Multiple Ionospheric Descending Layers Over Arecibo

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Abstract

Observations using Arecibo Observatory's highly sensitive Incoherent Scattering Radar (AO-ISR) show ionospheric descending layers from as high as $\sim 400$ km, much higher than earlier studies, with continuity down to 90 km. The AO-ISR was operated to observe the ion-line and plasma-line with coded-long-pulse for high temporal and spatial resolution of 35/10 seconds and 300 m, respectively, during 01-06 February 2019. We found multiple layering structures descending from 400 km to 90 km in all these six days. These layers are traditionally called intermediate descending layers (IDLs) ($\sim 130$ km and below F-peak), upper semi-diurnal daytime & nighttime layers (110 km-130 km), and lower diurnal layers($<110$ km). We have denoted the new daytime descending layers above the hmF2 as top-side descending layers (TDLs). All these layers are collectively named ion descending layers (IonDLs) since all of them are connected with some discontinuity at the F1-peak (i.e., 170 km), except for the daytime lower-diurnal layer. The most pronounced IonDLs occur in the twilight times. IonDLs mainly occur in shear zones of the vertical ion drifts and are favored by downward ion drifts, and their descent speeds increase with increasing altitude. The estimated phase velocities of the waves in the F-region are comparable with the descending speed of the IonDLs. Furthermore, IonDLs/IDLs occur with and without spread-F events but intensified spread-F events raise their beginning altitude. The TDLs and IDLs are driven by gravity waves with time periods of 1.5-4 hours.
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Key Points:

- We found ionospheric descending layers (IonDLs) that start near $\sim$400 km and descend down to $\sim$90 km.
- We observe traditional intermediate descending layers (IDLs) starting from $\sim$300-350 km (below $\sim$170 km) during the nighttime (daytime).
- The daytime top-side descending layers (from 400 km) and IDLs are governed by the gravity waves with periods of $\sim$1.5-4 hours.

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Abstract
Observations using Arecibo Observatory’s highly sensitive Incoherent Scattering Radar (AO-ISR) show ionospheric descending layers from as high as \( \sim 400 \) km, much higher than earlier studies, with continuity down to 90 km. The AO-ISR was operated to observe the ion-line and plasma-line with coded-long-pulse for high temporal and spatial resolution of 35/10 seconds and 300 m, respectively, during 01-06 February 2019. We found multiple layering structures descending from 400 km to 90 km in all these six days. These layers are traditionally called intermediate descending layers (IDLs) (>130 km and below F-peak), upper semi-diurnal daytime & nighttime layers (110 km-130 km), and lower diurnal layers(<110 km). We have denoted the new daytime descending layers above the hmF2 as top-side descending layers (TDLs). All these layers are collectively named ion descending layers (IonDLs) since all of them are connected with some discontinuity at the F1-peak (i.e., 170 km), except for the daytime lower-diurnal layer. The most pronounced IonDLs occur in the twilight times. IonDLs mainly occur in shear zones of the vertical ion drifts and are favored by downward ion drifts, and their descent speeds increase with increasing altitude. The estimated phase velocities of the waves in the F-region are comparable with the descending speed of the IonDLs. Furthermore, IonDLs/IDLs occur with and without spread-F events but intensified spread-F events raise their beginning altitude. The TDLs and IDLs are driven by gravity waves with time periods of 1.5-4 hours.

1 Introduction
Layering phenomena have been observed in the lower ionosphere for many decades (Christakis et al., 2009; Mathews, 1998; Whitehead, 1989; Mathews & Beken, 1979; Shen et al., 1976; Axford, 1963; Whitehead, 1961; McNicol & Gipps, 1951; Haldoupis, 2012; Earle et al., 2000; Fujitaka & Tohmatsu, 1971, 1973) globally, and in particular at Arecibo using the powerful 430 MHz incoherent scatter radar. Early power profile observations showed the remarkable complexity of so-called sporadic layers, and the development of the wind shear theory, as applied to metallic ions, has also proceeded over several decades (Axford, 1963; Whitehead, 1961; Mathews, 1998; Haldoupis, 2012; Selvaraj et al., 2017). The studies broadened to include somewhat higher altitudes, encompassing so-called intermediate descending layers (IDLs). Using recent Arecibo data, we have extended the observations to even higher altitudes, up to and beyond the F2-peak, and we have shown that gravity waves are a controlling factor at these altitudes, complementing the tidal control below and illuminating the importance of neutral atmospheric dynamics. The new observations are possible because of sufficient capabilities for data collection, storage, and computing so that the best observing techniques can be used over the full altitude range, allowing simultaneous high-resolution ion- and plasma-line profiles (Sulzer, 1986a; Djuth et al., 2004; Krall et al., 2020).

The sporadic E (Es) layers of enhanced ion density are commonly observed in the altitude range of 80-140 km using the radars, ionosonde, and sounding rocket measurements (Shen et al., 1976; McNicol & Gipps, 1951; Young et al., 1989; Whitehead, 1989). These Es layers are not ‘sporadic’ as the name implies but are frequently observed in the low and mid-latitudes (Mathews, 1998; Haldoupis, 2012). The main composition of the Es layers is metallic ions, which are deposited by meteor showers. Governing dynamics of those metallic layers were studied comprehensively using various observations and numerical simulations. In earlier times, sounding rockets, ionosonde, and Incoherent Scattering Radars (ISRs) are effectively used to explore the occurrence of multiple layers and their characteristics. For example, using the sequence of sounding rocket measurements, it is identified that the formation of ion layers at two different altitude ranges of 140 km and 110-120 km, respectively. It is also found that these layers descend with respect to time. Thus, these layers are also called descending ion layers (DILs). Later on, Fujitaka and Tohmatsu (1973) investigated the formation mechanism of the DILs by solving the
time-dependent continuity equation. They argued that the upper layer (i.e., 140 km) and lower layers (below 120 km) are formed by the semi-diurnal and diurnal tides, respectively.

Recently, using 14 years of the Arecibo Observatory’s ISR (AO-ISR) observations from 1986 to 2000, Christakis et al. (2009), comprehensively analyzed descending metallic Es (Sporadic E) layers at two different height regimes. Those two height regimes lie at ∼110(105) – 130 km and ∼80 – 110(105) km. They also found that the layers in the upper height regime are dominated by the semi-diurnal (Upper Semi-diurnal layer - US) tides that start at ∼130 km around midday (midnight), descending till ∼110 km (∼105 km) by midnight (sunrise). Furthermore, the US layer is classified into US Daytime (USD) and US Nighttime (USN) layers and temporally separated by 10-12 hours. Another height regime starts below ∼110 km, named the lower diurnal layer (Christakis et al., 2009).

To examine the physics of these (USN, USD, and lower diurnal) metallic layers in the altitude range of 80-160 km, Krall et al. (2020) used SAMI3 model (Sami3 is Also a Model of the Ionosphere) simulation for the winter condition. Their simulation successfully reproduced the USD and lower-diurnal layers, but the USN layer was less prominent. Their results showed that zonal, meridional winds and E x B drifts influence actual stratification at altitudes above 110 km. They showed that the meridional wind-driven ion velocities parallel to B could be responsible for the lower diurnal layer. Furthermore, they also emphasized that most of the observed metallic layer features in the model simulation were reproduced only by including the meridional wind forces.

Over Arecibo, Christakis et al. (2009) showed that the USD layer is well-defined and more frequent than the USN layer. They have also noted that the USD and USN layers are connected to the intermediate descending layers (IDLs). This IDL has manifested two descent layers per day from the F-region to the lower E-region (Mathews, 1998). Furthermore, these IDL merge with the existing layers under the control of diurnal tide (Mathews & Bekeny, 1979). In Some nights, multiple IDLs are observed at nearly 170 km over timescales of ∼2 hours by Earle et al. (2000). Earle et al. (2000) found that these multiple IDLs exhibited strong, diverse behavior from night to night that does not appear to be strongly correlated to geomagnetic activity, solar forcing, or average semi-diurnal tides. Furthermore, they also found that these IDLs stall, abruptly disappear, or even reverse direction in the midst of their descent rather than descending smoothly over periods of several hours. These behaviors seem to be common since it is seen in many reported results from different times (February 26, 1998, and September 12-13, 1994 by Figure 3 and 4 of Djuth et al. (2004); June 5-6, 2005 by Figure 4-6 and Figure 8-10 of Djuth et al. (2010); February 1-6, 2019 by Figure 1 and Figure 2 of Krall et al. (2020)).

Djuth et al. (2010) presented above mentioned figures but did not discuss the IDLs. They reported the gravity wave parameters, such as wave period, and half-vertical wavelength, by estimating them from the percentage of amplitude fluctuations of electron density. The presented wave parameters are time/altitude-averaged since Fourier analysis was used. At a given time and altitude, the wave parameters are essential to understand the contribution of the wave dynamics in the layering process at that time and space since there was variability over time and space in descending layers (Earle et al., 2000). Also, different dynamics govern the different altitude regimes of the descending layers; for example, the upper semi-diurnal layer and lower diurnal layer are controlled by the semi-diurnal tide and diurnal tides, respectively (Christakis et al., 2009; Krall et al., 2020).

Earle et al. (2000) mentioned these IDLs form near 170 km since their data is altitude-limited to 170 km, and also, there is a discontinuity in the layering process around that altitude. At the altitudes of IDLs, a recent study by Jiao et al. (2022) showed that TiCa⁺ (Thermosphere-Ionosphere Ca⁺) appear even beyond 170 km. Interestingly, these IDLs-like layers were observed in Ca⁺ lidar at Yanqing Station (40.42°N, 116.02°E) near Bei-
jing. They concluded that the descending layers carry the metallic Ca\(^{+}\) ions down to the sporadic E layer at \(\sim140\) km. They found that the TICa\(^{+}\) layer formed around \(\sim300\) km and descended to the lower altitudes over time, with the behaviors mentioned by Earle et al. (2000). Similar layers were also observed over Arecibo using AO Ca\(^{+}\) lidar (Raizada et al., 2020), but the altitudes were limited to \(\sim180\) km. Jiao et al. (2022) ruled out the long-range transport from low or high latitudes and hypothesized that regional vertical ion transport from the D-E to the F region occurs at the time of spread-F event by a combination of enhanced neutral wind electric field in the mid-latitude ionosphere.

Most of the earlier investigations on IDLs are mainly focused on the altitude range below 170 km (Earle et al., 2000; Fujitaka & Tohmatsu, 1971, 1973; Patra et al., 2002; Dos Santos et al., 2019) until recently by Jiao et al. (2022). From the same AO-ISR observations, IDLs were studied by Earle et al. (2000) and suggested that gravity waves or local modulations of the large-scale background winds may be more significant in forming these IDLs. Interestingly, Djuth et al. (2010) observed gravity waves' existence all the time over Arecibo. Since the lidar sees such layering processes over the mid-latitude location of Beijing in China, it is important to examine the IDLs above 170 km if it exists. And it is also important to estimate the wave parameters to understand better their participation in the layering processes of IDLs.

In this study, we focus on all the layers from 90 km to 350 km and beyond, particularly emphasizing the layer above 170 km and the plausible connection between these multiple layers. To understand the formation of these layers, we estimate the wave parameters as a function of altitude and time during February 1-6, 2019, using the observations of AO-ISR with the high temporal and spatial resolutions by the Coded Long Pulse (CLP) technique. Though the formation of the IDLs below 170 km could be explained by the tides and wind shear theory, the source and generation of the layers in the higher altitudes (above 170 km) are not understood well. Thus, the present study focuses on the dynamics that govern the different altitude regimes of the Ion descending layers (IonDLs) that bring the metal ions from the altitude of \(\sim350\) km and beyond to the E-region. It can be noted that term, IDL describes layers in altitudes from 130 to 350 km or more.

2 Observations and Data Analysis

We primarily used the ion-line data of the AO-ISR (18°20′N, 66°45′W), which was collected during quiet geomagnetic conditions on February 1-6, 2019 (world day), using the Coded Long Pulse (CLP) mode experiments (Sulzer, 1986a, 1986b). This CLP mode allowed us to make simultaneous measurements of the plasma line by taking advantage of the receiver’s wide bandwidth and the high sensitivity of the AO-ISR due to the spherical dish with a diameter of 300 m. This high-resolution technique measuring the entire incoherent scatter spectrum requires very fast sampling coupled with large data storage capability and computing with multiple processors. The AO-ISR was operated at a frequency of 430 MHz with a peak transmitter power of 1 MW. Other specifications used for the observations are given in Table 1. Given the advantage of CLP mode, the observations used a high range resolution of 300 m. Three range gates were averaged to enhance the signal-to-noise ratio of the power spectra, reducing the range resolution to 900 m. The total power and plasma parameters, such as electron density, electron temperature, ion temperature, and ion drift velocity at the line of sight, are obtained from the power spectra of ion-line with a range and temporal resolutions of 900 m and 35 s, respectively. Only the plasma frequency is used from the plasma-line datasets, and plasma-line measurements are primarily possible only during the daytime because of suprathermal enhancements due to the production of photo-electrons by solar ultraviolet radiation (Vierinen et al., 2017). In contrast, ion-line measurements are possible both during the day and night and thus are our primary tool for studying the descending layers.
Table 1. ISR specifications and other important parameters used for the observations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ion-Line</th>
<th>Plasma-Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days of observations</td>
<td>February 1-6, 2019</td>
<td>February 1-6, 2019</td>
</tr>
<tr>
<td>Mode</td>
<td>Coded Long Pulse</td>
<td>Coded Long Pulse</td>
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<td>Inter-pulse period</td>
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<td>10000 µs</td>
</tr>
<tr>
<td>Pulse length</td>
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<td>440 µs</td>
</tr>
<tr>
<td>Baud length (range resolution)</td>
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<td>2 µs (300 m)</td>
</tr>
<tr>
<td>No. of FFT points</td>
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</tr>
<tr>
<td>Zenith Angle</td>
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<td>1.06º</td>
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<tr>
<td>Azimuth Angle</td>
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<td>285º</td>
</tr>
<tr>
<td>Observational range (km)</td>
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<td>80-780 km</td>
</tr>
<tr>
<td>Observational Frequency range</td>
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<td>±15 MHz</td>
</tr>
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<td>Time resolution</td>
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<td>10 s</td>
</tr>
<tr>
<td>Range resolution</td>
<td>0.9 km</td>
<td>2.55 km</td>
</tr>
</tbody>
</table>

Figure 1. a) A sample electron density profile at 20:02 UT on February 04, 2019 b) Corresponding electron density gradient, and c) different wave modes in the electron density obtained using the complete ensemble empirical mode decomposition method.
Figure 1a presents a sample electron density profile from ion-line on February 2, 2019, at 21:21:05 AST (Atlantic Standard Time). It demonstrates that estimated electron densities possess wave perturbations in them. To identify the wave perturbations from the electron densities, the background electron densities were constructed in two steps. In step 1, a one-dimensional filter was performed along the altitude using the python-scipy filter with Gustafsson’s method to handle the edge of the signal (gust method). In step 2, a two-dimensional moving grid (as (Djuth et al., 2010)) with a length and width of 2 hours and 10 km (15 km) for daytime (nighttime) was used to average the data obtained from step 1. The outcome is used as a background electron density. The residuals of electron densities are calculated by subtracting the background electron density from the ISR-estimated electron density shown in Figure 1b.

The residuals of electron densities possess clear wave perturbations. To separate the waves based on their vertical wavelength and time period, an empirical mode decomposition analysis is performed on the residuals of the electron density along the altitude and time, respectively (Herawati et al., 2022; Purba et al., 2018; McDonald et al., 2007). The python code to perform the empirical mode decomposition (EMD) is available on GitHub at https://github.com/laszukdawid/PyEMD from Laszuk (2017). In EMD of complete Ensemble Empirical Mode Decomposition (CEEMDAN), parabolic extreme detection and parallel processing with five processors are used. Decomposed wave modes along the altitude are presented in Figure 1c.

In addition, normalized electron density residuals and decomposed wave modes from the spatial domain are presented as a function of time in Figure 2. Figure 2 presents the power residual in the background (color map) to show the IonDLs and connection among the wave modes. The power residuals will be discussed in detail along with other days in Figure 3. Normalized electron density residuals are presented on the power residuals in Figure 2a. The wave modes 2, 3, and 4 are presented in Figure 2b, c, and d, respectively. The lower mode number corresponds to the shorter vertical wavelength, and the higher mode number corresponds to the larger vertical wavelength. Low modes overlap with the upper semi-diurnal layers, whereas higher modes mostly overlap with the IDLs since layers’ thickness increases with altitude. The extracted wave modes indicate that multiple waves are present with a range of vertical wavelengths varying from smaller of ~1 km to larger wavelengths of ~200 km; the wave’s amplitude increases with altitude; each mode has one or more waves in it.

Zero-crossing modes are only taken for further analysis to calculate the wave parameters such as wavelength and phase speed. From the wave modes of the spatial domain, we estimated the wave amplitude (local maxima between the zero crossings), occurring height/altitude, and vertical half-wavelength (distance between zero crossings) as a function of size and time. The waves’ time period (2x time between zero crossings) and amplitude (local maxima between the zero crossings) are estimated from the time domain as a function of time and altitude. The wave’s phase velocity is calculated by tracking the same amplitude and half-vertical wavelength in successive wave-mode profiles.

3 Results

To show the descending layers from the AO-ISR observations, we performed point-wise smoothing along the altitude on the power profiles. We used 25 (covers 7.5 km) and 35 (covers 10.5 km) points smoothing for the heights of 90-145 km and 134-400 km, respectively. And then, to get the power residuals, the background power was subtracted from the total power. The obtained power residuals are presented as a function of local time (x-axis: Month-day time) and altitude in Figure 3. The power residuals are in arbitrary units (a.u.). The observation started at 15:29:37 AST on February 1, 2019, and continued till 07:02:42 AST on February 6, 2019. The vertical solid transparent maroon
Figure 2. Normalized electron density residuals and decomposed wave modes from the spatial domain are presented as a function of time and altitude.
line distinguishes the day and night. The plasma parameters are estimated from the ion-
line data for those altitudes above the horizontal maroon line. Ionospheric descending
layers appear all day and at all times during the period of 1-6 February 2019. The lower
diurnal layer clusters are present on all the days between ~90 and 120 km. In this fig-
ure, multiple IDLs appear continuous and connected, even though some discontinuities
exist in some places.

Figure 3. The power residuals as a function of local time (x-axis: MM-DD HH) and altitude

The intermediate descending layers (IDLs) appear brightly from ~300 km to ~130
km, even with some density clusters observed beyond the altitude of ~300 km during
nighttime. Tracing the brightness above 300 km shows that these IDLs are possibly start-
ing from the altitudes of ~300-350 km. During the daytime, IDLs mostly begin at an
altitude between ~250 and 300 km. On average, there is a ~50 km difference in start-
ing altitude of the IDLs between the daytime and night. Every night, a minimum of one
IDL is found at the altitude of ~275 km. During the day, a minimum of four IDLs are
found at the altitude of ~225 km. Around ~170 km, very few IDLs cross this altitude
region from upper altitudes to reach altitudes below 160 km. Below 160 km, the dense
IDLs connect to the Es layers, even though a few of those layers show discontinuity and
staging on their path before reaching the Es. Note here that the entire layer present from higher altitudes of 300 km or more to 90 km is defined as an ion descending layer (IonDLs) in the present study.

These IDLs are not identical and have day-to-day variability in strength, number of occurrences, altitude of occurrence, staging, and discontinuity. The IDL which occurs before sunset (without any discontinuity) and after sunset (with one discontinuity at \(\sim 170\) km), reaches the altitude of \(\sim 125\) km (before 12 AST on February 2 and 5) and \(\sim 100\) km (before 8 AST on February 3 from 19 AST on February 2), respectively. Hereafter they are named twilight IDLs. Most of the time, these twilight IDLs are better defined than any other IDLs, and their vertical descent continues for a longer distance than any other IDLs (e.g., February 2 and February 5 twilight IDLs). In addition to the twilight IDLs, three more daytime IDLs occasionally reach the low altitudes of 125 km, or even lower to 90 km (1\(^{st}\) daytime IDLs of February 2, 4\(^{th}\) daytime IDL of February 3 and 1-3\(^{rd}\) daytime IDLs of February 5). These daytime IDLs have less density at the altitude of the discontinuity region (around 170 km). From these IDLs, we found that the starting time of the upper semi-diurnal layers depends on the arrival time of the IDLs at that altitude since those are well connected. Hence, starting time and altitude of the upper semi-diurnal layers are not random.

To understand the favorable background conditions for the formation of the IDLs, we look into the ISR observed ion drift velocities at the line-of-sight (Vls) and the descending speed of the IDLs. The descending speed of the IDLs is manually estimated by tracking the layer’s brightness; the obtained results are co-plotted with the ion drift velocities as shown in Figure 4. ISR-measured ion drift velocities vary from -80 to 40 m \(s^{-1}\), and the magnitude of the drifts increases with increasing altitudes. Ion drift velocities are mostly downward in the altitudes of IonDLs during daytime and nighttime. Downward velocities are dominant during the daytime, whereas upward velocities are dominant during the nighttime for the entire altitude range. Upward drifts dominate above \(\sim 250\) km during the daytime. The highest downward drifts are observed during the twilight times. In the daytime, downward velocities range from -20 to -80 m \(s^{-1}\), whereas upward velocities range from 0 to 10 m \(s^{-1}\) in the nighttime. Eventually, daytime downward drifts (below 300 km) show descending features that coincide with the IonDLs. However, this descending signature is not found in the nighttime drifts. The drift direction frequently changes during the nighttime, whereas the daytime drift directions persist for a long-time in one direction (up or down) and change gradually. The daytime behavior continues during the twilight times as well.

Interestingly, descending features appear in daytime drifts, especially from 300 km to 200 km, where descending speed circles are unavailable since the descending layers are unable to trace at those altitudes in power residuals from ion-line datasets. In other words, descending features appear in daytime drifts above the topmost altitude of the descending speeds. The daytime IDLs are not visible in the power residuals above the peak of the F-region, possibly by the fall of the ion-line spectral power or the smoothing algorithm removing those layers from detection. Possibly, the power of those layers might be too low to resolve them in Figure 3 and trace them to get the descending speed. To examine the existence of IDLs beyond the daytime F-peak altitudes, we show the simultaneous observations of the plasma-line measurements from the AO-ISR. The plasma frequency residuals are estimated from the plasma-lines by filtering out the background plasma frequencies. The background plasma frequencies are estimated by following five steps procedure.

To construct the background plasma frequencies, two-dimensional (2D) high-pass and low-pass filters with a length and width of 5.5 hours and 30 km, respectively, are used on the ISR-measured plasma frequency (upshifted plasma frequency from 430 MHz); these filters were explained in detail by Kruse and Smith (2015). The background plasma frequency is extracted with the descending layers by a poorly constructed 2D low-pass
Figure 4. ISR-measured ion drift velocities and descending speed of the layers (filled color circles) as a function of time (accumulated hours) and altitude on (a) 1-3 February 2019 and (b) 3-6 February 2019.
filter at step-1 on ISR-measured plasma frequency. The output of step-1 had wave components which were removed by subtracting the output of the 2D high-pass filter on step-1 from the output of step-1 at step-2. In step-3, step-2 is repeated to remove the wave perturbations by using the output of step-2 and step-3. Step-3 contains the background plasma frequency, wave perturbations, and the unremoved component of layers. To remove the layers further in step-4, smoothing with a length of 6 hours is performed along the time on the output of step-3. The outcome of step-4 is used as a background plasma frequency. In step-5, the residuals of the plasma frequencies are estimated by subtracting the background plasma frequencies from the ISR-estimated plasma frequencies. From the residuals, the wave perturbations are also removed in step-4 since background plasma frequencies are constructed with the high-frequency components by the use of the high-pass filter in step-5. It is presented in Figure 5 along with the descending speed (colored circles). The dashed (maroon color) transparent line distinguishes the altitude regions of the processed (above) and unprocessed (below) ion-line, as well as the distinction between day and night.

During the daytime, plasma frequencies are observed as high as 400 km. Plasma frequency residuals are removed for nighttime because no plasma frequency is observed and also to show the layering structures from the ion-line to demonstrate the overlapping cases. Plasma frequency residuals are removed at the time of ~83 hours due to data gaps. Unlike the power residuals, the residuals of plasma frequencies display many daytime descending layers from 400 km with enhanced plasma frequencies as high as 1.5 MHz. A few of those layers are connected to those that occur below 170 km. At the discontinuity region of 170 km, traces of the layers are seen but not as well pronounced as the layers above this altitude. Traces from the power residuals of the ion-line data overlap with the layering of the plasma-line at the discontinuity region, as well as descending layers above 170 km. In some places, overlapping between the traces (descending speed) of the ion-line and layers from the plasma-lines is not as good as expected due to the errors in the manual trace, especially around 41 hours. From the good overlapping cases (at the time of ~35 hours, ~65 hours, ~87 hours, ~101 hours, ~105 hours, ~106 hours, and ~112 hours), the layers with higher descending speeds occur at the top or beyond of the altitudes of the traces of ion-line.

Interestingly at about 100 hours corresponding ~5 AM (AST), we have a remarkable effect. There are conjugate photoelectrons, but that does not mean that we necessarily see a plasma line. If the ionosphere has low density, then the plasma line is too broad to be easily detectable; that is, it does stand out above the noise because the power is spread out in frequency. But it becomes detectable with the density increase from the layer (verified by the circles from ion-line data). That is, the layer raises the density enough so that we can see the narrower plasma line. It disappears after the layer until the local (time) sun rises.

From the track of the layers, these descending layers with higher descending speeds occur above the F-region’s peak altitude. These occurring altitudes make it difficult to call those layers IDLs because IDL is the terminology used for the intermediate layers between the F-region and E-region. But the daytime descending layers occur well above the F2-peak, too, possibly higher than shown since the layering features in the plasma-line data are still present at the altitudes where the noise floor starts to dominate.

Hence, we name the daytime layers which occur above altitudes of the F2-peak and beyond (>250 km) as Top-side Descending Layers (TDLs). TDLs possess a higher descending speed than IDLs. Thus, densities descend with the altitude from 400 km or above to 90 km and are identified with different names at different altitude ranges. Since all of them are connected and mostly continuous, we name them altogether Ionospheric Descending Layers (IonDLs). Therefore, Hereafter the combination of all descending layers between 400 and 90 km is called IonDLs. It can be noted that the ion-line data shows undulations in some of the layers (around 65, 90, 112-115 hours) at the altitude of the
F2-peak, whereas these closely occurring multiple descending layers are unresolved in ion-line but well resolved in plasma-line data due to higher time resolution.

The traces of the descending layers’ in the power residuals and plasma frequency appear to be a single continuous layer from an upper altitude of 400 km or more to a lower altitude of 90 km. This makes it difficult to separate the IonDLs into lower diurnal, upper semi-diurnal, and intermediate layers. But these layers are separately studied in altitudes below 180 km due to discontinuities and different descending speeds at different altitude ranges. The altitude ranges are 130-180 km (IDLs), 110-130 km (US), and below 110 km (lower diurnal layer). Since the layers appear as a single and continuous layer with discontinuity, the same envelope of ions/mass is carried from the upper altitudes of 400 km or more to 90 km by the different governing dynamics (waves/tides) at different altitudes. Precisely, the governing dynamics change at discontinuity regions.

Figure 5. ISR-measured plasma frequency from the plasma line measurements and descending speed of the layers (filled color circles) as a function of time (accumulated hours) and altitude during (a) 1-3 February 2019 and (b) 3-6 February 2019.

Overall, the descending speed of the IonDLs varies from $\sim 0$ to $-20$ m s$^{-1}$. In that, the highest descending speed is noted for IDLs (above 130 km to F-region peak), i.e., $\sim -7.5$ to $-20$ m s$^{-1}$, and it decreases to $\sim -5$ to $-7.5$ m s$^{-1}$ for the layers located around 105-130 km. The lowest descending speed of $\sim 2$ m s$^{-1}$ is observed at the lower altitudes.
of 90-110 km. Thus, the descending speed of the IonDLs increases with increasing altitude from ∼90 km to ∼400 km. In some occasions, the descending speed of the IonDLs is comparable to the ion drift velocities. However, in general, the ion drift velocities are larger than the descending speed of the IonDLs. This suggests that ion drift alone may not govern the formation of the IonDLs. Thus, other factors, such as wave dynamics and wind, may also have control over the formation of the IonDLs. To understand the role of waves in the formation of the IonDLs, we estimate the wave parameters using the empirical mode decomposition method (as detailed in section 2).

Figure 6. Amplitude of the waves as a function of local time (accumulated hours) and altitude on (a) 1-3 February 2019 and (b) 3-6 February 2019. Solid vertical lines separate the days.

The wave amplitudes are estimated in terms of electron density instead of the percentage of amplitude fluctuations. Wave amplitudes in electron density provide more insight into understanding the effect of waves on the layering process. From the spatial domain, the estimated amplitude of the waves is presented as a function of time and altitude as shown in Figure 6a (1-3 February 2019) and b (3-6 February 2019). Since the IDLs and wave features are continuous, splitting the data into segments one day in duration is hard. There was a break in the observations of the ISR at around 69 hours which allowed us to split the data into two segments. In Figure 6, the x-axes show the time in accumulated hours from 15:29:37 AST on February 1, 2019, to 7:2:42 AST on February 6, 2019, and the power residuals are also shown in the background (same as in Figure 3).
As expected, the wave amplitudes increase as a function of altitude till ~250 km and decrease above. These wave amplitudes are ranging from $10^8 \text{ m}^{-3}$ (~120-200 km altitudes) to $5\times10^{10} \text{ m}^{-3}$ (above ~200 km altitude). The peak amplitude is $5\times10^{10} \text{ m}^{-3}$. Most often, the large amplitudes coincide with the IonDLs in the altitude range of ~175 km to ~400 km. On occasions, enhanced amplitudes are also seen in altitudes below ~175 km. The point to be noted here is that wave amplitudes are not calculated for the height below ~175 km during the daytime because the ion-line data was not analyzed below that height. Enhanced amplitudes of USN, IDLs, and track of USD from the power residuals show that those of USN and USD layers are connected to the IDLs as discussed earlier in the description of Figure 3. Though they are continuous layers most of the time, there is discontinuity around ~170 km altitudes, and staging around ~150 km and below altitudes are also evident; probably, these are the places where different governing dynamics take charge.

During the daytime, the amplitude of the waves is higher above ~175 km than at nighttime. The amplitudes of the waves are moderate on the well-structured twilight-descending layers below ~150 km and low in the other places. In many instances, the amplitudes show a well-organized layering structure and undulations over time (for example, 22 hours, 45 hours, 49 hours, 73 hours, 95 hours, 100 hours, and 119 hours in Figure 6). These undulations in the amplitudes are greater during nighttime than daytime. These undulations occur at higher altitudes during nighttime than daytime; these undulations might be due to the multiple structures occurring in a short time. In the twilight hours, the waves with high amplitudes were found at the lower altitudes, making it possible to connect with the E-region.

The half-vertical wavelength (top panel), time period (middle panel), and phase velocity (bottom panel) of the waves during 1-3 February 2019 and 4-6 February 2019 are shown in Figure 7 and 8, respectively. It is clear from these figures that the half-vertical wavelengths increase with increasing altitude. The shorter vertical wavelengths (<50 km) are dominant in the altitude ranges below ~200 km. The higher altitudes are dominated by high vertical wavelengths ranging from 75 km to 200 km. The descending layer features are also seen in the vertical wavelengths.

The time periods of the observed waves vary from a few minutes to 6 hours as shown in Figure 7b (1-3 February 2019) and 8b (3-6 February 2019). Periods less than 1.5 hours exist throughout the altitude and time, dominating below ~190 km. Above 170 km, the waves are dominated by various periods; there are many instances when different periods dominate at different times throughout the altitudes along with the descending features (mostly time periods of 1.75 - 4 hours). The wave periods are not constant over time; approximately every hour, different waves dominate even though the short time period waves always exist. Even though there is a day-to-day variability, the short periods of less than 3 hours are strongly present during 4-8 AST. After 8 AST, short periods are present, but the dominating waves possess longer periods of more than 3 hours. Notably, the time periods are not simple functions of altitude like half-vertical wavelengths. Also, the feature of the descending layers is seen in amplitudes, wavelengths, and time periods. But the descending layers from the power residuals are highly overlapping with the descending features of the wavelengths and amplitudes.

To calculate the phase velocity of the wave, phase points (phase of the wave) are tracked by following the descending features in the wavelengths and amplitudes. To track the phase point of the wave, similar wavelengths corresponding to similar positive amplitudes are tracked over time wherever altitude descending features are present in the amplitudes and wavelengths. Many neighboring values did not meet this tracking criterion. Therefore, the calculated phase velocities (number of points) are not as dense as wavelengths and amplitudes over time and space. The phase velocities are shown in Figure 7c (1-3 February 2019) and 8c (3-6 February 2019). The peak phase velocity is ~40 m s$^{-1}$, and overall, the phase velocities are less than -15 m s$^{-1}$ below 250 km over
Figure 7. (a) half-vertical wavelength, (b) time period, and (c) phase velocity of the waves as a function of local time (accumulated hours) and altitude during 1-3 February 2019. Solid vertical lines separate the days.
Due to the limited number of phase velocity points, most of the descending layers are clearly visible in the phase velocity map. On the IDLs, relatively high values of phase velocities of -30 to -40 m s\(^{-1}\) are estimated at higher altitudes of 250-400 km. The IDLs between \(\sim\)130 km and 200 km have phase velocities ranging from -10 m s\(^{-1}\) to -30 m s\(^{-1}\), and the phase velocities are less than -10 m s\(^{-1}\) below 120 km. Above the altitude of \(\sim\)200 km, the phase velocities ranging from -10 m s\(^{-1}\) to -40 m s\(^{-1}\). Therefore, these phase velocities vary as a function of altitude.

Figure 8. Same as Figure 7 but during 3-6 February 2019.

Descending speeds of the IonDLs are closely comparable with the phase velocities of the waves with some deviations. These variations could be due to the difference in tracks between the wave’s phases and manual trace. This suggests that various waves control the IonDLs formations and descend at different altitude regimes. But it is unclear what causes these enhanced ion/plasma densities in higher altitudes. In other words, what is the source of metallic ions in the F-region altitudes?

Recently, Jiao et al. (2022) reported the presence and descent of metallic Ca\(^+\) ion densities (called Thermosphere-Ionosphere Ca\(^+\) (TICa\(^+\)) layers) from \(\sim\)300 km to \(\sim\)90 km using a Ca\(^+\) lidar at Yanqing Station (40.42\(^\circ\)N, 116.02\(^\circ\)E) near Beijing. Since their
measurements are from a geomagnetic mid-latitude station such as Arecibo Observatory, it is worth comparing the altitudes of the TICa\(^+\) layers and IDLs to help in understanding the origin of the IDLs densities over Arecibo. Since their lidar observations were conducted only from evening through night, we selected the AO data on 4-5 February 2019 that has continuous layers from the F-region to the E-region during that time. To see the similarities, if any, we have shifted the AST to match the Beijing time.

**Figure 9.** (a) phase velocity and (b) time period during 4-5 February 2019 on the power residuals over Arecibo as a function of local time and altitude. And also, the half-vertical wavelengths corresponding to 4-5 February 2019 (but the local time is shifted to match the layers) on Ca\(^+\) ion densities of (c) 3 June 2021 and (d) 18 June 2021 as a function of Beijing local time and altitude. The densities of Ca\(^+\) on 3 June 2021 and 18 June 2021 are downloaded from the Zenodo repository (https://doi.org/10.5281/zenodo.7020759) as indicated in Jiao et al. (2022). The power residuals of AO-ISR on 4-5 February 2019 are presented with two different scales to distinguish the time of maximum density occurrence. In Figure 9a and b, vertical red lines represent the duration.
of the spread-F occurrence. During the Spread-F times, no enhanced power residuals are observed over Arecibo to indicate the upward transport of the densities. Phase velocity, the lower values filtered time period, and half-vertical wavelength show the layering structures and coincide with the IonDLs from power residuals. Therefore, we plot the half-vertical wavelengths over the Ca$^+$ ion densities as shown in Figure 9c and d. Layering structures in the wave parameters over Arecibo indicate that descending layers exist before the Spread-F times and after that layer corresponding to the spread-F time. The AO’s IonDLs show similar features as Ca$^+$ density layers over Beijing, starting from 250-300 km altitude and reaching the E-region. Jiao et al. (2022) reported that while descending, the layers move up and down before reaching the E-region. That feature is also seen in AO-ISR on 4-5 February 2019 till 21 AST in Figure 9a. This moving up and down feature over Arecibo is due to the overlapping of multiple layers. Even though those layers from Arecibo and Beijing show similar features, there is no signature of density uplifting over Arecibo, whereas it exists in Beijing observations. From this comparison, it is clear that the origin of the metallic ions could be located in the E-region as suggested by Jiao et al. (2022).

4 Discussion

From the ion-line, the intermediate descending layers (IDLs) occur strongly from ∼300 km to ∼130 km and have substantial local time/solar zenith angle and day-to-day variability. Starting altitude of these IDLs is possibly from ∼300-350 km (∼250-300 km) during the nighttime (daytime). We found that more IDLs occur in the daytime (at the altitude of ∼225 km) than in the nighttime (at the altitude of ∼275 km). During the observation period, the occurrence altitude of the nighttime IDLs is slightly higher than the daytime. The daytime descending layers are not traceable beyond the altitudes of F2-peak from the ion-line, whereas these descending layers’ continuation is observed in the plasma-line beyond the F2-peak. These daytime layers occur above altitudes of the F2-peak and beyond (> 250 km) and are named Top-side Descending Layers (TDLs). From the track of the layers, TDLs possess a higher descending speed than IDLs and any other known descending layers. The AO-ISR observations of the ion-line and plasma-line demonstrate that descending layers are coming from the topside of the F-region to the E-region, especially during daytime; collectively, all these layers can be called IonDLs.

Notably, these IonDLs are observed during quiet geomagnetic conditions. And occurring range/starting altitudes are higher than any previous reports from ISR, sounding rocket, coherent radar, lidar, and rocket observations (Earle et al., 2000; Fujitaka & Tohmatsu, 1971, 1973; Patra et al., 2002; Jiao et al., 2022). Predominant IonDLs reach the E region and/or the top of the E region from 350-400 km, which mostly crosses the discontinuity region of ∼170 km at twilight times. Twilight-time IDLs are better pronounced than those of the daytime and nighttime. Multiple TDLs and IDLs occurrence rates are higher during the daytime than at nighttime, but only a few reach the E region by crossing the discontinuity region (∼170 km). We found that the starting time of the upper semi-diurnal layers depends on the arrival time of the IDLs at that altitude since those are well connected and semi-diurnal layers are not generated separately.

Most of the earlier investigations reported the presence of IDLs up to 180 km (Christakis et al., 2009; Raizada et al., 2020; Earle et al., 2000; Fujitaka & Tohmatsu, 1973), and moreover, most of them are nighttime observations (Jiao et al., 2022). For example, Fujitaka and Tohmatsu (1973) stated morphology of the IDLs using the rocket observations that middle latitude IDLs usually observed after midnight at an altitude of 140 km. Using a Ca$^+$ metallic lidar, Raizada et al. (2020) reported descending metallic layers from 180 km over Arecibo during 29-30 November 2016. They also found a good correspondence between the metallic and ion layers observed by AO-ISR. This suggests that the IDLs primarily consist of metallic ions. In figure 3, it is obvious that the discontinuity region provides a trace of the connectivity between IDLs below and above during the day; twi-
light time IDLs are well connected even at the discontinuity region. In the present study, we have observed IDLs even throughout the day and night from an altitude of 400 km down to 90 km. Similar to IDLs, TDLs are also possibly made up of metallic ions since there are continuations in IonDLs. If it is the case, we can call these Ionospheric Descending Layers (IonDLs) Metallic Ion Descending Layers (MIDLs).

Even though IonDLs appear to be continuous, there are some discontinuities, particularly in the region where the upward ion drift velocities are present. On the other hand, downward ion drifts are continuous and change their direction gradually during the daytime, unlike nighttime. The downward drift velocity is dominant during the daytime; as a consequence, multiple IDLs are observed. Similarly, the continuous and extended vertical spatial coverage of the IDLs during the twilight time could be due to the enhanced downward ion drifts at those times. Ion drift velocities are observed to be low-magnitude negative and/or positive drifts just above or below the IDLs. Nighttime IDLs are relatively weak and short-lived, which might be due to frequent changes in the ion drift direction (up and down) throughout the altitudes.

It has been well reported that the convergence of the ions forms the Es through the wind shear driven by the tides and waves (Krall et al., 2020; Axford, 1963; Whitehead, 1961; Mathews, 1998; Haldoupis, 2012; Selvaraj et al., 2017). Based on the descending speed of the Es, USD, and USN layers, dominant control by the semidiurnal and diurnal tides is identified (Christakis et al., 2009). In the present study, we have found the starting altitude of the IDLs is as high as 400 km, where the upward propagating tidal influences are minimal. Thus, we believe that the gravity waves might be playing an important role in the formation of wind shear as these waves are always present over Arecibo (Djuth et al., 2010). Therefore, we look into the role of gravity waves with a period of less than 6 hours on the formation of the IonDLs.

Wave parameters are estimated using the empirical mode decomposition method. From the empirical mode decomposition, lower wave modes (short vertical wavelength) waves overlap with the upper semi-diurnal layers, whereas higher modes mostly overlap with the IDLs since the layers’ thickness increases with altitude. The extracted wave modes indicate that multiple waves are present with a range of half-vertical wavelengths varying from ∼1 km to as high as ∼200 km. The shorter half-vertical wavelengths less than ∼40 km and time periods less than 1.5 hours are present all the time and at altitudes.

As expected, the estimated half-vertical wavelengths increase with increasing altitude as reported by (Djuth et al., 2010). But the time period has a different feature; time periods have descending layer features frequently, and a few time periods dominate on a given layer throughout the altitude when periods are in the range of 1.45 hours to 6 hours. These results suggest that gravity waves with periods less than 6 hours could have a major role in the formation of TDLs and IDLs at higher altitudes. The gravity waves with time periods of less than 1.5 hours are present all the time and in this altitude range.

The phase velocities of the waves increase with increasing altitude as do the descending speeds of the IonDLs. The phase velocities of the IDLs are from -10 m s\(^{-1}\) to -40 m s\(^{-1}\) (-10 m s\(^{-1}\) to -30 m s\(^{-1}\)) above (below) the altitude of ∼200 km. The descending speeds of the IonDLs and phase velocities match or nearly wherever the high overlapping tracks occur. The differences in the tracks (of IonDLs and wave phases) are due to the error in the manual tracing by following the bright points in power residuals. The close comparison of the phase velocity and descending speed of the IonDLs further confirm that gravity waves possibly carry the densities on their phase fronts, that is, in the null zone of the wind shear.

It has been reported that the IDLs in the altitudes below ∼200 km are made up of molecular ions (Heelis, 1999; Miller et al., 1993) and/or metal ions (Chu et al., 2021;
Raizada et al., 2020; Krall et al., 2020). They argued various plausible sources for the presence of metallic ions at higher altitudes. For example, Raizada et al. (2020) suggested that the micrometeoroid mass flux could be a main source of metals and their ions in the upper atmosphere, particularly meteoroid sputtering in deposits of neutral metals above 120 km. In contrast, using a model simulation, Carter and Forbes (1999) showed that upward forcing from the equatorial electric field is critical to the global movement and that diurnal and semidiurnal tidal winds are responsible for the formation of dense ion layers in the 90-250 km height region. A recent study found that the Ca$^+$ metallic ion layers descending from 350 km to 80 km using Ca$^+$ lidar at Yanqing Station (40.42°N, 116.02°E) near Beijing, China (Jiao et al., 2022). They argued that these metallic Ca$^+$ ion densities could be transported from ~110 km (mostly where the strong sporadic Ca$^+$ ion layer is located) through a strong local vertical ion transport associated with enhanced E-region electric field and meridional winds at the time of spread-F event. Therefore, to check the possible connection of spread-F event to these IonDLs during this time, we investigate the background ionospheric conditions in the low- and mid-latitudes.

**Figure 10.** Lower values filtered (a) half-vertical wavelength and (b) time period along with the ROTI as a function of local (accumulated) time and altitude (pink-color-map) on power residuals during 1-3 February 2019.
Figure 11. Same as Figure 9 but during 3-6 February 2019.
Figure 10 and 11 present the lower values filtered (a) half-vertical wavelength and (b) time period along with the Rate of TEC index (ROTI) on power residuals during 1-3 February 2019 and 3-6 February 2019, respectively. The ROTI of more than 0.2 is considered representative of the equatorial plasma bubble/spread-F events, which is shown in dark orange color as a function of local time (accumulated time) and latitude (y-axis at the right-side) in Figure 10 and 11. In Figure 10 and 11, the solid maroon vertical lines indicate the midnight and day separations. The half-vertical wavelength and time period show multiple layering structures during the day and night. Those layering structures are not continuous in the vertical wavelengths and time periods because the lower values are filtered-out (these lower values occur almost all the time and at all altitudes). These filtered-out lower values provide the continuity of the layers, especially in the lower altitudes. As discussed earlier, altitude dependency is explicit in wavelengths but not time periods. The dominant time period associated with the descending layers is mainly 2-4 hours which is consistence with an earlier investigation by Raizada et al. (2020).

The ROTI data show the presence of Equatorial Plasma Bubble (EPB) during all the nights with day-to-day variation in onset time. However, we did not see any major changes change in the layering process before or after the spread-F events, except an up-lifting signature in the residuals above the altitude of 200 km at the time of intense spread-F corresponding to ROTI > = 0.5 (navy blue in the magenta color bar). The timings of those uplifts are 20-22 AST and 23-24 AST on 1 February 2019 and 3 February 2019, respectively. In those times, the IDLs started from the highest altitudes of ~350-400 km. For low ROTI corresponding to the very weak spread-F or no spread-F of 2 February 2019, IDLs are starting from the highest altitudes of ~350-400 km, particularly at midnight. For the other days, 4 and 5 February 2019, high ROTI values are seen, but there is no sign of density uplifting from the Es layer or in the F-region. Therefore, there is no consistent behavior of density uplifting in the residuals from the Es layer for the days corresponding to EPB. This refutes the argument that the equatorial electric field associated with global ion transport could be a source of the metallic ions for the observed IonDLs. Hence, it is also interesting to check the ionograms from the Arecibo latitudes to know local transport and the timings of the spread-F events on these latitudes.

The ionosonde at Ramey (18.5°N 292.9°E) was in operation during these days, and this location is 50 km from the AO. Ionosonde data are taken from https://giro.uml.edu/didbase/scaled.php. Figure 12 presents the peak electron density height of F1- (cyan), F2- (magenta), & E-layer (blue), and critical frequency of F- (orange), F2- (yellow), & E-layer (red) on (a) 1-3 February 2019 and (b) 3-6 February 2019 on the ISR measured power residuals as a function of local time and altitude. For the altitudes, the same left-side y-axis scale is used. The critical plasma frequencies are represented in MHz by the right-side y-axis scale. Due to the space limitation, the legend for the peak electron density heights is shown in Figure 12a, and the legend for the critical plasma frequencies are shown in Figure 12b even though both of them are plotted in Figure 12a and b. Peak altitudes of the F1-layer (hmF1) are observed below 200 km during the day, whereas the IDLs that begin at the discontinuity region are mostly below hmF1. Interestingly, there are discontinuities in the hmF1 whenever the corresponding IDLs descend too far from that altitude. Peak altitudes of the F2-layer (hmF2) occur at higher altitudes during nighttime than daytime. Interestingly, the IDLs are beginning from the F2-layer below the altitudes of hmF2 during nighttime and at the hmF2 altitudes during the daytime. These suggest that the IonDLs originated from the peak of the F-region. Dos Santos et al. (2019) also observed similar features, especially the beginning altitudes of the IDLs from the F2-layer below the altitudes of hmF2 over Brazilian equatorial and low-latitude regions. This suggests that the IonDLs formation could be global in nature. Furthermore, Dos Santos et al. (2019) connected these layers with 150 km echoes (which is a prominent daytime phenomenon in the equatorial and low latitude ionospheric valley region) and/or IDLs; this connection makes the further interpretation of their descending layers hard.
Figure 12. Peak electron density height of F1- (cyan), F2- (magenta), & E-layer (blue), and critical frequency of F- (orange), F2- (yellow), & E-layer (red) during (a) 1-3 February 2019 and (b) 3-6 February 2019 on the ISR measured power residuals as a function of local (accumulated) time and altitude.
Based on the ion-line, the starting altitude of the IDLs/descending layers is from the bottom of the hmF2 during nighttime and at the hmF2 altitudes during the daytime as nighttime descending layers reported by Dos Santos et al. (2019) from the observations using ionosonde. But these starting altitudes of the descending layers are not actually the starting altitudes of the descending layers because the plasma-line data sets show the starting altitudes well above the hmF2, especially during daytime. This issue is probably due to the density of the IDLs/Es below 170 km affecting the measurements of F1 and beyond in the ionosonde. Many instrumental techniques did not observe multiple IDLs during daytime above 170 km and hmF2, possibly due to the blanketing effect of the E-region. Given the advantage of the high sensitivity of AO-ISR, we could resolve these multiple descending layers.

These layers are visible to the instruments based on their capability. Earlier studies of Raizada et al. (2020); Dos Santos et al. (2019); Mathews and Bekeny (1979); Mathews (1998); Earle et al. (2000); Fujitaka and Tohmatsu (1973) limited the starting altitude of the descending layers, possibly by the capability of the instruments and/or limitations imposed by certain data sets or by the interest of the study.

Jiao et al. (2022) observed both the sudden sharp spike of hmF2 and uplift of Thermosphere-Ionosphere Ca$^+$ (TICa$^+$) ions around the same time; this uplift of ions are clearly visible till 150 km. Such sudden sharp spikes in hmF2 occurred over Ramey on many occasions, such as ~20 AST on 1-4 February 2019, but uplifting and distortion occurred only in two days of 1 and 3 February 2019 within a few hours in addition to the occurrence of multiple IDLs during all the day and night. These features contrast with Jiao et al. (2022). Thus, we propose a hypothesis that the localized enhanced electric field and meridional winds could only partially explain the source of the metallic layer’s uplift to the higher altitudes, and it requires further investigation. Moreover, we found the IonDLs in all six days, but it is worth exploring whether this has any seasonal, latitudinal, and longitudinal variations using the existing ISRs.

5 Summary

We studied ionospheric descending layers (IonDLs) and the role of wave activity on the formation of IonDLs using the AO-ISR’s ion-line and plasma-line data from the coded-long-pulse technique on 1-6 February 2019 during the geomagnetic quiet condition. The followings are the list of our results:

1. IonDLs are observed from 400 km to 90 km. Descending speeds of these layers increase with increasing altitude.
2. Descent of the IDLs is favored by the downward ion drifts. IDLs mainly occur in shearing zones in the vertical ion drifts at the line of sight.
3. Daytime top-side descending layers (TDLs) are newly discovered from the plasma-line; they occur above the altitude of F2-peak up to 400 km. These TDLs probably occur even beyond 400 km since layering features did not vanish till the noise floor dominates at the topmost altitudes of the plasma-line observations.
4. The intermediate descending layers (IDLs) occur from ~350 km to ~130 km and have substantial local time/solar zenith angle and day-to-day variability. Starting altitude of these IDLs is possibly from ~300-350 km (~250-300 km) during the nighttime (daytime). Multiple IDLs are observed more often in the daytime (at the altitude of ~225 km) than in the nighttime (at the altitude of ~275 km).
5. Twilight time IDLs are better pronounced than either daytime or nighttime; they mostly cross the discontinuity region of ~170 km and could reach the E region.
6. We found that all ionospheric descending layers, namely, TDL, IDL, USN, USD, and nighttime lower-diurnal layers, are connected together except daytime lower-
diurnal layers. This suggests that the source of the ion/metallic ion densities of these layers has a common origin.

7. The formation of the IDLs occurs in the F2-peak (bottom of F-peak) during the daytime (nighttime), and they are primarily driven by the gravity waves with a period varying from 1.5 to ∼4 hours.

8. Different waves govern TDLs and IDLs at different altitudes because the waves’ half-vertical wavelengths and phase velocities, as well as descending speeds, increase with increasing altitude. Half-vertical wavelengths vary from ∼1 km to ∼200 km (∼75 km to ∼200 km) for the IDLs (daytime TDLs).

9. IDLs occur with and without a concurrent spread-F event. However, intensified spread-F events raise the starting altitudes of the IDLs. Also, as IDLs descend, spread-F events distort them by the time they reach around 150 km. This distortion possibly delays their arrival time to ∼130 km to undergo a transition into USN.

IonDLs have starting altitudes as high as 400 km, and they vary from day to night. Nighttime IonDLs start from below the peak of the F-layer, and daytime IonDLs start as high as 400 km, well above the F2-peak altitude. Thus, the starting altitude of the nighttime IonDLs is the starting altitude of the nighttime IDLs. Moreover, daytime IonDLs are not bounded in the intermediate region between the F- and E-layer. The daytime IDLs are the layers that start below the discontinuity region of 170 km at the F1-peak without having connected to the daytime TDLs. Therefore during the daytime, the layers that occur above the altitude of 200 km are not the upper extension of the IDLs; instead, they are the continuation of TDLs, which start above the F2-peak altitude.

The IDLs and TDLs might be made up of metal ions since both are connected and resemble recent lidar observations (Jiao et al., 2022; Raizada et al., 2020). Those observations demonstrated that the IDLs are made up of metal ions. These metal ions further descend in altitudes as a result of wave activity. The waves at these layering altitudes possibly accumulate the densities by the wind shearing mechanism and bring them to the lower altitudes of the E-region. These metal ions are possibly meteoric in origin; meteors deposit the ions all the way through the E-region.

It can be noted that ions in the IonDLs are controlled by different governing mechanisms in different altitude regimes and therefore receive different terminology as TDL, IDL, USN, USD, and nighttime-lower diurnal layer. These IonDLs from 400 km could reach below 110 km and sustain/merge in addition to the locally formed Es layers at those heights. Therefore, we call them ion descending layers (IonDLs - same short form can be used). IonDLs have discontinuities. At the place of the discontinuity (160 km, 130 km, and 110 km), the accumulations of ions are left by the previous layering mechanism (gravity waves). And then, those ions are under the control of other layering mechanisms (tides). In this way, descending layers starting from TDLs could be transporting the metallic ions of meteoric origin from the topside/F-region of the ionosphere and dumping them into the lower E-region, similar to the transportation of debris on the ocean surface to the seashore by ocean waves.

Further studies are needed to understand the characteristics and formation mechanisms of the TDLs and IDLs by wind shear theory using the neutral winds and wave parameters. Also necessary are more observations of the effects of spread-F on IDLs, especially their local time variability, since there are discontinuities in the IDLs with/without a spread-F event. If IonDLs bring the densities down from the upper altitudes, it would be very interesting to study the densities associated with TDLs and IDLs over time in relation to the long-term negative trend in density in order to understand the relationship between the negative trend in density and descending layers.
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References


Figure 1.
Figure 2.
Figure 4.
Figure 6.
Figure 7.
Figure 8.
Figure 10.
Figure 12.