Title: Statistical Study of Medium-Scale Traveling Ionospheric Disturbances in Low-Latitude Ionosphere Using an Automatic Algorithm

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Abstract

This study investigates the medium–scale traveling ionospheric disturbances (MSTIDs) statistically at the low–latitude equatorial ionization anomaly (EIA) region in the northern hemisphere. We apply the automatic detection algorithm including the three-dimensional fast Fourier transform (3-D FFT) and support vector machine (SVM) on total electron content (TEC) observations, derived from a network of ground-based global navigation satellite system (GNSS) receivers in Taiwan (14.5°N geomagnetic latitude; 32.5° inclination), to identify MSTID from other waves or irregularity features. The obtained results are analyzed statistically to examine the behavior of low-latitude MSTIDs. Statistical results indicate the following characteristics. First, the southward (equatorward) MSTIDs are observed almost every day during 0800-2100 LT in Spring and Winter. At midnight, southward MSTIDs are more discernible in Summer and majority of them are propagating from Japan to Taiwan. Second, northward (poleward) MSTIDs are more frequently detected during 1200-2100 LT in Spring and Summer with the secondary peak of occurrence between day of year (DOY) 100-140. The characteristics of the MSTIDs are interpreted with additional observations from radio occultation (RO) soundings of FORMOSAT-3/COSMIC as well as modeled atmospheric waves from the high–resolution Whole Atmosphere Community Climate
Model (WACCM) suggesting that the nighttime MSTIDs in Summer is likely connected to the atmospheric gravity waves (AGWs).

**Keywords:** low-latitude MSTIDs, Support Vector Machine, Atmospheric Gravity Waves, Sporadic E layers

1. Introduction

Traveling ionospheric disturbances (TIDs) are known as the manifestation of atmospheric gravity waves (AGWs) of lower atmospheric origins (Hines, 1960) in the ionosphere. Among the TIDs, the disturbances with horizontal wavelength of 100-300 km and phase velocity of 50-300 m/s are classified as medium-scale TIDs (MSTIDs) (e.g. Hunsucker et al., 1982; Otsuka et al., 2013). MSTIDs were previously studied using various techniques in the middle latitudes such as all-sky airglow imagers, ionosondes, incoherent scatter radar, and total electron content (TEC) observations derived from ground-based global navigation satellite system (GNSS) receivers. (e.g., Bowman, 1985, 1989; Garcia et al., 2000; Saito et al., 2002; Shiokawa et al., 2003a, 2006; Otsuka et al., 2004, 2011; Amorim et al., 2011; Medvedev et al., 2017; Takeo et al., 2017).

MSTIDs were previously categorized into daytime and nighttime types according to their wave characteristics. The daytime MSTIDs at mid-latitude region in northern
hemisphere have feature of frontal alignment in east-west (E-W) direction propagating in meridional north-south (N-S) direction or frontal alignment of southwest-northeast (SW-NE) direction propagating in northwest-southeast (NW-SE) direction (Hernandez-Pajares et al., 2012; Kotake et al., 2006; Otsuka et al., 2011). On the other hand, the nighttime MSTID has a unique frontal alignment in the northwest-southeast (NW-SE) direction with propagation direction in equator westward direction (Behnke et al., 1979; Saito et al., 1998; Garcia et al., 2000; Shiokawa et al., 2003a; Kotake et al., 2006; Tsugawa et al., 2007a; Kubota et al., 2011; Hernández-Pajares et al., 2012; Rajesh et al., 2016). It is due to such a special frontal alignment, the phenomenon was originally explained by Perkins instability (c.f. Perkins et al., 1973, Behnke, 1979, Garcia et al., 2000).

As the growth rate of Perkins instability is much slower than the observations, previous studies suggested that the instability also requires seeding perturbation to induce the instability development. Kelley and Fukao (1991) recommended that AGWs could be a seeding mechanism to accelerate the Perkins instability. Huang et al. (1994) suggested that AGWs play an important role in formation of the nighttime MSTIDs due to the electrodynamic coupling, which was supported by follow-up observations (Miller et al., 1997; Nicolls and Kelley, 2005). Meanwhile, Shiokawa et al. (2003b) calculated the theoretical predicted growth of the Perkins instability. The result indicated that the
Perkins instability has low growth rate alone and it takes more than 2 hours, which is much longer than the observations. Recently, Chou et al. (2017, 2018), employed dense GNSS observations and simulations on the study of MSTIDs driven by typhoon and proposed that the severe weather driven concentric GWs (CGWs) could accelerate the Perkins instability by providing additional polarization electric field perturbations driven by the perturbation winds of CGWs.

Additionally, Sporadic E layer (EsL) instability is proposed as an important indirect driver of the nighttime MSTIDs (Cosgrove and Tsunoda, 2004), which is mainly produced by the effect of vertical wind shear in E region (Whitehead, 1961; Mathews, 1998; Carrasco et al., 2007; Haldoupis, 2011; Yeh et al., 2013). EsL instability can act as a vital character for accelerating growth of Perkins instability by projecting the polarization electric field perturbations to the F-region. Tsunoda (2006) showed the analytic results on the acceleration of the instability and Yokoyama et al. (2009) showed the self-consistent coupling of EsL and F layer Perkins instabilities through numerical simulations. Both studies have indicated the importance of this E and F layer coupling for growth of the MSTIDs.

Not only occurring at mid-latitude, observational studies also depicted characteristics of MSTIDs over the low-latitude regions (c.f. Shiokawa et al., 2006: Lee et al., 2008; MacDougall et al., 2011; Fukushima et al., 2012; Narayanan et al., 2014;
Jonah et al., 2016; Paulino et al., 2016; Figueiredo et al., 2018). For instance, the investigations using OI 630.0 nm airglow images taken by all-sky imager around the transition region of low to mid-latitudes (19.3°N dip latitude) reported by Narayanan et al. (2014) suggested that the MSTID could be inhibited by the equatorial ionospheric anomaly. Shiokawa et al. (2006) and Fukushima et al. (2012) suggested that the directionalities of MSTIDs over Kototabang (10.4°S dip latitude) are different from the typical MSTIDs observed at the mid-latitudes and attribute their formation by gravity waves. Paulino et al. (2016) carried out an investigation at the off-equatorial region, over São João do Cariri, by using airglow observations over nearly a solar cycle and speculated that the gravity waves are the likely source of the periodic MSTIDs.

As described above, MSTIDs were statistically studied in the ionosphere for quite a long time in mid-latitude region with some additional documentations over low-latitude region possibly driven by various physical mechanisms. Most of the studies, however, were performed mainly by adopting visual inspection of the observation data that requires time consuming efforts and could be influenced by subjective bias while inspecting the airglow images or TEC maps. Takeo et al. (2017) performed three-dimensional fast Fourier transform (3-D FFT) to detect the MSTIDs automatically in airglow imagers over a solar cycle for the first time. Here, our main goal is to develop an autonomous detection algorithm by combining the 3-D FFT and support vector
machine (SVM) to distinguish and categorize MSTIDs from other waves or irregularities in the GNSS-TEC maps.

In this study, the autonomously identified MSTIDs at low to mid-latitudes are statistically organized according to their wave parameters, i.e. wavelength, amplitude, propagation direction, seasonal and local time (LT) dependences. The possible mechanisms responsible for these low-latitude MSTIDs are discussed based on these statistical results with aids from the EsL observation obtained from the radio occultation (RO) observations of FORMOSAT-3/COSMIC (Yeh et al., 2014) and the AGWs simulated by the high-resolution Whole Atmosphere Community Climate Model (WACCM) (Liu et al., 2014).

2. Methodology

We develop an autonomous algorithm to detect MSTIDs by using both the 3-D FFT and the SVM. As the equatorial plasma bubbles (EPBs) affected by zonal neutral winds could appear in the reverse C-shape spatial distribution (Shiokawa et al. 2004; Kil et al., 2009) showing NW-SE (NE-SW) waveform in the northern (southern) hemisphere similar to the frontal alignment of MSTIDs, it is important to have the algorithm capable of distinguishing the two different instabilities. The algorithm is applied on the GNSS data around Taiwan (20-30°N, 115-125°E geographic
latitude/longitude and 15°N dip latitude) under the northern EIA crest during 2013-
2015 to study the characteristics, e.g. propagation direction, LT and seasonal
dependence, of MSTIDs and EPBs.

Before carrying out the 3-D FFT and SVM, a 60 mins. high pass filter is applied
to the GNSS-TEC data followed by interpolation of the filtered TECs into the fixed
grids with spatial resolution of ~0.5 deg. latitude/longitude in both zonal and meridional
direction with an accumulation period of 30 mins. It should be noted that we substitute
zero to the region with no available data owing to the limited coverage of GNSS
observation around Taiwan. The ionospheric pierce point (IPP) for converting slant to
vertical TEC is set at 300 km altitude. Figure 1a shows an example of the filtered TEC
over the region and Figure 1b illustrates the grids for the autonomous detection
algorithm.

We exploit the 3-D FFT method similar to that developed by Matsuda et al. (2014)
to the cumulative three-dimensional filtered TEC data for the zonal and meridional
wave numbers and angular frequency. It is noted that positive wave number represents
northward or eastward direction of propagation. The phase velocities ($V_p$) of the waves
are given in terms of the parameters obtained from the 3-D FFT as follows,

$$V_p = \sqrt{\left(\frac{\omega W_m}{2\pi K}\right)^2 + \left(\frac{\omega W_Z}{2\pi L}\right)^2}$$  \hspace{1cm} (1)
where $W_m$ and $W_z$ are meridional and zonal width of the detection region; $K$, $L$ and $\omega$ represent meridional wave numbers, zonal wave numbers and angular frequency, respectively. The propagation direction ($\theta$) is given as,

$$\theta = \emptyset + \tan^{-1} \left( \frac{W_m}{W_z} \frac{(L)}{K} \right)^2$$

(2)

where $\emptyset$ is the azimuth angle, which depends on the value of both zonal and meridional wave numbers.

The 3-D FFT will provide a weaker artificial enhancement of power spectral density (PSD) in the opposite direction than that of the true direction (Takeo et al., 2017). Therefore, the maximum PSD is taken to determine the direction for each computation to rule out the wrong directions in this study.

From the computed results together with the TEC observations, we obtain 10 kinds of parameters including horizontal wavelength, meridional and zonal wave numbers, phase velocity, propagation direction, angular frequency, PSD of the 3-D FFT, minimum TEC, day of year (DOY) and universal time (UT). These parameters are exploited for training the SVM model in order to distinguish MSTID, EPB and quiet time background ionosphere. The detailed procedures for creating the SVM model is
illustrated in Figure 2. In the SVM model, we create a ten-dimensional space where the coordinates stem from the 10 kinds of parameters mentioned above. The data are represented as points and are mapped into the 10-dimensional (10-D) space according to the corresponding values of each parameter. In the 10-D space, the SVM model separates different classes by computing the best boundaries called hyperplanes. New data are then mapped into that same space and are predicted into various classes based on the side of the hyperplane on which they might fall. Presumably, the hyperplane between anisotropy classes should be as wide as it could be to maintain the quality of the SVM model. Therefore, a soft-margin method, defining the width of a hyperplane in non-linear classification, is applied on supporting the hyperplane. We define a hyperplane with a soft-margin in the following form (Chen et al., 2004; Chang et al, 2011),

\[
|N_h \cdot x - b| \geq 1 \pm \varepsilon_i
\]  

(3)

where \(N_h\) represents the normal vector to the hyperplane; \(x\) refers to the normalized 10-D parameters; \(b\) is a normal constant; the normal constant (on the right-hand side of the equation) ”1” or “-1”, considering the absolute value, indicates two different classes; \(\varepsilon_i\) represents slack variable which determine the width of the soft-margin. It should be
apparent that the greater the value of slack variable is, the larger the breadth of the soft-
margin would be. In order to maintain the quality of classification, the slack variable
should as small as it could be where we set the value as 0.4 in our case.

In this study, a supervised learning method is used for classifying the different
classes. Supervised learning indicates that we have to label the classes for the raw data
to create input-output pairs before training the SVM model. In our case, we label the
different classes using discriminants and a little visual inspection for validation. During
the training processes, a solar maximum year, 2000, and a solar minimum year, 2009,
are used for training and testing the model quality since MSTIDs and EPBs have a
different solar activity dependence. Due to the 30 mins time resolution in the 3D-FFT
computation, the total number of data for these two years are around 35000. The dataset
is randomly separated into two groups including 80% of training data (~28000 piece)
and the other 20% of testing data (~7000 piece). The training data are used for training
the model by computing a hyperplane for categorizing anisotropy classes. On the other
hand, the testing data applied on testing the trained model are utilized for calculating
the accuracy rate of the SVM model prediction. Here, the accuracy is the ratio of
number of correct predictions to the total number of input samples. During the testing
processes, the dataset is repeatedly split into training data and testing data for five times
to test the model performance. The testing results indicate that our model has over 96% accuracy rate for distinguishing MSTID, EPB and ionosphere without irregularity.

3. Results and Discussions

In the analysis, we define the four seasons as follows: (1) Spring: from 6 February to 6 May for 3 months, centering on the spring equinox; (2) Summer: from 6 May to 6 August for 3 months, centering on the summer solstice; (3) Fall: from 6 August to 6 November for 3 months, centering on the fall equinox; and (4) Winter: from 6 November to 6 February for 3 months, centering on the winter solstice.

Since the EPB is a well-known phenomenon in the low-latitude ionosphere which was investigated intensively, it is conceivable to validate the characteristics of EPBs, using our algorithm, such as occurrence rate, propagation direction and seasonal dependence. Here, the occurrence rate is defined as the ratio between the number of events in which EPBs are observed (M) and the amount of data in which GNSS-TEC exist (N). Since the GNSS-TEC data are available every 30 seconds during 2013-2015, the value of N is identical in each occurrence rate computation.

The observed characteristics of EPBs during 2013-2015 can be summarized as follows (figure not shown). First, the EPBs are usually observed at the LT period of 2000-0200 with an eastward propagation direction. Second, the occurrence rate of EPBs
is higher in the solar maximum year of 2014, showing the dependence on the solar activity. Third, the cumulative occurrence rate for these years indicates that the seasonal occurrence rate of EPBs is descending in the order from Spring, Fall, Summer, to Winter. The characteristics of EPBs in their diurnal and seasonal variations are consistent with those reported in the previous studies (e.g. Sahai et al., 2000; Huang et al., 2002; Pimenta et al., 2003; Fejer et al., 2005; Gentile et al., 2006; Yao & Makela, 2007; Paulino et al., 2011; Sharma et al., 2014; Sun. et al., 2016) suggesting the reliability of our algorithm.

3.1 Observation Results

In this section, we display the annual variations (2013-2015) of the characteristics of MSTIDs by excluding the possible contamination coming from EPBs. The wavelength and horizontal phase velocity characteristic of MSTIDs over Taiwan are respectively among 100-400 km and 100-250 m/s which are consistent with the previous studies (e.g. Hunsucker et al., 1982; Otsuka et al., 2013). The occurrence rate of MSTIDs are calculated by using the same approach applied for calculation of the occurrence of EPBs described in Section 3. The results illustrate that the occurrence and propagation characteristics of MSTIDs have clear seasonal and LT dependences. The occurrence rate of southward MSTIDs (Figure 3a-c) indicates that they are more
discernable during 0800-2100 LT in Spring and Winter. During Summer, southward
MSTIDs mainly occur around 2100-0300 LT. On the contrary, the occurrence rate of
northward MSTIDs (Figure 3d-3f) demonstrates that they are more frequently observed
around 1200-2100 LT from Spring to Fall with a secondary peak occurring around
0000-0300 LT between DOY 100-140. In Figure 3g-3i, a transition boundary between
the northward and southwestward MSTIDs takes place three hours after sunset at
around 2100 LT during Summer. It is noteworthy that the LT dependence of the
southwestward MSTIDs takes place much later after sunset than those reported in the
previous literatures (Behnke et al., 1979; Saito et al., 1998; Garcia et al., 2000;
Shiokawa et al., 2003a; Kotake et al., 2006; Tsugawa et al., 2007a; Kubota et al., 2011;
Hernández-Pajares et al., 2012; Otsuka et al., 2013), which suggests an alternative
driving mechanism should be proposed. A rational explanation is that the
southwestward MSTIDs are mainly propagating from higher latitude to the lower
latitude over Taiwan region instead of being generated locally.

The filtered TEC over Japan and Taiwan (Figure 4a-4b) reveals the relationship
between the MSTIDs at low and mid latitudes. To identify the characteristics of the
MSTIDs over Japan and Taiwan, we organize filtered TEC as a function of distances
and time (Figure 4c). The filtered TEC along the orange dash line in Figure 4b is chosen
for organizing Figure 4c for studying the characteristics of MSTIDs in this case. The
daytime MSTIDs (Figure 4a) propagate toward southeast and northwest over Japan and Taiwan, respectively. On the contrary, the nighttime MSTIDs (Figure 4b) demonstrate that they are propagating southwestward over Japan and across a long distance to reach Taiwan region. In Figure 4c, results apparently show that the MSTIDs over Japan have greater wave amplitudes (~0.2 TECu, where 1 TECu = $10^{16}$ el/m$^2$) and longer wavelengths (~250 km) than those over Taiwan where the wave amplitude is around 0.1 TECu and the wavelength is about 100 km. The red rectangle in Figure 4c, therefore, illustrates that the MSTIDs around 1400-2100 UT (2200-0500 LT) over 22-28°N latitude are mainly coming from Japan as they have a greater TEC amplitude fluctuation and wavelengths than those in the same latitudes at earlier local times.

To further identify the relationship between the MSTIDs over Japan and Taiwan, we compare the propagation direction with normalized power spectral density (PSD) of MSTIDs (Figure 5) between DOY 100-300 during 2013-2015. The PSD derived from 3-D FFT indicates the power of the waves, which corresponds to the square of the amplitude fluctuation. The normalized PSD with greater value, indicating perturbations with greater wave amplitude, mainly occur three hours after sunset. This is in good agreement with the southwestward MSTID observations, further suggesting that these MSTIDs are mainly propagating from Japan instead of being generated over Taiwan.
3.2 Perkins /Es Layer Instability and MSTIDs

For the nighttime MSTIDs, Perkins instability (Perkins, 1973) was considered as the most plausible generation mechanism to explain the special wavefront alignment (NW-SE) of MSTIDs (Benke, 1979; Garcia et al., 2000). According to Shiokawa et al. (2003) and Tsunoda (2006), the linear growth rate \( \gamma_p \) of the Perkins instability can be given as:

\[
\gamma_p = \frac{g}{H_n < v_{in}>} \frac{sin^2(I) sin(\theta - \alpha) sin(\alpha)}{cos(\theta)}
\]

\[
= \frac{E_0 sin(\theta - \alpha) sin(\alpha) cos(I)}{BH_n} \frac{< v_{in}>_{at}}{< v_{in}>}
\]

(4)

where \( g \), \( H_n \) and \( v_{in} \) are the gravitational acceleration, scale height of neutral atmosphere and ion-neutral collision frequency; \( I \) represents the magnetic inclination; \( \theta \) is the angle of background electric field from east; \( \alpha \) means the angle between the direction normal to the frontal structure and east; \( E_0, B \) and are the background electric field and magnetic field; subscript 0t represents inclusion of a tangential component.

Notice that \( \alpha \) should be greater than zero but less than or equal to \( \theta \).

In Equation (4), the ion-neutral collision frequency is inversely proportional to the growth rate. The neutral density is small during solstices and magnetically quiet periods.
of solar activity, which generates a lower ion-neutral collision frequency. This effect could produce a high occurrence rate of nighttime MSTIDs during solstices and low solar flux years which agree with the previous literatures (e.g. Shiokawa et al., 2003a; Kotake et al., 2006).

On the other hand, a coupled electrodynamical system between EsL and F region also plays an important role to accelerate the growth rate for nighttime MSTIDs (e.g. Cosgrove & Tsunoda, 2004; Tsunoda, 2006; Yokoyama et al., 2009). In this study, we estimate the occurrence of EsL by using FORMOSAT-3/COSMIC (F3/C) radio occultation (RO) data for comparing with the MSTIDs characteristics in nighttime during 2013-2015. Resende et al. (2018) revealed that the S4 scintillation index derived from the F3/C RO profiles, which provide the disturbance information from the signal to noise ratio (SNR) of the electron density from GPS L1 band, is suitable to estimate the EsL at low latitudes due to their high correlation. In this case, an S4 threshold of 0.3 is set over 80-130 km altitudes (c.f. Whitehead, 1989; Chu et al., 2014; Yeh et al., 2014; Tsai et al., 2018) for evaluating the occurrence of EsL. It is noteworthy that the EsL do not have a conjugate effect but the MSTIDs are presented as conjugate structures in both hemispheres according to previous studies (Saito et al., 1998; Otsuka et al., 2004; Martinis et al., 2019). That is, the EsL occurring at one of the hemispheres could trigger the MSTID in both hemispheres, coherently. As a result, two detection regions are
formed, which are (i) Taiwan region, the same as mentioned in Section 2, and (ii) the conjugate region of Taiwan, the identical meridional and zonal breadth to (i) but centering at 120°E geomagnetic longitude; -4°S geomagnetic latitude, for investigating the EsL characteristics in nighttime during 2013-2015.

The EsL mainly occur in Summer but the occurrence is much less over Taiwan (Figure 6a) than over Japan (Otsuka et al., 2008) in nighttime, which is consistent with the previous study (Zhou et al., 2017). On the contrary, the southward/northward (Figure 6c/6d) MSTIDs still have considerable occurrence rate until 2200 LT in Spring and Winter/2100 LT in Spring to Fall with the identical propagation direction (Figure 6b) before and after the dusk terminator (black line). Also, the propagation direction of the northward MSTIDs (Figure 7) illustrates that the MSTIDs mainly propagate northwestward (wavefront of NE-SW direction) and exactly northward (wavefront of E-W direction), which are inconsistent with the theoretical wavefront alignment (NW-SE) of Perkins instability and EsL instability (Perkins, 1973; Cosgrove and Tsunoda, 2004). The anisotropy characteristics between EsL and MSTIDs rules out the possibility that the Perkins instability and EsL instability are responsible for generating the nighttime MSTIDs over Taiwan.

3.3 Gravity Waves and MSTIDs
As the characteristics of EsL (Perkins instability) do not favor MSTIDs generation and propagation, AGWs are considered as a plausible driver of the northward-propagating MSTIDs in Spring and Summer nighttime over Taiwan. The secondary peak of occurrence of northward MSTIDs taking place post-midnight between DOY 100-140 should be amenable to interpretation in terms of AGWs. Figure 8 displays an example of 557 nm airglow images on 29 April 2020 around 0209-0239 LT, obtained from an all sky imager operating at Tainan Astronomical Education Area (120.39°E; 23.18°N). The images, mainly contributed from about 95-97 km altitude, are used to evaluate the horizontal structures of AGWs during this period. Using the 3-D FFT, the series of airglow images demonstrate the salient northeastward propagation of AGWs with a horizontal phase velocity, horizontal wavelength, and period of ~114 m/s, ~83 km, and ~12 min. respectively over Taiwan. Meanwhile, the filtered TEC map with an IPP at 300 km altitude (Figure 9) reveals the northeastward MSTIDs with a horizontal phase velocity, horizontal wavelength, and period of ~147 m/s, ~151 km, and ~17 min., respectively. The nearly identical propagation direction and similar characteristics of AGWs and MSTIDs suggesting that AGWs should be responsible for the nighttime MSTIDs over Taiwan for this event. However, the time characteristic in the airglow images and filtered TEC maps are different in this case suggesting that further correlation between each other should be proposed.
To further understand the correlation between AGWs and MSTIDs, we evaluate the resolved AGWs derived from high-resolution WACCM among 30 June to 11 July. In the high resolution WACCM, the horizontal and vertical resolution are ~0.25° and ~700 m, respectively. In this case, we investigate AGWs horizontal structure at 5.8e-4hpa (~93 km) altitude (c.f. Zhou et al., 2002; Suzuki et al., 2007; Chun and Kim, 2008; Heale et al., 2020) in the WACCM. Taking 1400 UT on 9 July for example, the zonal wind (Figure 10a) and meridional wind (Figure 10b) patterns display several salient northwestward AGWs structures propagating over north Pacific Ocean and across a long distance ~2800 km along the Philippines, before reaching Taiwan. In this case, the waves structures mostly dissipate around 30°N geographic latitude by the stronger in phase background wind. In Figure 10c-10d, we estimate the morphological characteristics of AGWs as a function of time and distances by organizing the zonal and meridional wind along the yellow arrow in Figure 10a and 10b. Several long-lasting, ~12 hr, northwestward AGWs are found during this period with a horizontal wavelength of tens to hundreds of km and a horizontal phase velocity among 20-85 m/s which are consistent with previous literatures (Piani et al., 2000; Horinouchi et al., 2002; Sentman et al., 2003; Suzuki et al., 2007; Takeo et al., 2017; Tsuchiya et al., 2019).

In Figure 11, the propagation direction characteristic of AGWs (red line with stars), obtained from the 3-D FFT over Taiwan, is compared to the MSTID observations (blue
line) in Summer during 2013-2015. The locally generated MSTIDs mainly occurring
during 1200-2100 LT in Summer (Figure 3) are in good agreement with the
locally generated MSTIDs mainly occurring during 1200-2100 LT in Summer (Figure 3) are in good agreement with the corresponding WACCM output suggesting that AGWs may play a role in the generation of MSTIDs during this period. However, there is a clear disagreement occurring after 2000 LT showing southwestward propagation of MSTIDs while AGWs are northward. The disagreement confirms that the southwestward MSTIDs after 2100 LT mainly come from the southwestward propagation of MSTIDs originated from Japan as described in Section 3.1.

Tsugawa et al (2007a) suggested that the MSTID activity over Japan is highest in the nighttime during 2100-0300 JST in Summer (May-August or DOY 140-250). Since the amplitude of the MSTIDs over Japan is greater than that over Taiwan, it is difficult to isolate any influence of Japan MSTID’s in the overlapping TEC observations over Taiwan. However, the DOY from 100-140, when the southwestward MSTIDs over Japan were least observed could be the opportunity for the identification of locally generated MSTIDs over Taiwan. This characteristic of MSTIDs, when they are present, is consistent with a secondary occurrence peak of the northward MSTIDs over Taiwan suggesting that this secondary peak of northward MSTIDs could be identified owing to the least occurrence of MSTIDs over Japan during the period. Also, the propagation direction characteristic of AGWs after 2000 LT (Figure 11) is mainly propagating
northwestward which is consistent with the secondary peak of the MSTIDs observations (Figure 7). It suggests that AGWs is likely an important seeding driver for generation of the northward-propagating MSTIDs over Taiwan in nighttime in Summer. Based on the propagation directions and seasonal occurrences, we suggest that the AGWs have a great contribution to the low latitude MSTIDs in both daytime and nighttime in Summer.

4. Discussion

Regarding the southwestward MSTIDs taking place ~3 hours after sunset, an alternative explanation is that they are mainly coming from mid-latitude region. AGWs seeding, however, could be a plausible mechanism to accelerate the Perkins instability where the growth of the instability could be significantly enhanced and accelerated (Kelly and Fukao, 1991; Huang et al., 1994; Chou et al., 2017). Such a mechanism, hence, indicates that the southwestward MSTIDs could be generated locally due to the Perkins instability as well. In order to understand further about the generation mechanism of the southwestward MSTIDs, the occurrence rate of southwestward MSTIDs are compared between Japan and Taiwan. Otsuka et al. (2011) revealed that the occurrence rate is ~30% over Japan in a solar maximum year in nighttime in Summer. Our study, however, shows the higher occurrence rates of ~40% in a solar
maximum year. It should be apparent that the MSTIDs should be generated locally since
the higher occurrence rates over Taiwan is inconsistent with the hypothesis that the
southwestward MSTIDs mainly come from Japan. However, the solar activity condition
in our study (f10.7 index is 145.9 s.f.u.) is much weaker than that proposed by Otsuka
et al. (2011) (f10.7 index is 179.4 s.f.u.) suggesting that the further relationship between
the MSTIDs over Japan and Taiwan should be investigated in the future works.

5. Summary

In this study, we utilize both the 3-D FFT and SVM to statistically investigate the
MSTIDs in the low latitude equatorial ionization anomaly region over Taiwan during
2013-2015. As EPBs have some characteristics similar to MSTIDs, the occurrence of
EPBs is also investigated in order to distinguish it from the MSTIDs. Several important
features such as the variation of the propagation direction and occurrence rates are
revealed in this study. The main findings are summarized as follows.

1. The statistical results show that the seasonal, LT variations and solar activity
dependence are generally consistent to previous studies of MSTIDs and EPBs,
indicating that our algorithms could successfully distinguish EPBs and MSTIDs
in the TEC perturbations.
2. The occurrence rate and propagation direction of MSTIDs have clear seasonal and LT dependences. In Spring and Winter, southward MSTIDs are observed almost every day during 0800-2100 LT, and in Summer they appear mainly during 2100-0300 LT and have least occurrence in Autumn. On the contrary, northward MSTIDs are observed more frequently during 1200-2100 LT from Spring to Autumn with a secondary peak during 0000-0300 LT between DOY 100-140.

3. The propagation directions of MSTIDs patterns display a clear boundary for northward and southwestward MSTIDs at 2100 LT in Summer. During 1200-2100 LT, the MSTIDs mainly propagate northward and northwestward. On the other hand, the MSTIDs observed during 2100-0300 LT mainly propagating southwestward are majorly coming from Japan, mid-latitude region.

4. By comparing the occurrence of MSTIDs over Japan and Taiwan, we suggest that the MSTID in Taiwan region are influenced by the southwestward-propagating MSTIDs from Japan during 2100-0300 LT between DOY 140-250 due to the overlapping in TEC observations. A secondary occurrence peak of northward MSTIDs during 0000-0300 LT between DOY 100-140, therefore, could be generated owing to the least occurrence of MSTIDs over Japan.
5. The wavefront alignment characteristic of nighttime MSTIDs is inconsistent with the Perkins and EsL instability, ruling out the possibility of these generation mechanisms. In contrast, the relationship between $\lambda$557nm airglow images and filtered TEC map together with a simulation result from WACCM illustrate that MSTIDs over Taiwan are likely generated by AGWs during both daytime and nighttime in Summer due to the similar characteristics between MSTIDs and AGWs.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

List of abbreviations

AGWs : atmospheric gravity waves.
CGWs : concentric gravity waves.
DOY : day of year.
EIA : equatorial ionization anomaly.
EPBs : equatorial plasma bubbles.
EsL : sporadic E layer.

F3/C : FORMOSAT-3/COSMIC.

GNSS : global navigation satellite system.

IPP : ionospheric pierce point.

LT : local time.

MSTIDs : medium-scale traveling ionospheric disturbances.

PSD : power spectral density.

RO : radio occultation.

SNR : signal to noise ratio.

SVM : support vector machine.

S4 : scintillation index.

TEC : total electron content.

TIDs : traveling ionospheric disturbances.

UT : universal time.

WACCM : Whole Atmosphere Community Climate Model.

3-D FFT : three-dimensional fast Fourier transform.

**Availability of data and materials**
The GNSS-TEC data are provided by the Central Weather Bureau in Taiwan (https://gdms.cwb.gov.tw/) and Geospatial Information Authority in Japan (http://www.gsi.go.jp/ENGLISH/index.html). The F3/C data are provided by Taiwan Analysis Center for COSMIC (TACC) (https://tacc.cwb.gov.tw/v2/). The all sky imagers data are available on the all sky observatory (ALSO) (http://allsky-airglow.earth.ncku.edu.tw/PicWeb/MainHTML/2020/04/29). The f10.7 index is derived from OMNIWeb Service under Space Physics Data Facility (SPDF) in NASA (https://omniweb.gsfc.nasa.gov/).

**Competing interests**

The authors declare that they have no competing interests.

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**Authors' contributions**

PHC drafted the manuscript, created the SVM model, carried out 3D-FFT method, program coding and analyzed the data. CHL and PKR critically evaluated the text for scientific content and elaborated it. CHL and YO gave very important conceptions on analyzing the observational results. HLL dealt with the WACCM.
PKR and JTL established the airglow images. CHC constructed the TEC filter. All authors read and approved the final manuscript.

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**Figure 1**
Identification of GPSTEC perturbations over Taiwan. (a) 60 min. high-pass filtered GNSS-TEC for extracting the MSTID features. (b) Horizontal range of the ionospheric phenomena detection. The latitude and longitude range are 20-30°N and 115-125°E, respectively, with both zonal and meridional resolution of ~0.5 degree.

**Figure 2**
Flowchart of the procedure of creating an SVM model for classifying different ionospheric conditions.
Local time and seasonal variations of the MSTID obtained from 3D-FFT and SVM analysis over Taiwan during 2013-2015. It is divided into 10 days and half an hour per grid for calculating the occurrence rate of southward MSTIDs in (a) 2013 (b) 2014 (c) 2015 year and northward MSTIDs in (d) 2013 (e) 2014 (f) 2015 year. The propagation direction of MSTIDs is compared to the dusk terminator (black line) in (g) 2013 (h) 2014 (i) 2015 year.

Daytime and nighttime MSTID propagation over Japan and Taiwan. (a) An example of typical daytime MSTIDs over mid- and low-latitude region, and (b) example showing nighttime MSTIDs propagating from Japan to Taiwan. (c) The filtered TEC perturbations, along the orange dashed line in Figure 4b, organized as time-distance map.

A comparison between propagation direction and normalized PSD of MSTIDs with a dusk terminator (black line) over Taiwan. The southwestward MSTIDs (deep blue color) in the years (a) 2013 (b) 2014 (c) 2015 is in good agreement with the PSD with greater value (red color) in (d) 2013 (e) 2014 (f) 2015, suggesting that the southwestward MSTIDs have greater amplitudes than those propagating in other directions.
Figure 6

Comparison of EsL and MSTID occurrence. (a) The occurrence rate of EsL detected by FORMOSAT-3/COSMIC RO over Taiwan and the conjugate region of Taiwan in nighttime during 2013-2015. (b) The propagation direction of MSTIDs over Taiwan in nighttime during 2013-2015. (c) The occurrence rate of southward MSTIDs over Taiwan in nighttime during 2013-2015. (d) The occurrence rate of northward MSTIDs over Taiwan in nighttime during 2013-2015. The black lines indicate the dusk terminator.

Figure 7

The occurrence rate of (a) northwestward, (b) northward and (c) northeastward MSTIDs over Taiwan in nighttime during 2013-2015. The black lines indicate the dusk terminator.

Figure 8

The λ557nm airglow images derived from Tainan Astronomical Education Area on 29 April 2020.

Figure 9

Two-dimensional filtered GNSS-TEC maps over Taiwan on 29 April 2020.

Figure 10

Examples of (a) Zonal Wind and (b) Meridional Wind derived from high-resolution WACCM at 5.8e-4 hpa at 14:00 UT in 9 July. The yellow arrows indicate the propagation direction of the visible AGWs. (c) Zonal wind and (d) Meridional Wind-time-distance map along the yellow arrow in Figure 10a and 10b,
respectively. Each pair of the red symbols indicates an AGWs event. The numbers above the symbols represent the phase velocity of the AGWs.

**Figure 11**

Comparison between the propagation directions of MSTIDs and the AGWs derived from WACCM. The gray lines are the MSTID propagation direction during 2013-2015, and the blue line represents the averaged value during 2013-2015. The red line with stars displays the corresponding WACCM results.