### Oscillation of the Ionosphere Caused by the 2022 Tonga Volcanic Eruption Observed with SuperDARN Radars

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### Abstract

On 15 January 2022, the submarine volcano on the southwest Pacific island of Tonga violently erupted. Thus far, the ionospheric oscillation features caused by the volcanic eruption have not been identified. Here, observations from the Super Dual Auroral Radar Network (SuperDARN) radars and digisondes  $\cause{are}{were}$  employed to analyze ionospheric oscillations in the Northern Hemisphere caused by the volcanic eruption in Tonga. Due to the magnetic field conjugate effect, the ionospheric oscillations were observed much earlier than the arrival of surface air pressure waves, and the maximum negative line-of-sight (LOS) velocity of the ionospheric oscillations exceeded 100 m/s in the F layer. After the surface air pressure waves arrived, the maximum LOS velocity in the E layer approached 150 m/s. A maximum upward displacement of 100 km was observed in the ionosphere. This work provides a new perspective for understanding the strong ionospheric oscillation caused by geological hazards observed on Earth.

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### Key Points:

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14	•	Enhanced ionospheric irregularities with highly variable velocities were observed
15		after the Tonga volcanic eruption.
16	•	The maximum amplitude of the line-of-sight velocity of the ionospheric oscillation
17		approached 150 m/s in E layer.
18	•	The ionosphere was displaced upwards by as much as 100 km.

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### 19 Abstract

On 15 January 2022, the submarine volcano on the southwest Pacific island of Ton-20 ga violently erupted. Thus far, the ionospheric oscillation features caused by the volcanic 21 eruption have not been identified. Here, the field-aligned electron density irregularities 22 in the ionosphere detected by Super Dual Auroral Radar Network (SuperDARN) radars 23 are employed as tracers to analyse ionospheric oscillation in the Northern Hemisphere 24 caused by the volcanic eruption in Tonga. Due to the magnetic field conjugate effect, 25 the ionospheric oscillations were observed much earlier than expected, and the maximum 26 27 negative line-of-sight (LOS) velocity of the ionospheric oscillation exceeded 100 m/s in the F layer. After the surface air pressure wave arrived, the maximum LOS velocity in 28 the E layer approached 150 m/s. The ionosphere also experienced a maximum upward-29 s displacement of 100 km. This work provides a new perspective for understanding the 30 strong ionospheric oscillation caused by geological hazards observed on Earth. 31

### <sup>32</sup> Plain Language Summary

On 15 January 2022, an underwater volcano on the southwest Pacific island of Ton-33 ga erupted, triggering significant disturbances on the surface and in the ionosphere that 34 propagated worldwide. The oscillation features of the ionosphere caused by the volcanic 35 eruption have not been identified. The volcanic eruption caused numerous irregularities 36 in the ionosphere. These irregularities move with the ionosphere similar to how leaves 37 move in a rough sea. In this study, the ionospheric irregularities were observed and em-38 ployed as tracers to analyse the ionospheric oscillation. It was observed that the iono-39 spheric oscillation exhibited different features before and after the arrival of the surface 40 air pressure wave, including the maximum line-of-sight (LOS) velocity, the altitude of 41 the maximum LOS velocity, and the propagation direction. The amplitudes of the LOS 42 velocities of the ionospheric fluctuations approached 150 m/s, and the ionosphere expe-43 rienced a maximum upwards displacement of 100 km, which is the strongest ionospher-44 ic fluctuation caused by geological hazards ever observed. 45

### 46 **1** Introduction

At 04:14:45 UTC on 15 January, 2022, the Hunga Tonga-Hunga Ha'apai subma-47 rine volcano (hereafter referred to as the Tonga volcano, which is centred at  $20.546^{\circ}$ S, 48 175.390°W, explosively erupted. Immense ripples on the sea surface and in the atmo-49 sphere rapidly spread outward. The volcanic explosivity index (VEL) was estimated to 50 be 6, indicating that this eruption was one of the largest volcanic eruptions recorded in 51 the modern era (Poli & Shapiro, 2022). The volcanic eruption released a large amoun-52 t of material and energy into the atmosphere, with the highest overshooting tops of the 53 volcanic plume reaching the lower mesosphere at an altitude of  $\sim 55$  km according to 54 satellite imagery (Carr et al., 2022). The waves triggered by the Tonga volcanic erup-55 tion on the surface and in the ionosphere were observed worldwide by various ground-56 and space-based instrumentation (Adam, 2022; Wright et al., 2022; X. Liu et al., 2022). 57

It is well known that volcanic eruptions and earthquakes can produce measurable 58 ionospheric waves that travel thousands of kilometres (Roberts et al., 1982). Previous 59 studies on ionospheric disturbances caused by volcanic eruptions, earthquakes, or tsunamis 60 mainly involved TEC variations and horizontal phase velocities of the waves (C. H. Li-61 u et al., 1982; Heki, 2006; Dautermann et al., 2009), there are rare direct observation-62 s about the ionospheric oscillation velocity or amplitude caused by these natural haz-63 ards. After the Tonga vocanic eruption, the dense Global Navigation Satellite System (GNSS) receiver network was selected to rapidly analyse the total electron content (TEC) 65 perturbations associated with the volcanic eruption. Themens et al. (2022) identified t-66 wo large-scale traveling ionospheric disturbances (LSTIDs) with initial speeds of 950 67

<sup>68</sup> m/s and 555 m/s. Zhang et al. (2022) discovered that the radial two-way disturbance <sup>69</sup> propagation along the entire great circle lasted 4 days. This observation shows that the <sup>70</sup> waves travelled around the globe three times as Lamb waves with primary speeds in the <sup>71</sup> range of 300-350 m/s. Lin et al. (2022) observed the simultaneous occurrence of TID-<sup>72</sup> s in Australia and Japan between 0800 and 1000 universal time (UT) on 15 January 2022. <sup>73</sup> TIDs observed in Japan are attributed to the magnetic field conjugate effect. Howev-<sup>74</sup> er, the effects on the ionospheric oscillations have not been demonstrated.

Field-aligned electron density irregularities are small-scale density structures in the 75 76 ionospheric plasma. When the ionosphere fluctuates, these structures move with the ionosphere. Thus, the ionospheric irregularities are good tracers for ionospheric movemen-77 t. Super Dual Auroral Radar Network (SuperDARN) radars are powerful tools for ob-78 serving the motion of irregularities in the ionosphere (Chisham et al., 2007; Nishitani et 79 al., 2019). These radars receive backscatter echoes from irregularities in the D, E and 80 F layers of the ionosphere. Nishitani et al. (2011) observed the Doppler velocities of ground/sea 81 scatter echoes with a magnitude of 100 m/s that lasted for several minutes after the 2011 82 Tohoku Earthquake by using high temporal resolution (8s) data from (SuperDARN) Hokkai-83 do radar. However, the ionospheric echoes associated with geological hazards had nev-84 er been observed during previous events. Shinbori et al. (2022) studied the electromag-85 netic conjugate effect of ionospheric disturbances after the Tonga volcanic eruption by 86 using observations of the GNSS-TEC and SuperDARN Hokkaido radars. 87

In this study, ionospheric irregularities observed by using middle-latitude Super-88 DARN radars and digisondes were employed as tracers to study ionospheric oscillation 89 features in the Northern Hemisphere. Its very interesting that the ionospheric oscilla-90 tion had different features before and after the arrival of the surface air pressure wave, 91 including the maximum LOS velocity, the altitude of the maximum LOS velocity, and 92 the propagation direction. In particular, we find that the difference of oscillation veloc-93 ity in E and F layers of the ionosphere changed after the arrival of the surface air pres-94 sure wave. 95

### 96 2 Data

The SuperDARN is a global high frequency (HF), coherent scatter radar network 97 that consists of more than 30 radars that observe Earth's upper atmosphere beginning 98 at mid-latitudes and extending to polar regions in both hemispheres. There are 37 Su-99 perDARN radars now, with 22 radars located in high-latitude and polar regions and 15 100 radars located in mid-latitude regions. The SuperDARN radars are sensitive to Brag-101 g scattering from field-aligned electron density irregularities in the ionosphere (Greenwald 102 et al., 1995). These radars operate in the HF band of the radio spectrum between 8 and 103 20 MHz; at these frequencies, radar signals are refracted by the ionosphere. The signal-104 s return to the radar along the same path, with the incident radar signal orthogonal to 105 the magnetic field. The scale size of the irregularities from which the signal is scattered 106 is equal to one-half of the radar wavelength. The HF signals are refracted toward the 107 ground, and part of the signal may be reflected to the radar. Therefore, in addition to 108 the backscatter received from ionosphere irregularities, SuperDARN radars receive backscat-109 ters from the ground or sea surfaces. The transmission of a multipulse scheme is used 110 to calculate autocorrelation functions (ACFs) of the backscattered signals as a function 111 of range. In each range gate, the ACF is analysed by a fitting routine known as FITACF 112 that estimates the backscatter power, the LOS Doppler velocity of the irregularities and 113 the spectral width (Ribeiro et al., 2013). A typical SuperDARN radar monitors 16 or 114 24 beam directions separated by 3.24 degrees in the azimuthal direction, with the 75  $\sim$ 115 100 range gates along each beam separated by 45 km. The dwell time of each beam is 116 typically  $2 \sim 7$  s (integration period), which produces a  $1 \sim 2$  min azimuthal scan. 117



**Figure 1.** FOVs of the SuperDARN JME, HOK, HKW and BKS radars, with beam 0 of the JME radar and beam 4 of the HOK, HKW and BKS radars are shaded in blue. The black dots represent the locations of the Mohe and Boulder digisondes. The red triangle indicates the location of the Tonga volcano, and the red dot indicates the magnetically conjugate point of the volcano. The cyan curves indicate the magnetic latitude lines with 30 degree intervals.

The high-latitude SuperDARN radars are mainly employed to research the iono-118 spheric convection driven by solar wind and magnetospheric interactions. Compared with 119 radars located in high latitudes, mid-latitude radars are more suitable for research on 120 sub-auroral phenomena and ion-neutral interactions, for example, TIDs. During the vol-121 canic eruption in Tonga, data from four mid-latitude SuperDARN radars were available. 122 These radars included the Jiamusi radar (JME) in China (geographic coordinates of 46.816°N, 123 130.402°E), the Hokkaido East radar (HOK) (geographic coordinates of 43.53°N, 143.61°E) and 124 the Hokkaido West radar (HKW) in Japan (geographic coordinates of 43.54°N, 143.61°E), 125 and the Blackstone radar (BKS) in the United States (geographic coordinates of 37.10°N, 126 77.95°W). Observations from these four radars are used to analyse the ionospheric os-127 cillation in this study. The fields of view (FOVs) of the four radars are shown in Fig-128 ure 1, where beam 0 of the JME radar and beam 4 of the HOK, HKW and BKS radars 129 are shown in blue. The JME and BKS radars have 24 beams, while the HOK and HK-130 W radars have 16 beams. On 15 January 2022, all four radars were operating in normal 131 (fast) mode and sequentially sampled beams with a 2-3 s integration time for each beam; 132 thus, the whole FOV was sampled every minute. The operating frequencies of the HOK, 133 HKW and JME radars on 15 January 2022 were 11.07 MHz, 10.08 MHz, and 10.4 MHz, 134 respectively. The operating frequency of the BKS radar was 10.8 MHz before 1300 UT 135 and 11.5 MHz after 1300 UT. 136

The SuperDARN radars observe the LOS velocities of plasma. In addition to the 137 SuperDARN radar data, ionogram data from two digisondes located in Mohe (geograph-138 ic coordinates of 52.0° N, 122.52° E) and Boulder (geographic coordinates of 40.0°N, 105.3°W) 139 were applied to investigate the height variations in the ionosphere. The densities and height-140 s of the peaks of layers E, Es, F1, and F2 and electron density profiles up to 1000 km 141 can be automatically calculated by digisondes. The Mohe ionogram data were obtained 142 from the Chinese Meridian Project Database, and the Boulder ionogram data were ob-143 tained from the Digital Ionogram Database. 144

### 145 **3 Results**

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### 3.1 LOS velocity observed by Four SuperDARN Radars

Range-time-intensity (RTI) plots of the LOS Doppler velocities observed by (a) beam 147 4 of the HOK radar, (b) beam 0 of the JME radar, (c) beam 4 of the HKW radar and 148 (d) beam 4 of the BKS radar on 15 January 2022 are shown in Figure 2. The LOS Doppler 149 velocities are scaled according to the colour bar shown on the right. Negative velocities 150 represent plasma flows moving away from the radar, while positive velocities represen-151 t plasma flows moving toward the radar. The slant range is the total distance traversed 152 by the ray between the radar and the targets. The shadow in each panel indicates night. 153 As shown in Figure 1, beam 0 of the JME radar points to the geographical North Pole, 154 beam 4 of the HOK radar is almost parallel to beam 0 of the JME radar, and beam 4 155 of the HKW and BKS radars points westward. 156

Before 0800 UT, backscatters with LOS velocities of less than  $\pm 30$  m/s were ob-157 served by beam 4 of the HOK radar and classified as ground backscatters. Distinct iono-158 spheric backscatters began to be observed from 0800 UT on beam 4 of the HOK radar. 159 Plasma with negative LOS velocities were observed first, with a minimum of approxi-160 mately -100 m/s, followed by a very short positive LOS velocity period with a maximum 161 of approximately 60 m/s. Subsequently, the radar captured a second sudden transition 162 structure with a negative LOS velocity followed by a short positive LOS velocity peri-163 od, with velocity more rapid than the previous velocity. At 0900 UT, the radar observed 164 the third negative velocity period with slower velocities than the second period, which 165 lasted approximately one hour. From 0800 UT and 1000 UT, the location of the echoes 166 gradually moved to a further slant range. After 1000 UT, the radar started to observe 167 positive velocities with the location of the echoes gradually decreased to a closer slan-168 t range until 1130 UT. Beam 0 of the JME radar was approximately 1100 km west of 169 beam 4 of the HOK radar, and the two beams were nearly parallel to each other. The 170 radar observed similar ionospheric oscillation features with some time delay from beam 171 4 of the HOK radar. As shown in Figure 2(b), from 0900 UT to 1200 UT, the JME radar 172 also observed three negative/positive velocities periods, with a relatively short duration 173 for the first two positive velocity periods (10 minutes). The second negative/positive 174 velocity period between 0920 UT and 1020 UT was the most rapid. The slant range of 175 the observed echoes slowly increased from 0900 UT at approximately 500 km and rapid-176 ly dropped from a slant range of more than 1000 km at 1100 UT to a few hundreds of 177 kilometres. Beam 4 of the HKW radar points westward. Figure 2 (c) shows the obser-178 vation from beam 4 of the HKW radar is consistent with the observation from the HOK 179 and JME radar. The positive LOS velocity regions moved to a farther slant range over 180 time, indicating the westward propagation of the fluctuation. 181

Before 1130 UT, few backscatters in the slant range between 200 and 400 km (E 182 layer of the ionosphere based on ray tracing simulations, please refer to Figure S1 in the 183 supplemental material) were observed by beam 4 of the HOK radar. The magnitudes 184 of the LOS velocities in this slant range were weaker than those in the slant range greater 185 than 400 km (F layer of the ionosphere). At 1130 UT, the surface air pressure distur-186 bances caused by the Tonga volcanic eruption arrived at the HOK radar, based on the 187 speed of the air pressure wave of  $\sim 340$  m/s (Wright et al., 2022). Afterward, much backscat-188 ter appeared in the E region of the ionosphere, and the LOS velocities in the E region 189 exceeded  $\pm 150$  m/s and were stronger than those in the F region between 1130 UT and 190 1600 UT. After 1200 UT, the JME and HKW radar also observed an increase in the num-191 ber of ionospheric echoes. 192

According to the observations of HOK and JME radar between 0800 UT and 1200 UT, the propagation direction of the ionospheric oscillation was westward. After the arrival of the surface air pressure, the propagation direction turned northwestward. Figure S2 in the supplemental material show the wavefront observed by the HOK and JME

radar at 0850 UT, 0940 UT and 1133 UT. The horizontal phase velocity was approxi-197 mately 330 m/s, calculated by using the delay time and the distance between the HOK 198 radar and the JME radar. The propagation direction and horizontal phase velocity of 199 the ionospheric fluctuation observed by the SuperDARN radars were consistent with the 200 observation based on TEC observations (Lin et al., 2022). SuperDARN radars in East 201 Asia observed the strong ionospheric oscillations with three LOS velocity transitions from 202 0800 UT to 1200 UT, which may be attributed to the three main explosions of the vol-203 canic eruptions in Tonga (Astafyeva et al., 2022; Wright et al., 2022). During this pe-204 riod, the slant range of the echoes showed a trend of rising, falling, and then rising, im-205 plying the variation in the height of the ionosphere besides the oscillation in the hori-206 zontal direction. 207

The BKS radar is located in the western hemisphere and under different day-night 208 conditions during the period of interest. The backscatter received by the BKS radar was 209 considerably different from the backscatter received by the other three radars. Almost 210 all of the backscatter was ground scatter. The velocity variation in ground scatter for 211 the SuperDARN radars is usually attributed to vertical movement of the ionosphere. The 212 BKS radar received minimal backscatter before 1200 UT as the radar operating frequen-213 cy and ionospheric conditions were not suitable. With sunrise, the ionosphere builds up 214 and a band of ground scatter develops after 1230 UT. The slant range to the band varies 215 and the LOS velocity fluctuates within narrow limits (<30 m/s) throughout the day ow-216 ing to passage of TIDs, which is typical. However, after 1400 UT, ground scatter with 217 LOS velocities greater than 90 m/s was observed by beam 4 of the BKS radar, corre-218 sponding to a marked downward motion in the ionosphere. 219

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### 3.2 LOS velocity across different layers of ionosphere

To show the fluctuation velocity across different layers of the ionosphere, Figure 221 4 shows an RTI plot of the LOS Doppler velocity observed on beam 4 of the HOK radar 222 and line plots of the LOS velocities of range gates 2, 4, 10, 12, 14 and 16 for beam 4 of 223 the HOK radar, with 10 min smoothing applied. The positive/negative velocities indi-224 cate that the direction of the LOS velocity was toward/away from the radar. Range gates 225 2, 4, 10, 12, 14 and 16 correspond to slant ranges of 270, 360, 630, 720, 810 and 900 k-226 m, as indicated by the six black horizontal lines on Figure 3 (a). The blue vertical line 227 at 0800 UT indicates the arrival time of the disturbance propagated from the magnet-228 ic conjugate point of the Tonga volcanic eruption, while the blue vertical line at 1130 229 UT indicates the arrival time of the disturbance directly propagated from the Tonga vol-230 canic eruption. Between 0800 UT and 1130 UT, the maximum peak-to-peak amplitude 231 of the ionospheric fluctuation velocity was approximately 150 m/s at range gate 10 (F 232 region) and was associated with the two shock structures. During this period, the peak-233 to-peak amplitude observed at gate 2 (E region) was weaker than that observed in the 234 F region. After the arrival of the surface air pressure waves at 1130 UT, the maximum 235 LOS velocity was approximately  $\pm 150m/s$ , and the peak-to-peak amplitude of the iono-236 spheric fluctuation approached 300 m/s at range gate 4 (E region). The peak-to-peak 237 amplitude decreased over time and as the range gate increased. 238

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### 3.3 Uplift in the ionosphere by the volcanic eruption

The SuperDARN radars observed the LOS velocity of the irregularities. To inves-240 tigate the vertical motion of the ionosphere, we combined the observations of beam 4 of 241 the HKW radar and Mohe digisonde. Beam 4 of the HKW radar and the location of the 242 243 Mohe digisonde are shown in Figure 1. Figure 4 shows the RTI plot of the LOS Doppler velocities observed by beam 4 of the HOK radar, the F layer peak height (hmF2) as a 244 function of time obtained from the Mohe digisonde, and three representative ionogram-245 s to highlight the state of the ionosphere at specific times. The black horizontal dashed 246 line in Figure 4 (a) indicates the radar slant range corresponding to the Mohe digisonde. 247



Figure 2. Range-time-intensity plots of the LOS Doppler velocities observed by (a) beam 4 of the HOK radar, (b) beam 0 of the JME radar, (c) beam 4 of the HKW radar and (d) beam 4 of the BKS radar on 15 January 2022. The LOS Doppler velocities are scaled according to the colour bar shown on the right. The shadow in each panel indicates night.



**Figure 3.** Fluctuation velocity across different layers of ionosphere. (a) RTI plot of the LOS Doppler velocities observed by beam 4 of the HOK radar and line plots of the LOS velocities of range gates (b)16, (c) 14, (d) 12, (e) 10, (f) 4 and (g) 2 for beam 4 of the HOK radar, with 10 min smoothing applied. Range gates 2, 4, 10, 12, 14 and 16 correspond to slant ranges of 270, 360, 630, 720, 810 and 900 km, respectively, as indicated by the six black horizontal lines in Figure 4(a). The two vertical blue lines indicate the arrival time of the disturbance from the magnetic conjugate point of the volcanic eruption in Tonga and from the volcanic eruption itself.

The two vertical blue lines in Figure 4 (a) and (b) indicate the arrival time of the dis-248 turbance to the Mohe digison from the magnetic conjugate point of the volcanic erup-249 tion in Tonga at 0930 UT and from the volcanic eruption itself at 1230 UT, respective-250 ly. The cyan dashed line in Figure 4 (b) indicates the variation in the peak height of the 251 F layer during the quiet time (This is a polynomial fitting curve based on the observa-252 tion during 13 Jan 2022). As shown in Figure 4, the negative/positive LOS velocities of 253 the HKW radar correspond to the upwards/downwards motion, respectively, of the iono-254 sphere, which were were well captured by the Mohe digisonde, indicating that the LOS 255 velocities observed by the SuperDARN radars have a pronounced vertical component and 256 were not purely horizontal. After the arrival of the disturbance from the magnetic con-257 jugate point of the volcanic eruption at 0930 UT, the Mohe digisonde observed uplift of 258 the ionosphere from 245 km to about 326 km at 1030 UT, and then the height of the iono-259 sphere vibrated and fell to a normal height. After the disturbance from the volcanic erup-260 tion itself propagated to Mohe at approximately 1230 UT, the digisonde again observed 261 the uplift of the ionosphere. Excluding the diurnal variation in the peak height of the 262 F layer at the quiet time, the maximum amplitude of the vertical fluctuations caused by 263 the volcanic eruption in Tonga was approximately 80 km, as observed by the Mohe digisonde. 264 This finding indicates that the volcanic eruption caused strong vertical fluctuations of 265 the ionosphere in the midlatitude region of the northern hemisphere. This vertical move-266 ment may be attributed to the fact that magnetic field lines in middle latitudes are not 267 completely perpendicular to the ground, and so east-west electric fields in this region will 268 produce vertical movements of the ionosphere in addition to horizontal movements. 269

Joint observations of beam 4 of the BKS radar and Boulder digisonde also reveal 270 the vertical oscillation of the ionosphere (Please refer to Figure S3 in the supplemental 271 material). The position of the Boulder digisonde is beyond the 2000 km slant range of the the BKS radar, so the location of the digisonde was not marked in the figure. A max-273 imum positive velocity of approximately 90 m/s was observed on beam 4 of the BKS radar 274 from 1400 UT, which correspond to a marked downward motion in the ionosphere. The 275 Boulder digisonde also observed the rapid decrease in the peak height of the F layer from 276 1400 UT with an amplitude of more than 100 km, which is consistent with the obser-277 vation from the BKS radar. The disturbance from the magnetic conjugate point of the 278 volcanic eruption in Tonga and from the volcanic eruption itself arrived at the Boulder 279 digison at 0905 UT and 1215 UT, respectively, which was calculated based on the speed 280 of the air pressure wave of  $\sim 340$  m/s. Before 1400 UT, the Boulder digison observed 281 the uplift and fall in the ionosphere associated with the volcanic eruption. 282

### <sup>283</sup> 4 Discussion and Conclusion

According to the observation of SuperDARN radars in East Asia, the strongest LOS 284 velocity appeared in the F layer of the ionosphere due to the magnetic field conjugate 285 effect, and the amplitude of the velocity decreased with decreasing altitude. This find-286 ing indicates the magnetic field conjugate effect has a significant impact on the plasma 287 flow in the F layer at another hemisphere. During this period, the ionospheric plasma 288 flow was produced by an external electric field that is generated by an E layer dynamo 289 in the sunlit Southern Hemisphere. The two sudden increases of the plasma flow may 290 correspond to the two large Tonga eruption with a VEI value of 6, which can cause a sig-291 nificant enhancement of an E-region dynamo electric field. After the arrival of the sur-292 face air pressure wave, the strongest LOS velocity appeared in the E layer, and the am-293 plitude of the velocity decreased with increasing altitude. During this period, the iono-294 spheric conductivity of the E-region was very small due to the dark region, and the E 295 layer dynamo process was not effective on the ionospheric plasma motion in the F-region. 296 So, the E and F layer motions are directly produced by the neutral wind osculation as-297 sociated with the arrival of the air pressure wave. The collision frequency is much small-298 er in the F layer than in the E layer. This is because the ionospheric plasma motion in 299



Figure 4. Vertical variation of the ionosphere. (a) RTI plot of the LOS Doppler velocities observed by beam 4 of the HOK radar. The black horizontal dashed line in panel (a) indicates the slant range corresponding to the Mohe digisonde. (b) Ionospheric peak height of the F2 layer as a function of time obtained from the Mohe digisonde. The two vertical blue lines in panel (a) and (b) indicate the arrival time of the disturbance to the Mohe digisonde from the magnetic conjugate point of the volcanic eruption in Tonga and from the volcanic eruption itself, respectively. The cyan dashed curve in panel (b) indicates the variation in the peak height of the F layer of the ionosphere during the quiet time. Three representative ionograms are shown at (c) 0930 UT, (d) 1045 UT and (e) 1230 UT.

the F layer is more decoupled with the neutral wind oscillation than in the E layer. Therefore, the plasma motion is expected to be slower in the F layer than in the E layer.

The fluctuation caused by the magnetic field conjugate effect was detected by three 302 radars in East Asia, while the BKS radar in America did not record the fluctuation caused 303 by the magnetic field conjugate effect. This attributed to the fact that the radar oper-304 ating frequency and ionospheric conditions do not satisfy the conditions for receiving iono-305 spheric backscatters during the relevant period. In addition, the three midlatitude Su-306 perDARN radars in Australia and New Zealand in the Southern Hemisphere were not 307 operating during this period. If these radars were operational, they would provide ex-308 cellent observations for comparing movements in the ionosphere caused by volcanic erup-309 tions in the Southern and Northern hemispheres, and would contribute to a deeper un-310 derstanding of the mechanisms underlying the magnetic field conjugate effect. 311

In conclusion, impacts on ionospheric irregularities and ionospheric oscillation fea-312 tures in the Northern Hemisphere caused by the explosive Tonga volcanic eruption in 313 the southwest Pacific were clearly captured by midlatitude SuperDARN radars and digison-314 des. The ionospheric fluctuations observed by SuperDARN radars in East Asia propa-315 gated westward due to the magnetic field conjugate effect. After the surface pressure wave 316 arrived, the propagation direction was northwestward. The estimated propagation ve-317 locity of the ionospheric fluctuation was approximately  $320 \sim 340$  m/s. The distant and 318 upwards motion of the ionosphere was considerably more rapid and lasted longer than 319 the forwards and downwards motion. Because of different mechanisms, the maximum 320 peak-to-peak LOS velocity of the ionosphere exceeded 150 m/s appeared in F layer due 321 to the magnetic field conjugate effect, and the maximum peak-to-peak LOS velocity of 322 the ionosphere was approximately 300 m/s which appeared in the E layer due to the di-323 rect propagation of the wave from the Tonga volcano. The amplitude of the vertical rise 324 and fall of the ionosphere in the mid-latitude region of the Northern Hemisphere can reach 325 nearly 100 km due to the volcanic eruption. This event shows how geological hazards 326 can impact the ionosphere and cause space weather, raising concerns for vulnerable tech-327 nologies. 328

### <sup>329</sup> 5 Open Research

The raw SuperDARN data are available from the SuperDARN data server at the 330 National Space Science Center, Chinese Academy of Sciences (https://superdarn.nssdc.ac.cn/). 331 To access the data, users should log in, and go to 'Access data' to select the radar, dataset 332 and date. The Mohe ionogram data were obtained from the Chinese Meridian Project 333 Database (https://data.meridianproject.ac.cn/), to access the data, users also should log 334 in, and go to 'Download', then select 'Mohe station', and then choose 'Ionogram image 335 of digital ionosonde'. The Boulder ionogram data were obtained from the Digital Iono-336 gram Database (https://giro.uml.edu/didbase/). 337

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### Oscillations of the Ionosphere Caused by the 2022 Tonga Volcanic Eruption Observed with SuperDARN Radars

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### Key Points:

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14	•	Enhanced ionospheric irregularities with highly variable velocities were observed
15		after the Tonga volcanic eruption.
16	•	The maximum amplitude of the line-of-sight velocity of the ionospheric oscillation
17		approached 150 m/s in E layer.
18	•	The ionosphere was displaced upward by as much as 100 km.

• The ionosphere was displaced upward by as much as 100 km.

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### 19 Abstract

On 15 January 2022, the submarine volcano on the southwest Pacific island of Ton-20 ga violently erupted. Thus far, the ionospheric oscillation features caused by the volcanic 21 eruption have not been identified. Here, observations from the Super Dual Auroral Radar 22 Network (SuperDARN) radars and digisondes were employed to analyze ionospheric os-23 cillations in the Northern Hemisphere caused by the volcanic eruption in Tonga. Due 24 to the magnetic field conjugate effect, the ionospheric oscillations were observed much 25 earlier than the arrival of surface air pressure waves, and the maximum negative line-26 27 of-sight (LOS) velocity of the ionospheric oscillations exceeded 100 m/s in the F layer. After the surface air pressure waves arrived, the maximum LOS velocity in the E lay-28 er approached 150 m/s. A maximum upward displacement of 100 km was observed in 29 the ionosphere. This work provides a new perspective for understanding the strong iono-30 spheric oscillation caused by geological hazards observed on Earth. 31

### 32 Plain Language Summary

On 15 January 2022, an underwater volcano on the southwest Pacific island of Ton-33 ga erupted, triggering significant disturbances on the surface and in the ionosphere that 34 propagated worldwide. The oscillation features of the ionosphere caused by the volcanic 35 eruption have not been identified. The volcanic eruption caused numerous irregularities 36 in the ionosphere. These irregularities move with the ionosphere similar to how leaves 37 move in a rough sea. In this study, the ionospheric irregularities were observed and em-38 ployed as tracers to analyze the ionospheric oscillations. Different features of ionospher-39 ic oscillations, including the maximum line-of-sight (LOS) velocity, the altitude of the 40 maximum LOS velocity, and the propagation direction, were observed before and after 41 the arrival of the surface air pressure waves. The amplitudes of the LOS velocities of the 42 ionospheric fluctuations approached 150 m/s, and a maximum upward displacement of 43 100 km, which is the strongest ionospheric fluctuation caused by geological hazards ev-44 er observed. 45

### 46 **1** Introduction

At 04:14:45 UTC on 15 January, 2022, the Hunga Tonga-Hunga Ha'apai subma-47 rine volcano (hereafter referred to as the Tonga volcano), which is centered at  $20.546^{\circ}$ S, 48 175.390°W, explosively erupted. Immense ripples on the sea surface and in the atmo-49 sphere rapidly spread outward. The volcanic explosivity index (VEI) was estimated to 50 be 6, indicating that this eruption was one of the largest volcanic eruptions recorded in 51 the modern era (Poli & Shapiro, 2022). The volcanic eruption released a large amoun-52 t of material and energy into the atmosphere, with the highest overshooting tops of the 53 volcanic plume reaching the lower mesosphere at an altitude of  $\sim 55$  km according to 54 satellite imagery (Carr et al., 2022). The waves triggered by the Tonga volcanic erup-55 tion on the surface and in the ionosphere were observed worldwide by various ground-56 and space-based instrumentation (Adam, 2022; Wright et al., 2022; X. Liu et al., 2022). 57

It is well known that volcanic eruptions and earthquakes can produce measurable 58 ionospheric waves that travel thousands of kilometers (Roberts et al., 1982; Meng et al., 59 2019). Previous studies on ionospheric disturbances caused by volcanic eruptions, earth-60 quakes, or tsunamis mainly involved total electron content(TEC) variations and hori-61 zontal phase velocities of the waves (C. H. Liu et al., 1982; Heki, 2006; Dautermann et 62 al., 2009; Huang et al., 2019). Studies on direct observations of the ionospheric oscilla-63 tion velocity or amplitude caused by these natural hazards are rare(Nishitani et al., 2011). After the Tonga volcanic eruption, the dense Global Navigation Satellite System (GNSS) 65 receiver network was selected to rapidly analyze the TEC perturbations associated with 66 the volcanic eruption. Themens et al. (2022) identified two large-scale traveling ionospher-67

ic disturbances (LSTIDs) with initial speeds of 950 m/s and 555 m/s. The two LSTID-68 s exhibited strong directionality and slowed down substantially with radial distance. Flow-69 ing the two LSTIDs, medium-scale TIDs (MSTIDs) with speeds of 200-400 m/s were ob-70 served and propagated globally. Zhang et al. (2022) discovered that the radial two-way 71 disturbance propagation along the entire great circle lasted 4 days. This observation showed 72 that the waves travelled around the globe three times as Lamb waves with primary speed-73 s in the range of 300-350 m/s. Lin et al. (2022) observed the simultaneous occurrence 74 of concentric TIDs (CTIDs) in Australia and Japan between 0800 and 1000 universal 75 time (UT) on 15 January 2022. CTIDs observed in Japan were attributed to the mag-76 netic field conjugate effect. The authors explained that the polarization electric field o-77 riginated from an E-region dynamo driven by atmospheric disturbance waves in the South-78 ern Hemisphere can be transmitted to magnetically conjugate regions in the Northern 79 Hemisphere along conductive geomagnetic field lines with Alfvénic speed (300 km/s), 80 which is much faster than the speed of Lamb waves. The external electric field, which 81 originated from the conjugate hemisphere generated the CTIDs observed in Japan. Shinbori 82 et al. (2022) studied the electromagnetic conjugate effect of ionospheric disturbances af-83 ter the Tonga volcanic eruption by using observations from the GNSS-TEC and Super 84 Dual Auroral Radar Network (SuperDARN) Hokkaido radars, which further confirmed 85 the explanation by Lin et al. (2022). However, the Tonga volcanic eruption effects on 86 ionospheric oscillations, especially in the vertical direction, have not been well demon-87 strated. 88

Field-aligned electron density irregularities are small-scale density structures in the 89 ionospheric plasma. When the ionosphere fluctuates, these structures move with the iono-90 sphere. Thus, ionospheric irregularities are good tracers for ionospheric movement. Su-91 perDARN radars are powerful tools for observing the motion of irregularities in the iono-92 sphere (Chisham et al., 2007; Nishitani et al., 2019). In this study, ionospheric irregu-93 larities observed by using mid-latitude SuperDARN radars and digisondes were employed 94 as tracers to study ionospheric oscillation features in the Northern Hemisphere. It is very 95 interesting that there were different ionospheric oscillation features, such as the maxi-96 mum LOS velocity and the altitude of the maximum LOS velocity, before and after the 97 arrival of the surface air pressure waves, indicating that the mechanisms of ionospher-98 ic oscillations were different in the two stages. In particular, the observations also revealed 99 a significant vertical oscillation of the ionosphere caused by the volcanic eruption. 100

### 101 **2 Data**

SuperDARN is a global high frequency (HF), coherent scatter radar network that 102 consists of more than 30 radars that observe Earth's upper atmosphere beginning at mid-103 latitudes and extending to polar regions in both hemispheres. There are now 37 Super-104 DARN radars, with 22 radars located in high-latitude and polar regions and 15 radars 105 located in mid-latitude regions. The SuperDARN radars are sensitive to Bragg scatter-106 ing from field-aligned electron density irregularities in the ionosphere (Greenwald et al., 107 1995). These radars operate in the HF band of the radio spectrum between 8 and 20 MHz; 108 at these frequencies, radar signals are refracted by the ionosphere. The signals return 109 to the radar along the same path, with the incident radar signal orthogonal to the mag-110 netic field. The scale size of the irregularities from which the signal is scattered is equal 111 to one-half of the radar wavelength. The HF signals are refracted toward the ground, 112 and part of the signal may be reflected to the radar. Therefore, in addition to the backscat-113 ter received from ionospheric irregularities, SuperDARN radars receive backscatter from 114 the ground or sea surface. The transmission of a multipulse scheme is used to calculate 115 autocorrelation functions (ACFs) of the backscattered signals as a function of range. In 116 each range gate, the ACF is analyzed by a fitting routine known as FITACF that esti-117 mates the backscatter power, the LOS Doppler velocity of the irregularities and the spec-118 tral width (Ribeiro et al., 2013). A typical SuperDARN radar monitors 16 or 24 beam 119

directions separated by 3.24 degrees in the azimuthal direction, with the 75  $\sim$  100 range gates along each beam separated by 45 km. The dwell time of each beam is typically 2  $\sim$ 7 s (integration period), which produces a 1  $\sim$  2 min azimuthal scan.

The high-latitude SuperDARN radars are mainly employed to research the iono-123 spheric convection driven by solar wind and magnetospheric interactions. Compared with 124 radars located in high latitudes, mid-latitude radars are more suitable for research on 125 sub-auroral phenomena and ion-neutral interactions, for example, TIDs. During the vol-126 canic eruption in Tonga, data from four mid-latitude SuperDARN radars were available. 127 These radars included the Jiamusi radar (JME) in China (geographic coordinates of 46.816°N, 128 130.402°E), the Hokkaido East radar (HOK) (geographic coordinates of 43.53°N, 143.61°E), 129 the Hokkaido West radar (HKW) in Japan (geographic coordinates of 43.54°N, 143.61°E), 130 and the Blackstone radar (BKS) in the United States (geographic coordinates of 37.10°N, 131 77.95°W). Observations from these four radars were used to analyze the ionospheric os-132 cillations in this study. The fields of view (FOVs) of the four radars are shown in Fig-133 ure 1, where beam 0 of the JME radar and beam 4 of the HOK, HKW and BKS radars 134 are shown in blue. Beam 0 is the east-most beam of these four radars. The JME and 135 BKS radars have 24 beams, while the HOK and HKW radars have 16 beams. On 15 Jan-136 uary 2022, all four radars were operating in normal (fast) mode, and sequentially sam-137 pled beams with a 2-3 s integration time for each beam; thus, the whole FOV was sam-138 pled every minute. The operating frequencies of the HOK, HKW and JME radars on 139 15 January 2022 were 11.07 MHz, 10.08 MHz, and 10.4 MHz, respectively. The operat-140 ing frequency of the BKS radar was 10.8 MHz before 1300 UT and 11.5 MHz after 1300 141 UT. 142

The SuperDARN radars are used to observe the LOS velocities of plasma. In ad-143 dition to the SuperDARN radar data, ionogram data from two digisondes located in Mo-144 he, Heilongjiang, China (geographic coordinates of 52.0° N, 122.52° E) and Boulder, Col-145 orado, USA (geographic coordinates of 40.0°N, 105.3°W) were used to investigate the 146 height variations in the ionosphere. The densities and heights of the peaks of layers E, 147 Es, F1, and F2 and electron density profiles up to 1000 km can be automatically calcu-148 lated by digisondes. The Mohe ionogram data were obtained from the Chinese Merid-149 ian Project Database, and the Boulder ionogram data were obtained from the Digital 150 Ionogram Database (Reinisch & Galkin, 2011). 151

### 152 3 Results

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### 3.1 LOS velocity observed by the four SuperDARN radars

Range-time-intensity (RTI) plots of the LOS Doppler velocities observed by (a) beam 154 4 of the HOK radar, (b) beam 0 of the JME radar, (c) beam 4 of the HKW radar and 155 (d) beam 4 of the BKS radar on 15 January 2022 are shown in Figure 2. The LOS Doppler 156 velocities are scaled according to the color bar shown on the right. Negative velocities 157 represent plasma flows moving away from the radar, while positive velocities represen-158 t plasma flows moving toward the radar. The slant range is the total distance traversed 159 by the ray between the radar and the targets. The shadow in each panel indicates night. 160 As shown in Figure 1, beam 0 of the JME radar points to the geographical North Pole, 161 beam 4 of the HOK radar is almost parallel to beam 0 of the JME radar, and beam 4 162 of the HKW and BKS radars points westward. 163

Before 0800 UT, backscatter with LOS velocities of less than  $\pm 30$  m/s was observed by beam 4 of the HOK radar and classified as ground backscatter. Distinct ionospheric backscatter began to be observed from 0800 UT on beam 4 of the HOK radar. Plasma with negative LOS velocities were observed first, with a minimum of approximately -100 m/s, followed by a very short positive LOS velocity period with a maximum of approximately 60 m/s. Subsequently, a second sudden transition structure with a neg-



**Figure 1.** FOVs of the SuperDARN JME, HOK, HKW and BKS radars, where, beam 0 of the JME radar and beam 4 of the HOK, HKW and BKS radars are shaded in blue. The black dots represent the locations of the Mohe and Boulder digisondes. The red triangle indicates the location of the Tonga volcano, and the red dot indicates the magnetically conjugate point of the volcano. The cyan curves indicate the magnetic latitude lines with 30 degree intervals.

ative LOS velocity was captured; this was followed by a short positive LOS velocity pe-170 riod, with velocity more rapid than the previous velocity. At 0900 UT, the third neg-171 ative velocity period, which lasted approximately one hour, with slower velocities than 172 the second period, was observed. From 0800 UT and 1000 UT, the location of the echoes 173 gradually moved to a further slant range. After 1000 UT, positive velocities were observed 174 by the radars, and the location of the echoes gradually decreased to a closer slant range 175 until 1130 UT. Beam 0 of the JME radar was approximately 1100 km west of beam 4 176 of the HOK radar, and the two beams were nearly parallel to each other. Similar iono-177 spheric oscillation features with some time delay were observed from beam 4 of the HOK 178 radar. As shown in Figure 2(b), from 0900 UT to 1200 UT, three negative/positive ve-179 locity periods, with a relatively short duration for the first two positive velocity period-180 s (10 minutes), were observed by the JME radar. The second negative/positive veloc-181 ity period between 0920 UT and 1020 UT was the most rapid. The slant range of the 182 observed echoes slowly increased from 0900 UT at approximately 500 km and rapidly 183 dropped from a slant range of more than 1000 km at 1100 UT to a few hundred kilome-184 ters. Beam 4 of the HKW radar points westward. Figure 2 (c) shows that the observa-185 tions from beam 4 of the HKW radar are consistent with the observations from the HOK 186 and JME radars. The positive LOS velocity regions moved to a farther slant range over 187 time, indicating the westward propagation of the fluctuation. 188

Before 1120 UT, few backscatter in the slant range between 200 and 400 km (E lay-189 er of the ionosphere based on ray tracing simulations, please refer to Figure S1 in the 190 supplemental material) were observed by beam 4 of the HOK radar. The magnitudes 191 of the LOS velocities in this slant range were weaker than those in the slant range greater 192 than 400 km (F layer of the ionosphere). According to data from surface pressure sta-193 tions, Wright et al. (2022) identified surface air pressure propagated as a Lamb wave at 194 a phase speed of  $318.2\pm 6$  m/s. Shinbori et al. (2022) showed that the surface air pres-195 sure waves propagated to Japan at around 1120 UT as Lamb mode waves based on the 196 thermal infrared grid data observed by the Himawari 8 satellite. After 1120 UT, much 197 backscatter appeared in the E region of the ionosphere and were observed by the HOK 198

radar; the LOS velocities in the E layer exceeded  $\pm 150$  m/s and were stronger than those in the F region between 1120 UT and 1600 UT. After 1200 UT, the JME and HKW radars also observed an increase in the number of ionospheric echoes in the E layer.

According to the observations from the HOK and JME radars between 0800 UT 202 and 1200 UT, the propagation direction of the ionospheric oscillation was westward. Af-203 ter the arrival of the surface air pressure waves, the propagation direction turned north-204 westward. Figure S2 in the supplemental material show the wavefronts observed by the 205 HOK and JME radars at 0850 UT, 0940 UT and 1133 UT. The horizontal phase veloc-206 ity was approximately 330 m/s, which was calculated by using the delay time and the 207 distance between the HOK radar and the JME radar. The propagation direction and 208 horizontal phase velocity of the ionospheric fluctuations observed by the SuperDARN 209 radars were consistent with the observations based on the TEC(Lin et al., 2022), which 210 indicates that this group of oscillations was due to magnetic conjugate effect. Shinbori 211 et al. (2022) also showed that the LOS Doppler velocity observed by the SuperDARN 212 Hokkaido east radar was associated with the passage of TEC perturbations due to mag-213 netic conjugate effect. Strong ionospheric oscillations were observed by the SuperDARN 214 radars in East Asia, with three LOS velocity transitions from 0800 UT to 1200 UT that 215 may be attributed to the three main explosions of the volcanic eruptions in Tonga (Astafyeva 216 et al., 2022; Wright et al., 2022). During this period, the slant range of the echoes showed 217 a trend of rising, falling, and then rising, implying variations in the height of the iono-218 sphere in addition to oscillations in the horizontal direction. 219

The BKS radar is located in the Western Hemisphere and under different day-night 220 conditions during the period of interest. The backscatter received by the BKS radar was 221 considerably different from the backscatter received by the other three radars. Almost 222 all of the backscatter was ground scatter. The velocity variation in ground scatter for 223 the SuperDARN radars is usually attributed to vertical movement of the ionosphere. The 224 BKS radar received minimal backscatter before 1200 UT as the radar operating frequen-225 cy and ionospheric conditions were not suitable. With sunrise, the ionosphere builds up 226 and a band of ground scatter developed after 1230 UT. The slant range to the band varies 227 and the LOS velocity fluctuates within narrow limits (<30 m/s) throughout the day ow-228 ing to passage of TIDs, which is typical. However, after 1400 UT, ground scatter with 229 LOS velocities greater than 90 m/s was observed by beam 4 of the BKS radar, corre-230 sponding to a marked downward motion in the ionosphere. Figure S3 in the supplemen-231 tal material shows the radar observations at 1440 UT, 1445 UT, and 1450 UT. This fig-232 ure clearly shows the downward motion of the ionosphere propagating northeastward. 233 We estimated that the propagation velocity of the ionospheric fluctuation was approx-234 imately 320 m/s. 235

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### 3.2 LOS velocity across different layers of ionosphere

To show the fluctuation velocity across different layers of the ionosphere, Figure 237 3 shows an RTI plot of the LOS Doppler velocity observed by beam 4 of the HOK radar 238 and line plots of the LOS velocities of range gates 2, 4, 10, 12, 14 and 16 for beam 4 of 239 the HOK radar, with 10 min smoothing applied. The positive/negative velocities indi-240 cate that the direction of the LOS velocity was toward/away from the radar. Range gates 241 2, 4, 10, 12, 14 and 16 correspond to slant ranges of 270, 360, 630, 720, 810 and 900 k-242 m, as indicated by the six black horizontal lines on Figure 3 (a). The blue vertical line 243 at 0800 UT indicates the arrival time of the disturbance propagated from the magnet-244 ic conjugate point of the Tonga volcanic eruption, while the blue vertical line at 1120 245 UT indicates the arrival time of the disturbance directly propagated from the Tonga vol-246 canic eruption. Between 0800 UT and 1120 UT, the maximum peak-to-peak amplitude 247 of the ionospheric fluctuation velocity was approximately 150 m/s at range gate 10 (F 248 layer) and was associated with the two shock structures. During this period, the peak-249 to-peak amplitude observed at gate 2 (E layer) was weaker than that observed in the F 250



Figure 2. Range-time-intensity plots of the LOS Doppler velocities observed by (a) beam 4 of the HOK radar, (b) beam 0 of the JME radar, (c) beam 4 of the HKW radar and (d) beam 4 of the BKS radar on 15 January 2022. The LOS Doppler velocities are scaled according to the color bar shown on the right. The shadow in each panel indicates night. The two blue vertical lines in (a), (b) and (c) indicates the arrival time of the two groups of oscillations.



**Figure 3.** Fluctuation velocity across different layers of the ionosphere. (a) RTI plot of the LOS Doppler velocities observed by beam 4 of the HOK radar and line plots of the LOS velocities of range gates (b)16, (c) 14, (d) 12, (e) 10, (f) 4 and (g) 2 for beam 4 of the HOK radar, with 10 min smoothing applied. Range gates 2, 4, 10, 12, 14 and 16 correspond to slant ranges of 270, 360, 630, 720, 810 and 900 km, respectively, as indicated by the six black horizontal lines in Figure 4(a). The two vertical blue lines indicate the arrival time of the disturbance from the magnetic conjugate point of the volcanic eruption in Tonga and from the volcanic eruption itself.

layer. After the arrival of the surface air pressure waves at around 1120 UT, the maximum LOS velocity was approximately  $\pm 150m/s$ , and the peak-to-peak amplitude of the ionospheric fluctuation approached 300 m/s at range gate 4 (E layer). The peak-to-peak amplitude decreased over time and as the range gate increased.

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### 3.3 Uplift in the ionosphere by the volcanic eruption

The SuperDARN radars observed the LOS velocity of the irregularities. To inves-256 tigate the vertical motion of the ionosphere, we combined the observations from beam 257 4 of the HKW radar and Mohe digisonde. Beam 4 of the HKW radar and the location 258 of the Mohe digisonde are shown in Figure 1. Figure 4 shows the RTI plot of the LOS 259 Doppler velocities observed by beam 4 of the HOK radar, the F layer peak height (hm-260 F2) as a function of time obtained from the Mohe digisonde, and three representative 261 ionograms to highlight the state of the ionosphere at specific times. The black horizon-262 tal dashed line in Figure 4 (a) indicates the radar slant range corresponding to the Mo-263

he digisonde. The two vertical blue lines in Figure 4 (a) and (b) indicate the arrival time 264 of the disturbance to the Mohe digison from the magnetic conjugate point of the vol-265 canic eruption in Tonga at 0930 UT and from the volcanic eruption itself at 1230 UT, 266 respectively. The cyan dashed line in Figure 4 (b) indicates the variation in the peak height of the F layer during the quiet time (polynomial fitting curve based on observations on 268 13 Jan 2022). As shown in Figure 4, the negative/positive LOS velocities of the HKW 269 radar correspond to the upward/downward motion, respectively, of the ionosphere, which 270 were captured by the Mohe digisonde, indicating that the LOS velocities observed by the 271 SuperDARN radars have a pronounced vertical component and were not purely horizon-272 tal. After the arrival of the disturbance from the magnetic conjugate point of the vol-273 canic eruption at 0930 UT, an uplift of the ionosphere from 245 km to about 326 km was 274 observed by the Mohe digison at 1030 UT, and then the height of the ionosphere vi-275 brated and fell to a normal height. After the disturbance from the volcanic eruption it-276 self propagated to Mohe at approximately 1230 UT, the uplift of the ionosphere was a-277 gain observed by the digisonde. Excluding the diurnal variation in the peak height of 278 the F layer at the quiet time, the maximum amplitude of the vertical fluctuations caused 279 by the volcanic eruption in Tonga was approximately 80 km, as observed by the Mohe 280 digisonde. This finding indicates that the volcanic eruption caused strong vertical fluc-281 tuations of the ionosphere in the midlatitude region of the Northern Hemisphere. This 282 vertical movement may be attributed to the fact that magnetic field lines in mid lati-283 tudes are not completely perpendicular to the ground; thus, east-west electric fields in 284 this region will produce vertical movements of the ionosphere in addition to horizontal 285 movements. 286

Joint observations from beam 4 of the BKS radar and Boulder digisonde also re-287 vealed the vertical oscillation of the ionosphere (see Figure S4 in the supplemental ma-288 terial). The position of the Boulder digison is beyond the 2000 km slant range of the 289 BKS radar, so the location of the digisonde was not marked in the figure. A maximum 290 positive velocity of approximately 90 m/s was observed by beam 4 of the BKS radar from 291 1400 UT, which corresponds to a marked downward motion in the ionosphere. The Boul-292 der digisonde also observed the rapid decrease in the peak height of the F layer from 1400 293 UT with an amplitude of more than 100 km, which is consistent with the observation 294 from the BKS radar. The disturbance from the magnetic conjugate point of the volcanic 295 eruption in Tonga and from the volcanic eruption itself arrived at the Boulder digisonde 296 at 0905 UT and 1215 UT, respectively, which was calculated based on the speed of the 297 Lamb wave. 298

### <sup>299</sup> 4 Discussion and Conclusion

Figure S5 in the supplemental material shows the RTI plots of the LOS Doppler 300 velocities observed by the four SuperDARN radars on 14 January 2022 and 15 January 301 2022 with the SYM-H index. It was noted that there was a moderate storm during 14-302 15 January 2022, with the SYM-H index dropping to -101 nT at 2217 UT on 14 January 303 2022. Analyses by Lin et al. (2022) and Shinbori et al. (2022) showed that the IMF Bz 304 turned northward at 2330 UT on 14 January 2022, and the AE index remained at a very 305 low level from 0400 UT to 1100 UT on 15 January 2022. When the eruption occurred, 306 the storm was in the late recovery phase. Geomagnetic storms are known to generate 307 LSTIDs that propagate from high latitudes to equatorward (e.g., Richmond, 1978, and 308 others). The perturbations propagated westward and northwestward in East Asia and 309 propagated northeastward in the United States. The propagation direction and veloc-310 ity were different from the propagation feature of the storm-time LSTIDs, and they were 311 consistent with the features of the TIDs caused by the volcanic eruption. 312

According to the observations from the SuperDARN radars in East Asia, the strongest LOS velocity appeared in the F layer of the ionosphere due to the magnetic field conjugate effect, and the amplitude of the velocity decreased with decreasing altitude. This



Figure 4. Vertical variation of the ionosphere. (a) RTI plot of the LOS Doppler velocities observed by beam 4 of the HOK radar. The black horizontal dashed line in panel (a) indicates the slant range corresponding to the Mohe digisonde. (b) Ionospheric peak height of the F2 layer as a function of time obtained from the Mohe digisonde. The two vertical blue lines in panel (a) and (b) indicate the arrival time of the disturbance to the Mohe digisonde from the magnetic conjugate point of the volcanic eruption in Tonga and from the volcanic eruption itself, respectively. The cyan dashed curve in panel (b) indicates the variation in the peak height of the F layer of the ionosphere during the quiet time. Three representative ionograms are shown at (c) 0930 UT, (d) 1045 UT and (e) 1230 UT.

finding indicates that the magnetic field conjugate effect has a significant impact on the 316 plasma flow in the F layer in another hemisphere. During this period, the ionospheric 317 plasma flow was produced by an external electric field that was generated by an E lay-318 er dynamo in the sunlit Southern Hemisphere. The two sudden increases of the plasma 319 flow may correspond to the two large Tonga eruptions with VEI values of 6, which can 320 cause a significant enhancement of an E-region dynamo electric field. After the arrival 321 of surface air pressure waves, the strongest LOS velocity appeared in the E layer, and 322 the amplitude of the velocity decreased with increasing altitude. During this period, the 323 ionospheric conductivity of the E-region was very small due to the dark region, and the 324 E layer dynamo process was not effective on the ionospheric plasma motion in the F-region. 325 Thus, the E and F layer motions were directly produced by the neutral wind osculation 326 associated with arrival of the air pressure waves. The collision frequency was much s-327 maller in the F layer than in the E layer. Therefore, the plasma motion was expected 328 to be slower in the F layer than in the E layer. 329

The fluctuation caused by the magnetic field conjugate effect was detected by three 330 radars in East Asia, while the BKS radar in America did not record fluctuations caused 331 by the magnetic field conjugate effect. This was attributed to the fact that the radar op-332 erating frequency and ionospheric conditions did satisfy the conditions for receiving iono-333 spheric backscatter during the relevant period. In addition, the three midlatitude Su-334 perDARN radars in Australia and New Zealand in the Southern Hemisphere were not 335 operating during this period. If these radars were operational, they would have provid-336 ed excellent observations for comparing movements in the ionosphere caused by volcanic 337 eruptions in the Southern and Northern Hemispheres, and would have contributed to a 338 deeper understanding of the mechanisms underlying the magnetic field conjugate effec-339 t. 340

In conclusion, impacts on ionospheric irregularities and ionospheric oscillation fea-341 tures in the Northern Hemisphere caused by the explosive Tonga volcanic eruption in 342 the southwest Pacific were clearly captured by midlatitude SuperDARN radars and digison-343 des. The ionospheric fluctuations observed by SuperDARN radars in East Asia propa-344 gated westward due to the magnetic field conjugate effect. After the surface pressure waves 345 arrived, the propagation direction was northwestward. The distant and upward motion-346 s of the ionosphere was considerably more rapid and lasted longer than the forward and 347 downward motions. Because of different mechanisms, the maximum peak-to-peak LOS 348 velocity of the ionosphere exceeded 150 m/s appeared in F layer due to the magnetic field 349 conjugate effect, and the maximum peak-to-peak LOS velocity of the ionosphere was ap-350 proximately 300 m/s and appeared in the E layer due to the direct propagation of the 351 wave from the Tonga volcano. The amplitude of the vertical rise and fall of the ionosphere 352 in the mid-latitude region of the Northern Hemisphere reached nearly 100 km due to the 353 volcanic eruption. This event shows how geological hazards can impact the ionosphere 354 and cause space weather, raising concerns for vulnerable technologies. 355

### **5 Open Research**

The raw SuperDARN data are available from the SuperDARN data server at the 357 National Space Science Center, Chinese Academy of Sciences (https://superdarn.nssdc.ac.cn/). 358 To access the data, users should log in, and go to 'Access data' to select the radar, dataset 359 and date. The Mohe ionogram data were obtained from the Chinese Meridian Project 360 Database (https://data.meridianproject.ac.cn/), to access the data, users also should log 361 in, and go to 'Download', then select 'Mohe station', and then choose 'Ionogram image of digital ionosonde'. The Boulder ionogram data were obtained from the Digital Iono-363 gram Database (http://spase.info/SMWG/Observatory/GIRO). The SYM-H index can 364 be downloaded from World Data Center for Geomagnetism, Kyoto (doi:10.14989/267216). 365

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## Supporting information for "Oscillations of the Ionosphere Caused by the 2022 Tonga Volcanic Eruption Observed with SuperDARN Radars"

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Contents of this file Figure S1 to S5



**Figure S1. 1 Ray-tracing simulation**. Propagation paths of HF rays in the ionosphere at 1200 UT for beam 4 of the HOK radar on 15 Jan 2022 obtained using ray-tracing simulator. Ionospheric electron densities from the International Reference Ionosphere (IRI) are plotted in the background. Each HF ray is plotted in gray and the length of a ray path to a scatter point is the slant range. The black segments indicate regions with good aspect conditions, i.e., regions where the rays are within 1° of orthogonality with the background geomagnetic field (magenta lines) and where the radar could observe ionospheric scatter. The solid white traces serve as range markers: the first trace from the transmitter is at 180 km, and all subsequent traces are 225 km apart.



**Figure S2. Wavefront observed by the SuperDARN radars.** LOS velocity observations from the JME and HOK radars at 0850 UT, 0940 UT and 1133 UT in terms of geographic coordinates. The blue curve represents an arc on the great circle centered on the magnetic conjugate point of the Tonga volcano in the Northern Hemisphere, and the orange curve represents an arc on the great circle centered on the Tonga volcano.



**Figure S3.** LOS velocity observations from the BKS radar at 1440 UT, 1445 UT and 1450 UT in terms of the geographic coordinates.



**Figure S4. Vertical variation in the ionosphere in North America.** (a) RTI plot of the LOS Doppler velocities observed from beam 4 of the BKS radar, (b) peak height of the F layer of the ionosphere as a function of time obtained from the Boulder digisonde, and three representative ionograms at (c) 0905 UT, (d) 1400 UT and (e) 1600 UT. The two vertical blue lines in panel (b) indicate the arrival time of the disturbance to the Boulder digisonde from the magnetic conjugate point of the volcanic eruption in Tonga and from the volcanic eruption itself. The cyan dashed curve in panel (b) indicates the variation in the peak height of the F layer of the ionosphere during quiet time.



**Figure S5.** The RTI plots of the LOS Doppler velocities observed by the four SuperDARN radars on 14 January 2022 and 15 January 2022 with the SYM-H index.