Omnipresent vertically coherent fluctuations in the ionosphere with a possible worldwide-midlatitude extent

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[1] Incoherent Scatter Radar power profile observations at Arecibo, Millstone Hill, and the Poker Flat AMISR have revealed the continuous presence of Coherent Omnipresent Fluctuations in the Ionosphere (COFIs) with periods ranging from roughly 30 to 60 minutes and apparent vertical wavelengths increasing with altitude from tens to hundreds of kilometers. Upon high-pass filtering of the Incoherent Scatter Radar power profile and electron concentration data, the COFIs are seen unambiguously and ubiquitously in Arecibo results from 22–23 March 2004, 5–6 June, 21–25 September, and 17–20 November 2005, as well as Millstone Hill results from 4 October to 4 November 2002. The COFIs are strong throughout the F region, often spanning altitudes of 160 km to above 500 km, and are detected day and night in the F2 layer. In fact, the COFIs are seen at every time and altitude that there is sufficient plasma to detect them. The COFIs are also observed at Poker Flat, although the poor signal-to-noise ratio over segments of the data makes it difficult to determine whether or not they are always present. The consistent detection of the COFIs, along with the longitudinal alignment and large latitudinal spread of the observation sites, suggests that these waves are always present over at least North America. This phenomenon appears to have been reported in Total Electron Concentration (TEC) maps of the ionosphere over much of North America Tsugawa et al. (2007b) as well as in airglow images from Arecibo and many other midlatitude sites around the world. These observations give us insight into the horizontal properties of the waves. While Medium-Scale Ionospheric Disturbances (MSTIDs) are generally associated with aurorally generated acoustic gravity waves, the properties of the COFIs may suggest otherwise. We present other possible source mechanisms, notably a possible link to oscillations in the solar wind and magnetosphere. We have observed consistent fluctuations with periods of about an hour observed in magnetic field measurements taken at geosynchronous altitudes by the Geostationary Operational Environmental Satellites (GOES)-10 and -12 satellites, which may be linked to the COFIs. We give corresponding solar wind results from ACE and discuss possible coupling mechanisms.

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1. Introduction

[2] *Livneh et al.* [2007] reported continuous quasiperiodic waves with periods of around 1 hour in the F region over Arecibo, Puerto Rico. This document extends those results to Millstone Hill, Massachusetts and Poker Flat, Alaska. This nearly "steady state" phenomenon has been observed over all of the data sets studied to date. To avoid confusion with other reported phenomena, we shall refer to the phenomenon we report in this paper as Coherent Omnipresent Waves (COFIs). The literature abounds with examples of similar but apparently transient phenomena, Traveling Ionospheric Disturbances (TIDs). TIDs are, as their name suggests, moving fluctuations in the ionosphere observed in the plasma concentration, velocity and/or temperature. While TIDs are traditionally thought to be the ionospheric traces of in situ forcing by neutral Acoustic Gravity Waves (AGWs) [e.g., *Francis*, 1975; *Hocke and Schlegel*, 1996], the properties of these COFIs suggest the possibility of a different, electrodynamic mechanism(s) for their existence. We next review the relevant AGW and non-AGW TID related literature and observations.

[3] AGWs may be generated whenever a parcel of air is vertically displaced and the buoyancy force acts to restore it to its original height. If an AGW exists at the height of the ionosphere, it perturbs the plasma via collisional coupling that varies strongly with altitude and may be observed as a TID using radio methods including Incoherent Scatter Radar (ISR). In this paper we report on TIDs observed by three ISRs, one located at Millstone Hill, Massachusetts

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(42.6°N, 71.5°W); another at Arecibo, Puerto Rico (18.3°N, 66.8°W); and the third at Poker Flat, Alaska (65.1°N, 147.4°W).

[4] TIDs may be caused by AGWs arising from a variety of sources including wind flow over mountains, convection, and tropospheric weather systems. AGWs/TIDs also originate in the high-latitude thermosphere from Joule heating and Lorentz force inputs caused by auroral processes [e.g., *Hocke and Schlegel*, 1996], and can propagate to midlatitudes by traveling horizontally through the thermosphere or by bouncing obliquely between the earth's surface and the temperature gradient in the lower thermosphere. The mode of propagation affects the distance to which an AGW can propagate [*Mayr et al.*, 1990]. TIDs are generally sorted into three categories: large, medium, and small scale depending on their periods and wavelengths. Medium- and large-scale TIDs are also divided by whether their horizontal speeds are larger or small than the lower atmospheric sound speed of roughly 300 m/s. The slowest of the groups, the medium-scale traveling ionospheric disturbances (MSTIDs) have horizontal speeds of 100 and 250 m/s, while large-scale TIDs have speeds of between 400 and 1000 m/sec. Further information on AGWs/TIDs may be found in the reviews by *Hocke and Schlegel* [1996], *Hunsucker* [1982], and *Francis* [1975] and the references contained therein. For a more extensive review of the AGW-related TID background pertinent to this paper, see the study by *Livneh et al.* [2007].

[5] In the past, very accurate measurements of electron concentration were made at Arecibo Observatory, Puerto Rico, by applying the coded long-pulse (CLP) radar technique [*Sulzer*, 1986] to the "plasma line" signal enhanced by daytime photoelectrons (PEPL) [*Djuth et al.*, 1994]. In the lower thermosphere above Arecibo, background neutral waves couple to the ionospheric plasma, typically yielding a plus/minus 3–10% electron concentration fluctuation spectrum of waves [*Djuth et al.*, 1997, 2004]. However, more recent observations indicate that electron concentration perturbations as large as 15% can occur. The detailed study of *Djuth et al.* [1997] showed that the observed wavelengths were generally consistent with the simplified AGW theory of *Hines* [1964]. Large-amplitude waves were always unquenched by kinematic viscosity. However, there were some small-amplitude waves in the quenching zone. *Hines* [1974] noticed similar features in sodium vapor trail observations and offered a more detailed explanation in his postscript to the paper by *Hines* [1964]. Calculations presented by *Vadas and Fritts* [2006] resolve this issue entirely by taking into account the growth of the vertical wavelength above the altitude where dissipation starts to affect the AGW. The corresponding phase velocities of the observed electron density perturbation at Arecibo are always directed downward with increasing time, and hence energy flows upward. At altitudes above ~170 km, the vertical half wavelength quickly becomes very large exceeding 100 km at altitudes above 300 km altitude. Using Arecibo ISR power profile observations, *Livneh et al.* [2007] found that these quasiperiodic waves were consistently present over the full extent of the Arecibo F region for two ~ 35-hour observational periods; 22–23 March 2004 and 5–6 June 2005. These waves had quasi-periods of ~1 hour and had apparent vertical wavelengths increasing with altitude from tens to greater than one hundred kilometers. The present study focuses on further observations of these waves at Arecibo, Millstone, and Poker Flat.

[6] Beginning in November 2004, more extensive PEPL observations were conducted at Arecibo. These measurements reveal a wide spectrum of apparently AGW-related ionospheric plasma perturbations that confirm that the wave phase is directed downward from the highest altitudes (~450–500 km) measurable with the PEPL technique down to the lowest altitudes near 115 km. The altitude coverage of the observations is determined primarily by radar peak power, although other factors related to electron Landau damping at the highest altitudes and electron neutral collisions at the lowest altitudes also play key roles. Filtered ion-line power profile measurements presented in Figure 1 and those displayed in the study by *Livneh et al.* [2007] show similar downward phase progression as indicated the by narrow tilted/curved regions of enhanced and depleted ion-line power. While the PEPL observations are very accurate, the power profile results given here have the singular advantage that they are available day and night while the PEPL approach works only in the daylight hours.

[7] Information regarding the horizontal characteristics of the COFIs comes from two sources. The first is airglow imager results taken by the Penn State All-Sky Imager at Arecibo (PSASI). While the link between the COFIs discussed here and the moving depletions seen in the imager is confined only to optically suitable nighttime hours they provide our only concurrent horizontal glimpse of the phenomenon. Using PSASI, *Seker et al.* [2008] give these COFIs as observed on 22–23 March 2004 at Arecibo tentative a horizontal wavelength of ~150 km, and horizontal phase velocities of ~150 km/hour to the southwest. *Garcia et al.* [2000] also observed MSTIDs in airglow images from Arecibo and give speeds of 50 to 170 m/s and horizontal wavelengths of 50 to 500 km. Similar structures have often been observed in airglow imagers over Brazil [*Pimenta et al.*, 2008], Japan [e.g., *Taylor et al.*, 1998; *Shiokawa et al.*, 2006], and over Japan and at its geomagnetic conjugate point in Australia [*Otsuka et al.*, 2004]. Another likely observation of the phenomenon is the GPS-TEC results of *Tsugawa et al.* [2007b] where TIDs with horizontal wavelengths ranging from 300–1000 km were observed over North America.

[8] Although TIDs are traditionally thought to be plasma traces of AGWs, the plasma decouples from the neutral atmosphere above ~130 km [e.g., *Sangalli et al.*, 2009; Figure 5]. Also, AGWs of the dimensions needed to produce the observed TIDs dissipate at heights of around ~200 km [*Livneh et al.*, 2007; *Vadas*, 2007]. However, we observe TID "waves" extending coherently to heights of ~750 km. We note that as the ionospheric plasma decouples from neutral atmospheric collisional forcing, it becomes electrodynamically incompressible for parallel to **B** motions. This causes all parallel to **B** motions along a given field line to be proportional to the net integrated parallel to **B** forces along that line, and not in general to any local forces.

[9] Hence we must consider an alternative explanation for the CQPOW origin, namely that they are caused by fluctuations in the solar wind and magnetosphere. *Dyrud et al.*

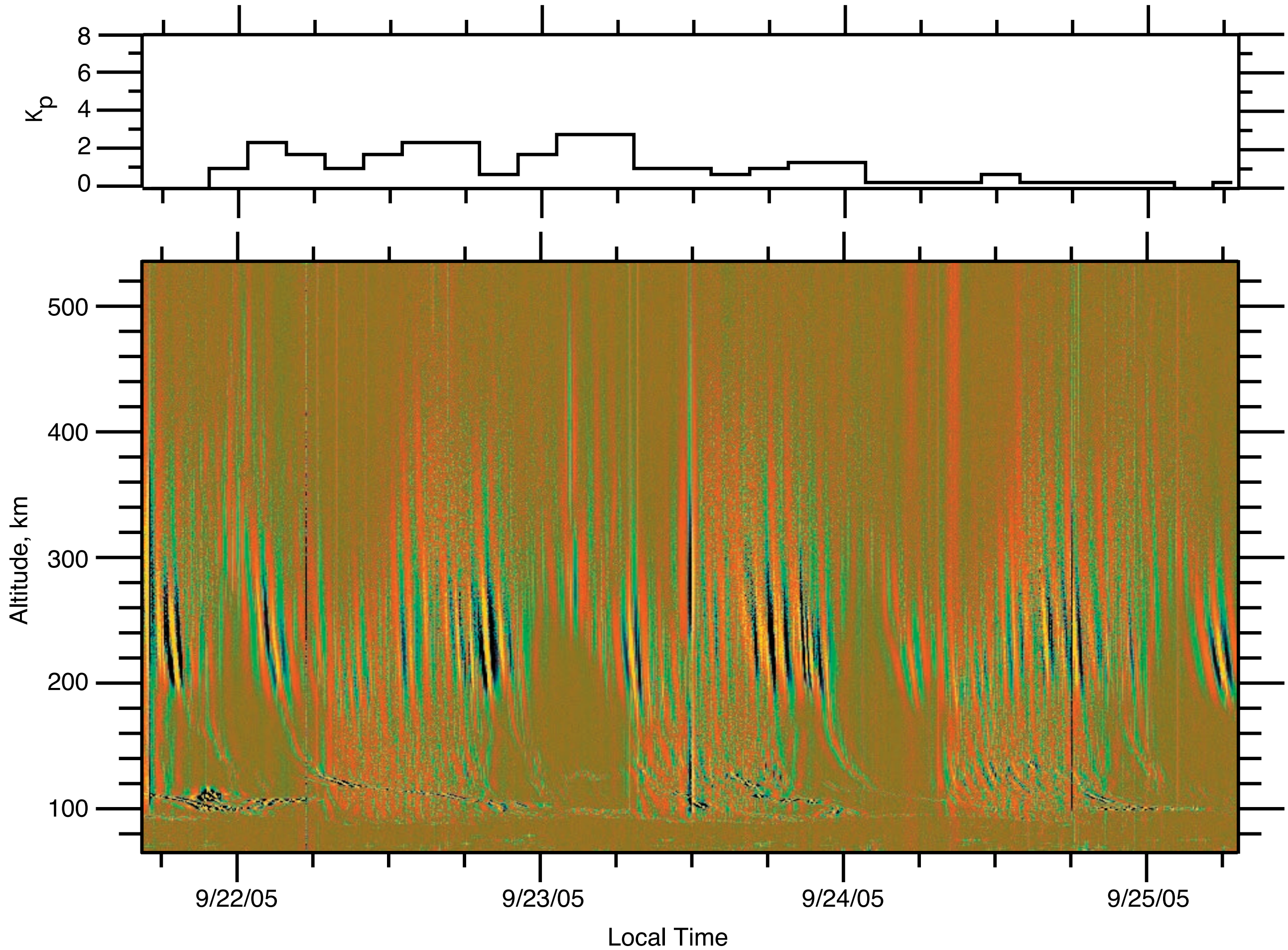

Figure 1. High-pass filtered power profile data from Arecibo Radio Observatory in Puerto Rico with the geomagnetic index, K_p shown above. The COFIs are clearly visible as the near vertical "stripes" everywhere that there is sufficient signal-to-noise ratio to observe them. Notice how the waves appear very clearly when one views their vertical profiles here as opposed to simply a time series taken at 300 km as shown in Figure 5.

[2008] observed the effects of solar wind oscillations in the ionosphere over Arecibo. They observed 0.1% variations at a frequency of 1.7 mHz (~10-minute period) in the Arecibo plasma frequency at the F region peak. They link this to the commonly observed solar wind fluctuations of similar frequency [e.g., *Kepko and Spence*, 2003]. We have observed consistent oscillations of 0.5- to 1-hour period (similar to that of the COFIs we observe) in the magnetosphere, specifically in magnetic field measurements taken at geosynchronous orbit by the GOES-10 and -12. It is possible that these fluctuations couple into the ionosphere to create the observed MSTIDs in a manner akin to those with 10-minute periods reported by *Dyrud et al.* [2008]. We postulate that these ~2% $\Delta\mathbf{B}/\mathbf{B}$ fluctuations, as an alternative source for the observed COFIs. Further evidence of solar wind effects on the ionosphere was reported by *Kelley et al.* [2003] and *Huang et al.* [2007] who found that oscillations in the Interplanetary Electric Field (IEF) caused morphologically similar variations in the electric field of the equatorial ionosphere. The possibility of the solar wind and magnetospheric origin of these COFIs is addressed more thoroughly in the discussion section.

2. Signal Processing

[10] Four multiday ISR power profile data sets from Arecibo Observatory, a 32-day period of electron concentration profiles from Millstone Hill Observatory's ISR, and a 5 day period of electron concentration profiles from the Poker Flat ISR (PFISR) were inspected for evidence of COFIs. The Arecibo and Millstone data sets used a fixed vertical beam, while the PFISR beam was pointed parallel to B. The first two data sets from Arecibo are discussed extensively in the study by *Livneh et al.* [2007] and each consists of roughly 35 hours of power profiles taken from 22–23 March 2004 and 5–6 June 2005. The other two Arecibo data sets are somewhat longer than these two, with the first of these consisting of 3.65 days of power profile observations with an inter-pulse period (IPP) of 10 milliseconds, beginning at 1623 on 21 September 2005 and

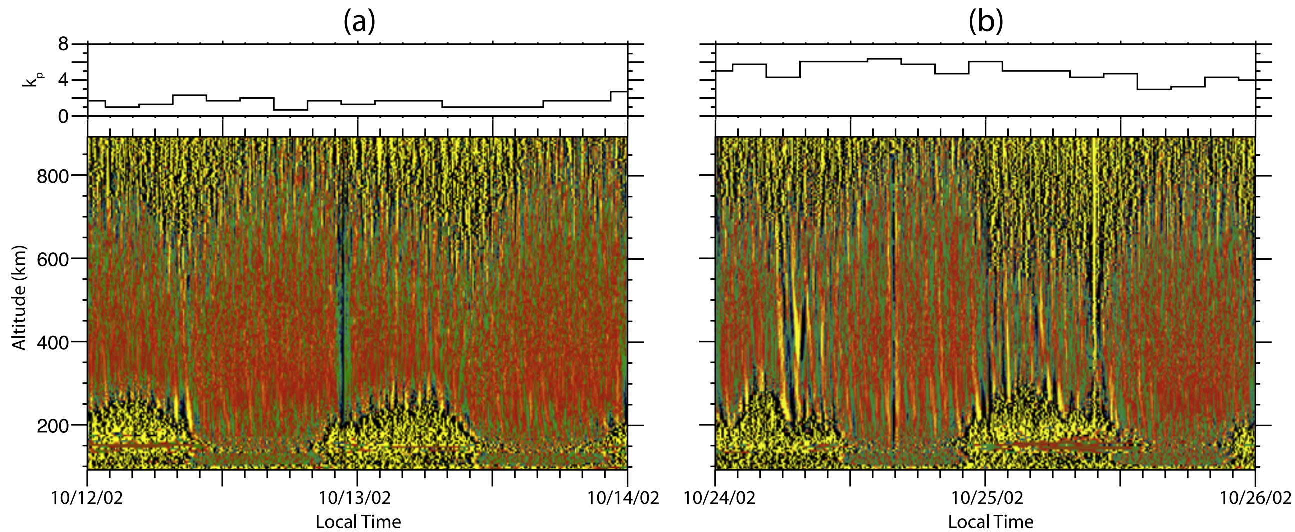

Figure 2. (a) Millstone Hill observations at low K_p. Figure 2a shows high-pass filtered electron concentration data from Millstone Hill Observatory in Massachusetts, along with K_p shown above. The COFIs are clearly visible as the near vertical stripes but are not as stark as those seen in Figure 1 at Arecibo because they have smaller amplitude and the actual data have lower signal-to-noise ratio, sampling rate, and altitude resolution than that in Figure 1. (b) Millstone Hill observations at high K_p. The waves appear stronger than at low K_p, suggesting that the phenomenon is positively correlated with high geomagnetic activity. The stripes (COFIs) in the Millstone observations as seen in Figure 2b as well as in Figure 2a are more vertical than those at Arecibo (Figure 1), meaning that the waves have a larger vertical wavelength here. This is to be expected as the geomagnetic field is more vertical at Millstone than Arecibo.

ending at 0800 on 25 September 2005. The second Arecibo data set was identical to the first except that it only spanned 2.65 days, from 1213 AST on 17 November 2005 and ending at 0346 on 20 November 2005. All times are the local Atlantic Standard Time (AST). Both of these data sets had altitude ranges of 59 to 530 km with an altitude resolution of 0.3 km.

[11] The Millstone Hill data set was obtained from the Madrigal database and spanned the 32 days from 4 October to 4 November 2002 as discussed in the study by *Zhang et al.* [2005]. It is composed of electron concentration profiles spanning an altitude range of 92 to 888 km, with a resolution of roughly 4.5 km. The inter-pulse period (IPP) of this data varied according to mode. As is evident in Figures 2a and 2b, the resolution of the Arecibo data sets far exceeds that of the Millstone results. For consistency, the Millstone data was resampled using linear interpolation to match the altitude and time sampling intervals of the Arecibo data. Two data sets were obtained from the Poker Flat Incoherent Scatter Radar (PFISR). The first spanned from the evening of 28 June to the morning of 3 July 2007, with a sampling period of 5 minutes.

[12] To see the COFIs more clearly, the data was subjected to several stages of processing. A detailed account of all of the processing performed to highlight the waves is given in the study by *Livneh et al.* [2007], along with a rigorous substantiation of the validity of the results. Essentially, the COFIs were ''extracted'' from the data by removing the effects of the diurnal variations in the background ionosphere. The major wave extracting operation was high-pass filtering with pass- and stop-band edge periods of 1 and 2 hours respectively. This same procedure was performed on all of the Arecibo data sets. The procedure was also performed on the Poker and Millstone Hill data with the omission of interference/meteor removal. Also, since it was already in electron concentration, the Millstone/Poker data did not require conversion to signal power expressed in Kelvins. Although the Arecibo and Millstone/Poker data are in different forms: signal temperature and electron concentration respectively, the same wave extraction routines were applied to both. This is reasonable because signal temperature is proportional to electron concentration at each range [*Mathews*, 1986] although the so-called range squared ''correction'' is not applied to the Arecibo data. The only new step applied to the non-Arecibo results was a linear interpolation and resampling to simulate the altitude and time sampling intervals of the Arecibo data as stated above. The satellite observations underwent the same processing as a single constant altitude strip of the ISR data: they were resampled and high-pass filtered using the same algorithm that was used for the radar data.

3. Observations

[13] Vertically coherent quasiperiodic waves with periods of 30 to 60 minutes were continuously seen throughout the processed results from both Arecibo and Millstone Hill. Similar structures were seen in the PFISR results wherever an adequate signal-to-noise ratio was available. Because of space constraints, only a portion of the results is shown in this paper; please contact the author for the remaining images. For the high-resolution 22 March 2004 and 5 June

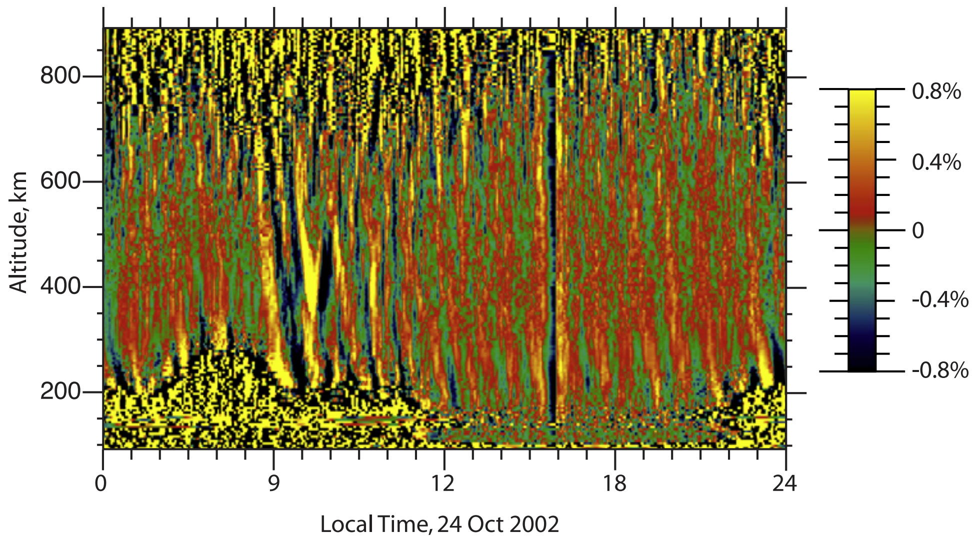

Figure 3. This plot shows the percentage deviations in electron concentration caused by the COFIs relative to the total background electron concentration as observed by the Millstone Hill ISR. These observations were taken on 24 October 2002, a relatively geomagnetically active day, and the deviations are roughly ±0.6%. For less active days, the percentage deviations tend to be roughly half this amplitude.

2005 Arecibo results, please see Figures 2 and 3 of *Livneh et al.* [2007] and *Seker et al.* [2008].

3.1. Arecibo Observations

[14] Figure 1 shows processed Arecibo ISR results from 21–25 September 2005, along with the geomagnetic index, Kp for the same period. COFIs are clearly seen throughout the image wherever there is sufficient plasma to reveal them. This result echoes those found at Arecibo by *Livneh et al.* [2007] for 22–23 March 2004 and 5–6 June 2005. Processed results from the other data set mentioned above, that from 17–20 November 2005 also display a similar outcome. All of these periods are geomagnetically quiet, that is, their geomagnetic index, Kp is small (generally below 2.5). COFIs were also observed at Arecibo via an airglow imaging camera. For further discussion relating the Arecibo airglow imager observations to the COFIs observed with the ISR, please see the study by *Livneh et al.* [2007] and *Seker et al.* [2008]. Notice the increase of apparent vertical wavelength with height that is usually taken as being characteristic of thermospheric AGWs. It is also apparent from this figure that the shorter period (~30 minutes) oscillations are confined to the lower F region with only the longer period (greater than 50 minutes) seen above the F region peak near 300 km. A constant altitude strip taken from the F region peak at Arecibo indicates that the COFIs cause a ±5% deviation there. As we shall see, this is about 10 times stronger than the COFIs observed at Millstone Hill.

3.2. Millstone Observations

[15] The Millstone Hill (dip angle of ~70°) results are taken from a 31-day observational run from 4 October to 4 November 2002. The electron concentration results were processed in the manner discussed in the previous section. Two 2-day segments of the processed results are shown in Figures 2a and 2b. The remainder of the Millstone Hill results are not shown here because of space constraints. Figure 2a shows a 2-day period of COFIs with low geomagnetic index, while the Figure 2b results are taken from a period where Kp is higher. Notice that the COFIs are seen in both images, albeit with greater apparent intensity during the period of elevated Kp. The Millstone results are similar to the AO results but have a larger apparent vertical wavelength at low altitudes than seen at Arecibo. The fact that the dip angle at Millstone is ~70° while ~45° at Arecibo may be significant to this result and is discussed later. The COFIs are also weaker at Millstone Hill. At the F region peak, they only cause variations of ±0.3% in the electron concentration at low K_p and ±0.6% for the more geomagnetically active observations. Figure 3 shows the percentage deviation of electron concentration relative to the background caused by the COFIs for 24 October 2002. A similar plot from Arecibo is shown in Figure 3 of *Livneh et al.* [2007].

3.3. Poker Flat Observations

[16] Poker Flat is located at a high latitude so it gets substantial sun exposure only in the summer months. This means that summer is the ideal time to search for the COFIs as the F region of the ionosphere will be continuously present. Data sets obtained from near the summer solstice showed consistent wave activity, albeit with a lower signal-to-noise ratio than at Arecibo and Millstone. Figure 4 shows filtered Poker Flat ISR results looking parallel to the geomagnetic field for 28 June to 3 July 2007. The magnetic dip angle at Poker Flat is 78° so the beam was pointing 12° south of zenith to point parallel to **B**. Notice that the TIDs are visible as the near vertical lines in the lower F region. Here the TIDs appear to have a larger vertical wavelength than those observed at Arecibo and Millstone Hill and are much weaker. It is difficult to discern the percentage level of electron concentration fluctuation for the COFIs at PFISR as

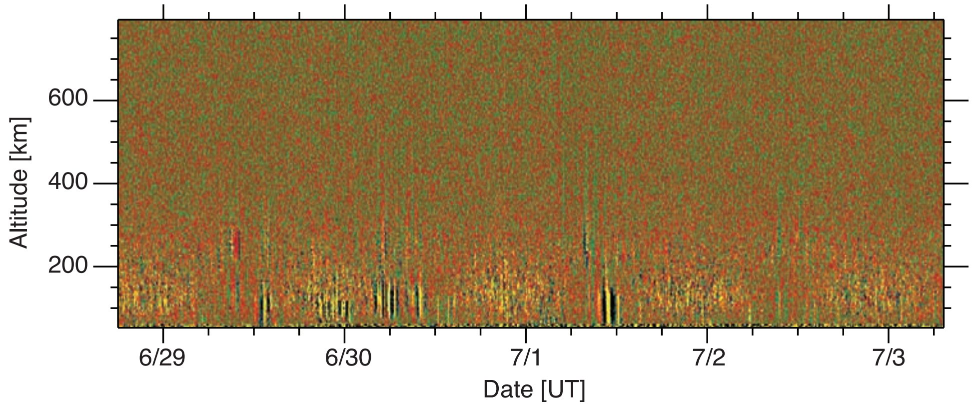

Figure 4. A 4-day summer period of high-pass filtered electron concentration data from Poker Flat ISR in Alaska. Here the waves appear to be much weaker than at Arecibo and Millstone.

they are similar to the noise level but it is certainly significantly smaller than at Millstone Hill.

3.4. Satellite Observations

[17] In the search for possible sources of the observed COFIs we examined data from the magnetometers aboard the GOES 10 and 12 satellites positioned over the geographic equator at geosynchronous orbit and at 135° and 75°W longitude, respectively. GOES-12 is longitudinally close to Arecibo Observatory which is at 66.8°W. Total magnetic field magnitude results taken at geosynchronous orbit by these satellites exhibit nearly continuous fluctuations with periods very similar to those of the COFIs observed by the ISRs (~30 to 60 minutes). Figures 5a and 5b shows these fluctuations along with data from the Arecibo ISR and solar wind results from the Advanced Composition Explorer (ACE) satellite, which orbits an Earth-Sun gravitational balance point 1.5 million km toward the sun (the L1 point). The fluctuations observed by the GOES-10 and -12 satellites may be linked to the observed COFIs as explained in the discussion section. Note that the 10% fluctuation level relative to the median of the background of the measurement is indicated for each of the data sets.

[18] The ACE satellite measures the solar wind (SW) parameters at the L1 point including the Interplanetary Magnetic Field (IMF), the solar wind number density and the SW velocity. It has been shown that variations in the pressure of the solar wind cause the magnetopause to vary in location thereby creating fluctuations in the B field in the magnetosphere [*Kepko and Spence*, 2003]. Thus we examined the SW pressure (half of the density times the square of the velocity) and the B_z component of the IMF for those periods for which we have Arecibo ISR data. While periods of <2 hours were routinely present in both data sets, a strong correlation could not be found with the COFIs observed with the ISRs. However, since the solar wind must first couple to the magnetosphere before being transmitted into the ionosphere, a strong numerical correlation with the ISR data is perhaps not to be expected.

[19] Ion drift data from the Defense Meteorological Satellite Program (DMSP) satellites was examined for evidence of the COFIs. The DMSP satellites orbit the earth at a height of ~840 km and are equipped with ion drift meters. While COFIs appear to exist at heights approaching 840 km in the ISR results, coherent wave activity could not be detected at cross-orbit speeds greater than the instrument's quantization level. This does not mean that the wave-associated drift does not exist, only that it is not strong enough to be detected by the DMSP drift meters that are more often used to study the large drifts caused by auroral activity.

4. Discussion

[20] Spatially coherent COFIs with quasi-periods of 30 minutes to over 60 minutes and apparent vertical wavelengths increasing with altitude from 10s to 100s of kilometers were observed ubiquitously at all locations, albeit with greater amplitudes at lower latitudes. While the periods of the observed TIDs vary over ~30–60 minutes, the vertical coherence of the structures is strong proof of their physical validity. In fact, as seen in Figure 5, a constant altitude strip of the processed Arecibo data from 22 September 2005 does not appear to be cleanly quasiperiodic. It is only the vertical coherence of the COFIs, as seen in the Altitude-Time-Intensity plots of Figures 1 through 4 that clearly distinguishes the COFIs from mere random fluctuations.

[21] The presence of the COFIs appears to be unaffected by seasonal and geomagnetic variations. Figure 2 showed that COFIs were seen ubiquitously at Millstone for both high and low K_p. With our current database, we cannot determine whether this is the case at Arecibo, as all of our observations are from periods of low to moderate K_p. We have observed the COFIs in data sets from all 4 seasons at Arecibo.

[22] The COFIs may have been observed by other instruments, thereby giving us a glimpse of their horizontal properties. Observations of traveling ionospheric airglow depletions at Arecibo were reported by *Seker et al.* [2008]. More recent work by *Seker et al.* found these waves for the majority of their clear sky observations. For a three year data set, an All-Sky Imager at AO revealed that the MSTIDs were present ~75% (123 out of 167 nights) of the time for the clear sky, moon down, and low Kp (<4) conditions. One such observation was concurrent with our 22–24 March 2004 COFIs observation from Arecibo and gives a horizon-

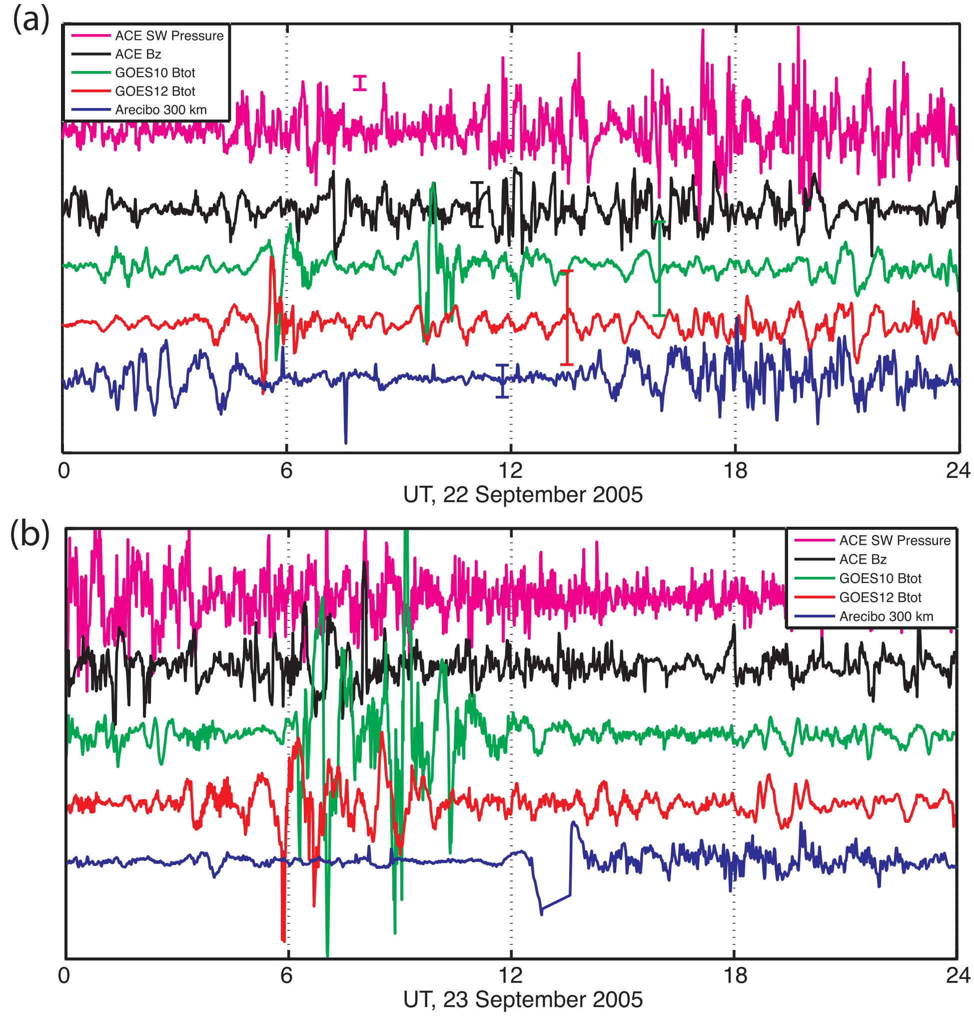

Figure 5. Concurrent observations of (top to bottom) the solar wind pressure (ACE), the solar wind vertical magnetic field, Bz (ACE), the total B field at geosynchronous orbit at the equator with longitudes of 135°W (GOES-10) and 75°W (GOES-12), and signal temperature at 300 km altitude at Arecibo Radio Observatory for (a, b) 2 days. Notice the strong periodicity of the GOES results. The constant altitude strip of Arecibo data here appears somewhat chaotic and semiperiodic. It is only once the vertical properties of the ionosphere data are seen as in Figure 1 that the coherence of the COFIs becomes clear. The "I" bars on the figure show the amplitude of a nominal 10% fluctuation for each of the measurements of like color.

tal wavelength close to 200km with a velocity of 150–250 km/hr. *Mendillo et al.* [1997] and *Garcia et al.* [2000] also reported such MSTIDs over Arecibo. MSTIDs with similar properties were also frequently observed by All-Sky Imagers at other locations such as El Leoncito, Argentina by *Martinis et al.* [2006], and at conjugate points in Japan and Australia by *Shiokawa et al.* [2005] during the FRONT3 campaign, during which the MSTIDs were observed for almost all clear-sky nights.

[23] An interesting result comes from the southern hemisphere airglow imager observations taken at Cachoeira Paulista, Brazil (22.7°S, 45°W, magnetic declination 20°W) by *Pimenta et al.* [2008]. They saw MSTID bands which they called Dark Band Structures (DBS) with wavefronts aligned northeast to southwest and propagating toward the northwest. This orientation and propagation direction present a mirror image through the equator of MSTIDs observed by airglow imagers in the northern hemisphere. These have wavefronts aligned northwest to southeast and travel in a southwest direction. The *Pimenta et al.* [2008] results imply that the MSTIDs are mapped along geomagnetic field lines between the northern and southern hemisphere, that is, an ionospheric fluctuation in one hemisphere is mapped electrodynamically to its geomagnetic conjugate point in the opposite hemisphere. The implication is that whenever we observe the waves in the northern hemisphere, they must be present at the conjugate points in the southern hemisphere.

[24] *Tsugawa et al.* [2007a] observed very similar MSTID bands coincidentally with both the TEC maps over Japan and an All-Sky Imager; and reported that the MSTIDs were present 85% of the time. Similar waves were reported by *Tsugawa et al.* [2007b] using many GPS receivers to create a TEC map for North America. They reported seeing

MSTIDs in both daytime and nighttime observations using this technique. An interesting outcome of the observations made by Tsugawa et al. is that the MSTIDs appeared to increase in amplitude at lower latitude rather than decrease; a strange result if the COFIs have auroral origins as is commonly assumed. Another important note is that they found that the propagation direction of the MSTIDs over North America changed from southeastward in the daytime to southwestward in the nighttime with MSTIDs in the two propagation directions superimposed on each other in the late afternoon.

[25] As the nature and source of the COFIs is unknown, we will now examine the three most likely explanations. The first is the traditional explanation for MSTIDs, that they are caused by acoustic gravity waves (AGWs) in the auroral zone. The second is that they are due to AGWs that are generated locally. Lastly, we present a completely non-AGW explanation; that the COFIs are caused by electrodynamic coupling of magnetic field oscillations observed in the magnetosphere most likely caused by solar wind processes to the ionosphere.

4.1. Aurorally Generated Acoustic Gravity Waves

[26] The traditional explanation for MSTIDs of this type is that they are passive plasma imprints of aurorally generated acoustic gravity waves created in the high-latitude thermosphere through Joule heating and the Lorentz force [e.g., *Francis*, 1975; *Hocke and Schlegel*, 1996]. *Bristow and Greenwald* [1996] and *Bristow et al.* [1994, 1996] have repeatedly found AGWs and AGW sources present in the high-latitude ionosphere. A comparison of our observations with two AGW dispersion relationships was shown in Figure 10 of our first paper on the subject [*Livneh et al.*, 2007]. The observed vertical wavelength of the COFIs differed strongly from that calculated for the ideal, lossless case [e.g., *Hines*, 1965] but resembled the vertical wavelength calculated by using the AGW model of *Vadas* [2007] that takes dissipative effects into account. It is important to note that above ~200 km, parallel to **B** plasma motions are due to the total integrated forcing along a field line and therefore we cannot observe an AGW locally. *Djuth et al.* [2004] found that their wave observations over Arecibo were consistent with the AGW dispersion relationship. Modeling results [e.g., *Kirchengast et al.*, 1996] also show strong agreement between this scenario and TIDs observed by the EISCAT radar, features which are morphologically similar to the COFIs we observe.

[27] However, for the COFIs we observe to be due to aurorally generated thermospheric AGWs, the AGWs must travel from the auroral zone to Arecibo. There is considerable uncertainty over whether or not this is possible. *Vadas* [2007] suggests that gravity waves with the observed parameters will dissipate less than 1000 km from their source. In contrast, *Mayr et al.* [1990] have shown that gravity waves could propagate large distances in either of two modes. According to *Mayr et al.* [1990] waves might propagate horizontally through the thermosphere, being ducted by the temperature gradient in the mesopause region, or they may propagate in the ducted earth-reflected mode, leaking into the upper atmosphere. Regardless of whether AGWs can survive travel over >5000 km, a fact that disputes the aurorally generated AGW hypothesis is our finding, echoed by the TEC results of *Tsugawa et al.* [2007a] that the wave amplitude appears to increase with decreasing latitude. For the auroral AGW theory to be valid, the AGWs may have to grow in amplitude as they propagate away from their source. This does not seem likely.

[28] The ISR results show consistent evidence of these quasiperiodic COFIs, but auroral activity is much more sporadic. So for the aurora to be the source of the phenomenon, the COFIs would have to be band-pass filtered by a "tuned" thermosphere-ionosphere system. This has been successfully modeled by *Millward* [1994] using the Sheffield/UCL coupled ionosphere-thermosphere model. They found that temporally random auroral bursts launched AGWs with preferred periods "strongly biased toward 40–50 minutes", a result that fits very well with our observations. So while the consistency of the COFIs may not favor an auroral origin, it needn't preclude it either.

[29] AGWs of the periods and horizontal wavelengths of the COFIs we report dissipate at heights of ~200 km [e.g., *Vadas*, 2007], while we observe these COFIs up to ~750 km in the ISR data. It is therefore unlikely that wave observations at heights greater than 200 km are due to in situ passive plasma tracing of AGWs, even if the COFIs are indeed caused by AGWs. Rather, there must be some purely electrodynamic effects moving the plasma at heights greater than 200 km. A possible scenario is that the AGW-induced periodic plasma motions in the lower F region push the higher plasma up and down the geomagnetic field lines. At these heights, plasma motion becomes incompressible along the geomagnetic field lines [*Kelley*, 1989]. Thus what we observe above 200 km is the motion of the plasma along the field lines and not direct tracing of AGWs while below ~200 km we progressively see the AGWs more directly. It is important to note that large-scale traveling ionospheric disturbances can easily travel from the auroral zone to Arecibo, but these are sporadic events which are clearly not the same phenomenon as the COFIs.

4.2. Locally Generated AGWs

[30] As there is uncertainty as to whether the COFIs are due to aurorally generated AGWs, two other possibilities suggest themselves: non-auroral AGWs and a completely non-AGW hypothesis. Since the Arecibo observations are the most compelling we must locate a source near Puerto Rico. *Thome and Rao* [1969] performed ray tracing calculations and estimated that the local source of the Arecibo AGWs was at a ground distance of ~550 km. This calculation assumed that the source was at tropospheric altitudes. AGWs can be locally generated by the passage of tropospheric storms [e.g., *Boska and Sauli*, 2001; *Sauli*, 2001]. Given the size of the current database, it is difficult to argue that tropospheric storms are always present at just the right range (e.g., 500–600 km) to account for all observations. A typical observation period is 48 hours, so a storm would have to be active day and night for a relatively long period of time. It is possible that trade winds flowing over orographic features on a Leeward Island (e.g., Barbuda) could give rise to the necessary AGWs. Barbuda is in the correct location to generate AGWs above Arecibo, but the tallest feature on this island is in the highlands, and it is only 42 meters above sea level. If Trade Winds blowing across the highland region of Barbuda are hypothesized as

the AGW source, then there should be major seasonal variations in the thermospheric waves seen at Arecibo. The Trade Winds in this region change direction depending on the month of the year. During the months April through June the average Trade Winds at Barbuda are in the direction of Arecibo, whereas during the months July through March they are not. In fact, during the period November through February, one would not expect to see any such AGWs above Arecibo, yet we have several observations of thermospheric waves during this time period.

[31] *Maximenko et al.* [2008] show that small (∼2 cm in height) stationary striations separated by ∼400 km are present in most regions of the world's oceans. The ocean surrounding Puerto Rico from the northeast to the southwest contains these jet-like features at the appropriate distance for AGW generation. The striations are located in a large region that would allow Trade Winds to blow across them year-round in the direction of Puerto Rico. Model calculations are required to determine whether the speed of the Trade Winds (5–7 m/s in regions of interest) are large enough to initiate AGW propagation into the Arecibo thermosphere.

[32] Large tsunamis (50–60 cm amplitude on open water, 300–400 km in wavelength) such as the Sumatra tsunami of 26 December 2004 produce internal gravity waves in the neutral atmosphere that give rise to very large disturbances in the overlying ionosphere [*Occhipinti et al.*, 2006]. However, even very small tsunamis (1–2 cm amplitude on open water) generate significant TIDs readily observable with a Global Positioning Satellite (GPS) network [*Lognonne et al.*, 2006a, 2006b]. Of course, the sensitivity of the Arecibo ISR system is much greater than GPS, so the existence of such waves above Arecibo would readily be detected. Natural infragravity ocean waves traveling over deep (4 km) water and having periods of ∼5–6 min and amplitudes of 1–2 cm have been observed with a few broadband seismographs at the bottom of the Pacific and Atlantic Oceans. (See *Tanimoto* [2005], and the references therein.) In the ocean north of Puerto Rico (depths of 5–6 km) these waves would have wavelengths of the order of 66–72 km and propagate in a nearly lossless manner. Ocean waves with periods greater than 6 min and therefore longer wavelengths cannot be detected with the deep-water seismographs because of the dominant contribution of the atmosphere at these periods. Thus the presence of small-amplitude infragravity waves having wavelengths of the order of 100–200 km has yet to be explored. Such waves would refract off the Puerto Rico trench (8,648 m in depth) northeast of Arecibo and potentially give rise to other ocean waves/structures that could either generate AGWs directly or interact with the Trade Winds to produce the observed thermospheric waves. We are in the process of examining the ocean surface within 500–600 km of Arecibo with the aid of satellite altimetry to determine whether the ocean is a viable source of the waves.

[33] This hypothesis has the advantage of fitting well with the Arecibo ISR observations. However, it does not explain why we also observed the COFIs at Millstone, nor why the COFIs are likely observed worldwide: over all of North America by *Tsugawa et al.* [2007b], over Japan [e.g., *Oliver et al.*, 1997; *Taylor et al.*, 1998; *Shiokawa et al.*, 2006], and over Australia [*Otsuka et al.*, 2004]. Still, it is possible that the COFIs are indeed locally generated at all of these locations or that we are observing something different at Arecibo than elsewhere and thus this hypothesis is a strong one.

4.3. Non-AGW Hypothesis

[34] As discussed above, the AGW based explanation for these COFIs is certainly possible but suffers from some difficulties. An alternative explanation is that the COFIs are caused by oscillations in the solar wind that couple to the ionosphere via the magnetosphere. The link between ULF fluctuations in the solar wind and those in the magnetosphere has been established [e.g., *Kepko and Spence*, 2003] convincingly showed that variations in the solar wind pressure forced the magnetopause to move thereby compressing and expanding the magnetosphere and causing similar (in time and frequency) variations in the earth's magnetic field. They found this to be true for the often observed frequencies of 1.3, 1.9, 2.6 and 3.4 mHz. More importantly for the COFIs we observe, they found significant SW-magnetosphere coupling at frequencies below 1 mHz, namely at 0.1, 0.2, and 0.56 mHz which translate into periods of 167, 83, and 31 minutes, respectively. These frequencies are similar to those of the coherent COFIs we observed with the radars and suggest that at least the solar wind and magnetosphere are coupled at the relevant frequencies.

[35] We have examined solar wind pressure and Bz results from the ACE satellite for those periods where we have Arecibo ISR data. Figures 5a and 5b show high-passed ACE data plotted along with concurrent data from GOES and Arecibo. Both the solar wind pressure and the Bz time series show significant periodicity at the 30- to 60-minute period range, although the pressures seem to contain significantly more high-frequency variability as well. However, neither of the solar wind parameters (i.e., Bz and pressure) have the consistent periodicity that is seen in the total magnetic field measurements at geosynchronous orbit seen at both GOES satellites. We therefore conclude that there must be some "filtering" or "tuning" mechanism that favors the 30- to 60-minute periods as solar wind energy couples to the magnetosphere.

[36] In searching for possible magnetospheric links to the COFIs, we processed GOES 10 and 12 magnetometer data for the periods for which we have ISR observations from Arecibo. We have found quasi-continuous ∼45-minute period fluctuations in the total magnetic field measurements at geosynchronous orbit. Figures 5a and 5b show concurrent high-pass filtered observations of the solar wind pressure and Bz from ACE, the geomagnetic field at geosynchronous altitude from GOES-10 and -12, and incoherent scatter power (proportional to electron concentration) at 300 km at Arecibo. Notice the consistency of the fluctuations in the GOES results. In this representation, the oscillations in the GOES results are even more consistent than those from Arecibo. In fact, the COFIs are only totally apparent in the Arecibo data when the data is displayed as signal power as a function of altitude and time as in Figure 1. We next examine the evidence for a link between the oscillations in the magnetosphere (GOES) and those in the ionosphere (ISR, imager, and TEC observations).

[37] *Villante et al.* [2003] examined ground magnetometer data at L'Aquila (AQ, Central Italy, corrected geomagnetic latitude 36.2°N) for the same time interval for which *Kepko et al.* [2002] had shown a link between fluctuations in the solar wind and the magnetosphere. They found that the H component of the geomagnetic field as observed at AQ showed variations matching those in the SW pressure and to the magnetospheric magnetic field magnitude as measured by GOES-8 and -12. These variations had periods of roughly 30 minutes, similar to the COFIs we observe. This is a convincing demonstration of a SW-magnetosphere-ionosphere link at this frequency.

[38] *Dyrud et al.* [2008] obtained 204 minutes of concurrent data from the solar wind (WIND satellite), magnetosphere (GOES) and the ionosphere (Arecibo) to search for coupling of oscillations between them. For their observations, they used both the linefeed and the Gregorian beams of the Arecibo Observatory and pointed them 15° south and north of zenith, respectively to give a horizontal perspective to their observations. They found that 1.7 mHz deviations of about 1% (the COFIs we observe are fluctuations of roughly 5% in electron concentration) in the ionospheric plasma line at the F region peak observed by both Arecibo beams were concurrent with similar 1.7 mHz oscillations regularly observed in the solar wind and magnetosphere, and that these oscillations propagated from north to south at an apparent speed of 500 m/s. While the data set they used is too short (204 minutes) to properly examine (at least in the frequency domain) oscillations with the periods of the COFIs ($\sim$45 minutes), and the propagation velocity of the waves they observe is far higher than that of the COFIs, their results also provide strong evidence of coupling between oscillations in the solar wind and the peak of the Arecibo F region.

[39] Solar wind and magnetospheric activity has been found to affect the equatorial ionosphere. *Kelley et al.* [1979] showed that for a rapid change from steady southward to northward interplanetary magnetic field, the zonal equatorial electric field changes direction. During a magnetic storm, *Kelley et al.* [2003] found that fluctuations in the solar wind of periods similar to those of the COFIs were clearly observed in the E field of the equatorial ionosphere as measured using the Jicamarca Radio Observatory in Peru. They also "detected the event in other radars in the U. S. chain but not with as much clarity", implying that the solar wind penetration is stronger at the equator than at higher latitudes. This echoes the findings in the aforementioned GPS/TEC results of *Tsugawa et al.* [2007b] who reported that the amplitudes of the MSTIDs increased with decreasing latitude. While the COFIs we report are a steady state or "quiet time" phenomenon, the fact that the effects of the solar wind have been observed in the equatorial and midlatitude ionosphere suggests that the COFIs may in fact be due to solar wind-magnetosphere-ionosphere coupling. Still, it is unclear which magnetospheric process could generate the COFIs. Nor is it clear what magnetospheric process would be seen more strongly at low rather than high latitudes.

[40] While it is true that the COFIs exhibit the increase in vertical wavelength with altitude that is characteristic of AGWs in the thermosphere [e.g., *Livneh et al.*, 2007], the increasing wavelength may also be explained by gradual decoupling between the ions and the neutrals in the lower ionosphere while above $\sim$150 km the plasma motion parallel to **B** is incompressible. Absent large-scale E fields, the plasma moves strictly along the geomagnetic field lines above around 200 km altitude. Below this altitude, the effects of the neutral atmosphere are progressively more apparent on the plasma motions. Thus the periodic MSTID induced motion of the plasma is increasingly "damped", forced to move horizontally, by the surrounding neutral atmosphere as the altitude decreases into the lower F region. This may account for the apparent smaller vertical wavelength at lower altitudes. This does not, however, account for the fact that we see COFIs with periods as short as 25 minutes in the lower F region while in the upper F region, only COFIs with periods greater than 50 minutes are observed. This problem may perhaps be solved by postulating that in the lower F region and upper E region we are observing several different processes that do not extend to higher altitudes.

5. Conclusions

[41] Vertically and temporally continuous COFIs with quasi-periods of $\sim$30–60 minutes have been observed throughout ISR electron concentration (or total power surrogate) results from Arecibo, and Millstone Hill, apparently regardless of season or geomagnetic activity. Their properties suggest that they are something other than the commonly reported transient MSTIDs which are attributed to AGWs propagating from the auroral zone. While the sporadic large-scale traveling ionospheric disturbances can propagate to Arecibo, the COFIs are clearly a different phenomenon. Thus it is an open question as to whether the COFIs are due to auroral AGWs. A perhaps more hopeful hypothesis is that the COFIs are traces of AGWs generated locally. Although this hypothesis cannot account for the observation of COFIs at geographically diverse locations, it fits very well with the most spectacular COFIs results, those from Arecibo Observatory.

[42] Another possibility is that the COFIs are not imprints of AGWs at all but are instead oscillations in the ionospheric plasma that are electrodynamically coupled to consisted periodic fluctuations in the magnetospheric geomagnetic field as observed by magnetometers aboard the GOES satellites. This explanation has the advantage of a consistent, observable source but despite several papers reporting observations of magnetosphere/ionosphere wave coupling [e.g., *Kelley et al.*, 2003; *Dyrud et al.*, 2008], the physics of such a link are not well understood at this time and so this hypothesis remains a speculative one.

[43] All three of these explanations seem plausible and perhaps all are true to some extent. It is possible that the waves seen in the lower F region are caused by local AGWs while the COFIs in the upper F region are caused by the magnetospheric **B** field oscillations. The upper F region electrodynamic waves may then "connect" to the lower F region AGW imprints when the two are in phase.

[44] The fact that the COFIs are seen everywhere and at all times in ISR data from three distant locations suggests that they are always present over at least North America, a conclusion echoed by GPS-TEC results taken by *Tsugawa et al.* [2007b]. Data from other ISR locations worldwide

would be helpful in determining the geographical extent of the COFIs. Whether the COFIs are caused by either the magnetospheric fluctuations or by aurorally or oceanically excited gravity waves, a worldwide, or at least worldwide-midlatitude extent is likely. Incoherent Scatter Radar "world day" observing programs have been established to further study these COFIs.

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