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Some characteristics of large-scale travelling ionospheric disturbances and a relationship between the F_2 layer height rises of these disturbances and equatorial pre-sunrise events

G. G. Bowman and I. K. Mortimer

School of Mathematics and Physics, Physics Division, The University of Queensland, Brisbane, Queensland, Australia

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Abstract. Initially some characteristics of large-scale travelling ionospheric disturbances (LS-TIDs) have been discussed briefly particularly as reported in the early literature. These discussions also involve the literature on the generation of LS-TIDs at times of geomagnetic bays. Secondly, the possibility that LS-TIDs may be responsible for the F_2 layer equatorial pre-sunrise height rises is investigated. Tabulations at hourly intervals of $h'F$ at Huancayo and Washington for a Rz max period (1957–1960) have been used to identify height rises. For a three-hour interval at Huancayo $h'F$ levels equal to or greater than 40 km of medians are used to identify the pre-sunrise height rises. Also height rises at Washington, which occurred earlier than those at Huancayo, have been considered for evidence of travelling disturbances. For 40 events analysed using geomagnetic bays and Washington height rises, a few hours before they occur at Huancayo, indicate the statistical significance of an association with LS-TIDs. Similar results of statistical significance have been obtained using Washington events and bays on average 34 h before 46 Huancayo events. These delays ranged from 29 h to 38 h. The results indicate that bays which occur the day before are responsible for LS-TIDs which encircle the earth.

Keywords. Ionosphere (Equatorial ionosphere; Ionospheric disturbances; Mid-latitude ionosphere)

Correspondence to: I. K. Mortimer
(ian@physics.uq.edu.au)

1 Introduction

Some characteristics of nighttime large-scale travelling ionospheric disturbances (LS-TIDs) will be examined, particularly as reported earlier in the literature, and as detected by ionograms. Francis (1975) has made an extensive study of the theoretical and experimental aspects of the influence which the propagation of atmospheric gravity waves (AGWs) has on the ionosphere. Both medium-scale travelling ionospheric disturbances (MS-TIDs) and LS-TIDs have been considered. Francis (1975) states, p. 1011 "TIDs of both classes have been observed to propagate for thousands of km without apparent attenuation. Large-scale TIDs observed at mid latitudes invariably move towards the equator, and their occurrence is strongly correlated with severe magnetic storms". However early investigations at Brisbane have shown that LS-TIDs can also be recorded at other times. An early report by Davis (1971) indicates that as well as during disturbed conditions, LS-TIDs are also observed during less active geomagnetic conditions.

Francis (1975) discusses (p. 1040) a result by Davis (1971) which shows a relationship between the generation of LS-TIDs and auroral-zone substorms. These relationships were found for substorms in the evening sector, not only on a one to one basis but also when considered statistically. Figures 1a and 1b are reproductions of Figs. 3 are 2 (respectively) of Bowman (1978). They illustrate the use which has been made in the past of steep substorm onsets for the generation times of LS-TIDs. Figure 1 will be discussed in some detail later. An example of a steep substorm onset is illustrated in Fig. 4 of Bowman (1978). Other examples are shown by Fig. 4 of Bowman (1992).

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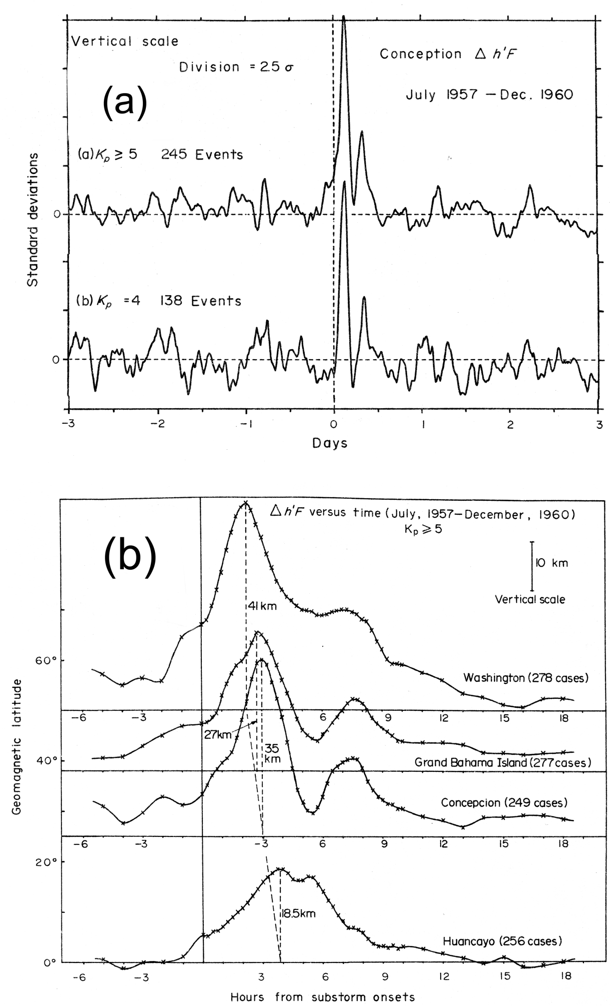


Fig. 1. Reproductions of average $\Delta h'F$ levels relative to substorm onsets from **(a)** Fig. 3 of Bowman (1978) for Conception and **(b)** Fig. 2 of Bowman (1978) for a range of stations as LS-TIDs propagate towards the equator.

Section 2 will review briefly the literature which explains a few characteristics of LS-TIDs, some of which will be shown in Sect. 3 to be particularly relevant to the occurrence of equatorial pre-sunrise F_2 layer height rises at Huancayo. Fejer (2002) and Fejer et al. (2008) have shown that vertical drifts which are related to these height rises are associated with geomagnetic activity (GA). These analyses will use published data of geomagnetic bays, which can be imagined as involving both steep substorm onsets as well as those events where onsets are not so steep. Although these bays are recorded to the nearest minute, the analyses will use them to the nearest hour. Publications by Bartels, Romana and Veldkamp (1961–1964) will be used to identify the bays.

The other data used will involve tabulations of $h'F$ events for both the equatorial station, Huancayo (Hu), and the high-latitude station, Washington (Wa). Both stations have a local time which is 5 h earlier than universal time (UT) or LT=UT−5 h. However most of the analyses will use UT rather than LT. Table 1 of Bowman and Mortimer (2009) lists subdivisions of the year into periods J, D, and E. This investigation will use period D for months around the December solstice and period E for the equinoctial months. Also the equatorial nighttime ionosphere has been divided into three 3 h intervals, one of which, INTR, will be used here for Huancayo. The INTR covers the pre-sunrise interval of local times, 03:00, 04:00 and 05:00. The UT times are 08:00, 09:00 and 10:00. For Washington, and also for the recording of geomagnetic bays, four 3 h intervals have been used. They range from 21:00 to 08:00 (UT) on the next day. They are called intervals A, B, C and D, and are listed in Table 1.

The more significant Huancayo pre-sunrise height rises (from lower levels) will be identified as those having $h'F$ values ≥40 km greater than the particular median for the hour involved. Each one of these events will be recognised as contributing to $h'F$ HIGHs (or Hu $\Delta h'F$) for the interval (INTR). Any extension into INTR of large pre-sunrise height increases produced by electric fields in the post-sunset period has not been considered. Table 2 lists the geomagnetic coordinates of stations which will be used here.

Table 1. Subdivisions.

	Universal Time
INTA	06:00, 07:00, 08:00
INTB	03:00, 04:00, 05:00
INTC	00:00, 01:00, 02:00
INTD	21:00, 22:00, 23:00

Table 2. Geomagnetic coordinates.

Station	Latitude	Longitude
Halley Bay	−65.76	24.28
Hobart	−51.32	224.17
Washington	50.03	360.24
Brisbane	−35.74	226.87
Grand Bahama	37.93	349.96
Concepcion	−25.12	356.15
Cape York	−20.17	212.49
Huancayo	−0.6	353.18

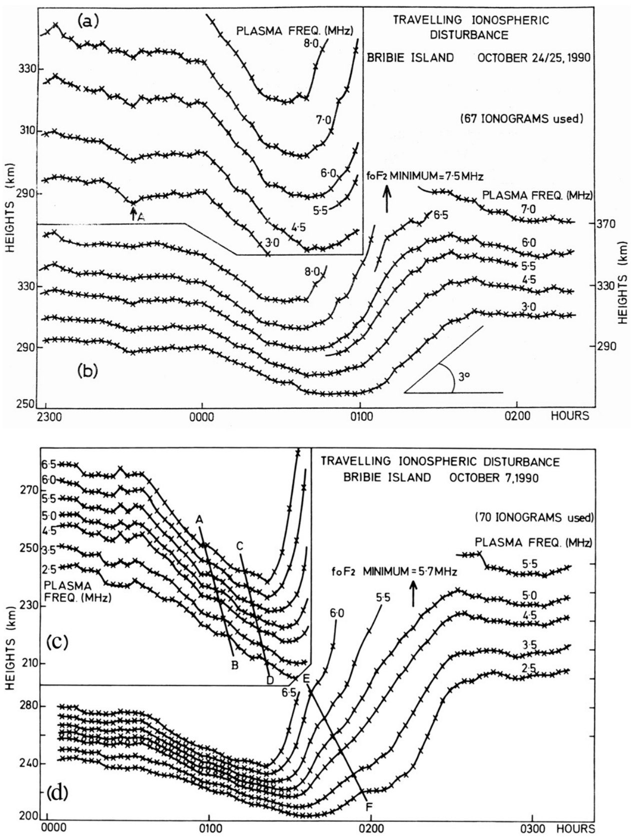


Fig. 2. Reproductions of LS-TID induced F_2 layer changes from **(a)**, **(b)** Fig. 5 of Bowman (1992) and **(c)**, **(d)** Fig. 19 of Bowman (1992).

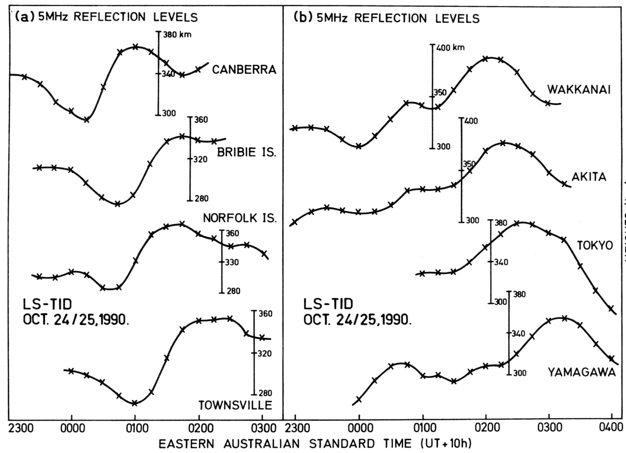


Fig. 3. A reproduction of Fig. 2 of Bowman (1992) showing LS-TID propagation **(a)** in Australia involving a speed of $507\,\mathrm{m\,s^{-1}}$ and **(b)** in Japan where the speed was $443\,\mathrm{m\,s^{-1}}$.

2 Some characteristics of LS-TIDs

Figure 4 of Bowman (1978) illustrates the use of an individual substorm onset to determine, as a LS-TID propagates towards the equator, the delay times at various ionosonde stations. For this event the delay time at Huancayo, for the start of a height rise, is 2.5 h and the LS-TID speed is $740\,\mathrm{m\,s^{-1}}$. Similarly Figs. 1 and 2 of Hajkowicz (1983a) show the delays which occur at various stations following an impulsive-type absorption event as measured by a riometer. Substorm activity was also present. Earlier analyses have used multiple substorm-onsets, sometimes using hundreds of events, to obtain delays statistically. Such analyses are shown here by Fig. 1a and b. Also the measurements of a chain of riometers were used by Hajkowicz (1983b) to detect an isolated LS-TID source near College, Alaska. This source area was confined to 17° of longitude and L-values between 5.0 and 5.3 for latitudes. Hajkowicz (1983a) states, p. 175 "It is suggested that the onset of TIDs is associated with high-energy particle precipitation, manifested by the occurrence of auroral absorption events. Similarity of absorption increases at the southern and northern conjugate points, …, would indicate that large-scale TIDs are simultaneously generated in both hemispheres." Ding et al. (2007) have detected a LS-TID source located between geomagnetic latitudes of 61° and 66°, and between geographic longitudes of 70° and 80°. French (1968) investigated an ionospheric disturbance associated with a specific substorm onset. The earlier analyses have assumed that it seems most likely that LS-TIDs are generated during impulsive absorption events (see Hajkowicz, 1983a, b). Similarly, LS-TIDs are also generated by upper atmosphere nuclear explosions (see Bowman, 1962; Bowman and Mainstone, 1964).

If for a sequence of ionograms the virtual ranges are recorded at spaced frequencies in the manner shown by Fig. 2 some characteristics of LS-TIDs can be identified, for single events during the passage of AGWs. For the lowest frequency used, the virtual range will be close to the true range. In particular large scale structures (LSSs) lasting for 30 min and more are recorded. Figures 2a–d are reproductions of Figs. 5 and 19 of Bowman (1992). The ionograms used were spaced at 3 min intervals. The diagrams show initially a height reduction followed by a more significant height rise about an hour later. Electron-density depletions are also recorded. As shown, the height rise on Fig. 2a, b involves a tilt of only 3°, which is a consequence of the fast speeds of LS-TIDs. Average results have been found for the two plots of Fig. 2 and four others. Table 3 lists the results obtained. For MS-TIDs, wavetrains with periodicities of around 10 min have been called medium scale structures (MSSs) as explained by Bowman and Mortimer (2008). These structures for MS-TIDs are often tilted significantly which allows spread-F traces to be recorded on ionograms. However for LS-TIDs, wavetrain periodicities of around 17 min are shown by Figs. 7 and 8 of Bowman (1996) as does Fig. 9 of Bowman (1992). Similar results are reported by Williams et al. (1988). For LS-TIDs Oya (1982), who used satellite recordings, found speeds ranging

Table 3. Mid-latitude LSSs of LS-TIDs (6 plots).

LSSs	$\Delta fo\mathrm{F}_2$ MHz	$h'F$ fall km	$h'F$ rise km	rise time min
Averages	-0.8	33	60	63

Table 4. Very fast LS-TIDs.

Literature	Speeds (ms^{-1})
Bowman (1962)	1666
Bowman and Mainstone (1964)	840
French (1968)	910–1030
Davis (1971)	1300
Tsugawa et al. (2006)	1198
Lynn et al. (2008)	1300

from 230 ms^{-1} to 760 ms^{-1} and wavetrain periodicities of 17 min. Although spread-F is recorded sometimes during the passage of LS-TIDs, it has been shown by Bowman (1996), using experimental evidence, that the spread-F is produced by MS-TIDs which coexist with the LS-TIDs.

Movements of LS-TIDs from auroral-zone regions towards the equator can be shown by using ionograms from a number of stations. Figure 3, which has been reproduced from Fig. 2 of Bowman (1992) shows associated height rises for both hemispheres. Northern-Hemisphere substorms, one of them related to events shown by Fig. 3, are shown by Fig. 4 of Bowman (1992). In the Southern Hemisphere for the Australian results, there needs to be a substorm in a conjugate location. Figure 3 of Hajkowicz (1983b) illustrates evidence of similar height rises at stations from both hemispheres. For Japan the LS-TID speed was 560 ms^{-1} and for Australia it was 630 ms^{-1}. These height changes were related to a particular conjugate event which involved a substorm onset and a riometer measurement. The Kp index was 5. In an early report Davis (1971) noted that LS-TIDs are observed, p. 4625 "... for fairly quiet and highly disturbed conditions." For the event shown by Fig. 3 the Kp index was 3. Speeds in the Northern and Southern Hemispheres were 443 ms^{-1} and 507 ms^{-1}, respectively. The Northern Hemisphere (Japanese) disturbance travelled in south-west directions and that for the Southern Hemisphere (Australian) in a north-north east direction. Movements towards the south-west have been found by other investigators (e.g. see Ding et al., 2008; Perevalova et al., 2008). It does not seem likely that the conjugate impulsive absorption levels will be the same. Therefore different LS-TID speeds can be expected. LS-TIDs have often been investigated during the occurrence of geomagnetic storms (e.g. see Hajkowicz, 1991; Karpachev et al., 2007; Lynn et al., 2008). Figure 7 of the investigation by Karpachev et al. (2007) shows $\Delta h'F$ and $\Delta fo\mathrm{F}_2$ changes for several stations as a LS-TID moved towards the equator following a substorm onset. The speed was about 600 ms^{-1}. For Okinawa, an equatorial anomaly-crest station, the height increase was 170 km and electron-density depletion as high as 4 MHz. For this event the Kp index was 7. Another feature to be considered is the occurrence, at these times, of sporadic E which will be discussed later. Also, LS-TIDs have been detected at ground level using microbarographics (Bowman and Shrestha, 1966; Khan, 1970). Ionograms for four Australian stations on 15 May 1969 for the progress of a LS-TID during a geomagnetic storm are shown by Fig. 4. This figure has been reproduced from Fig. 5 of Bowman (1990). The F_2-layer trace is sometimes distorted at these times, and can show both F_1-layer and F_2-layer traces. Such an ionogram is illustrated on Fig. 4 by the ionogram at 22:45 (LT) for Brisbane. For this event (15 May 1969) Fig. 1 of Bowman (1977) shows a plot around this time which is similar to those shown by Fig. 2. As before the characteristics shown involve a height reduction, a height increase, and an electron-density depletion. The speed for this event was 300 ms^{-1}. Concerning distorted traces associated with travelling disturbances, in an early report, King (1966) states, p. 961, "Mixing raises the recombination rate for ionospheric electrons so that $fo\mathrm{F}_2$ is depressed and the division of the F region into F_1 and F_2 enhanced."

Figure 1a and b shows the results obtained by using the times of substorm onsets at 15 min intervals to investigate statistically mostly more than 200 events. The delayed occurrence (after substorms) of height maxima for LS-TIDs is obtained, it would seem, with reasonable accuracy. The analyses in Sect. 3 will consider these delays. The diagrams of Fig. 1 show two modes for LS-TIDs the one with the shortest delay being much more significant than the other. For Kp$\geq$5, Fig. 1b shows for Washington a delay time of 2.0 h, while 4.0 h is recorded for Huancayo. For Concepcion the delay is 3.0 h. For Kp=4 and Concepcion, Fig. 1a shows the standard-deviation displacement for the main mode to be 8.5σ and the delay 3.0 h. Displacements of Hu $\Delta h'F \geq 40$ which will be used in Sect. 3 will be for the more energetic events as for Fig. 1b the average displacement for Huancayo is only 20 km. Ding et al. (2008), using more than 100 Northern-Hemisphere LS-TIDs, found that 33% travelled mostly in southerly directions, while 42% travel in south-south-west or south-west directions. Because of the particular location of Halley Bay, which was used for the results shown by Fig. 1, it seems likely that these results involve north/south propagation.

Other LS-TIDs can be generated by nuclear explosions. In the upper atmosphere over the Pacific Ocean nuclear explosions were detonated on 1 August 1958 and 9 July 1962. Disturbances in the F_2 region of the ionosphere have been reported by Bowman (1962) and Bowman and Mainstone (1964). Three LS-TID modes were detected for each event

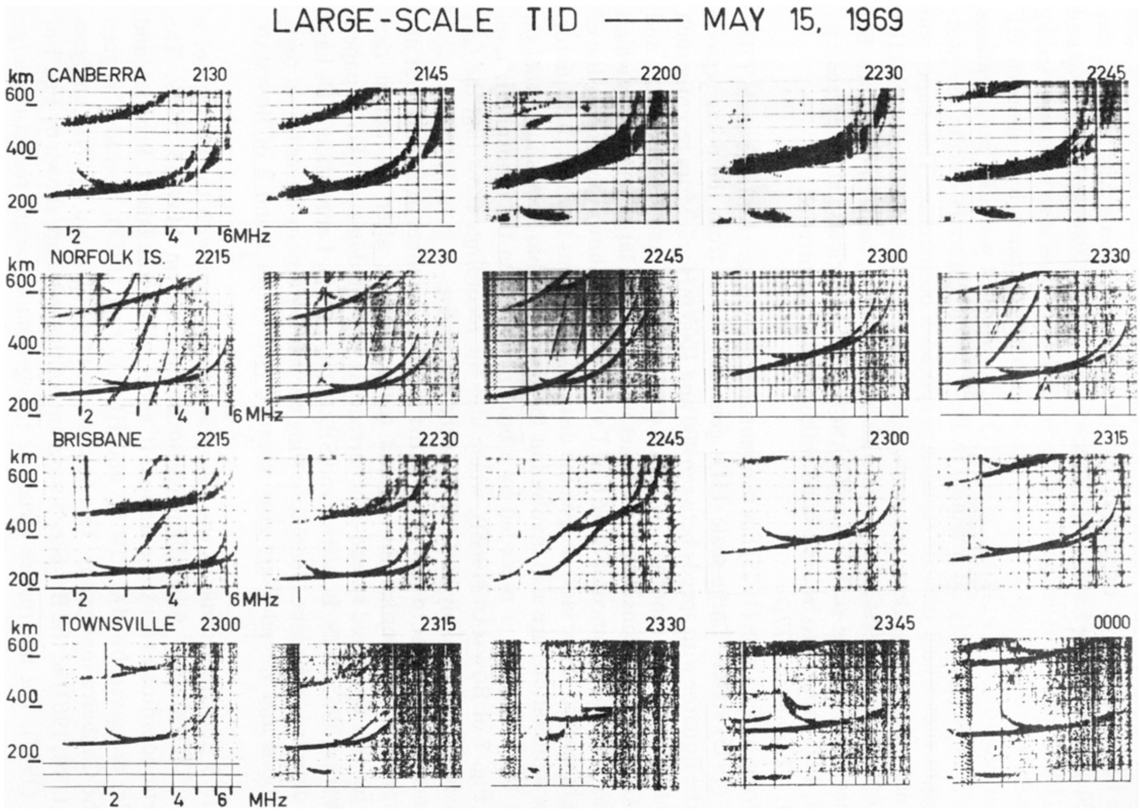
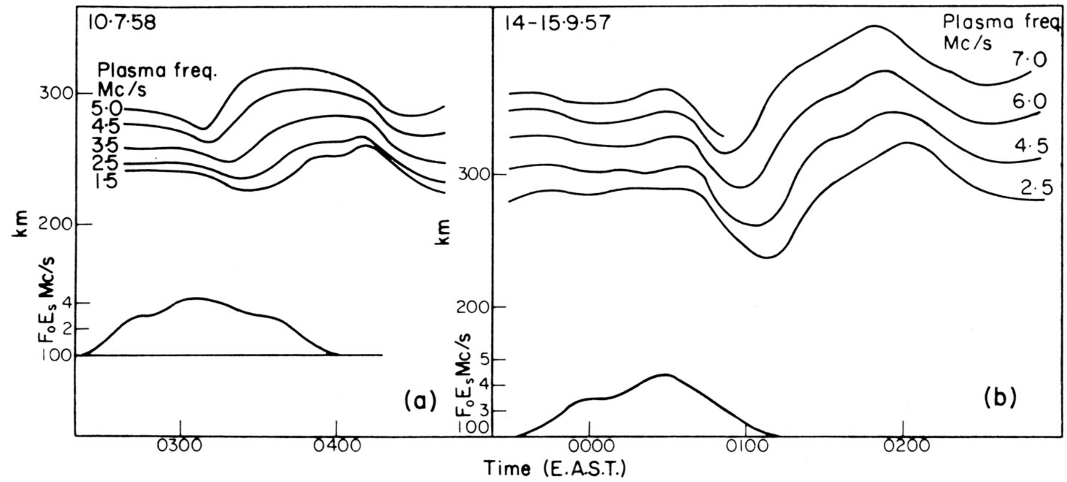


Fig. 4. A reproduction of Fig. 5 of Bowman (1990) showing LS-TID propagation at 4 Australian stations. Distorted ionogram traces include one (Brisbane, 2245) which shows F_1 and F_2 layer traces.

involving different speeds. For two modes with the lowest speeds the LS-TID characteristics were found to be consistent with those generated at substorm onsets. It may be important to indicate that the propagation method for these disturbances does not depend on GA, as for these two events the Kp index was 4 and 1. For the slower modes the first event involved speeds of 647 $\mathrm{ms^{-1}}$ and 333 $\mathrm{ms^{-1}}$, while for the second event these were 320 $\mathrm{ms^{-1}}$ and 220 $\mathrm{ms^{-1}}$. Table 4 lists the speeds found for the very fast LS-TIDs, along with results from four other investigations. The event reported by Lynn et al. (2008) was obtained using data from 15 stations, as their Fig. 6 shows. Using the MU radar in Japan, Reddy et al. (1990) have detected these three modes although no speeds were calculated. It seems likely that the first event of the three may involve a very fast speed as significant height rises commenced within an hour of a substorm onset and the F_2 layer reached a height of 600 km. For LS-TIDs Francis (1975) suggests speeds ranging from 400 to 1000 $\mathrm{ms^{-1}}$.

Another characteristic of LS-TIDs is their ability to encircle the earth. This phenomenon of earth encircling TIDs (EETs) was considered earlier by Bowman (1965). Using a worldwide set of ionosonde stations Bowman (1965) noted that not only did height rises become significant about an hour after they started to rise but also there is some occurrence about 30 h later. These results are shown by Fig. 4c of Bowman (1965) where for the 360 cases used, it is indicated that the delayed occurrence has some statistical significance. The height rises were associated with storm sudden commencements. Figures 6 and 8 of Bowman (1965) show Brisbane ionograms related to this phenomenon. This Fig. 6 (Bowman, 1965) illustrates the occurrence at 20:40 (LT) on 8 July 1958 and another at 03:30 on 10 July 1958 (see arrows). The second event involves a *fo*F_2 reduction and a height decrease followed by a height increase. The second occurrence after encirclement is illustrated here by Fig. 5a which has been reproduced from Fig. 7 of Bowman (1965). For the event on 8 July 1958 the Kp index was 9 and ΣKp equal to 55. The occurrence of Es has also been involved. Figure 5c, which has been reproduced from Table 2 of Bowman (1965) lists the details of 10 events involving EETs. The average time interval for encirclement was 30 h.

Of particular interest are events which occurred in 1946 during the sunspot maximum before the one around 1957 which involved the International Geophysical Year (IGY). Figures 6 and 7 show tracings of ionograms from the Australian stations, Hobart, Brisbane, Townsville and Cape York. These figures have been reproduced from Figs. 10 and 11 of Bowman (1965). For the first event the GA was quite high



(c)

Item	Station	Time used	Time of sudden commence-ment	Times of arrival: 1st Disturbance	Times of arrival: 2nd Disturbance	Time interval	Reference
1	Brisbane	E.A.S.T.	1424 12.6.49	2030 13.6.49	0400 15.6.49	31 hr 30 min	
2	Kokubunji	J.S.T.	1200 22.3.50	2100 22.3.50	0400 24.3.50	31 hr 00 min	Fig. 1 of Nakata and Araki (1950).
3	Brisbane	E.A.S.T.	1046 25.6.57	2230 25.6.57	0340 27.6.57	29 hr 10 min	Fig. 3 of Heisler (1963).
4	Townsville	E.A.S.T.	1046 13.9.57	1730 13.9.57	0030 15.9.57	31 hr 00 min	
5	Brisbane	E.A.S.T.	1046 13.9.57	1810 13.9.57	0120 15.9.57	31 hr 10 min	Fig. 7 of this paper.
6	Canberra	E.A.S.T.	1046 13.9.57	1900 13.9 57	0220 15.9.57	31 hr 20 min	
7	Brisbane	E.A.S.T.	1713 28.6.58	2200 28.6.58	0400 30.6.58	30 hr 00 min	
8	Brisbane	E.A.S.T.	1748 8.7.58	2040 8.7.58	0330 10.7.58	30 hr 50 min	Fig. 6 and Fig. 7 of this paper.
9	Brisbane	E.A.S.T.	1748 8.7.58	0140 9.7.58	0740 10.7.58	30 hr 00 min	Fig. 6 of this paper.
10	Brisbane	E.A.S.T.	1842 26.3.59	2100 26.3.59	0200 28.3.59	29 hr 00 min	
					Average time interval	30 hr 00 min	

Fig. 5. A reproduction of **(a)** and **(b)** of Fig. 7 of Bowman (1965) involving LS- TID induced *fo*Es and other changes, **(a)** involves encirclement of the earth. **(c)** a reproduction of Table 2 of Bowman (1965) involving 10 encirclements by LS-TIDs.

(Kp=9 and ΣKp=59). Figure 6 shows the progress on 22 September 1946 for 3600 km across the east coast of Australia during a geomagnetic storm. The ionograms show distorted traces, height rises and significant multiple-hop Es occurrence. The speed was 396 ms^{-1}. Similar ionospheric disturbance conditions are shown by Fig. 7 when this disturbance returns on 24 September 1946. On this occasion the speed was 382 ms^{-1}. Table 1 of Bowman (1965) shows that the average times for the encirclements for each of the four stations was 29.5 h. Hobart is a high latitude station and Cape York is situated close to an equatorial anomaly-crest location.

3 Pre-sunrise height rises at Huancayo

The statistical significance of relationships between night-time equatorial F_2 layer height changes and GA, as detected by vertical drifts, is shown by Fig. 4 of Fejer (2002). These associations involve height decreases for the post-sunset period, and height increases during the pre-sunrise period. The height decreases have been considered by Bowman and Mortimer (2010). The possible statistical significance of an association between the pre-sunrise height increases and LS-TIDs has been examined here. These height changes have also been reported by Fejer et al. (2008). Figure 1b illustrates, statistically the occurrence at several stations of height rises produced by LS-TIDs on their way to the equator. These LS-TIDs were generated at times of hundreds of substorm onsets. Following the substorms, the maximum height is delayed at Washington by 2.0 h and Huancayo by 4.0 h. Because over two hundred events were used these delays will be statistical averages. It is expected that for individual events somewhat different delays may occur. At Huancayo the events, shown by Fig. 1b, were considered for any hour of the night, and since the substorms were recorded at Halley Bay, the propagation of these LS-TIDs would have been essentially north/south. The main objective of this investigation has been to establish whether or not equatorial pre-sunrise height rises are associated with LS-TIDs. There were

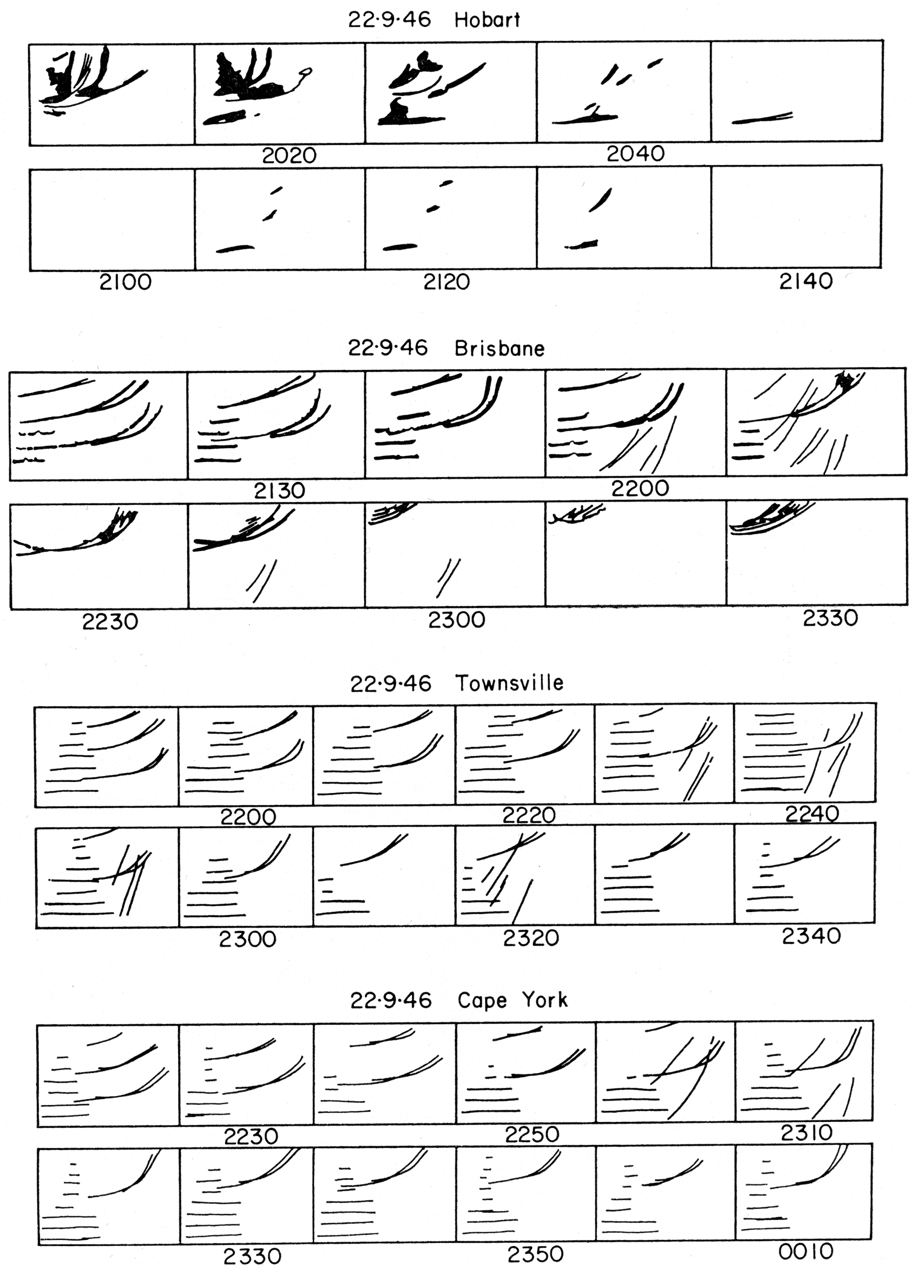


Fig. 6. A reproduction of Fig. 10 of Bowman (1965) which shows the propagation of a LS-TID at 4 Australian stations on September 22, 1946. Ionogram tracings are used, and a speed of 396 ms^{-1} is indicated.

125 Huancayo $h'F$ HIGHs detected for the four years examined. Except for 14 events, on 62 other occasions geomagnetic bays were recorded on the same night of the events for times ranging from 21:00 to 05:00 (UT). However, on 46 other occasions bays were detected, for the night before the events, at times ranging from 19:00 to 04:00 (UT). On 45 of these occasions no related bay was found on the nights for the $h'F$ HIGHs. The recording of bays to the nearest hour was noted and the hours for the occurrence of $h'F$ HIGHs was also known. Consequently 46 delay times were available ranging from 29 h to 38 h. The average value was 33.9 h. After allowing 4.0 h for any LS-TIDs to reach Huancayo, the delay for encirclement becomes 29.9 h. This is virtually the same delay found for mid-latitude LS-TIDs to encircle the earth (see Sect. 2). Thus EETs would seem to be involved.

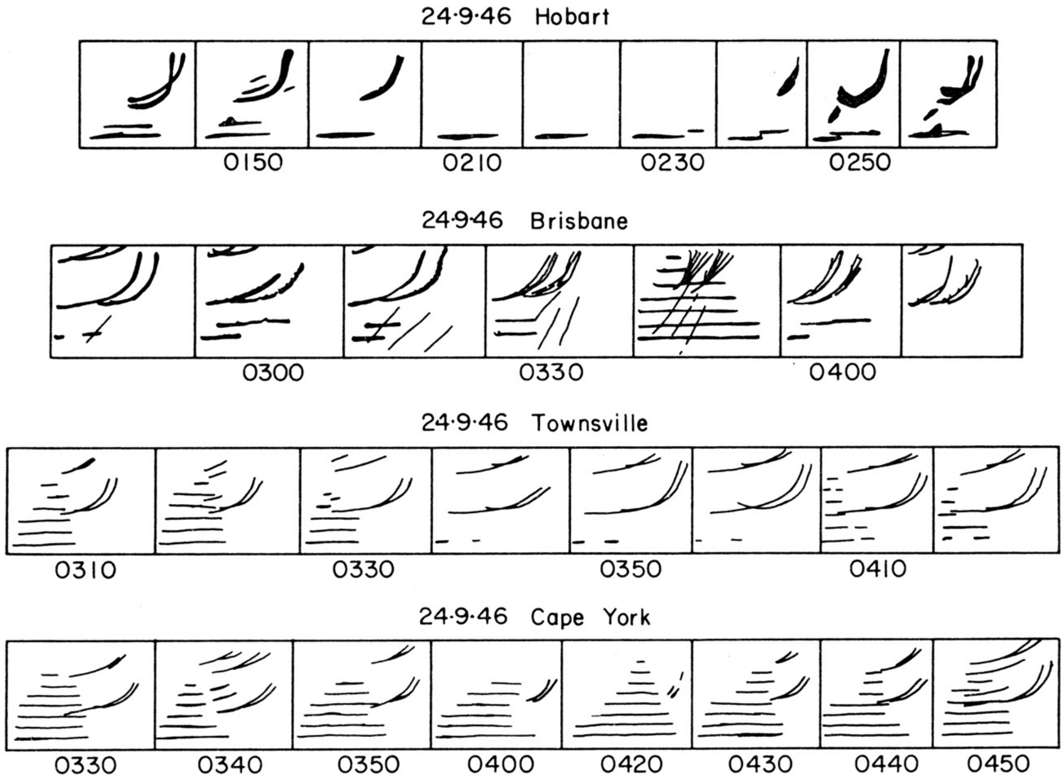


Fig. 7. A reproduction of Fig. 11 of Bowman (1965) illustrating return of the LS-TID shown by Fig. 6. The date is 24 September 1946 and involves an encirclement of the earth. The speed is 382 ms^{-1}.

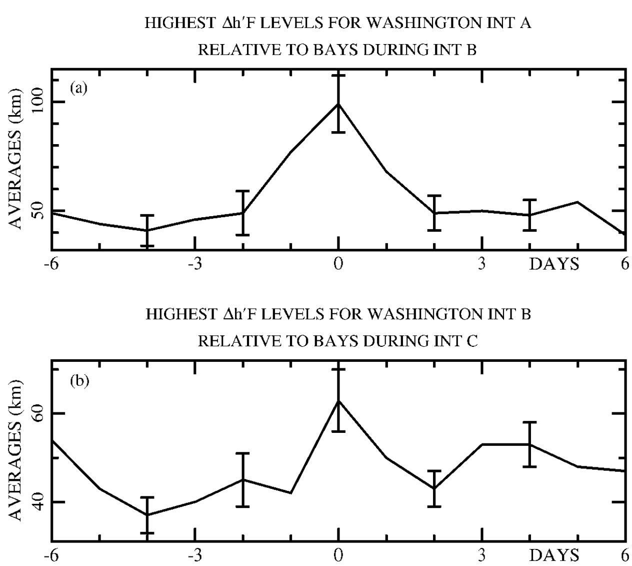


Fig. 8. High Wa $\Delta h'F$ values relative to **(a)** 17 INTB bays and **(b)** 23 INTC bays.

The fact that bays have been found a few hours before 62 equatorial pre-sunrise height rises does by itself suggest that LS-TIDs may be involved. However, this investigation will examine whether or not these bays have an influence on Washington height rises which are expected a few hours before any LS-TIDs arrive at Huancayo. The bays detected which might be related, occur at different times, as Table 1 indicates. The bays were grouped into intervals of 3 h (INTs A, B, C and D). The Washington height changes have been identified by the parameter Wa $\Delta h'F$, which is used to involve any height level which exceeds 250 km. The Wa $\Delta h'F$ events used in the analyses were the highest values in each of the 3 h intervals considered. The results of a superimposed-epoch analysis involving 17 events with bays on the same day as the Ha $h'F$ HIGHs are shown by Fig. 8a. The Wa $\Delta h'F$ values in INTA were examined relative to bays in INTB. Figure 8a shows average Wa $\Delta h'F$ levels for the event days and for six days before and after. By considering the centre hour of each interval as an approximation, the Wa $\Delta h'F$ levels 2h before the Hu $\Delta h'F$ HIGHs indicate a result of statistical significance. For these occasions the bays occur 5 h before the Huancayo events (see Fig. 1b). The results suggest the existence of LS-TIDs which travel in north/south directions. Similar results are shown by Fig. 8b where Wa $\Delta h'F$ levels for INTB are compared with bays which occur during INTC. There were 23 events for this analysis. Again displacements on event days are statistically significant. Using the intervals centre hours as before, the bays occur 8 h before the

Huancayo events, and the Wa $\Delta h'F$ levels 5 h before. The longer delays may indicate LS-TIDs which travel in south-west directions. The bays in INTD involve events at earlier times. Any relationship these might have with LS-TIDs has not been considered here.

Figure 9a gives results from an analysis involving again a relationship between height changes at Washington (Wa $\Delta h'F$) for INTA and height changes for INTR at Huancayo. As INTA was used, as before considering the centre times of the intervals used (INTA and INTR), a 2 h delay is involved. The analysis used 46 bays which occurred on the previous day about 34 h before the Huancayo events. The analysis is similar to that for Fig. 8, and a statistically significant relationship is revealed. This is expected if LS-TIDs are involved. Bays or substorm-onsets were not considered for the early work on EETs which is described in Sect. 2. Figure 9b shows the distribution in times for the 46 bays. Most of them occur at 21:00, 22:00 or 23:00 (UT). The pre-sunrise height changes for Huancayo (Hu $h'F$ HIGHs) have been noted for both the 62 events with bays on the same day and 46 events on the previous day. Average displacements ($h'F$ HIGHs) were 78.5 km for the 62 events and 79.6 km for the 46 events. This suggests, at least as judged by the displacements, that the EETs have energy which is comparable with disturbances from bays on the same day. Furthermore Fig. 9a shows that at Washington EETs have an average displacement (Wa $\Delta h'F$) of 100 km whereas the results indicate that on other days the average is just 50 km. Thus LS-TIDs seem capable of continuing to travel even after one encirclement.

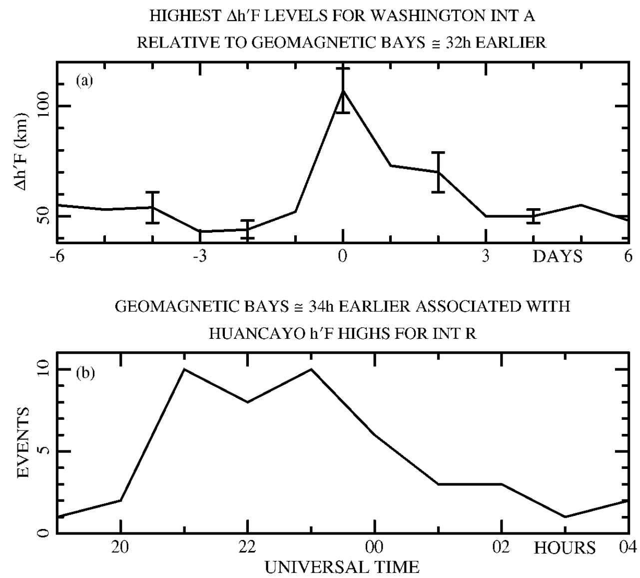


Fig. 9. (a) High Wa $\Delta h'F$ relative to 46 bays on the previous day and **(b)** the occurrence in UT times of these 46 bays.

4 Discussion and conclusions

In Sect. 2 a brief review was made, using mainly the earlier literature, for some characteristics of LS-TIDs. Using substorm onsets for the times of generation of LS-TIDs with statistical analyses it was possible, with some degree of accuracy, to calculate delay times for stations at different latitudes. The delays for Washington and Huancayo have been used for the analyses. Statistically it was shown that two different modes of the propagation of LS-TIDs were recorded. The first of these is more important and is the one usually investigated. Other results have shown that a third very-fast mode also sometimes exists. The review also considers the early work which detected that LS-TIDs sometimes encircle the earth.

For relatively mild conditions (no geomagnetic storms) Fig. 2 and Table 3 indicate that, during the passage of LS-TIDs, the average ionospheric F_2 layer height rise is 66 km. The height rise has an electron density depletion of about 1 MHz. Any $fo\mathrm{F}_2$ increase for the small height fall was not considered. However, for more disturbed conditions, at times of geomagnetic storms, small $fo\mathrm{F}_2$ increases are recorded during height falls. For example, Fig. 7 of Karpachev et al. (2007) shows for Tokyo a $fo\mathrm{F}_2$ increase for a height fall to the median value. This height fall and a subsequent height rise of 200 km were responsible for $fo\mathrm{F}_2$ changes of $+2$ MHz and -2 MHz respectively. The magnitude of these $fo\mathrm{F}_2$ changes are just twice the approximately 1MHz value shown by Fig. 3 for height increases.

The possibility that LS-TIDs may be associated with the occurrence of equatorial pre-sunrise height increases has been investigated. The times of geomagnetic bays which might be associated with Huancayo $h'F$ HIGHs have been considered. Bays on the same day have been located in different three-hour intervals and found to be of significance as Fig. 8a and b shows. These two plots involved delayed occurrence at Huancayo on average, of 5 h and 8 h, respectively. Generally if there were no bays on event days but these occurred on the previous day the selection of bays was centred around 22:00 (UT). Using this time and the centre time for INTR (09:00 UT) gives a delay time of 35 h, a delay which is comparable with the 33.9 h average delay found using all 46 events (see Sect. 3). For the single event in the review which involves encirclement of the earth (Figs. 6 and 7), initially the speed was 396 $\mathrm{ms^{-1}}$ and 29.5 h later 382 $\mathrm{ms^{-1}}$. Thus for the average encirclement time of 30 h, found for the analysis using 46 events, it seems likely that the average speed is about 400 $\mathrm{ms^{-1}}$. Francis (1975) states that gravity waves, p. 1011 "... appear to grow as they travel away from their source. The Earth's curvature presents no barrier to long-distance propagation of such waves because they are refracted around the Earth by the gravitational field". The analyses have provided experimental evidence which supports the proposal that, for the equatorial pre-sunrise F_2-layer height rises, the occurrence of LS-TIDs is responsible.

Table 5. Geomagnetic bays associated with Huancayo $h'F$ HIGHs.

$h'F$ HIGHs without bays	17
Bays during INTB	17
Bays during INTC	23
Bays during INTD	22
Bays ∼about 34 h earlier	46
Total Huancayo $h'F$ HIGHs	125

At times of geomagnetic storms, a phenomenon is known to occur, particularly at the equator, which satellites have recorded. It involves significant ionospheric height rises and electron-density depletions. Kil and Paxton (2006) have noted that plasma bubbles are always present at these times and so used the term storm-induced big bubbles ((SIBB). In summarizing SIBB results Kil et al. (2006) state [1] "They occur in the equatorial region at night, are elongated in the north-south direction, have steep walls, and always co-exist with plasma bubbles." Satellite recordings by Lee et al. (2002) have detected displacements of over 1400 km along a satellite path and a disturbance which extends at least 4500 km in the longitudinal direction. LS-TIDs have the same characteristics as SIBBs (see Table 3). During geomagnetic storms these features are enhanced. For example, as explained in Sect. 2, Fig. 7 of Karpachev et al. (2007) illustrates that, during a geomagnetic storm, the characteristics are enhanced for both $\Delta h'F$ changes (as large as 200 km) and for $\Delta fo\mathrm{F}_2$ changes (as large as 4 MHz). Also, plasma bubbles can be recognised as an alternative name for spread-F. Spread-F is often recorded when height rises are produced by LS-TIDs, particularly when these height rises are large. Experimental evidence (Bowman, 1990) has indicated that spread-F results from off-vertical specular reflections from tilted isoionic surfaces associated with gravity-wave wave-trains with periodicities of about 10 min. For equatorial regions also papers by Rottger (1973); Abdu et al. (1981); Flaherty et al. (1996); Sales et al. (1996) and Whalen (1996) are relevant. In view of the similarities which have been explained, it is suggested that LS-TIDs may be primarily responsible for SIBBs.

Recordings of SIBBs have been made by Greenspan et al. (1991) and one of their results of interest is shown by their Figs. 3c and 5c. These figures indicate topside height increases and electron-density depletions. About the same time of these results by Greenspan et al. (1991) ground-based ionosonde recordings have been made by Batista et al. (1991) at the Brazilian equatorial station, Forteleza (Fz). As expected if LS-TIDs are involved, height rises occur at Fz commencing at 21:00 (UT), just 3 h after a substorm onset. Figure 4 of Bowman (1978) shows that, for a speed of 740 ms^{-1}, a LS-TID arrives at Huancayo just 2.5 h after a substorm onset. At Fz the height exceeded 900 km for 2.5 h from 22:30 (UT) and significant electron-density depletions were recorded. A disturbed ionosphere involved F_1-layer traces being recorded. For LS-TIDs a bifurcation into F_1 and F_2 layers is observed at times in mid-latitudes. This is illustrated in Fig. 4. For a speed of 600 ms^{-1} (2220 $\mathrm{km\,h}^{-1}$) any LS-TID would be expected to arrive at Cachoeira Paulista (CP), some 2000 km to the south, about 1 h later. Similar events were recorded at CP about 1h later with the height again exceeding 900 km, and also Es echoes were recorded (see Fig. 1 at Batista et al., 1991). Also, Es echoes were observed at CP. Comparisons can be made with the topside results of Greenspan et al. (1991). Disturbance conditions (height increases and electron-density depletions) extend for more than 4500 km along the satellite path. If the 2.5 h of height increases at Fz are relevant, it can be expected that at 2220 km per hour disturbance conditions would extend about 5000 km, which is a distance comparable with the topside result. The vertical drift measured at Fz was 200 ms^{-1}, whereas it is normally 40 ms^{-1}. As Fig. 5c of Greenspan et al. (1991) shows the topside vertical drift does approach 200 ms^{-1}. The proposed LS-TID arrives at the equator at the same time as the usual post-sunrise height rise is expected. This post-sunrise height rise is expected to be large in a Rz max year (see Table 5 of Bowman and Mortimer, 2008). The large height rise observed can be explained by the combination of these two features (a height rise due to the electric field and one caused by a LS-TID). The experimental evidence thus seems to support the hypothesis that LS-TIDs are responsible for SIBBs.

Finally, the early mid-latitude results suggest that EETs might occur occasionally. However for over 100 LS-TID events, in the pre-sunrise interval, about half of them involve EETs. Also after travelling many kilometres these EETs appear to have lost little of their energy.

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