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Propagating ionospheric waves observed throughout east Asia during the WAGS October 1985 campaign

G. O. Walker,[1] *Y. W. Wong,*[1] *J. H. K. Ma,*[2] *T. Kikuchi,*[3] *K. Nozaki,*[3] *Y. N. Huang,*[4] *and V. Badillo*[5]

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The propagation of acoustic gravity waves has been observed by an investigation of their effects upon the ionosphere over distances ranging up to 3400 km and extending from mid-latitudes (45.4°N) to low latitudes (14.7°N) in east Asia. Recognizable wave structures were observed mainly on low sounding frequency, virtual height *h'f* and to a lesser extent f_oF_2 time variations, obtained from ionograms taken at 10 ionosonde stations, sounding at 5-min intervals throughout the period October 15–19, 1985. Investigations were mainly confined to the nighttimes, since during the day large latitudinal gradients of ionization (associated mainly with the equatorial anomaly) together with movements of the equatorial anomaly crest obscured the observation of waves. In general, inferred propagation of the waves was southward, but three cases of northward propagation were observed, the former having a range of periods 40–210 min, while the latter were consistently about 70 min. The waves structures, mostly, differed depending upon whether they were located to the north or south of Yamagawa (31.2°N). There was some evidence of the predomination of longer-period waves to the south, the shorter-period waves observed to the north being apparently damped out in their propagation southward. The southward propagating waves exhibited upward energy propagation, while at Hong Kong (22.3°N) there was some evidence of downward phase propagation with a shift to lower periods at lower heights. It has not been possible to identify the origins of the detected waves, but it is clear that sources existed within and outside the latitude range covered by the ionosonde sounding stations (14.7°–45.4°N).

1. INTRODUCTION

Acoustic gravity waves (AGWs) can be generated by impulse sources in the atmosphere (see review by *Yeh and Liu* [1974]), and their observed effects of periodic electron density variations in the ionosphere have been linked with localized sources such as atmospheric nuclear detonations and earthquakes [e.g., *Row*, 1967]. However, it has been inferred that many of the observed AGWs have been generated in the auroral region by Joule heating and Lorentz forces associated with the auroral electrojet and localized heating of the atmosphere by intense precipitation of charged particles, these mechanisms being particularly prevalent during magnetic storms (see review by *Hunsucker* [1982]). The so-called "large-scale" AGWs of period 30 min to 3 hours have been observed to propagate equatorward over distances of several thousand kilometers, giving rise to periodic ionospheric variations differing in phase at meridional, spaced stations [e.g., *Morgan*, 1983]. The "medium-scale" AGWs of period 15 min to 1 hour, though, seem to propagate over much shorter distances (less than 1000 km) and may have as their sources meteorological disturbances [*Waldock and Jones*, 1986].

Previous investigations of AGWs have been mostly confined to mid and high latitudes. Recently, the detected wave propagation characteristics have been obtained from simultaneous measurements at closely separated stations, for example, using ionosonde sounding at 150 km spacing [*Morgan*, 1983; *Tedd and Morgan*, 1985] and using HF Doppler at 80 km spacing [*Waldock and Jones*, 1987]. Traveling ionospheric disturbances (TIDs) have been detected, moving over long distances (3000 km), from recognizable "kinks" in ionograms [e.g., *Heisler*, 1963]. Although such disturbances may have been associated

[1]Department of Physics, University of Hong Kong.
[2]Department of Applied Physics, Hong Kong Polytechnic.
[3]Radio Research Laboratories, Ministry of Posts and Telecommunications, Tokyo.
[4]Telecommunication Training Institute, Taipei.
[5]Manila Observatory.

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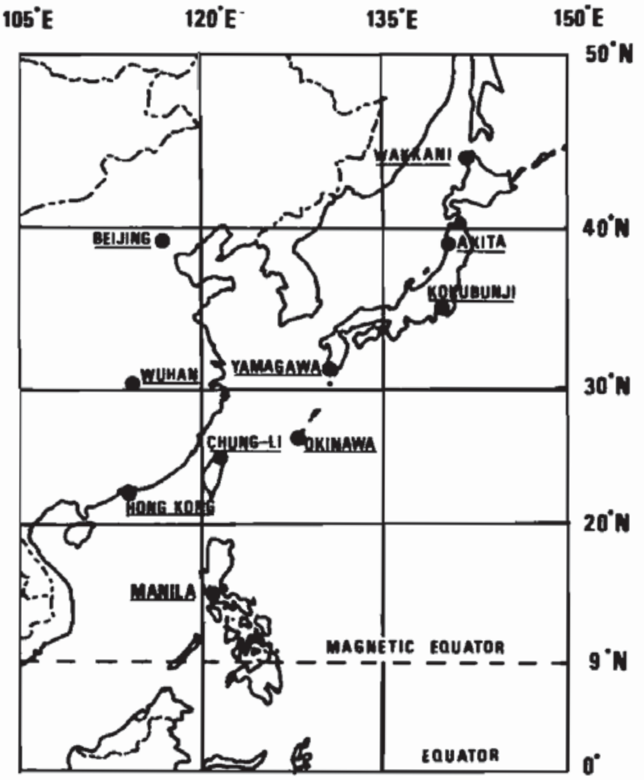


Fig. 1. Map showing the distribution of ionosonde stations.

with AGWs, they do not constitute direct evidence of such waves and their long-distance propagation.

The present investigation attempts to follow the propagation of AGWs over a long distance (3400 km) using a meridional chain of ionosonde stations extending to a very low latitude of 14.7°N (see Figure 1). Numerical simulations of aurora-generated gravity waves (see review by *Richmond and Roble* [1979]) predict that the generated wave trains should be damped out rapidly, so that, possibly, only single wave periods may be observed and only waves of period greater than 1 hour are expected to propagate to lower latitudes. The present results, taken during the Worldwide Atmospheric Gravity Wave Study (WAGS) October 1985 campaign, afford an opportunity of testing these predictions.

2. DATA COLLATION AND ANALYSIS

During the WAGS October 1985 Campaign, i.e., October 15–19 (Julian days 288–292), ionosonde sounding of the local ionosphere was carried out at 5-min intervals at all stations listed in Table 1, excepting Hong Kong where ionograms were taken every minute. It can be seen from Table 1 that the stations were distributed over a relatively wide range of latitude (45.4°N–14.7°N), extending to a very low latitude (magnetic dip at Manila, 12.0°N) and were confined to a relatively narrow longitude range (27.6°). Altogether, over 11,000 ionograms were analyzed for virtual heights at specific frequencies and the F region critical frequencies during the campaign. All stations derived and supplied for this paper accurate data for some or all of the parameters (1) $h'2$, $h'3$, (2) $h'6$, $h'8$, $h'F$, and (3) f_oF_2, with the exceptions of Beijing and Wuhan, for which only lower-accuracy diurnal plots were available. (Note: $h'f$ values corresponded to the lowest virtual heights of the ordinary ray traces, on the ionograms, for a frequency of f.0 MHz). In general, the measurement-reading accuracies were 2.5 km for the $h'f$ and 0.05 MHz for the f_oF_2 values, though these accuracies were improved upon by about 50% using a digital ionosonde at Hong Kong.

However, some of the sequentially taken data exhibited a certain randomness, probably due to weak signals and difficulty in reading the ionograms, and so in the final analysis the data were smoothed using three-value running means. This had the effect of introducing a low cutoff period of 15 min for the detection of waves. In addition, it is well known that TIDs can produce distorted and additional "satellite traces" on ionograms [*Lobb and Titheridge*, 1977]. These satellite traces consist of long-delay echoes observed on the next later time base sweep of the ionosonde and are due to the focusing of the radio waves by concave density-height contours, producing 13- and 14-hop reflections. Such phenomena can often be discriminated against, and the data have been rejected from our analysis (for example, see Figure 2 where satellite trace is clearly distinguishable).

Figure 2 is an example of an automatic plotting out of ionogram echo height traces at a prescribed

TABLE 1. Locations of Ionosonde Stations

Station	Symbol	Latitude, °N	Longitude, °E
Wakkani	WA	45.38	141.68
Beijing	BJ	39.90	116.40
Akita	AK	39.72	140.13
Kokubunji	KO	35.70	139.48
Yamagawa	YA	31.20	130.62
Wuhan	WH	30.60	114.33
Okinawa	OK	26.27	127.27
Chung-Li	CL	24.90	121.50
Hong Kong	HK	22.28	114.12
Manila	MN	14.70	121.10

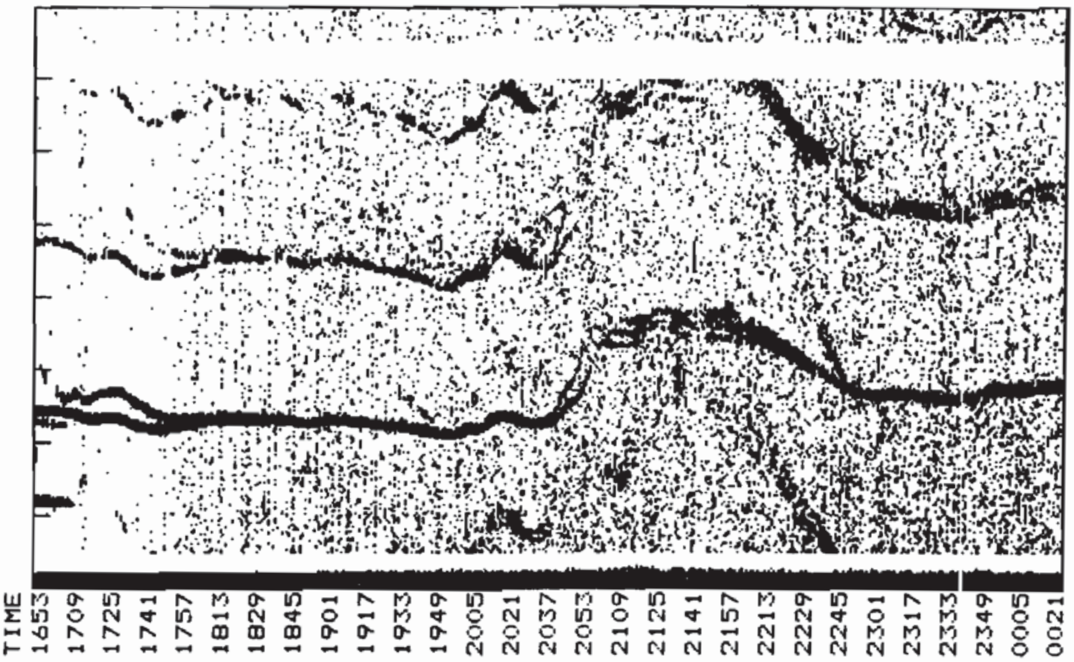


Fig. 2. An example of an automatic plot-out of echo height traces corresponding to a range of sounding frequency 3.1 3.2 MHz using 1-min-interval ionograms taken at Hong Kong. The lower satellite trace 2005–2245 LT (120 E) is due to 13-hop reflections between the sea and the focusing concave electron density–height contour associated with a moving TID. Day is October 17 (Julian day 290).

frequency from the 1-min-interval ionograms which were recorded on magnetic tape cassettes using an IPS-42 digital ionosonde and processed using the DBD-43 system and an IBM-PC. By using a digitizing tablet and visually selecting the lowest ordinary ray trace height from the background "noise," the extraordinary trace, and satellite traces, *h′f* plots such as those given in Figure 6 were derived.

During the daytime the diurnal variability of the ionosphere at low latitudes is very dependent upon hour-to-hour variations in the development of the equatorial anomaly, and this may obscure the detection of any propagating waves of period of approximately 1 hour or less. Daily, a pronounced latitudinal crest of ionization occurs roughly overhead at Hong Kong (30.5°N dip angle), but the crest position may vary with a northward or southward movement several times during any day (see Figure 3). These movements are due to (1) eastward electric field variations near the magnetic equator (affecting the **E** × **B** upward drift mechanism) and (2) meridional winds moving ionization up or down magnetic field lines, and furthermore there may be very significant longitudinal differences (see review by *Walker* [1981]). At mid to low latitudes the large electron density gradients associated with the equatorial anomaly crest tend to obscure any superimposed small periodic electron density wave structures, which might be observed from f_oF_2 variations. During the campaign, only on the day of October 17 were there observed clearly defined propagating wave structures (see Figure 3). It was decided to concentrate our investigations upon the period between sunset and sunrise, during which the ambient conditions of the lower-latitude ionosphere should be more stable and propagating waves should be more easily observed.

The results have been plotted as time sequences for all the stations, using isofrequency contours of virtual height, since as pointed out by *Morgan* [1983] the speed and direction of the waves should be essentially independent of height and a single spectral component may be expected to predominate. However, more than one spectral component may be present, and so it was decided to determine the phase time delays between stations by visual inspection of the time sequences, rather than use a more elaborate correlation method. Propagation characteristics of the waves were estimated from these time delays, and reasonably consistent results were obtained using different groupings of stations. Considering the large ionization gradients with latitude at low latitudes, this analysis might have been improved upon by converting all our data to true heights and using isotime-height contours in electron density space [*Tedd*

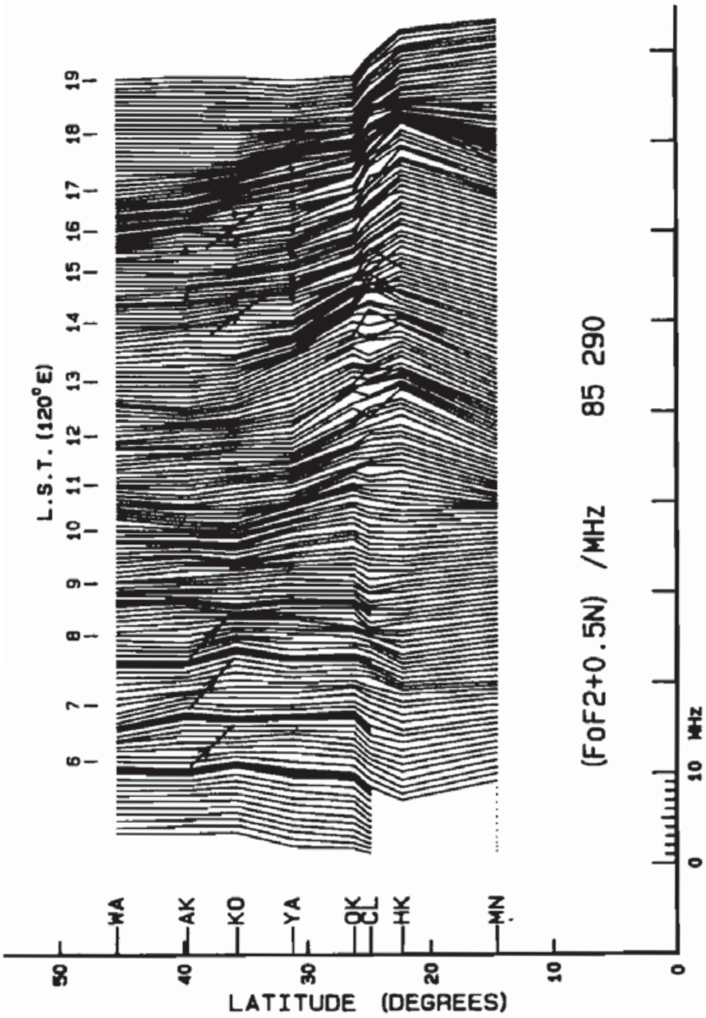


Fig. 3. At each 5-min interval, $f_o F_2$ values for stations given in Table 1 were plotted and the points joined to give an indication of the $f_o F_2$-latitude profile. In order to separate the profiles, 0.5 MHz was added to the $f_o F_2$ values after each 5-min time increase. Period corresponded to 0500–1900 LT (120°E) on October 17, 1985 (Julian day 290).

and Morgan, 1985]; however, this would have been a major task for such a large data base.

Spectral analysis of the isofrequency virtual height–time sequences was carried out for certain selected periods with a view to investigating any variation of the component periods with latitude and, at Hong Kong, with height variations. The sequence of data was first transformed to a periodogram, and then a modified Daniel window was used to produce a smoother power spectrum estimate [see *Bloomfield*, 1976].

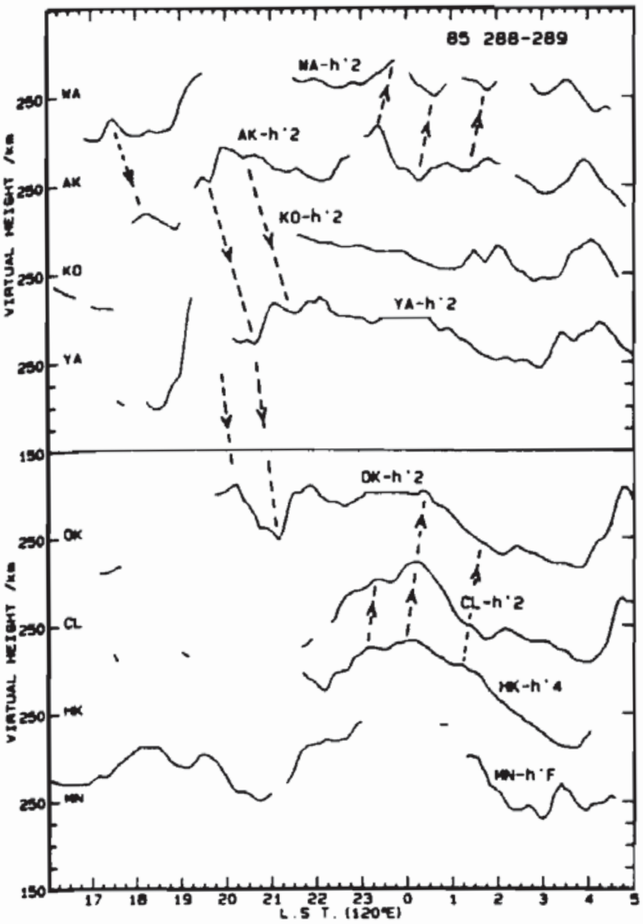
3. RESULTS AND DISCUSSION

The virtual height $h'f$ and critical frequency $f_o F_2$ variations with time for the period 1600–0500 LT (120°E; UT = LT − 8 hours) during the WAGS campaign October 15–19, 1985 (Julian days 288–292) are given for various stations in Figure 4, with latitude increasing from bottom to top. Often, very definite wave structures on the $h'f$ variations were observed throughout each night, but corresponding $f_o F_2$ variations were less discernable. These variations were always exactly in antiphase, as might be expected at nighttime, at low latitudes, where a reservoir of ionization is stored at higher levels toward the magnetic equator (this can be seen from Figure 4 since $f_o F_2$ increases from about 2.0 MHz at midlatitudes to about 5.0 MHz at low latitudes). If, for example, there was a lowering of atmospheric height by an AGW, this would result in a movement of ionization down the magnetic field tubes from a slightly lower latitude, thus enhancing the $f_o F_2$ and reducing $h'f$. The predominant direction of travel of the waves was, in general, roughly southward with these structures becoming indistinguishable south of Yamagawa (31.2°N), though northward propagating waves were observed on three occasions. We will now discuss the results of the four nighttime periods in turn. (See Figures 4 and 6 and Table 2.)

October 15–16 (J.D. 288–289)

Following sunset a large TID accompanied by a wave structure of period 40 min propagated as far south as Chung-Li (24.9°N). This TID showed up very clearly as sharp crests of ionization (or $f_o F_2$), this "pulse" broadening over a longer time period as it moved south, probably owing to dispersion of the component waves. After midnight, less common, northward propagating waves were observed, both at the low and higher latitudes, but although they seemed to have similar periods of 70 min, the higher-latitude waves traveled with a greater speed (500 m s^{-1} compared with 300 m s^{-1}). On this occasion, identical wave structures to those observed on the $h'f$ variations at Wakkani and Akita were also observed at Beijing (not given in this paper), the latter two stations being of very similar latitude and separated by a longitude difference of 23.7° (see Table 1). At Hong Kong, similar 60- to 70-min-period wave structures were observed on the $h'f$ plots for f = 2, 4, and 6

Fig. 4. (Opposite) Plots of the smoothed 5-min-interval values of (left) the virtual height $h'2$ corresponding to a sounding frequency of 2.0 MHz (with the exceptions of Hong Kong and Manila for which $h'4$ and $h'F$, were used, respectively) and (right) the critical frequency $f_o F_2$ for the period 1600–0500 LT (120°E), or 0800–2100 UT, for stations listed in Table 1, during the days October 15–19, 1985 (Julian days 288–292).


85 288-289
MA-h'2
AK-h'2
KO-h'2
YA-h'2
OK-h'2
CL-h'2
HK-h'4
MN-h'F
MA
AK
KO
YA
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HK
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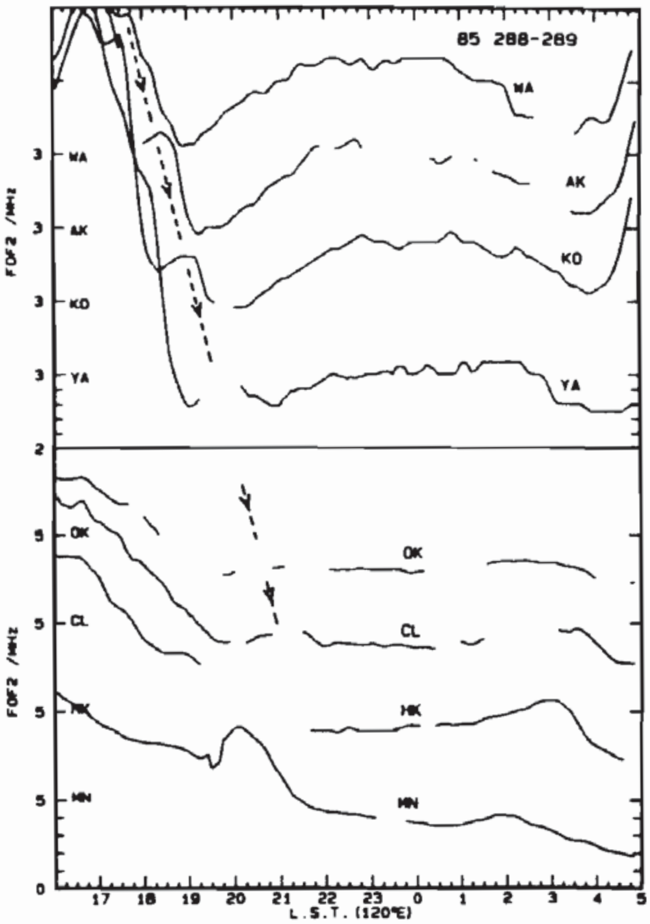
VIRTUAL HEIGHT /km
L.S.T. (120°E)


85 288-289
MA
AK
KO
YA
OK
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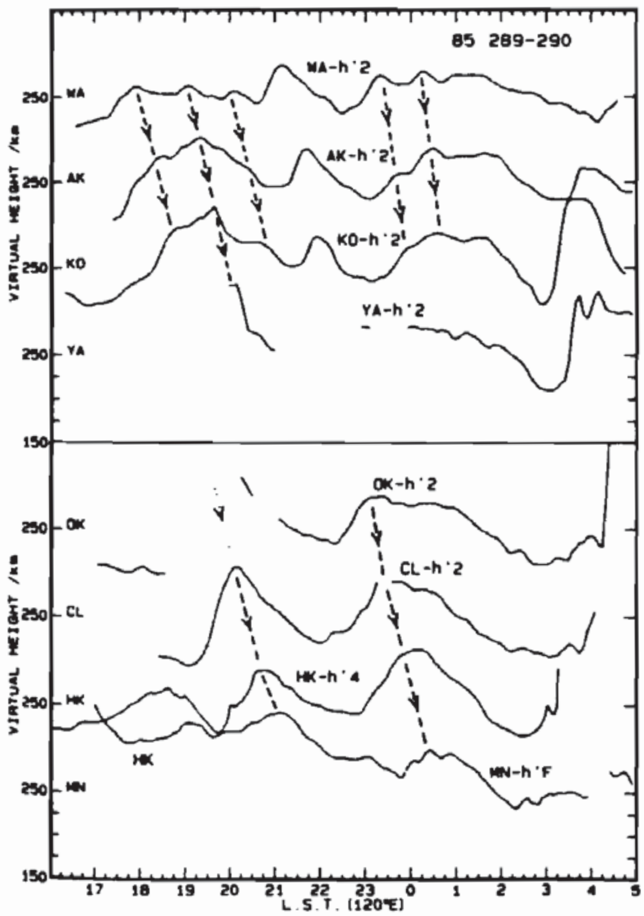
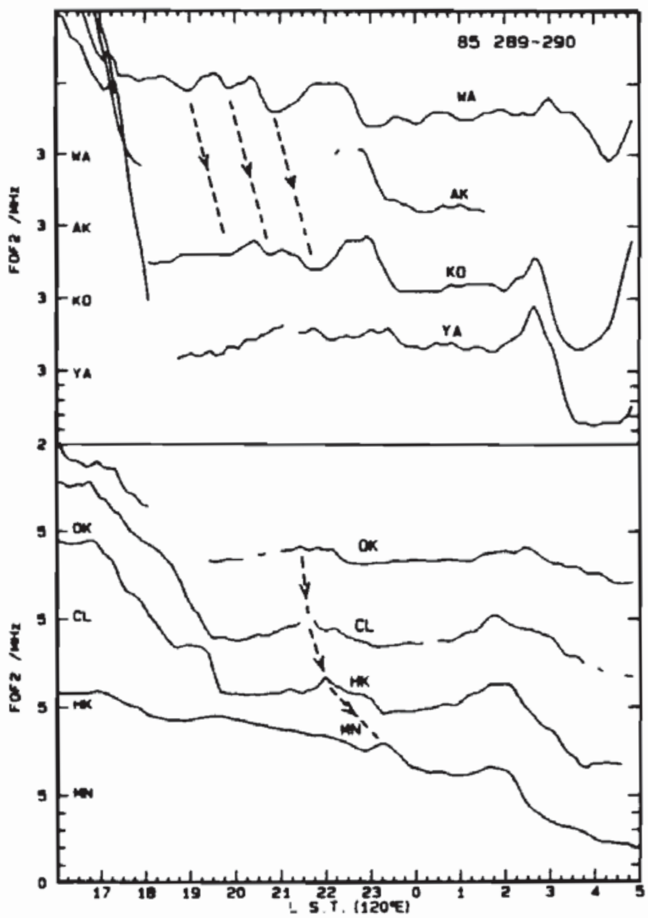
HK
MN
FOF2 /MHz
L.S.T. (120°E)


85 289-290
MA-h'2
AK-h'2
KO-h'2
YA-h'2
OK-h'2
CL-h'2
HK-h'4
MN-h'F
HK
MA
AK
KO
YA
OK
CL
HK
MN
VIRTUAL HEIGHT /km
L.S.T. (120°E)


85 289-290
MA
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L.S.T. (120°E)

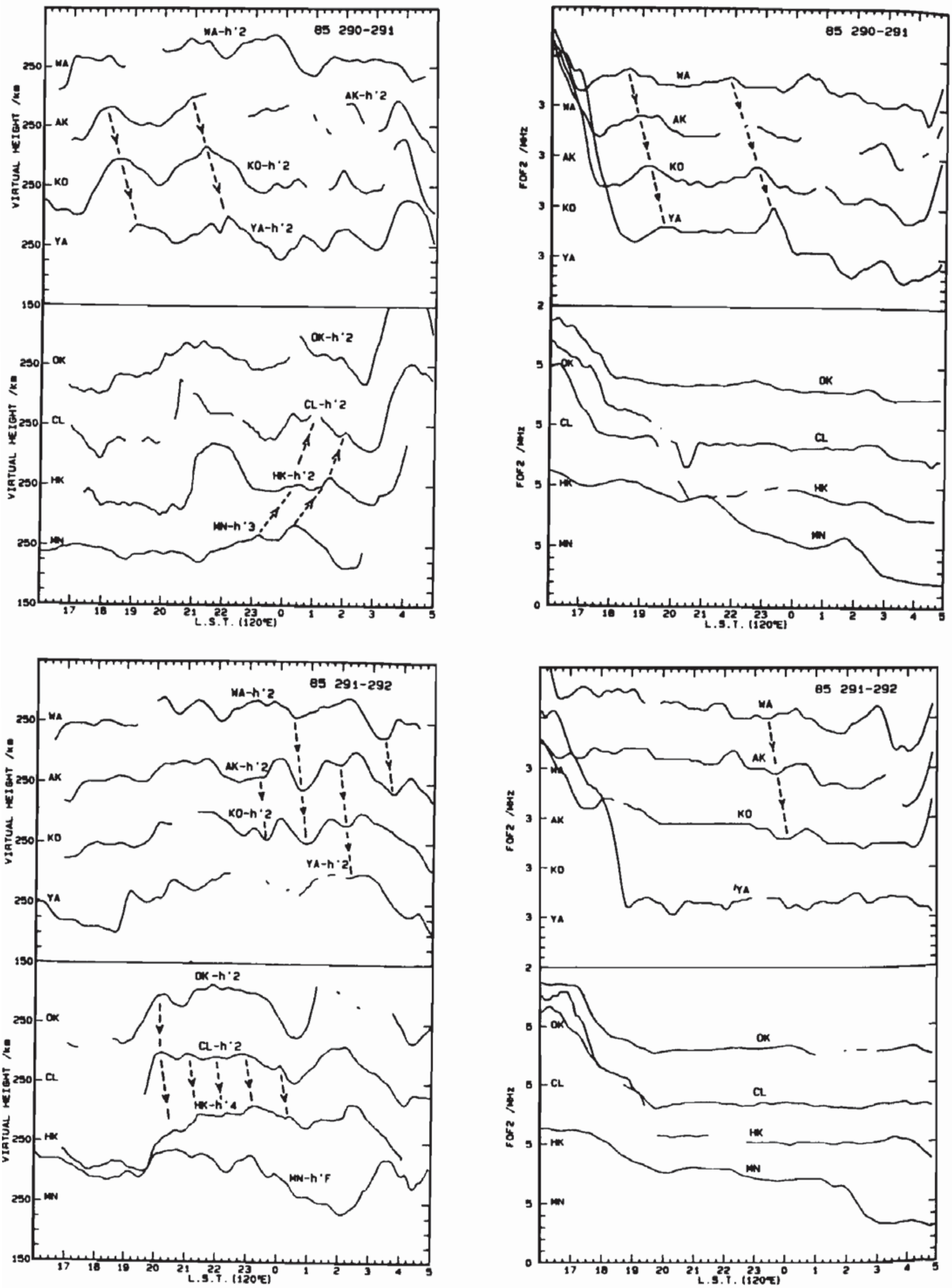

Fig. 4. (continued)

TABLE 2. Characteristics of Observed Ionospheric Wave Structures

Event	Data	LT, 120 E	Speed, m s^{-1}	Direction, E of N	Period, min.	Wavelength, km
			Julian days 288–289			
1	f_oF_2	1700–2200	230 ± 20	190 ± 10	single pulse	
1	h'	1700–2200	240 ± 20	190 ± 10	40 ± 10	600 ± 100
2	h'	0000–0200	500 ± 60	assumed 0	70 ± 10	2000 ± 400
3	h'	0000–0200	290 ± 40	4 ± 4	70 ± 10	1200 ± 300
			Julian days 289–290			
1	h'	1700–2200	550 ± 20	180 ± 30	65 ± 10	2200 ± 300
2	h'	2300–0200	550 ± 20	150 ± 10	55 ± 10	1800 ± 400
3	f_oF_2	2100–0000	200 ± 10	180 ± 10	single pulse	
3	h'	2000–0200	240 ± 10	180 ± 10	210 ± 10	3000 ± 300
			Julian days 290–291			
1	f_oF_2	1800–0000	400 ± 30	190 ± 10	200 ± 10	4800 ± 600
1	h'	1800–0000	320 ± 60	180 ± 10	190 ± 10	3600 ± 900
2	h'	2300–0200	190 ± 10	0 ± 5	65 ± 10	740 ± 200
			Julian days 291–292			
1	h'	0000–0300	460 ± 20	170 ± 10	100 ± 10	2700 ± 400
2	h'	2000–2300	190 ± 20	170 ± 10	45 ± 10	510 ± 200
			Julian day 290			
1	f_oF_2	0600–0900	150 ± 15	assumed 180	~120	~1800
2	f_oF_2	1400–1700	200 ± 15	assumed 180	~70	~2200

Direction is in degrees measured clockwise from north.

during the period 2200–0200 LT (see Figure 6). During the earlier period, 1700–1930 LT, waves of period 30–40 min were observed, but clearly these seemed localized and did not propagate to other latitudes. Both sets of $h'f$ waves observed at Hong Kong showed downward phase propagation, and the power spectrum showed a shift to shorter periods at lower heights (see Figure 7).

October 16–17 (J.D. 289–290)

Throughout this night all observed waves appeared to propagate southward and were of similar period (45–65 min) to the north of Yamagawa, while those to the south were of a much longer period, 200 min. From a study of the descending latitude $h'f$ profiles it can be seen that longer-period waves predominated the further the waves propagated southward. It is interesting to note that the only occasion on which significant wave structures were observed in the electron content diurnal plots obtained at Hong Kong (not given in paper) was on this night, 1700–2200 LT, and the period was also 45–60 min. A careful examination of the corresponding $h'f$ plots for Hong Kong (Figure 6) shows that lower-period waves (30–60 min) were present throughout the night, though of rather small amplitude. The larger-scale structures showed downward phase propagation.

October 17–18 (J.D. 290–291)

Unlike on the previous evenings the wave structures propagating southward to Yamagawa were of much longer period (approximately 200 min), these being observed very clearly on both the $h'f$ and f_oF_2 profiles. Within a rather narrow range of latitude (2.6°) at low latitudes a unique event occurred at 2000–2200 LT on this same evening. The $h'2$ values increased rapidly around 2000 LT at Chung-Li and about 30 min later at Hong Kong. A "bite-out" depletion of duration 30 min in f_oF_2 at Chung-Li was followed by a depletion of approximately 2 hour duration at Hong Kong. This dispersed "TID" thus appeared to travel westward. Similar localized ionization troughs have been observed at higher latitudes [*Bowman*, 1969], but this appears to be the first report of one at such a low latitude. During this period (2000–2300 LT) a lower satellite trace was observed on the Hong Kong ionograms (see Figure 2). Calculations show that this was due to 13-hop reflections to-and-fro between the focusing concave electron density height contours (Figure 6) and the sea (forming an effective reflector). It is also interesting to note that there occurred a 25-nT bite-out trough in the horizontal magnetic field measured near Chung-Li from 2100 to 2200 LT, indicating a probable decrease in the E region current carrier density accompanying the F region ionization trough. (It is unlikely to be due to a westward electric field, since this would have resulted in a decrease of ionospheric heights.) After the passage of the ionization trough, 65-min-period waves were observed to propagate northward from Manila (14.7°N). Some of the shorter-period structures on the $h'f$ profiles at Hong Kong showed downward phase propagation (Figure 6), while the power spectrum showed a shift to shorter periods at lower heights (Figure 7). Also shown in Figure 7 are power spectra in descending order of latitude for this particular evening. The component of period 190–200 min which we have observed directly from the $h'f$ profiles at the higher latitudes is clearly visible, and toward low latitudes, lower-period wave components appear in agreement with our directly observed 65-min-period wave. However, actual spectra are complex and include components other than those we have been able to use in our analysis.

October 18–19 (J.D. 291–292)

At the higher latitudes, waves of period 100 min predominated throughout the night, and these propagated southward to Kokubunji (35.7°N) (only clear after midnight). At Hong Kong (22.3°N), 45-min-period waves were distinct on the $h'f$ plots (Figure 6) from 2000 to 2300 LT, and these showed downward phase propagation. From the station $h'f$ profiles (Figure 4) it appears that these 45-min-period waves propagated southward from Okinawa to Manila, though later the $h'F$ trace at Manila becomes difficult to analyze because of the presence of other larger-amplitude "wave" structures.

October 17 (J.D. 290)

As explained in section 2, there are difficulties in observing propagating ionospheric waves during the daytime at low latitudes due to the variability of the location of a large ionization crest roughly centered around 30° magnetic dip, commonly referred to as the equatorial anomaly [see *Walker*, 1981]. However, wave structures were discernable on the $f_o F_2$-latitude profiles for (only) the day of October 7, and these have been indicated in Figure 3 for the periods 0600–0900 LT and 1400–1700 LT. For the first period the latitude "waveforms" have been drawn at roughly half-period intervals (60 min). Wave propagation southward to lower latitudes can be seen, with the change of phase particularly clear between Akita and Kokubunji. For the later period of the day the wave structure propagation became clearer by indicating (the solid circles in Figure 3) the times of least change of $f_o F_2$ with movement from lower to higher latitude through a station value at a particular time (least inflexion in the latitude connecting lines), indicating minimum disturbance produced by the wave. In both cases of observed waves it is clear that near the equatorial anomaly crest detection became more difficult (at lower latitudes) owing to large latitudinal gradients of ionization. However, the early morning waves were obscured at lower latitudes because of ionization gradients caused by (1) longitude differences between stations (sunrise effect) and (2) an equatorward wind producing a crest in the vicinity of Hong Kong, before the appearance of the daily equatorial anomaly crest.

4. CONCLUSIONS

It is considered that the results of this present investigation have demonstrated the propagation of acoustic gravity waves by their effects on the ionosphere over distances ranging up to 3400 km and extending from mid-latitudes (45.4°N) to low latitudes (14.7°N). Recognizable wave structures were observed on low sounding frequency virtual height $h'f$ and critical frequency $f_o F_2$-time variations, obtained at 10 ionosonde stations situated in east Asia. The 5-min interval results were, of necessity, smoothed by deriving three-value running means, giving a 15-min lower period cutoff.

During the daytime the observation of ionospheric wave-modulated structures was found to be extremely difficult toward the low latitudes owing to the presence of large latitudinal ionization gradients associated with the equatorial anomaly and the variability of the location of the equatorial anomaly crest, though waves were observed on one of the days (October 17) propagating southward in the early morning and late afternoon. Thus it was decided to confine the main investigations of this paper to the period sunset to sunrise, during which less overwhelming dynamic latitude-produced changes in the ambient ionosphere might be expected.

Table 2 gives the computed characteristics for the

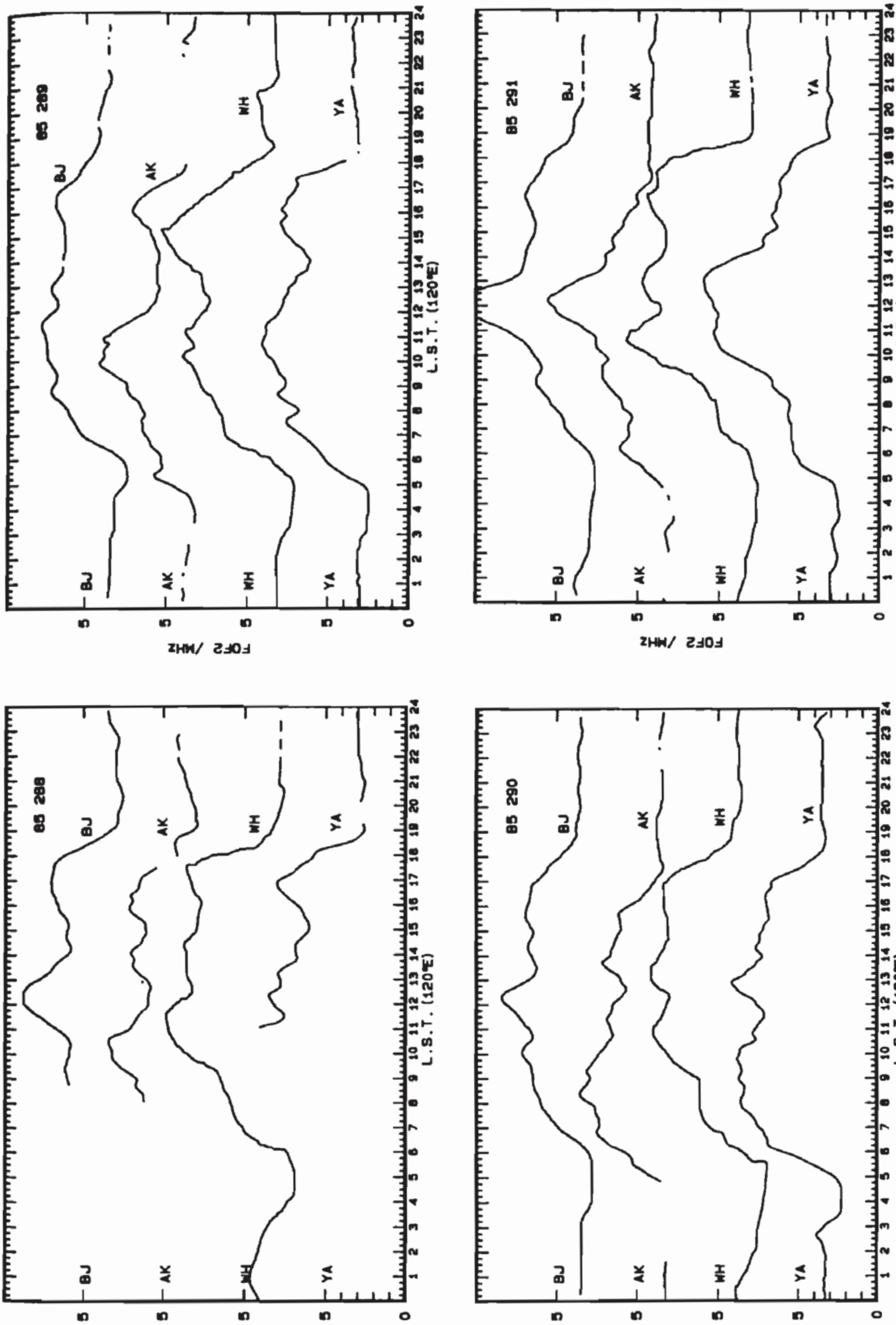

Fig. 5. Plots of the 5-min-interval values of the critical frequency f_oF_2 for the period 0000–2400 (LT) (120°E; UT = LT − 8 hours) for similar latitude but differing longitude stations (paired stations are Beijing (BJ) and Akita (AK) and Wuhan (WH) and Yamagawa (YA)) for the days October 15–19, 1985 (Julian days 288–291).

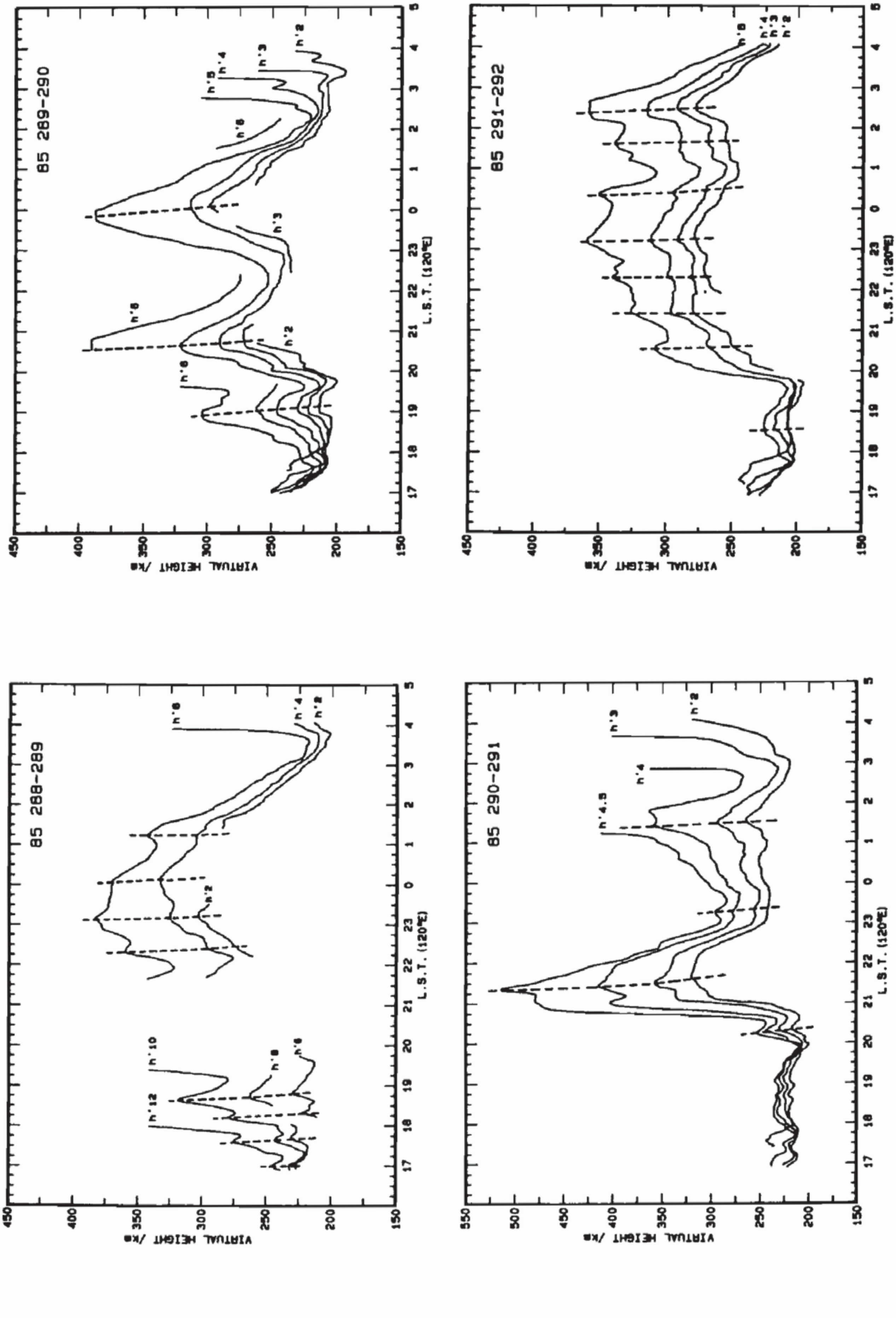

Fig. 6. Continuous plots of the virtual heights *h'f* corresponding to a sounding frequency *f*.0 MHz obtained at Hong Kong (22.3°N, 114.1°E) for the period 1600–0500 LT (120°E), or 0800–2100 UT, during the days October 15–19, 1985 (Julian days 288–292).

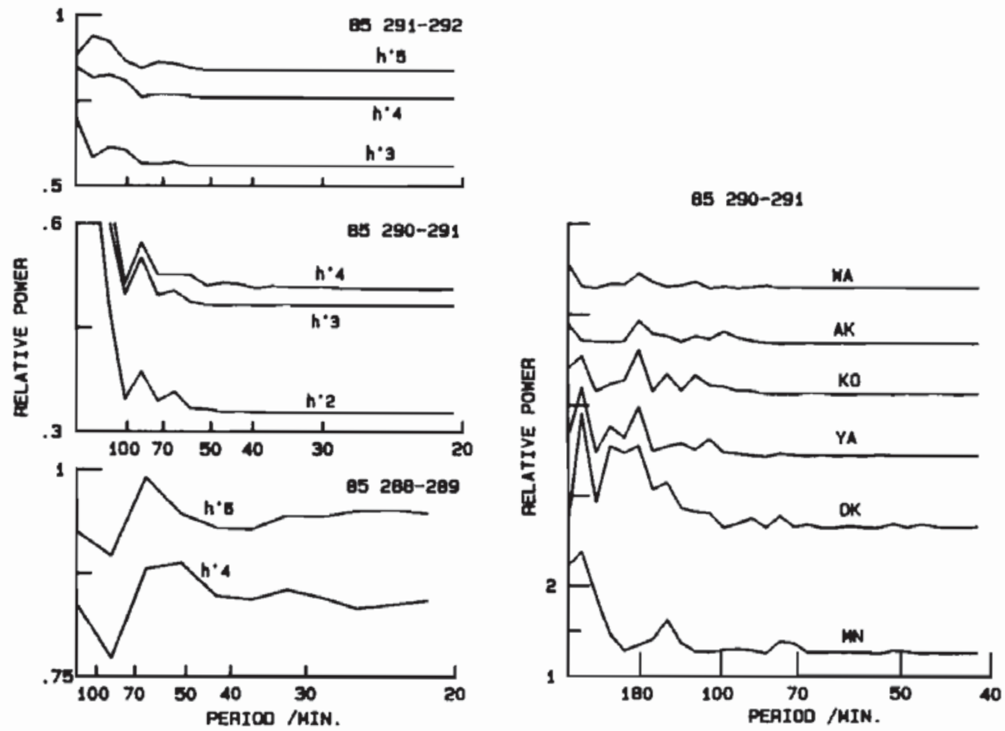

Fig. 7. Power spectra of the virtual height–time sequences (left) for Hong Kong (22.3°N, 114.1°E), showing the variation with $h'f$ (sounding frequency f) for certain selected observation periods and (right) for stations as given in Figure 4.

observed ionospheric wave structures. We may summarize our findings as follows:

1. As well as the previous mentioned difficulties of observing wave structures at low latitudes during the daytime, due mainly to the equatorial anomaly, large differences in the diurnal variations of $f_o F_2$ at stations of very similar latitude yet differing in longitude by 24°–26° have been observed (Figure 5). Thus the present type of investigation at low latitudes seems more suited to the period sunset-sunrise.

2. Wave structures were observed mainly on the $h'f$-time variation profiles and to a lesser extent on the $f_o F_2$-time variation profiles on all four evenings.

3. Implied directions of propagation of the acoustic gravity waves were, mainly, almost southward, but three cases were observed of northward propagation.

4. In general, different wave structures were observed north and south of Yamagawa (31.2°N). An exception was the 70-min-period waves observed traveling northward at 0000–0200 LT on October 16 (J.D. 289) at both low latitudes and mid-latitudes. (These may have had different source origins, and the greater computed traveling speed (and wavelength) of the mid-latitude waves may be due to the necessary assumption made that the waves were traveling directly north in this region.)

5. The periods of the northward propagating waves were consistently approximately 70 min, in contrast to a range of periods 40–210 min for those propagating south.

6. No systematic variation of period with propagation distance was observed. This result seems to contradict the theoretical prediction of horizontal wavelength increasing linearly with horizontal range given by *Francis* [1975], who considered an auroral electrojet source and included Earth reflection of the AGWs.

7. Our results support the view of many other workers that the longer-period waves are able to travel the longest distances, to low latitudes, with the least damping (see review by *Richmond and Roble* [1979]).

8. From the $h'f$-time profiles obtained at Hong Kong (Figure 6) there is evidence of downward phase propagation of the observed waves. In addition, for the southward propagating waves, clear detection was only possible toward low latitudes by employing increasingly higher-level (higher-frequency) $h'f$ profiles, implying upward propagation of wave energy over the latitude range of 45.4°N–14.7°N.

9. There is some evidence for a slight shift of period of observed waves toward the lower end of the spectrum with a decrease in height at Hong

Kong (22.3°N) (see Figure 7, J.D. 291–292, J.D. 288–289).

10. It has not been possible in this investigation to trace the origins of the acoustic gravity waves causing the observed ionospheric modulation wave structures. Our present results, however, indicate that as well as sources existing to the north of Wakkani (45.5°), there were others at lower latitudes, with the northward propagating waves on one occasion appearing to originate from a latitude lower than that of Manila (14.7°N) (see JD 289–290 plots in Figure 4). For the southward propagating waves observed in this investigation it would be interesting to compare results taken during the WAGS campaign at higher latitudes.

The results of this paper show the advantage of such a collaborative campaign as WAGS. The information about AGWs obtained from a single or a few near stations must be very limited and, certainly, no long-distance propagation tracing is possible. The use of basic ionosonde data (needing careful analysis, however) from normal existing sounding stations, scattered throughout the world, could provide a relatively inexpensive and powerful method for further studies of AGWs.

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REFERENCES

Bloomfield, P., *Fourier Analysis of Time Series: An Introduction*, 258 pp., John Wiley, New York, 1976.

Bowman, G. G., Ionisation troughs below the F_2-layer maximum, *Planet. Space Sci., 17*, 777–796, 1969.

Francis, S. H., Global propagation of atmospheric gravity waves: A review, *J. Atmos. Terr. Phys., 37*, 1011–1054, 1975.

Heisler, L. H., Observation of movement of perturbations in the *F* region, *J. Atmos. Terr. Phys., 25*, 71, 71–86, 1963.

Hunsucker, R. D., Atmospheric gravity waves generated in the high-latitude ionosphere: A review, *Rev. Geophys., 20*, 293–315, 1982.

Lobb, R. J., and T. E. Titheridge, The effects of travelling ionospheric disturbances on ionograms, *J. Atmos. Terr. Phys., 39*, 129–138, 1977.

Morgan, M. G., Locating TID sources with a north-south chain of rapid-run ionosondes in western Quebec, *Radio Sci., 18*, 1066–1076, 1983.

Richmond, A. D., and R. G. Roble, Dynamic effects of aurora-generated gravity waves on the mid-latitude ionosphere, *J. Atmos. Terr. Phys., 41*, 841–852, 1979.

Row, R. V., Acoustic gravity waves in the upper atmosphere due to a nuclear detonation and an earthquake, *J. Geophys. Res., 72*, 1599–1610, 1967.

Tedd, B. L., and M. G. Morgan, TID observations at spaced geographic locations, *J. Geophys. Res., 90*, 12,307–12,319, 1985.

Waldock, J. A., and T. B. Jones, HF Doppler observations of medium-scale travelling ionospheric disturbances at mid-latitudes, *J. Atmos. Terr. Phys., 48*, 245–260, 1986.

Waldock, J. A., and T. B. Jones, Source regions of medium scale travelling ionospheric disturbances observed at mid-latitudes, *J. Atmos. Terr. Phys., 49*, 105–114, 1987.

Walker, G. O., Longitudinal structure of the *F*-region equatorial anomaly—A review, *J. Atmos. Terr. Phys., 43*, 763–774, 1981.

Yeh, K. C., and C. H. Liu, Acoustic gravity waves in the upper atmosphere, *Rev. Geophys., 12*, 193–216, 1974.

V. Badillo, Manila Observatory, P. O. Box 1231, Manila, Philippines, 2800.

Y. N. Huang, Telecommunications Training Institute, 168 Minchu Road, Panchiao, Taipei, Taiwan 220, Republic of China.

T. Kikuchi and K. Nozaki, Radio Research Laboratories, Ministry of Posts and Telecommunications 2-1, Nukui-Kitamachi 4-chome, Koganei-shi, Tokyo 184, Japan.

J. H. K. Ma, Department of Applied Physics, Hong Kong Polytechnic, Hung Hom, Hong Kong.

G. O. Walker and Y. W. Wong, Department of Physics, University of Hong Kong, Hong Kong.