Lower Atmosphere/Thermosphere/Ionosphere Coupling Due to Tides

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The study of middle atmosphere tides has progressed rapidly due to advances in both observations and theory. Mesospheric tidal measurements during ATMAP (Atmospheric Tides Middle Atmosphere Program) in particular have provided the means to begin addressing the detailed coupling between the lower and upper atmosphere due to tidal waves. The Lower Thermosphere Coupling Study (LTCS) is extending the domain of interest to the thermosphere. Some results of the first LTCS campaign during September 1987, encompassing observations from 14 instruments, are described. These include the derivation of an empirical model of the data set, a method to extrapolate mesosphere predictions and/or data sets into the 100–130 km altitude region, and a means to derive boundary conditions for global thermospheric models which simulate the effects of upward propagating tides on the model solutions. The theoretical models exhibit encouraging agreement with the data, particularly for mid- and high latitudes. Surprisingly, worst agreement occurs for observations made at Arecibo, a low latitude site. This has been tentatively attributed to the neglect of electrodynamics in the model. The observations also suggest the presence of a strong (2, 3) mode during the LTCS-1 campaign, which appears unusual for an equinox period. Recent works which investigate the question of tidal set-up times and the effects of transients are briefly discussed. These topics are particularly relevant to discussion of LTCS-1 observations since the interval included two isolated periods of geomagnetic activity.

1. Introduction

Thermospheric tidal waves are identified as large scale oscillations in the atmospheric state variables with periods that are integral submultiples of a solar (or lunar) day while the horizontal wavelengths are integral submultiples of the earth radius. The vertical wavelengths are much smaller than the zonal horizontal wavelengths. Tides figure prominently in the theoretical understanding of various atmospheric phenomena. In the thermosphere, for example, the tides are invoked in the explanation of the mid-night temperature anomaly at low latitudes (MAYR *et al.*, 1979), the midnight collapse of the ionosphere at Arecibo (CRARY and FORBES, 1986), and the phase differences of O and N₂ above 200 km (MAYR and HARRIS, 1977). RICHMOND (1971) noted that the horizontal and vertical structure of the tidal winds determine the morphology and magnitude of the global current system. The importance of tides to the detailed understanding of the upper atmosphere has stimulated tremendous activity in the last few years in tidal research. Much progress has been made by the serendipitous melding of developments in both observations and theory: mesospheric tidal observations have been organized into tidal climatologies (MANSON *et al.*, 1989a) which have

been used to derive empirical descriptions of tides in the lower thermosphere (FORBES and SALAH, 1991) along with boundary conditions for thermospheric general circulation models (FORBES and VIAL, 1989).

In the upper thermosphere, the tidal response is largely generated in situ by solar heating, with some contribution arising from coupling with the ion neutral momentum transfer (FORBES and GARRETT, 1976). In contrast, the region from 90 to 150 km is strongly affected, even dominated, by tidal waves excited in the lower atmosphere which propagate

Fig. 1. Contours of log 10 electron densities. a) observations, from EMERY *et al.*, 1981; b) calculations from an ionospheric model which included no neutral winds; c) same as b, but height-independent diurnal and semidiurnal winds included; d) same as c, but terdiurnal winds included; e) same as d, but height dependence now assumed for semidiurnal winds. From CRARY and FORBES, 1986.

into the thermosphere (e.g. FORBES, 1982). The tidal waves, then, provide an important means for coupling the lower and upper atmosphere.

Support for the existence and importance of tidal/ionosphere coupling is found in recent works by CRARY and FORBES (1986) and FORBES and ROBLE (1990). CRARY and FORBES investigated the midnight collapse of the ionosphere at Arecibo, i.e., a sharp decrease in the height of the peak electron density which occurs near local midnight. It is often followed by a precipitous rise in the peak electron density shortly before local sunrise; Fig. 1(a) presents a typical example. The phenomenon has been observed on well over half the nights that incoherent scatter radar data were obtained. CRARY and FORBES performed four model simulations of the low latitude ionosphere, which 1) did not include neutral winds; 2) included height-independent diurnal and semidiurnal winds; 3) included height-independent diurnal, semidiurnal, and terdiurnal winds; and 4) included a height dependence in the semidiurnal winds (but not in the diurnal and terdiurnal winds). The modelled electron densities are shown in Fig. 1(b) through 1(e) as a function of height and local time. It is seen that 1) neutral winds are required to produce a behavior similar to that observed; and 2) terdiurnal winds appear to play a key role in driving the midnight collapse at Arecibo. The simulations with terdiurnal winds (Fig. 1(d)) are in much better agreement with the data, particularly with regard to the amplitude of the nighttime rise and fall of $h_{\max}$; the sharpness and magnitude of the morning rise; and the low electron densities predicted before sunrise.

These results prompted FORBES and ROBLE (1990) to investigate the coupling between the neutral atmosphere and ionosphere using a simplified model, in which $n_{\max}$, $h_{\max}$ and the field-aligned neutral winds were allowed to interact. These simulations were compared with a model run in which the ionosphere was prescribed by an empirical model; i.e., there was no neutral atmosphere/ionosphere coupling. Difference fields were computed for the meridional and zonal winds and electron densities predicted by the two model runs, which are shown in Fig. 2, along with the neutral winds and electron densities computed by the "interactive" model. The main feature of interest is seen in the meridional wind difference field (Fig. 2(c)): the interaction of the neutral winds and simplified ionosphere has generated a terdiurnal component in the neutral meridional wind. The implication is that the semidiurnal variations of neutral winds and electron densities couple to produce a terdiurnal wave, which was inferred from the work of CRARY and FORBES previously described.

Ionosphere/tidal coupling may also be inferred through comparison of the zonal and meridional wind morphology predicted by the interactive model. Note that, unlike the meridional winds which exhibit strong regular semidiurnal tidal variations (Fig. 2(a)), the zonal winds only exhibit semidiurnal waves in the lower thermosphere (Fig. 2(b)). FORBES and ROBLE explain the difference by noting that zonal winds suffer maximum ion drag, and that the electron densities predicted by the interactive model are enhanced in the daytime thermosphere below 200 km, relative to the non-interactive model (Fig. 2(f)). The enhanced electron densities effectively blocked the penetration of the semidiurnal zonal winds to higher altitudes as a result of greater ion drag.

The tremendous activity in the field of atmospheric waves makes it impossible to discuss in a short review all recent and current work. Discussion will therefore be limited to advances made in a few specific areas which will illustrate the breadth and scope of the research being done. Emphasis is on the semidiurnal thermospheric variations. The second section provides a brief background on tidal observations and models while the third section presents examples of recent progress in these areas. A summary is presented in the final section, along with future goals and requirements.

Fig. 2. Calculations of neutral winds and temperatures from a simplified thermospheric which allowed $n_{\max}$ and $h_{\max}$ to interact with the neutral meridional winds: a) neutral meridional winds with the interactive model; positive northward; b) neutral zonal winds from the interactive model, positive eastward; c) difference fields, meridional winds, for the interactive and non-interactive ionosphere calculations; d) same as c, for zonal winds; e) log 10 electron densities calculated by the interactive model; f) difference field for the electron densities from the interactive and non-interactive ionosphere model. From FORBES and ROBLE, 1990.

2. Background

2.1 Observations

In the 80–100 km altitude region, observations of neutral winds are obtained by partial reflection and meteor radars. From 100–140 km, incoherent scatter radars (ISR) measure ion drifts and ion temperatures which can be analyzed to provide neutral winds and temperatures, respectively. The incoherent scatter radars also obtain measurements in the upper thermosphere (above 200 km). Measurements in the altitude range 140–200 km are problematic to analyze because the neutral composition, required in the data reduction, is changing from molecular to atomic species and is therefore poorly determined. Some tidal information has also been obtained by spacecraft; for example, HEDIN *et al.* (1980) and HERRERO *et al.* (1983) present tidal components of composition and/or temperature derived from Atmosphere Explorer (AE) satellite data; more recently, BURRAGE *et al.* (1991) presented maps of diurnal and semidiurnal tides in N_2 , O, and temperature at low latitudes during solstice solar cycle minimum conditions derived from AE data.

In all cases, the observations used to derive tidal information consist of a time series, preferably extending over several days. The time series is fit with a Fourier series to determine the mean and typically the diurnal and/or semidiurnal amplitudes and phases. In practice, it has made little difference if the observations are averaged into one day of data and fit with the Fourier series, or if the multi-day series is fit (WAND, 1976). At low and mid latitudes, ISR measurements are restricted to daylight hours when electron densities are large enough to provide good signal-to-noise ratios.

References for the acquisition and reduction of mesospheric radar data appear in VINCENT (1984) and MANSON *et al.* (1989a). Reviews of ISR measurements and data reduction are those of HARPER *et al.* (1976), WAND and EVANS (1981) and JOHNSON (1991); the latter focuses on high latitudes.

2.2 Modeling

As mentioned in the introduction, the emphasis here is on thermospheric tides; thus, only numerical models of the thermosphere are discussed here. The thermospheric general circulation models (GCMs) developed by the National Center for Atmospheric Research (NCAR) (e.g. ROBLE *et al.*, 1988) and University College of London (UCL) (e.g. FULLER-ROWELL *et al.*, 1987) numerically calculate the three-dimensional time-dependent neutral and ion densities, temperatures, and winds. The time series of the model variables are Fourier decomposed to provide predictions of the diurnal and semidiurnal tides as a function of altitude, latitude, season, solar cycle, and geomagnetic activity. An important feature of both the NCAR and UCL theoretical models is the coupling of the ionosphere with the neutral atmosphere. This capability allows the investigation of the interaction of tidal and large scale gravity waves with the ionosphere with a minimum of simplifications and assumptions. The effect of ion-neutral momentum coupling on the thermospheric waves will also be more accurately represented in the coupled models.

Thermospheric tidal waves are generated by in situ absorption of solar UV and EUV energy and ion neutral momentum coupling through the ion drag term. For semidiurnal waves, there is also a contribution from waves which were excited in the lower atmosphere and penetrate the thermosphere. (Upward propagating diurnal waves are largely restricted to low latitudes and are damped near 105–110 km.) The models' formulation typically includes explicit representation of the first two tidal sources and the subsequent generation of tides.

The source due to upward propagating waves is parameterized by the method of HONG and LINDZEN (1976) which has been described by FORBES (1987) and FESEN *et al.* (1986, 1991); a brief summary follows.

At any height in the upper atmosphere, the upward propagating waves will impose periodic variations on the densities, temperatures, and velocities. This is simulated in the numerical models by imposing a wave-like perturbation on the geopotential at the model lower boundary, usually near 100 km:

$$G(\theta, t) = \sum_n g_n \Theta_n(\theta) e^{i(2\pi t/12 + 2\lambda)} \quad (1)$$

where G represents the geopotential, θ is the latitude, t is the local time in hours, g_n are complex coefficients identified by amplitudes and phases, Θ represents the Hough functions, and λ is the longitude. This expression is written explicitly for semidiurnal (westward) propagating tides; the summation is over the n contributing modes (2, 2), (2, 3), (2, 4), (2, 5) and (2, 6). The latitudinal distribution of the geopotential is described by Hough functions, which are well-tabulated functions of Legendre polynomials and are shown in Fig. 3. Similar variations will be induced in the other model fields which can be related to the

Fig. 3. Semidiurnal hough functions for temperatures (top), zonal winds (middle), and meridional winds (bottom). The curve labeled “ n ” represents the structure of the 2, n mode: e.g., the curve labeled “3” is the 2, 3 mode.

geopotential through application of classical tidal theory (CHAPMAN and LINDZEN, 1970). The resulting waves evolve as dictated by the physics of the model. The “free parameters” describing the waves are their amplitudes and phases, which are adjustable parameters in the model. Initially, these were determined by trial and error, but recent advances in observations and modelling have provided a better means of representing the upward propagating waves, which will be described below.

3. Recent Progress

3.1 Observations

One of the major advances in the observational study of mesospheric and thermospheric tides and gravity waves is the implementation of coordinated multi-instrument global observation campaigns of several days duration, such as the Global Thermospheric Mapping Study (GTMS) and the World Acoustic/Gravity Wave Study (WAGS). Individual campaigns provide enhanced altitude and latitude coverage of the tidal parameters; seasonal and solar cycle variations can be addressed as the data accumulate. Two campaigns have focused on atmospheric tides and are described further below: the Atmospheric Tides Middle Atmosphere Project (ATMAP) (FORBES, 1984, 1986); and the Lower Thermosphere Coupling Study (LTCS) of the Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) and World Ionosphere/Thermosphere Study (WITS) programs (FORBES, 1990). ATMAP employed meteor and partial reflection radars, covering the nominal altitude region of 80–100 km. LTCS incorporates mesospheric radar data plus observations from incoherent scatter radars operating mainly at altitudes above 100 km. Data from other instruments will be utilized as these become available.

Observations taken during ATMAP have been summarized by AVERY *et al.* (1989), MANSON *et al.* (1989a), and VINCENT *et al.* (1989). The observed tidal winds exhibited great day to day variability, with the diurnal tides more variable than the semidiurnal (e.g. MANSON *et al.*, 1989a). An important result of the project was that the consistency between observations at different stations was improved substantially if the observing periods extended over at least 10 days (FORBES, 1986), a suggestion made earlier by MANSON *et al.* (1985).

A major advantage of the mesospheric radar data set vs. the ISR data set is the availability of data from southern hemisphere stations. VINCENT *et al.* (1988) present a comparison of tidal winds observed at Adelaide (35°S, 138°E) and Kyoto (35°N, 136°E) which form a geographically conjugate pair. They found substantial asymmetry about the equator for the diurnal tidal winds, which were significantly larger in the southern hemisphere. The tentative explanation is that the wind asymmetries are caused by hemispheric asymmetries in the background mean winds and dissipation. The semidiurnal winds were found to be similar in strength and phase structure, with the exception of a 4–6 hour phase difference in the zonal winds at the two sites. This behavior is suggestive of an asymmetric mode dominating the mid-latitude semidiurnal tidal response.

An important product of the ATMAP program was the derivation of tidal wind climatologies for mid-latitudes. Data averaged over 10 or 30 days were used to produce maps of the diurnal and semidiurnal eastward and northward winds as a function of altitude and month (MANSON *et al.*, 1989a). An example is shown in Fig. 4, which presents the 10-day averaged semidiurnal meridional winds (top) and zonal winds (bottom) during 1985 at Saskatoon (52°N). The dark regions indicate regions of mean west-ward zonal winds. The data show that maximum amplitudes occur near the equinoxes, and are generally associated with

Fig. 4. Mesospheric tidal climatology at Saskatoon, 1985–1986: Semidiurnal meridional winds (top) and zonal winds (bottom), with amplitudes (phases) to left (right). Shaded region indicates periods of westward mean zonal flow. From MANSON *et al.* (1989a).

regions where the mean winds reverse. Phase transitions are quite rapid between the solstices and equinoxes. This implies that averaging the data over periods of 30 days or longer would smear much of the structure evident in the plots. As will be discussed below, these data have important applications in the theoretical modelling of thermospheric tides. Similar maps of the monthly averaged altitude profiles of vertical motions in the middle atmosphere are beginning to be accumulated (e.g. MEEK and MANSON, 1989).

Coordinated observations of both mesospheric and thermospheric tides were obtained by the first LTCS campaign, September 21–26, 1987; a special issue of the *Journal of Geophysical Research* presents some of the results from LTCS-1. Although the period is representative of equinox, solar cycle minimum conditions, there were isolated periods of geomagnetic activity. Data were obtained by 14 instruments: nine partial reflection and meteor radars and four ISR radars. The mesospheric data were described by MANSON *et al.*

(1990). The ISR data are presented by SALAH *et al.* (1991), TETENBAUM *et al.* (1990), JOHNSON (1991), JOHNSON and VIRDI (1991), and REESE *et al.* (1991).

The LTCS-1 data provide the first set of simultaneous measurements of the lower thermosphere at low, mid and high geographic latitudes, through observations obtained by the Arecibo (18.3°N), Millstone Hill (42.6°N), and Sondrestrom (67°N) and EISCAT (69.5°N) radars. Arecibo and Millstone are near 70°W geographic longitude, with Sondrestrom relatively nearby at 50°W. EISCAT is near 20°E geographic longitude. Sondrestrom and EISCAT thus have similar geographic latitude, but are separated by 8° geomagnetic latitude and 70° geographic longitude. The availability of simultaneous data from two high-latitude stations permits more detailed study of the dynamic polar region. The acquisition of ISR data from high latitudes is a recent development which will provide more constraints on the theoretical models.

A comparison of the mean, diurnal, and semidiurnal horizontal winds at the two high latitude radars during LTCS-1 is presented by JOHNSON and VIRDI (1991). The mean, diurnal and semidiurnal flows were found to exhibit similar structures at both locations, which was attributed to the dominance of latitudinal over longitudinal influences. A sharp eastward surge was observed in the zonal winds just after midnight at both stations during the geomagnetically disturbed period from September 22 to 23. REESE *et al.* (1991) analyzed the total neutral density variations at Sondrestrom from about 90–110 km and found good agreement with the empirical MSIS-86 densities. A tidal decomposition of the data showed that the diurnal and semidiurnal density amplitudes were of roughly equal magnitude, with the diurnal (semidiurnal) phases consistent with trapped (propagating) waves. Comparison with a NCAR Thermosphere/Ionosphere General Circulation Model (TIGCM) simulation showed that the model seriously underestimated the tidal amplitudes, by up to two orders of magnitude. They speculated that this might be due to inadequacies in the model lower boundary conditions.

The ISR LTCS-1 wind and temperature data from low, mid- and high latitudes are summarized in Figs. 5 and 6, from SALAH *et al.* (1991); comparisons to an empirical model are also made. The semidiurnal temperature amplitudes at 110 km (Fig. 5, bottom) are quite small and decrease with latitude, while the phases increase with latitude. At 120 km (Fig. 5, top), the amplitudes are much larger than at 110 km at low and high latitudes, with a minimum at mid latitudes; the phases also show an inflection at mid-latitudes. The empirical model results, from FORBES and VIAL (1991) (described below) are in good agreement for the phases. However, the model amplitudes are too small, particularly at 120 km for Arecibo and Sondrestrom. The disagreement is not surprising in light of the results shown in Fig. 6 which presents the semidiurnal temperatures observed at Millstone Hill along with the model predictions. The model simulations can be decomposed into contributions of the individual Hough modes which are also shown. It is obvious that the relative phasing between the modes has tremendous influence on the resulting variation: slight shifts in phase may produce greatly different results at particular altitudes. As will be discussed later, analysis of the mesospheric radar data indicated that a large asymmetric mode was present during this period (FORBES and SALAH, 1991), possibly due to asymmetries in the stratospheric ozone heating (TEITELBAUM and COT, 1979).

The continuity of the mesospheric and thermospheric radar data at 43°W was investigated by CLARK and SALAH (1991), who found good consistency in the amplitudes and phases of the semidiurnal winds. CLARK and SALAH also tested the semidiurnal tidal components derived from the Millstone Hill data by comparing the winds at 100 km derived from the Millstone

Fig. 5. Observations (solid curves) of semidiurnal temperatures during LTCS-1 at Arecibo (18°N), Millstone Hill (43°N), and Sondrestrom (67°N). Observations are for altitudes of 110 km (bottom) and 120 km (top). Dashed curves indicate model results of FORBES and VIAL (1991). From SALAH *et al.*, 1991.

Hill radar to those inferred from a nearby meteor radar at Durham. The ISR data only extend over 8–12 hours during daytimes at low and mid-latitudes, while mesospheric radar are capable of observing over the full 24 hour cycle. Thus, the meteor radar data can be analyzed for evidence of longer period waves. The comparison showed that there was little contamination of the semidiurnal wave by one or two day waves, and that the assumption of a purely semidiurnal oscillation in the lower thermosphere at Millstone Hill is valid.

3.2 Modelling and theoretical investigations

The monthly climatologies of winds derived from the mesospheric radar data have made a major contribution to progress in modelling thermospheric tides. The mesospheric winds were used by FORBES and VIAL (1989) to test their comprehensive model of atmospheric tides. This model extends from the ground to about 300 km, but is not realistic above about 100 km due to inadequacies in parameterizing diffusive processes. The FORBES and VIAL model provided the first numerical predictions of the atmospheric tides on a monthly basis. For the first time, hemispheric asymmetries in the background atmosphere were included in a tidal model, resulting in a more complex, and realistic, seasonal and latitudinal structure. The model predictions of temperatures along with winds complemented the information available from the mesospheric radars. The model climatology in the 80–100 km region was found to

Fig. 6. Observations of semidiurnal neutral temperature during LTCS-1 at Millstone Hill (solid curve with dots). Amplitudes (phases) are to the left (right). Model results of FORBES and VIAL (1991) indicated by solid curve with crosses, along with contributions from individual tidal modes. From SALAH *et al.*, 1991.

be in encouraging agreement with the monthly averaged data, but there are discrepancies. The model semidiurnal tidal amplitudes tend to be smaller than observed, with some phase differences. In particular, the semidiurnal amplitudes are a factor of two smaller than observations indicate at September, the month of the LTCS-1 campaign.

The relative success of the FORBES and VIAL model to simulate the upper mesospheric region encouraged the authors to extend the model into the lower thermosphere. The model variables near 100 km were extrapolated into the 100–140 km region using Hough Mode Extensions (HMEs) (FORBES and HAGAN, 1982), functions which describe the latitude and altitude structure of the semidiurnal waves in the thermosphere. Based on the classical Hough modes which are invariant with height, the HMEs vary with altitude and latitude to account for the effects of dissipation in the thermosphere. The method and resulting monthly maps of the semidiurnal tides in the 100–140 km region are described in FORBES and VIAL (1991). Comparison to limited incoherent scatter radar data showed that the model amplitudes are generally 20–50% smaller than those observed, while the model phases tend to lead the observations at low and mid-latitudes for all heights. Coincidentally, the worst agreement between the model predictions and the ISR data occurred for the month of September, the month of the first LTCS campaign.

The lower thermospheric semidiurnal winds and temperatures predicted by the FORBES and VIAL (1991) empirical model exhibit distinct seasonal variations; an example is shown in Fig. 7 for the semidiurnal temperatures in January and March. The March temperature simulation (Fig. 7(a)) is quite symmetric, apparently dominated by a (2, 4) mode; the January amplitude maxima (Fig. 7(b)) are shifted in latitude and altitude relative to March and suggest a (2, 3) mode. At fixed location, the winter amplitudes are larger than the summer amplitudes while the transition from solstice to equinox behavior is fast, particularly in the spring. The latitudinal structure is then predicted to be dependent on season (and vice versa), mandating

Fig. 7. Semidiurnal temperature amplitudes during January (top) and March (bottom) from the model of FORBES and VIAL (1991).

observational campaigns of sufficient frequency and duration to resolve the tidal morphology.

The altitude and latitude structure of the semidiurnal winds and temperatures predicted by the FORBES and VIAL (1991) model for September were compared with the LTCS-1 data set by FORBES and SALAH (1991). Consistent with the discussion above, the Arecibo and

Millstone Hill observations were fairly poorly modelled, with phase discrepancies of several hours and model amplitudes up to 50% too small. An empirical representation of the LTCS-1 observations was then formulated by FORBES and SALAH: the data were fit in a least squares sense with HMEs, using multiple linear regression (BEVINGTON, 1969). This approach was used in tidal studies by GARRETT and FORBES (1978), and is similar in concept to the formulation of the empirical MSIS model of neutral atmosphere and composition (e.g. HEDIN, 1987). The technique is useful because it provides a means to organize future data into a self-consistent global representation. The LTCS-1 data are well represented by the empirical model, which is hardly surprising. Comparison with the numerical FORBES and VIAL (1991) lower thermosphere model described above shows that the (2, 3) mode was significantly enhanced (by almost an order of magnitude) during the LTCS campaign.

FORBES and SALAH also tested the reliability of deriving semidiurnal tidal modes from a fairly small number of stations with latitudinal gaps. A mock data base was constructed from the atmospheric tidal model of FORBES (1982). Tidal components of the model winds and temperatures were derived using "data" from various combinations of "stations" in the model and compared to the "correct" tidal components: i.e., those derived from the fit to model winds and temperatures at all gridpoints. It was found that both ISR and mesosphere radar data are necessary to provide accurate estimates of the contributing tidal modes. Data from the southern hemisphere, particularly at mid to high latitudes, and data from above 100 km must both be available to resolve the asymmetric modes adequately.

An important aspect of both the numerical and empirical models described above is their description of the semidiurnal tides near 100 km, the level typically near the lower boundary of thermospheric general circulation models. The mesospheric and/or empirical models then may provide a representation of the upward propagating tidal waves which can be incorporated into the thermospheric numerical models. This has been done for the TIGCM which now incorporates the decomposition of the semidiurnal tidal waves near 100 km provided by the FORBES and VIAL (1989) lower atmosphere model. In essence, the thermospheric model is driven by the lower atmosphere model, which more realistically reflects the coupling between the two atmospheric regions. Since the FORBES and VIAL lower atmosphere model provides monthly simulations of mesospheric tides, monthly model predictions of thermospheric tides are possible for the first time.

Support for the seasonal variation of the tidal components near 100 km is found in the mesosphere climatology maps, and also in a simulation of the lower thermosphere tides by PARISH *et al.* (1990). In that study, theoretical predictions by the UCL model of the semidiurnal waves at high latitudes were compared with EISCAT data from May and July 1987. The model was able to simulate the data reasonably well only if the parameterization of the upward propagating tides at the model lower boundary was different for the two months.

The FORBES and VIAL model predictions of the lower boundary forcing were used in the TIGCM simulations of the LTCS-1 lower thermosphere semidiurnal winds and temperatures. However, the March values from FORBES and VIAL were used since the model shows worst agreement with mesospheric data during September. An example of the model simulations are shown in Fig. 8 from FESEN and ROBLE (1991); the figure shows the comparison of the model predictions of semidiurnal meridional winds with the observations at low, mid-, and high latitudes. This field exhibits the best agreement between model and data for all three sites. The model amplitudes tend to be smaller than those observed, although they do fall within the error bars in nearly all cases. The observations all indicate a much greater degree of

Fig. 8. TIGCM simulations of LTCS-1 observations of semidiurnal meridional winds at Sondrestrom (top), Millstone Hill (middle), and Arecibo (bottom). Amplitudes (phases) to left (right). Model simulations are shown by broken curves. From FESEN and ROBLE, 1991.

vertical structure than is predicted by the model, and the observed phases are not well represented. Comparison of the model results with the semidiurnal zonal and temperature data shows that, in general, the model simulates the Millstone Hill observations best, and the Arecibo observations worst. The discrepancy at Arecibo is possibly due to the neglect of interactive electric fields within the model. The disagreement is disappointing, but hardly surprising—the theoretical understanding of the quiet time tides is still a challenge. In addition, the geomagnetic activity that occurred during the LTCS-1 period complicates both the inference of tides from the data and their simulation by the models.

Recently, a spectral TGCM has been developed by MIKKELSEN and LARSEN (1991). Its primary advantage is increased horizontal resolution, which will improve the representation of high latitudes, higher order tidal modes and the forcing functions, and the resolution of short period waves such as gravity waves. The first use of the model was to investigate high

latitude dynamics, specifically, the coupling between the auroral circulation and the waves propagating into the thermosphere from the lower atmosphere. The authors note the inherent difficulty in deducing tidal components at high latitudes, since it is difficult to isolate tidal features from those induced by magnetospheric forcings. Nonetheless, the model simulations showed that the upward propagating waves affected the model fields to some extent at all heights; the *E* region in particular was greatly influenced by the externally forced tides. The magnitude of the effect depends on the relative phasing of the thermal tidal sources, which are fixed with respect to the sun, and the waves generated by auroral sources. MIKKELSEN and LARSEN attempted to estimate the influence of non-linear effects on the model predictions by forming difference fields: i.e., model simulations which neglected lower atmosphere tidal

Fig. 9. Hodographs of the wind differences calculated from the spectral model of MIKKELSEN and LARSEN (1991) which indicate the contribution of non-linear interactions to the wind fields in the polar thermosphere. Hodographs are plotted for each 10 degrees latitude and every 3 hr local time at 00 UT. Latitude extent of plot is to 40°N. The curves show the variation of the position of the tip of the difference wind vector as a function of height as shown explicitly for the hodograph at 60°N at 0300 LT. From MIKKELSEN and LARSEN, 1991.

waves and simulations without solar forcing but including the waves were subtracted from simulations which incorporated both processes. A non-zero difference field then indicates some contribution from non-linear effects. Figure 9, reproduced from MIKKELSEN and LARSEN (1991), shows hodographs of the difference field for the winds. It is seen that maximum wind differences, thus maximum contributions from non-linear interactions, are found in the *E* region: differences of 200 m s^{-1} are predicted in the dusk cell between 120 and 150 km. Although smaller, non-linear effects can be discerned in the *F* region at isolated locations.

3.3 The effects of transients

A long standing question in thermospheric tidal theory concerns the set-up times for the tidal oscillations: the time required to establish a stationary global tidal oscillation of fixed period. The observed day-to-day variability of the tides may be due to the presence of waves with periods (slightly) different than tidal periods. VIAL *et al.* (1991) note that “tidal variability” is a contradiction in terms, since tides have fixed periods by definition. This question is by no means academic: if observations are made over periods less than the set-up time, true tidal oscillations will not be resolved. There are obvious implications for observations during impulsive events such as geomagnetic disturbances. Theoretical model predictions can only be rigorously tested by comparison with tidal components uncontaminated by transient effects.

BERNARD (1981) defined the setup time as that required for a wave to make one circuit of the earth at the latitude of the wave’s maximum amplitude. BERNARD deduced setup times of 12 (2.5) days for the main diurnal (semidiurnal) waves. Little more was done on this problem

Fig. 10. Effects of introducing impulsive perturbations on steady diurnal (top) and semidiurnal (bottom) eastward winds at 85 km. From VIAL *et al.*, 1991.

until two recent works by VIAL *et al.* (1991) and WALTERSCHEID (1990).

VIAL and FORBES used a numerical model to investigate the diurnal and semidiurnal tidal response to forcings of 12 or 24 hours which included a transient perturbation. The transient forcing introduced oscillations into the (1, 1) and (2, 2) mode which persisted for weeks; see, e.g. Fig. 10. Three possible definitions of set-up time were formulated by the authors: 1) the minimum time necessary to achieve steady state; 2) the e-folding time for the oscillations to damp out; and 3) the time needed for amplitudes to attain a certain percentage of the steady state solutions. In all cases, the set-up time for the (2, 2) mode was found to be several weeks, reinforcing the necessity to obtain measurements over at least 6–10 days to deduce meaningful tidal components. The diurnal set-up times were found to be shorter, on the order of 6–20 days.

WALTERSCHEID (1990) numerically simulated shallow water gravity waves in a channel to investigate the effect of local sources of perturbations on the tidal waves. He estimated the set-up time as the time required to obtain an observable steady state standing wave at fixed latitude. This set-up time is then some multiple of that defined by BERNARD (1981). Specifically, WALTERSCHEID estimates set-up times of weeks for the (2, 2) mode and months for some diurnal modes. This is in distinct contrast to FORBES and VIAL, who find the diurnal set-up times to be smaller than those for the semidiurnals, regardless of the definition of set-up time used. WALTERSCHEID notes that such long set-up times have interesting consequences: the tides may be unstable to a large degree, especially during seasonal transitions, which are most pronounced near equinoxes.

4. Summary

Tidal studies have benefited greatly from the collaboration between mesospheric and thermospheric researchers. The mesospheric data base has been used in conjunction with theoretical model predictions to derive a parameterization of tidal waves propagating from the lower atmosphere into the thermosphere. Thus, the coupling between the lower and upper atmosphere is physically realistic, if not self-consistent.

Future progress in tidal research will depend on continued acquisition of high-quality, global, simultaneous data over a range of altitudes. The addition of high-latitude and southern hemisphere mesospheric radar sites has provided key information for the decomposition of the diurnal and semidiurnal waves. The thermospheric radar community has also added high latitude sites, which greatly improves resolution of the latitudinal wave structure and the dynamic processes in the polar regions. Theoretical models continue to mature, and detailed validation studies are underway. Topics for further effort include:

- the effects of the tides on the ionosphere. With the advent of coupled thermosphere/ionosphere models which incorporate tidal sources, it is now possible to investigate the coupling between the lower and upper atmosphere realistically. The acquisition of multi-day, global observations remains a high priority to test the models and the theoretical understanding.

- the investigation of shorter period waves. Six and eight hour waves have been fairly routinely deduced for some time from mesospheric and thermospheric data (e.g. SALAH and EVANS, 1973; AMAYENC, 1974; TONG *et al.*, 1988; MANSON *et al.*, 1989b). However, little theoretical investigation has been done. Predictions of these waves by the TIGCM and UCL models are trivial, but the investigation must await reasonable simulations of the diurnal and

semidiurnal waves since coupling between these modes may contribute to the shorter period waves (e.g. GLASS and FELLOUS, 1975).

- the simulation of the diurnal tides. Although not emphasized here, the diurnal tides remain an important topic for theoretical and observational study. Recent studies have focused on the dissipation of the diurnal tides (FORBES and HAGAN, 1988; FORBES and VINCENT, 1989; and HINES, 1989) and the generation of diurnal waves by the upward propagating tidal waves (PARISH, 1989).

- the determination of vertical velocities in the middle atmosphere. Until recently, very few observations of vertical velocities have been published; theoretical predictions were equally hard to find. However, mesospheric data are now beginning to be accumulated. For example, MEEK and MANSON (1989) collected data at Saskatoon for one year for altitudes of about 65 to 110 km. The data were averaged into a map of velocities by altitude and month. The observations show the summer motions to be down-ward, but the winter motions to be height-dependent: the winter vertical velocity was upward (downward) below (above) 85 km. The cause for this behavior is unknown. Significant diurnal variations were also seen which were larger than predicted by tidal models.

- the interaction of the thermospheric tides with the zonal mean circulation. Several studies have been done which concentrated mainly on the upper mesosphere and lower thermosphere (e.g. MIYAHARA and WU, 1989; WU *et al.*, 1989). These found that dissipation of the tidal waves generated significant contributions to the zonal mean winds. The atmospheric models in such studies are typically not fully self-consistent. The thermospheric general circulation models solve the full non-linear primitive equations, simulating the coupled atmosphere-ionosphere system, and may provide a more accurate representation of the consequences of tidal interaction with the mean flow.

- the interaction of the tides with gravity waves is a relatively unexplored topic which is gaining attention. During geomagnetically disturbed periods, the identification of tidal features is debatable while the question of tidal set-up times becomes increasingly important.

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