Adv. Polar Upper Atmos. Res., **17**, 167–176, 2003

Report

An overview of the terdiurnal tide observed by polar radars and optics

Takehiko Aso

Antarctic Environment Research Center, National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515

(Received May 9, 2003; Accepted June 9, 2003)

Abstract: A terdiurnal 8 hr period component is often observed in the radar and optical measurements of wind and temperature field at mesospheric heights. This might be either a global tidal wave of the 3rd harmonics of diurnal tide or locally confined gravity wave component or normal mode Lamb waves. Observationally, it has been found that in winter it is more evident and stable with longer vertical wavelength than in summer. Here, a brief overview is given in view of the latitudinal comparison of modeled and recently observed terdiurnal components, mostly at higher latitudes which might reflect higher order modes and relevant generation mechanism either by solar direct drive or by non-linear interaction or by local agent.

key words: atmospheric tide, terdiurnal tide, meteor radar, polar region, optics

1. Introduction

A terdiurnal or 8 hr period component of atmospheric oscillations is basically a third harmonic tidal oscillation and has been found in the temperature and wind fields in various radar and optical observations. If it is a global and migrating "tidal" wave with zonal wavenumber three, it is excited either by the third harmonic of heating due to solar insolation absorption by water vapor and ozone in the lower atmosphere and also *in-situ* by EUV and UV absorption in the lower thermosphere or by nonlinear interaction of migrating diurnal and semi-diurnal tides. Global tidal structure is attained after the transience in propagation and formation of standing wave structure in the latitudinal direction.

Besides the global migrating 8 hr tide, intradiurnal Lamb waves with similar periods (Forbes *et al.*, 1999; Portnyagin *et al.*, 2000) and transient and localized gravity wave activity with a period of 8 hr might often be detected in a mono-static observation and might contribute to apparent terdiurnal tidal variability. Non-linear processes of either local 24 hr or diurnal oscillation or global diurnal tide will also contribute to variability in 8 hr component as their third harmonics. The more probable candidate of variability of this terdiurnal tidal component is a non-linear wave-wave interaction between diurnal and semidiurnal tides. Teitelbaum *et al.* (1989) compared the 8 hr oscillation of mid-latitude radar observations with their numerical model. They surmised that the observed slightly larger vertical phase gradient seems to be more consistent with non-linear excitation than the direct solar driven tide. The model also indicates a very rapid excursion in the latitudinal phase profile due possibly to complexities of involved tidal components.

Here, more recent observations are briefly discussed and compared with these and other modeling.

2. Observed 8 hr component

An 8 hr component is generally smaller than the diurnal 24 hr and semidiurnal 12 hr components, but has definitely been identified in various radar and optical observations. Earlier observations at Garchy (47°N) show small amplitude with intermittent occurrence like internal gravity waves and short vertical wavelength of 35 km with appreciable variability, from which they conjectured the superposition of thermal terdiurnal tide and the secondary wave generated by the non-linear interaction of diurnal and semidiurnal tides (Glass and Fellous, 1975). Of course this intermittency can be interpreted in terms of localized internal gravity wave as well.

EISCAT radar long-term runs have contributed to the detection of the 8 hr component at northern higher latitudes. Williams *et al.* (1994) reported in their monostatic CP2 beam swinging method that the amplitude is 15–25 ms^{-1} and phase gradient is fairly small with some uncertainty but with inferred vertical wavelength of about 100 km. Climatological *E* region neutral wind analysis over 56 days of the EISCAT data during 1986 and 1996 by Nozawa and Brekke (1999) indicates an 8 hr component amplitude of around 10 ms^{-1} very roughly with stable phase gradient especially in the meridional component from 0700 LT at 101 km to 0420 LT at 118 km with vertical wavelength of about 50 km. Seasonal grouping for summer, winter and equinox suggests less steady amplitude and fairly erratic phase excursions except in the meridional component above about 100 km. This might be due to averaging of inherent intermittency of this terdiurnal component.

MF radar observations by Manson and Meek (1986) show climatology of tides at Saskatoon (52°N, 107°W). One-year's observations in 1981 reveal that amplitudes of the terdiurnal component are several ms^{-1} below 100 km, and have a greater tendency to increase with height more in winter than in summer. The phase gradients are large and irregular in summer, suggesting vertical wavelength as small as 25 km at 90 km for the meridional wind, whereas in winter phase is almost constant and consistent with quadrature relation between northward maximum around 0700 LT and eastward maximum around 0100 LT. Based on these and long-term observations at Garchy (47°N) and Montpazier (44°N), Teitelbaum *et al.* (1989) presented a detailed analysis of an 8 hr oscillation. They did numerical modeling of non-linearly excited terdiurnal tide and even a secondary diurnal component excited as a non-linear difference of primary diurnal and semidiurnal tidal waves. The results show that the non-linear wave is almost comparable in amplitude and also in its latitudinal structure with solar-driven wave. In winter, the observed amplitudes are fairly large and phase varies less than the modeled solar driven plus non-linear waves. In summer, model amplitudes fit better to the observations up to 100 km and phase profiles reproduce well a bit steeper excursion in the observation, including its jump around 85 km due to interference between the solar driven and the secondary waves. This might be due to short vertical wavelength of the involved primary diurnal wave. They surmised that the observed terdiurnal tide is due to the superposed solar driven and secondary waves at least in summer, and that the larger amplitude in winter is not due to the solar heating but due to relative phase of two components. However, more stable or long vertical wavelength phase in winter cannot be reliably interpreted by referring to the phase structures or dominant modes of the primary 12 hr and 24 hr waves which tend to be superposed by short vertical wavelength higher order modes generated by strong winter westerly flow. They also suspected the possible contribution of a non-solar mode and/or gravity wave of 8 hr period.

A University of Western Ontario MF radar near London, Canada (43°N, 81°W) reports interesting signatures of the 8 hr component based on long-term observations from 1992 to 1996. Thayaparan (1997) confirms that the amplitudes in winter are 4–7 ms^{-1} and generally larger than those in summer which are 2–3 ms^{-1} for zonal and 1–2 ms^{-1} for meridional wind. They also show that the phase profile in winter is almost constant in evident contrast to short vertical wavelength in summer, which is fairly consistent with earlier findings. They also noted short-term variability which is ascribed to non-linear interaction of diurnal and semidiurnal tides and a tidal/gravity wave interaction.

Quite recently, Smith (2000) published a paper on the terdiurnal tide observed by the HRDI instrument onboard the UARS satellite. In this case, the results reflect middle to lower latitude global structures of this 8 hr component averaged in time over a month or more and in height several kilometers around 95 km. It is shown that the terdiurnal component has annual averaged amplitude of 5 ms^{-1} (meridional) and 15 ms^{-1} (zonal) with zonal wavenumber three global structures, and that northward maximum occurs at 0400–0500 LT at mid-latitude. A correlation between terdiurnal amplitude and diurnal and semidiurnal amplitudes, which they believe to be the signature of non-linear coupling, seems weak for this seasonal time scale, due possibly to averaging out of intermittent secondary waves.

Recent optical observations have also revealed significant signatures of 8 hr components. At the northern polar station in Eureka (80°N), Fabry-Perot Interferometer measurements of the horizontal wind from airglow emission around 92 km and Michelson Interferometer temperature from hydroxyl layer around 85 km delineate tidal oscillations especially in winter at ~97 km (Oznovich *et al.*, 1997). An 8 hr component is discussed in view of phase relation between wind and temperature to identify between a tide and an inertio-gravity wave. They concluded that the 8 hr oscillation in two weeks in November observation as either evanescent or dissipating tide, which has amplitude of 3.5 ms^{-1}, and northward phase of 5.3 and eastward phase of 7.1 LT and temperature variation of 1.7 K in phase with eastward wind. Actually, evanescence is inferred from phase relation and energy density changes at 85 and 97 km heights. In spite of its scarcity in altitude coverage, this is really an important observation in the high latitude winter season, which complements radars relying on scattering from electron density fluctuations.

3. Theoretical basis for the terdiurnal tide

Classical Hough functions and associated velocity expansion functions of the terdiurnal tide are shown in Fig. 1. Equivalent depths for (3,3), (3,4), (3,5), and (3,6) are 12.89, 7.661, 5.085, and 3.625 km, respectively, which translate to vertical wavelengths of 110 and 80 km, respectively for the latter two (3,5) and (3,6) modes in the isothermal atmosphere of 275 K. It is then anticipated that the solar driven global terdiurnal tide has basically long vertical wavelength. A ter-diurnal tidal forcing is due to the third harmonics of the solar UV absorption heating by water vapor and ozone. Groves and Wilson (1982) performed numerical prediction of terdiurnal tide in the observed surface pressure which has 179 μbar in anti-symmetric (3,4) mode amplitude at solstices as compared with moderate annual mean (3,3) amplitude of 55 μbar with phase around 2 LT. They interpreted the phase reversal between January and July solstices due to anti-symmetric (3,4) forcing, which , however, underpredict the observed amplitude.

Numerical modeling on terdiurnal tidal wind has been done by Teitelbaum *et al.*

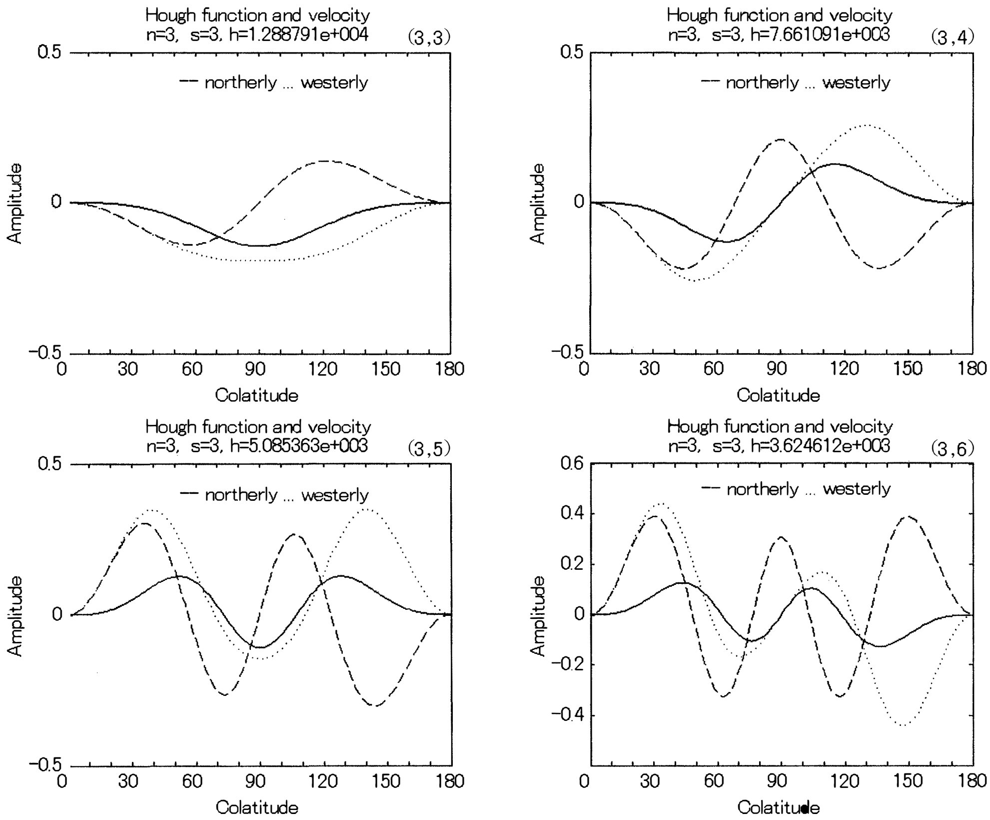

Fig. 1. Hough functions (solid line) and velocity expansion functions (dashed line for northerly and dotted line for westerly velocity) for terdiurnal tidal modes (3,3), (3,4), (3,5), and (3,6).

(1989) by using the so-called inviscid model in which second order partial differential equation is solved for the geopotential perturbation. They also employed small parameter expansion similar to the harmonic balance method to estimate non-linear coupling due to advection terms. They suggested observed short vertical wavelength and larger amplitude especially in winter are consistent with inferred contribution of nonlinearly excited 8 hr component.

Recently, Smith and Ortland (2001) carried out both linear and non-linear modeling of terdiurnal tide by assuming CIRA climatology model. They surmised strong hemispheric asymmetry apparent in the modeling due to its sensitivity of wave propagation to background state.

Then, a GCM model developed by Kyushu Univ. (Miyahara *et al.*, 1999) also very unambiguously predict the global structure of terdiurnal tide. A terdiurnal tide in this model inevitably includes non-linear tidal coupling along with interactions with mean field and other wave regimes, and numerical “experiment” or associated mechanistic modeling should be carried out to extract relevant underlying physical processes.

A Kyushu GCM modeling reveals terdiurnal tide at higher latitudes with amplitude larger in winter than in summer. The phase of northward wind sticks to 0400 LT at 80 km in winter with vertical wavelength of 50 km and rapid change related to amplitude minimum. In summer the phase is less stable with shorter vertical wavelength. These features are fairly consistent with other numerical models. (Miyahara and Kawano, private communication).

Herein, an inviscid ATM2 model (Aso *et al.*, 1987) is used to predict ter-diurnal tides, which includes the effects of dissipation due to diffusion and of the seasonal change of latitudinal temperature gradient and mean zonal wind, and can be suggestive of basic features of the terdiurnal tide and its variabilities. We express the forcing as $J=i\sigma C_p\tau$ (W/kg) as in Chapman and Lindzen (1970) where σ is the angular frequency, C_p is the specific heat, and τ is the approximate temperature response without dynamical effect. τ is assumed based on Groves and Wilson (1982), and peak value of τ for the fundamental (3.3) mode for ozone absorption heating is set to 0.16 K and 0.003 K for near infrared water vapor absorption. Higher modes assume comparatively smaller values.

Altitude profile of heating is also adapted from simple profile by Chapman and Lindzen (1970) with a peak at 50 km and 10 km for ozone and water vapor, respectively. Decomposing the solar heating into diurnal harmonics specifies the magnitude and phase of respective forcing mode. The phase for diurnal and semidiurnal forcing is local noon 1200 LT, and accordingly 0000 LT for the semidiurnal component. For the terdiurnal component, however, the forcing is negative at 1200 LT and maximum in τ occurs at 0200 LT, 90 deg phase lag relative to the heating. Also, Smith and Ortland (2001) suggests reversal of phase in forcing at higher latitudes.

In Fig. 2 is shown the altitude profiles of horizontal wind components for the basic terdiurnal (3,3) mode in the equinox and solstice background wind conditions for ATM2. Northward maximum is at 0400 LT, eastward at 0600 and temperature phase (not shown) is around 0200 LT for very basic no wind conditions, corresponding to the evanescent nature of this fundamental mode whose latitudinal structure is depicted in the inset. Background zonal wind gives rise to mode coupling and renders the

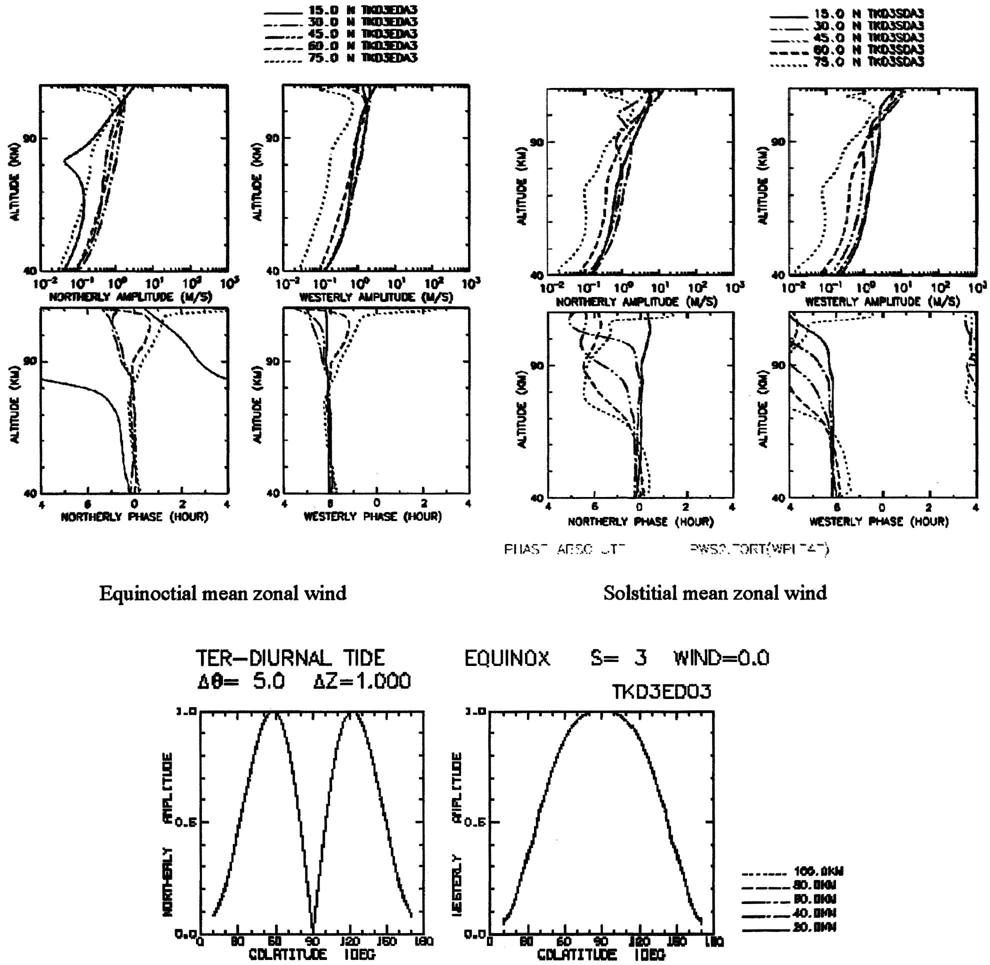

Fig. 2. ATM2 modeling of ter-diurnal basic (3,3) mode for equinox & solstice mean wind conditions.

profiles more variable as in the semidiurnal tide (Aso *et al.*, 1981) and solstitial wind renders the phase gradient steeper due to higher modes generated by mode coupling.

Figure 3 illustrates latitudinal—height contour plot of amplitude and phase of the terdiurnal tide under summer solstice condition. Amplitude shows three peaks at around 100 km with alternating reversed phase between two neighboring peaks for northerly component. This corresponds to anti-symmetric (3,4) mode structures shown in Fig. 1. As a matter of fact, basic symmetrical (3,3) mode is almost evanescent and its vertical decay distance except 1/2H (H: scale height) is 30 km for typical temperature of 275 K and rarely appears at meteor heights in contract to semidiurnal (2,2) mode which is likewise evanescent but exhibits itself in the observation. It must be also mentioned that KU-GCM latitude-height plot also indicates three peaks at 110 km, which is fairly compatible with ATM2 model.

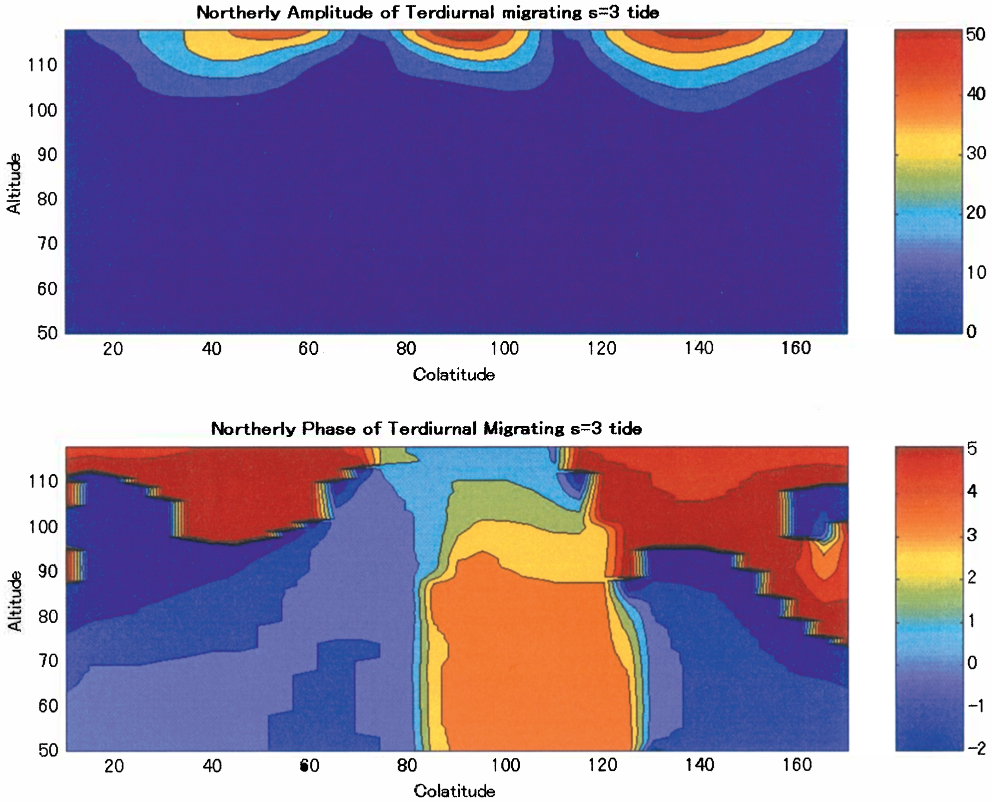

Fig. 3. A latitudinal–height contour plot of amplitude and phase of the terdiurnal tide under summer solstice condition by ATM2 model.

4. Discussions and concluding remarks

Terdiurnal tide observed so far manifests its relatively smaller amplitude compared to diurnal and semidiurnal components. Seasonal characteristics are evident in larger amplitude and steady phase with longer vertical wavelength in winter compared to summer.

The fact that northward wind maximizes around 0400 LT and temperature around 0200 LT corresponding to forcing maximum at local midnight is basically supported. However complications arising from dissipations, wave-mean flow and wave-wave interaction along with superposed local gravity wave and Lamb waves exist to give fairly variable nature of this tidal component.

In Fig. 4 is illustrated the comparison of latitudinal profile of the phase of terdiurnal eastward wind component at 95 km adapted from non-linear and solar-driven plots, a-1 and a-2 by Teitelbaum *et al.* (1989) with observations and theoretical values described in the preceding section. These are b: ESR (Aso *et al.*, 1999), c: Eureka (Oznøvich *et al.* 1997), d: EISCAT Tromso (Nozawa and Brekke, 1999), e-1 and 2: Syowa MF (Tsutsumi, Private commmunication), f-1 and 2: Garchy (Teitelbaum *et al.*,

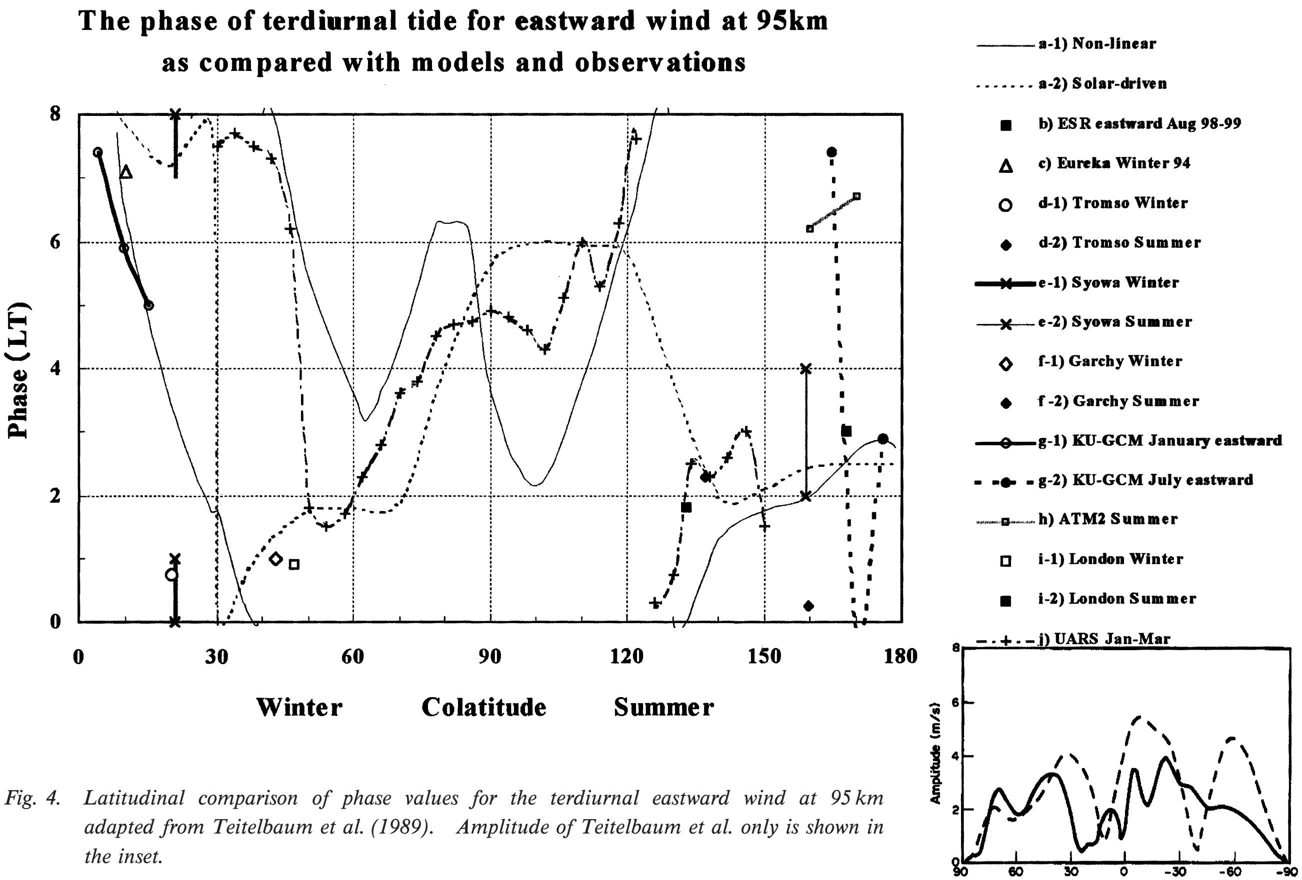

Fig. 4. Latitudinal comparison of phase values for the terdiurnal eastward wind at 95 km adapted from Teitelbaum et al. (1989). Amplitude of Teitelbaum et al. only is shown in the inset.

1989), g-1 and 2: KU-GCM (Miyahara and Kawano, private communication), h: ATM 2 model (Aso *et al.*, 1987), i-1 and 2: London (Thayaparan, 1997), and j: UARS (Smith, 2000). In comparison, northward wind is shifted by ± 2 hrs in the northern and summer hemispheres, respectively. Basic value of 0600 LT for eastward phase is envisaged only at summer lower latitudes.

At winter high latitudes, KU-GCM model happens to be close to Teitelbaum *et al.*'s non-linear model and not quite inconsistent with Tromsø radar and Eureka optical data. In summer polar region, ESR and Syowa MF radar values are compatible with Teitelbaum *et al.*'s model but KU-GCM does suggest large anti-phase excursion as in the winter non-linear model. UARS data averaged for early January to mid March is roughly in between the solar-driven direct and non-linearly excited components at middle to low latitudes.

An apparent diversity, especially at polar latitudes, might stem from a few aspects. One is the inherent variability of smaller amplitude 8 hr tide which is excited either directly by 3rd harmonics of solar heating in the course of propagation from below. Also, excitation by non-linear coupling by dominant diurnal and semidiurnal tides inevitably involves variability due to appreciable variability of these seed components. An 8 hr component can also be from an inertia-gravity wave regime which is excited by local disturbances which, then, might lose some coherence in phase relative to global tidal mode. Also intradiurnal Lamb waves with period near 8 hrs are worthy of further study. In summary, in elucidating observational results, long-term averaging over, say, 30 days or longer might give a basic solar driven ter-diurnal tide while short-term feature tends to be affected by intermittent non-linearly excited tidal component or just local 8 hr variation superposed to the basic solar driven terdiurnal component. From numerical models, it seems anti-symmetric (3,4) mode prevails at meteor heights for solstitial conditions whereas in equinox (3,5) mode shows up more evidently than (3,3) mode which is highly evanescent. These modes might appear if tidal analyses are made from long term average and short-time variabilities are averaged out. Otherwise, A thorough survey of this terdiurnal component by global and coincident observations of velocity field and temperatures for various time scales are still to be made for further studies on relative contribution of these 8 hr components and unambiguous identification of the ter-diurnal tide.

Acknowledgments

This work is supported by the Grand-in-Aid for Scientific Research of MEXT and JSPS. The author thanks Drs. Jeff Forbes, Anne Smith and Saburo Miyahara for their kind comments and discussions.

The editor thanks the referee for his help in evaluating this paper.

References

Aso, T., Nonoyama, T. and Kato, S. (1981): Numerical simulation of semidiurnal atmospheric tides. J. Geophys. Res., **86**, 11388–11400.

Aso, T., Ito, S. and Kato, S. (1987): Background wind effect on the diurnal tide in the middle atmosphere. J.

Geomagn. Geoelectr., **39**, 297–3005.

Aso, T., Van Eyken, A. and Williams, P.J.S. (1999): EISCAT Svalbard radar-derived tidal features in the lower thermosphere as compared with the numerical modeling ATM2. Adv. Polar Upper Atmos. Res., **13**, 48–56.

Chapman, S. and Lindzen, R. S. (1970): Atmospheric Tides. Dordrecht, Reidel, 201 p.

Forbes, J.M., Palo, S.E., Zhang, X., Portnyagin, Y.I., Makarov, N.A. and Merzlyakov, E.G. (1999): Lamb waves in the lower thermosphere: Observational evidence and global consequences. J. Geophys. Res., **104**, 17107–17115.

Glass, M. and Fellous, J.L. (1975): The eight-hourly (terdiurnal) component of atmospheric tides. Space Res., **15**, 191–197.

Groves, G.V. and Wilson, A. (1982): Diurnal, semi-diurnal and terdiurnal Hough components of surface pressure. J. Atmos. Terr. Phys., **44**, 599–611.

Manson, A.H. and Meek, C.E. (1986): Dynamics of the middle atmosphere at Saskatoon (52°N, 107°W): a spectral study during 1981, 1982. J. Atmos. Terr. Phys., **48**, 1039–1055.

Miyahara, S., Miyoshi, Y. and Yamashita, K. (1999): Variations of migrating and non-migrating tides simulated by the middle atmosphere circulation model at Kyushu University. Adv. Space. Res., **24**, 1549–1558.

Nozawa, S. and Brekke, A. (1999): Studies of the auroral *E* region neutral wind through a solar cycle: Quiet days. J. Geophys. Res., **104**, 45–66.

Oznovich, I., McEwen, D.J., Sivjee, G.G. and Walterscheid, R.L. (1997): Tidal oscillations of the Arctic upper mesosphere and lower thermosphere in winter. J. Geophys. Res., **102**, 4511–4520.

Portnyagin, Y.I., Forbes, J.M., Merzlyakov, E.G., Makarov, N.A. and Palo, S.E. (2000): Intradiurnal wind variations observed in the lower thermosphere over the South Pole. Ann. Geophys., **18**, 547–554.

Smith, A.K. (2000): Structure of the terdiurnal tide at 95 km. Geophys. Res. Lett., **27**, 177–180.

Smith, A.K. and Ortland, D.A. (2001): Modeling and analysis of the structure and generation of the terdiurnal tide. J. Atmos. Sci., **58**, 3116–3134.

Teitelbaum, H., Vial, F., Manson, A.H., Giraldez, R. and Massebeuf, M. (1989): Non-linear interaction between the diurnal and semidiurnal tides: terdiurnal and diurnal secondary waves. J. Atmos. Terr. Phys., **51**, 627–634.

Thayaparan, T. (1997): The terdiurnal tide in the mesosphere and lower thermosphere over London, Canada (43°N, 81°W). J. Geophys. Res., **102**, 21695–21708.

Williams, P.J.S., Virdi, T.S., Jones, G.O.L. and Huuskonen, A. (1994): A comparison of three methods of measuring tidal oscillations in the lower thermosphere using EISCAT common programmes. J. Atmos. Terr. Phys., **56**, 1347–1359.