URSI GASS 2023, Sapporo, Japan, 19 – 26 August 2023

Modeling Atmosphere-Ionosphere Coupling on Gravity Waves during 2019 Typhoon 15 and 19 using FDTD Method

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Abstract

Atmospheric Gravity Waves (AGWs) are important phenomena that propagate heat to wider areas in the atmosphere through heat convection. It is especially occurred during typhoons, propagating radially from the typhoon's eye. UEC's VLF network has two parallel paths from the VLF transmitter NPM in Hawaii to receiving stations Moshiri (MSR) and Yamaguchi (YMG) in Japan to monitor the ionospheric perturbation due to powerful typhoons. These paths are used to observe the propagation of the gravity waves during Typhoons 15 and 19 in 2019 which occurred in the Pacific Ocean. The spectrum intensity of VLF signals on NPM-YMG and NPM-MSR showed that there is the possibility of AGWs occurrence on September 4th and 5th during Typhoon 15 and October 7th and 8th during Typhoon 19. The spatial dependence of ionospheric perturbation is modeled using a 2D Finite Difference Time Domain (FDTD). The perturbation height variations on NPM-YMG and NPM-MSR from the simulation are then compared to the fluctuation of the observation VLF signal during Typhoons. The ionospheric perturbation variation over time shows a similar fluctuation pattern on September 4th and 5th during Typhoon 15 in NPM-YMG and NPM-MSR with a delay of 2.5 hours and 2 hours respectively. It fluctuated in the ionospheric height between 88 km to 83 km over 2 hours period. This fluctuation indicates the amplitude of the gravity wave propagation. It is then calculated that the gravity waves on Typhoon 15 have a phase velocity of 94.2 m/s and 117.8 m/s on September 4th and 5th respectively.

1 Introduction

Tropical Cyclones (TCs) are a source of Atmospheric Gravity Waves (AGWs), a phenomenon of energy transfer to wider areas in the atmosphere through heat convection that propagates upward and outward from the center TCs. Several research analyzed lower ionospheric response in tropical depressions[1]. The GWs caused the disturbance in the atmosphere and can be observed by satellite or VLF networks [2]–[4]. However, it was hard to observe the phase velocity of GWs only using a VLF path.

Several typhoons that hit Japan begin in the Pacific Ocean southeast of Japan. It comes close to Japan and changes direction upward near Japan. UEC has a pair parallel VLF path orthogonally from those Typhoons. The YMG-NPM (Yamaguchi and NPM, Hawaii) path was located north of the Typhoon, and the MSR-NPM (Moshiri and NPM, Hawaii) path was located further north. It is possible to observe the GWs propagation from VLF signal fluctuation from YMG-NPM and MSR-NPM paths.

Typhoons 15 and 19 in 2019 occurred south of the YMG-NPM path. It has been observed for its correlation to lower ionospheric perturbation and lightning activity [5]. This research will observe the fluctuation during Typhoons 15 and 19 and observe the GWs propagation in the YMG-NPM path and the MSR-NPM path. The ionospheric perturbation will be modeled by FDTD and compared with the VLF signal fluctuation. the correlation between ionospheric perturbation between those two VLF paths will be calculated as perturbation height variations and phase velocity.

2 Observation Data Set

The University of Electro-Communications (UEC) operates VLF transmitter receiver networks all around Japan. Two of the receivers in the network are located at Moshiri and Yamaguchi. These receivers, together with the NPM transmitter station in Hawaii form two parallel paths relative to the several Typhoons that occurred in the North Pacific Ocean. Figure 1 shows the path of Typhoon 15 and its location on 04 Sep. 2019 compared to the YMG-NPM and MSR-NPM paths. This configuration will be used to observe the propagation of gravity waves from the Typhoon. The observed Typhoons are Typhoons 15 and 19 in 2019. To measure lightning activity around the typhoon and Fresnel zone area, Earth Networks Total Lightning Network (ENTLN) sensor data (including 16 total lightning sensors deployed and jointly-operating with Earth Networks around Japan (JTLN)). The network provides the lightning position, time, discharge polarity, and peak current of Cloud-to-Ground lightning (CGs). The activity of Typhoons is observed using brightness temperature data set from Band 13 of the Weather Satellite of MT-SAT 8. It has an observation wavelength of visible, near-infrared, and infrared with a 10-minute time resolution.

Typhoon 15 in 2019 occurred between 04 – 10 Sep. 2019 and has a maximum wind speed of 85 knots on 08 Sep. 2019. Brightness temperature and lightning activity during typhoons are monitored around the center of the typhoon and VLF networks. Figure 2 shows the brightness temperature and lightning activity during typhoon 15 and its correlation with the fluctuation of observed VLF signals. There are high fluctuations of the VLF signal during and after the peak of brightness temperature on 31 Aug. and 04 Sep. 2019. There are also high fluctuations of VLF signal during high lightning activity in the Fresnel zone on 08 Sep. 2019 at NPM-MSR and on 02 Sep. 2019 at YMG-NPM. The lightning activity inside the Fresnel Zone forms ionospheric perturbation. However, depending on the perturbation's location, the VLF signal fluctuation could be low as shown on 09 Sep. 2019 at YMG-NPM.

3 Gravity Waves on Typhoons 15 and 19

Atmospheric Gravity waves (AGWs) were observed from the wavelet spectrum of VLF signal fluctuation during Typhoons. The wavelet spectrograms on a 60-80-minute period at MSR-NPM and YMG-NPM during Typhoon 15 are observed with the correlation of brightness temperature and lightning activities. It is shown in Figure 3. High-spectrum intensity occurred mostly following high brightness temperature on 31 Aug., 04 Sep., and 05 Sep. 2019. High lightning activity in Fresnel Zone does not result in the occurrence of high intensity of the wavelet spectrum. The spectrum intensity on 02 Sep. 2019 at YMG-NPM is high but only at the beginning of the night. It is possibly caused by lightning activity in the Fresnel Zone. The lightning activity in the center of the Typhoon occurred during the peak of brightness temperature on 04 Sep. 2019. It is hard to analyze whether this affects the spectrum intensity or not. If we compare the wavelet spectrum intensity at MSR-NPM and YMG-NPM in Figures 3a and 3b, it has a similar pattern. It shows that the gravity waves on a 60-80-minute period propagate radially from the center of the typhoon through the YMG-NPM path and then to the MSR-NPM path. If the delay in the ionospheric perturbation pattern between the YMG-NPM path and the MSR-NPM path can be observed, it is possible to calculate the group or phase velocities of AGWs.

In comparison to Typhoon 15, AGWs are also observed during Typhoon 19 with a similar method. Typhoon 19 in 2019 occurred between 05 – 13 Oct. 2019 and has a maximum wind speed of 105 knots on 08 – 10 Oct. 2019. There is a big fluctuation of the VLF signal on 09 Oct. 2019 at both MSR-NPM and YMG-NPM paths when the brightness temperature in the center of the Typhoon is high. However, on 09 Oct. 2019, the Typhoon has already close to the YMG-NPM path and spread widely to the MSR-NPM path. These conditions cause difficulty to observe the AGWs. During Typhoon 19, lightning activity in the Fresnel zone on the YMG-NPM path is high and caused many fluctuations. The observed point of GWs propagation on Typhoon 19 is chosen on 08 Oct. 2019 because it has a similar spectrum on MSR-NPM and YMG-NPM paths There is less lightning activity on 08 Oct. 2019 at both paths.

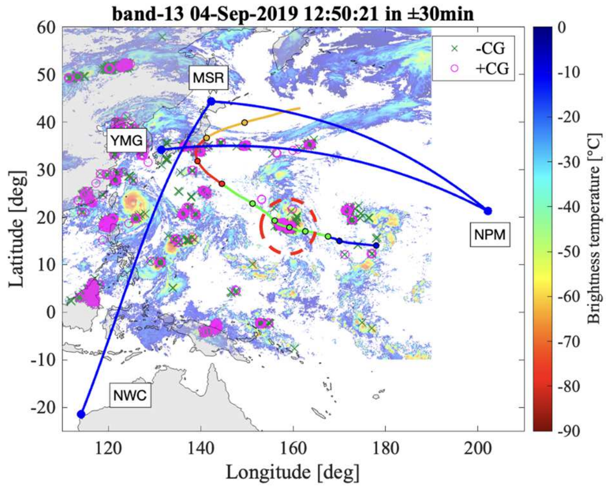
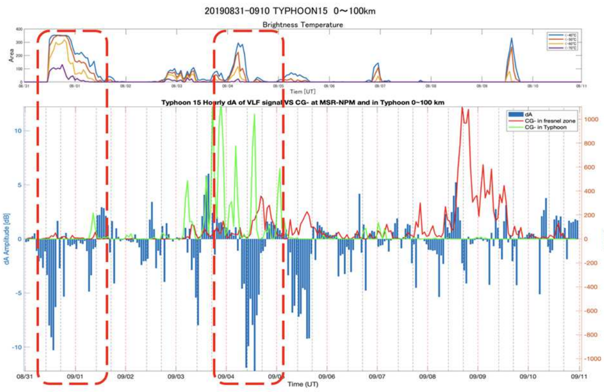
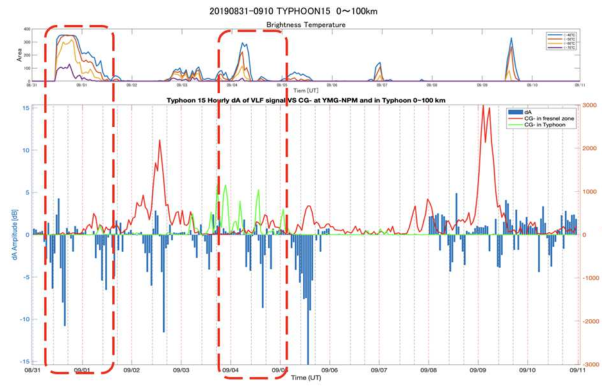


Figure 1. Typhoon 15 location on 04 Sep. 2019 and the YMG-NPM and MSR-NPM VLF great circle paths.



(a)



(b)

Figure 2. *dA* of VLF signal and its correlation with brightness temperature and thunder activity on Typhoon 15 (a) at MSR-NPM and (b) at YMG-NPM

4 FDTD Model of Ionospheric Perturbation

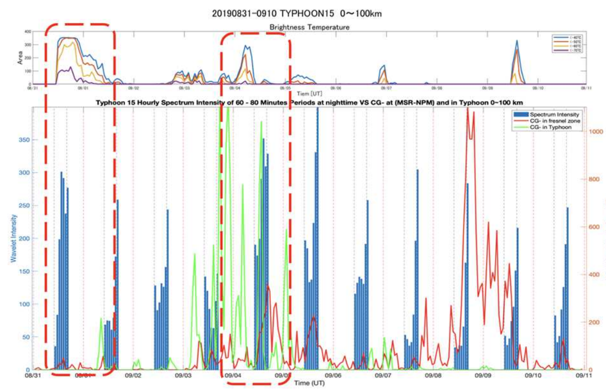
The fluctuation of the observed VLF signals will be compared with the ionospheric perturbation model. The model is generated with 2D FDTD to calculate the height of ionospheric perturbation which results in the fluctuation of the VLF signal. The AGWs are assumed to propagate radially from the center of the Typhoon. The model uses constant perturbation with the variation in its height, h', from 70 to 92 km as shown in Figure 4. The background parameter used in this model are $\beta = 0.5$ km, $h = 85$ km, $dr = 1$ km, and $ds = r \times 1.57 \times 10^{-4}$ degree.

The results of the simulation are shown in Figure 5 for both YMG-NPM and MSR-NPM. With a reference height of 85 km. The VLF signal amplitude could increase or decrease depending on the variation in ionospheric perturbation height. It is also shown that the MSR-NPM path is more sensitive to the VLF fluctuation than the YMG-NPM. These results will be compared to the fluctuation of observed VLF signals on 04 – 05 Sep. 2019 for Typhoon 15 and 08 Oct. 2019 for Typhoon 19. However, this model only includes the perturbation variation due to AGWs not including the perturbation due to lightning activity.

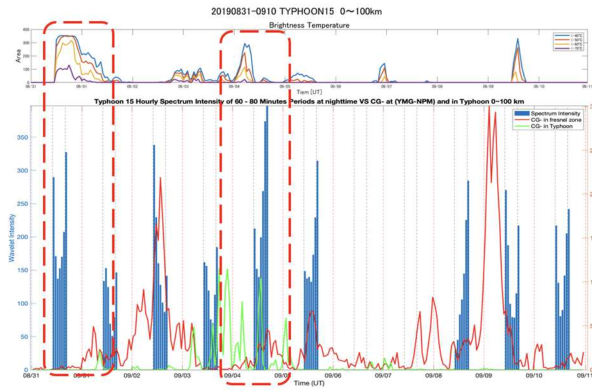
5 Results and Discussion

The ionospheric perturbation height variation from the FDTD model in Figure 5 is compared with the VLF fluctuations with a time resolution of half an hour on 04 and 05 Sep. 2019. The results are shown in Figure 6 and Figure 7. It shows that on 04 Sep. 2019, the ionospheric perturbation heights have a similar fluctuation at 11:45 – 12:45 UT at MSR-NPM and at 13:15 – 14:15 UT with a delay of 2.5 hours. The analyzed time window is rather short due to the solar terminator time. It also shows that the lightning activity does not affect much in perturbation height. On 05 Sep. 2019, the lightning activity was higher. the ionospheric perturbation height fluctuates similarly at 10:15 – 12:15 at YMG-NPM and at 12:15 – 14:15 at MSR-NPM with a delay of 2 hours. However, between 11:15 – 12:15, there was no change at YMG-NPM because it is less sensitive to small fluctuations with a 1 km height in resolution. These perturbation height variations over time define the height of gravity waves propagating between the YMG-NPM and the MSR-NPM paths. The perturbation height variation for Typhoon 19 on 08 Oct. 2019 is shown in **Figure 8**. Due to high lightning activity in the Fresnel zone of the YMG-NPM path, the perturbation height variation fluctuates highly. It's hard to tell the propagation of AGWs in this case. The constant perturbation model doesn't fit the case when lightning activity causes high disturbance in the Fresnel zone.

From the results of Figures 6 and 7, with the distance between MSR-NPM and YMG-NPM paths being ~848 km on 04 and 05 Sep. 2019 and time delay of 2.5 hours and 2 hours respectively, the phase velocity of GWs on 09/04 is 94.2 m/s and 117.8 m/s on 09/05. The theoretical value of phase velocity is $V_{gx} = 103.9$ m/s and group velocity is $V_{gz} = 52$ m/s. This value of phase velocity is not too far from the calculated value.



(a)



(b)

Figure 3. The wavelet spectrogram intensity at nighttime on a 60-80 minutes period and its correlation with brightness temperature and thunder activity on Typhoon 15 (a) at MSR-NPM and (b) at YMG-NPM

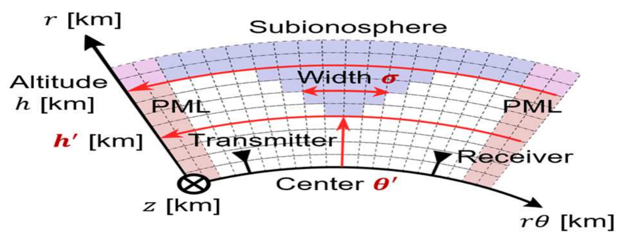


Figure 4. Simulation coordinate of the 2D FDTD model for VLF wave propagation between transmitter and receiver (YMG-NPM and MSR-NPM).

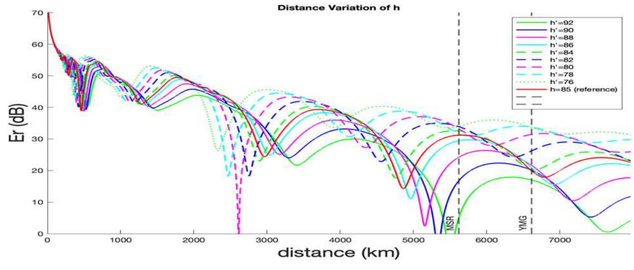


Figure 5. Perturbation height variation from the 2D FDTD model with MSR and YMG as receiver stations.

6 Conclusion

On Typhoon 15 (2019), the wavelet spectrogram of the VLF signal at MSR-NPM and YMG-NPM paths shows strong wave activity around a 60 – 80-minute period. The enhancement of the wave activity was observed especially on 31 Aug., 04 Sep., and 05 Sep. 2019 at both MSR-NPM and YMG-NPM paths following the high intensity of brightness temperature at the center of Typhoon. On the other hand, lightning activity mostly affects the fluctuation in the VLF signal but not in the wavelet spectrogram. The fluctuation is higher when the lightning activity occurred closer to the receiver thus determining the location and intensity of ionospheric perturbation.

The model of ionospheric perturbation caused by GWs uses a constant model as ionospheric perturbation height. In our model, GWs are assumed to propagate radially from the center of the Typhoon over distances crossing the YMG-NPM path and then to MSR-NPM paths. The 2D FDTD model results in different fluctuations in ionospheric perturbation height variations. The results are compared to the VLF fluctuation at YMG-NPM and MSR-NPM. There is a similar pattern at both paths with a delay of 2.5 and 2 hours on 04 Sep. and 05 Sep. 2019 respectively. From the time delay, the calculated phase velocities are 94.2 m/s and 117.8 m/s on 04 Sep. and 05 Sep. 2019 respectively.

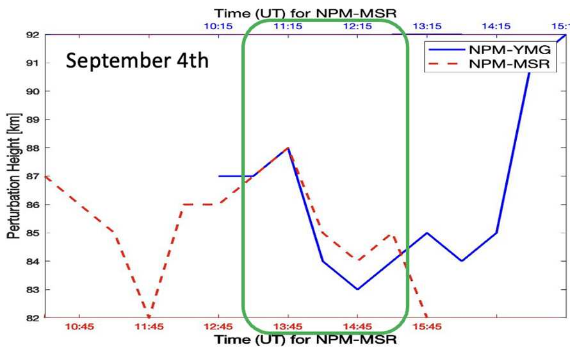


Figure 6. Comparison of perturbation height variation over time between MSR-NPM and YMG-NPM paths with a delay of 2.5 hours on 09/04 during Typhoon 15.

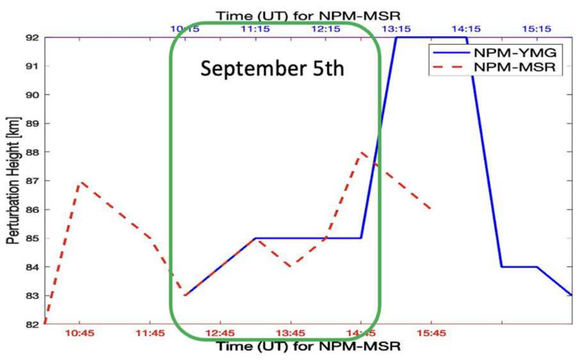


Figure 7. Comparison of perturbation height variation over time between MSR-NPM and YMG-NPM paths with a delay of 2 hours on 09/05 during Typhoon 15.

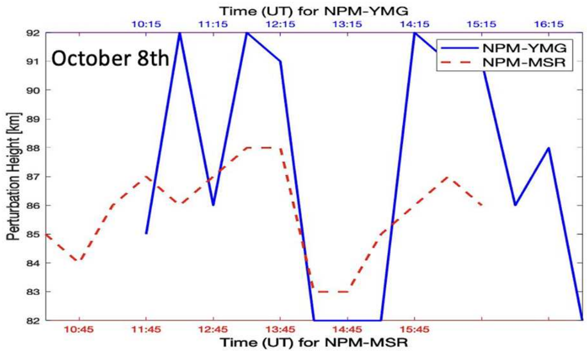


Figure 8. Comparison of perturbation height variation over time between MSR-NPM and YMG-NPM paths with a delay of 1.5 hours on 10/08 during Typhoon 19.

Acknowledgment

This research was funded by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) Japan. The author thanks ISEE, Nagoya University, and T. Eguchi, Yamaguchi University, for helping UEC's VLF observations in MSR and YMG. The authors also thank Dr. Sujay Pal and Dr. Alexander Shvets for useful discussion.

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