Solar tides in the middle atmosphere. I: Description of satellite observations and comparison with theoretical calculations at equinox

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SUMMARY

In recent years several refinements have been made in the numerical computation of solar atmospheric tides between 30 and 60 km. Although comparisons have been made with winds observed by rockets it has not been possible until now to test these predictions against a globally extensive set of observations. In this paper we describe techniques for obtaining such observations from measurements made by the stratospheric sounding units (SSU) on the TIROS-N series of satellites. These unique data are compared with calculations of the radiance variations expected from the SSU based on classical tidal theory at equinox.

1. INTRODUCTION

Solar tides in the middle atmosphere constitute a class of globally coherent gravity waves largely excited by the daily modulation in solar heating due to the absorption of radiation by water vapour and ozone. Their contribution to the diurnal variation in temperature at any point is determined by the dynamical response of the whole atmosphere to the modulated heating field. The classical theoretical description of this phenomenon, summarized by Chapman and Lindzen (1970), assumes a stationary inviscid atmosphere as the mean state and represents the tidal fields in terms of eigenfunctions known as Hough modes, each of which has a characteristic horizontal and vertical structure. The predictions of this theory have been refined in recent years by the inclusion of mean winds, meridional temperature gradients and more accurate representations of the heating functions (Lindzen and Hong 1974; Forbes and Garrett 1979; Lindzen 1979; Walterscheid and Venkateswaran 1979a, b; Walterscheid et al. 1980; Walterscheid and DeVore 1981), but their essential features have been little changed. Briefly, the atmospheric response to the insolation cycle is expected to be dominated by diurnal and semidiurnal components, with the greatest amplitudes being found in tropical latitudes.

Observational confirmation of tidal theory between 30 and 60 km has mostly depended hitherto on rocket measurements of winds (Reed et al. 1969; Reed 1972; Groves 1976). Lindzen (1979) considered that the agreement between theory and these observations was satisfactory for the diurnal tide and reasonable for the semidiurnal—although Hoxit and Henry (1973), using data from five years of daily rocket temperature measurements, reported significant departures from Lindzen's theory. Most other rocket observations were confined to short periods at a handful of launch sites, and demonstrated substantial day-to-day variability due presumably to the influence of locally excited gravity waves, non-migrating (i.e. longitudinally evanescent) tidal modes and variability in the heating functions (Groves 1976). They cannot therefore provide a stringent test of theoretical calculations. The greatly extended coverage (both spatial and temporal) available from a satellite instrument affords the opportunity for a comprehensive study of tidal structure and variability, and thereby a much more rigorous test of the theory.

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The stratospheric sounding units (SSU) mounted on the TIROS-N satellite and the NOAA operational meteorological series are three-channel pressure-modulated radiometers. The channels are numbered 25, 26 and 27, and have weighting functions about 15 km wide centred around 15, 6 and 2 mb, as shown in Fig. 1. These weighting functions are narrow enough to resolve most of the major tidal modes, which have vertical wavelengths of 25 km or more (section 3). A full description of the instrument has been given by Miller et al. (1980). The satellites are in sun-synchronous orbits, so each northbound or southbound orbit observes at the same local time of day for a given latitude. By comparing zonal mean radiances (zonal mean referring to an average of observations within a given latitude band) averaged over a few days from the northbound and southbound orbits the tidal component of the radiance difference between the two may be isolated. The combination of extensive coverage and excellent instrumental precision available from the SSU provides the first opportunity to study diurnal radiance variations on a global basis.

Preliminary results from the TIROS-N and NOAA-6 satellites were reported by Pick and Brownscombe (1981). These showed that the radiance difference between 0730 and 1930 h local time, and between 0300 and 1500 h, reached a maximum at mid-latitudes and a minimum at the equator. Groves and Tuck (1981) showed this feature to be irreconcilable with a radiative–photochemical model, and suggested the need to consider atmospheric tides in order to explain the observations.

By combining the data from two satellites with different equator crossing times it is possible to obtain observations of zonal mean radiance four times a day. Using such observations Brownscombe and Schlapp (1983) were able to identify clearly the gravitationally excited lunar semidiurnal tide as an approximately 15-day modulation of the radiance differences. However, to investigate solar tides with these data a very precise intercalibration of the two instruments is required. Nash and Brownscombe (1983)

Figure 1. SSU weighting functions.
showed that the relative radiometric calibrations and weighting functions of the SSUs can be determined with a precision of $\sim 0.2 \text{ mW m}^{-2}\text{sr}^{-1}(\text{cm}^2)^{-1}$ (henceforth abbreviated to radiance unit, r.u.) which is adequate for data from two SSUs to be combined in solar tidal studies.

In this paper we describe the techniques used to combine the observations from two SSUs. Results for the autumn equinox of 1981 from the NOAA-6 and NOAA-7 satellites are presented, and compared with the predictions of classical tidal theory. Although the broad features of the theory are confirmed by the observations, significant discrepancies are evident, and these are discussed. A more comprehensive set of observations, with enhanced vertical resolution and greater temporal coverage, will be presented in part II of this paper.

2. Observational Method

SSUs have now been flown on four of the current series of NOAA sun-synchronous polar-orbiting meteorological satellites. From July 1979 two satellites with equator-crossing times of 0300 h (and 1500 h) and 0730 h (and 1930 h) have been in orbit except for a period between the failure of TIROS-N in February 1981 and the launch of NOAA-7 in June of that year. Each SSU scans across the track of its orbit, measuring the radiance at 35, 25, 15 and 5 degrees either side of the nadir. An example of the variation in radiance observed across a scan is shown in Fig. 2. The characteristic 'U' shape of this curve is caused by the increase in height of the weighting function with increasing scan angle, combined with the increase of temperature with height in this part of the stratosphere. A systematic difference is also evident in Fig. 2 between observations at the same scan angle on opposite sides of the nadir. For an individual scan, such differences may be attributed to meridional temperature gradients, since the latitude of observation does change with scan position. This effect was removed by dividing the data from each

![Image of radiance variation with scan position](image)

Figure 2. An example of the variation of radiance with scan position for channel 26. The data represent a 15-day average in September 1981 taken from the NOAA-6 southbound orbit (1930 h) in the equatorial zone. Standard deviations in the plotted mean values are smaller than the size of the symbols.
scan position into fifteen latitude zones, 10° wide, extending from 75°N to 75°S. A fifteen-day zonal average of these data then allowed the effects both of lunar tides and meridional temperature gradients to be eliminated. Radiance differences that remain between observations on opposite sides of the scan may therefore be attributed to solar tidal influences, caused by differences in the local time of each radiance measurement. Such time differences between scan positions 1 and 8 increase from about 45 minutes at the equator to 1½ hours at 60° latitude. Thus the SSU measures not only the radiance at the sub-satellite point (from the observations at 5° to the nadir) but also the corresponding rate of change of radiance with time.

Small corrections were applied to the different scan positions to compensate for field-of-view-dependent radiance errors, based on calibrations performed on the ground and in orbit. Gradients of radiance against local time were deduced principally from the differences between scan positions 1 and 8 (Fig. 2), corrected as shown in Table 1. The uncertainties in the radiance differences shown in Table 1 result from our imprecise knowledge of radiance offsets at different scan positions obtained during ground calibrations. Such systematic errors do not contribute to random noise in the radiance differences.

Since no two SSUs are absolutely identical, small differences in the peak heights of the weighting functions exist between different instruments. Such differences between NOAA-6 and NOAA-7 were estimated using the comparison described by Nash and Brownscombe (1983). When combined with the observed variation of radiance with scan angle (and therefore weighting function height) these differences gave rise to radiance offsets, used to adjust the NOAA-6 measurements for direct comparison with those of NOAA-7. These offsets were combined with known calibration differences between the satellites to give the values shown in Table 1. The NOAA-7 satellite was chosen as the standard since its weighting functions corresponded more closely to the original specification for the SSU.

The uncertainties shown in the third column of Table 1 limit the accuracy with which data from both satellites may be combined in tidal studies. However, the radiance difference between scan positions 1 and 8, and between northbound and southbound orbits for the same satellite, are independent of such errors and should therefore be more reliable. To estimate the uncertainty in such differences three factors must be considered: (i) Instrumental noise. Since the data used here are averaged over both longitude and time this random error is small, causing an uncertainty in the radiance difference between scan positions 1 and 8 of less than 0·03 r.u. for channel 27, 0·02 r.u. for channel 26 and 0·015 r.u. for channel 25.

(ii) In-orbit drift of the radiometer's calibration, primarily due to changes in the temperature of the instrument. This was estimated by Nash and Brownscombe (1983) to contribute an uncertainty of 0·07 r.u. to the difference between northbound and

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**TABLE 1. CORRECTIONS APPLIED TO NOAA-6 RADIANCES AND RADIANCE DIFFERENCES TO ENSURE COMPATIBILITY WITH NOAA-7**

<table>
<thead>
<tr>
<th>Channel number</th>
<th>Nominal pressure (mb)</th>
<th>Mean radiance</th>
<th>Radiance difference between scan position 1 and 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>15</td>
<td>0 ± 0·06</td>
<td>0 ± 0·05</td>
</tr>
<tr>
<td>26</td>
<td>5</td>
<td>0·7 ± 0·1</td>
<td>-0·06 ± 0·05</td>
</tr>
<tr>
<td>27</td>
<td>1·5</td>
<td>0·4 ± 0·2</td>
<td>-0·14 ± 0·10</td>
</tr>
</tbody>
</table>
southbound orbit measurements. (It should be noted that this error does not affect the gradient estimates.)

(iii) Atmospheric variability (due to lunar tides and non-tidal effects). In equatorial regions the stratosphere is relatively quiescent, and the uncertainty from these sources does not exceed that attributable to instrument noise. Away from the equator, however, the variability increases, causing up to four times as much uncertainty at southern mid-latitudes. Complete longitudinal coverage of data is not usually obtained, and the variability in the positions of missing data contributes to the overall variability in the zonal mean values discussed here.

These factors introduce an uncertainty in the radiance difference between northbound and southbound orbits of $\sim 0.1\ r.u.$ The uncertainty in the radiance difference across a scan depends on the channel and on latitude, ranging from $\sim 0.015\ r.u.$ at the equator for channel 25 to a maximum of $0.17\ r.u.$ at $50^\circ$S for channel 26. In addition to these random errors, the uncertainties in systematic offsets shown in Table 1 allow possible adjustments of the across-scan differences of $\pm 0.05\ r.u.$ for southbound orbits and $\pm 0.05\ r.u.$ for northbound orbits for channels 25 and 26 and $\pm 0.1\ r.u.$ in a similar way for channel 27.

3. **Calculations**

In classical tidal theory the equations of motion are written for oscillations in a stationary, inviscid background atmosphere. Details of this procedure may be found in Chapman and Lindzen (1970), and a brief outline only is given here. Solutions for the globally coherent diurnal and semidiurnal tides are obtained by postulating expressions for the wind components and temperature which are periodic both in longitude and time. The altitude and latitude dependences of the resulting homogeneous equation (with no heating functions) are separable, the former giving rise to a vertical structure equation and the latter leading to the Laplace tidal equation, the solutions of which form an infinite set of eigenfunctions known as Hough modes and associated eigenvalues or separation constants, known as equivalent depths. The inhomogeneous equation is also separable provided that the thermal forcing is expanded in terms of Hough modes.

The vertical structure of each Hough mode is determined by its equivalent depth. Positive values smaller than about 10 km imply vertical wave propagation while equivalent depths outside this range imply vertical trapping. Table 2 enumerates this property for

<table>
<thead>
<tr>
<th>Mode</th>
<th>Equivalent depth (km)</th>
<th>Wavelength (propagating mode)</th>
<th>Scale height (trapped mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(1, -2)$</td>
<td>$-12.2$</td>
<td></td>
<td>$11.7$</td>
</tr>
<tr>
<td>$(1, -4)$</td>
<td>$-1.76$</td>
<td></td>
<td>$6.3$</td>
</tr>
<tr>
<td>$(1, 1)$</td>
<td>$0.69$</td>
<td>$28.3$</td>
<td></td>
</tr>
<tr>
<td>$(1, 3)$</td>
<td>$0.12$</td>
<td>$11.4$</td>
<td></td>
</tr>
<tr>
<td>$(2, 2)$</td>
<td>$7.9$</td>
<td>$284.6$</td>
<td></td>
</tr>
<tr>
<td>$(2, 4)$</td>
<td>$2.1$</td>
<td>$54.5$</td>
<td></td>
</tr>
<tr>
<td>$(2, 6)$</td>
<td>$0.96$</td>
<td>$33.9$</td>
<td></td>
</tr>
</tbody>
</table>

*Note.* The first index of each Hough mode refers to the number of periods per day and the second distinguishes the different modes of a given period.
the Hough modes included in this study. The tidal fields were calculated by solving the vertical structure equation numerically on a vertical grid of 2000 points extending up to 160 km, with vertical velocity taken to vanish at the ground. An isothermal atmosphere at 275 K was assumed; sensitivity to the chosen temperature was investigated and found to be negligible except at the equator, where a decrease of 21 K in the isothermal temperature retarded the maxima and minima of the tidal variation by about one hour. The effect of a vertical variation in temperature was investigated by incorporating the equatorial profile for September given by Houghton (1977). The tidal variations differed significantly from the basic case (275 K isothermal) only at the equator, where a small retardation (1 hr) in phase and a reduction in the amplitude of the semidiurnal component were seen. The salient features, however, were consistent with those discussed below.

To simulate the radiances observed by the SSU the temperature variations were evaluated at 21 pressure levels 3-85 km apart at seven latitudes extending from the equator to 57°N. The tidal components were superimposed on a basic zonal mean temperature field, and the combination used to simulate the radiances according to:

$$\text{simulated radiance} = \sum W_i B(T_i)$$

where $W_i$ is the normalized weighting function and $B(T_i)$ the black-body function at pressure level $i$. The average zonal mean temperatures for September 1981 as measured by the stratospheric and mesospheric sounder (SAMS) on the Nimbus-7 satellite were used as the basic field.

Several decompositions of the tidal forcing function in terms of Hough modes have been reported in the literature since the simple analytical expressions of Chapman and Lindzen (1970). Recent determinations (Forbes and Garrett 1979; Walterscheid et al. 1980; Hamilton 1981a; Groves 1982a, b) show heating functions due to ozone which peak more strongly near the stratopause than their predecessor, and heating functions due to water vapour which contain comparatively little excitation in the stratosphere. Walterscheid and DeVore (1981) reported that calculations of the semidiurnal tide are more sensitive to the adopted heating functions than to non-classical effects such as mean winds and meridional temperature gradients. To investigate the uncertainty in the radiance calculations from this source we have therefore repeated them with a number of different heating rate formulations. Calculations using Chapman and Lindzen's expressions were compared with those using Groves's (1982a, b) and Hamilton's (1981a) heating functions for autumn equinox conditions. The vertical structure predicted for the forcing of the

![Figure 3. A comparison of the three tidal heating functions used for the (2, 2) component.](image)
semidiurnal (2, 2) mode from each author is shown in Fig. 3, clearly illustrating the difference between the earlier and later determinations.

Some errors in the tidal calculations will arise because the set of Hough functions included in this study is incomplete. An estimate of these errors was obtained by calculating the ozone heating rate as a function of latitude and decomposing it into Hough components. (The method used was similar to that described by Walterscheid et al. 1980.) On reconstructing the heating rate using only the modes listed in Table 2, agreement with the original calculations was found to be better than 20% from 0° to 60° latitude. Poleward of 60°, however, very large differences were seen. Comparison between radiance observations and theory will therefore be restricted to the former interval, and an uncertainty of 10% adopted for the theoretical calculations due to the neglect of higher-order Hough modes. This is somewhat less than the error in reconstructed heating rates because the effect of higher-order modes tends to be smoothed out by the SSU weighting functions.

4. RESULTS AND DISCUSSION

Figures 4, 5 and 6 compare observations obtained during the second half of September 1981 with the various theoretical predictions of radiance for the latitude bands 5°N–5°S, 25°–35°N and S and 45°–55°N and S. Observations from intermediate latitudes showed smooth trends between those presented here. The predictions of classical tidal theory using tidal forcing functions which are symmetrical about the equator at equinox result in tidal solutions which are also symmetric about the equator. Thus observed differences between the hemispheres highlight shortcomings in this model. It should be emphasized that both the relative values and the slopes of these observations are consistent with data from other 15-day periods in September and October 1981 (although steady changes in the structure shown by the observations are seen around equinox) and that the same pattern was seen in data from other years during these months, as discussed in more detail below.

In the equatorial zone (Fig. 4) the observed radiance variation of channels 25 and 26 is dominated by the semidiurnal component. This is also responsible for much of the variation of channel 27, although a definite diurnal component is discernible here. The slopes for all three channels, however, strongly suggest that higher frequency components are not negligible—a feature, indeed, seen at all other latitudes. Away from the tropics, the semidiurnal component diminishes in amplitude, so that in mid-latitudes (particularly for the two lowest channels) it is the diurnal component which dominates. In all cases, clear differences are present between the observations from channel 27 and those from the other two, with interhemispheric differences also occurring for this top channel between 25° and 35° (especially the slope at 1930 h).

Theoretical calculations based on the heating functions of Groves (1982a, b) and Hamilton (1981a) yielded very similar predictions of radiance variation, but these differed markedly from those based on Chapman and Lindzen’s (1970) formulations. Such differences were also noted for semidiurnal tidal amplitudes by Walterscheid and DeVore (1981). Recent evaluations of tidal forcing functions have considered the detailed distribution of ozone and water vapour, as well as up-to-date parametrizations of radiative transfer processes, and may be considered to have rendered obsolete Lindzen’s early analytical expressions. The agreement between radiance calculations based on Groves’s and Hamilton’s heating functions therefore suggests that comparatively little uncertainty in the calculations may be attributed to the choice of heating functions. It should also be noted that the differences in absolute magnitude between the observed and calculated
Figure 4. Observed radiance variations for the three channels in the equatorial zone (5°N–5°S) compared with theoretical predictions based on the following heating functions:

--- Groves (1982a, b); --- Hamilton (1981a); ---- Chapman and Lindzen (1970).
Lines drawn through the observed points represent the rates of change of radiance. Small displacements between the scales for the observed and predicted radiances are caused by differences in the zonal mean temperature profiles measured by the SAMS and the SSU (see text).

Radiances introduce a discrepancy of less than 3% in the radiance variations. These differences arise because of the different periods over which SAMS and SSU data were obtained, as well as small anomalies known to exist between radiance profiles derived from the two instruments (Barnett and Corney 1984).

Qualitatively, the theoretical calculations reproduce many of the broad features of the observations. Most of the energy of the semidiurnal tide is found in the (2, 2) Hough mode, which has its greatest amplitude equatorward of 30° (Lindzen 1979), thus explaining the latitude distribution of the semidiurnal component in radiance. All the main semidiurnal modes, especially (2, 2), propagate vertically with long wavelengths (Table 2), making them readily detectable by the SSU. The main propagating diurnal mode, (1, 1), also has its greatest amplitude in tropical latitudes, but its vertical wavelength of 28 km causes some variation in phase across an SSU weighting function and therefore a somewhat diminished detection efficiency. Higher-order propagating diurnal modes have much smaller wavelengths and are effectively smoothed out in the SSU response. In extratropical latitudes the diurnal tide is dominated by the trapped mode (1, −2), causing the energy of the sun's forcing to remain near to the level of excitation. Since the mode is trapped its phase is constant with height and the diurnal radiance variation is not very different from that expected from a purely radiative-photochemical calculation, as reported by Groves and Tuck (1981).

Quantitatively, however, serious discrepancies are evident between theory and observation. In equatorial regions the amplitude of the variation seen on channels 25
Figure 5. Observed and calculated radiance variations in the 25°–35° latitude zones. Key as for Fig. 4; closed circles denote northern hemisphere values and open circles southern hemisphere values.

Figure 6. Observed and calculated radiance variations in the 45°–55° latitude zones. Key as for Fig. 5.
and 26 is reasonably consistent with theory. The predictions for channel 27, however, greatly exceed the observed amplitude, especially in its diurnal component. The inclusion of mean winds and meridional temperature gradients in the tidal calculations (the so-called non-classical approach) is known to diminish the amplitude of the semidiurnal tide (Lindzen and Hong 1974) but to have very little effect on the diurnal (Forbes 1982). Indeed, Walterscheid and DeVore’s (1981) calculations predict a reduction by a factor of two in the amplitude of (2, 2) above 40 km due to non-classical effects, which would bring the semidiurnal component of the radiance variation into good agreement with the observations. The discrepancy for the diurnal component is not so easily resolved, but since it is most apparent for the uppermost channel one may plausibly propose some damping mechanism for the (1, 1) mode in the lower mesosphere possibly linked to the generation of convective instability and turbulence. Such mechanisms have been suggested in the literature (Lindzen 1981; Forbes 1982) but have not been quantitatively elucidated for the diurnal tide. To test this idea, the sensitivity to a Newtonian cooling profile as used by Rogers and Pyle (1984) was investigated. This produced a small reduction in the amplitude for channel 27 and a phase change to a minimum at 0800 h. This is in the correct direction for better agreement with the observations and the inclusion of realistic dissipation mechanisms might reconcile theory with observations.

A more irreconcilable discrepancy between observation and theory lies in the phase of the radiance variation. This is exemplified most clearly by the slope of the observation near 0730 h, which is positive for all three channels—in contrast to the predicted behaviour, especially in equatorial regions. Some evidence has been found in equatorial latitudes for a longitudinal modulation in the SSU radiance variation (D. R. Pick, private communication), presumably caused by non-migrating tidal modes, but the effect of this on the slope at 0730 h is very small. With only four sampling times, terdiurnal and higher components in the radiance variation cannot be adequately resolved, and the anomaly in the slopes could be attributed to one or more of these. It is possible, however, that the discrepancy lies at least partly in the phase of the two major components. No account was taken in the derivation of the heating functions of the diurnal variation in ozone concentration above 40 km, with its pronounced minimum in mid-afternoon between 45 and 60 km (Pallister and Tuck 1983; Vaughan 1984). Additionally, Lindzen (1978) suggested that a diurnal modulation in the tropospheric rainfall rate could reconcile the difference between the predicted and observed phase in the semidiurnal surface pressure oscillation, by delaying the maximum pressure by about 30–60 minutes. Some confirmation of Lindzen’s hypothesis was provided by Hamilton (1981b, c) who also deduced a significant influence on the diurnal tide from the same cause. Neither of these factors could be readily included in the radiance calculations, but it seems that the inclusion of rainfall-induced effects on the semidiurnal tide only worsens the disparity between the predicted and observed slope at 0730 h. Some improvement for channel 27 might follow the inclusion of a realistic dissipation mechanism for the diurnal tide, but further work is clearly needed to resolve this discrepancy.

Away from the equator the relative influence of propagating tidal modes diminishes, bringing better agreement between theory and observation. Indeed, bearing in mind the uncertainties in the observations and the limited number of tidal modes included in the calculations, a remarkably good agreement is seen for channels 25 and 26. Although it is fair to point out that such a close agreement was not seen with data from some of the other fifteen-day periods we have studied (to be described in part II), no major discrepancies with theory were found. The agreement for channel 27, however, is not so good. For the 25°–35° zones, as at the equator, a consideration of non-classical effects would reduce the predicted amplitude of the semidiurnal radiance variation, bringing it
nearer to the observed value. However, such effects cannot explain the anomalous slopes seen around 1930 h for both hemispheres in the 45°–55° zones and from 25°S to 35°S. These slopes suggest that higher frequency tidal components are present in the radiance variations at latitudes well away from the equator.

In order to emphasize the repeatability of our observations from year to year, Fig. 7 shows the variation with latitude of the radiance difference for channel 27 between the southbound (~1930 h) and northbound (~0730 h) orbits of NOAA-6 averaged over the latter half of September 1980, 1981 and 1982. The greatest interannual differences occur in southern midlatitudes, where the atmospheric variability is greatest, but the three curves do show excellent agreement and emphasize the potential of observations such as these in studies of atmospheric tides. Included also in Fig. 7 is a theoretical prediction of the latitude variation, which differs from the observations in a number of salient features. The overestimate of the diurnal radiance component in equatorial latitudes for channel 27 has already been discussed, and is particularly striking in Fig. 7. In addition, neither the underestimate northward of 20°N nor the interhemispheric asymmetry in 1980 and 1982 can readily be explained (the possible error attributed earlier to mode truncation would cause a distinctive latitudinal variation rather than a uniform reduction in the radiance difference, and is in any case too small to account for these departures). As mentioned above, further work is necessary for a comprehensive explanation of the SSU observations.

5. CONCLUSIONS

In this paper we have shown how radiance information from high precision radiometers on sun-synchronous polar-orbiting satellites can be used to investigate the diurnal variation in radiance. By averaging the observations over longitude and time, local and transient effects can be removed, isolating the periodic and globally coherent part of the variation. A sample of results obtained around the autumn equinox of 1981 displayed a distinctive latitudinal structure, with a predominantly semidiurnal variation in equatorial latitudes changing to a diurnal pattern outside the tropics. Evidence for higher frequency components was also found at all latitudes.

The observations were compared with predicted radiance variations calculated using classical tidal theory. Recent evaluations of the tidal forcing functions were chosen, and
although these gave predictions markedly different to the earlier heating functions of Chapman and Lindzen (1970), good agreement was found between radiance variations based on the heating functions of Groves (1982a, b) and Hamilton (1981a). Qualitatively, the theoretical predictions reproduced most of the observed features, but quantitative agreement was not so good, especially in the equatorial zone. Some of the discrepancies (e.g. the amplitude of the semidiurnal component) could be accounted for by known shortcomings in classical tidal theory, but others remained unresolved. Prominent among the latter was the magnitude of the diurnal component on the uppermost channel and the slopes at 0730 h on all three channels around the equator, interhemispheric differences in the 25°–35° zones and the evidence for terdiurnal or higher frequency components in midlatitudes.

Some evidence was shown to illustrate the reproducible nature of the SSU observations over adjacent fifteen-day periods and from the same periods in different years. This emphasizes the great potential of such global observations in the study of atmospheric tides. Further data, covering all seasons and with enhanced vertical resolution, will be presented in part II.

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REFERENCES


1982b Hough components of water vapour heating. ibid., 44, 281–290


Reed, R. J., Oard, M. J. and Sieminski, M. 1969 A comparison of observed and theoretical diurnal tidal motions between 30 and 60 km. *ibid.*, **97**, 456–459


1979b *ibid.*, Part II: Numerical results. **36**, 1636–1662