# A Survey of Small-Scale Waves and Wave-Like Phenomena in Jupiter's Atmosphere Detected by JunoCam

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#### Abstract

In the first 20 orbits of the Juno spacecraft around Jupiter, we have identified a variety of wave-like features in images made by its public-outreach camera, JunoCam. Because of Juno's unprecedented and repeated proximity to Jupiter's cloud tops during its close approaches, JunoCam has detected more wave structures than any previous surveys. Most of the waves appear in long wave packets, oriented east-west and populated by narrow wave crests. Spacing between crests were measured as small as  $^{30}$  km, shorter than any previously measured. Some waves are associated with atmospheric features, but others are not ostensibly associated with any visible cloud phenomena and thus may be generated by dynamical forcing below the visible cloud tops. Some waves also appear to be converging and others appear to be overlapping, possibly at different atmospheric levels. Another type of wave has a series of fronts that appear to be radiating outward from the center of a cyclone. Most of these waves appear within 5° of latitude from the equator, but we have detected waves covering planetocentric latitudes between 20°S and 45°N. The great majority of the waves appear in regions associated with prograde motions of the mean zonal flow. Juno was unable to measure the velocity of wave features to diagnose the wave types due to its close and rapid flybys. However, both by our

own upper limits on wave motions and by analogy with previous measurements, we expect that the waves JunoCam detected near the equator are inertia-gravity waves.

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### 43 Abstract

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45 In the first 20 orbits of the Juno spacecraft around Jupiter, we have identified a variety of wave-46 like features in images made by its public-outreach camera, JunoCam. Because of Juno's 47 unprecedented and repeated proximity to Jupiter's cloud tops during its close approaches, 48 JunoCam has detected more wave structures than any previous surveys. Most of the waves 49 appear in long wave packets, oriented east-west and populated by narrow wave crests. Spacing 50 between crests were measured as small as ~30 km, shorter than any previously measured. Some 51 waves are associated with atmospheric features, but others are not ostensibly associated with any 52 visible cloud phenomena and thus may be generated by dynamical forcing below the visible 53 cloud tops. Some waves also appear to be converging and others appear to be overlapping, 54 possibly at different atmospheric levels. Another type of wave has a series of fronts that appear 55 to be radiating outward from the center of a cyclone. Most of these waves appear within  $5^{\circ}$  of 56 latitude from the equator, but we have detected waves covering planetocentric latitudes between 57 The great majority of the waves appear in regions associated with prograde  $20^{\circ}$ S and  $45^{\circ}$ N. 58 motions of the mean zonal flow. Juno was unable to measure the velocity of wave features to diagnose the wave types due to its close and rapid flybys. However, both by our own upper 59 60 limits on wave motions and by analogy with previous measurements, we expect that the waves 61 JunoCam detected near the equator are inertia-gravity waves.

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63 Plain Language Summary

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65 The JunoCam camera aboard NASA's Juno mission to Jupiter has detected wave-like features over its 20 orbits that are smaller and more numerous than ever seen before in Jupiter's 66 atmosphere. Most of the waves are in elongated wave packets, spread out in an east-west 67 68 direction, with wave crests that are often perpendicular to the packet orientation; others follow 69 curved paths. The space between wave crests can be as short as 30 kilometers. Some waves can 70 appear close to other atmospheric features in Jupiter, while others seem to have no relationship 71 with anything nearby. In one case, wave crests appear to be radiating outward from the center of 72 a cyclone. Most waves are expected to be atmospheric gravity waves - vertical ripples that form 73 in the atmosphere above something that disturbs air flow, such as a thunderstorm updraft, 74 perturbations of flow around other features, or from some disturbance from below that JunoCam 75 does not detect. JunoCam is uniquely qualified to make such discoveries, with its wide-angle field of view that delivers sweeping vistas of the giant planet's atmosphere as the spacecraft 76 77 swoops within about 2,100 miles (3,400 kilometers) of Jupiter's cloud tops during each science 78 pass. 79

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### 83 1. Introduction

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85 The Juno mission's JunoCam instrument (Hansen et al. 2017), conceived as a public-86 outreach camera, has provided a surprising wealth of scientific results. These include the first 87 close-up examination of Jupiter's polar regions (Orton et al. 2017), in particular the unexpected 88 presence and properties of constellations of cyclonic vortices around each pole (Adriani et al. 89 2018a, Tabataba-Vakili et al. 2019). JunoCam's proximity to Jupiter's cloud tops has also 90 provided high-resolution details of Jupiter's Great Red Spot and its environment (Sánchez-91 Lavega *et al.* 2018). These studies have been enabled by JunoCam's wide field of view  $(58^{\circ})$ 92 and the close proximity of the spacecraft to the clouds being imaged, with target distances as 93 small as 3,500 km near closest approaches ("perijoves"), yielding a horizontal pixel-to-pixel 94 spacing as good as 3 km.

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96 We have used JunoCam's coverage over a wide range of latitudes, coupled with its high 97 spatial resolving power, to examine all of our images for various phenomena in Jupiter's clouds. 98 Small-scale waves, with wavelengths (distances between wave crests) less than ~300 km, were 99 first detected in 1979 by Voyager (Hunt and Muller, 1979) and have been detected by Galileo 100 (e.g. Bosak & Ingersoll, 2002) and New Horizons (e.g. Reuter et al., 2007) since then, as well as 101 by the near-infrared JIRAM instrument on Juno (Adriani et al., 2018; Fletcher et al. 2018). 102 Larger waves, with scales of 1200 km or greater, have since also been detected from the Earth 103 using Hubble Space Telescope (HST) and ground-based imaging (Simon et al., 2018). A 104 summary of observations of these waves is given in Table 1, which includes and updates similar 105 information in Table 1 of Simon et al. (2015) and various tables in Simon et al. (2018). Table 1 106 includes a JunoCam wave feature examined by Sánchez-Lavega et al. (2018) that we will also consider in this report. No waves were detected by the Cassini mission, most likely because 107 108 Cassini was too far from Jupiter for adequate spatial resolution, but other reasons as possible. 109 Virtually none were seen by Galileo imaging despite several close, although spatially limited, 110 passes. The planet-encircling New Horizons waves were a surprise, as were the larger waves 111 observed by HST and ground-based imaging for the past four years, which Cassini would have 112 detected. During the Cassini epoch, there may not have been sufficient contrast to detect waves or waves were simply not propagating because of conditions unknown. 113

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Below, we describe how the measurements are made, followed by a survey of the different types of atmospheric waves we have detected - along with any analogous wave formations in the Earth's atmosphere. We then discuss quantitative properties of the waves and conclude with an analysis and discussion section.

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### 121 2. Description of the measurements

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JunoCam is a CCD-based camera, spanning a 58° field of view. The instrument is a "push-frame" imager, taking advantage of Juno's 2 RPM spin to sweep its 58° swath to build spatial and spectral coverage without involving a shuttering mechanism. Thus, sequential images are acquired in broadband blue, green and red filters plus a narrow-band filter centered

127 on a 889-nm methane absorption band. Time-delayed integration of multiple pixel rows builds 128 up the signal-to-noise ratio. Hansen et al. (2017) provide details of the instrument and its modes 129 of operation. Sequential images are typically rendered in red-green-blue ("RGB") composites, 130 with the "methane filter" acquired and rendered separately, and the RGB images cover all latitudes on nearly all perijoves. The spatial resolution varies with the distance to the planet, 131 132 which changes with each orbit: successive perijoves move approximately one degree of latitude 133 north. For all the waves we discuss in this report, the spatial resolution is much finer than the 134 distances reported in each case.

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136 In order to determine properties of the features, each image was transformed into a 137 cylindrical cartesian map in longitude and latitude. This was done independently of the standard 138 coordinate-transformation approach using the SPICE system (Acton 1996), as image timing, 139 orientation in the spacecraft coordinate system and optics distortion were still being determined. 140 We used limb fitting to constrain these properties, as the limb appears in all of our images. 141 Current SPICE data show good agreement with these maps, with the limb-fitting approach 142 showing an uncertainty better than 2° in the position of the south pole, as reported by Tabataba-143 Vakili et al. (2019). Further details of this mapping process are provided by Adriani et al. (2018: 144 see their Supplementary Information) and by Tabataba-Vakili et al. (2019). All JunoCam 145 images are publicly available on the Mission Juno web site:

146 https://www.missionjuno.swri.edu/junocam/processing.

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Figure 1 shows an example of a full JunoCam image, rendered in a cylindrically mapped format, together with an excerpt ("crop") of the image in which we identify wave-like features.

150 The mapped versions were adjusted to compensate for the variation of illumination across the 151 field. We found that a second-order power-law enhancement of color composites allowed wave 152 features to be identified more readily. For the images shown below, as well as in the 153 Supplemental Information, we further stretched each red, green and blue color independently for ease of identification by the reader. We also applied unsharp-mask sharpening in a few cases to 154 155 make faint waves appear more prominently. Several coauthors independently searched manually through all of the JunoCam images in order to identify wave-like features that were candidates 156 157 for this study. For detailed quantitative measurements, we used additional high-pass filtering to 158 isolate fine-scale features. Our quantitative measurements are based on maps of the images 159 rendered with 180 pixels per degree of latitude and longitude, together with high-pass filtering. 160 We did not find identifiable wave features in any methane-band images. As a result, our 161 discussion will be limited to enhanced RGB-composite images. We did not see any consistent 162 differences in the contrast of wave features between the colors in images, which do not have any 163 radiometric calibration.

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### 165 3. Results

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167 3.1 Overview.

We limited the search for and characterization of waves to observations between perijoves 1 and 20 (2016 August 27 – 2019 May 29). Hereafter we will abbreviate "perijove" as "PJ". During PJ2 (2016 October 19), no close-up images were made of Jupiter's atmosphere as

172 the result of a spacecraft "safing" event immediately before close approach. During PJ19 (2019 173 April 6), JunoCam only took distant images of Jupiter, as a result of an unusual orientation of the 174 spacecraft for most of that perijove in order to enable scanning in longitude by Juno's 175 Microwave Radiometer (MWR) instrument. The Supplemental Information to this report 176 documents and illustrates all of the images in which we identified wave-like features with more than two wave fronts, together with a visual aid to identify the waves. In this report we select 177 178 particular images that provide examples of the wide variety of waves and wave-like phenomena 179 and their properties. The reader is free to observe all the images that are available in various 180 processed forms on the Mission Juno web site in order to verify or refute our selections, as well 181 as to identify potential additional candidates.

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3.2 Types of wave-like features.

Our survey of JunoCam images has revealed a surprising variety of features with wavelike morphologies. In order to be inclusive in our inventory, we include here (and in the Supplemental Information file) features with any regularly repeated patterns that are three or more in number. The survey below includes many features that have not been discussed previously in the context of atmospheric waves in Jupiter. They are presented in terms of differences in visual morphology, without implication that this differentiation arises from the associated responsible dynamics.

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3.2.1 Long wave packets with short, dark wave fronts represent 79% of the types of
waves in our inventory, especially in the Equatorial Zone (EZ) that were also detected in
previous studies, particularly from Voyager imaging (Table 1).

196 3.2.1.1. Orthogonal wave crests. Figure 2 shows two examples of these waves in which 197 the wave front is more-or-less orthogonal to the direction of the wave packet. The morphology 198 of the waves shown in Fig. 2 is most similar to those waves described in the articles cited in 199 Table 1, although they are an order of magnitude smaller. They are most commonly referred to 200 as mesoscale waves, by analogy to their appearance in the Earth's atmosphere. Our search 201 through JunoCam images (see the images in the Supplemental Information file) did not appear to 202 sample any of the longer-wavelength (~1200-1900 km) packets detected by previous studies 203 (Table 1), most likely as a result of the limited area over which JunoCam images can cover.

204 3.2.1.2. "Tilted" wave crests. Even more commonly, the detected packets have wave 205 fronts that are not oriented orthogonally to the wavefront direction. Several examples of these 206 "tilted" wave fronts are shown in Figure 3. Simon et al. (2015) stated that this is consistent with 207 an interpretation of the waves as baroclinic instabilities that tilt northward and westward with 208 altitude, as noted on a theoretical basis by Holton (1992) and by observations of waves in the 209 Earth's atmosphere (e.g. Blackmon et al. 1984). This implies that we are sensing the upper 210 levels of such waves. Several images reveal the presence of large numbers of similar waves, as shown in the various panels of Figure 4. The waves are most often short with wave packets 211 212 oriented east-west, although there are many wave packets not ostensibly oriented in any preferred direction (Fig. 4D). Some clearly cross one another, implying that the sources of their 213 214 origin are not uniform. Simon et al. (2015b) argue that, if the waves are baroclinic instabilities, 215 then their meridional extent depends on the Rossby radius of deformation, which they estimate as between 500 and 1400 km near the equator, which is where most of our detections of these 216 217 waves lie. The Rossby radius of deformation is also where energy is transferred from smallscale turbulence to zonal winds (see Salyk et al. 2006, Young and Read 2017). Since the mean of both meridional extent (~250 km on average) and wavelength (distance between wave crests, ~170 km), are much shorter than the Rossby deformation radius, it is logical to assume that they are formed by and interact with small-scale turbulence, and thereby propagate the waves in all directions. This is consistent with our observation that few, if any, of these waves are clearly associated with other atmospheric features.

224 3.2.1.3. Curved wave packets. Sometimes the short wavefronts are aligned in wave 225 packets that themselves appear to be curved, are associated with larger features, and are not 226 located in the EZ. Figure 5 shows two examples. Figure 5A shows the short wave-packets 227 associated with the curved northern boundary of the Great Red Spot (GRS) near 15.8°S, 228 described by Sánchez-Lavega et al. (2018). This is the first of two cases in which multiple 229 images of waves were made, the result of intensive targeting of the GRS by Juno at PJ7. 230 Sánchez-Lavega et al. (2018) estimated a phase speed for the wave of 45±20 m/s relative to the 231 very rapid local flow and determined that they were consistent with internal gravity waves, given 232 estimates for the Richardson number for that part of the atmosphere that were based on the 233 vertical wind shear deduced from temperature maps of the region (Fletcher et al. 2010). Two 234 other examples of such wave packets imaged at PJ15 are shown. Figure 5B shows one on the 235 south edge of a bright anticyclonic eddy in the NEB near 15.8°N, and Figure 5C shows one on 236 the south edge of a dark cyclonic circulation in the SEB near 17.3°S. Just as for the wave trains 237 in the northern edge of the GRS (Fig. 5A), these two wave packets are located on or near the 238 peaks of retrograde (westward) flows that are probably accelerated in these locations because of 239 the circulation.

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241 Another curved wavefront example is shown in Figure 5D: a dark, lobate feature with 242 short wave crests that are most clearly detectable along its periphery. This feature is located in 243 the chaotic region to the west of the GRS (see Fig. 6 for context). Interestingly, the entire chaotic 244 region covers a much larger area to the northwest and west of the GRS, but these waves only 245 appear in the region shown in Figure 5D. The dark part of this lobate feature appears only 246 slightly brighter in 5-µm radiance than its surroundings using contemporaneous NASA Infrared 247 Telescope Facility (IRTF) observations. Thus, it is likely to be a region of very moderate dry 248 downwelling that only partially clears out particles in cloud layers. Although the series of wave 249 crests appears to line the sharply curved periphery of the dark feature, the crests are more likely 250 to be roughly parallel streaks in a haze that overlies the entire region, with their visibility over 251 the darker regions of this image strongly subdued. This interpretation is reinforced by studies of 252 the winds from Juno-supporting observations by HST (Wong et al. 2020). Figure 6 shows the 253 results of tracking winds in this region. Relative to the mean zonal winds, the residual winds 254 shown in this figure appear to be flowing up toward the northwest along the dark lobe with 255 speeds of 65±17 m/s. Thus, the waves appearing in Fig. 5D are aligned with the local retrograde 256 flow in high-shear regions. In this respect, they are similar to the curved wave packets described 257 in the preceding paragraph.

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3.2.2. Short wave packets with wide wave fronts, shown in Figures 7 and 8, are also detected in our survey. In the Earth's atmosphere, such waves are often associated with thunderstorms producing a brief impulse period with radiating waves. Other curved features situated adjacent to each other are shown in the Supplemental Information file, which are shorter and difficult to distinguish from different albedo clouds that are stretched along streamlines (see

Figs PJ05\_108, PJ14\_25a, PJ14\_25b, and PJ14\_25c.) Somewhat similar features were detected in a Voyager image of "spiral" waves to the west of a dark brown cyclonic feature commonly called a 'barge' (Simon et al. 2018). Although there is some overlap between these waves and those described in section 3.2.1 in a spectrum of the length-to-width ratio of waves, these waves appear to occupy a generally distinct locus in plot of the length vs width of waves (see Fig. SI3-2 in the Supplemental Information).

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271 Other waves are even more distinct. The arrows in Figure 8 show extremely long, closely 272 spaced parallel lines that could be waves. Just as for the wave packets illustrated in Figure 7, 273 both are curved. The pair of lines indicated in the upper part of the figure appear to have no 274 visual association with any nearby feature, although they are situated between the bright 275 (possibly upwelling) spot to the north and the darker region to its south. This darker region is an 276 extension (sometimes called a "festoon") of a blue-gray region along the southern boundary of the North Equatorial Belt associated with bright 5-µm radiances, called a "5-µm hot spot". The 277 narrow dark lines indicated in the bottom of Figure 8 are close to the southern boundary of the 278 279 dark festoon. Although they could simply be long streaks associated with streamlines of flow 280 along the festoon, they appear to be particularly narrow and well defined with sharp edges, particularly at their eastern extents. This differentiates them particularly from far less distinct 281 282 streaks along the northern boundary of the festoon. They are also accompanied by shorter crests 283 that are aligned perpendicular to the length of the lines. These orthogonal waves are not 284 explicitly indicated in Figure 8 by white grids in order to make the extent of the long lines 285 clearer, but they are illustrated in the same region shown in the Supplemental Information file as 286 Figure 20\_34a. Orton et al. (2017) detected linear features in the north polar region, but they 287 were associated with the edge of a well-defined haze region whose boundary could be traced 288 using the 890-nm "methane" JunoCam filter. JunoCam did not take images of the features 289 indicated in Figure 8 with the 890-nm filter, and they are below the spatial-resolution limits of 290 Earth-based imaging in similar filters. The closest morphological analogies in the Earth's 291 atmosphere might be roll clouds, formerly known as cumulus cloud streets, e.g. Yang and Geerts 292 (2014), which are most often detached from but associated with a cumulonimbus base. These 293 are now classified as volutus clouds (https://cloudatlas.wmo.int/clouds-species-volutus.html) by 294 the International Cloud Atlas. Another possibility is that they represent a version of transverse 295 cirrus clouds, identified in upper-level tropospheric structures in the Earth's atmosphere (Knox et 296 al.2010).

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298 3.2.3. Wave packets with bright features appear different from the waves indicated up to 299 this point (Figs. 2-7), which are recognizable by their dark or alternating dark-to-light crests. 300 JunoCam has imaged many waves and wave-like features that are manifested as regular, repeated 301 patterns of bright clouds, visually similar to terrestrial water-based clouds. We presume that 302 differences between darker and brighter wave crests could be the composition of the material 303 affected. Possibly the waves themselves induce condensation of bright white clouds along their 304 crests, similar to what was seen in the mid-NEB on much larger scales by Fletcher et al. (2017). 305 This might imply differences in altitude, e.g. perturbations of an upper-tropospheric haze layer 306 near 200-300 mbar (e.g. Sromovsky et al., 2017, and Braude et al. 2020) versus those of a 307 condensate cloud, such as a layer of "cirrus" NH<sub>3</sub> ice particles near the 600-mbar condensation 308 level. This corresponds to an altitude difference near the equator of roughly 15-20 km, an 309 interval on the order of or less than an atmospheric scale height.

311 Figure 9 shows a variety of examples of regular spacings between light-colored clouds 312 detected by JunoCam. We lack the means to determine whether dark regions adjacent to lighter 313 ones simply represent lower-albedo regions that are relatively cloudless or actual shadows of the 314 brighter clouds. One likely exception to this are the clouds associated with the wave packet in 315 the upper-left area of Figure 9A, which appear similar to terrestrial cirrocumulus clouds that 316 have shadows associated with them. (If all of the dark area to the right of the largest dark region 317 is a shadow, then the height of the largest cloud relative to the region around the cloud is on the 318 order of 10 km.) We repeat the caveat of Simon et al. (2015) that such dark features may not be 319 shadows but local regions of aerosol clearing "as atmosphere parcels rise and ices condense out 320 to make the wave crests". The clouds in the other panels are often arranged in a straight line or a 321 segmented straight line with cirrus-like wisps trailing away from them. Figure 10 shows other 322 regular patterns of bright clouds that are associated with narrower white features. The narrow 323 meridional extent of these clouds (~150 km or less) is potentially the result of a very 324 meridionally constrained flow. We note that both are curved and could be associated with 325 constraining wind flows.

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327 Figure 11 shows four instances of very bright, discrete clouds forming regular, extended 328 patterns. These clouds extend to higher altitudes than their surroundings, as evidenced by 329 shadows that often accompany them. Individual clouds such as these appear in various locations 330 elsewhere in the planet, and we will describe and analyze them as a class in a separate report. 331 We include this subset of them in our description of a distinct type of wave. Figure 11A shows a 332 close up of such clouds, an expanded portion of Fig. PJ04\_103b in the Supplemental Information 333 file. A wave packet can be seen that appears to be controlling small, bright cloud features. 334 These are located in a bright patch that is part of a complex system of upwelling disturbances in 335 the North Equatorial Belt (NEB), also known as 'rifts'. Figure 11B shows a weak anticyclonic 336 feature, in the center of which is a central bright cloud, accompanied to its southeast through 337 southwest by short linear arrays of similar bright clouds. Two are shown with white grids that 338 indicate individual cloud features that are resolved. Figures 11C and 11D also show individual 339 clouds that comprise a wave packet, similar to the linear packet shown in Figure 11A. In Figure 340 11C, the clouds appear like balls or small smears, whereas in Figure 11D they appear like C-341 shaped arcs. If the dark regions accompanying the clouds in Figs. 11B, 11C and 11D are 342 shadows, it would imply that they are clouds whose tops are higher than the surrounding darker 343 cloud deck. Based on the incident angle of illumination, we estimate from the length of its 344 shadow that the central cloud in Fig. 11B is only 3-4 km above the surrounding cloud deck. A similar estimate for the range of shadow lengths associated with various bright clouds in Fig. 345 346 11C implies that they are 5-12 km above the surrounding cloud deck. From the shadows 347 associated with several C-shaped arcs in Fig. 11D, we estimate that they rise as much as 6-13 km 348 above the background cloud deck. There are other similar features in both Figs. 11C and 11D, 349 but they are not fully resolved. Although we cannot determine with absolute certainty that these 350 clouds extend down to the level of the surrounding cloud deck, that is the impression one gets if 351 the accompanying dark regions are interpreted as shadows. If these bright clouds do extend vertically downward to the surrounding cloud deck, then they appear less like linear versions of 352 353 stratiform clouds on the Earth, than a series of upwelling cumulus clouds in which the 354 intervening spaces between them simply represent regions of compensating subsidence. 355

356 3.2.4. Lee waves are stationary waves generated by the vertical deflection of winds over 357 an obstacle, such as a mountain, a thermal updraft or a vertical vortex. Unlike the Earth, there 358 are no mountains in Jupiter's atmosphere, but there may indeed be the dynamical equivalent. If 359 the long streaks in Figure 12 that stretch diagonally (upper left to the lower right) in the figure are tracking streamlines associated with local winds, and the winds are moving from the 360 361 northwest to the southeast (upper left to the lower right in the figure), then the lee wave is the 362 three-wavefront feature indicated by the white grid lines that is orthogonal to the flow. This 363 requires that the local winds are passing not only around the bright upwelling anticyclonic vortex 364 in the upper left of the frame, but also over it, consistent with very subtle streaks seen over the 365 bright vortex. We note that not only the three waves indicated but also the lines that appear to be 366 tracing the wind flow are elevated above the background cloud field, as marked by the shadows 367 on their eastern sides. The most prominent of the shadows is on the eastern side of the central 368 wave, the length of which implies that the peak of the wave is some 10 km about the background cloud deck. This is, in fact, the only example of such a wave in our survey. One reason could be 369 370 that other atmospheric features are too high to permit flow over them, compared with the 371 relatively young anticyclonic vortex in Figure 12.

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373 3.2.5. Waves associated with large vortices are shown in Figure 13. Figure 13A shows a 374 very compact cyclonic feature with a set of extended radial wavefronts in the North Equatorial 375 Belt. These resemble similar structures in terrestrial cyclonic hurricanes. The waves delineated 376 in Figure 13A show morphological similarities to "transverse cirrus bands" (hereafter 'TCB') 377 identified in upper-level tropospheric structures on Earth (Knox et al. 2010). TCB are defined by 378 the American Meteorology Society as "Irregularly spaced bandlike cirrus clouds that form 379 nearly perpendicular to a jet stream axis. They are usually visible in the strongest portions of the 380 subtropical jet and can also be seen in tropical cyclone outflow regions." (American 381 Meteorological Society 1999). TCBs are also frequently observed in midlatitude mesoscale 382 convective systems (MCS) and in extra-tropical cyclones. Numerical studies (Trier et al. 2010, 383 Kim et al. 2014) have successfully replicated these cloud features and therefore have provided 384 insight to their formation. Currently, there is no consensus regarding the dynamics responsible 385 for TCB in all their observed forms (Knox et al. 2010). Multiple interacting factors that have 386 been implicated in the genesis of these features, including gravity waves, Kelvin-Helmholtz 387 instabilities, weak or negative moist static stabilities, and vertical wind shears (Dixon et al. 2000, 388 Trier et al. 2010, Knox et al. 2010).

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390 There are some common characteristics that TCB share in the Earth's atmosphere. First, 391 the bands frequently originate in a region of anticyclonic vorticity, positive divergence, and in 392 weak or negative static stability (Trier et al. 2010). Second, the majority of the bands appear in 393 regions of strong relative vorticity gradient, and often persist beyond the life of the originating 394 MCS (Lenz 2009). Third, the bands are often oriented along the vertical wind gradient, which 395 provides surprising evidence they share some dynamical characteristics with boundary-layer 396 horizontal convective roll vortices (Trier et al 2010, Kim et al. 2014), commonly observed on 397 Earth as cloud streets (Yang & Geerts 2006). Fourth, there is evidence that gravity waves 398 propagating below the cirrus cloud deck, the release of latent heat within the bands, and 399 longwave cooling above and longwave warming below the bands appears to favor the formation 400 of TCB. In addition to Figure 13A, the wave-like features shown in Figs. 2A, 3D, 4A, 5, 9A, 401 and 9C appear similar to terrestrial TBC. Although it is difficult to know if they are true analogs in the absence of detailed horizontal wind measurements of these clouds (as well as temperature
measurements to understand the 3D wind gradients), their morphologies are suggestive. If this is
the case, then complex small-scale dynamics may be operating in and below the Jovian ammonia
cloud deck not dissimilar to those on Earth.

406

407 The wave features in Figure 13A bear some resemblance to similar features found in 408 tropical cyclones. Animations of tropical cyclones show high-frequency circular gravity waves in 409 the central dense overcast cirrus shield ('CDO', Molinari et al. 2014) emanating from vigorous 410 convection in or near the eyewall. Perhaps more relevant to the appearance of the features in 411 Figure 13A, radial-aligned TCB are also commonly observed as 'spokes', which are more or less 412 oriented orthogonally to the gravity waves. In many cases, the circulation of the parent vortex 413 twists the spokes to appear like the teeth of a circular saw blade or as long thin curved filaments. 414 In addition, shallow-water numerical modeling of vortex dynamics using the Explicit Planetary 415 Isentropic Coordinate (EPIC; Dowling et al. 1998) in Brueshaber et al. (2019) also display 416 curved wave-like features similar to those in Figure 13A, but their waves are certainly due to 417 gravity waves formed during the merger of like-signed vortices for which we have no direct 418 evidence in this figure.

419

420 On the other hand, for the much larger anticyclonic white oval in Figure 13B, it is 421 possible that the curved cloud features appearing there to be a manifestation of gravity waves. 422 The spatial resolution of this image is sufficient to see both the internal spiral structure of the 423 white oval and a regular set of dark bands extending to its exterior. Anticyclones on Jupiter, such 424 this one, often feature a high-speed 'collar' surrounding a calmer interior (e.g., Marcus 1993). 425 The shear of the high-speed wind against slower winds outside of the vortex may be sufficient to 426 generate a Kelvin-Helmholtz wave, which may explain the scalloped appearance of the white 427 clouds adjacent to the surrounding red clouds.

428 429

430 3.2.6. Long, parallel dark streaks are detectable at mid-latitudes. Long streaks are seen in many 431 areas of Jupiter's cloud system, usually with a non-uniform and chaotic pattern (e.g. the diagonal 432 ones in Fig. 12). But, as shown in Figure 14, some are seen in very regularly spaced parallel 433 bands. In several cases, the parallel banding is not only regularly spaced but sinusoidal in 434 behavior, with a distance between crests ranging between 280 and 360 km. All such features 435 are detected far from the equator. Their orientation suggests that they are tracing out the direction 436 of flow on streamlines, in often complicated patterns, with lengths from 500 km to 3800 km (an upper limit that may be constrained by JunoCam's field of view). Almost all of the parallel 437 streaks in the examples shown in Fig. 14 are associated with larger atmospheric features, 438 439 although those features do not appear to be located where the streaks originate. In Figure 14A, 440 one set of these appears to be 'flowing' around an anticyclonic vortex in the lower left. It and a 441 set of streaks in the center of the feature have topography, with shadows apparent on their 442 eastern sides. In Figure 14B, long streaks possibly are associated with streamlines 'flowing' 443 around small, red anticyclonic vortices. The NTB was very turbulent at the time of these 444 observations, following a great disturbance in the preceding months (see Sánchez-Lavega et al. 445 2017). A semi-transparent triplet of short, dark bands in the top left of this figure can be seen 446 lying across longer bands that appear to be tracing wind flow. Figure 14C shows parallel streaks 447 located between a weak cyclonic eddy on the left and a bright wave-like streak aligned with the

448 SEBs retrograde jet, at the bottom edge of the panel. Figure 14D shows several parallel cloud 449 streaks in this turbulent part of the North North Temperate Belt (NNTB). Some are associated 450 with the small cyclonic vortex in the lower right side of the panel. Often, the streaks appear to 451 be on top of other features, implying that they represent flow that is manifested in a haze layer overlying deeper cloud layers. The best analog to these features lies not in the Earth's 452 453 atmosphere but in Saturn's. Ingersoll et al. (2018) examine high-resolution images of Saturn's 454 clouds taken during the Cassini mission's "proximal orbits". Their Figure 3 shows a flow around 455 a vortex that is very similar to one around the vortex in Figure 11A. For their similar "thread-456 like filamentary clouds", they suggest that the implied laminar flow implies extremely low 457 values of diffusivity and dissipation, which further quantitative analysis of these observations 458 may verify is the case for these scales in Jupiter, as well.

459

460 3.2.7. Unusual features are shown in Figure 15, which we might classify as waves only in the most general sense. Figure 15A shows a series of features with a regular spacing: three curved 461 462 wavefronts next to an unusual series of relatively dark ovals indicated by the arrows. The dark 463 ovals may be connected dynamically to the wavefronts, because they continue in the same direction and have roughly the same wavelength. The morphology of the three wave fronts 464 implies that flow is from the northwest. We do not see an array of short, dark, curved lines 465 elsewhere, so their spatial association with each other is extremely unusual. They are located 466 467 near the boundary between the turbulent northern component and the smooth, orange southern component of the North Temperate Belt. Figure 15B shows a limited series of repeated patterns 468 469 along the southern edge of an unusual white band located at the turbulent boundary between the 470 northern and southern components of the North Temperate Zone. This short sequence bears 471 some resemblance to a Karman vortex street, although one that may be dissipating or disrupted.

472 473

### 474 3.3 Quantitative measurements of wave properties.

475 476

478

477 3.3.1. Measurements of meridional distribution and size properties.

479 Measurements were made of physical properties of all of the waves and wave-like 480 features discussed. A table of all of these is available in the Supplemental Information file. 481 Features are identified by Perijove and File number. Measured quantities are: the number of 482 waves, the mean System-III longitude, mean planetocentric latitude, length and width of the 483 wave train, the mean wavelength (distance between crests) and the tilt of the wave with respect 484 to the orientation of the wave packet.

485

486 Figure 16 shows a histogram of the occurrence of waves as a function of latitude. In 487 order for the reader to distinguish between different classes of wave-like features, some of which 488 are arguably not propagating waves, we have separated out the different types of waves by 489 morphology as discussed in the preceding sections. Table 2 shows our count of the different 490 categories of waves. The overwhelming majority of wave-like features are clustered between 491 7°S and 6°N latitude, the relatively bright EZ. These features are dominated by long wave 492 packets with short wave crests, the type of waves detected by Hunt and Muller (1979) and 493 discussed by Simon et al. (2015a) as mesoscale waves observed at low latitudes by previous

494 imaging experiments. These waves fall within the relatively bright EZ and appear to be sub-495 clustered with fewer waves between 1°S and the equator than between either 7°S and 1°S or the 496 equator and 6°N. The next most populous category are waves with short packet lengths and long 497 crests, which appear to be distinct not only because they appear to be clustered differently in 498 length vs. width ratios, but also because they mostly populate latitudes between 1°N and 3°N. Waves that are generally associated with or influenced by larger features, most often associated 499 500 with curved wave packets, are the next most abundant feature. These include the curved wave 501 packets at the northern boundary of the GRS (Fig. 5A), the wave packets on the southern edge of 502 a cyclonic circulation in the SEB (Fig. 5b) and on the southern edge of an anticyclonic eddy (Fig. 503 5C), wave packets associated with the lobate feature in the chaotic region west of the GRS (Fig. 504 5D), and parallel stripes near a weak eddy (Fig. 14C). All are located in regions of retrograde 505 flow, as shown in Figure 17. All other types of features are detected less frequently (Table 2) 506 and are scattered in the northern hemisphere. No waves of any type were detected south of 7°S 507 other than the ones between 17°S and 20°S that are associated with larger features. There may be 508 a small selection effect associated with the observations, since latitudes in the northern 509 hemisphere are observed with an average spatial resolution that is higher than in the southern 510 hemisphere, arising from the fact that the Juno spacecraft perijove is in the northern hemisphere and moving northward by about a degree of latitude for each successive, highly elliptical orbit. 511 512 Perijove latitudes ranged from 3.8°N for PJ1 to 20.3°N for PJ20. Arguing against this is the fact 513 that waves were detected in the southern hemisphere with wavelengths between 70 km and 200 514 km, meaning that waves of this size range would have been detectable elsewhere if they were 515 present. Such waves might, in fact, be present but undetectable if the hazes making them visible 516 in the northern hemisphere were not present in the southern hemisphere outside the EZ, for some 517 reason.

518

519 Is the observed distribution of waves associated with other indicators of upwelling or 520 turbulence? Clearly the preponderance of waves in the EZ is not correlated with the frequency 521 of lightning detections, as no detections of lightning have been associated with that region, either 522 historically (e.g. Borucki & Magalhães 1992, Little et al. 1999, Dyudina et al. 2004) or in the 523 broad survey by the Juno Microwave Radiometer (Brown et al. 2018) that is sensitive to 524 lightning discharges in the EZ (Juno's Waves instrument, Imai et al. [2018] could not detect 525 lightning in the EZ because the field lines do not reach Juno's orbit.). The presence of water ice is one indirect measure of upwelling, and its detection from Voyager IRIS data by Simon-Miller 526 527 et al. (2000) revealed a distribution that included the EZ but was significantly higher at latitudes 528 south of  $\sim 10^{\circ}$ S. This is consistent with our results only in the limited sense that several waves 529 were associated with the GRS and its surroundings. Another indirect measure is the presence of 530 pristine ammonia ice, as measured most recently by New Horizons (Reuter et al. 2007), which 531 determined that spectrally identifiable ammonia clouds (SAICs) occurred "near active storms or 532 upwelling regions", which includes some regions in the EZ and is more broadly consistent with 533 several of our specific observations at higher latitudes. New Horizons did not detect SAICs near 534 the GRS, as the typically chaotic region to its northwest was not active during the New Horizons 535 encounter. From the Juno mission itself, the striking deep column of concentrated ammonia at 2°N to 5°N detected by the Microwave Radiometer (MWR) instrument implies upwelling (Li et 536 537 al. 2017, Bolton et al. 2017), which is consistent with the concentration of waves there. This is 538 consistent with contemporaneous ground-based observations (de Pater et al. 2019, Fletcher et al. 539 2016, 2020). However, we detected an equal number of waves in the southern component of the

540 EZ, where there was not nearly as great a concentration of ammonia gas, so this particular 541 correlation is imperfect. We note that from studies of cloud properties from reflected sunlight, 542 the full EZ is known as a region in which tropospheric clouds and hazes extend higher than other 543 locations on the planet outside the GRS, as evidenced by the general concentration of upper-544 atmospheric opacity historically (e.g. West et al. 1986) and in more recent work (see Figs. 4 and 545 12 of Sromovsky et al. 2017, Fig 13B of Braude et al. 2020) or by the distribution of 546 disequilibrium constituents (see Fig. 4 of Orton et al. 2017b). This is consistent with the entire 547 EZ being a region of general upwelling.

548

549 Figure 17 plots the distribution of mean wavelengths for different types of waves and 550 wave-like features as a function of latitude, co-plotted with mean zonal wind velocity. The 551 minimum distance between crests is 29.1 km for the spacing between the discrete white features 552 shown in Fig. 10A. Not significantly larger is the 30.9 km between crests of waves in a low-553 latitude long wave packet with short crests. These values are available in Table 1 of the 554 Supplementary Information file. The variability of wavelengths within a single packet is 555 typically no greater than 20-30%. The equatorial waves with long packets and short crests in the EZ have wavelengths that are clustered between 30 km and 320 km, with most between 80 and 556 230 km in size. The bimodal appearance of the distribution of EZ waves is not consistent with 557 558 the distribution of waves detected from Voyager (Simon et al. 2015a), which also has several 559 wave packets distributed at latitudes south of the EZ (see Figure 17). Similar to our study, most 560 of these are associated with the GRS. Similar to Voyager, all the waves detected in JunoCam 561 images in regions of retrograde flow are associated with discrete atmospheric features, such as 562 the GRS. The virtual absence of waves observed in Voyager images covering the northern 563 hemisphere is ostensibly the opposite of what we observe with JunoCam, although the key in 564 Figure 16 shows that many of the wave-like features in the northern hemisphere might not have 565 been categorized as waves by Voyager investigators.

566

567 3.3.2. Measurements of wave phase speed.

The most diagnostic criterion between different types of waves is the propagation speed. 568 The waves in the EZ were discovered by Voyager 1 and described by Hunt & Muller (1979), 569 570 who found them to have low or zero speeds relative to their surroundings (whether in a plume 571 tail or equatorial clouds). Simon et al. (2015b) also found little relative motion for these waves in Voyager 2 and Galileo Orbiter images. Arregi et al.(2009), studying Galileo Orbiter images, 572 573 likewise found no measurable relative motion for waves on the equator, but a phase velocity of 574 35 (+/-8) m/s for waves at 3°S. Simon et al. (2015b) adopted the conclusions of Flasar & 575 Gierasch (1986), Bosak & Ingersoll (2002) and Arregi et al. (2009) that these waves detected by 576 Voyager and Galileo images were best classified as inertia-gravity (IG) waves, a conclusion we 577 do not revisit here. On the other hand, Simon et al. (2015b) differentiated the waves detected by 578 New Horizons as Kelvin waves from those by Galileo and Voyager as IG waves on the basis of 579 their phase velocity, crest length, and location; they measured a non-zero velocity (80±5 km/s) 580 relative to the local zonal wind for the Kelvin waves that are confined to the equator compared with the IG waves, which are near stationary (upper limits to the phase velocity of 40 m/s or 581 less). Unfortunately, the Juno spacecraft and orbit configuration that provides such close-up 582 583 observations of Jupiter's clouds strongly limits our ability to determine velocities, and regions 584 are rarely observed at adequate spatial resolution more than once per perijove. Subsequent 585 perijoves typically observe longitudes that are far from the preceding one. Observations of the

586 Great Red Spot in PJ7 are one exception (Sánchez-Lavega et al. 2018), as noted above. Another 587 is the circulation associated with a large cyclonic feature observed by both JunoCam and ground-588 based facilities (Iñurrigarro et al. 2020).

589

590 We made another attempt in PJ20 to observe one region several times during a perijove, focusing on the northern component of the EZ, Images 33 through 37 (formally 591 592 JNCE 2019043 20C00033 V01 through JNCE 2019043 20C00037 V01). We examined 593 these quite carefully using a recently developed upgrade in our geometric calibration, which used 594 limb-crossing times to correct for otherwise undetected errors in the data-acquisition timing. 595 The results showed no change in the location of waves (marked in Fig. PJ20\_34a in the Supplemental Information file near 27.5°W longitude and 0.5°N latitude) over the 6 min, 4-sec 596 597 interval between the first and last images of this sequence. We quantify this using a very 598 conservative standard of 2 pixels for the pointing uncertainty, equivalent to 14 km for Image 33 599 and 18 km for Image 37 – a linear dependence on the distance of the spacecraft from the waves. 600 Using 16 km as an estimate of the mean displacement, this is equivalent to an upper limit for the 601 phase speed of 44 m/s, a value consistent with a supposition that these are IG waves.

602

603 Moreover, based on morphology alone, the New Horizons waves were slightly curved, 604 had a consistent distance between wave fronts of 305±25 km, a wave train that spanned the 605 entire visible equator (more than 200,000 km in packet length), and were centered at the equator, 606 spanning  $\pm 2^{\circ}$  in latitude (see Figs. 1 and 2 of Simon et al. 2015). The waves that we detected 607 here have a broad range of wavelengths and crest lengths, are located at latitudes significantly far 608 from  $\pm 1.5^{\circ}$  of the equator, and many wave packets are very short. Therefore, we suggest that 609 these types of waves detected in JunoCam images, more similar to those seen in Voyager and 610 Galileo observations, are most likely to be IG in origin.

611

### 612 4. Conclusions and future work

613

614 Juno's public-outreach camera, JunoCam, detected a plethora of waves or wave-like 615 features in its first 20 perijove passes. Of these 157 features, 100 are waves with long, somewhat linear packets and short crests are identified as mesoscale waves, consistent with earlier studies. 616 617 Many of these have wave crests that are nearly orthogonal to the wave packet orientation, 618 although others that were tilted compared with this orientation. Another 25 wave packets were 619 detected with short packets and long crests. As a group, they are likely to be features that are 620 truly propagating waves. They are more in number than was detected by Voyager imaging in 621 1979, and they include waves that are smaller in wavelength than any detected by previous missions. These waves form the vast majority of features detected in this study, and they are 622 concentrated in a latitude range between 5°S and 7°N. Short wave packets often appear in several 623 624 different orientations and sometimes overlap one another. Almost none of these appear to be 625 associated with other features except for waves that appear to be oriented in lines of local flow, including packets with crests that appear darker than the local background or with bright 626 627 features. These bright features appear both as discrete, tall clouds with shadows that imply they are higher than the background darker cloud deck, and simply as brighter features that have 628 629 wispy "tails" and are connected to one another by an equally bright but narrow, elongated cloud. 630 The difference between wide and narrow packets is presumably related to the width of the flow 631 that is responsible for the wave. There were fewer waves in the EZ between the equator and

632 1°N than there were immediately north and south of this band, which was different from the
 633 waves detected by Voyager imaging in 1979 that were more equally distributed.

634

635 Other waves, prominently those outside the EZ, are clearly associated with or influenced 636 by other features. These include short-crested packets following the slightly curved path at the 637 northern extent of the GRS, others associated with an anticyclonic eddy in the NEB and a 638 cyclonic circulation in the SEB, and one associated with the turbulent flow west of the GRS. 639 Three lee waves were detected in the wake of an upwelling anticyclonic vortex that were some 640 10 km above the surrounding cloud deck. More features were detected that had repeated, wave-641 like features but may not represent propagating waves. Some of the linear arrangements of 642 discrete white clouds followed the edges of vortices; although regular in spacing, these features 643 may not represent propagating waves so much as alternating positions of upwelling and 644 subsiding vertical flows. Several features appeared within or emanating from vortices. Two sets 645 of extremely long, curved features were detected near the edges of a southwestern extension of a 646 dark blue-gray region associated with high 5-µm radiances at the southern edge of the NEB. 647 Long, sinuous parallel streaks were detected, some with nearly sinusoidal lateral variability, that were analogous to features observed by the highest-resolution imaging of Saturn's atmosphere 648 649 by Cassini (Ingersoll et al. 2018). No waves were detected south of 7°S that were not associated 650 with larger vortices, such as the GRS. No waves or wave-like features were detected in regions 651 of retrograde mean zonal flow that were not associated with larger features, similar to the waves detected by Voyager imaging. 652

653

654 We had limited opportunities to classify waves on the basis of phase speed. Sánchez-Lavega et al. (2018) determined that the waves located at the northern extent of the GRS were 655 internal gravity waves from their propagation speed with respect to the local flow, based on a 656 657 displacement over a 9-minute interval between initial and final images. (Internal gravity waves are similar to IG waves but where Coriolis forces are not considered to be important.) JunoCam 658 659 seldom observes features more than once, and usually with insufficient time to note a displacement. Our attempt to observe features in the EZ on PJ20 resulted in a 6-minute interval 660 661 over which no motions were detected for equatorial features, providing an upper limit of wave motions that was not inconsistent with inertia-gravity waves. However, the waves detected in 662 663 the EZ were not located directly at the equator, which bounded the Kelvin waves detected by New Horizons imaging (Simon et al. 2015b). Otherwise, the waves detected in the EZ are 664 morphologically similar to those detected by Voyager, which Simon et al. (2015b) classified as 665 inertia-gravity waves. These waves may well be associated generally with the upwelling winds 666 667 that characterize the EZ.

668

669 Work will continue to document and detect waves and wave-like features in Jupiter's 670 atmosphere, including further attempts to examine regions over longer time intervals, although we note that observations of waves in the EZ will be lower in spatial resolution as the latitude of 671 successive perijoves migrates northward by about 1° per perijove. We will also look for 672 673 simultaneous measurements of waves in the near infrared by the JIRAM experiment to provide 674 some constraints on the altitude of these features, which were otherwise only loosely constrained 675 by occasional measurements of associated shadows. Furthermore, we expect that we and others 676 will use these observations as a motivation to engage in comparisons with terrestrial analogs and numerical simulations that will further our understanding of the origin of these features and their 677

678 implications for the dynamics of Jupiter's atmosphere at these small scales and their relation to679 the larger picture of planetary dynamics at depth.

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681

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697

All the images used in this study are available for direct download from the Mission Juno site:
 https://www.missionjuno.swri.edu/

700

We note that preliminary results, including a version of Figure 11, were included in a NASA
 press release: https://www.jpl.nasa.gov/news/news.php?feature=7264.

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### 705 References

- Acton, C. H. 1996. Ancillary data services of NASA's navigation and ancillary information
   facility. *Planet. Space Sci.* 44, 65-70.
- Adriani, A., Mura, A., Orton, G., Hansen, C., Altieri, F., Moriconi, M. L., Rogers, J., Eichstädt,
- 710 G., Momary, T., Ingersoll, A., Filacchione, G., Sindoni, G., Tabataba-Vakili, F., Dinelli, B.
- 711 M., Fabiano, F., Bolton, S. J., Connerney, J. E. P., Atreya, S. K., Lunine, J. I., Tosi, F.,
- 712 Migliorini, A., Grassi, D., Piccioni, G., Noschese, R., Cicchetti, A., Plainaki, C., Olivieri, A.,
- 713 O'Neill, M. E., Turrini, D., Stefani, S., Sordini, R., Amoroso, M. (2018a) Clusters of cyclones
- 714 encircling Jupiter's poles. *Nature*. 555, 216-219. doi 10.1038/nature25491.
- 715 Adriani, A., Moriconi, M. L., Altieri, F., Sindoni, G., Ingersoll, A. P., Grassi, D., Mura, A.,
- 716 Atreya, S. K., Orton, G., Lunine, J. I., Fletcher, L. N., Simon, A. A., Melin, H., Tosi, Ciccetti,
- A., Noschese, R., Sordini, R., Levin, S., Bolton, S., Plainaki, C., Olivieri, A. (2018b).
- 718 Characterization of mesoscale waves in the Jupiter NEB by Jupiter InfraRed Auroral Mapper
- 719 on board Juno. *Astron. J.* **156**, 246 (12pp).
- 720 American Meteorological Society (1999). Glossary of Meteorology, 2<sup>nd</sup> edition, American
- 721 Meteorological Society: Boston, MA.

- Allison, M. (1990). Planetary waves in Jupiter's equatorial atmosphere. *Icarus* 83, 282-307.
- Arregi, J., Rojas, J. F., Hueso, R., Sanchez-Lavega, A. (2009) Gravity waves in Jupiter's
   equatorial clouds observed by the Galileo orbiter. *Icarus 202*, 358-360.
- Blackmon, M.L., Lee, Y.-H., & Wallace, J. A. (1984) Horizonal structure of 500 mb height
   fluctuations with long, intermediate and short time scales. J. Atmos. Sci. 41, 961.
- Bolton, S. J., Adriani, A., Adumitroaie, V., Anderson, J., Atreya, S., Boxham, J., Brown, S.,
- 728 Connerney, J. E. P., DeJong, E., Folkner, W., Gautier, D., Gulkis, S., Guillot, T., Hansen, C.,
- Hubbard, W. B., Iess, L., Ingersoll, A., Janssen, M., Jorgensen, J., Kaspi, Y., Levin, S. M., Li,
- C., Lunine, J., Miguel, Y., Orton, G., Owen, T., Ravine, M., Smith, E., Steffes, P., Stone, E.,
- Stevenson, D., Thorne, R., Waite, J. (2017). Jupiter's interior and deep atmosphere: The first
  close polar pass with the Juno spacecraft. *Science* 356, 821-825.
- Borucki, W. J., Magalhães, J. A. (1992) Analysis of Voyager 2 images of Jovian lightning. *Icarus 96*, 1-14.
- Bosak, T. and Ingersoll, A. P. (2002). Shear instabilities as a probe of Jupiter's atmosphere. *Icarus 158*, 401-409.
- 737 Braude, A. S., Irwin, P. G. J., Orton, G. S., Fletcher, L. N. (2020). Colour and tropospheric cloud
- structure of Jupiter from MUSE/VLT: Retrieving a Universal chromophore. *Icarus 338* In press,
- 739 doi: 10.1016/j.icarus.2019.113589.
- 740 Brown, S., Janssen, M., Adumitroaie, V., Atreya, S., Bolton, S., Gulkis, S., Ingersoll, A., Levin,
- 741 S., Li, Cl., Li, L., Lu nine, J., Misra, S., Orton, G. Steffes, P., Tabataba-Vakili, F., Kolmasova,
- I., Imai, M, Santolik, O., Kurth, W., Hospodarsky, G., Gurnett, D., Connerney, J. (2018).
- Prevalent lightning sferics at 600 megahertz near Jupiter's poles. *Nature 558*, 87–90.
  doi.org/10.1038/s41586-018-0156-5.
- Brueshaber, S., Sayanagi, K., M., Dowling, T. E. (2019). Dynamical regions of giant planet polar
  vortices. *Icarus 323*, 46-61. doi 10.1016/j.icarus. 2019.02.001
- de Pater, I., Sault, R. J., Moeckel, C., Moullet, A., Wong, M. H., Goullaud, C., DeBoer, D.,
- Butler, B. J., Bjoraker, G., Adamkovics, M., Cosentino, R., Donnelly, P. T., Fletcher, L. N.,
- Kasaba, Y., Orton, G. S., Rogers, J. H., Sinclair, J. A., Villard, E. (2019) First ALMA
  millimeter-wavelength maps of Jupiter, with a multiwavelength study of convection. *Astrophys. J.* 158, 139 (17pp).
- Dixon, R.S., Browning, K.A., Shutts, G.J. (2000). The mystery of striated cloud heads in satellite
   imagery. *Atmospheric Science Letters*, doi:10.1006/asle.2000.0001
- 754 Dyudina, U. A., Del Genio, A. D, Ingersoll, A. O., Porco, C. C., West, R. A., Vasavada, A. R.,
- Barbara, J. M. (2004). Lightning on Jupiter observed in the Ha line by the Cassini imaging
  science subsystem. *Icarus* 172, 24-36.
- Flasar, F. M. and Gierasch, P. J. (1986). Mesoscale waves as a probe of Jupiter's deep
  atmosphere. J. Atmos. Sci. 43, 2683-2707.
- 759 Fletcher, L. N., Orton, G. S., Mousis, O., Yanamandra-Fisher, P., Parrish, P. D., Irwin, P. G. J.,
- 760 Edkins, E, Baines, K. H., Line, M. R., Vanzi, T., Fujiyoshi, T., Fuse, T. (2010). Jupiter's Great
- Red Spot: High-resolution thermal imaging from 1995 to 2008. *Icarus* **208**, 306-328.
- 762 Fletcher, L. N., Melin, H., Adriani, A., Simon, A. A., Sanchez-Lavega, A., Donnelly, P. T.,
- Antuñano, A., Orton, G. S., Hueso, R., Moriconi, M. L., Altieri, F., Sindoni, G. 2018. Jupiter's
  mesoscale waves observed at 5 μm by ground-based observations and Juno JIRAM. *Astron. J.* **156**, 67 (13pp).
- 766 Fletcher, L. N., Greathouse, T. K., Orton, G. S., Sinclair, J. A., Giles, R. S., Irwin, P. G. J.,
- 767 Encrenaz, T. (2016) Mid-infrared mapping of Jupiter's temperatures, aerosol opacity and

- chemical distributions with IRTF/TEXES. Icarus 278, 128-161. doi
- 769 10.1016/j.icarus.2016.06.008
- Fletcher, L. N., Orton, G. S., Greathouse, T. K., Zhang, Z., Oyafuso, F. A., Levin, S. J., Li, C.,
  Bolton, S., Janssen, M., Mettig, H.-J., Rogers, J. H., Eichstädt, G., Hansen, C., Melin, H.,
- Grassi, D., Mura, A., Adriani, A. (2020). Jupiter's equatorial plumes and hot spots: Spectral
   mapping from Gemini/TEXES and Juno/MWR. J. Geophys. Res. (this issue).
- Hansen, C., Caplinger, M. A., Ingersoll, Ravine, M. A., Jensen, E., Bolton, S., Orton, G. 2017.
- Junocam: Juno's outreach camera. *Space Sci. Rev. 217*, 475-506. doi:10.1007/s/11214-0140079-x.
- Holton, J. R. 1992. An Introduction to Dynamic Meteorology (3<sup>rd</sup> ed.; New York; Academic
   Press).
- Hunt, G. E., and Muller, J.-P. (1979). Voyager observations of small-scale waves in the
  equatorial region of the jovian atmosphere. *Nature 280*, 778-780.
- 781 Imai, M., Santolik, O., Brown, S., Kolmasova, IO., Kurth, W., Janssen, M., Hospodarsky, G.,
- Gurnett, D., Bolton, S., Levin, S. (2018). Jupiter lightning-induced whistler and sferic events
  with Waves and MWR during Juno perijoves. Geophys. Res. Lett. 45, 7268-7276.
- 784 doi.org/10.1029/2018GL078864.
- Ingersoll, A. P., Ewald, S. P., Sayanagi, K. M., Blalock, J. J. (2018). Saturn's atmospheres at 1-10
  kilometer resolution. *Geophys. Res. Lett.* 45, 7851–7856. doi.org/10.1029/2018GL079255.
- Iñurrigarro, P., Hueso, R., Legarreta, J., Sánchez-Lavega, A., Eichstädt, G., Rogers, J. H., Orton,
  G. S., Hansen, C. J., Pérez-Hoyos, S., Rojas, J. F., Gómez-Forrellad, J. M. 2020. Observations
  and numerical modelling of a convective disturbance in a large-scale cyclone in Jupiter's South
- 790 Temperate Belt. *Icarus*. **336**, 113475.
- Kim, J-H., Chun, H-Y., Sharman, R.D., Trier, S.B. (2014). The role of vertical shear on aviation
   turbulence within cirrus bands of a simulated western Pacific cyclone. *Monthly Weather Review*, 142, 2794-2812.
- Knox, J. A., Bachmeier, A. S., Carter, W. M., Tarantino, J. E., Paulik, L. C., Wilson, E. N.,
  Bechdol, G. S., Mays, M. J. (2010). Transverse cirrus bands in weather systems: a grand tour
  of an enduring enigma. *Weather 65*, 36-41.
- Lenz, A., Bedka, K.M., Feltz, W.F., Ackerman, S.A. (2009). Convectively induced transverse
  band signatures in satellite imagery. *Weather and Forecasting*, 24, 1362-1373.
- Li, C., Ingersoll, A., Janssen, M., Levin, S., Bolton, S., Adumitroaie, V., Allison, M., Arballo,
- A., Belotti, A., Brown, S., Ewald, S., Jewell, J., Misra, S., Orton, G., Oyafuso, F., Steffes, P.,
  Williamson, R. (2017). The distribution of ammonia on Jupiter from a preliminary inversion of
- 302 Juno microwave radiometer data. *Geophys. Res. Lett.* 44, 5317-5325.
- Li, L., Ingersoll, A. P., Vasavada, A. R., Simon-Miller, A. A., Achterberg, R. K., Ewald, S. P.,
- B04 Dyudina, U. A., Porco, C. C., West, R. A., Flasar, F. M. (2006). Waves in Jupiter's atmosphere
  B05 observed by the Cassini ISS and CIRS instruments. *s*, 416-429.
- Little, B., Anger, C. D., Ingersoll, A. P., Vasavada, A. R., Senske, D. A., Breneman, H. H.,
  Borucki, W. J., Galileo SSI Team (1999) Galileo images of lightning on Jupiter. *Icarus 142*,
  306-323.
- Marcus, P.S. (1993). Jupiter's Great Red Spot and Other Vortices. Ann. Rev. Astron. Astrophys.
  31, 523-573.
- 811 Molinari, J., Duran, P., and Vollaro, D. (2014). Low Richardson number in the tropical cyclone
- 812 outflow layer. *Journal of the Atmospheric Sciences*. 71, 3164-3179.

- 813 Orton, G. S., Hansen, C., Caplinger, M., Ravine, M., Atreya, S., Ingersoll, A. P., Jensen, E.,
- 814 Momary, T., Lipkman, L., Krysak, D., Zimdar, R., Bolton, S. (2017a) The first close-up
- 815 images of Jupiter's polar regions: results from the Juno mission JunoCam instrument. *Geophys.*816 *Res. Lett.* 44, 4599-4606. doi:10.1002/2016GL072443.
- 817 Orton, G. S., Momary, T., Ingersoll, A. P., Adriani, A., Hansen, C. J., Janssen, M., Arballo, J.,
- Atreya, S. K., Bolton, S., Brown, S., Caplinger, M., Grassi, D., Li, C., Levin, S., Moriconi, M.
- L., Mura, A., Sindoni, G. (2017b) Multiple-wavelength sensing of Jupiter during the Juno
- 820 mission's first perijove passage. Geophys. Res. Lett. 44, 4607-4614 doi:
- 821 10.1002/2017GL073019.
- Porco, C. C., West, R. A., McEwen, A., Del Genio, A. D., Ingersoll, A. P., Thomas, P., Squyres,
  S., Dones, L., Murray, C. D., Johnson, T. V., Burns, J. A., Brahic, A., Neukum, G., Veverka,
- J., Barbara, J. M., Denk, T., Evans, M., Ferrier, J. J., Geissler, P., Helfenstein, P., Roatsch, T.,
- Throop, H., Tiscareno, M., Vasavada, A. R. (2003). Cassini imaging of Jupiter's atmosphere,
  satellites, and rings. *Science 299*, 1541-1547.
- Reuter, D. C., Simon-Miller, A. A., Lunsford, A., Baines, K. H., Cheng, A. F., Jennings, D. E.,
  Olkin, C. B., Spencer, J. R., Stern, S. A., Weaver, H. A., Young, L. A. (2007). Jupiter cloud
  composition, stratification, convection, and wave motion: A view from New Horizons. Science
- 830 318, 223-225. doi 10.1126/science.1147618.
- Rogers, J. (1995), The Giant Planet Jupiter, 418 pp., Cambridge Univ. Press, Cambridge, U. K.
- Salyk, C., Ingersoll, A. P., Lorre, J., Vasavada, A., Del Genio, A. D. (2006) Interaction between
  eddies and mean flow in Jupiter's atmosphere: Analysis of Cassini imaging data. *Icarus 185*,
  430-442.
- Sánchez-Lavega, A., Hueso, R., Eichstädt, G., Orton, G., Rogers, J., Hansen, C. J., Momary, T.,
  Tabataba-Vakili, F., Bolton, S. (2018). The rich dynamics of Jupiter's Great Red Spot from
- 837 JunoCam Juno images. *Astron. J.* 156, 162 (9 pp).
- Simon-Miller, A. A., B. Conrath, P. J. Gierasch, R. F. Beebe. (2000). A detection of water ice on
  Jupiter with Voyager IRIS. *145*, 454-461.
- Simon, A. A., Li, L., Reuter, D. C. (2015a). Small-scale waves on Jupiter: A reanalysis of New
  Horizons, Voyager, and Galileo data. *Geophys. Res. Lett.* 42, 2612-2618, doi:
- 842 10.1002/2015GL063433.
- Simon, A. A., Wong, M. H., Orton, G. s. (2015b). First results from the Hubble OPAL program:
  Jupiter in 2015. *Astrophys. J.* 812:55 (8pp).
- Simon, A. A., Hueso, R., Iñurrigarro, P., Sánchez-Lavega, A., Morales-Juberías, R., Cosentino,
  R., Fletcher, L. N., Wong, M. H., Hsu, A. I. de Pater, I., Orton, G. S., Colas, F., Delcroix, M.,
- Peach, D., Gómez-Forrellad, J.-M. (2018). A new, long-lived, jupiter mesoscale wave observed
  at visible wavelengths. *Astron. J.*, *156:79* (18pp).
- 849 Sromovsky, L. A., Baines, K. H., Fry, P. M., Carlson, R. W. (2017) A possibly universal red
- chromophore for modeling color variations on Jupiter. *Icarus 291*, 232-244. doi
- 851 10.1016/j.icarus.21016.12.014.
- Sugiyama, K., Nakajima, K., Odaka, M., Kuramoto, K., Hayashi, Y.-Y. (2014). Numerical
  simulations of Jupiter's moist convection layer: Structure and dynamics in statistically steady
  states. *Icarus* 229, 71-91.
- 855 Sugiyama, K., Nakajima, K., Odaka, M., Kuramoto, K., Hayashi, Y.-Y. (2014). Corrigendum to:
- 856 "Numerical simulations of Jupiter's moist convection layer: Structure and dynamics in
- statistically steady states. Icarus 229, 71-91]". *Icarus 231*, 407-408.

- 858 Tabataba-Vakili, F., Rogers, J. H., Eichstädt, G., Orton, G. S., Hansen, C. J., Momary, T. W.,
- 859 Sinclair, J. A., Giles, R. S., Caplinger, A., Ravine, M. A., Bolton, S. J. (2019). Long-term
- tracking of circumpolar cyclones on Jupiter from polar observations with JunoCam. *Icarus*. In
   press.
- Trier, S.B., Sharman, R.D., Fovell, R.G., Frehlich, R.G. (2010). Numerical simulation of radial
  cloud bands within the upper-level outflow of an observed mesoscale convective system. *Journal of the Atmospheric Sciences*. 67, 2990-2990.
- West, R.A., Strobel, D. F., Tomasko, M. G. (1986). Clouds, aerosols, and photochemistry in the Jovian atmosphere. *Icarus* 65, 161-217. doi 10.1016/0019-1035(86)90135-1
- Wong, M. H., Simon, A. A., Tollefson, J. W., de pater, I., Barnett M., Hsu, A. I. Stephens, A.,
  Orton, S. G. Fleming, S. W., Januszewski, W., Roman, A., Goullaud, C., Bjoraker, G. L,
- Atreya, S. K., Adriani, A. (2020). High-resolution UV/optical/IR imaging of Jupiter in 2016–
  2019. Astrophysical Journal Supplement Series. Submitted.
- 871 Yang, Q. and Geerts, B. (2014). Horizontal convective rolls in cold air over water:
- 872 Characteristics of coherent plumes detected by an airborne radar. *Monthly Weather Rev. 134*,
  873 2373-2395.
- 874 Young, R. M. B., Read, P. L. (2017). Forward and inverse kinetic energy cascades in Jupiter's
- turbulent weather layer. *Nature Physics 13*, 1135.
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## 878 Tables

Observing Platform	Associated	Range of	Range of
(year)	Publications	Planetocentric	Wavelengths
•		Latitudes	(km)
Voyager (1979)	Hunt & Muller	27°S-27°N	70-430
	(1979),		
	Flasar & Gierasch		
	(1986)		
Galileo (1996)	Bosak & Ingersoll	13 <sup>°</sup> S	300
	(2002)		
Galileo (1999)	Arregi et al. (2009),	0.2°N, 3.6°N	155-205
	Simon et al. (2015)		
Galileo (2001)	Arregi et al. (2009)	1.8 <sup>°</sup> S	
			195-215
New Horizons	Reuter et al. (2007),	0°-1.1°N	280-330
(2007)	Simon et al. (2015)		
Juno/JIRAM (2017)	Adriani et al. (2018),	14°-15°N	1400-1900
	Fletcher et al. (2018)		
Juno/JunoCam	Sánchez-Lavega et al.	16 <sup>°</sup> S	35
(2017)	(2018)		
Hubble Space	Simon et al. (2018)	$14.5^{\circ} \pm 2.5^{\circ} N$	1220-1340
Telescope (2012-			
2018)			
Ground-Based	Simon et al. (2018)	$14.5^{\circ} \pm 2.5^{\circ} N$	1220-1340
Visible Observations			
(2017)			
Ground-Based 5-µm	Fletcher et al. (2018)	$14.5^{\circ} \pm 2.5^{\circ} N$	1300-1600
Observations (2016-			
2017)			

881 Table 1. Summary of previous observations of small-scale waves in Jupiter's clouds detected at 882  $5 \mu m$  or shorter wavelengths. (Some values are also displayed in Figure 16.) The waves

addressed by Sánchez-Lavega et al. (2018) are associated with the Great Red Spot.

Type of Wave-Like Feature (section where discussed)	Number of Features
Long packets, short crests (3.2.1)	100
Wide wave crests (3.2.2)	25
Curved packets (3.2.1)	9
Small white clouds (3.2.3)	9
Regularly spaced dark features (3.2.7)	6
Emanating from vortex (3.2.5)	4
Extremely long curved features (3.2.2)	2
Lee waves (3.2.4)	1

896 Table 2. Number of features in each morphological category, listed in order of frequency. These 897 include features not illustrated in the figures associated with the main article but included in the

898

Supplementary Information file. The total number of waves or wave-like features is 157. The 899 category of waves with long packets and short crests dominates the total. Quantitative properties

900 of these waves are shown in the Table of Section SI2 of the Supplemental Information file. They

901 are also shown graphically in Figs. 16, 17 and Figs. SI3-1 through SI3-3 of the Supplemental

902 Information file.

Figures





Figure 1. Example of excerpting a portion of a wave-like feature from a JunoCam image from
planetocentric latitudes 3°S - 4°S. This is a cylindrical mapping of a color-composited Image
JNCE\_2017297\_09C00088\_V01 (which here and elsewhere we simply identify as Image 99 from
PJ9. The extracted panel is also shown as Figure 10B and in the Supplemental Information file
as Figure PJ09\_88 with a grid indicating the location of peak radiances in the wave-like feature.

3.0 A. PJ3 Image 111 Planetocentric Latitude 2.0  $\Pi$ 1.0 **1**0.0 9.0 8.0 7.0 6.0 System-III Longitude -1.0 **B. PJ20 Image 36** Planetocentric Latitude -1.5 -2.0 -2.5 -3.0 🎞 26.5 I I I I I I I I I I 26.0 25.5 24.0 25.0 24.5 23.5 System-III Longitude

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917 Figure 2. Excerpts from JunoCam color-composite maps of images in PJ3 illustrating isolated 918 wave packets with shorter wave fronts that are orthogonal to the orientation of the wave packet. 919 In this and all other similar figures in this report, the colors have been stretched extensively in 920 order to make the waves as visible as possible; they have absolutely no relationship with the true 921 colors of the planet. In this and some sequent images here and in the Supplemental Information 922 file, broad vertical or diagonal colored bands are artefacts of strong image enhancement to

923 *distinguish otherwise faint features.* 



Figure 3. Excerpts from JunoCam maps of images in PJ8 (Panel A), PJ17 (Panels B and C) and PJ18 (Panel D). These illustrate individual wave packets with shorter wave fronts that are not-orthogonal (i.e. they are "tilted") with respect to the orientation of the wave packet direction.







Figure 5. Examples of short wavefronts associated with a curved wave packet. A: Wavefronts associated with the curvature of the northern boundary of the GRS. A version of this panel appears in Figure 8 of Sánchez-Lavega et al. (2018). B: Wavefronts along the southern edge of an anticyclonic eddy in the NEB. C: Wavefronts on the south edge of a cyclonic circulation in the SEB. D. Wavefronts that cross a relatively dark lobate feature in the South Equatorial Belt (SEB), a part of a turbulent region west of the Great Red Spot.





Figure 6. Contextual HST WFC3 image for Figure 5D, showing its position with respect to the GRS. The inset shows the wind field derived from tracking cloud features over a 45-minute interval, as a residual after subtracting the mean zonal wind profile. The winds appear to be a maximum at the western (left) end of the blue lobate feature, with a marked drop in velocities, i.e. a region of wind shear, at the edges of the feature. This image was taken within a few minutes of the time at which the JunoCam image in Fig. 5D was observed



942 Figure 7. Excerpts from maps showing waves whose wave fronts are larger than the wave packet 943 length. Both are curved and located in the Equatorial Zone. Panel A shows a pair of wave

944 packets, overlapping each other, the westernmost of which contains at least three wave fronts 945 that are much longer than the packet. The overlapping easternmost wave packet has wave fronts

945 that are much longer than the packet. The overlapping easternmost wave packet has wave fronts 946 and a length that are roughly equal in size. Panel B shows a series of curved waves that appear

947 to extend past the boundaries of the full image



Figure 8. Extremely long, curved features detected in PJ20. Two unusually long features that may be waves were detected near the southwestern extension ("festoon") of a 5-µm hot spot, seen here as the dark area. North of the dark area of the festoon is a pair of lines, whose beginnings and ends are marked by white arrows. Among the many waves found south of the festoon, is a set of three closely spaced parallel lines, noted by the arrows that do not begin or end at the same position. Only for two of them is the western end evident. We note that some mild unsharp masking has been applied to this image in order to resolve for the reader the three dark curves at their eastern ends. (The locations of many more of the waves present in this figure are indicated in Figure PJ20\_34 in the Supplemental Information file.) 



PJ12\_90a in the Supplemental Information file. The feature is reminiscent of ocean foam, with side-by-side elongated features that are not uniformly directed and may be higher than the surrounding cloud deck, with a consistent darkening on Figure 9. Examples of wave packets defined by bright clouds, all in the Equatorial Zone. Panel A shows a wave packet whose length is roughly equal to its width. Its constituent clouds are clearly higher than their surroundings, given the strong topographic clues from consistent shadowing on their eastern sides. Panel B shows a line of regular clouds with longer, curved southwestern extensions. Panel C shows a similar wave packet of white clouds with narrow wavefronts and a slight curvature. Panel D shows a very curious type of irregular wave-like feature, extracted from the northeastern portion of Fig. their eastern sides that might be shadowing.



967 968 Figure 10. Two detections of regular patterns of relatively bright clouds apparently associated 969 with a fainter central bright region. Both instances involve curved lines. The wave packet in 970 Panel A is associated with a similar but fainter pattern to its north, whereas the wave packet in 971 Panel B has no such association. Both are in the southern component of the Equatorial Zone.







978 Figure 12. The single unambiguous detection of lee waves in the JunoCam images. We can presume that the long streaks appearing diagonally in this figure are tracking the streamlines of local winds. The lee waves indicated by the white grid lines are orthogonal to the elongated streaks and are likely to be downwind of the bright convective plume in the upper part of this image.




Figure 13. Wave-like features detected near vortices. Panel A shows a very compact cyclonic
feature with a set of extended radial wavefronts in the North Equatorial Belt (NEB). Panel B
shows a regular set of dark lines emerging from the ends of the internal spiral structures in an
anticyclonic white oval.









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Figure 15. Unusual quasi-wave-like features in the northern hemisphere. Panel A illustrates three curved wavefronts next to relatively dark circular features indicated by the arrows. Panel B shows a series of repeated patterns in the North Temperate Zone.



1007 Figure 16. Histogram of waves and wave-like features detected in PJ1-20 by JunoCam. Different

1008 types of waves and wave-like features are denoted by different colors and identified by the key.

1009 Each corresponds to a different wave morphology as discussed in Section 3.2. The bin size is 1°

*in latitude*.





1013 Figure 17. Wavelengths of waves and wave-like features detected in PJ1, PJ3-PJ20 by JunoCam.

1014 Measurements of different types of wave morphologies are color-coded as in Figure 15. Mean

1015 zonal wind velocities for 2017-2018 (Wong et al. 2020) are plotted in blue. Values for Voyager,

1016 New Horizons and Galileo are taken from their respective references in Table 1. Wavelengths

1017 for wave packets detected by HST and ground-based images (Simon et al. 2018, Fletcher et al.

1018 2018) are greater than 1100 m/s and clustered around 14.5°N (see Table 1).

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1020

- A Survey of Small-Scale Waves and Wave-Like Phenomena in 1 Jupiter's Atmosphere Detected by JunoCam 2 3 4 Glenn S. Orton<sup>1</sup>, Fachreddin Tabataba-Vakili<sup>1</sup>, Gerald Eichstädt<sup>2</sup>, John Rogers<sup>3</sup>, Candice J. Hansen<sup>4</sup>, Thomas W. Momary<sup>1</sup>, Andrew P. Ingersoll<sup>5</sup>, Shawn Brueshaber<sup>6</sup>, Michael 5 H. Wong<sup>7</sup>, Amy A. Simon<sup>8</sup>, Leigh N. Fletcher<sup>9</sup>, Michael Ravine<sup>10</sup>, Michael Caplinger<sup>10</sup>, Dakota 6 7 Smith<sup>11</sup>, Scott J. Bolton<sup>12</sup>, Stephen M. Levin<sup>1</sup>, James A. Sinclair<sup>1</sup>, Chloe Thepenier<sup>13</sup>, Hamish 8 Nicholson<sup>14</sup>, Abigail Anthony<sup>15</sup> 9 10 <sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA 11 <sup>2</sup>Independent scholar, Stuttgart, Germany <sup>3</sup>British Astronomical Association, London, UK 12 13 <sup>4</sup>Planetary Science Institute, Tucson, Arizona, USA 14 <sup>5</sup>California Institute of Technology, Pasadena, California, USA <sup>6</sup>Western Michigan University, Kalamazoo, Michigan, USA 15 <sup>7</sup>University of California, Berkeley, California, USA; SETI Institute, Mountain View, California, 16 17 USA 18 <sup>8</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA 19 <sup>9</sup>University of Leicester, Leicester, UK 20 <sup>10</sup>Malin Space Science Systems, San Diego, California, USA 21 <sup>11</sup>National Center for Atmospheric Research, Boulder, Colorado, USA 22 <sup>12</sup>Southwest Research Institute, San Antonio, Texas, USA 23 <sup>13</sup>Glendale Community College, Glendale, California, USA<sup>+</sup> 24 <sup>14</sup>Harvard College, Cambridge, Massachusetts, USA 25 <sup>15</sup>Golden West College, Huntington Beach, California, USA<sup>††</sup> 26 27 28 Corresponding author: Glenn Orton (glenn.orton@jpl.nasa.gov) 29 30 31 *†*currently at the University of California, Davis 32 *††currently at the University of California, Berkeley* 33 34 Key Points: 35 -In the first 20 orbits of the Juno mission, over 150 waves and wave-like features have been 36 detected by the JunoCam public-outreach camera. 37 -A wide variety of wave morphologies were detected over a wide latitude range, but the great 38 majority were found near Jupiter's equator. 39 -By analogy with previous studies of waves in Jupiter's atmosphere, most of the waves detected
- 40 are likely to be inertia-gravity waves.
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- 42

#### 43 Abstract

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45 In the first 20 orbits of the Juno spacecraft around Jupiter, we have identified a variety of wave-46 like features in images made by its public-outreach camera, JunoCam. Because of Juno's unprecedented and repeated proximity to Jupiter's cloud tops during its close approaches, 47 48 JunoCam has detected more wave structures than any previous surveys. Most of the waves appear 49 in long wave packets, oriented east-west and populated by narrow wave crests. Spacing between 50 crests were measured as small as ~30 km, shorter than any previously measured. Some waves are 51 associated with atmospheric features, but others are not ostensibly associated with any visible 52 cloud phenomena and thus may be generated by dynamical forcing below the visible cloud tops. 53 Some waves also appear to be converging and others appear to be overlapping, possibly at different 54 atmospheric levels. Another type of wave has a series of fronts that appear to be radiating outward 55 from the center of a cyclone. Most of these waves appear within  $5^{\circ}$  of latitude from the equator, 56 but we have detected waves covering planetocentric latitudes between 20°S and 45°N. The great 57 majority of the waves appear in regions associated with prograde motions of the mean zonal flow. 58 Juno was unable to measure the velocity of wave features to diagnose the wave types due to its 59 close and rapid flybys. However, both by our own upper limits on wave motions and by analogy 60 with previous measurements, we expect that the waves JunoCam detected near the equator are inertia-gravity waves. 61

62

63 Plain Language Summary

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65 The JunoCam camera aboard NASA's Juno mission to Jupiter has detected wave-like features over its 20 orbits that are smaller and more numerous than ever seen before in Jupiter's atmosphere. 66 Most of the waves are in elongated wave packets, spread out in an east-west direction, with wave 67 68 crests that are often perpendicular to the packet orientation; others follow curved paths. The space 69 between wave crests can be as short as 30 kilometers. Some waves can appear close to other 70 atmospheric features in Jupiter, while others seem to have no relationship with anything nearby. 71 In one case, wave crests appear to be radiating outward from the center of a cyclone. Most waves 72 are expected to be atmospheric gravity waves - vertical ripples that form in the atmosphere above 73 something that disturbs air flow, such as a thunderstorm updraft, perturbations of flow around 74 other features, or from some disturbance from below that JunoCam does not detect. JunoCam is 75 uniquely qualified to make such discoveries, with its wide-angle field of view that delivers 76 sweeping vistas of the giant planet's atmosphere as the spacecraft swoops within about 2,100 miles 77 (3,400 kilometers) of Jupiter's cloud tops during each science pass.

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## 81 1. Introduction

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83 The Juno mission's JunoCam instrument (Hansen et al. 2017), conceived as a public-84 outreach camera, has provided a surprising wealth of scientific results. These include the first 85 close-up examination of Jupiter's polar regions (Orton *et al.* 2017), in particular the unexpected presence and properties of constellations of cyclonic vortices around each pole (Adriani et al. 86 87 2018a, Tabataba-Vakili et al. 2019). JunoCam's proximity to Jupiter's cloud tops has also provided high-resolution details of Jupiter's Great Red Spot and its environment (Sánchez-Lavega 88 89 et al. 2018). These studies have been enabled by JunoCam's wide field of view (58°) and the 90 close proximity of the spacecraft to the clouds being imaged, with target distances as small as 3,500 km near closest approaches ("perijoves"), yielding a horizontal pixel-to-pixel spacing as 91 92 good as 3 km.

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94 We have used JunoCam's coverage over a wide range of latitudes, coupled with its high 95 spatial resolving power, to examine all of our images for various phenomena in Jupiter's clouds. Small-scale waves, with wavelengths (distances between wave crests) less than ~300 km, were 96 97 first detected in 1979 by Voyager (Hunt and Muller, 1979) and have been detected by Galileo (e.g. 98 Bosak & Ingersoll, 2002) and New Horizons (e.g. Reuter et al., 2007) since then, as well as by the 99 near-infrared JIRAM instrument on Juno (Adriani et al., 2018; Fletcher et al. 2018). Larger waves, 100 with scales of 1200 km or greater, have since also been detected from the Earth using Hubble 101 Space Telescope (HST) and ground-based imaging (Simon et al., 2018). A summary of 102 observations of these waves is given in Table 1, which includes and updates similar information 103 in Table 1 of Simon et al. (2015) and various tables in Simon et al. (2018). Table 1 includes a JunoCam wave feature examined by Sánchez-Lavega et al. (2018) that we will also consider in 104 105 this report. No waves were detected by the Cassini mission, most likely because Cassini was too 106 far from Jupiter for adequate spatial resolution, but other reasons as possible. Virtually none were 107 seen by Galileo imaging despite several close, although spatially limited, passes. The planet-108 encircling New Horizons waves were a surprise, as were the larger waves observed by HST and 109 ground-based imaging for the past four years, which Cassini would have detected. During the 110 Cassini epoch, there may not have been sufficient contrast to detect waves or waves were simply 111 not propagating because of conditions unknown. 112

Below, we describe how the measurements are made, followed by a survey of the different types of atmospheric waves we have detected - along with any analogous wave formations in the Earth's atmosphere. We then discuss quantitative properties of the waves and conclude with an analysis and discussion section.

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## 119 2. Description of the measurements

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JunoCam is a CCD-based camera, spanning a 58° field of view. The instrument is a "pushframe" imager, taking advantage of Juno's 2 RPM spin to sweep its 58° swath to build spatial and spectral coverage without involving a shuttering mechanism. Thus, sequential images are acquired in broadband blue, green and red filters plus a narrow-band filter centered on a 889-nm methane absorption band. Time-delayed integration of multiple pixel rows builds up the signal-to-noise ratio. Hansen *et al.* (2017) provide details of the instrument and its modes of operation. Sequential images are typically rendered in red-green-blue ("RGB") composites, with the "methane filter" acquired and rendered separately, and the RGB images cover all latitudes on nearly all perijoves. The spatial resolution varies with the distance to the planet, which changes with each orbit: successive perijoves move approximately one degree of latitude north. For all the waves we discuss in this report, the spatial resolution is much finer than the distances reported in each case.

132

133 In order to determine properties of the features, each image was transformed into a 134 cylindrical cartesian map in longitude and latitude. This was done independently of the standard 135 coordinate-transformation approach using the SPICE system (Acton 1996), as image timing, 136 orientation in the spacecraft coordinate system and optics distortion were still being determined. 137 We used limb fitting to constrain these properties, as the limb appears in all of our images. Current 138 SPICE data show good agreement with these maps, with the limb-fitting approach showing an 139 uncertainty better than 2° in the position of the south pole, as reported by Tabataba-Vakili et al. 140 (2019). Further details of this mapping process are provided by Adriani et al. (2018: see their 141 Supplementary Information) and by Tabataba-Vakili et al. (2019). All JunoCam images are 142 publicly available on the Mission Juno web site:

- 143 https://www.missionjuno.swri.edu/junocam/processing.
- 144

Figure 1 shows an example of a full JunoCam image, rendered in a cylindrically mapped format, together with an excerpt ("crop") of the image in which we identify wave-like features.

147 The mapped versions were adjusted to compensate for the variation of illumination across the field.

We found that a second-order power-law enhancement of color composites allowed wave features 148 149 to be identified more readily. For the images shown below, as well as in the Supplemental 150 Information, we further stretched each red, green and blue color independently for ease of identification by the reader. We also applied unsharp-mask sharpening in a few cases to make 151 152 faint waves appear more prominently. Several coauthors independently searched manually through 153 all of the JunoCam images in order to identify wave-like features that were candidates for this 154 study. For detailed quantitative measurements, we used additional high-pass filtering to isolate 155 fine-scale features. Our quantitative measurements are based on maps of the images rendered with 156 180 pixels per degree of latitude and longitude, together with high-pass filtering. We did not find 157 identifiable wave features in any methane-band images. As a result, our discussion will be limited 158 to enhanced RGB-composite images. We did not see any consistent differences in the contrast of 159 wave features between the colors in images, which do not have any radiometric calibration.

160

# 161 3. Results

162 163

3.1 Overview.

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We limited the search for and characterization of waves to observations between perijoves 166 1 and 20 (2016 August 27 – 2019 May 29). Hereafter we will abbreviate "perijove" as "PJ". 167 During PJ2 (2016 October 19), no close-up images were made of Jupiter's atmosphere as the result 168 of a spacecraft "safing" event immediately before close approach. During PJ19 (2019 April 6), 169 JunoCam only took distant images of Jupiter, as a result of an unusual orientation of the spacecraft 170 for most of that perijove in order to enable scanning in longitude by Juno's Microwave Radiometer (MWR) instrument. The Supplemental Information to this report documents and illustrates <u>all</u> of the images in which we identified wave-like features with more than two wave fronts, together with a visual aid to identify the waves. In this report we select particular images that provide examples of the wide variety of waves and wave-like phenomena and their properties. The reader is free to observe all the images that are available in various processed forms on the Mission Juno web site in order to verify or refute our selections, as well as to identify potential additional candidates.

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3.2 Types of wave-like features.

Our survey of JunoCam images has revealed a surprising variety of features with wavelike morphologies. In order to be inclusive in our inventory, we include here (and in the Supplemental Information file) features with any regularly repeated patterns that are three or more in number. The survey below includes many features that have not been discussed previously in the context of atmospheric waves in Jupiter. They are presented in terms of differences in visual morphology, without implication that this differentiation arises from the associated responsible dynamics.

188

189 3.2.1 Long wave packets with short, dark wave fronts represent 79% of the types of waves
 190 in our inventory, especially in the Equatorial Zone (EZ) that were also detected in previous studies,
 191 particularly from Voyager imaging (Table 1).

192 3.2.1.1. Orthogonal wave crests. Figure 2 shows two examples of these waves in which the 193 wave front is more-or-less orthogonal to the direction of the wave packet. The morphology of the 194 waves shown in Fig. 2 is most similar to those waves described in the articles cited in Table 1, 195 although they are an order of magnitude smaller. They are most commonly referred to as mesoscale 196 waves, by analogy to their appearance in the Earth's atmosphere. Our search through JunoCam 197 images (see the images in the Supplemental Information file) did not appear to sample any of the 198 longer-wavelength (~1200-1900 km) packets detected by previous studies (Table 1), most likely 199 as a result of the limited area over which JunoCam images can cover.

200 3.2.1.2. "Tilted" wave crests. Even more commonly, the detected packets have wave 201 fronts that are not oriented orthogonally to the wavefront direction. Several examples of these 202 "tilted" wave fronts are shown in Figure 3. Simon et al. (2015) stated that this is consistent with 203 an interpretation of the waves as baroclinic instabilities that tilt northward and westward with 204 altitude, as noted on a theoretical basis by Holton (1992) and by observations of waves in the 205 Earth's atmosphere (e.g. Blackmon et al. 1984). This implies that we are sensing the upper 206 levels of such waves. Several images reveal the presence of large numbers of similar waves, as 207 shown in the various panels of Figure 4. The waves are most often short with wave packets 208 oriented east-west, although there are many wave packets not ostensibly oriented in any 209 preferred direction (Fig. 4D). Some clearly cross one another, implying that the sources of their 210 origin are not uniform. Simon et al. (2015b) argue that, if the waves are baroclinic instabilities, 211 then their meridional extent depends on the Rossby radius of deformation, which they estimate 212 as between 500 and 1400 km near the equator, which is where most of our detections of these 213 waves lie. The Rossby radius of deformation is also where energy is transferred from small-214 scale turbulence to zonal winds (see Salyk et al. 2006, Young and Read 2017). Since the mean 215 of both meridional extent (~250 km on average) and wavelength (distance between wave crests, 216  $\sim$ 170 km), are much shorter than the Rossby deformation radius, it is logical to assume that they

are formed by and interact with small-scale turbulence, and thereby propagate the waves in all

directions. This is consistent with our observation that few, if any, of these waves are clearly associated with other atmospheric features.

220 3.2.1.3. Curved wave packets. Sometimes the short wavefronts are aligned in wave packets that themselves appear to be curved, are associated with larger features, and are not located in the 221 222 EZ. Figure 5 shows two examples. Figure 5A shows the short wave-packets associated with the 223 curved northern boundary of the Great Red Spot (GRS) near 15.8°S, described by Sánchez-Lavega 224 et al. (2018). This is the first of two cases in which multiple images of waves were made, the result 225 of intensive targeting of the GRS by Juno at PJ7. Sánchez-Lavega et al. (2018) estimated a phase 226 speed for the wave of 45±20 m/s relative to the very rapid local flow and determined that they 227 were consistent with internal gravity waves, given estimates for the Richardson number for that 228 part of the atmosphere that were based on the vertical wind shear deduced from temperature maps 229 of the region (Fletcher et al. 2010). Two other examples of such wave packets imaged at PJ15 are 230 shown. Figure 5B shows one on the south edge of a bright anticyclonic eddy in the NEB near 231 15.8°N, and Figure 5C shows one on the south edge of a dark cyclonic circulation in the SEB near 232 17.3°S. Just as for the wave trains in the northern edge of the GRS (Fig. 5A), these two wave 233 packets are located on or near the peaks of retrograde (westward) flows that are probably 234 accelerated in these locations because of the circulation. 235

236 Another curved wavefront example is shown in Figure 5D: a dark, lobate feature with short 237 wave crests that are most clearly detectable along its periphery. This feature is located in the 238 chaotic region to the west of the GRS (see Fig. 6 for context). Interestingly, the entire chaotic 239 region covers a much larger area to the northwest and west of the GRS, but these waves only 240 appear in the region shown in Figure 5D. The dark part of this lobate feature appears only slightly 241 brighter in 5-µm radiance than its surroundings using contemporaneous NASA Infrared Telescope 242 Facility (IRTF) observations. Thus, it is likely to be a region of very moderate dry downwelling 243 that only partially clears out particles in cloud layers. Although the series of wave crests appears 244 to line the sharply curved periphery of the dark feature, the crests are more likely to be roughly 245 parallel streaks in a haze that overlies the entire region, with their visibility over the darker regions 246 of this image strongly subdued. This interpretation is reinforced by studies of the winds from 247 Juno-supporting observations by HST (Wong et al. 2020). Figure 6 shows the results of tracking 248 winds in this region. Relative to the mean zonal winds, the residual winds shown in this figure 249 appear to be flowing up toward the northwest along the dark lobe with speeds of  $65\pm17$  m/s. Thus, 250 the waves appearing in Fig. 5D are aligned with the local retrograde flow in high-shear regions. In 251 this respect, they are similar to the curved wave packets described in the preceding paragraph.

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253 3.2.2. Short wave packets with wide wave fronts, shown in Figures 7 and 8, are also 254 detected in our survey. In the Earth's atmosphere, such waves are often associated with 255 thunderstorms producing a brief impulse period with radiating waves. Other curved features 256 situated adjacent to each other are shown in the Supplemental Information file, which are shorter 257 and difficult to distinguish from different albedo clouds that are stretched along streamlines (see 258 Figs PJ05 108, PJ14 25a, PJ14 25b, and PJ14 25c.) Somewhat similar features were detected 259 in a Voyager image of "spiral" waves to the west of a dark brown cyclonic feature commonly 260 called a 'barge' (Simon et al. 2018). Although there is some overlap between these waves and 261 those described in section 3.2.1 in a spectrum of the length-to-width ratio of waves, these waves

appear to occupy a generally distinct locus in plot of the length vs width of waves (see Fig. SI3-2in the Supplemental Information).

264

265 Other waves are even more distinct. The arrows in Figure 8 show extremely long, closely spaced parallel lines that could be waves. Just as for the wave packets illustrated in Figure 7, both 266 267 are curved. The pair of lines indicated in the upper part of the figure appear to have no visual 268 association with any nearby feature, although they are situated between the bright (possibly 269 upwelling) spot to the north and the darker region to its south. This darker region is an extension 270 (sometimes called a "festoon") of a blue-gray region along the southern boundary of the North 271 Equatorial Belt associated with bright 5-µm radiances, called a "5-µm hot spot". The narrow dark 272 lines indicated in the bottom of Figure 8 are close to the southern boundary of the dark festoon. 273 Although they could simply be long streaks associated with streamlines of flow along the festoon, 274 they appear to be particularly narrow and well defined with sharp edges, particularly at their eastern extents. This differentiates them particularly from far less distinct streaks along the northern 275 276 boundary of the festoon. They are also accompanied by shorter crests that are aligned 277 perpendicular to the length of the lines. These orthogonal waves are not explicitly indicated in 278 Figure 8 by white grids in order to make the extent of the long lines clearer, but they are illustrated 279 in the same region shown in the Supplemental Information file as Figure 20 34a. Orton et al. 280 (2017) detected linear features in the north polar region, but they were associated with the edge of 281 a well-defined haze region whose boundary could be traced using the 890-nm "methane" JunoCam 282 filter. JunoCam did not take images of the features indicated in Figure 8 with the 890-nm filter, 283 and they are below the spatial-resolution limits of Earth-based imaging in similar filters. The 284 closest morphological analogies in the Earth's atmosphere might be roll clouds, formerly known 285 as cumulus cloud streets, e.g. Yang and Geerts (2014), which are most often detached from but 286 associated with a cumulonimbus base. These are now classified as volutus clouds 287 (https://cloudatlas.wmo.int/clouds-species-volutus.html) by the International Cloud Atlas. 288 Another possibility is that they represent a version of transverse cirrus clouds, identified in upper-289 level tropospheric structures in the Earth's atmosphere (Knox et al.2010).

290

291 3.2.3. Wave packets with bright features appear different from the waves indicated up to 292 this point (Figs. 2-7), which are recognizable by their dark or alternating dark-to-light crests. 293 JunoCam has imaged many waves and wave-like features that are manifested as regular, repeated 294 patterns of bright clouds, visually similar to terrestrial water-based clouds. We presume that 295 differences between darker and brighter wave crests could be the composition of the material 296 affected. Possibly the waves themselves induce condensation of bright white clouds along their 297 crests, similar to what was seen in the mid-NEB on much larger scales by Fletcher et al. (2017). 298 This might imply differences in altitude, e.g. perturbations of an upper-tropospheric haze layer near 200-300 mbar (e.g. Sromovsky et al., 2017, and Braude et al. 2020) versus those of a 299 300 condensate cloud, such as a layer of "cirrus" NH<sub>3</sub> ice particles near the 600-mbar condensation 301 level. This corresponds to an altitude difference near the equator of roughly 15-20 km, an interval 302 on the order of or less than an atmospheric scale height.

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Figure 9 shows a variety of examples of regular spacings between light-colored clouds detected by JunoCam. We lack the means to determine whether dark regions adjacent to lighter ones simply represent lower-albedo regions that are relatively cloudless or actual shadows of the brighter clouds. One likely exception to this are the clouds associated with the wave packet in the

308 upper-left area of Figure 9A, which appear similar to terrestrial cirrocumulus clouds that have 309 shadows associated with them. (If all of the dark area to the right of the largest dark region is a 310 shadow, then the height of the largest cloud relative to the region around the cloud is on the order 311 of 10 km.) We repeat the caveat of Simon et al. (2015) that such dark features may not be shadows but local regions of aerosol clearing "as atmosphere parcels rise and ices condense out to make the 312 313 wave crests". The clouds in the other panels are often arranged in a straight line or a segmented 314 straight line with cirrus-like wisps trailing away from them. Figure 10 shows other regular patterns 315 of bright clouds that are associated with narrower white features. The narrow meridional extent of 316 these clouds (~150 km or less) is potentially the result of a very meridionally constrained flow. 317 We note that both are curved and could be associated with constraining wind flows.

318

319 Figure 11 shows four instances of very bright, discrete clouds forming regular, extended 320 patterns. These clouds extend to higher altitudes than their surroundings, as evidenced by shadows 321 that often accompany them. Individual clouds such as these appear in various locations elsewhere 322 in the planet, and we will describe and analyze them as a class in a separate report. We include 323 this subset of them in our description of a distinct type of wave. Figure 11A shows a close up of 324 such clouds, an expanded portion of Fig. PJ04 103b in the Supplemental Information file. A wave 325 packet can be seen that appears to be controlling small, bright cloud features. These are located in 326 a bright patch that is part of a complex system of upwelling disturbances in the North Equatorial 327 Belt (NEB), also known as 'rifts'. Figure 11B shows a weak anticyclonic feature, in the center of 328 which is a central bright cloud, accompanied to its southeast through southwest by short linear 329 arrays of similar bright clouds. Two are shown with white grids that indicate individual cloud 330 features that are resolved. Figures 11C and 11D also show individual clouds that comprise a wave 331 packet, similar to the linear packet shown in Figure 11A. In Figure 11C, the clouds appear like 332 balls or small smears, whereas in Figure 11D they appear like C-shaped arcs. If the dark regions 333 accompanying the clouds in Figs. 11B, 11C and 11D are shadows, it would imply that they are 334 clouds whose tops are higher than the surrounding darker cloud deck. Based on the incident angle 335 of illumination, we estimate from the length of its shadow that the central cloud in Fig. 11B is only 336 3-4 km above the surrounding cloud deck. A similar estimate for the range of shadow lengths 337 associated with various bright clouds in Fig. 11C implies that they are 5-12 km above the 338 surrounding cloud deck. From the shadows associated with several C-shaped arcs in Fig. 11D, we 339 estimate that they rise as much as 6-13 km above the background cloud deck. There are other 340 similar features in both Figs. 11C and 11D, but they are not fully resolved. Although we cannot 341 determine with absolute certainty that these clouds extend down to the level of the surrounding 342 cloud deck, that is the impression one gets if the accompanying dark regions are interpreted as 343 shadows. If these bright clouds do extend vertically downward to the surrounding cloud deck, 344 then they appear less like linear versions of stratiform clouds on the Earth, than a series of 345 upwelling cumulus clouds in which the intervening spaces between them simply represent regions 346 of compensating subsidence.

347

348 3.2.4. Lee waves are stationary waves generated by the vertical deflection of winds over 349 an obstacle, such as a mountain, a thermal updraft or a vertical vortex. Unlike the Earth, there are 350 no mountains in Jupiter's atmosphere, but there may indeed be the dynamical equivalent. If the 351 long streaks in Figure 12 that stretch diagonally (upper left to the lower right) in the figure are 352 tracking streamlines associated with local winds, and the winds are moving from the northwest to 353 the southeast (upper left to the lower right in the figure), then the lee wave is the three-wavefront 354 feature indicated by the white grid lines that is orthogonal to the flow. This requires that the local 355 winds are passing not only around the bright upwelling anticyclonic vortex in the upper left of the 356 frame, but also over it, consistent with very subtle streaks seen over the bright vortex. We note 357 that not only the three waves indicated but also the lines that appear to be tracing the wind flow are elevated above the background cloud field, as marked by the shadows on their eastern sides. 358 359 The most prominent of the shadows is on the eastern side of the central wave, the length of which 360 implies that the peak of the wave is some 10 km about the background cloud deck. This is, in fact, 361 the only example of such a wave in our survey. One reason could be that other atmospheric 362 features are too high to permit flow over them, compared with the relatively young anticyclonic 363 vortex in Figure 12.

364

365 3.2.5. Waves associated with large vortices are shown in Figure 13. Figure 13A shows a 366 very compact cyclonic feature with a set of extended radial wavefronts in the North Equatorial Belt. These resemble similar structures in terrestrial cyclonic hurricanes. The waves delineated 367 368 in Figure 13A show morphological similarities to "transverse cirrus bands" (hereafter 'TCB') 369 identified in upper-level tropospheric structures on Earth (Knox et al. 2010). TCB are defined by 370 the American Meteorology Society as "Irregularly spaced bandlike cirrus clouds that form nearly 371 perpendicular to a jet stream axis. They are usually visible in the strongest portions of the subtropical jet and can also be seen in tropical cyclone outflow regions." (American 372 373 Meteorological Society 1999). TCBs are also frequently observed in midlatitude mesoscale 374 convective systems (MCS) and in extra-tropical cyclones. Numerical studies (Trier et al. 2010, 375 Kim et al. 2014) have successfully replicated these cloud features and therefore have provided insight to their formation. Currently, there is no consensus regarding the dynamics responsible for 376 TCB in all their observed forms (Knox et al. 2010). Multiple interacting factors that have been 377 378 implicated in the genesis of these features, including gravity waves, Kelvin-Helmholtz 379 instabilities, weak or negative moist static stabilities, and vertical wind shears (Dixon et al. 2000, 380 Trier et al. 2010, Knox et al. 2010).

381

382 There are some common characteristics that TCB share in the Earth's atmosphere. First, 383 the bands frequently originate in a region of anticyclonic vorticity, positive divergence, and in 384 weak or negative static stability (Trier et al. 2010). Second, the majority of the bands appear in 385 regions of strong relative vorticity gradient, and often persist beyond the life of the originating 386 MCS (Lenz 2009). Third, the bands are often oriented along the vertical wind gradient, which 387 provides surprising evidence they share some dynamical characteristics with boundary-layer 388 horizontal convective roll vortices (Trier et al 2010, Kim et al. 2014), commonly observed on Earth 389 as cloud streets (Yang & Geerts 2006). Fourth, there is evidence that gravity waves propagating 390 below the cirrus cloud deck, the release of latent heat within the bands, and longwave cooling 391 above and longwave warming below the bands appears to favor the formation of TCB. In addition 392 to Figure 13A, the wave-like features shown in Figs. 2A, 3D, 4A, 5, 9A, and 9C appear similar to 393 terrestrial TBC. Although it is difficult to know if they are true analogs in the absence of detailed 394 horizontal wind measurements of these clouds (as well as temperature measurements to understand 395 the 3D wind gradients), their morphologies are suggestive. If this is the case, then complex small-396 scale dynamics may be operating in and below the Jovian ammonia cloud deck not dissimilar to 397 those on Earth.

399 The wave features in Figure 13A bear some resemblance to similar features found in 400 tropical cyclones. Animations of tropical cyclones show high-frequency circular gravity waves in the central dense overcast cirrus shield ('CDO', Molinari et al. 2014) emanating from vigorous 401 402 convection in or near the eyewall. Perhaps more relevant to the appearance of the features in Figure 403 13A, radial-aligned TCB are also commonly observed as 'spokes', which are more or less oriented 404 orthogonally to the gravity waves. In many cases, the circulation of the parent vortex twists the 405 spokes to appear like the teeth of a circular saw blade or as long thin curved filaments. In addition, 406 shallow-water numerical modeling of vortex dynamics using the Explicit Planetary Isentropic 407 Coordinate (EPIC; Dowling et al. 1998) in Brueshaber et al. (2019) also display curved wave-like 408 features similar to those in Figure 13A, but their waves are certainly due to gravity waves formed 409 during the merger of like-signed vortices for which we have no direct evidence in this figure.

410

411 On the other hand, for the much larger anticyclonic white oval in Figure 13B, it is possible 412 that the curved cloud features appearing there to be a manifestation of gravity waves. The spatial 413 resolution of this image is sufficient to see both the internal spiral structure of the white oval and 414 a regular set of dark bands extending to its exterior. Anticyclones on Jupiter, such this one, often 415 feature a high-speed 'collar' surrounding a calmer interior (e.g., Marcus 1993). The shear of the 416 high-speed wind against slower winds outside of the vortex may be sufficient to generate a Kelvin-417 Helmholtz wave, which may explain the scalloped appearance of the white clouds adjacent to the 418 surrounding red clouds.

419

420 421 3.2.6. Long, parallel dark streaks are detectable at mid-latitudes. Long streaks are seen in many 422 areas of Jupiter's cloud system, usually with a non-uniform and chaotic pattern (e.g. the diagonal 423 ones in Fig. 12). But, as shown in Figure 14, some are seen in very regularly spaced parallel bands. 424 In several cases, the parallel banding is not only regularly spaced but sinusoidal in behavior, with 425 a distance between crests ranging between 280 and 360 km. All such features are detected far 426 from the equator. Their orientation suggests that they are tracing out the direction of flow on 427 streamlines, in often complicated patterns, with lengths from 500 km to 3800 km (an upper limit 428 that may be constrained by JunoCam's field of view). Almost all of the parallel streaks in the 429 examples shown in Fig. 14 are associated with larger atmospheric features, although those features 430 do not appear to be located where the streaks originate. In Figure 14A, one set of these appears to 431 be 'flowing' around an anticyclonic vortex in the lower left. It and a set of streaks in the center of 432 the feature have topography, with shadows apparent on their eastern sides. In Figure 14B, long 433 streaks possibly are associated with streamlines 'flowing' around small, red anticyclonic vortices. 434 The NTB was very turbulent at the time of these observations, following a great disturbance in the 435 preceding months (see Sánchez-Lavega et al. 2017). A semi-transparent triplet of short, dark bands 436 in the top left of this figure can be seen lying across longer bands that appear to be tracing wind 437 flow. Figure 14C shows parallel streaks located between a weak cyclonic eddy on the left and a 438 bright wave-like streak aligned with the SEBs retrograde jet, at the bottom edge of the panel. 439 Figure 14D shows several parallel cloud streaks in this turbulent part of the North North Temperate 440 Belt (NNTB). Some are associated with the small cyclonic vortex in the lower right side of the 441 panel. Often, the streaks appear to be on top of other features, implying that they represent flow 442 that is manifested in a haze layer overlying deeper cloud layers. The best analog to these features lies not in the Earth's atmosphere but in Saturn's. Ingersoll et al. (2018) examine high-resolution 443 444 images of Saturn's clouds taken during the Cassini mission's "proximal orbits". Their Figure 3

shows a flow around a vortex that is very similar to one around the vortex in Figure 11A. For their similar "thread-like filamentary clouds", they suggest that the implied laminar flow implies extremely low values of diffusivity and dissipation, which further quantitative analysis of these observations may verify is the case for these scales in Jupiter, as well.

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450 3.2.7. Unusual features are shown in Figure 15, which we might classify as waves only in the most 451 general sense. Figure 15A shows a series of features with a regular spacing: three curved 452 wavefronts next to an unusual series of relatively dark ovals indicated by the arrows. The dark 453 ovals may be connected dynamically to the wavefronts, because they continue in the same 454 direction and have roughly the same wavelength. The morphology of the three wave fronts implies 455 that flow is from the northwest. We do not see an array of short, dark, curved lines elsewhere, so 456 their spatial association with each other is extremely unusual. They are located near the boundary 457 between the turbulent northern component and the smooth, orange southern component of the 458 North Temperate Belt. Figure 15B shows a limited series of repeated patterns along the southern 459 edge of an unusual white band located at the turbulent boundary between the northern and southern 460 components of the North Temperate Zone. This short sequence bears some resemblance to a Karman vortex street, although one that may be dissipating or disrupted. 461

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### 464 3.3 Quantitative measurements of wave properties.

- 465 466
- 467 3.3.1. Measurements of meridional distribution and size properties.
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Measurements were made of physical properties of all of the waves and wave-like features discussed. A table of all of these is available in the Supplemental Information file. Features are identified by Perijove and File number. Measured quantities are: the number of waves, the mean System-III longitude, mean planetocentric latitude, length and width of the wave train, the mean wavelength (distance between crests) and the tilt of the wave with respect to the orientation of the wave packet.

476 Figure 16 shows a histogram of the occurrence of waves as a function of latitude. In order 477 for the reader to distinguish between different classes of wave-like features, some of which are 478 arguably not propagating waves, we have separated out the different types of waves by 479 morphology as discussed in the preceding sections. Table 2 shows our count of the different 480 categories of waves. The overwhelming majority of wave-like features are clustered between 7°S 481 and 6°N latitude, the relatively bright EZ. These features are dominated by long wave packets 482 with short wave crests, the type of waves detected by Hunt and Muller (1979) and discussed by 483 Simon et al. (2015a) as mesoscale waves observed at low latitudes by previous imaging 484 experiments. These waves fall within the relatively bright EZ and appear to be sub-clustered with 485 fewer waves between 1°S and the equator than between either 7°S and 1°S or the equator and 6°N. 486 The next most populous category are waves with short packet lengths and long crests, which appear 487 to be distinct not only because they appear to be clustered differently in length vs. width ratios, but

488 also because they mostly populate latitudes between 1°N and 3°N. Waves that are generally 489 associated with or influenced by larger features, most often associated with curved wave packets, 490 are the next most abundant feature. These include the curved wave packets at the northern 491 boundary of the GRS (Fig. 5A), the wave packets on the southern edge of a cyclonic circulation in 492 the SEB (Fig. 5b) and on the southern edge of an anticyclonic eddy (Fig. 5C), wave packets 493 associated with the lobate feature in the chaotic region west of the GRS (Fig. 5D), and parallel 494 stripes near a weak eddy (Fig. 14C). All are located in regions of retrograde flow, as shown in 495 Figure 17. All other types of features are detected less frequently (Table 2) and are scattered in 496 the northern hemisphere. No waves of any type were detected south of 7°S other than the ones 497 between 17°S and 20°S that are associated with larger features. There may be a small selection 498 effect associated with the observations, since latitudes in the northern hemisphere are observed 499 with an average spatial resolution that is higher than in the southern hemisphere, arising from the 500 fact that the Juno spacecraft perijove is in the northern hemisphere and moving northward by about 501 a degree of latitude for each successive, highly elliptical orbit. Perijove latitudes ranged from 502 3.8°N for PJ1 to 20.3°N for PJ20. Arguing against this is the fact that waves were detected in the 503 southern hemisphere with wavelengths between 70 km and 200 km, meaning that waves of this 504 size range would have been detectable elsewhere if they were present. Such waves might, in fact, 505 be present but undetectable if the hazes making them visible in the northern hemisphere were not 506 present in the southern hemisphere outside the EZ, for some reason.

507

508 Is the observed distribution of waves associated with other indicators of upwelling or 509 turbulence? Clearly the preponderance of waves in the EZ is not correlated with the frequency of 510 lightning detections, as no detections of lightning have been associated with that region, either 511 historically (e.g. Borucki & Magalhães 1992, Little et al. 1999, Dyudina et al. 2004) or in the broad 512 survey by the Juno Microwave Radiometer (Brown et al. 2018) that is sensitive to lightning 513 discharges in the EZ (Juno's Waves instrument, Imai et al. [2018] could not detect lightning in the 514 EZ because the field lines do not reach Juno's orbit.). The presence of water ice is one indirect 515 measure of upwelling, and its detection from Voyager IRIS data by Simon-Miller et al. (2000) revealed a distribution that included the EZ but was significantly higher at latitudes south of ~10°S. 516 517 This is consistent with our results only in the limited sense that several waves were associated with the GRS and its surroundings. Another indirect measure is the presence of pristine ammonia ice, 518 519 as measured most recently by New Horizons (Reuter et al. 2007), which determined that spectrally 520 identifiable ammonia clouds (SAICs) occurred "near active storms or upwelling regions", which 521 includes some regions in the EZ and is more broadly consistent with several of our specific 522 observations at higher latitudes. New Horizons did not detect SAICs near the GRS, as the typically 523 chaotic region to its northwest was not active during the New Horizons encounter. From the Juno 524 mission itself, the striking deep column of concentrated ammonia at 2°N to 5°N detected by the 525 Microwave Radiometer (MWR) instrument implies upwelling (Li et al. 2017, Bolton et al. 2017), 526 which is consistent with the concentration of waves there. This is consistent with 527 contemporaneous ground-based observations (de Pater et al. 2019, Fletcher et al. 2016, 2020). 528 However, we detected an equal number of waves in the southern component of the EZ, where there 529 was not nearly as great a concentration of ammonia gas, so this particular correlation is imperfect. 530 We note that from studies of cloud properties from reflected sunlight, the full EZ is known as a 531 region in which tropospheric clouds and hazes extend higher than other locations on the planet 532 outside the GRS, as evidenced by the general concentration of upper-atmospheric opacity 533 historically (e.g. West et al. 1986) and in more recent work (see Figs. 4 and 12 of Sromovsky et 534 al. 2017, Fig 13B of Braude et al. 2020) or by the distribution of disequilibrium constituents (see 535 Fig. 4 of Orton et al. 2017b). This is consistent with the entire EZ being a region of general 536 upwelling.

538 Figure 17 plots the distribution of mean wavelengths for different types of waves and wave-539 like features as a function of latitude, co-plotted with mean zonal wind velocity. The minimum 540 distance between crests is 29.1 km for the spacing between the discrete white features shown in 541 Fig. 10A. Not significantly larger is the 30.9 km between crests of waves in a low-latitude long 542 wave packet with short crests. These values are available in Table 1 of the Supplementary 543 Information file. The variability of wavelengths within a single packet is typically no greater than 544 20-30%. The equatorial waves with long packets and short crests in the EZ have wavelengths that 545 are clustered between 30 km and 320 km, with most between 80 and 230 km in size. The bimodal 546 appearance of the distribution of EZ waves is not consistent with the distribution of waves detected 547 from Voyager (Simon et al. 2015a), which also has several wave packets distributed at latitudes 548 south of the EZ (see Figure 17). Similar to our study, most of these are associated with the GRS. 549 Similar to Voyager, all the waves detected in JunoCam images in regions of retrograde flow are 550 associated with discrete atmospheric features, such as the GRS. The virtual absence of waves 551 observed in Voyager images covering the northern hemisphere is ostensibly the opposite of what 552 we observe with JunoCam, although the key in Figure 16 shows that many of the wave-like 553 features in the northern hemisphere might not have been categorized as waves by Voyager 554 investigators.

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537

#### 556 3.3.2. Measurements of wave phase speed.

557 The most diagnostic criterion between different types of waves is the propagation speed. 558 The waves in the EZ were discovered by Voyager 1 and described by Hunt & Muller (1979), who 559 found them to have low or zero speeds relative to their surroundings (whether in a plume tail or 560 equatorial clouds). Simon et al. (2015b) also found little relative motion for these waves in 561 Voyager 2 and Galileo Orbiter images. Arregi et al.(2009), studying Galileo Orbiter images, likewise found no measurable relative motion for waves on the equator, but a phase velocity of 35 562 563 (+/-8) m/s for waves at 3°S. Simon et al. (2015b) adopted the conclusions of Flasar & Gierasch 564 (1986), Bosak & Ingersoll (2002) and Arregi et al. (2009) that these waves detected by Voyager 565 and Galileo images were best classified as inertia-gravity (IG) waves, a conclusion we do not 566 revisit here. On the other hand, Simon et al. (2015b) differentiated the waves detected by New 567 Horizons as Kelvin waves from those by Galileo and Voyager as IG waves on the basis of their 568 phase velocity, crest length, and location; they measured a non-zero velocity (80±5 km/s) relative 569 to the local zonal wind for the Kelvin waves that are confined to the equator compared with the IG 570 waves, which are near stationary (upper limits to the phase velocity of 40 m/s or less). 571 Unfortunately, the Juno spacecraft and orbit configuration that provides such close-up observations of Jupiter's clouds strongly limits our ability to determine velocities, and regions are 572 573 rarely observed at adequate spatial resolution more than once per perijove. Subsequent perijoves 574 typically observe longitudes that are far from the preceding one. Observations of the Great Red 575 Spot in PJ7 are one exception (Sánchez-Lavega et al. 2018), as noted above. Another is the 576 circulation associated with a large cyclonic feature observed by both JunoCam and ground-based 577 facilities (Iñurrigarro et al. 2020).

578

579 We made another attempt in PJ20 to observe one region several times during a perijove, 580 focusing on the northern component of the EZ, Images 33 through 37 (formally 581 JNCE\_2019043\_20C00033\_V01 through JNCE\_2019043\_20C00037\_V01). We examined these 582 quite carefully using a recently developed upgrade in our geometric calibration, which used limb-

583 crossing times to correct for otherwise undetected errors in the data-acquisition timing. The results 584 showed no change in the location of waves (marked in Fig. PJ20 34a in the Supplemental 585 Information file near 27.5°W longitude and 0.5°N latitude) over the 6 min, 4-sec interval between 586 the first and last images of this sequence. We quantify this using a very conservative standard of 587 2 pixels for the pointing uncertainty, equivalent to 14 km for Image 33 and 18 km for Image 37 – 588 a linear dependence on the distance of the spacecraft from the waves. Using 16 km as an estimate 589 of the mean displacement, this is equivalent to an upper limit for the phase speed of 44 m/s, a value 590 consistent with a supposition that these are IG waves.

591

592 Moreover, based on morphology alone, the New Horizons waves were slightly curved, had 593 a consistent distance between wave fronts of 305±25 km, a wave train that spanned the entire 594 visible equator (more than 200,000 km in packet length), and were centered at the equator, 595 spanning  $\pm 2^{\circ}$  in latitude (see Figs. 1 and 2 of Simon et al. 2015). The waves that we detected here 596 have a broad range of wavelengths and crest lengths, are located at latitudes significantly far from 597  $\pm 1.5^{\circ}$  of the equator, and many wave packets are very short. Therefore, we suggest that these types 598 of waves detected in JunoCam images, more similar to those seen in Voyager and Galileo 599 observations, are most likely to be IG in origin.

600

# 601 4. Conclusions and future work

603 Juno's public-outreach camera, JunoCam, detected a plethora of waves or wave-like 604 features in its first 20 perijove passes. Of these 157 features, 100 are waves with long, somewhat 605 linear packets and short crests are identified as mesoscale waves, consistent with earlier studies. 606 Many of these have wave crests that are nearly orthogonal to the wave packet orientation, although 607 others that were tilted compared with this orientation. Another 25 wave packets were detected 608 with short packets and long crests. As a group, they are likely to be features that are truly 609 propagating waves. They are more in number than was detected by Voyager imaging in 1979, and 610 they include waves that are smaller in wavelength than any detected by previous missions. These 611 waves form the vast majority of features detected in this study, and they are concentrated in a 612 latitude range between 5°S and 7°N. Short wave packets often appear in several different 613 orientations and sometimes overlap one another. Almost none of these appear to be associated 614 with other features except for waves that appear to be oriented in lines of local flow, including 615 packets with crests that appear darker than the local background or with bright features. These 616 bright features appear both as discrete, tall clouds with shadows that imply they are higher than 617 the background darker cloud deck, and simply as brighter features that have wispy "tails" and are 618 connected to one another by an equally bright but narrow, elongated cloud. The difference 619 between wide and narrow packets is presumably related to the width of the flow that is responsible 620 for the wave. There were fewer waves in the EZ between the equator and 1°N than there were 621 immediately north and south of this band, which was different from the waves detected by Voyager 622 imaging in 1979 that were more equally distributed.

623

Other waves, prominently those outside the EZ, are clearly associated with or influenced by other features. These include short-crested packets following the slightly curved path at the northern extent of the GRS, others associated with an anticyclonic eddy in the NEB and a cyclonic circulation in the SEB, and one associated with the turbulent flow west of the GRS. Three lee waves were detected in the wake of an upwelling anticyclonic vortex that were some 10 km above 629 the surrounding cloud deck. More features were detected that had repeated, wave-like features but 630 may not represent propagating waves. Some of the linear arrangements of discrete white clouds 631 followed the edges of vortices; although regular in spacing, these features may not represent 632 propagating waves so much as alternating positions of upwelling and subsiding vertical flows. 633 Several features appeared within or emanating from vortices. Two sets of extremely long, curved 634 features were detected near the edges of a southwestern extension of a dark blue-gray region 635 associated with high 5-µm radiances at the southern edge of the NEB. Long, sinuous parallel 636 streaks were detected, some with nearly sinusoidal lateral variability, that were analogous to 637 features observed by the highest-resolution imaging of Saturn's atmosphere by Cassini (Ingersoll 638 et al. 2018). No waves were detected south of 7°S that were not associated with larger vortices, 639 such as the GRS. No waves or wave-like features were detected in regions of retrograde mean 640 zonal flow that were not associated with larger features, similar to the waves detected by Voyager 641 imaging.

642

643 We had limited opportunities to classify waves on the basis of phase speed. Sánchez-644 Lavega et al. (2018) determined that the waves located at the northern extent of the GRS were 645 internal gravity waves from their propagation speed with respect to the local flow, based on a 646 displacement over a 9-minute interval between initial and final images. (Internal gravity waves 647 are similar to IG waves but where Coriolis forces are not considered to be important.) JunoCam 648 seldom observes features more than once, and usually with insufficient time to note a 649 displacement. Our attempt to observe features in the EZ on PJ20 resulted in a 6-minute interval 650 over which no motions were detected for equatorial features, providing an upper limit of wave 651 motions that was not inconsistent with inertia-gravity waves. However, the waves detected in the 652 EZ were not located directly at the equator, which bounded the Kelvin waves detected by New 653 Horizons imaging (Simon et al. 2015b). Otherwise, the waves detected in the EZ are 654 morphologically similar to those detected by Voyager, which Simon et al. (2015b) classified as 655 inertia-gravity waves. These waves may well be associated generally with the upwelling winds 656 that characterize the EZ. 657

658 Work will continue to document and detect waves and wave-like features in Jupiter's 659 atmosphere, including further attempts to examine regions over longer time intervals, although we note that observations of waves in the EZ will be lower in spatial resolution as the latitude of 660 successive perijoves migrates northward by about 1° per perijove. We will also look for 661 662 simultaneous measurements of waves in the near infrared by the JIRAM experiment to provide 663 some constraints on the altitude of these features, which were otherwise only loosely constrained 664 by occasional measurements of associated shadows. Furthermore, we expect that we and others 665 will use these observations as a motivation to engage in comparisons with terrestrial analogs and 666 numerical simulations that will further our understanding of the origin of these features and their implications for the dynamics of Jupiter's atmosphere at these small scales and their relation to the 667 668 larger picture of planetary dynamics at depth.

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670

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- 686
- All the images used in this study are available for direct download from the Mission Juno site:
   https://www.missionjuno.swri.edu/
- 689

690 We note that preliminary results, including a version of Figure 11, were included in a NASA press 691 release: https://www.jpl.nasa.gov/news/news.php?feature=7264.

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## 694 References

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Acton, C. H. 1996. Ancillary data services of NASA's navigation and ancillary information
 facility. *Planet. Space Sci.* 44, 65-70.

- Adriani, A., Mura, A., Orton, G., Hansen, C., Altieri, F., Moriconi, M. L., Rogers, J., Eichstädt,
   G., Momary, T., Ingersoll, A., Filacchione, G., Sindoni, G., Tabataba-Vakili, F., Dinelli, B.
- Monary, T., Ingerson, A., Fraccinone, G., Sindoni, G., Tabataba-Vakin, F., Dinem, J
   M., Fabiano, F., Bolton, S. J., Connerney, J. E. P., Atreya, S. K., Lunine, J. I., Tosi, F.,
- 701 Migliorini, A., Grassi, D., Piccioni, G., Noschese, R., Cicchetti, A., Plainaki, C., Olivieri, A.,
- 701 Wigholini, A., Orassi, D., Freefoni, G., Nosenese, K., Cleenetti, A., Frankki, C., Onvieri, A.,
   702 O'Neill, M. E., Turrini, D., Stefani, S., Sordini, R., Amoroso, M. (2018a) Clusters of cyclones
   703 encircling Jupiter's poles. *Nature*. 555, 216-219. doi 10.1038/nature25491.
- Adriani, A., Moriconi, M. L., Altieri, F., Sindoni, G., Ingersoll, A. P., Grassi, D., Mura, A.,
- 705 Atreya, S. K., Orton, G., Lunine, J. I., Fletcher, L. N., Simon, A. A., Melin, H., Tosi, Ciccetti,
- A., Noschese, R., Sordini, R., Levin, S., Bolton, S., Plainaki, C., Olivieri, A. (2018b).
- 707 Characterization of mesoscale waves in the Jupiter NEB by Jupiter InfraRed Auroral Mapper
   708 on board Juno. *Astron. J.* 156, 246 (12pp).
- American Meteorological Society (1999). Glossary of Meteorology, 2<sup>nd</sup> edition, American
   Meteorological Society: Boston, MA.
- Allison, M. (1990). Planetary waves in Jupiter's equatorial atmosphere. *Icarus 83*, 282-307.
- Arregi, J., Rojas, J. F., Hueso, R., Sanchez-Lavega, A. (2009) Gravity waves in Jupiter's
  equatorial clouds observed by the Galileo orbiter. *Icarus 202*, 358-360.
- Blackmon, M.L., Lee, Y.-H., & Wallace, J. A. (1984) Horizonal structure of 500 mb height
   fluctuations with long, intermediate and short time scales. J. Atmos. Sci. 41, 961.
- 716 Bolton, S. J., Adriani, A., Adumitroaie, V., Anderson, J., Atreya, S., Boxham, J., Brown, S.,
- 717 Connerney, J. E. P., DeJong, E., Folkner, W., Gautier, D., Gulkis, S., Guillot, T., Hansen, C.,
- 718 Hubbard, W. B., Iess, L., Ingersoll, A., Janssen, M., Jorgensen, J., Kaspi, Y., Levin, S. M., Li,

- C., Lunine, J., Miguel, Y., Orton, G., Owen, T., Ravine, M., Smith, E., Steffes, P., Stone, E.,
- 520 Stevenson, D., Thorne, R., Waite, J. (2017). Jupiter's interior and deep atmosphere: The first close polar pass with the Juno spacecraft. *Science* **356**, 821-825.
- Borucki, W. J., Magalhães, J. A. (1992) Analysis of Voyager 2 images of Jovian lightning.
   *Icarus 96*, 1-14.
- Bosak, T. and Ingersoll, A. P. (2002). Shear instabilities as a probe of Jupiter's atmosphere.
   *Icarus 158*, 401-409.
- Braude, A. S., Irwin, P. G. J., Orton, G. S., Fletcher, L. N. (2020). Colour and tropospheric cloud
   structure of Jupiter from MUSE/VLT: Retrieving a Universal chromophore. *Icarus* In press.
- Brown, S., Janssen, M., Adumitroaie, V., Atreya, S., Bolton, S., Gulkis, S., Ingersoll, A., Levin,
  S., Li, Cl., Li, L., Lu nine, J., Misra, S., Orton, G. Steffes, P., Tabataba-Vakili, F., Kolmasova,
- 730 I., Imai, M, Santolik, O., Kurth, W., Hospodarsky, G., Gurnett, D., Connerney, J. (2018).
- 731 Prevalent lightning sferics at 600 megahertz near Jupiter's poles. *Nature 558*, 87–90.
- 732 doi.org/10.1038/s41586-018-0156-5.
- Brueshaber, S., Sayanagi, K., M., Dowling, T. E. (2019). Dynamical regions of giant planet polar
  vortices. *Icarus 323*, 46-61. doi 10.1016/j.icarus. 2019.02.001
- de Pater, I., Sault, R. J., Moeckel, C., Moullet, A., Wong, M. H., Goullaud, C., DeBoer, D.,
- Butler, B. J., Bjoraker, G., Adamkovics, M., Cosentino, R., Donnelly, P. T., Fletcher, L. N.,
- 737 Kasaba, Y., Orton, G. S., Rogers, J. H., Sinclair, J. A., Villard, E. (2019) First ALMA
- millimeter-wavelength maps of Jupiter, with a multiwavelength study of convection.
   *Astrophys. J. 158*, 139 (17pp).
- Dixon, R.S., Browning, K.A., Shutts, G.J. (2000). The mystery of striated cloud heads in satellite
   imagery. *Atmospheric Science Letters*, doi:10.1006/asle.2000.0001
- 742 Dyudina, U. A., Del Genio, A. D, Ingersoll, A. O., Porco, C. C., West, R. A., Vasavada, A. R.,
- Barbara, J. M. (2004). Lightning on Jupiter observed in the Ha line by the Cassini imaging
  science subsystem. *Icarus 172*, 24-36.
- Flasar, F. M. and Gierasch, P. J. (1986). Mesoscale waves as a probe of Jupiter's deep
  atmosphere. *J. Atmos. Sci.* 43, 2683-2707.
- Fletcher, L. N., Orton, G. S., Mousis, O., Yanamandra-Fisher, P., Parrish, P. D., Irwin, P. G. J.,
  Edkins, E, Baines, K. H., Line, M. R., Vanzi, T., Fujiyoshi, T., Fuse, T. (2010). Jupiter's Great
  Red Spot: High-resolution thermal imaging from 1995 to 2008. *Icarus* 208, 306-328..
- 750 Fletcher, L. N., Melin, H., Adriani, A., Simon, A. A., Sanchez-Lavega, A., Donnelly, P. T.,
- Antuñano, A., Orton, G. S., Hueso, R., Moriconi, M. L., Altieri, F., Sindoni, G. 2018. Jupiter's
   mesoscale waves observed at 5 µm by ground-based observations and Juno JIRAM. *Astron. J.*
- 753 **156**, 67 (13pp).
- 754 Fletcher, L. N., Greathouse, T. K., Orton, G. S., Sinclair, J. A., Giles, R. S., Irwin, P. G. J.,
- Encrenaz, T. (2016) Mid-infrared mapping of Jupiter's temperatures, aerosol opacity and
- chemical distributions with IRTF/TEXES. Icarus 278, 128-161. doi
- 757 10.1016/j.icarus.2016.06.008
- Fletcher, L. N., Orton, G. S., Greathouse, T. K., Zhang, Z., Oyafuso, F. A., Levin, S. J., Li, C.,
  Bolton, S., Janssen, M., Mettig, H.-J., Rogers, J. H., Eichstädt, G., Hansen, C., Melin, H.,
- Grassi, D., Mura, A., Adriani, A. (2020). Jupiter's equatorial plumes and hot spots: Spectral
   mapping from Gemini/TEXES and Juno/MWR. J. Geophys. Res. (this issue).
- Hansen, C., Caplinger, M. A., Ingersoll, Ravine, M. A., Jensen, E., Bolton, S., Orton, G. 2017.
- 763 Junocam: Juno's outreach camera. *Space Sci. Rev.* 217, 475-506. doi:10.1007/s/11214-014-
- 764 0079-x.

- Holton, J. R. 1992. An Introduction to Dynamic Meteorology (3<sup>rd</sup> ed.; New York; Academic
   Press).
- Hunt, G. E., and Muller, J.-P. (1979). Voyager observations of small-scale waves in the
  equatorial region of the jovian atmosphere. *Nature 280*, 778-780.
- 769 Imai, M., Santolik, O., Brown, S., Kolmasova, IO., Kurth, W., Janssen, M., Hospodarsky, G.,
- Gurnett, D., Bolton, S., Levin, S. (2018). Jupiter lightning-induced whistler and sferic events
  with Waves and MWR during Juno perijoves. Geophys. Res. Lett. 45, 7268-7276.
- 772 doi.org/10.1029/2018GL078864.
- Ingersoll, A. P., Ewald, S. P., Sayanagi, K. M., Blalock, J. J. (2018). Saturn's atmospheres at 1-10
  kilometer resolution. *Geophys. Res. Lett.* 45, 7851–7856. doi.org/10.1029/2018GL079255.
- Iñurrigarro, P., Hueso, R., Legarreta, J., Sánchez-Lavega, A., Eichstädt, G., Rogers, J. H., Orton,
  G. S., Hansen, C. J., Pérez-Hoyos, S., Rojas, J. F., Gómez-Forrellad, J. M. 2020. Observations
  and numerical modelling of a convective disturbance in a large-scale cyclone in Jupiter's South
- 778 Temperate Belt. *Icarus*. **336**, 113475.
- Kim, J-H., Chun, H-Y., Sharman, R.D., Trier, S.B. (2014). The role of vertical shear on aviation
   turbulence within cirrus bands of a simulated western Pacific cyclone. *Monthly Weather Review, 142, 2794-2812.*
- Knox, J. A., Bachmeier, A. S., Carter, W. M., Tarantino, J. E., Paulik, L. C., Wilson, E. N.,
  Bechdol, G. S., Mays, M. J. (2010). Transverse cirrus bands in weather systems: a grand tour
  of an enduring enigma. *Weather 65*, 36-41.
- Lenz, A., Bedka, K.M., Feltz, W.F., Ackerman, S.A. (2009). Convectively induced transverse
  band signatures in satellite imagery. *Weather and Forecasting*, *24*, 1362-1373.
- 187 Li, C., Ingersoll, A., Janssen, M., Levin, S., Bolton, S., Adumitroaie, V., Allison, M., Arballo,
- A., Belotti, A., Brown, S., Ewald, S., Jewell, J., Misra, S., Orton, G., Oyafuso, F., Steffes, P.,
  Williamson, R. (2017). The distribution of ammonia on Jupiter from a preliminary inversion of
- Juno microwave radiometer data. *Geophys. Res. Lett.* 44, 5317-5325.
- Li, L., Ingersoll, A. P., Vasavada, A. R., Simon-Miller, A. A., Achterberg, R. K., Ewald, S. P.,
  Dyudina, U. A., Porco, C. C., West, R. A., Flasar, F. M. (2006). Waves in Jupiter's atmosphere
  observed by the Cassini ISS and CIRS instruments. *s*, 416-429.
- Little, B., Anger, C. D., Ingersoll, A. P., Vasavada, A. R., Senske, D. A., Breneman, H. H.,
- Borucki, W. J., Galileo SSI Team (1999) Galileo images of lightning on Jupiter. *Icarus 142*,
  306-323.
- Marcus, P.S. (1993). Jupiter's Great Red Spot and Other Vortices. *Ann. Rev. Astron. Astrophys. 31*, 523-573.
- Molinari, J., Duran, P., and Vollaro, D. (2014). Low Richardson number in the tropical cyclone outflow layer. *Journal of the Atmospheric Sciences*. *71*, 3164-3179.
- 801 Orton, G. S., Hansen, C., Caplinger, M., Ravine, M., Atreya, S., Ingersoll, A. P., Jensen, E.,
- 802 Momary, T., Lipkman, L., Krysak, D., Zimdar, R., Bolton, S. (2017a) The first close-up
- images of Jupiter's polar regions: results from the Juno mission JunoCam instrument. *Geophys. Res. Lett.* 44, 4599-4606. doi:10.1002/2016GL072443.
- 805 Orton, G. S., Momary, T., Ingersoll, A. P., Adriani, A., Hansen, C. J., Janssen, M., Arballo, J.,
- Atreya, S. K., Bolton, S., Brown, S., Caplinger, M., Grassi, D., Li, C., Levin, S., Moriconi, M.
- L., Mura, A., Sindoni, G. (2017b) Multiple-wavelength sensing of Jupiter during the Juno
- 808 mission's first perijove passage. Geophys. Res. Lett. 44, 4607-4614 doi:
- 809 10.1002/2017GL073019.

- 810 Porco, C. C., West, R. A., McEwen, A., Del Genio, A. D., Ingersoll, A. P., Thomas, P., Squyres,
- 811 S., Dones, L., Murray, C. D., Johnson, T. V., Burns, J. A., Brahic, A., Neukum, G., Veverka,
- J., Barbara, J. M., Denk, T., Evans, M., Ferrier, J. J., Geissler, P., Helfenstein, P., Roatsch, T.,
- Throop, H., Tiscareno, M., Vasavada, A. R. (2003). Cassini imaging of Jupiter's atmosphere,
  satellites, and rings. *Science 299*, 1541-1547.
- 815 Reuter, D. C., Simon-Miller, A. A., Lunsford, A., Baines, K. H., Cheng, A. F., Jennings, D. E.,
- 816 Olkin, C. B., Spencer, J. R., Stern, S. A., Weaver, H. A., Young, L. A. (2007). Jupiter cloud
- 817 composition, stratification, convection, and wave motion: A view from New Horizons. Science
- 818 318, 223-225. doi 10.1126/science.1147618.
- 819 Rogers, J. (1995), The Giant Planet Jupiter, 418 pp., Cambridge Univ. Press, Cambridge, U. K.
- Salyk, C., Ingersoll, A. P., Lorre, J., Vasavada, A., Del Genio, A. D. (2006) Interaction between
  eddies and mean flow in Jupiter's atmosphere: Analysis of Cassini imaging data. *Icarus 185*,
  430-442.
- 823 Sánchez-Lavega, A., Hueso, R., Eichstädt, G., Orton, G., Rogers, J., Hansen, C. J., Momary, T.,
- Tabataba-Vakili, F., Bolton, S. (2018). The rich dynamics of Jupiter's Great Red Spot from
  JunoCam Juno images. *Astron. J.* 156, 162 (9 pp).
- Simon-Miller, A. A., B. Conrath, P. J. Gierasch, R. F. Beebe. (2000). A detection of water ice on
  Jupiter with Voyager IRIS. *145*, 454-461.
- Simon, A. A., Li, L., Reuter, D. C. (2015a). Small-scale waves on Jupiter: A reanalysis of New
  Horizons, Voyager, and Galileo data. *Geophys. Res. Lett.* 42, 2612-2618, doi:
- 830 10.1002/2015GL063433.
- Simon, A. A., Wong, M. H., Orton, G. s. (2015b). First results from the Hubble OPAL program:
  Jupiter in 2015. *Astrophys. J.* 812:55 (8pp).
- 833 Simon, A. A., Hueso, R., Iñurrigarro, P., Sánchez-Lavega, A., Morales-Juberías, R., Cosentino,
- 834 R., Fletcher, L. N., Wong, M. H., Hsu, A. I. de Pater, I., Orton, G. S., Colas, F., Delcroix, M.,
- Peach, D., Gómez-Forrellad, J.-M. (2018). A new, long-lived, jupiter mesoscale wave observed
  at visible wavelengths. *Astron. J.*, *156*:79 (18pp).
- Sromovsky, L. A., Baines, K. H., Fry, P. M., Carlson, R. W. (2017) A possibly universal red
  chromophore for modeling color variations on Jupiter. *Icarus 291*, 232-244. doi
  10.1016/i.icarus.21016.12.014.
- 840 Sugiyama, K., Nakajima, K., Odaka, M., Kuramoto, K., Hayashi, Y.-Y. (2014). Numerical
- simulations of Jupiter's moist convection layer: Structure and dynamics in statistically steady
  states. *Icarus* 229, 71-91.
- Sugiyama, K., Nakajima, K., Odaka, M., Kuramoto, K., Hayashi, Y.-Y. (2014). Corrigendum to:
  "Numerical simulations of Jupiter's moist convection layer: Structure and dynamics in
  statistically steady states. Icarus 229, 71-91]". *Icarus 231*, 407-408.
- 846 Tabataba-Vakili, F., Rogers, J. H., Eichstädt, G., Orton, G. S., Hansen, C. J., Momary, T. W.,
- 847 Sinclair, J. A., Giles, R. S., Caplinger, A., Ravine, M. A., Bolton, S. J. (2019). Long-term
- tracking of circumpolar cyclones on Jupiter from polar observations with JunoCam. *Icarus*. In
   press.
- 850 Trier, S.B., Sharman, R.D., Fovell, R.G., Frehlich, R.G. (2010). Numerical simulation of radial
- cloud bands within the upper-level outflow of an observed mesoscale convective system. *Journal of the Atmospheric Sciences*. 67, 2990-2990.
- 853 West, R.A., Strobel, D. F., Tomasko, M. G. (1986). Clouds, aerosols, and photochemistry in the
- S54 Jovian atmosphere. *Icarus 65*, 161-217. doi 10.1016/0019-1035(86)90135-1

- 855 Wong, M. H., Simon, A. A., Tollefson, J. W., de pater, I., Barnett M., Hsu, A. I. Stephens, A.,
- 856 Orton, S. G. Fleming, S. W., Januszewski, W., Roman, A., Goullaud, C., Bjoraker, G. L,
- Atreya, S. K., Adriani, A. (2020). High-resolution UV/optical/IR imaging of Jupiter in 2016–
  2019. Astrophysical Journal Supplement Series. Submitted.
- 859 Yang, Q. and Geerts, B. (2014). Horizontal convective rolls in cold air over water:
- Characteristics of coherent plumes detected by an airborne radar. *Monthly Weather Rev. 134*,
  2373-2395.
- 862 Young, R. M. B., Read, P. L. (2017). Forward and inverse kinetic energy cascades in Jupiter's
- turbulent weather layer. *Nature Physics 13*, 1135.
- 865

# 866 Tables

Observing Platform	Associated	Range of	Range of
(year)	Publications	Planetocentric	Wavelengths
		Latitudes	(km)
Voyager (1979)	Hunt & Muller	27°S-27°N	70-430
	(1979),		
	Flasar & Gierasch		
	(1986)		
Galileo (1996)	Bosak & Ingersoll (2002)	13°S	300
Galileo (1999)	Arregi et al. (2009),	0.2°N, 3.6°N	155-205
	Simon et al. (2015)		
Galileo (2001)	Arregi et al. (2009)	1.8°S	
			195-215
New Horizons	Reuter et al. (2007),	0°-1.1°N	280-330
(2007)	Simon et al. (2015)		
Juno/JIRAM (2017)	Adriani et al. (2018),	14°-15°N	1400-1900
	Fletcher et al. (2018)		
Juno/JunoCam	Sánchez-Lavega et al.	16°S	35
(2017)	(2018)		
Hubble Space	Simon et al. (2018)	$14.5^{\circ} \pm 2.5^{\circ} N$	1220-1340
Telescope (2012-			
2018)			
Ground-Based	Simon et al. (2018)	$14.5^{\circ} \pm 2.5^{\circ} N$	1220-1340
Visible Observations			
(2017)			1200 1 (00
Ground-Based 5-µm	Fletcher et al. (2018)	$14.5 \pm 2.5 \text{ N}$	1300-1600
Observations (2016-			
2017)			

Table 1. Summary of previous observations of small-scale waves in Jupiter's clouds detected at 5
 µm or shorter wavelengths. (Some values are also displayed in Figure 16.) The waves addressed

871 by Sánchez-Lavega et al. (2018) are associated with the Great Red Spot.

Type of Wave-Like Feature (section where discussed)	Number of Features
Long packets, short crests (3.2.1)	100
Wide wave crests (3.2.2)	25
Curved packets (3.2.1)	9
Small white clouds (3.2.3)	9
Regularly spaced dark features (3.2.7)	6
Emanating from vortex (3.2.5)	4
Extremely long curved features (3.2.2)	2
Lee waves (3.2.4)	1

Table 2. Number of features in each morphological category, listed in order of frequency. These
include features not illustrated in the figures associated with the main article but included in the
Supplementary Information file. The total number of waves or wave-like features is 157. The

886 Supplementary Information file. The total number of waves or wave-like features is 157. The 887 category of waves with long packets and short crests dominates the total. Quantitative properties

of these waves are shown in the Table of Section SI2 of the Supplemental Information file. They

are also shown graphically in Figs. 16, 17 and Figs. SI3-1 through SI3-3 of the Supplemental

889 are also shown graphically in Figs. 10, 17 and Figs. 515-1 inroug 890 Information file.

Figures





Figure 1. Example of excerpting a portion of a wave-like feature from a JunoCam image from
planetocentric latitudes 3°S - 4°S. This is a cylindrical mapping of a color-composited Image
JNCE\_2017297\_09C00088\_V01 (which here and elsewhere we simply identify as Image 99 from
PJ9. The extracted panel is also shown as Figure 10B and in the Supplemental Information file
as Figure PJ09\_88 with a grid indicating the location of peak radiances in the wave-like feature.

3.0 A. PJ3 Image 111 Planetocentric Latitude 2.0 1.0 **1**0.0 9.0 8.0 7.0 6.0 System-III Longitude -1.0 **B. PJ20 Image 36** Planetocentric Latitude -1.5 -2.0 -2.5 -3.0 🎞 26.5 TELEVITE 26.0 25.5 25.0 24.5 24.0 23.5 System-III Longitude

903 904

902

Figure 2. Excerpts from JunoCam color-composite maps of images in PJ3 illustrating isolated wave packets with shorter wave fronts that are orthogonal to the orientation of the wave packet. In this and all other similar figures in this report, the colors have been stretched extensively in order to make the waves as visible as possible; they have absolutely no relationship with the true colors of the planet. In this and some sequent images here and in the Supplemental Information file, broad vertical or diagonal colored bands are artefacts of strong image enhancement to

911 *distinguish otherwise faint features.* 





Figure 3. Excerpts from JunoCam maps of images in PJ8 (Panel A), PJ17 (Panels B and C) and PJ18 (Panel D). These illustrate individual wave packets with shorter wave fronts that are not-orthogonal (i.e. they are z tilted ) with respect to the orientation of the wave packet direction.











Sys III W Longitude

921 922 Figure 6. Contextual HST WFC3 image for Figure 5D, showing its position with respect to the 923 GRS. The inset shows the wind field derived from tracking cloud features over a 45-minute interval, as a residual after subtracting the mean zonal wind profile. The winds appear to be a 924 925 maximum at the western (left) end of the blue lobate feature, with a marked drop in velocities, i.e. 926 a region of wind shear, at the edges of the feature. This image was taken within a few minutes of

- 927 the time at which the JunoCam image in Fig. 5D was observed
- 928



<sup>Figure 7. Excerpts from maps showing waves whose wave fronts are larger than the wave packet
length. Both are curved and located in the Equatorial Zone. Panel A shows a pair of wave packets,</sup> 

<sup>932</sup> overlapping each other, the westernmost of which contains at least three wave fronts that are much

<sup>933</sup> longer than the packet. The overlapping easternmost wave packet has wave fronts and a length

<sup>934</sup> that are roughly equal in size. Panel B shows a series of curved waves that appear to extend past

<sup>935</sup> *the boundaries of the full image* 



937 Figure 8. Extremely long, curved features detected in PJ20. Two unusually long features that may be waves were detected near the southwestern extension ("festoon") of a 5-µm hot spot, seen here as the dark area. North of the dark area of the festoon is a pair of lines, whose beginnings and ends are marked by white arrows. Among the many waves found south of the festoon, is a set of three closely spaced parallel lines, noted by the arrows that do not begin or end at the same position. Only for two of them is the western end evident. We note that some mild unsharp masking has been applied to this image in order to resolve for the reader the three dark curves at their eastern ends. (The locations of many more of the waves present in this figure are indicated in Figure PJ20 34 in the Supplemental Information file.) 



953 954 Figure 9. Examples of wave packets defined by bright clouds, all in the Equatorial Zone. Panel A shows a wave packet whose length is roughly equal to its width. Its constituent clouds are clearly higher than their surroundings, given the strong PJ12\_90a in the Supplemental Information file. The feature is reminiscent of ocean foam, with side-by-side elongated features that are not uniformly directed and may be higher than the surrounding cloud deck, with a consistent darkening on their curved southwestern extensions. Panel C shows a similar wave packet of white clouds with narrow wavefronts and a slight topographic clues from consistent shadowing on their eastern sides. Panel B shows a line of regular clouds with longer, curvature. Panel D shows a very curious type of irregular wave-like feature, extracted from the northeastern portion of Fig. eastern sides that might be shadowing.


955 956 Figure 10. Two detections of regular patterns of relatively bright clouds apparently associated 957 with a fainter central bright region. Both instances involve curved lines. The wave packet in 958 Panel A is associated with a similar but fainter pattern to its north, whereas the wave packet in 959 Panel B has no such association. Both are in the southern component of the Equatorial Zone.







966

Figure 12. The single unambiguous detection of lee waves in the JunoCam images. We can presume that the long streaks appearing diagonally in this figure are tracking the streamlines of

local winds. The lee waves indicated by the white grid lines are orthogonal to the elongated streaks

and are likely to be downwind of the bright convective plume in the upper part of this image.





973 Figure 13. Wave-like features detected near vortices. Panel A shows a very compact cyclonic
974 feature with a set of extended radial wavefronts in the North Equatorial Belt (NEB). Panel B shows
975 a regular set of dark lines emerging from the ends of the internal spiral structures in an
976 anticyclonic white oval.









984

Figure 15. Unusual quasi-wave-like features in the northern hemisphere. Panel A illustrates three curved wavefronts next to relatively dark circular features indicated by the arrows. Panel B shows a series of repeated patterns in the North Temperate Zone.





993 994 Figure 16. Histogram of waves and wave-like features detected in PJ1-20 by JunoCam. Different

995 types of waves and wave-like features are denoted by different colors and identified by the key.

996 Each corresponds to a different wave morphology as discussed in Section 3.2. The bin size is 1°

997 in latitude.





Figure 17. Wavelengths of waves and wave-like features detected in PJ1, PJ3-PJ20 by JunoCam.
Measurements of different types of wave morphologies are color-coded as in Figure 15. Mean

1002 zonal wind velocities for 2017-2018 (Wong et al. 2020) are plotted in blue. Values for Voyager,

1003 New Horizons and Galileo are taken from their respective references in Table 1. Wavelengths

1004 for wave packets detected by HST and ground-based images (Simon et al. 2018, Fletcher et al.

1005 2018) are greater than 1100 m/s and clustered around 14.5°N (see Table 1).

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