep-Oct)	1	+2.0		40.6	
		WS-6 (Jun-Nov)	1	-9.3		41.3	
		WS-7 (Mar-Jul)	1	-4.0	(oscillating)	41.0	0.1
		LRS-1 (Mar-Sep)	1	-8.9	4.6	41.1	0.2
	NNTB dark streaks						
		(p.& f.ends)	7(18)	-2.0	5.8	38.0	0.4
NNTBs jet	Dark spots		(55)	-81.3	5.9	34.7	0.3
NTC-A	AWO (w.s.C) (Jul-Sep)		1	16.5		32.3	
	F. rifted region		8	28.6	1.9	32.0	0.3
	P. rifted region		2(4)	20.9	3.7	31.6	0.4
NTC-B	Dark spots		17	-67.3	3.2	27.8	0.3
NTBs jet outbreak:							
NTC-C	Dark spots f. plumes		7(8)	-262.5	8.2	23.8	0.3
NTC-D	Bright plumes:						
		First 2-4 days	3	-350.1	8.1	22.9	0.2
		Later	3	-377.4	3.0	23.0	0.0
NTropC	WSZ	(Feb-Apr)	1	-6.6		18.8	
	WSZ	(Apr-Sep)	1	-4.8		18.5	
	NTropZ AWOs (>1 month)		5	-1.1	1.5	18.4	0.26
		(except WSZ)					
	White NEBn bays		3	10.0	4.3	17.6	0.30
	Dark NTropZ projections		5	12.8	5.2	17.5	0.35
	Dark NEB spots (inc. barges)		8	2.4	6.5	15.9	0.32

Figure 2 presents slices from maps throughout 2020 to give an overview of changes in major belts and zones. The greatest changes were in the NTB, NTropZ and NEB, with great upheavals in those domains. Since Report no.4, we have posted cylindrical maps of the planet from late July (Report no.6) and early Sep. (Report no.7) and others in our JunoCam reports. Figures 3-6 present maps from mid-Sep. to Dec.

High northern domains

N5 & N6 domains: *Background notes, copied from our long-term report [Ref.1]:*

The drift rates of AWOs in the N4 and N5 domains, as in the N2, S3 and S4 domains, are very variable and show sudden unpredictable alternations between slow and fast rates. Circumstantial evidence suggests that some of these speed changes are caused by interactions with FFRs: specifically, that high-latitude AWOs naturally drift fast, but can be blocked by encounters with FFRs moving with the zonal slow current (ZSC).

The N6 domain approximately coincides with a visibly bland zone. We have tracked a very few features in this domain, all of them rapidly-prograding white ovals under the influence of the N6 or N7 jets. The northernmost was at 67.3ºN and drifted at DL2 = -91 deg/mth, close to the N7 jet.

[The N5 domain)] ...As in N4, most spot tracks have positive DL2 (they are at 59-61ºN) and their ZDP has the same blunt retrograde form as the ZWP. We therefore suggest that the domain structure is the same: this blunt retrograde current is a ZSC (to be named the N5TC) and there is no true retrograde jet, apart from presumed circulation within the FFRs. Also as in N4, from 2010 onwards we have recorded white spots at higher latitudes (62.5—63.5ºN) with much faster speeds (DL2 = -10 to -57). There is no difference in ZDP between long-lived (large) AWOs and other white spots....

The mean speed of the N5TC: For white spots, there is an obvious peak...around DL2 = +13. There is a long 'tail' toward prograde speeds.... Dark spots...also peak at about DL2 = +13. Averages are as follows:
Mean of all spots between 58.0 and 62.0ºN (except 2 outliers): DL2 = +12.7 (±4.2) (N=33).
Mean of all spots between 63.0 and 65.0ºN (except 1 outlier): DL2 = -48.0 (±5.3) (N=5).

Ref.1: Rogers J, Adamoli G, Jacquesson M, Vedovato M, & Mettig H-J (2017),
'Jupiter's high northern latitudes: patterns and dynamics of the N3 to N6 domains.'
https://britastro.org/node/11328

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 on maps from Hubble (OPAL: Aug.25) and JunoCam (esp. PJ29: Sep.16). The JUPOS tracks are shown on the JUPOS chart [Supplement B] and summarised in a Zonal Drift Profile (ZDP) in Figure 7A.

We even recorded two spots at 66 and 65.5°N [numbers w2 & w3; w2 is in Figure 9], which we identify as small AWOs in the middle of the N6 domain (Bland Zone in JunoCam maps). They were rapidly prograding, but the speed of w2 was close to the velocity minimum that substitutes for a retrograde jet in this narrow domain according to the Cassini ZWP.

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 (PJ20, PJ23, PJ25, PJ29, PJ30) (e.g. Figure 8). Its track is well shown in the JUPOS chart, and its drift varies with latitude, as shown by the variation in proportion of green and blue points along slow and fast segments of the track. There were particularly interesting changes around this AWO in 2020 Aug-Sep. (Figure 9a,b,c), when we got an unusually detailed record of its coordinated changes in speed and latitude, which were typical of AWOs in high-latitude domains in being sudden (sometimes taking no more than a few days) and apparently induced by interacting with adjacent features. Thanks to the maps from Hubble and JunoCam, we can identify these features as FFRs and AWOs.

Figure 9 shows these interactions. First the N5 AWO decelerated as it encountered a very faint, southerly, slow-moving light spot (w5), which we identify as a N5 FFR (59.0°N, DL2 = +6 deg/mth). During this conjunction, around Aug.16-18, w5 became part of a larger presumptive FFR that wrapped around the southern edge of the N5 AWO, so it is understandable that this FFR could entrain the AWO. Then the AWO accelerated upon encountering a smaller, northerly, very fast-moving white spot in the N6 domain (w2), probably a tiny AWO (66.1°N, DL2 = -39) which appeared to swerve north of it and may then be visible on its p. side. Then the large

N5 AWO decelerated again, upon encountering a smaller, southerly, slow-moving white spot (w4) which was a smaller N5 AWO (59.1°N, DL2 = +5); this could be seen on the S edge of the N5 AWO on Oct.3.

In each case, the smaller spot passed north or south of the large AWO, and may have survived for a few days after the encounter. It is remarkable that the large AWO, not the smaller spot, changes its speed during these events, but we believe that the smaller N5 spots are representative of the slow current for the domain ('N5TC'), which governs the larger FFRs as well [ref.1, box above]; so the deceleration events are actually bringing the large AWO into line with the major features of the N5 domain. Between 59.0-62.0°N, spots w5 & w8 were FFRs, with speeds DL2 = +6 and +11 deg/mth; spots w4, w9 & w10 were small AWOs with mean speed DL2 = +13.7 (±7.7). For comparison, the mean speed for the N5TC as defined in our long-term report was +13.

The latitude of the large AWO correlated with its speed and was close to the Cassini ZWP, as usual (Fig.7A), but the detailed coverage this year shows for the first time that the latitude changes were often slower than the speed changes (Fig.7B). When the oval had high speed & high latitude, it would migrate temporarily to a higher latitude than indicated by the ZWP, before migrating back closer to the ZWP (e.g., mean lat. 62.9° [early May] --> 63.7° [mid-May to late July] --> ~62-63° [early to mid August]). This anomaly could be due to the oval deflecting the N6 prograde jet around it, which seems plausible from the JunoCam images, and is the obverse of the behaviour that we have reported in other domains when anticyclonic ovals distort the retrograde jet. Conversely, when the oval had low speed & low latitude (positive DL2, 60-62°N), it would wander in latitude, consistent with the almost flat ZWP in this range.

Also, there are white spots in the N4 domain to the south, whose tracks are partially parallel to that of the N5 AWO, although the Hubble map (Aug.25) shows no direct connection to it.

N4 domain

As usual, we achieved a complete JUPOS chart by combining the charts for the N (52-56°N) & S (48-52°N) halves of the N4 domain, because some features moved up and down in latitude, sometimes without changing speed.

One example was the white spot at L2 ~ 345 --> 365 --> 330 [W1] (Fig.10B). This was one of two N4 AWOs, which were the main features in N4 to have rapid prograding speeds at some times.. Then they were always at high latitude, and partially paralleling the large N5 AWO which lay between them to the north (Fig.9).

Averages for all spots between 50°N and 53.2°N inclusive (17 bright & 7 dark): DL2 = +7.2 (±3.2), range +1.2 to +13.1 deg/30d. This matches the ZSC (N4TC), mean DL2 = +5.5 deg/30d (2003-2016) [ref.1, box above].

The ZDP (Fig.10A) is very close to the ZWP from spacecraft, showing only a slight cyclonic gradient across this latitude range. Several spots in this range (not further north) drifted in latitude without significant change of speed, i.e. behaving as though the ZDP were flat (at least locally) in spite of the slight mean gradient. Further north there is a steep anticyclonic gradient with latitude up to the N5 jet, and the AWOs moved up and down this gradient (Fig.10A). Fig.10B shows how AWO W1 exhibited all these behaviours: at its slowest (steady DL2 = +12) it wandered down then up in the N4TC latitude range before migrating further up to 53.5°N a few days *before* its speed accelerated accordingly. Thereafter, with a very fast mean speed of -27 deg/30d, it oscillated in speed and latitude, in good agreement with the ZWP.

N3 domain

The sharp latitudinal separation of the zonal slow currents for the N4 and N3 domains (N4TC and N3TC), with their different drift rates as documented historically, is very distinct in the 2020 JUPOS charts. The N3TC has mean DL2 = -18.6 (±2.3) deg/mth (1999-2016) [ref.1]. The N3 chart confirms that the N3TC dominates this domain: it is clearly displayed by ~11 spots, both bright and dark, which mostly have DL2 ≈ -18. However, the two best-tracked white spots had some track segments with DL2 = -29 and -32 respectively, and a small group of spots had DL2 ≈ -38.

N2 (N.N. Temperate) domain

The following account follows on from Report no.4. The maps in Fig.11 show the features.

NNTZ AWOs:

Four major AWOs were tracked in 2020, but two of them merged in late October:

LRS-1: White from July to Nov., with a dark rim that may have faded in Nov. (Figs.18 & 30). Its drift rate continued to oscillate, with a slightly lower mean speed than before, but with period increasing to ~3 months. It was still recorded in a methane image on Dec.9. A single measurement in early Jan., 2021, suggests that the drift since Oct. had stabilised at DL2 = -4.

WS-4: Likewise, white from July to Nov. (Fig.9), with a dark rim that may have faded in Nov. Since early July it was well tracked, with DL2 varying irregularly, from -4 (July) to -11 (late Aug.) to +2 (Sep.& Oct.) the faster again (Nov.). A smaller white oval approached it and possibly merged with it in late Oct.

WS-6 & 7: Two bright white ovals, WS-7 having a dark rim (Fig.12). The drift rate of WS-7 continued to oscillate up to early Aug., then it had DL2 = +5, rapidly approaching WS-6, until Oct.2. Then it accelerated briefly to delay the encounter, but they did meet in late Oct., merging around Oct.29-31. The actual merger was resolved on Oct.29 (Fig.12; also see original image in Fig.26). The merged oval remained large and bright and methane-bright in Dec. WS6 had a steady drift DL2 = -9 from June to early Dec., not perturbed by the merger with WS-7.

The ZDP for all the features tracked in the N2 domain is shown in Fig.13. It is quite simple: all types of features follow the same ZDP which, typically, matches the Cassini ZWP in the negative DL2 range but has mostly lesser retrograding speeds in the positive DL2 range. This year, in contrast to some earlier years, the AWOs all followed the same ZDP/ZWP regardless of their size.

Many of these features were small dark spots in the anticyclonic part of the domain (39.4—42.4°N), rarely lasting for more than a month, which had a great range of speeds (Fig.13). Most had DL2 in the range from -10 to +21.

A tiny dark spot f. WS4 in early August had exceptional drift: DL2 = +48 deg/mth, at 39.7°N, i.e. in the NNTBn retrograde jet but retrograding much more rapidly than previously recorded (Fig.13). It then moved N until it was caught in the prograding flow for a week, before resuming retrograde drift with DL2 = +25 into Sep., alongside pale sector A.

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 (PJ28, PJ29, PJ31, PJ32; though a more complex form of interface was viewed at PJ27). The NNTB was not evidently affected by the great NTBs jet outbreak, in contrast to previous such events [see box below].

The more distinct sectors were as follows, listed in order of increasing longitude from WS-4, continuing from Report no.4; see maps in Fig.11.

A) Pale ochre segment spanning approx. L3 ~ 160-200 from July to Dec. (This was a former dark segment that had split and faded away in June.)

B) A short dark segment around L2~140, L3~220, which appeared in July. (This sector had been a FFR from April to June.) In Sep. the dark segment shrank, sometimes appearing brown, and became indistinct, though a dark NNTB persisted across this sector. In Dec. there was a distinct dark segment from L3 ~ 204-244 (L2 ~ 315-357[early Dec], 325-360 [late]).

C) A long sector p. and f. WS-7, resembling a FFR but with a dark central strip, in July & Aug. It disappeared in Sep. as WS-7 converged on WS-6.

D) F. WS-6, in Feb.-March there had been a very dark sector that became dark red-brown in April-May. K. Horikawa (ALPO-Japan) showed that its p. end had the unusual rapid drift rate of DL2 = -22 deg/mth, passing WS-6 in May before becoming indistinct. This NNTB became lighter in June, but its p. part was still present in July & Aug. as a long brown or ochre sector f. WS6. Its f. part was dark but irregular in July, then became a FFR in Aug.& Sep. The turbulent NNTBs p. (downstream of) this new FFR may have been the source of NNTBs jet spots (see below).

E, F) The sector of NNTZ f. LRS-1 had been exceptionally disturbed from April to June, and it was still darkened and disturbed from July to (at least) Oct., although dark segments of NNTB on its S side behaved normally. There was a well-defined short dark NNTB segment (E) in July, which became brown in late Aug. and faded in Sep. As it disappeared, another short dark NNTB segment (F) developed in Oct., just f. the prograding LRS-1 and p. the fading segment E.

G) A FFR p. WS-4, from July to early Oct. (at least).

The NNTB dark segments were at 38°N and had NNTC drifts, ranging from DL2 = -7.5 to +6 deg/mth (**Table 1**). A few dark spots had similar drifts and latitudes.

NNTBs jet (N2 jet):

The high abundance of small dark spots on this jet continued, surprisingly undiminished by the NTBs jet outbreak [see box below]. In Aug-Sep., the spots were still present at most longitudes. (They are marked by red lines on the maps in Fig.11.) In contrast to the earlier uniform speeds, their drift rates were more diverse, and they tended to decelerate along their course. From late July onwards, the spots were mainly appearing near L2~260 [L3~340] (Aug.1) --> L2~210 [L3~300] (Oct.1), i.e. downstream of a vigorous FFR. And they disappeared somewhere around L2 ~ 310—30 [L3 ~ 30—110], where there was some interaction with spots in the NTZ (see below).

We reported mean DL2 = -80 (±2) deg/mth up to June (Report no.4). In July the drift became more variable; several short-lived spots had very fast drifts up to ~-106 (not included in the m), whereas the main spots decelerated, the slowest speed being -60; they also tended to move to slightly lower latitude. Mean drift rates for the main tracks from July onwards were -83.4 (±4.9; n=14) before deceleration and -72.0 (±8.2; n=7) after deceleration, with some overlap in the ranges. The ZDP is in Fig.14: it fits on the Cassini ZWP below the Cassini peak at 35°N, but continues up to faster speeds (DL2 = -94) between 35-36°N; this exactly matches the ZWP observed by Voyager. We have seen this ZDP pattern before in this N2 jet (& also in the S2 jet), in 2011-12 & 2005-06 [Rogers & Adamoli (2015), 'Jupiter in 2011/12: Final report up to 2012 Feb.' http://www.britastro.org/jupiter/2011report09.htm], though not in 2013-15. This suggests that the N2 jet profile is variable.

Effect of previous NTBs jet outbreaks on the NNTB

It is clear that NTBs outbreaks normally suppress visible activity on the NNTBs jet, as summarised in [ref.2]*. In 2012 and 2016-17, they also appeared to whiten most or all of the NNTB:

In 2012: "The NNTB was essentially invisible in 2012 July-August, being replaced by a broad white zone from NTZ to NNTZ .... Super-fast NTBs outbreaks generally suppress activity in the NNTBs jet stream (see Discussion)." --[ref.2]*.

In 2016-17, up to 2016 Dec. the NNTB was present all around the planet and carried many dark spots on the NNTBs jet, then it disappeared over >190° longitude from 2017 Jan. onwards. Activity on the NNTBs jet did not completely stop, but both the density and size of spots seemed to be much reduced; they recovered fully in 2017 March. We concluded that the NTBs outbreak probably whitened much of the NNTB and diminished the visible activity on the NNTBs, as in most previous such outbreaks, even though modern hi-res images still reveal some residual activity. –[2016/17 Reports nos.6 & 10]

*Ref.2: Rogers JH & Adamoli G (2019 June) JBAA 129 (no.3), 158-169. 'Jupiter's North Equatorial Belt and Jet: III. The 'great northern upheaval' in 2012.' https://britastro.org/node/15629. Also at: http://arxiv.org/abs/1809.09736

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. The maps in Figure 15 show the radical changes during this upheaval, which we summarise as follows.

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 sector, 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., as the initial NTBO's did not perturb either the rifted region or the NTC-B activity. Then as the expanding 'wake' of NTBO-1 passed the rifted region in Sep., production of NTC-B spots was no longer observable. However the rifted region probably survived, as described below. Alongside its f. end, continuously from March to Dec., was a small bright AWO in the NTZ at 32°N [spot C below].

After the end of Sep., the JUPOS chart is sparse. But there was a real change in the NTB around that time. 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, and a persisting gap probably representing the rifted sector.

Terminology in the North Temperate domain and NTBs outbreak:

Zonal drift rates in the NTB latitudes fall into four groups, historically called the N. Temperate Current (NTC-) A, B, C & D (see **Table 1**). NTC-A is the (retrograding) zonal slow current. NTC-B is the prograding flow in the mid-NTB shear latitude. NTC-C (the fast NTBs jet, DL1 ~ -1 to -2 deg/day) governed some historical NTBs jet outbreaks and also the dark spots in the tails of the outbreaks in the present era. NTC-D (DL1 ~ -4 to -5 deg/day), which I designate as 'super-fast', is the full speed of the NTBs jet, and is the speed of the plumes in these outbreaks.

We use the term 'outbreak' to mean a vigorous meteorological eruption, either of a single convective plume or a larger stormy disturbance. In the NTB context it can refer both to the individual plumes, and to the upheaval as a whole. I have labelled the three plumes 'NTBO-1,-2,-3', and Mizumoto distinguishes between 'plumes 1,2,3' and 'outbreaks 1,2,3' where the latter includes the turbulent 'tail' or 'wake' that grew following each of them.

Dr Sanchez-Lavega and colleagues refer to NTBs jet outbreaks as NTB Disturbances (not to be confused with N. Temperate Disturbances as described in our reports). They are also sometimes referred to as NTB Revivals, which indeed corresponds to the upheavals of recent decades, but historically some NTBs jet outbreaks have not caused revival of the NTB, and some revivals of the NTB have occurred without a known jet outbreak.

References on previous NTBs jet outbreaks:

3. Rogers J & Mettig H-J (2008), 'Jupiter in 2007: Final Numerical Report.' http://www.britastro.org/jupiter/2007report20.htm

4. Rogers JH & Adamoli G (2019) JBAA 129 (no.3), 158-169. 'Jupiter's North Equatorial Belt and Jet: III. The 'great northern upheaval' in 2012.' https://britastro.org/node/15629. Also at: http://arxiv.org/abs/1809.09736

5. Sanchez-Lavega A et al.(2017). 'A planetary-scale disturbance in the most intense Jovian atmospheric jet from JunoCam and ground-based observations.' Geophysical Research Letters 44, 4679–4686. https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2017GL073421 [The 2016-17 NTBs outbreak]

NTZ and NTB(N):

The NTZ and NTB(N) were surprisingly little affected by this upheaval. The JUPOS chart shows that features moved with the usual N. Temperate Current A (NTC-A; see box above). The speeds fell into two groups: DL2 ~ +17 to +21 deg/mth, for the rifted region and features p. it and the AWO at its f. end; and DL2 ~ +30 deg/mth, f. the rifted region. The main features labelled on the chart had drifts as follows (DS = dark spot or streak):

A) DS (April-Aug.): Mean DL2 ~+19 deg/mth.

B) DS (Aug-Oct.): Mostly +24. In Aug-Sep. this was a distinct dark part of the streaky narrow grey NTB(N) (p. the rifted sector), which faded in Sep-Oct. leaving this little streak, dark brown in Oct. It may have been subsumed in the renewed dark grey NTB(N) again thereafter.

C) AWO alongside f. end of rifted sector (Mar-Dec.) (Figs.18 & 30B): +9 (Mar-Apr., 32.5°N), +19 (May & June), +16.5 (July-Sep., 32.3°N), +21.5 (Oct- Dec., 32.3°N). This AWO was weakly methane-bright in the Hubble map on Aug. 25, and in some ground-based images in Sep. (e.g. Sep.8 & 13, C.Go) but not in others (Sep.12, 23, 25) (Fig.18).

D) F. end NTD (Feb-Apr.): ~+29 (32.1°N).

E) DS (March-June): Oscillating wildly; mean ~ +30.

F) DS/streak (March-July): Oscillating; mean ~+29.

G) Succession of dark spots or streaks (May-Oct.): the last one, long-lived, oscillating, ~+30.

H) DS --> 2 DSs in NTZ (Sep-Oct.): the p. spot, ~+16. [see below]

Feature H (marked on the maps in Figures 11 & 15) was a pair of prominent dark spots in the NTZ at ~33°N in Oct., a little way f. the AWO. They did not develop from former NNTBs jet spots, but apparently developed from a similar spot marked on the Sep.7-8 map. No NNTBs jet spots disappeared here before late Sep. then, three successive NNTBs jet spots failed to pass spot H. Despite this, there was no proper N. Temperate Disturbance after April.

The spots f. the AWO (C) were notable for their oscillations (E,F,G) or other instability (G,H), and were then replaced by a wave pattern in Nov.(see below). Also f. the AWO, slightly further north within the NTZ, two small prograding dark spots at 33°N merged to form one with DL2 = -14 deg/mth (33.1°N), which disappeared on encountering the AWO. Another spot behaved similarly later (DL2 = -10, 33.0°N).

All these features, including the late-stage waves, adhered well to a ZDP which had lower peak retrograding speeds than the Cassini ZWP (Fig.14).

After the NTBs outbreak extended past the rifted sector, the latter was still recognisable in maps of Sep.7-8 (hi-res) and 15-16 (Fig.15), continuing on its previous track, with the AWO still at its f. end. In Oct., maps of decreasing resolution did not clearly resolve rifts, but this sector was included in a long 'NTBZ' at ~27°N. In Nov. this NTBZ had a well-defined f. end, an oblique dark feature adjacent to the AWO, so despite the low resolution it is likely that this was still the rifted sector. (Unfortunately the JunoCam maps at PJ29-PJ31 did not cover this region.)

Throughout Nov., there was a wave pattern on the NTBn at many longitudes although not alongside the putative rifted sector (Fig.15; also see Fig.30, below). Such a wave pattern often becomes visible some time after a NTBs jet outbreak. The last best image, on Dec.15 (Foster) (CM2=41, CM3=158), shows regular waves on NTBn all across the disk, with a mean wavelength of 10°. Three dark projections in this wavetrain, at 31-32°N, had DL2 = +24 to +27, +29.5, and +35: i.e. the wavetrain did not show significant drift relative to the NTC-A.

N. Temperate Current B (NTC-B):

Small dark spots continued to arise just p. the rifted sector and prograde rapidly in the mid-NTB latitude, 28°N. From April to early June they were quite sparse and short-lived, but in June a more impressive outbreak began. From approx. June 12 to July 21, 14 such spots appeared, fairly evenly spaced: on average, one every 2.8 days with a separation of 6°. Some merged or disappeared as they prograded, but several survived for ~2 months, expiring near L2 ~ 0 in late Aug. & Sep. As the expanding 'wake' of NTBO-1 passed the rifted region in Sep., production of NTC-B spots was no longer observable, and only a few of the oldest ones survived for another week or two. The mean

DL2 (June-Sep.) = -67.3 (±3.2; n=17) deg/mth; range -62 to -72 for most tracks. (In April-May, there was one spot with DL2 = -56, one with -67. Later, some spots first appeared with DL2 = -59 before moving to lower latitude and accelerating.)

The NTBs jet outbreak

This great upheaval followed the same pattern as previous ones, but this was the best-observed ever, allowing minor components to be described for the first time. In view of the usual 5-year periodicity, 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. These were all covered in our regular reports, and there are final accounts of 2007 in [ref.3 in box above], and of 2012 with a general discussion in [ref.4], and of 2016 from a professional angle in [ref.5].

Bulletins on the 2020 outbreak were given in our 2020 reports no.6 (the first plume, Aug.18-25) and no.7 (up to Sep.11), with many images. Here we continue the account, including results from JUPOS measurements, but not repeating all the previous material, and not covering all aspects exhaustively. For a more complete account, along with a comprehensive set of maps, the reader should consult the website of the ALPO-Japan. Maps, charts, animations & reports by Shinji Mizumoto (including speed measurements by Kuniaki Horikawa) have been posted there:

http://alpo-j.sakura.ne.jp/Latest/j_Cylindrical_Maps/j_Cylindrical_Maps.htm

including a final graphical-style report on 'The 2020 NTBs Jetstream outbreak':

http://alpo-j.sakura.ne.jp/Latest/j_Cylindrical_Maps/NTBs_outbreak_report_E.pdf

Some material from their accounts is republished here by kind permission of Shinji Mizumoto.

Figures 16-26 show images and maps from August to October, illustrating many aspects of the upheaval. Fig.19 highlights the main features. Fig.27 is Mizumoto's chart of the outbreak (the equivalent JUPOS chart is in Supplement B). Fig.28 shows how the NTBs jet speeds in 2020 fit into the pattern over the past series of cycles.

Before the outbreak, only a few inconspicuous little flecks indicated the presence of the super-fast jet. We noticed one on May 13-18 with DL1 ~ -4 deg/day (Report no.4), and G.A. has identified two more, on July 9-14 and 27-30, at 23.5 (±0.6)°N, with DL1 = -3.6 deg/day. This was no faster than a year earlier (Fig.28), so did not predict the imminence of the outbreak.

The 2020 NTBs jet outbreak started on Aug.18. Following 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 (see Reports nos.6&7 for details). 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.

Table 2 below gives their data. **Table 2A** gives the dates of the three plumes. **Table 2B** gives the average speeds for the plumes and the subsequent dark spots, both from ALPOJ and from JUPOS. Individual speeds are given in the ALPOJ report online, and in **Table 2C** from JUPOS.

The detailed coverage in 2020 revealed that each plume accelerated in its first few days. In **Table 2B**, this is documented in the JUPOS drift rates but the ALPOJ drift rates are averaged over the whole track. Even so, the sustained speeds are slightly lower than in most previous such outbreaks (Fig.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. (See Report no.7 for some initial discussion, and below for more.) On the N and S edges of the wake were streaks of methane-bright cloud from the plume, which became items 3 & 4 below.

In report no.7 we noted that these dark spots were produced f. plume 1 every 4-5 days, when they would form a regular chain, but on intervening dates, the wake appeared more chaotic. This process continued f. plume 1 for one more cycle, to reach n=6 distinct spots on Sep.11-13. (Thereafter, the whole wake became chaotic on a smaller scale.) The same process occurred f. plume 2, with n = 1 (Sep.6), 2 (Sep.9), 3 (Sep.12), 4 (Sep.21). The spacing of these dark spots, 12-20 deg longitude with mean ~14 deg, accords with their production about every 4-5 days. The relationship to waves of similar wavelength along the NEBn edge is discussed below.

Table 2A: Dates of the NTBs plumes:

NTBO-1: appeared Aug.18; disappeared Oct.7-14.

NTBO-2: appeared Sep.1-2; disappeared Sep.25-28.

NTBO-3: appeared Sep.7-8; disappeared Sep.19-22.

Dates of appearance are from our Report no.7. The first date is for a tiny 'pinprick' spot that would have been missed in earlier decades; the second is for the obvious bright spot.

Dates of disappearance are from Mizumoto's final report. The range of dates indicates that each plume weakened abruptly but could still be traced for a few days before it finally vanished.

Table 2B:

Average drift rates in NTBs outbreak										
		DL1 (°/d)	(±)	DL1 (°/30d)	(±)	*u* (m/s)	(±)	Lat.(g)	(±)	N
Bright plumes										
ALPOJ		-4.78	0.22	-143.4	6.6	159.9	2.8	23.2	0.1	3
JUPOS	1st 2-4d	-4.04	0.27	-121.2	8.1	153.1	3.7	22.85	0.15	3
	Later	-4.95	0.1	-148.5	3.0	165.3	1.3	23.0	0.0	3.0
Dark spots f. plumes										
ALPOJ		-0.78	0.49	-23.4	14.7	106.6	6.2	24.0	0.3	10.0
JUPOS		-1.12	0.27	-33.6	8.2	113.3	3.5	23.8	0.3	8.0

[the ALPOJ analysis included some later, slower dark spots]

Table 2C: JUPOS data for the individual plumes:

NTBs outbreak: Bright plumes (JUPOS data, G.A. analysis)					
spot	*time interval*	*DL1(°/30d)*	*U3(m/s)*	*Lat.(graphic)*	*n*
#1	Aug 18 – 20	-119.9	152.8	22.7	10
	Aug 21 – Oct 4	-149.9	166.0	23.0	68
#2	Sep 1 – 5	-129.8	157.0	22.9	11
	Sep 7 – 15	-146.3	164.2	23.1	12
	Sep 16 – 29	-152.0	166.8	23.0	9
#3	Sep 8 – 11	-113.7	149.6	23.0	8
	Sep 12 – 19	-145.8	164.1	23.0	9

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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). The best-documented, a very small spot f. outbreak 1, had DL1 = +0.4 deg/day. Even slower ones emerged f. outbreak 2, a string of evanescent white streaks and spots with DL1 ~ +3 deg/day (Figs. 18 & 27).

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 under 'Effects on NTropZ').

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. We noted one such in Report no.7, reported from Sep.4-6 at the f. end of the tail of plume 1, and notably methane-bright when near the limb. On Sep.8-9 the second dark spot in the wake was also an anticyclonic dark ring, and both rings were methane-bright when near the limb. The second one did not retain this form; but the first did, up to Sep.20, when it was at L1=320, just p. the decaying remnant of plume 3 (Fig.23). It then disappeared.

But a pair of similar spots (dark anticyclonic rings, methane-bright) developed likewise from the westernmost two dark spots in the wake of plume 2 in late Sep. (Figs.21 & 22). Both the westernmost two dark spots were distinct rings on Sep.22. They were not generally methane-bright then, but became so by Oct.2; they are marked with red triangles on Fig.25. Likewise, there was a methane-bright spot f. the wake of plume 3 on Sep.20-23 (Fig.24).

Weakening / Disappearance of Plumes:

As predicted, each plume disappeared at about the time when it caught up with the turbulent 'tail' 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. Quoting Mizumoto's report: "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). Plume 2 and 3 also disappeared through a similar process. The three elements other than the plume (dark spots, NTBs white clouds, & NTrZs white clouds) also weakened to become diffuse after the disappearance of the plume."

We can expand this account as follows; it applies to the demise of all three plumes. (The phenomena are shown in Fig.23 for the demise of plume 3, Fig.24 for the demise of plume 2, & Fig.25 for the demise of plume 1.) Small white 'NTBs clouds', slightly north of the plumes' latitudes, emanated from the f. end of each wake ~14 days after the plume arose, and trailed following the wake, with DL1 near zero (best established for the cloud f. outbreak 1: DL1 = +13 deg/30d [G.A.]). 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.) The plume itself abruptly became much fainter than before, in RGB and in CH4, on the first date listed in the **Table**; but a small faint remnant of it could be tracked in RGB & CH4 for a few days thereafter. (The remnant of plume 1 also decelerated during this final phase.) On the last date listed in the **Table**, the plume was no longer visible and the chaotic wake covered the region.

> *This may be similar to a phenomenon we reported in the 2007 outbreak, that short-lived super-fast bright spots lasting only a few days appeared at the f. end of the wake of the longest-lived plume, although they were not then close to any following plume [ref.3 in box above, Fig.31].

The sudden fading of both plume 2 and plume 1 began just as they were passing the NEB methane-dark patch (see below), and thus, had just passed the remnant of WSZ two days earlier. Was this just a coincidence?

The subsequent revival and maturation of the NTB was summarised above, and the effects on the NTropZ are covered below.

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 (20.5°N) 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 'NTropZ white clouds' which often intruded as oblique rifts into the belt. As we noted in Report no.7, these waves often appeared aligned with the similarly periodic dark spots in the wake of plume 1 (and later, of plume 2).

The NEBn waves f. outbreak 1 (Fig.23) were almost stationary in System 3, and were in a sector where there was a series of cyclonic and anticyclonic ovals drifting with DL3 ~ +0.13 deg/day (DL2 ~ -4 deg/mth). These ovals were very small at the height of the NTBs outbreak, but had been well defined earlier; the HST map on Aug.25 shows a series of 5 anticyclonic vortices spaced at intervals of ~17° or nearly twice that (Fig.15), although these did not entail large waves on NEBn at the time. Apparently 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 (Report no.7). [In 4 days, a typical interval between production of NTBs dark spots, the NTBs dark spots would travel ~33°, so a new dark spot would form only on every second alignment with the NEBn waves.]

Surprisingly, these waves were not associated with methane-dark waves, in contrast to the prominent methane patterns seen during the NEEs in 2000-01 and 2015-17. We attributed those to undulations on the NEBn jet, and the pattern of alternating cyclonic and anticyclonic vortices in NEBn in 2020 must have entailed similar undulations. But in 2020, there was just a single very intense methane-dark patch (see below) and no others. This needs further investigation.

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. From mid-Oct. to early Nov., different sectors of the NTropZ showed:
--bright white strips of 'NTropZs clouds' (21°N) forming the wave pattern along the NEBn (20°N)
--elsewhere duller due to further turbulent streaks and the incipient reddish NTBs;
--incipient dull reddish fringe on some sectors of NTBs (~23°N).
By mid-Nov., the NTBs had a narrow reddish fringe at most longitudes, alongside a very narrow NTropZ that was still 'warm' tinted, i.e. fawn-coloured, in contrast to the white NTZ. There were a few reddish blobs in NTropZ, prograding..

The state of the NTropZ in Nov. is shown in Figs.30-32. The NTropZ is still streaked, with a reddish NTBs fringe, and an overall 'warm' (redder) tint contrasting with the 'cold' (bluer) tint of the NTZ. Indeed, the NTB-NTropZ-NEB-EZ(N)-EB were all reddish in Nov., resembling the 'great northern upheavals' seen in 2012 and 2017 [see Discussion below].

In Dec., there was a NTBs reddish fringe and a quiet fawn-coloured NTropZ all around the planet. So by the end of the apparition, the region was generally quiescent.

In Nov., there were also several prograding red blobs in the NTropZ (Figs. 5, 29, 30). The best-observed one was tracked at DL1 = +1.3 deg/day (DL3 = -6.1 deg/day) (Oct.31-Nov.12). This is an unusual speed, and the speed and latitude show that it is on the S flank of the NTBs jet. Fortuitously, it was viewed close up in the PJ30 images, and was revealed as a well-formed anticyclonic vortex.

There were several such red blobs: on Nov.6 they were at L1 ~ 280 (described above), and L1 = 242 & 177 (shown on the first two images in Fig.30). The latter two had a slightly faster drift, very roughly DL1 ~ +0.6 deg/day, though one of them decelerated to ~+1.5 deg/day (it was last seen on Dec.9). At least one was methane-bright [L1=240, Nov.2, Foster] – this was seen forming on Oct.29 at L1 =233 as a methane-bright eddy within the NEBn wave pattern (Fig.26).

The speeds and latitudes of these red blobs could fit onto a plausible ZDP along with the dark spots seen earlier in the outbreak (Fig.14), which could suggest a ZWP with peak speed typical of the NTC-C, in contrast to the Cassini and pre-outbreak ZWP with peak speed closer to NTC-D. This would fit in with the idea that the jet at cloud-top level 'collapses' to lower speed during the outbreak. However, the speeds of these spots may be slower than the zonal wind speeds.

Discussion

Was this the last NTBs outbreak in the series?

Although the pale 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 occurred after all super-fast NTBs outbreaks since 1970, except that of 1990 – which was the final one in a quinquennial series [ref.7 in box below]. 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. If the jet speed recovers to an intermediate level, another super-fast outbreak will be expected; but if a set of anticyclonic vortices develops with lesser speed, as in 1991, we could expect that state to be stable for some years.

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 (see below) 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 [see box below, esp. ref.7*].

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 [ref.7 in box below]. 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.

Background information on NEB Expansion Events:

Background information and overviews of individual events can be found in the following accounts that we have published: for all from 1987 to 2009: Ref.6; for 2012: Ref.7; for 2015-2017: Ref.8. More detailed information is in the interim reports on this web site.

6. Rogers JH (2019) JBAA 129 (no.1), 13-26. 'Jupiter's North Equatorial Belt and Jet: I. Cyclic expansions and planetary waves.' https://britastro.org/node/9140

7. Rogers JH & Adamoli G (2019) JBAA 129 (no.3), 158-169. 'Jupiter's North Equatorial Belt and Jet: III. The 'great northern upheaval' in 2012.' https://britastro.org/node/15629

8. Rogers JH et al.(2019) EPSC Abstracts Vol. 13, EPSC-DPS2019-302. 'The cyclic expansions of Jupiter's North Equatorial Belt in 2015-2017.' https://www.britastro.org/node/19341

The near-synchronicity of NTBs outbreaks and NEEs from 2012 to 2020 was possible, despite the typical periodicities of 5 years for the NTB and 3 years for the NEB, because there was an additional, incomplete NEE in 2014-15, and the interval between NTBOs shortened from 5 to 4 years:

NEB rifts initiating NEEs: 2012 March, [2014 autumn, abortive], 2016 Oct., 2020 Feb.

NTBs jet outbreaks: 2012 April, 2016 Sep., 2020 Aug.

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 [see box above]. These are usually associated with a new bright 'rift' that is more northerly than usual in the belt, but the subsequent expansion of the dark belt can occur in various ways, either from a distinct origin or more irregularly around the planet. They have been occurring at intervals of 3-5 years since 1988, and the last was in 2017. A new NEE developed in the first half of 2020, and was mostly covered in our Reports nos.3&4 (with illustrations). Here we simply repeat the summary of it from Report no.4 (2020 July 29):

> "The NEB is still impressively disturbed; it looks as though a NEB Expansion Event (NEE) is taking place. As described in Report no.3, this started in mid-February when a bright spot at ~14ºN [adjacent to WSZ] initiated a complex rift system [Figure 7A]. The initial white spot (up to Feb.17) was inconspicuous; by Feb.26-29, multiple tiny bright spots and streaks had appeared p. WSZ; by March 9, the rift system had mostly low contrast but was expanding rapidly. Hi-res images showed that it developed into a very turbulent sector throughout March. Figure 7B shows the development in a set of maps from Feb. to June. In late March, some sectors of NEB p. White Spot Z (WSZ) were inflated northward to 20ºN with this turbulence, and stabilised as expanded sectors of NEB while new ones were appearing further p.
>
> In May and June, the NEE made some progress, but also appeared to be fading in parts. The big rifted region (which spans the full width of the belt) has come round to its original longitude again and appears to be disrupting the expanded sector..... Nevertheless, the maps from late June (Figure 1) and July (Figure 2) show that the belt has expanded to 20ºN at most longitudes."

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., by which time it was embedded in the expanded NEBn. Preceding WSZ, in June, there were several other white ovals which appeared to be fairly stable AWOs, all with DL2 in the range ~0 to -3 deg/mth. One (WS-a) had persisted since 2017, but others had appeared more recently. As of mid-June there are three pairs of them, designated as follows: WSZ & WS-n; WS-a & WS-o; & two new ones. But WS-o had shrunk to a tiny spot, embedded in a large dark brown patch of expanded NEB. Unusual large cyclonic pale ovals had also developed along this sector, and were well shown in some JunoCam maps.

WSZ had been rapidly prograding as usual during solar conjunction, but then slowed down, and maintained DL2 = -4.8 from late April to Sep. Other AWOs (inc. WS-a, n, o) were almost stationary in L2 (**Table 1**).

WSZ is shown in Figures 12, 15, 16, 23, 24, 25, 26. It was still a white oval, weakly methane-bright, embedded in the expanded NEBn, when NTBs plume 1 passed it on Sep.8. 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. JunoCam got a close-up image of the former WS-n at PJ28. Another such spot was recorded mainly as a small anticyclonic dark brown spot ['ADS' on charts, at L2 = 80 --> 70], and was seen close-up by JunoCam at PJ29. Both were well-formed anticyclonic vortices.

However, WSZ and possibly others were reappearing in December (see below), after the disturbances quietened down. Although WSZ decelerated briefly when plume 1 passed, its mean speed thereafter seems to have been the same as it was during the summer.

WSZ and perhaps other AWOs thus recapitulated the disappearance and reappearance that they showed during all 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.

There were small dark spots in the NEB at 15-16°N, i.e. barges or precursors thereof, but mostly short-lived as the belt was so disturbed. Like the AWOs, they had typical NTropC drifts close to System 2 (**Table 1**).

Along what remained of the usual NEBn edge, at 17-18°N, there were various dark projections and white bays, moving under the influence of the retrograde jet at 17°N, and thus distinct from the bays accommodating AWOs. Their DL2 ranged from +5 to +17 deg/mth. They were short-lived (only one projection lasted more than 14 days). They apparently included waves along the jet, which may have been suffering interference with stationary (NTropC) features. Some of these features were mentioned in our Reports no.3 (waves with DL2 = +6 in Feb., +11 in March) and no.4 (bays, DL2 = +9 (±4), April-June). We also tracked a single white spot with the peak jet speed (DL2 = +25, 17.6°N, July 29 – Aug.20).

The ZDP for all these features is in Fig.14. Curiously, all the points lie to the right of the spacecraft ZWP (i.e. the spots are all moving faster eastward); normally this would only be expected for features with DL2>0.

The methane-dark patch (MDP) in NEB

During some previous NEB expansion events, notably in 2000-01 and 2015-17, a prominent 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 the shrunken WS-o. These waves were short-lived, only appearing in mid-May and fading in mid-June as NEB rifts began to disrupt this sector. (See Report no.4 for more details.)

Separately, in July & August, observers noticed a very methane-dark patch (MDP) on the NEB (see Report no.5) It had appeared at the end of June, being first visible in CH4 images on June 27 (B. Adcock, towards the limb), July 5 (M. Delcroix), & July 7 (R. Smith, near the limb). A hi-res RGB image on July 7 (F.&G. Carvalho) showed no special feature to explain the MDP's appearance. The MDP was more conspicuous when near the limb, i.e. it showed more than the usual limb-darkening, consistent with it being a clearing in the upper hazes.

The MDP is shown in Figs.16, 17, 23, 24, 26. , including several hi-res RGB images of its location.

It was conspicuous in CH4 images on July 22-30 (Report no.5, Fig.2 & Map 4). It coincided with a deeply brown patch at L3 ~ ~ 240 [L2 ~ 160]. Sometimes a tiny spot resembling the shrunken AWOs (WS-a, -n, -o) was detected within it, and there was a dark barge on its f. edge in July & Aug., which was also methane-dark. (Some time between August 3 and 8, a brilliant white point erupted on the S edge of this barge. Outbreaks adjacent to barges have been observed before, and this one occurred as an elaborate rift system was moving through that region. Another such eruption on the S edge of the barge was visible on Aug.18-19.)

The MDP was similar to the earlier large methane-dark wave no.2 over a prominent brown patch around tiny WS-o in 2020 June. But the MDP itself was more extended and did not correspond to any distinct cloud pattern, although it often corresponded to a darker brown area of NEB. Although it appeared as a diffuse dark patch in lo-res images, in hi-res images it often appeared irregular and streaky. It was well documented at all wavelengths in the Hubble OPAL images on Aug.25, which confirmed a grey anticyclonic vortex within it (also in C. Go's images on Aug.26: Fig.16); extraordinarily, this vortex was deeply methane-dark, while the more diffuse methane-dark, UV-bright patch covered it and the adjacent dark brown area.

The MDP was still very prominent up to early Oct. NTBs plume 1 passed it on Sep.10; plume 2 suddenly faded as it passed the MDP on Sep.25; and plume 1 passed it again on Oct.8, just as that plume also began to fade.

The drift of the MDP is plotted in Fig.33. In July & Aug. it was stationary at L2~159 (L3 ~ 239-->248) (~30° p. WSZ), but from mid-Sep. it developed positive drift – surprising as it was then no longer fixed in relation to the adjacent visible NEB features. In Sep. it passed across the dark barge that had been on its f. edge, and by Oct.9 & 14 the MDP was well clear of the barge and overlapped the remnant of WSZ (Figs.24 & 26) – and the MDP was starting to fade. On Oct.22 & 29 Fig.26), the MDP seemed to be disappearing -- amid vigorous motions associated with bright new rifts in the NEB, NEBn, and NTropZ [see caption to these fine images in Fig.26]. It was no longer visible in CH4 images on Nov.5 & 7 (Foster), although the barge on its f. side was still methane-dark.

The MDP is difficult to explain. It resembled the methane-dark waves that appeared around most of the NEB during some previous NEB expansion events, notably in 2000-01 and 2015-17 – and particularly the large reddish-brown anticyclonic bulges that have sometime been especially methane-dark within them, including wave no.2 in 2020 June. We assume that, like them, it represented a warm, clear patch in the atmosphere above the visible clouds. But this intensely methane-dark patch was uniquely isolated. For much of its life it contained a small anticyclonic vortex, and lay adjacent to a cyclonic dark barge, although it did not appear to be an organised circulation. But from mid-Sep. onwards it drifted 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 when it encountered the remnant of WSZ, just as that region was particularly disturbed by bright rifts and swirls.

NEB Rifts

An expanding rift system affected the NEB throughout the apparition, and initiated the NEE as mentioned above (Reports no.3&4). From Report no.4 (2020 July 29):

> "As described in Report no.3, this started in mid-February when a bright spot at ~14ºN [adjacent to WSZ] initiated a complex rift system.... The large rift system has continued to expand, its p. end having DL2 ~ -130 deg/mth (-4.3 deg/day), and the f. end DL2 ~ -80 deg/mth (-2.7 deg/day). Individual white spots have been tracked at both these speeds and a range in between."

From March onwards, there were extensive bands of rifts covering ~100° in March, ~150° in April-May, and ≥180° in June-July. Their drifts have been assessed using JUPOS charts with different longitude systems and different latitude ranges; a colour coded JUPOS chart shows the latitude dependence of the drift rates most clearly **(Supplement B)**. These charts suggest that the drifts of most of these rifts, both individual white spots and broader bands, were DL2 ~ -2.6 to -4.1 deg/day (mean -3.2 ±0.5 deg/day), i.e. typical for rift systems. But they suggest that the f. end of the whole rift system had DL2 ~ -2.0 deg/day in March, representing the progression of the initial disturbance from near WSZ in Feb., and then accelerating gradually to reach ~ -3 deg/day in June and -4 deg/day in August. From late August, several additional slow-moving white spots generated on the northern edge of the main rift system were observed, lagging behind it, with DL2 ~-1.6 (±0.2) deg/day (presumably in the middle of the expanded NEB). On the other hand, in the southern part of the NEB, some short-lived white spots were recorded with DL2 ~ -5.4 deg/day.

The NEB from July to Dec.

Figure 15 shows maps of the NEB from July to Nov., continuing the series in Report no.4.

The NEB was fully expanded to 20.5°N from late July onwards, apart from a sector from L2 ~ 0-60 (L3 ~ 80-140) where the northern extension remained lighter until overtaken by a large rifted sector in early Sep. Large rifted sectors were common in these months (see below), though the turbulence was quite small-scale and low-contrast, without large bright rifts.

In Oct., with these turbulent sectors as well as rifting of the NEBn edge due to the NTBs jet outbreak (see above), 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. Methane-bright 'NTropZs clouds' from the NTBs outbreak occasionally still intruded as rifts into the NEBn (as described in Sep., & also notably on Oct.22 – Fig.26): one was imaged on Dec.6, involved with an AWO at L2 ~71. NEB rifts were also reappearing: rifting was seen in southern NEB p. the barge at L2=218 on Dec.9 & 11, and a bright white spot in mid-NEB on Dec.20.

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. Three of the AWOs may be WSZ, WS-a and WS-o reappearing after their obscurity, and there seem to be several new ones as well.

Figure legends

Figure 1. ZDP from JUPOS data from the NNTZ to the mid-NEB, compared with the ZWP 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. Colours and intensities are uncalibrated and in some maps have been adjusted to give more consistent overall balance. (Polar darkening was removed after May.)

Figure 3. Map from Sep.15; images & map by Andy Casely, giving the best overview of the NTBs outbreak. (Another map from various images on the same date, by Rob Bullen, was posted in our Juno PJ29 report & is in a forthcoming issue of the *Journal of the BAA*.)

Figure 4. Map from Oct.20-22 (by Shinji Mizumoto).

Figure 5. Map from Nov.6-9 (by Rob Bullen; previously posted in our PJ30 report).

Figure 6. Map from Dec.25-27 (Shinji Mizumoto; previously posted in our PJ31 report).

Figure 7. (A) Zonal drift profile for the N5 domain, including some data from 2019 for the large AWO, compared with the ZWP from Cassini. (B) Drift of the large N5 AWO in L2 and in latitude.

Figure 8. Closeup view of the large N5 AWO from JunoCam at PJ29 (from our PJ29 report).

Figure 9(a,b,c). Images of the high northern latitudes in Aug.& Sep., showing motions around the large N5 AWO (indicated by a white arrowhead). Other persistent, tracked white spots are indicated with colour-coded arrows.

Figure 10. (A) Zonal drift profile for the N4 domain, compared with the ZWP from Cassini.
(B) Drift of an N4 AWO in L2 and in latitude.

Figure 11. Maps covering the N2 domain from July to Nov.

Figure 12. Excerpts from maps of the N hemisphere in October showing the merger of NN-WS-6 & 7, as well as waves along the NEBn after the NTBs outbreak, and the remnant of White Spot Z. (By Shinji Mizumoto). (For original images see Fig.26.)

Figure 13. ZDP for the N2 domain.

Figure 14. ZDP from JUPOS data from the NNTZ to the mid-NEB, annotated. The pale blue curve is the ZWP from Cassini [Porco et al., 2003]. The pale mauve curves indicate possible ZDPs which diverge from the Cassini ZWP. (Annotated version of Fig.1.)

Figure 15. Maps covering the N. Temperate & Tropical domains from July to Nov.

The following figures show large collections of images and maps from Aug. to Oct., covering both the NTBs outbreak in all its aspects, and the effects in the NEBn, and the methane-dark patch (MDP).

Figure 16. Images from Aug.25-29, in RGB & CH4, including the NEB sector with WSZ and the MDP. Compare the HST map on Aug.25 (Fig.15). Plus a CH4 image from Sep.10 showing NTBO-1 passing the NEB methane-dark patch (MDP).

Figure 17. RGB & CH4 images from Sep.15&20, showing the NTBs jet outbreak, and the MDP in the NEB. *Top row:* RGB images on Sep.15, by three observers, showing NTBO-1; its wake spans the disk. *Middle row:* matching CH4 images. *Bottom row:* CH4 images on Sep.20. Compare RGB images in Fig.20.

Figure 18. Images on Sep.23, in RGB & CH4; the RGB images are one rotation apart and can be blinked to show the winds. Notable features are indicated, esp. those that are methane-bright.

Figure 19. Map from Sep.15 (copied from Fig.3), showing the key features of the NTBs outbreak. The three plumes are labelled NTBO-1,2,3. Each has a 'wake' or 'tail' of length proportional to its age. The wake of NTBO-2 has three dark spots; that of NTBO-1 has more but on this date they are in the irregular phase of their cycle (see text). Note that NTropZs white clouds are invading the NEBn in a wave-like pattern around the anticyclonic features such as WSZ and the MDP.

Figure 20. Hi-res images showing details of the NTBs outbreak (Sep.18-30).
Left & middle columns: Pairs of images showing rapid motions; the top two pairs also show the MDP in the NEB (compare Fig.17 for CH4 images & Fig.24 for a map). The bottom two pairs show the demise of NTBO-3.
Right column: Image showing NTBO-1, & the GRS & oval BA.

Figure 21. Images on Sep.14, showing NTBO-2, with the very dark spot developing at the f. end of its wake, which is wrapped in methane-bright streaks that dominate it when seen near the limb. (The maps in Fig.22 show the dark spot in the context of the growing NTBO-2 wake, and higher-resolution images are in Fig.18.)

Figure 22. Maps of NTBO-2 and its wake (by Shinji Mizumoto), Sep.15-24, plotted in L1. (Also see Figs. 18 & 21.) They show the wake expanding from 3 to 4 dark spots (dark blue lines), aligned with wave structure on the NEBn; the westernmost dark spot is an anticyclonic ring; bright spots and streaks extend Nf. from it (dark green lines).

Figure 23. Maps by Mizumoto (with scales at the top in L1) have been realigned on the NEBn features. They show the main series of NEBn circulations including WSZ and the MDP, and NTBO-1 passing them; waves in NEBn induced by the passage of the wake of NTBO-1; and the MDP, including its dissociation from the tropospheric features when it began retrograding. Also shows the demise of NTBO-3.

Figure 24. Images from Sep.20-29, including CH4 images, including the demise of NTBO-2, and the MDP. *Top left:* Pair of maps from A. Casely on Sep.20, allowing precise registration of visible & CH4 maps. *Bottom left:* Drift of the MDP in L2.

Figure 25. Maps (Oct.2-14, by Shinji Mizumoto) showing the demise of the NTBO-1 plume (small red arrow at left) as it catches up with the wake of NTBO-3. Two dark spots in the wake of NTBO-2 are anticyclonic, methane-bright rings (red arrowheads). Note a small methane-bright white spot (white arrowhead) f. the NTBO-2 wake on Oct.2&3, ~17° p. the NTBO-1 plume, and the same or another on Oct.7&9 as the plume starts to weaken. Original images are in Fig.26 & the map series is continued in Fig.12.

Figure 26. Images in RGB & CH4 (Oct.1-14), showing the MDP & WSZ & demise of NTBO plume 1, which started fading as it passed WSZ & the MDP. (Also see Mizumoto's maps from these & subsequent images: Fig.25 & Fig.12.). Also note methane-bright anticyclonic rings in NTropZ as described above. The MDP is due S of NN-WS-6&7, but gradually retrograding relative to them. The last 2 images, Oct.22 & 29 (by Foster), are spectacular, showing vigorous activity: NN-WS-6&7 merging; bright new rifts in the NEB, another bright intrusion from NTropZs into NEBn, perturbing the remnant of WSZ; & origin of a prograding red blob in NTropZ from an eddy in the NTropZ/NEBn waves.

Figure 27. Chart of longitudes vs time for the spots in the NTBs jet outbreak, by Shinji Mizumoto. (The equivalent JUPOS chart is in **Supplement B**.)

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

Figure 29. Some v-hi-res images from Oct.21 to Nov.9, when everything from the NTB to the EB was reddish, giving the appearance of a 'great northern disturbance'. The images of Nov.7 & 9 cover the PJ30 track, including the red blob in NTropZ that was imaged by JunoCam.

Figure 30. Hi-res images in Nov. Features include:
(A) A wavetrain on NTBn, wavelength 8-10°; two prominent peaks are marked with green spots of different shades. A train of 5 very dark spots in the NNTBs jet is approaching (the 1st & 5th are numbered in red). (They are shown in the JUPOS chart: DL2 = -80, decelerating around Nov.17 as they come alongside the NTBn waves). The first spot appears to interact with the prominent NTBn projection, but continues past it with no evidence for recirculation. The NTropZ is streaky and slightly reddish, with red blobs prograding in it [Nov.4,8,13]. AWOs are reappearing in the NEBn.
(B) The small bright NTZ AWO, at the f. end of the rifted sector of NTB (which is rapidly variable). A very dark streak of NTB(N) developing f. it. No N2 jet spots reach the AWO, but a pair of tiny dark spots in NNTBs & NTZ prograde up to it at DL2 ~ -1 deg/day (Nov.3 & 6).

Figure 31. Multispectral image sets: (A) Manos Kardasis (Oct.24); (B) Trevor Barry (Nov.6); (C) Antonio Cidadão (Nov.9).

Figure 32. Set of RGB & CH4 images all around the planet in Dec., with arrows indicating NEBn AWOs (red) & barges (black).