

Mapping the Zonal Structure of Titan's Northern Polar Vortex

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Abstract

Saturn exhibits an obliquity of 26.7° such that the largest moon, Titan, experiences seasonal variations including the formation of a polar vortex in the winter hemisphere. Titan's polar vortex is characterised by cold stratospheric temperatures due to the lack of insolation over the winter pole, and an increase in trace gas abundance as a result of complex organic chemistry in the upper atmosphere combined with polar subsidence. Meridional variations in temperature and gas abundance across the vortex have previously been investigated, but there has not yet been any in-depth study of the zonal variations in the temperature or composition of the northern vortex. Here we present the first comprehensive two-dimensional seasonal mapping of Titan's northern winter vortex. Using 18 nadir mapping sequences observed by the Composite InfraRed Spectrometer (CIRS) instrument on-board Cassini, we investigate the evolution of the vortex over almost half a Titan year, from late winter through to mid summer ($L_s = 326 - 86^\circ$, 2007–2017). We find the stratospheric symmetry axis to be tilted from the solid body rotation axis by around 3.5° , although our results for the azimuthal orientation of the tilt are inconclusive. We find that the northern vortex appears to remain zonally uniform in both temperature and composition at all times. A comparison with vortices observed on Earth, Mars, and Venus shows that large-scale wave mechanisms that are important

31 on other terrestrial planets are not as significant in Titan’s atmosphere. This
32 allows the northern vortex to be more symmetrical and persist longer through-
33 out the annual cycle compared to other terrestrial planets.

34 1. Introduction

35 Titan is the largest moon of Saturn and is host to a thick, nitrogen domi-
36 nated atmosphere (around 98%) with methane the second most abundant gas,
37 at around 1.48% in the stratosphere, and with a surface pressure of approxi-
38 mately 1500 mbar (Fulchignoni et al., 2005). Titan’s rotation is tidally locked to
39 Saturn, such that the length of a Titan day is the length of time taken to com-
40 plete one orbit – 15.9 Earth days. Furthermore, Saturn exhibits an obliquity of
41 26.7° meaning that Titan, which orbits in Saturn’s equatorial plane, experiences
42 seasonal variations over a Titan year – 29.5 Earth years.

43 In Titan’s upper atmosphere, nitrogen and methane molecules undergo
44 photolysis by interaction with UV photons and magnetospheric electrons to
45 produce free radicals which can go on to recombine with one another to create
46 various complex hydrocarbon (C_xH_y) and nitrile ($H_xC_yN_z$) compounds (Wil-
47 son and Atreya, 2004; Lavvas et al., 2008; Krasnopolsky, 2009; Vuitton et al.,
48 2019). These gases subside over the cold winter pole where they are shielded
49 from UV photons, resulting in an increased trace gas abundance in the vortex.
50 They also have a wide range of photochemical lifetimes, allowing their use as
51 chemical probes of different atmospheric dynamics in the vortex (Teanby et al.,
52 2008a).

53 Titan General Circulation Models (GCMs) attempt to replicate the circula-
54 tion of Titan’s atmosphere. We do not yet have year round observations of
55 Titan and so GCMs provide us with an opportunity to investigate how the at-
56 mosphere may behave over longer time periods than we have observed. Such
57 models predict a relatively simple pole to pole meridional circulation, with an
58 upwelling of gas in the summer hemisphere, which subsides over the winter
59 pole. The circulation is expected to reverse as each hemisphere moves from

60 summer into winter and vice versa. A brief two cell system around equinox
 61 which sees gas rising from the equator and subsiding at the poles is predicted
 62 between the transition (Hourdin et al., 1995; Newman et al., 2011; Lebonnois
 63 et al., 2012). Such models are in broad agreement with observations of trace
 64 gas enrichment in the polar vortex (Teanby et al., 2012; Vinatier et al., 2015). Ti-
 65 tan’s entire stratosphere is also tilted, such that the stratospheric rotation axis
 66 is offset from the solid body rotation axis by around 4° (Achterberg et al., 2008).
 67 The exact mechanism responsible for this feature is not yet fully understood.
 68 However, an early CIRS analysis of polar temperatures identified the offset
 69 and suggested that it is the result of the atmospheric spin adjusting itself to the
 70 angular momentum transfer from solar heating (Achterberg et al., 2008). Fur-
 71 ther studies found similar results using haze albedo, composition and zonal
 72 wind velocity measurements (Roman et al., 2009; Teanby et al., 2010; West et al.,
 73 2016).

74 The Cassini spacecraft toured the Saturnian system from 2004 through to
 75 2017, performing 127 targeted fly-bys of Titan over this time period, providing
 76 almost half a Titan year of observations (Nixon et al., 2019). Titan’s northern
 77 spring equinox occurred in August 2009, meaning Cassini observes seasonal
 78 changes on Titan as northern winter evolves into northern summer. Many
 79 trace gases in Titan’s atmosphere are found to be very IR-active and so by using
 80 IR spectra recorded by the Composite InfraRed Spectrometer (CIRS) on-board
 81 Cassini, information about the temperature and composition of Titan’s atmo-
 82 sphere can be derived (Teanby et al., 2019).

83 Previous CIRS based studies of Titan’s northern vortex have used both limb
 84 and nadir observations. Limb data recorded by CIRS does not provide suf-
 85 ficient coverage to investigate zonal variations, and most nadir studies have
 86 taken zonally averaged measurements to investigate meridional variations.
 87 These studies have shown evidence of strong latitudinal gradients in both tem-
 88 perature (Achterberg et al., 2008; Vinatier et al., 2015; Teanby et al., 2019; Sylvestre
 89 et al., 2019) and composition (Teanby et al., 2008a; Sylvestre et al., 2018) to-
 90 wards the pole in the winter hemisphere and evidence of varying gas abundance-

91 altitude gradients depending on the season, latitude and the photochemical
92 lifetime of the gas (Teanby et al., 2006; Vinatier et al., 2010; Teanby et al., 2012;
93 Vinatier et al., 2015; Coustenis et al., 2016; Teanby et al., 2017).

94 Cassini provides us with a unique opportunity to study the breakup of Ti-
95 tan’s northern polar vortex. Comparing the differences and similarities be-
96 tween polar vortices on other planets may provide a useful insight into the
97 mechanisms driving their evolution. For example, the polar vortices of Earth
98 and Mars are both observed to become highly distorted over their lifetime
99 (Waugh and Randel, 1999; Mitchell et al., 2015; Waugh et al., 2016) with the
100 generation of Sudden Stratospheric Warmings (SSWs) facilitating the rapid
101 breakdown of the vortex (termed the final warming) depending on their tim-
102 ing in winter. Flasar and Achterberg (2009) present a comparison between the
103 vortices of Titan and Earth. The polar vortex on Venus also displays a highly
104 asymmetric distribution, with the formation of a so-called “vortex dipole” or
105 ‘S’ shaped centre (Taylor et al., 1979). However, Venus’ rotation axis is almost
106 perpendicular to its orbital plane and so the vortex formation is not seasonal,
107 but more likely driven by internal dynamical processes (Flasar and Achterberg,
108 2009).

109 Whilst a few early Titan CIRS observations have been investigated for zonal
110 temperature (Achterberg et al., 2008) and composition (Teanby et al., 2008a)
111 variations, there has not yet been an extensive study of the zonal structure in
112 Titan’s temperature and trace gas abundances over the entire Cassini mission.

113 In this paper we present two analyses: (i) a new method to determine the
114 magnitude and orientation of Titan’s stratospheric tilt using only Cassini-CIRS
115 trace gas emissions and (ii) a study of the zonal variations of the temperature
116 and composition of Titan’s northern polar vortex throughout the Cassini mis-
117 sion, from northern midwinter through to northern midsummer.

118 2. CIRS Observations

119 CIRS is a remote sensing Fourier transform spectrometer onboard the Cassini
120 spacecraft, measuring thermal emissions from the IR spectrum in the range

121 $10 - 1500 \text{ cm}^{-1}$ ($1 \text{ mm} - 7 \text{ }\mu\text{m}$) (Flasar et al., 2004; Jennings et al., 2017). Many
 122 of the complex gas species found in Titan’s atmosphere exhibit strong emis-
 123 sion features in this wavenumber range, providing the opportunity to retrieve
 124 atmospheric temperature and composition from IR spectra. CIRS covers this
 125 range by use of two interferometers occupying a common scanning mechanism
 126 and telescope. The far-IR part of the spectrum ($10 - 600 \text{ cm}^{-1}$) is measured by
 127 a polarising interferometer (FP1), whilst the mid-IR part of the spectrum is
 128 measured by a Michelson interferometer split across two focal planes (FP3:
 129 $600 - 1100 \text{ cm}^{-1}$, FP4: $1100 - 1500 \text{ cm}^{-1}$). The instrument has an apodized
 130 spectral resolution which can be adjusted from 0.5 to 15.5 cm^{-1} . For the pur-
 131 pose of this study we will use mid-IR measurements (FP3, FP4) with a spectral
 132 resolution of 2.5 cm^{-1} , as these focal planes have better spatial resolution than
 133 FP1, and the wavenumber range covers both the ν_4 CH_4 band ($1240 - 1360 \text{ cm}^{-1}$)
 134 in FP4 and a variety of trace gas emissions in FP3. A resolution of 2.5 cm^{-1}
 135 is sufficiently fine to resolve individual gas peaks and can be acquired fast
 136 enough to allow mapping observations which are ideal for studying zonal
 137 structure. Depending on season and latitude, these observations will probe
 138 pressure levels from around 10 mbar up to 0.01 mbar , with contribution func-
 139 tions typically peaking between 1 and 0.1 mbar .

140 In selecting our observations we place a few constraints. In order to study
 141 the pole, we require that the data includes measurements extending up to at
 142 least 85°N . Our observations must also provide substantial spatial coverage
 143 around the polar region in order to measure zonal variations. To meet this
 144 criteria, the observations selected have an average FOV span in FP3 and FP4
 145 of around 2.5° of latitude at subspacecraft point. In each observation, CIRS
 146 typically measures around 4000 individual spectra in each of the FP3 and FP4
 147 focal planes.

148 As the emission angle of an observation increases, so too does the path
 149 length through the atmosphere, leading to an artificial increase in the observed
 150 IR emissions, or “limb brightening”. To minimise the effect of limb brightening
 151 around our polar data, we reject observations with a sub-spacecraft-latitude

less than 40° N. This ensures a maximum emission angle of 50° at the pole.

Nixon et al. (2019) summarise the CIRS coverage of Titan over the Cassini mission. Applying our criteria we have 18 observations available for this study, ranging from early 2007 through to late 2016 (late northern winter through mid northern summer on Titan). These observations are not evenly distributed in time, with the largest gap between observations being around 4 years, from May 2009 to April 2013 – equivalent to around 0.14 Titan years. Due to the sparse temporal coverage, we are unlikely to be able to track the progression of individual features (if present) between observations, however we can treat each observation as a snapshot of Titan’s atmosphere at the given time and identify any asymmetry or zonal structure present in the vortex. The selection criteria are illustrated in figure 1 and the selected observations are listed in table 1.

To improve the signal-to-noise ratio of the data, the observations are calibrated using the DS4000 (version 4.2) calibration, which more effectively removes the instrument and sky background contributions than the standard calibration (Jennings et al., 2017). A binning technique was also performed whereby a tessellation of Titan’s surface into equal area hexagonal bins allows spectra recorded within each bin to be averaged. This method is performed for each observation as this helps to improve the signal to noise ratio of data in bins distributed evenly across the surface, with the relatively small bin size (approximately 1.5°) and nearly stationary subspacecraft point ensuring that only spectra recorded at similar emission angles are grouped together in each observation (Teanby et al., 2006) .

3. Analysis

3.1. Stratospheric Tilt Correction

As previously discussed, Titan’s middle atmosphere is offset from the geographic pole by about 4° . Before investigating the zonal symmetry in the vortex, we must remove the effect of the tilt of the entire atmospheric circulation. We present here a new method to determine the magnitude and orientation

CIRS Observation	Date	L_s (°)	Latitude (°N)	FP4 N	FP3 N	FP4 FOV (°)	FP3 FOV (°)
CIRS_037TLMIDIRTMAP002_PRIME	12/01/2007	326.95	44.6	1936	1960	2.14	2.14
CIRS_038TLMIDIRTMAP001_PRIME	28/01/2007	327.51	51.5	1902	2132	2.50	2.50
CIRS_098TLMIDIRTMAP002_PRIME	22/12/2008	352.04	44.6	2864	2863	2.42	2.42
CIRS_107TLMIDIRTMAP002_PRIME	28/03/2009	355.35	58.7	4098	4092	2.54	2.54
CIRS_107TLMIDIRTMAP001_PRIME	03/04/2009	355.56	58.4	2490	2382	2.04	2.10
CIRS_110TLMIDIRTMAP001_PRIME	05/01/2009	356.66	56.5	4180	4183	1.88	1.88
CIRS_185TLMIDIRTMAP001_PRIME	05/04/2013	43.76	41.9	1678	1435	2.16	2.24
CIRS_195TLMIDIRTMAP001_PRIME	25/07/2013	47.28	57.8	7124	7134	2.68	2.69
CIRS_197TLMIDIRTMAP001_PRIME	11/09/2013	48.78	65.8	3749	3800	2.60	2.61
CIRS_198TLMIDIRTMAP001_PRIME	13/10/2013	49.78	72.6	7419	7382	2.63	2.62
CIRS_199TLMIDIRTMAP001_PRIME	30/11/2013	51.27	76.4	2276	2280	2.46	2.45
CIRS_200TLMIDIRTMAP001_PRIME	01/01/2014	52.27	69.7	4816	4792	2.41	2.41
CIRS_203TLMIDIRTMAP001_PRIME	06/04/2014	55.25	50.0	3283	3301	2.19	2.18
CIRS_204TLMIDIRTMAP002_PRIME	18/05/2014	56.53	45.7	2732	2728	2.11	2.11
CIRS_238TLMIDIRTMAP002_PRIME	25/07/2016	80.99	41.4	5263	5287	2.20	2.19
CIRS_253TLMIDIRTMAP001_PRIME	14/12/2016	85.29	42.9	4373	4417	2.84	2.84
CIRS_253TLMIDIRTMAP002_PRIME	14/12/2016	85.31	75.3	3063	3105	2.61	2.61
CIRS_253TLMIDIRTMAP004_PRIME	14/12/2016	85.33	78.3	1780	1779	2.92	2.92

Table 1: CIRS Observations used in this study. L_s is the solar longitude, Latitude is the sub spacecraft latitude. N indicates number of spectra measured in observation and FOV is the average field of view span at subspacecraft point.

182 of the atmospheric tilt using only IR emissions of vortex enriched trace gas
 183 species. Using IR emissions instead of properties derived from retrieval cal-
 184 culations means we can minimise the effects of retrieval bias and also directly
 185 account for the effect of emission angle. For this analysis, three gas emission
 186 peaks were used: 628cm^{-1} (C_4H_2), 634cm^{-1} (C_3H_4), 663cm^{-1} (HC_3N) as the
 187 IR emission of these wavenumbers exhibit a greater radiance in the polar re-
 188 gion compared to more equatorial latitudes as seen in figure 2. Figure 2 shows
 189 maps of trace gas emissions displaying significant variation over the north pole
 190 throughout the lifetime of the Cassini mission, with greatly reduced emissions
 191 by the end of the mission indicating an increase in mixing across the vortex,
 192 likely caused by its weakening.

193 This polar enhancement is expected as Titan GCMs predict maximum sub-
 194 sidence to occur over the pole, increasing the gas abundance in this region.
 195 From these models, we expect that the temperature and composition should
 196 be broadly uniform around the vortex and so the IR emissions of trace gases
 197 should be symmetric around the vortex.

198 We attempt to find the centre of the distribution of the chosen gas emissions,
 199 and therefore the position of the tilt, by using a minimum χ^2 method. We grid
 200 search over possible offset positions in the range 80°N to 90°N and 0°W to
 201 360°W with 0.1° spacing in each direction.

202 As discussed earlier, large emission angles can cause observed radiances to
 203 be artificially enhanced. This is purely an effect of the geometry of the obser-
 204 vation, and must be taken into consideration when comparing emission val-
 205 ues. We expect that the influence of limb brightening on radiance measured
 206 at similar emission angles will be comparable. Therefore, to remove any de-
 207 pendence on emission angle we must only compare radiances measured at the
 208 same emission angle. To simplify this method, we rotate the data into a frame
 209 centered around the subspacecraft point (zenith). In this frame, emission angle
 210 monotonically increases with angular distance from zenith, ϵ , whilst having no
 211 variation with the azimuth, α , which has zero defined as the line adjoining the
 212 subspacecraft point and the chosen pole position, or spacecraft-pole-meridian

(SPM). Figure 3 illustrates the geometry of the frame change and coordinate system. Since we can only compare values at equal emission angle, we have one less degree of freedom and now are effectively calculating a χ^2 value for the distribution of emissions either side of the SPM, with χ^2 for each offset position defined as

$$\chi^2(\phi_p, \theta_p) = \sum_{\epsilon=0}^{\pi/2} \sum_{\alpha=0}^{\pi} \left(\frac{y(\epsilon, \alpha) - y(\epsilon, -\alpha)}{\sqrt{\sigma(\epsilon, \alpha) + \sigma(\epsilon, -\alpha)}} \right)^2$$

where ϕ_p and θ_p are the azimuth of the atmospheric pole in the selected reference frame and the offset from the geographic pole respectively, $y(\epsilon, \alpha)$ is the measured radiance at an angle ϵ from zenith and an angle α from the SPM and $\sigma(\epsilon, \alpha)$ is the corresponding error.

A limitation of this method is that we can only calculate a χ^2 profile as a function of α for each observation. In other words, for any given observation, our minimum χ^2 value reveals a line originating at the spacecraft along which the best fitting offset position lies. However, combining these χ^2 values for multiple observations (the sub spacecraft point varies between observations) allows us to calculate the best fitting offset location over the entire mission. This further reduces any bias of limb brightening present in the atmospheric pole estimate. We can also rotate the azimuths of each χ^2 profile in order to find the minimum location in any chosen reference frame. Three frames were selected; solar (sub solar point as the reference point), Saturn (0° W as the reference point) and inertial (sub solar point at equinox as the reference point), with the frame returning the smallest χ^2 value providing the best fit to the offset.

3.2. Retrieval Methods

We use the radiative transfer retrieval code, NEMESIS (Irwin et al., 2008) to retrieve continuous temperature profiles and abundances of selected gases from our CIRS spectra. In order to retrieve a parameter, NEMESIS uses a correlated-k based (Lacis and Oinas, 1991) constrained iterative non-linear retrieval method (Rodgers, 1976). Temperature and composition are retrieved by iteratively generating a synthetic spectra and modifying model parameters in

241 order to minimise a cost function between observed and synthetic spectra to
242 give the best fitting model.

243 Our forward model includes gas abundances measured from a variety of
244 sources. We set the methane abundance to the values measured by the Cassini-
245 Huygens probe GCMS (Niemann et al., 2010) (1.48%). For the remaining trace
246 gases a uniform mixing ratio is assumed above the condensation level using
247 data collected from previous CIRS studies (Coustenis et al., 2007, 2016; de Kok
248 et al., 2007; Flasar et al., 2005).

249 This study aims to perform retrievals using IR spectra recorded at various
250 latitudes and seasons on Titan. Titan’s atmosphere can vary quite significantly
251 depending on these factors and so to construct a reliable a-priori temperature
252 profile we use the database of temperature profiles from Teanby et al. (2019).

253 A two stage retrieval process is adopted following Teanby et al. (2019).
254 First, a continuous temperature profile is obtained from the ν_4 CH₄ band cen-
255 tered about $1240 - 1360 \text{ cm}^{-1}$ (FP4) for the binned spectra detailed in section
256 2. Assuming the CH₄ abundance to be constant and well mixed throughout
257 the stratosphere allows us to disentangle temperature and composition over
258 this wavenumber range. Second, we perform abundance retrievals over the
259 $620 - 733 \text{ cm}^{-1}$ range (FP3) by fixing the retrieved temperature profile and
260 scaling the uniform gas profiles. Retrieved properties also have an associated
261 uncertainty, derived from the variance for each wavenumber in the spectrum
262 and an additional forward model error. Figures 6 and 7 show example fitted
263 spectra for the ν_4 CH₄ band and FP3 gas emissions respectively.

264 We can also inspect the regions which our retrievals are sensitive to by ex-
265 amining the contribution functions for selected wavenumbers. The contribu-
266 tion function is defined as the rate of change of radiance (at a given wavenum-
267 ber) with respect to the parameter being retrieved. Figure 5 shows contribu-
268 tion functions for the ν_4 CH₄ band and C₄H₂ (628 cm^{-1}), HC₃N (663 cm^{-1})
269 and HCN (713 cm^{-1}) emissions obtained from spectra recorded near the north
270 pole during winter and summer. The ν_4 band contribution functions can be
271 seen to peak between the $10 - 0.001 \text{ mbar}$ pressure level depending on latitude

and season, indicating that most temperature information originates in this region. The composition contribution functions typically peak between 10 – 0.01 mbar depending on the latitude, season and photochemical lifetime of the gas species, with a primary peak between 10 – 1 mbar and a secondary peak near 0.1 mbar caused by the hot stratopause over the polar region (Teanby et al., 2008b).

3.3. Vortex Asymmetry

With each observation rotated into the stratospheric tilt frame, we are now in a position to investigate the zonal variations in temperature and composition of the vortex. We perform the inversion method detailed in 3.2 to retrieve continuous temperature profiles and trace gas abundances.

In searching for zonal asymmetry, our analysis must continue to be robust to the effects of viewing geometry. We use a similar method to section 3.1 where coordinates equidistant from the Spacecraft-pole-meridian (SPM) have the same emission angle, and so are directly comparable. For a zonally symmetric distribution, we expect the difference between these comparable values to be scattered about 0. Figure 8 illustrates a typical example of temperatures within a latitudinal band spanning 1° which are zonally evenly distributed. We use a χ^2 method to determine whether or not there is significant variation in each latitude band and therefore the vortex, where χ^2 is defined as

$$\chi^2(\theta) = \sum_{\phi=0}^{\pi} \left(\frac{y(\phi, \theta) - y(-\phi, \theta)}{\sqrt{\sigma(\phi, \theta) + \sigma(-\phi, \theta)}} \right)^2$$

where $y(\phi, \theta)$ is the parameter in the selected latitude band, θ , at an angle ϕ from the spacecraft-pole meridian, and $\sigma(\phi, \theta)$ is the error of the parameter. We calculate χ^2 for each latitude using the parameters retrieved in a 1° latitude band between θ and $\theta + 1^\circ$ such that emission angles remain comparable between measurements.

In the case of our continuous temperature profile retrievals, the retrieval error is used. However, for our scaled abundance profiles the retrieval error only

299 represents the uncertainty of a uniform gas abundance profile for each species,
 300 and so does not encapsulate realistic uncertainties on the gas species abun-
 301 dance. To obtain more reliable error estimates, we use values obtained from
 302 retrieved limb profiles at the 1 mbar level by Vinatier et al. (2010, 2015). The
 303 only gas species which are both present in our retrieval range ($620 - 733 \text{ cm}^{-1}$)
 304 and have limb profiles available are C_4H_2 , HC_3N and HCN . These gases also
 305 exhibit the sharpest latitudinal gradients and so are most suitable for looking
 306 for asymmetry (Teanby et al., 2019).

307 **4. Results**

308 *4.1. Stratospheric Tilt Correction*

309 The orientation of the tilt was measured with three trace gas emissions and
 310 relative to three reference frames; Saturn, solar and inertial. The minimum
 311 χ^2 values for each offset frame and wavenumber were plotted along with the
 312 $1-\sigma$ and $3-\sigma$ contours and are shown in figure 4. In all three frames a tilt of
 313 around 3.5° was observed, however the inertial frame resulted in the lowest
 314 spread between the best fit pole minimums for each gas emission, and the
 315 area covered by the $3-\sigma$ bounds appeared to be most compact in the inertial
 316 frame. The results for all 3 frames are shown in table 2. The uncertainties
 317 in the three frames are similar, however, when applying the tilts to the asym-
 318 metry analysis, the temperature and composition χ^2 asymmetry values were
 319 seen to consistently cross the $3-\sigma$ threshold for all but the inertial frame. To
 320 investigate the quality of each offset orientation, we examine the zonal asym-
 321 metry variation with pressure for each observation, as seen in figure 9. Over
 322 all observations, the inertial frame is seen to consistently produce no signifi-
 323 cant asymmetry. However, it does not always produce the least asymmetry for
 324 any given observation. This suggests that while the inertial offset provides the
 325 best fitting pole location overall, it may not accurately represent the true offset
 326 orientation. Each flyby was subsequently rotated into the inertial frame for the
 327 vortex asymmetry analysis.

Reference Frame	Offset (°)	Longitude (°W)
Saturn	3.7 ± 0.7	290 ± 10
Solar	3.5 ± 0.8	125 ± 30
Inertial	3.4 ± 0.6	115 ± 8

Table 2: Results of the atmospheric tilt analysis. Magnitudes in all frames are similar, with the inertial frame giving the most concise errors on magnitude and longitude. Magnitude measured as degrees from geographic pole and longitude measured in °W of the reference frame origin.

Since the results are dependent on the position of the spacecraft for each observation it is important to ensure there is no sampling bias in any frame. Figure 4 shows the distribution of the sub spacecraft point with respect to the reference frame for each observation. In all frames the spacecraft positions appear to be well distributed around the pole, suggesting that the results are not skewed in favour of any particular frame.

4.2. Vortex Asymmetry

To demonstrate the seasonal variation in the vortex temperature and composition, figure 10 shows maps of the temperature distribution at the 1 mbar pressure level, and gas abundance distributions for selected gases obtained from retrievals using CIRS data. The binning of data is visible on the maps of figure 10 and care should be taken not to interpret the binning grid as an atmospheric structure. Figure 11 provides quantitative examples of latitudinal variations in the retrieved properties throughout the Cassini mission. Temperature gradients are seen to decrease in the northern summer as the polar stratosphere begins to heat up. Varying gradients in vortex composition are also seen in C_4H_2 , HC_3N , HCN abundance depending on the season and photochemical lifetime of the gas.

The measure of zonal temperature asymmetry is shown in figure 12 which shows the χ^2 values at various pressure levels in the vortex temperature distribution as a function of latitude for the observations listed in table 1. The χ^2 values corresponding to the 1- σ and 3- σ confidence boundaries are also plotted for each latitude. 1- σ and 3- σ values correspond to the χ^2 required to produce a P-value of 0.3173 and 0.0027 respectively, for $N - 1$ degrees of freedom where

352 N is the number of parameters in the latitude band. The temperature distri-
 353 bution in a latitude band is considered to be significantly asymmetric if the
 354 calculated value is greater than the $3\text{-}\sigma$ value. Throughout all 18 observations,
 355 there appears to be no significant asymmetry in the vortex temperature at the
 356 0.5, 1 or 2 mbar levels, suggesting that the vortex’s temperature distribution is
 357 zonally symmetric.

358 Similarly, figure 13 shows the χ^2 values for zonal asymmetry in the distri-
 359 bution of C_4H_2 , HC_3N and HCN abundance in the vortex as a function of lati-
 360 tude. Amongst the earlier observations we see some zonal variation in the gas
 361 abundances northward of around 50° compared to later observations where
 362 there is little evidence of variation. This is to be expected since the vortex be-
 363 comes greatly depleted in trace gas species by the end of the mission, as seen
 364 in the abundance maps in figure 10 and latitudinal profile examples in figure
 365 11. However, at no point during the mission do we see the abundance asym-
 366 metry surpassing $3\text{-}\sigma$, suggesting that the vortex is also zonally symmetric in
 367 its composition.

368 The method outlined in section 3.3 would not detect any variations in the
 369 temperature or composition which were symmetric about the spacecraft-pole-
 370 meridian. However, as seen in figure 4, the subspacecraft point is well dis-
 371 tributed in longitude around the pole and so it is unlikely such an asymmetry
 372 would be absent in all 18 observations.

373 5. Discussion

374 Despite the ambiguity in the offset orientation, the magnitude of our result
 375 is in broad agreement with the previous studies which found the stratospheric
 376 tilt to be offset from the pole by $4.1 \pm 0.2^\circ$, $3.8 \pm 0.9^\circ$, $4.0 \pm 1.5^\circ$ and approx-
 377 imately 4.5° for temperature, haze albedo asymmetry, composition and zonal
 378 wind velocity measurements respectively (Achterberg et al., 2008; Roman et al.,
 379 2009; Teanby et al., 2010; West et al., 2016). Previously Achterberg et al. (2008)
 380 suggested that the tilt is a result of the response of Titan’s circulation to so-
 381 lar heating in the atmosphere and so is fixed in the solar frame. Tokano (2010)

382 later predicted a similar offset in their GCM, also noting a westward rotation of
 383 the tilt offset with a period of 1 Titan day and varying magnitude with season.
 384 They investigate possible mechanisms for the motion of the tilt, proposing that
 385 thermal tides cause periodic oscillations in the zonal wind in large parts of the
 386 atmosphere which acts to tilt the atmospheric angular momentum vector from
 387 the solid body rotation axis. Whilst Saturn’s gravitational waves are present
 388 on Titan they exhibit a wavenumber 2 feature and are much less dominant in
 389 the stratosphere than thermal tides, and Rossby waves must propagate with an
 390 eastwards group velocity, leaving thermal tides as the most plausible mecha-
 391 nism for this feature. However, Achterberg et al. (2011) later found that the tilt
 392 appears to remain stationary in the inertial frame and a small increase in offset
 393 magnitude was observed moving into spring, where Tokano (2010) predicted
 394 a reduction in magnitude. Furthermore, several studies have suggested that
 395 the radiative time constant in Titan’s middle atmosphere is short enough that
 396 seasonal effects are expected but long enough such that diurnal effects are not
 397 expected (Flasar et al., 1981; Strobel et al., 2010; Lebonnois et al., 2014).

398 Our results make use of data over a wider time period than previous stud-
 399 ies, however due to the need to combine multiple datasets to obtain one mea-
 400 surement of the offset position and the relatively few number of datasets avail-
 401 able, we can only find the best fitting offset over the entire Cassini mission. It
 402 may be possible that there is indeed a precession of the tilt, which our method
 403 would not see due to a lack of temporal resolution. In any case, we search for
 404 the stratospheric tilt only to correct our observations so that we can investigate
 405 zonal asymmetries in the vortex.

406 Throughout all 18 observations, we investigate the zonal distributions of
 407 temperature at various pressure levels and at no point do we see any signs
 408 of significant asymmetry (χ^2 asymmetry values greater than the $3\text{-}\sigma$ level) as
 409 shown in figure 12. In some cases the temperature distributions are seen to
 410 surpass $1\text{-}\sigma$ suggesting there may be some degree of temperature asymmetry
 411 present around the vortex. Similarly, we investigate the zonal distribution of
 412 three trace gases; C_4H_2 , HC_3N and HCN . We do not see the χ^2 asymmetry

413 values to cross the $3\text{-}\sigma$ threshold at any point, indicating that the vortex com-
414 position remains uniform zonally.

415 Comparing Titan’s uniform northern vortex with the vortices of other plan-
416 ets may help us better understand what processes govern its evolution. On
417 Earth, similar studies have investigated the size and shape of the northern
418 and southern hemisphere vortices. Waugh and Randel (1999); Mitchell et al.
419 (2013) show that Earth’s northern vortex appears to be much more distorted
420 and elongated than the southern vortex. The large variability in vortex shape
421 is attributed to upward propagation of Rossby waves from the troposphere
422 which act to perturb the vortex (Andrews et al., 1987; Waugh and Randel, 1999;
423 Mitchell et al., 2015). Greater variability in the northern hemisphere topog-
424 raphy as well as land-sea temperature contrasts results in the generation of
425 stronger planetary waves in the north, weakening the vortex more than in the
426 south. These waves can also contribute to extreme vortex events called Sudden
427 Stratospheric warmings (SSWs) which can see stratospheric temperatures rise
428 by tens of degrees and help to facilitate rapid breakdown of the vortex (Waugh
429 et al., 2016). Similarly, on Mars the southern vortex is seen to be highly variable,
430 more so than in the north (Mitchell et al., 2015; Waugh et al., 2016). The Martian
431 polar atmosphere is also seen to exhibit SSW-like events, or Rapid Polar Warm-
432 ings (RPWs) (Mitchell et al., 2015), with a variety of factors attributed to their
433 origin. The variable topography in the southern hemisphere generates Rossby
434 waves which can act to perturb the vortex, as on Earth. Inhomogeneities in
435 the atmosphere such as dust storms or CO_2 condensation also have an impor-
436 tant effect on the zonal circulation (Newman et al., 2002; Guzewich et al., 2016;
437 Toigo et al., 2017; Rostami et al., 2018). No such SSW or RPW type event has
438 been observed on Titan.

439 Titan’s topography is relatively flat in comparison to other solar system
440 bodies (Lorenz et al., 2011), suggesting that the generation and upward prop-
441 agation of strong Rossby waves from the troposphere is less likely than on
442 Earth and Mars. The absence of these planetary waves making their way into
443 the stratosphere could explain how the vortex remains symmetric as it evolves,

444 and the lack of SSW-like events which may otherwise perturb the zonal circu-
 445 lation. Figure 14 shows a cross section of the mean topography between lati-
 446 tudes where the meridional gradients are typically strongest in the vortices: 50
 447 – 70°N for Titan and Earth and 50 – 70°S for Mars. The topographic data was
 448 obtained from Cassini Radar measurements for Titan (Lorenz et al., 2013), the
 449 USGS GTOPO30 Digital Elevation Model for Earth and the Mars Orbiter Laser
 450 Altimeter from the Mars Global Surveyor spacecraft (Zuber et al., 1992; Smith
 451 et al., 2001). The elevations are measured as height above sea level (Earth), the
 452 difference between planetary radius and the areoid (Mars) and surface height
 453 relative to a sphere of radius 2575 km (Titan).

454 An additional factor which may lead to the zonal symmetry is the inability
 455 of Rossby waves to propagate vertically into the stratosphere on Titan. Char-
 456 ney and Drazin (1961) demonstrated that the vertical propagation of Rossby
 457 waves is dependent on the background flow. For stationary Rossby waves, the
 458 Charney-Drazin criterion states that vertical propagation is only possible on
 459 the condition that $0 < u < u_c$, where u is the background flow and u_c is the
 460 Rossby critical velocity, with positive velocity defined in the eastward direc-
 461 tion.

462 Assuming a constant background flow, the Rossby critical velocity can be
 463 derived from the wave dispersion relation for a Rossby wave and the Quasi-
 464 Geostrophic Potential Vorticity relations, and written

$$u_c = \frac{\beta}{k^2 + l^2 + \frac{1}{4L_d^2}}$$

465 where $\beta = \frac{\partial f}{\partial y} = \frac{2\Omega \cos \theta}{a}$ is the Rossby parameter, with Ω , θ and a the rotation
 466 rate, latitude and radius respectively and $L_d = \frac{NH}{f}$ is the Rossby deformation
 467 Radius with N , H and f the Brunt-Väisälä frequency, scale height and corio-
 468 lis frequency respectively and k , l are the zonal and meridional wavenumbers
 469 of the wave. Figure 15 shows the variation of u_c with zonal wavenumber for
 470 Earth, Mars and Titan with meridional wavenumber 0 in the middle-latitudes
 471 (45°N). N was set equal to $2 \times 10^{-2} \text{ s}^{-1}$ for Earth (Ogura and Phillips, 1962),

472 $1 \times 10^{-2} \text{ s}^{-1}$ for Mars (the average value between $45^\circ\text{S} - 70^\circ\text{S}$ taken from Ando
 473 et al. (2012)) and $4 \times 10^{-3} \text{ s}^{-1}$ for Titan (Brown et al., 2010). For H , values of 7
 474 km for Earth (Taylor and J. Lary, 2006), 10 km for Mars (Gierasch and Goody,
 475 1968) and 20 km for Titan (Coustenis and Taylor, 2008) were used. The val-
 476 ues of H and N used for Titan and Mars are single estimates and are not as
 477 well measured as the values for Earth. However, they are used only to predict
 478 the typical critical wind speeds in the respective atmospheres and so are ade-
 479 quate for this study. Also plotted are typical zonal wind speeds for each body,
 480 with an upper value of 35 ms^{-1} near the tropopause for Titan as measured by
 481 the Huygens probe (Bird et al., 2005), 30 ms^{-1} for Earth near the tropopause
 482 (Hoinka, 1999) and 20 ms^{-1} for the lower Martian atmosphere as measured by
 483 the Schiaparelli module on the ExoMars rover during descent (Aboudan et al.,
 484 2018).

485 The critical velocity is much larger on Earth and Mars than Titan, indicating
 486 that stationary Rossby waves can propagate upwards through a much larger
 487 range of wind speeds there. For the longest waves, the largest critical velocity
 488 on Titan is seen to be less than 20 ms^{-1} . The only in situ measurement of
 489 Titan’s winds was performed by the Huygens DWE, which recorded a zonal
 490 wind profile which increases to greater than 40 ms^{-1} at 10 mbar in the lower
 491 stratosphere (Bird et al., 2005). GCMs also predict winds in excess of 40 ms^{-1} at
 492 the 10 mbar level (Newman et al., 2011; Lebonnois et al., 2012). The calculated
 493 critical velocity for even the largest wave is much less than the measured and
 494 predicted wind speeds in the lower stratosphere. It may be possible then that
 495 stationary Rossby waves are unable to propagate vertically in the winds in
 496 Titan’s stratosphere, and therefore topographically forced stationary Rossby
 497 waves do not play a role in the breakup of the polar vortex on Titan. This
 498 could lead to a longer lived vortex on Titan than on Earth or Mars and could
 499 explain the persistence of Titan’s north polar vortex well into northern summer
 500 discussed by Teanby et al. (2019).

501 The northern vortex of Venus is observed to be highly asymmetric with the
 502 existence of a ‘polar dipole’ first identified by Taylor et al. (1979). Yamamoto

503 and Takahashi (2015) suggest that the superposition of a diurnal tide and tran-
 504 sient baroclinic waves in the polar region can create irregular vortex shapes.
 505 As mentioned previously, Titan’s middle atmosphere is not expected to be sen-
 506 sitive to diurnal effects. Leovy and Pollack (1973) first showed that the com-
 507 bination of Titan’s slow rotation rate and large Rossby radius of deformation
 508 (comparable to its radius) produce conditions in which baroclinic waves can-
 509 not efficiently transport heat, and that axisymmetric meridional circulations
 510 dominate. Mitchell and Vallis (2010) later demonstrated that baroclinic insta-
 511 bility is unable to form in a superrotating atmosphere, suggesting that baro-
 512 clinic waves should not be present in the atmosphere of Titan or Venus. How-
 513 ever, Sugimoto et al. (2014) argue that on Venus the instability is formed at the
 514 cloud level, leading to the generation of such waves. Whilst the conditions for
 515 baroclinic instability are not expected to be met in superrotating atmospheres
 516 in general, if there is a mechanism producing it on Venus but not Titan it may
 517 offer an explanation as to the differences in their vortices.

518 Topographically forced Rossby waves are not the only mechanism which
 519 could contribute to the break up of the polar vortex. Teanby et al. (2008a) noted
 520 an increase in abundance of HCN, C₂H₂ and C₄H₂ extending from the vortex
 521 region towards the equator at altitudes of around 200-300km ($\approx 1 - 0.1$ mbar).
 522 They suggest that horizontal mixing by gravity waves and barotropic instabili-
 523 ties are responsible. Lorenz et al. (2014) later identified the existence of internal
 524 gravity waves in Titan’s lower stratosphere using Huygens in situ measure-
 525 ments. Wavelengths of 3-8km and amplitudes of 3K were indicated. They
 526 noted that Titan’s zonal winds likely form a critical layer for the upward prop-
 527 agation of gravity waves, with the 8km waves as the dominant wave above
 528 the critical layer. Whilst such gravity waves may play a role in the breakup
 529 for the vortex, the CIRS nadir observations used in this analysis is unlikely to
 530 be able to resolve them due to their small vertical scales and fine zonal struc-
 531 ture, however CIRS limb data may be adequate to investigate the influence of
 532 such waves on the vortex breakup. Furthermore, although Teanby et al. (2008a)
 533 suggest barotropic instabilities may be present and important for transporting

534 gases from the vortex towards the equator, the lack of asymmetry in the tem-
535 perature and composition across the vortex indicate that such instabilities are
536 not resolvable with CIRS nadir data, even if they are present.

537 6. Conclusion

538 In this study, we used 18 CIRS nadir mapping observations covering half a
539 Titan year to investigate the evolution of Titan’s northern polar vortex. Using
540 IR gas emissions in the vortex region we found the stratospheric rotation axis
541 to be offset from the solid body rotation axis by $3.4 \pm 0.6^\circ$, in broad agreement
542 with previous studies which found values of $4.1 \pm 0.2^\circ$, $3.8 \pm 0.9^\circ$, $4.0 \pm 1.5^\circ$
543 and approximately 4.5° (Achterberg et al., 2008; Roman et al., 2009; Teanby
544 et al., 2010; West et al., 2016), although peculiarly find the level of asymmetry
545 in the vortex is minimised when the offset is fixed in an inertial frame. How-
546 ever, examination of the level of asymmetry present in each observation after
547 correction for the offset indicates that at times the quality of the inertial frame
548 fit is indistinguishable from the solar or Saturn fixed-frames. This suggests we
549 cannot rule out precession of the atmospheric symmetry axis.

550 By producing temperature and composition maps of the northern polar re-
551 gions we also find that the vortex shows no sign of significant zonal variations
552 in temperature or gas abundance at any point, and remains broadly axisym-
553 metric in shape as it evolves and breaks up, uniformly increasing or decreasing
554 in size throughout its lifetime. This suggests Titan’s vortex behaves differently
555 to those on Earth, Mars and Venus. Alongside seasonal radiation changes, an
556 important factor in the breakup of the polar vortex on Earth is mixed Rossby-
557 gravity waves which can be produced by large scale topography and land-sea
558 contrasts. Similarly, the breakup of the polar vortex on Mars is influenced by
559 seasonal radiation changes and dust and CO₂ variability in the atmosphere
560 which absorb short wave radiation causing rapid warming of the vortex. The
561 relatively flat topography of Titan and the fast superrotating zonal winds pro-
562 duce unfavourable conditions for the upward propagation of Rossby waves
563 into the stratosphere where they could disturb the vortex. Venus’ atmosphere

is also superrotating, but strong thermal tides and possible baroclinic waves act to perturb the zonal flow. Long radiative timescales in Titan’s stratosphere likely prevent such diurnal tides and baroclinic waves are not expected to form. Other wave mechanisms such as gravity waves may play a role in the breakup of the vortex on a finer scale, but no large scale Rossby waves appear to perturb the vortex. This could explain the long duration of Titan’s northern polar vortex observed by Cassini (Teanby et al., 2019) and the high degree of zonal symmetry we observe.

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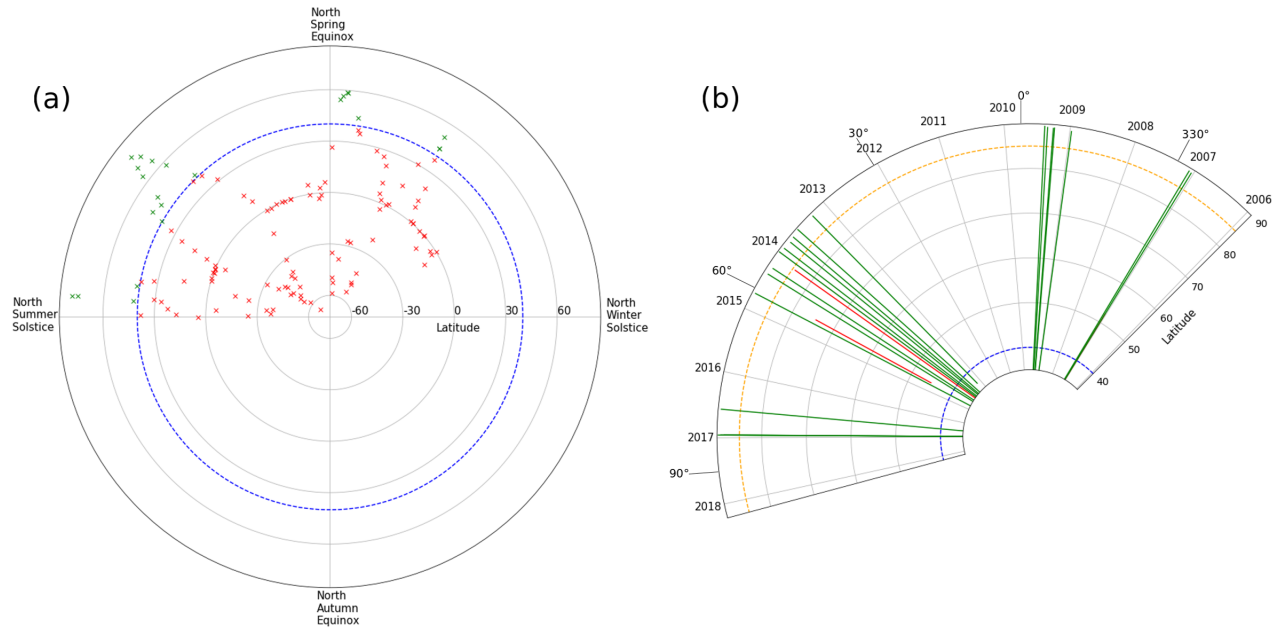


Figure 1: CIRS data available for this study. (a): Seasonal coverage by CIRS is roughly half a Titan year. Markers indicate sub spacecraft latitude for each observation. Blue dashed line indicates the 40° sub spacecraft latitude criterion. Green markers indicate sub spacecraft latitude is greater than criterion. Red markers indicate sub spacecraft latitude is less than criterion. (b): Calendar year coverage and maximum latitudinal extent of each observation meeting criterion from (a), with solar longitude marked in 30° intervals. Orange dashed line indicates the 85°N coverage criterion. Green lines show latitudinal coverage of observations which meet criterion. Red lines show coverage of observations which do not meet criterion.

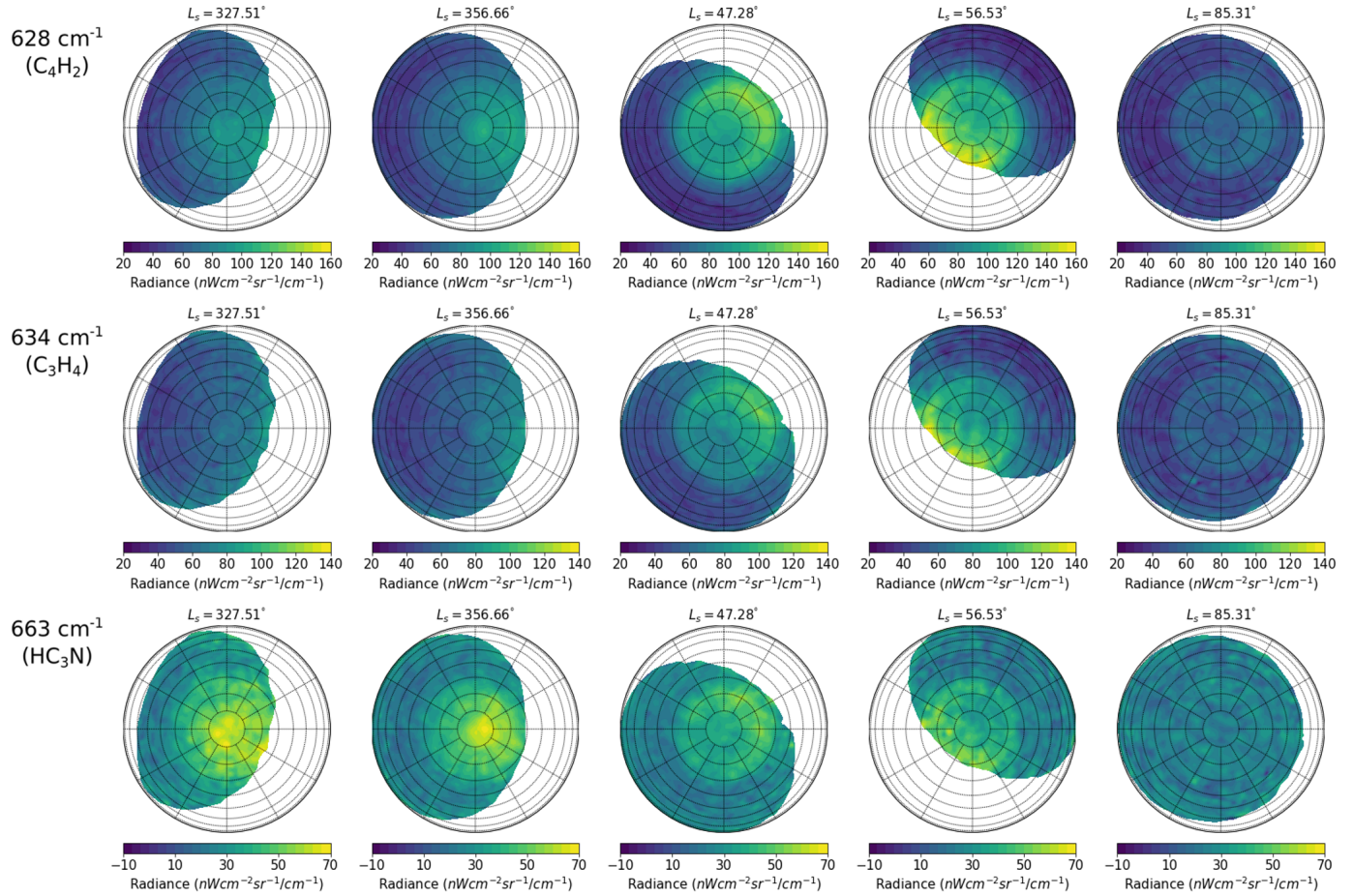


Figure 2: IR emission maps of north pole recorded by CIRS from 2007 (northern winter, $L_s = 327.51^\circ$) to late 2016 (northern summer, $L_s = 85.31^\circ$). Gas emissions are seen to be greatly reduced by summer despite the expected heating of the polar atmosphere, indicating a decrease in gas abundance.

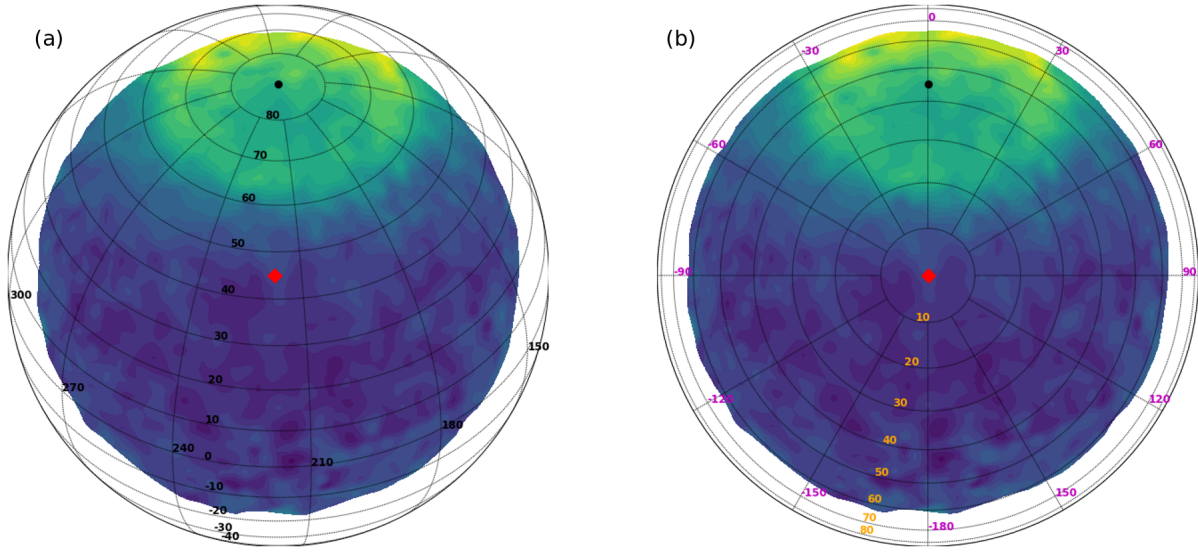


Figure 3: Maps of $628\text{cm}^{-1}(\text{C}_4\text{H}_2)$ at $L_s = 56.53^\circ$ as seen in Figure 2 in two coordinate frames. (a) Latitude-longitude frame as seen from Cassini with geographic pole marked as a black circle and sub spacecraft point marked as a red diamond and latitudes and longitudes noted in black. (b) Azimuth-angular distance frame as seen from Cassini with zero azimuth (α , purple) lies along SPM and emission angle is constant along lines equidistant from zenith (ϵ , orange). Limb brightening can be seen as the vortex IR emissions are seen to be greater at larger angular distance (larger emission angle) from Cassini.

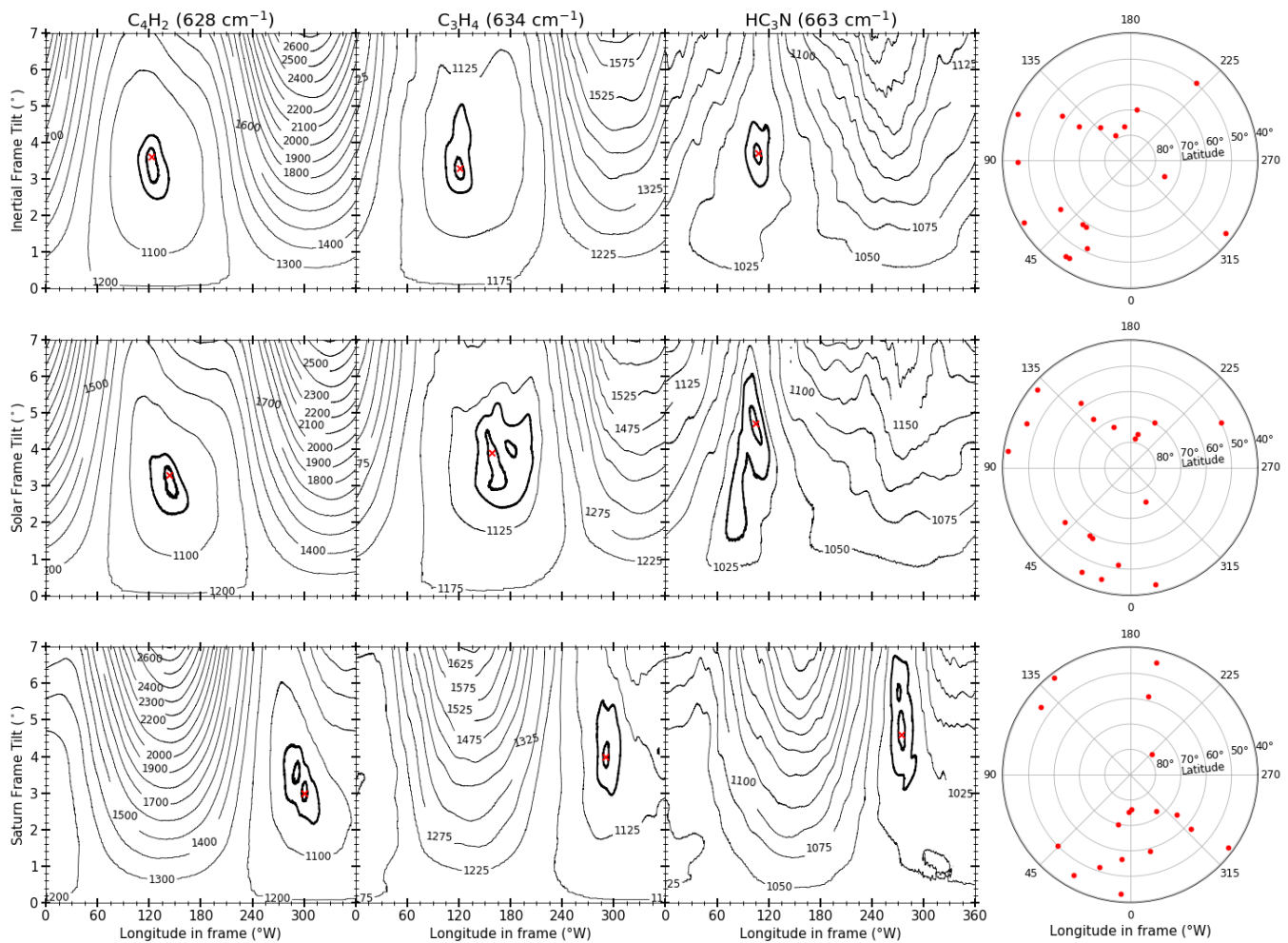


Figure 4: Contour maps of χ^2 values as a function of tilt and frame longitude for best fitting stratospheric tilt over all 18 observations listed in table 1. χ^2 values calculated using emissions from three vortex enriched gases (first 3 columns) are shown in three unique reference frames (rows). Minima are marked with an X and thick contours indicate 1- σ and 3- σ confidence intervals. Fourth column shows the sub-spacecraft points of all observations in each reference frame.

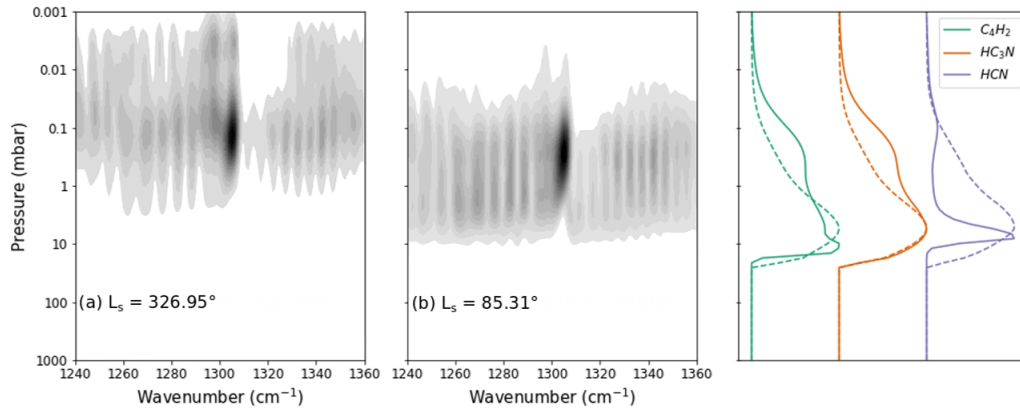


Figure 5: Contribution functions for temperature at the north pole in (a) northern winter and (b) northern summer. Temperature contributions are seen to peak close to 0.1 mbar during the winter, and closer to 1 mbar in the summer. Right panel shows contribution functions for composition at the north pole for northern winter (solid lines) and northern summer (dashed lines).

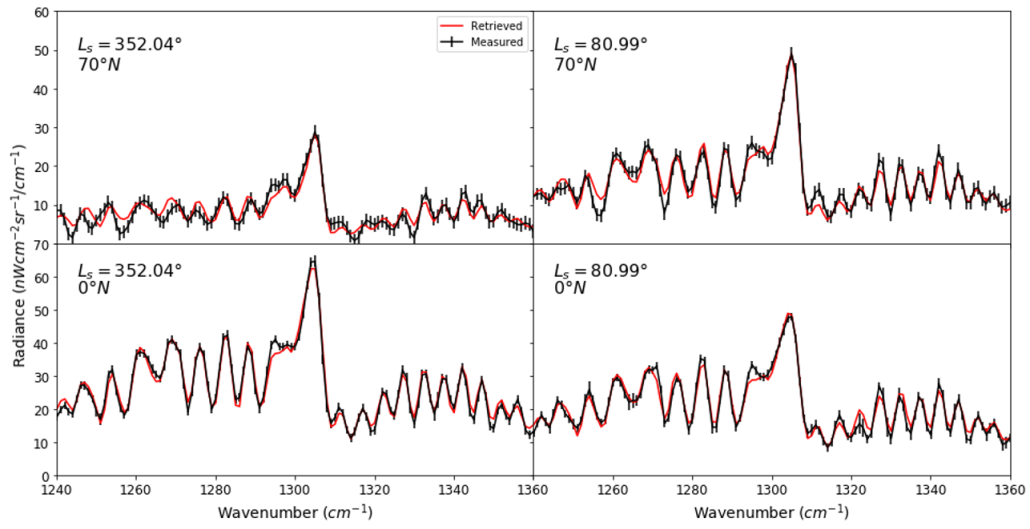


Figure 6: Examples of measured (black) and retrieved (red) spectra for the ν_4 methane band in FP4 shown near the pole and equator for both northern winter ($L_s = 352.04^\circ$) and northern summer ($L_s = 80.99^\circ$). Continuous temperature profiles are derived from the ν_4 methane band.

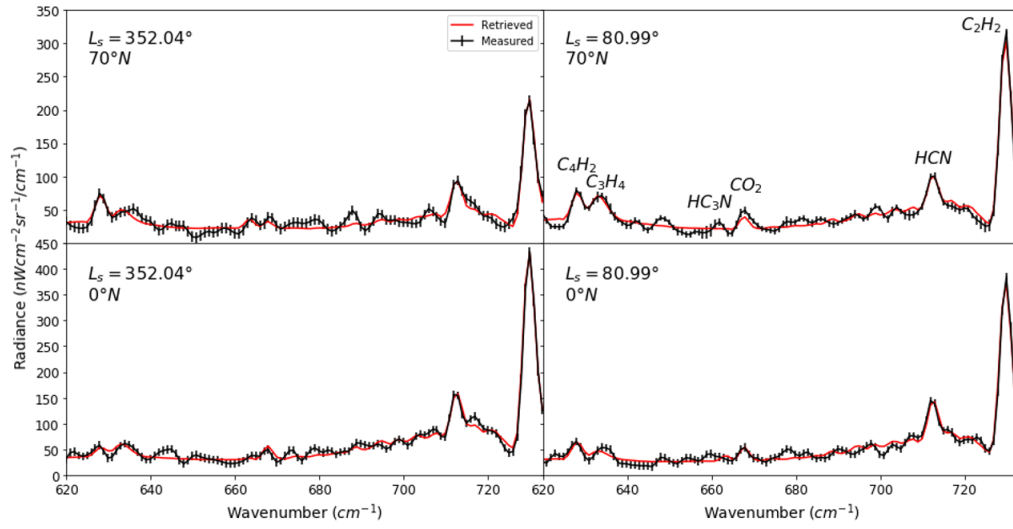


Figure 7: Examples of measured (black) and retrieved (red) spectra in a selected range of FP3 with many gas emissions present, shown near the pole and equator for both northern winter ($L_s = 352.04^\circ$) and northern summer ($L_s = 80.99^\circ$). Emissions for some trace gases such as C_4H_2 , C_3H_4 , HC_3N and HCN are greater in the polar region than at the equator, particularly during the winter where the polar vortex is strong and gases are more abundant.

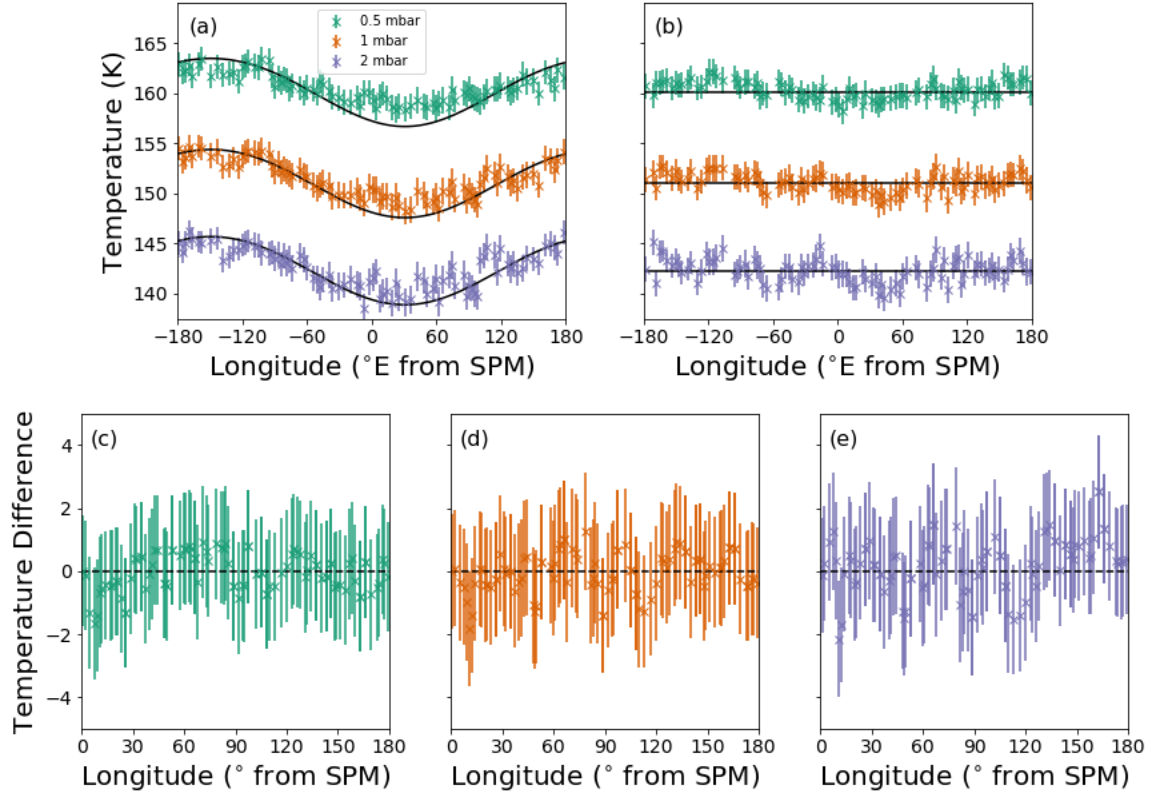


Figure 8: (a) Zonal variation in temperature at 3 pressure levels between $62\text{--}63^\circ\text{N}$ for $L_s = 356.66^\circ$. Wavenumber 1 feature can be seen in temperature distribution. (b) Zonal variations in the same latitude band after correction for the stratospheric tilt. Solid black line indicates the best fitting straight line, with (a) showing the best fitting straight line transformed back into the untilted frame. (c), (d) and (e) show the difference in temperature at the 0.5, 1 and 2 mbar levels respectively as a function of unsigned angular distance from the SPM in the tilted frame. The uncertainty on temperatures are derived in the retrieval process. All 3 temperature differences are seen to be distributed around 0 indicating no significant asymmetry in this latitude band.

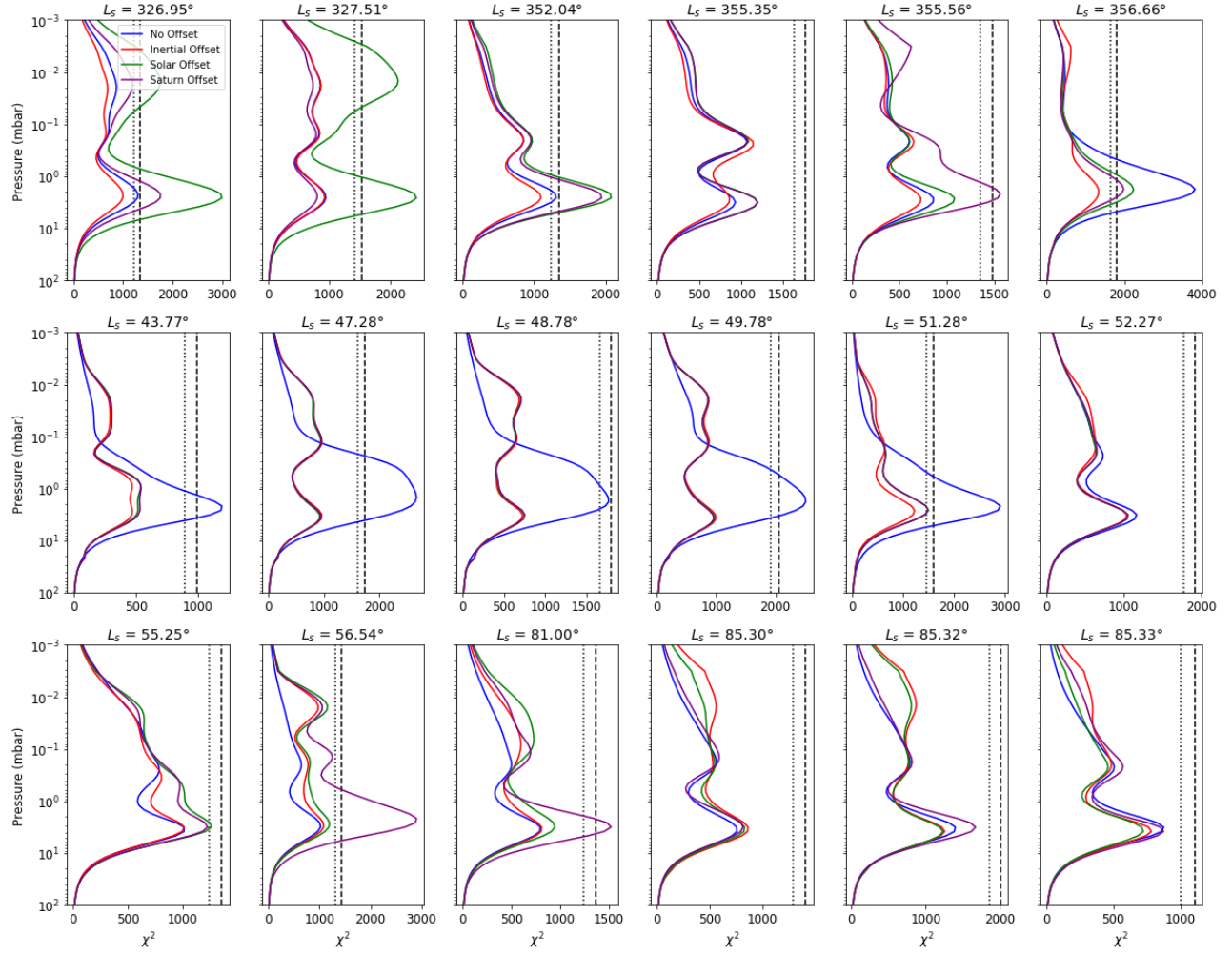


Figure 9: Polar asymmetry of the temperature in the northern hemisphere from 40° northwards. Asymmetry for four offset orientations shown. $1\text{-}\sigma$ and $3\text{-}\sigma$ significance thresholds for asymmetry are shown by the dotted and dashed lines respectively.

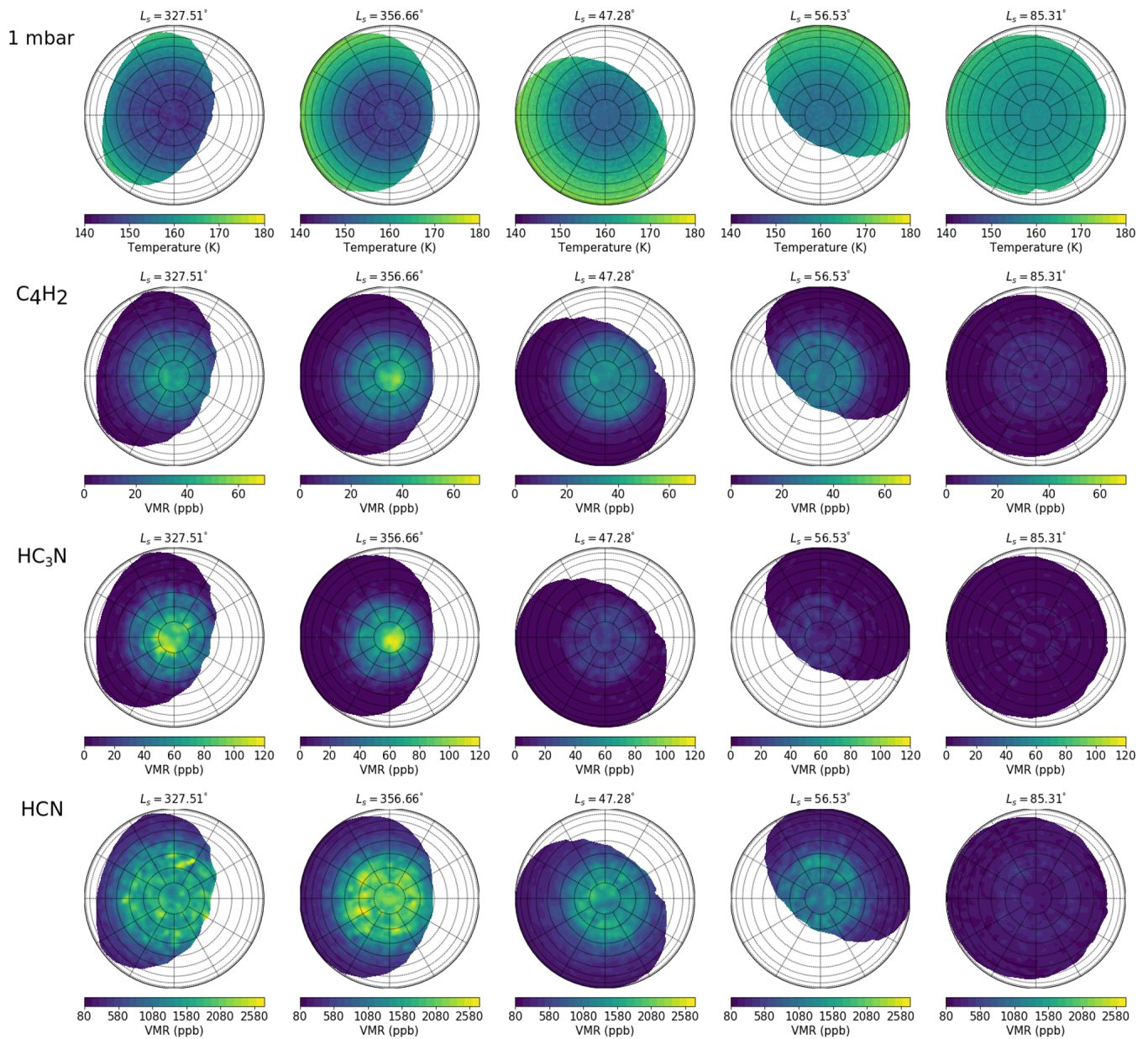


Figure 10: Maps of temperature at 1 mbar and C₄H₂, HC₃N, HCN abundance in the northern hemisphere at various points in the Titan year illustrate the seasonal variations in the vortex.

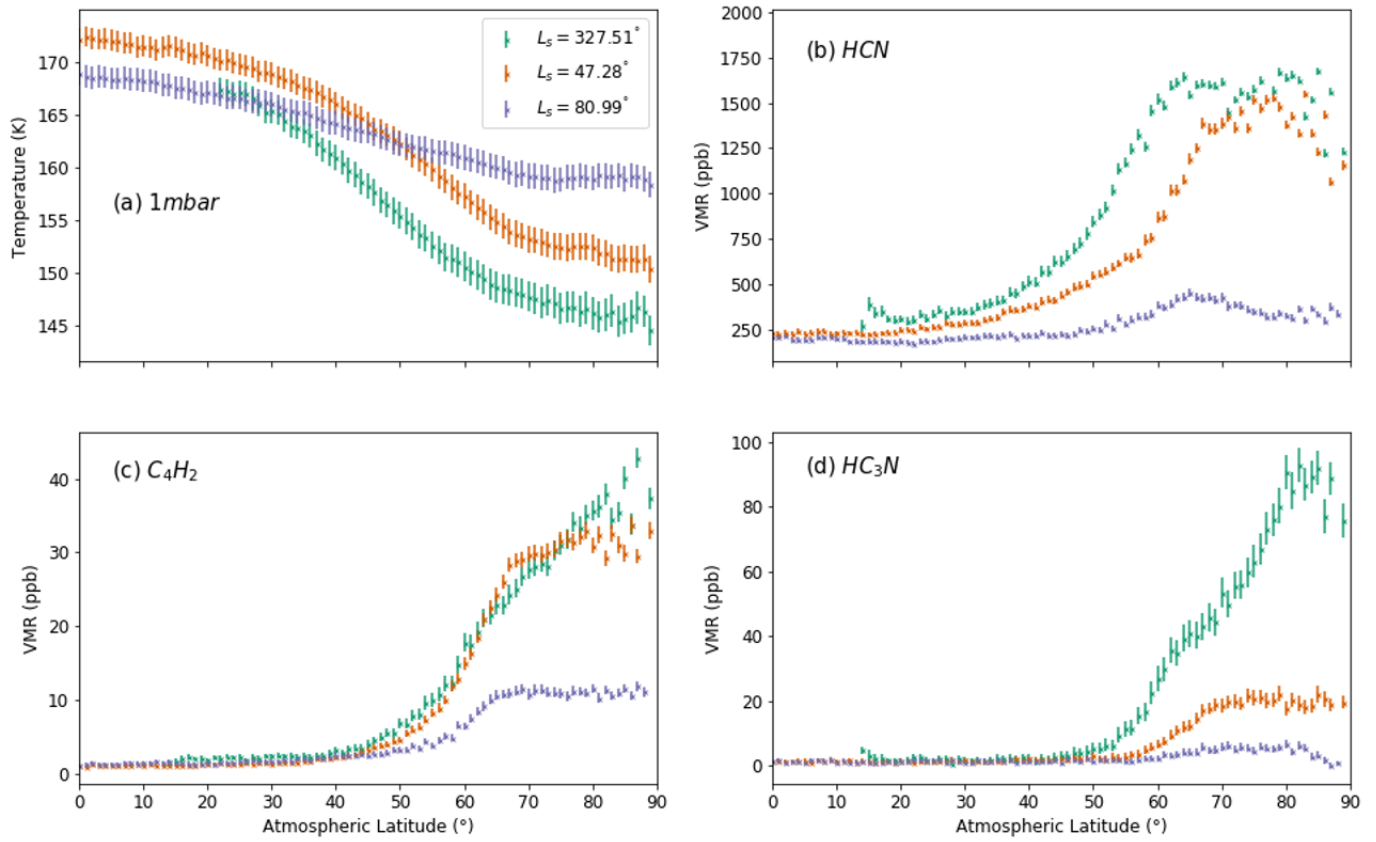


Figure 11: Latitudinal variations in zonal mean temperature and composition in the northern hemisphere for observations at three different times; northern winter (green), early northern summer (orange) and mid northern summer (purple). The uncertainty on temperature and composition are derived in the retrieval process.

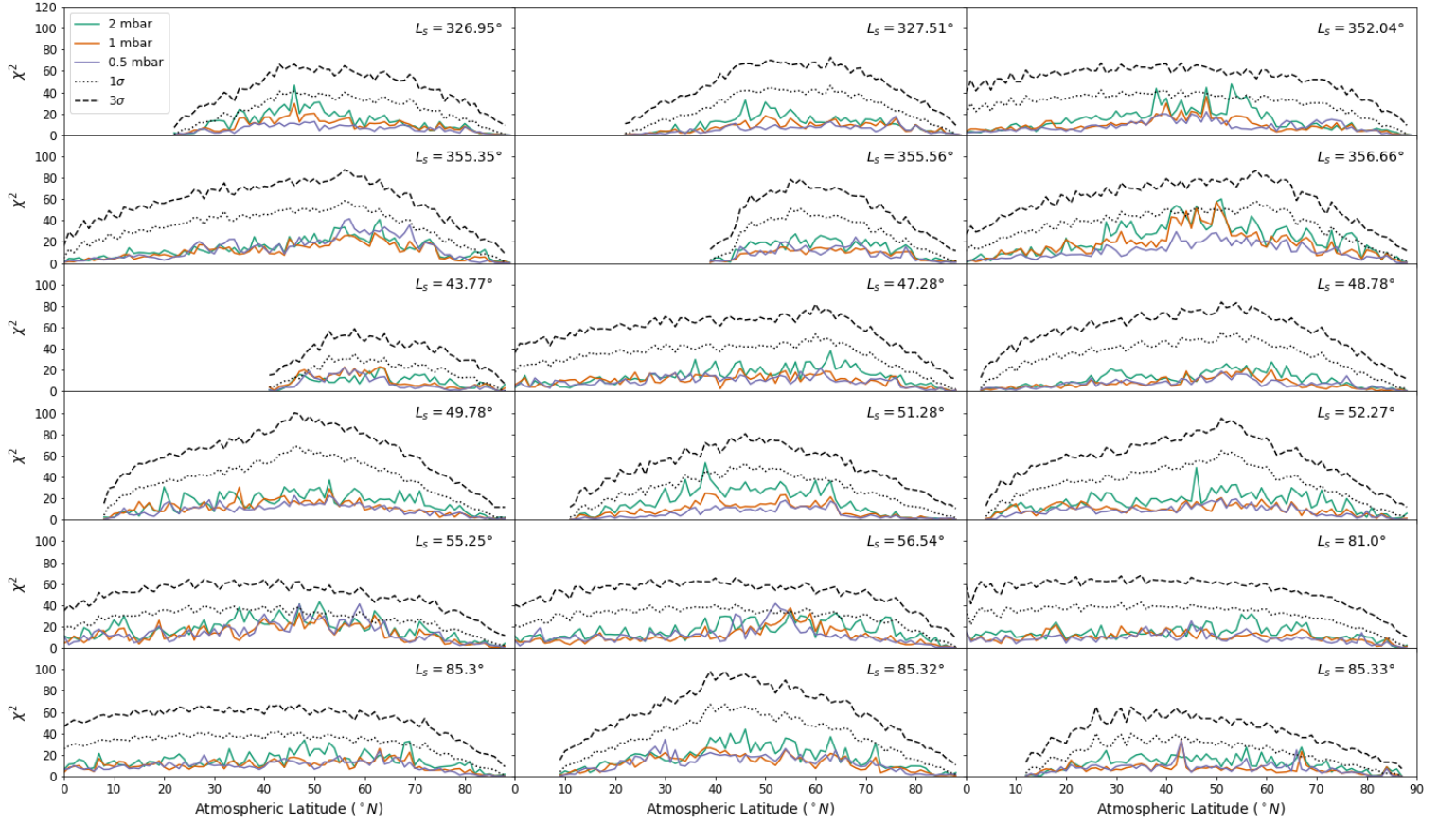


Figure 12: χ^2 values calculated at all latitudes in northern hemisphere for temperatures at 3 pressure levels and all selected observations. 1- σ and 3- σ confidence boundary also shown as dotted and dashed black lines respectively.

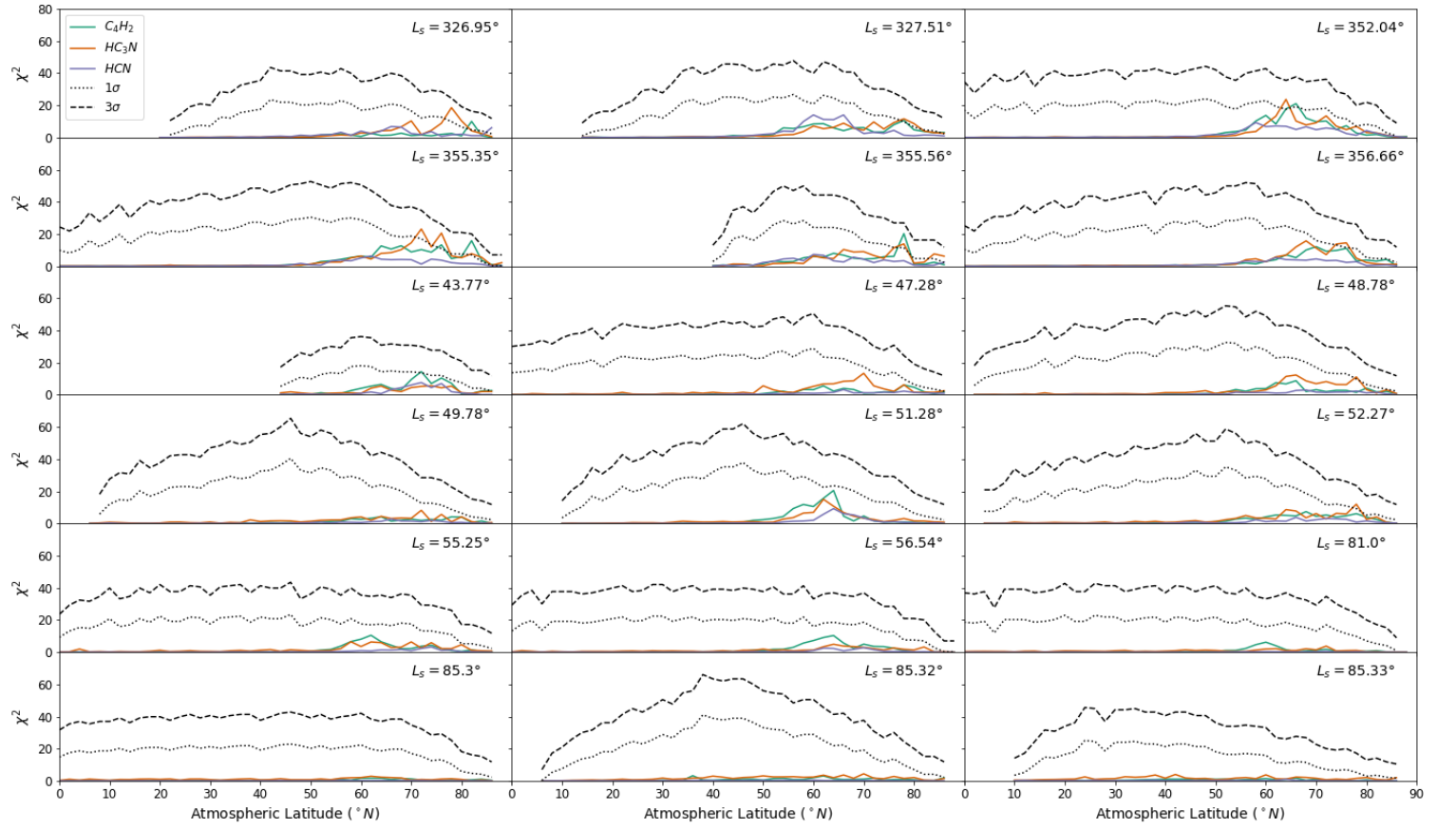


Figure 13: Similar to figure 12, but with χ^2 values for composition asymmetry.

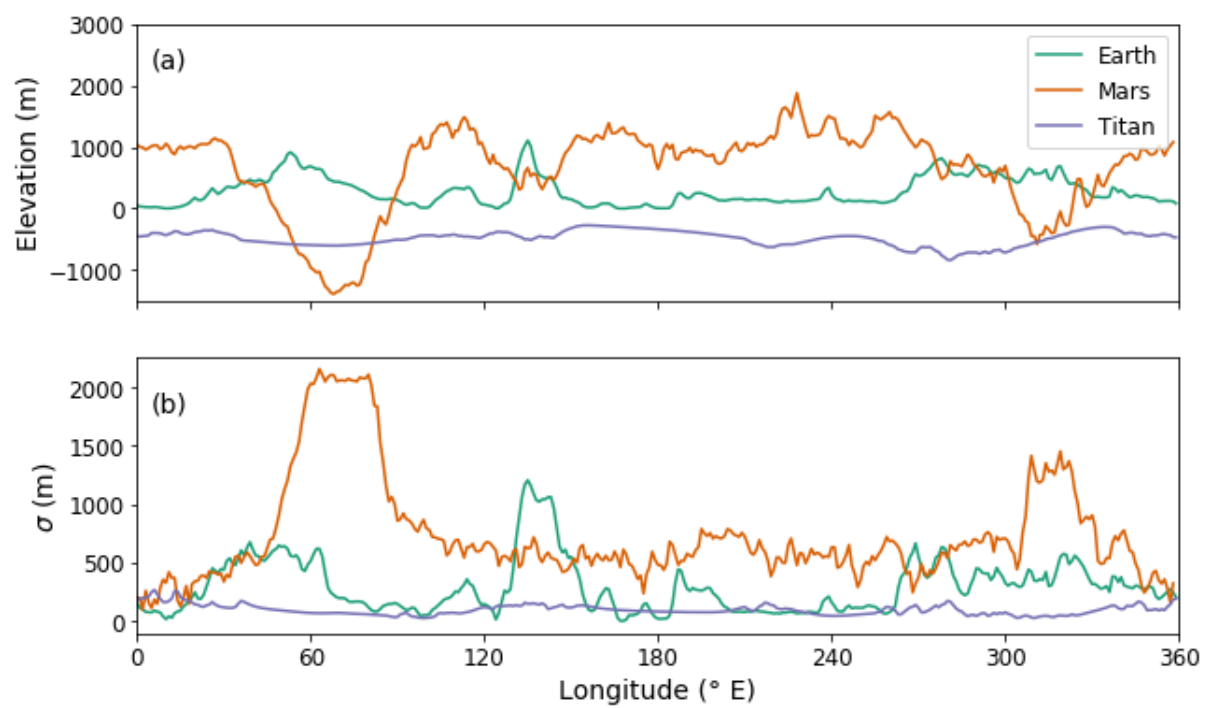


Figure 14: (a) Mean topography for Titan and Earth between 50-70 $^{\circ}$ N and Mars between 50-70 $^{\circ}$ S. (b) Standard deviation of the topography.

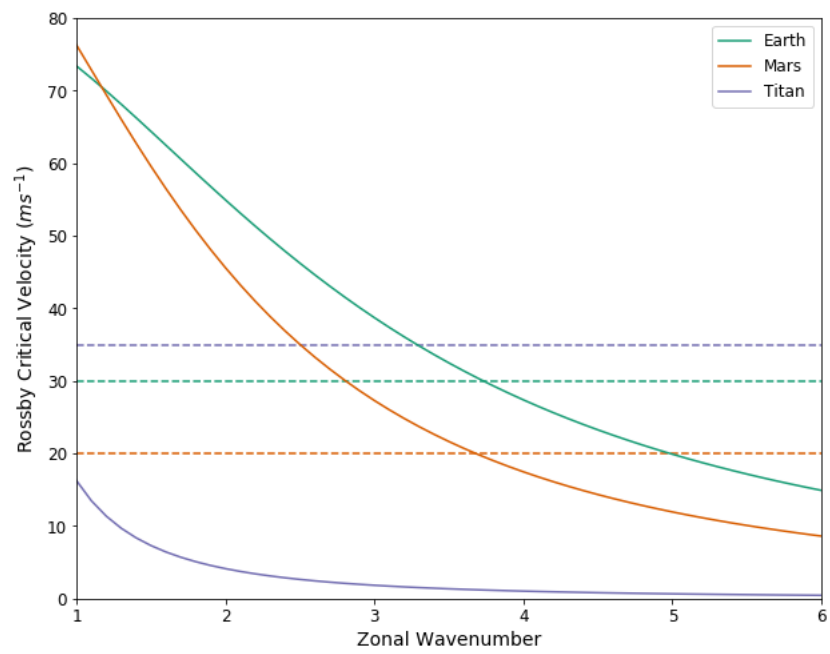


Figure 15: Variation of the Rossby critical velocity with zonal wavenumber for a Rossby wave with a meridional wavenumber of 0 for Earth, Mars and Titan. Typical zonal wind speeds in the lower atmosphere shown as dashed lines.