Journal of Atmospheric and Solar–Terrestrial Physics 156 (2017) 15–23

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar–Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Ionospheric plasma disturbances generated by naturally occurring large-scale anomalous heat sources

Rezy Pradipta[a,c,*], Min-Chang Lee[b,c], Anthea J. Coster[d], Craig A. Tepley[e], Michael P. Sulzer[e], Sixto A. Gonzalez[e]

[a] *Institute for Scientific Research, Boston College, Chestnut Hill, MA, United States*
[b] *Department of Electrical and Computer Engineering, Boston University, Boston, MA, United States*
[c] *Space Propulsion Laboratory, Massachusetts Institute of Technology, Cambridge, MA, United States*
[d] *MIT Haystack Observatory, Westford, MA, United States*
[e] *Arecibo Observatory, Arecibo, PR, United States*

A B S T R A C T

We report the findings from our investigation on the possibility of large-scale anomalous thermal gradients to generate acoustic-gravity waves (AGWs) and traveling ionospheric disturbances (TIDs). In particular, here we consider the case of summer 2006 North American heat wave event as a concrete example of such large-scale natural thermal gradients. This special scenario of AGW/TID generation was formulated based on the results of our experiments at the Arecibo Observatory in July 2006, followed by a systematic monitoring/surveillance of total electron content (TEC) fluctuations over North America in 2005–2007 using the MIT Haystack Observatory's Madrigal database. The data from our Arecibo experiments indicate a continual occurrence of intense AGW/TID over the Caribbean on 21–24 July 2006, and the Madrigal TEC data analysis shows that the overall level of TID activity over North America had increased by ~0.2 TECU during the summer 2006 heat wave event. Our proposed scenario is in agreement with these empirical observations, and is generally consistent with a number of past ionospheric HF heating experiments related to AGW/TID generation.

1. Introduction

In this work, we investigated the potential role of large-scale thermal gradients in generating acoustic-gravity waves (AGWs) and traveling ionospheric disturbances (TIDs). Such large-scale thermal gradients can occur naturally in the form of severe and prolonged heat wave events, which have become more frequent and common in recent years. Under controlled condition in ionospheric HF heating experiments, such thermal gradients can also be formed since neutral particle heating was found to be significant during heating experiments conducted at Arecibo in the past (Gonzalez et al., 2005). In addition, thermal expansion followed by enhanced recombination of F-region plasmas during HF heating experiments could lead to the creation of rising plasma bubbles and sharp plasma density gradients that augment natural spread-F process (Lee et al., 1998, 1999). Moreover, artificial thermal gradients formed during ionospheric HF heating experiments also have the potential to generate AGW/TID, as demonstrated in HAARP experiments (Pradipta, 2012; Pradipta et al., 2015a). These bits of information become the basis for us to consider large-scale natural thermal gradients (such as those associated with severe and prolonged heat wave events) as a physically plausible source of AGW/TID.

We begin this paper with a report on our multidiagnostic experiments at Arecibo in July 2006, which contained an overlap with the summer 2006 North American heat wave event (Section 2). During these Arecibo experiments, intense TIDs were continually observed; and as an interpretation, we thereby proposed a scenario/hypothesis in which the severe heat wave event over North America at that time could be a natural source responsible for the AGW/TID (Section 3). This hypothesis was subsequently tested by monitoring the level of ionospheric total electron content (TEC) fluctuations over North America throughout the summer months of 2005, 2006, and 2007. It was found that the level of TEC fluctuations over North America had increased promptly during the 2006 heat wave event (Section 4). We also elaborate further on the scientific and practical implications of these experimental findings, including some long-term climatic impacts (Section 5). In conclusion, our analysis suggests that large-scale thermal gradients associated with severe and prolonged heat wave

* Corresponding author at: Institute for Scientific Research, Boston College, Chestnut Hill, MA, United States.
E-mail address: rezy.pradipta@bc.edu (R. Pradipta).

http://dx.doi.org/10.1016/j.jastp.2017.02.010
Received 10 November 2016; Received in revised form 25 January 2017; Accepted 21 February 2017
Available online 22 February 2017
1364-6826/

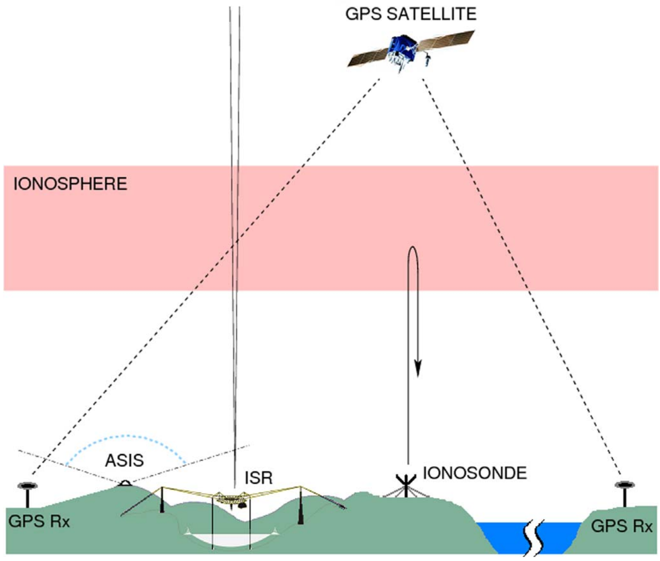

Fig. 1. A cartoon illustration of radio and optical diagnostic instruments for our summer 2006 Arecibo experiments. The incoherent scatter radar (ISR), ionosonde, and our all-sky imaging system (ASIS) are located at the Arecibo Observatory. One of the GPS receiver stations is at Isabella, PR, and the other is at St. Croix, USVI.

events have the capacity to act as a source of AGW/TID (Section 6). While the absolute magnitude of such increase in TID activity due to heat wave events might be relatively small (~0.2 TECU rise in RMS fluctuations above normal background), their impacts on space-related technology probably should not be underestimated.

2. Summer 2006 Arecibo experiments

2.1. Experimental setup

In our Arecibo experiments on 21–24 July 2006, we operated the 430 MHz incoherent scatter radar (ISR), the Canadian Advanced Digital Ionosonde (CADI), and our all-sky imaging system (ASIS) to monitor the ionospheric plasma conditions. In addition, we also examined some total electron content (TEC) data from two nearby GPS receiver stations (PUR3 at Isabella, PR; and CRO1 at St. Croix, USVI) that routinely operate and collect data. The overall setup of our multi-diagnostic experiments at Arecibo is schematically illustrated in Fig. 1.

The Arecibo ISR beam was pointed vertically in our experiments to measure the ionospheric plasma density profile as a function of altitude. The amount of radar backscatter power is directly proportional to the electron density within the scattering volume according to the formula $P_b \propto n_e/(1 + T_e/T_i)$ (Evans, 1969). Since our experiments were conducted during the nighttime, the temperature ratio T_e/T_i would not be altitude-dependent; as electrons and ions generally would have reached a thermal equilibrium. For this backscatter power measurement, we used a 13-baud Barker code with 4 μs baud length to modulate the transmitted radar pulse. This setting gives us a 600 m altitude resolution in the radar backscatter power profile. The measurements had to be averaged over multiple radar pulses in order to cancel out as much noise as possible, and the integration time that we applied in this case was 10 s (i.e. 1000 pulses). Moreover, we need to mention that this Barker-code backscatter power operation had to be interrupted for ~10 min duration every half an hour to perform plasma line measurements using the coded long pulse (CLP) technique (Sulzer, 1986). These interruptions give rise to some periodic gaps in the radar backscatter power data.

Meanwhile, the ionosonde recorded ionograms throughout our experiments in order to determine the foF2 values and to detect the presence of any spread-F echoes. It took about 1 min to acquire a complete ionogram, and ionograms were recorded once every 5 min. Both the transmit and receive antennas of the ionosonde are located at the Arecibo Observatory. Thus, the wide field-of-view of the ionosonde (~90° beamwidth) fully covered the narrow pencil beam of the Arecibo ISR (~0.16° beamwidth) at essentially all altitudes at all times.

Furthermore, we mounted our all-sky imaging system (ASIS) at Arecibo Observatory's Airglow Lab in order to obtain optical measurements for our experiments. With a field-of-view close to ~180°, it provided wide-coverage maps of the airglow emission pattern from ionospheric E- and F-regions above Puerto Rico. For the most part, we used the 5577 Å green line (from an altitude of ~90 km) and the 6300 Å red line (from altitude range around ~250 km) OI emissions (Chamberlain, 1961) to cross-check with the ISR and ionosonde data.

In addition, we also examined some total electron content (TEC) data that had been routinely collected by several GPS receiver stations in the Caribbean area. In particular, the most relevant GPS receiver stations for our investigation were the two closest to the Arecibo Observatory. One of them was the PUR3 station (at Isabella, PR, ~20 km west of Arecibo) and the other was the CRO1 station (at St. Croix, USVI, ~150 km east of Arecibo). For this part of our study, the ionospheric piercing point (IPP) of the GPS TEC data was set at an altitude of 450 km — matching the approximate height of the topside ionosphere as seen in the ISR data.

2.2. Observations from the Arecibo experiments

Fig. 2 shows the recorded Arecibo ISR data from our experiment on the night of 23/24 July 2006. The top panel depicts a range-time-intensity (RTI) plot of the normalized radar backscatter power starting from approximately 21:30 LT on 23 July 2006 until 01:00 LT on 24 July 2006. Meanwhile, the bottom panel depicts an RTI plot of the net backscatter power during this time period (obtained by time-differen-

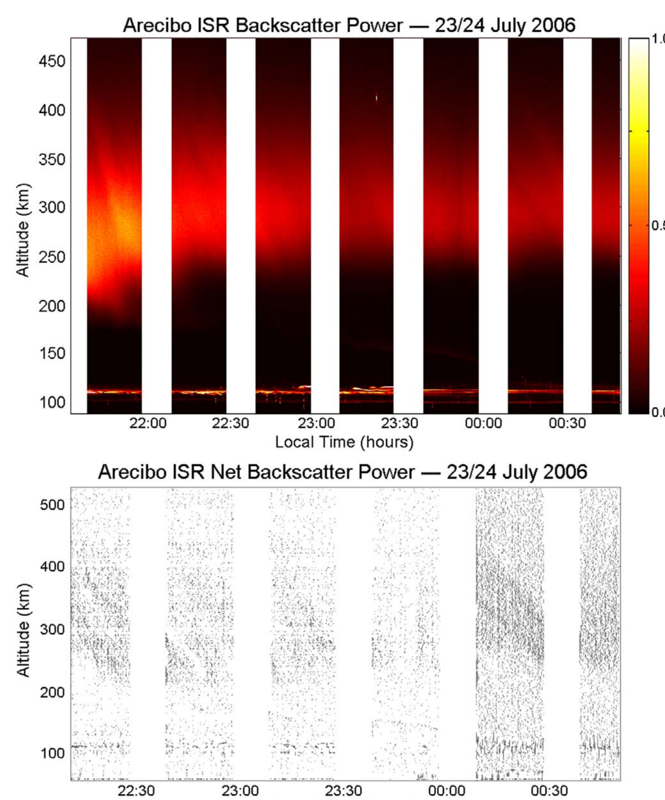

Fig. 2. RTI plot of Arecibo ISR backscatter power data from our experiment on the night of 23/24 July 2006 (top panel). RTI plot of the net backscatter power derived using time-differencing (bottom panel). The TIDs can be identified based on the characteristic pattern of slanted stripes in these RTI plots.