Migrating and Non-migrating Tides in the MLT region

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Contents of this talk

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   • Definition of Migrating and Non-migrating tides
   • Solutions of Laplace's tidal equation
     Hough Functions, Equivalent depth
   • Sources of migrating tides

2. Examples of observed structure of tidal waves in the MLT region
   • Migrating diurnal and semidiurnal tides
   • Non-migrating tides

3. Dissipation of tides in the MLT region
   • Eddy diffusion
   • Molecular diffusion
   • Radiative cooling
   • Convective instability
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4. Excitation and propagation mechanisms of non-migrating tides
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   • Effects of background mean zonal winds

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Definition

Migrating tides
The phase propagates westward synchronized with the diurnal motion of the sun.

\[ u \propto e^{i(n\sigma + s\lambda)} \]
\[ \sigma = \frac{2\pi}{1 \text{ solar day}} \]

n=s=1 (diurnal), and n=s=2 (semi-diurnal)

Non-migrating tides
The phase propagates westward or eastward, but not synchronized with the diurnal motion of the sun, or zonally homogeneous oscillation.

\[ u \propto e^{i(n\sigma + s\lambda)} \]
\[ \sigma = \frac{2\pi}{1 \text{ solar day}} \]

n=1 (diurnal), and n=2 (semi-diurnal)
s = 0, \pm 1, \pm 2, \pm 3, \ldots
s \neq 1 (diurnal), and s \neq 2 (semi-diurnal)
Migrating diurnal tide, October

0 UT
Diurnal Westward S=1, u(m/s)

CONTOUR INTERVAL = 5.000E+00

6 UT
Diurnal Westward S=1, u(m/s)

CONTOUR INTERVAL = 5.000E+00

12 UT
Diurnal Westward S=1, u(m/s)

CONTOUR INTERVAL = 5.000E+00

18 UT
Diurnal Westward S=1, u(m/s)

CONTOUR INTERVAL = 5.000E+00

Diurnal westward moving S=1, u(m/s) \( z = 98 \text{ km} \)
Nonmigrating diurnal tide, October

Diurnal westward moving \( S=2, \ u(\text{m/s}) \ z = 98 \text{ km} \)
Migrating and nonmigrating diurnal tides, October

0 UT
Diurnal Westward $S=1+2$, $u(m/s)$

6 UT
Diurnal Westward $S=1+2$, $u(m/s)$

12 UT
Diurnal Westward $S=1+2$, $u(m/s)$

18 UT
Diurnal Westward $S=1+2$, $u(m/s)$

Diurnal westward moving $S=1+2$, $u(m/s)$ $z = 98$ km
Migrating semidiurnal tide, October

Semidiurnal westward moving $S=2, \ u(\text{m/s}) \ z = 98 \ \text{km}$
Non-migrating semidiurnal tide, October

Semi-diurnal Westward S=1, u(m/s)

0 UT

3 UT

6 UT

9 UT

Semidiurnal westward moving S=1, u(m/s) z = 98 km
Migrating and non-migrating semidiurnal tides

0 UT
Semidiurnal westward $S=2+1, u(m/s)$

3 UT
Semidiurnal westward $S=2+1, u(m/s)$

6 UT
Semidiurnal westward $S=2+1, u(m/s)$

9 UT
Semidiurnal westward $S=2+1, u(m/s)$

Semidiurnal westward moving $S=2+1, u(m/s)$ $z = 98$ km
$S = 1$
Westward

\[ \sqrt{\frac{h}{2\Omega a}} \]

$h$: Equivalent depth

Vertical wave length
\[ \lambda = \left( \sqrt{\frac{\kappa}{hH}} - \frac{1}{4H^2/2\pi} \right)^{-1} \]

\[ H = \frac{RT}{g} \]: Sale height.

\[ \lambda_1 \sim 25 \sim 30 \text{ km} \]
\[ \lambda_1: \text{N.P.} \]
\[ \lambda_2 \sim 130 \text{ km} \]
\[ \lambda_3 \sim 80 \text{ km} \]

Longuet-
Higgins
(1967)

Semi-diurnal
diurnal

Period (days)
$h < 0$

$\lambda : N. P.$

Figure 176.
$s = 2$

Westward

$\lambda_1 \approx 340 \text{ km}$

$\lambda_2 \approx 50 \text{ km}$

$\lambda_3 \approx 30 \text{ km}$
Fig. 1. Top: Hough functions for diurnal modes normalized to a maximum value of unity. Keys and normalization factors for each Hough mode are as follows: (1, 1) solid line, 0.606; (1, 2) dashed line, 1.034; (1, 2) dotted line, 1.054; (1, 4) dashed-dotted line, 0.513; (1, 2) dashed-double dotted line, 0.641. Bottom: Northerly velocity expansion functions for diurnal modes normalized to a maximum value of unity. Normalization factors are 0.026, 0.126, 0.100, 0.024, and 0.015, respectively. Center: Westerly velocity expansion functions for diurnal modes normalized to a maximum value of unity. Normalization factors are 0.038, 0.130, 0.110, 0.024, and 0.018, respectively.
Vertical wavelengths of some tidal modes
Isothermal Atmosphere: T=250 K

Diurnal (km)

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<th>Mode</th>
<th>(1,-2)</th>
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<th>(1,3)</th>
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Non-migrating

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<td>s=-5, E</td>
<td>31</td>
<td>21</td>
<td>15</td>
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Fig. 1 Meridional cross section of tide-generating heating for solstice.

Miyahara (1984)
Fig. 16. Meridional cross section of the induced mean zonal winds. Dashed lines denote easterlies. The contour interval is 20 ms$^{-1}$. 

Feb. 12 to May 3, 1993
McLandress et al. (1996)

Wu et al. (1993)
Fig. 1. Contours of meridional wind amplitude (solid lines) and phase (dashed lines) of the diurnal tide observed by WINDII for March/April 1992 and 1993 at a 45°E to 135°E, b 135°E to 135°W, c 135°W to 45°W, and d 45°W to 45°E longitude sectors. Amplitude contours > 50 m/s are shaded. The phase (local time of maximum) is contoured using a 3-h interval.

Fig. 2a-d. Contours of meridional wind amplitude (solid lines) and phase (dashed lines) of the diurnal tide observed by WINDII for December 1992, 1993 and January 1993, 1994 at: a 45°E to 135°E, b 135°E to 135°W, c 135°W to 45°W, and d 45°W to 45°E longitude sectors. Amplitude contours > 40 m/s are shaded. The phase (local time of maximum) is contoured using a 3-h interval.
Fig. 1. Average spectrogram of the hourly meridional winds over the four directions of measurement. The spectrogram is formed by sliding 10-day spectra in increments of 3 days from 19 January 1995 to 26 January 1996.
Fig. 3.13. Altitude distribution of the amplitude of the solar diurnal component of $u$ at 15° intervals of latitude; isothermal basic state assumed. After Lindzen (1967a).

Fig. 4. Vertical profiles of (a) amplitudes and (b) phases, of zonal velocities of the diurnal tide at various latitudes.
Figure 3. Amplitude of the diurnal temperature oscillation over the equator for different distributions of the cooling rate coefficient: ——, standard; ——, without photochemical acceleration; ---, zero.

Figure 7. Time-height cross-section of the Richardson number over the equator.

Lindzen (1968)
Fig. 1. The radiative damping rate (solid) and the vertical eddy diffusion coefficient (dashed).

Akmaev et al. (1992)
Monthly mean amplitudes of diurnal tides (UARS - HRDI)

Vertical eddy diffusion coefficients derived from HRDI data

Khattatov et al., (1997)
Middle Atmosphere Circulation Model at Kyushu University

- T21L55, General Circulation Model (GCM)
- Height Range: Ground through about 150 km
- Solar Radiation: having diurnal cycle,
  - H$_2$O, O$_3$, and O$_2$ heating,
  - H$_2$O: Predicted in the model
  (Troposphere: non-zonal)
  - O$_3$, and O$_2$: zonally symmetric distribution
- Infrared radiation: Fomichev's parameterization
  Troposphere: Chou's parameterization
- Land Temperature: Predicted in the model
- SST: Prescribed monthly mean SST
- Tropospheric physical processes
  - Latent heat, Topography, etc.
- Dissipation processes in the MLT
  - Molecular viscosity and conductivity
  - Ion drag (Local time dependent)
  - Dry convective adjustment
  - Eddy diffusion
  - Rayleigh Friction (Only for the zonal mean zonal winds in the MLT)
  - No gravity wave drag parameterization
\textbf{V: Northward wind}

\textbf{JAN.}

\textbf{MIGRATING DIURNAL}

\textbf{NON-MIGRATING}

\textbf{Jan. D. W. S=0}

\textbf{Jan. D. W. S=1}

\textbf{Jan. D. W. S=2}

\textbf{Jan. D. W. S=3}

\textbf{Jan. D. W. S=4}

\textbf{Jan. D. W. S=5}

\textbf{CONTOUR INTERVAL = 2.000E+00}

\textbf{CONTOUR INTERVAL = 1.000E+01}

\textbf{CONTOUR INTERVAL = 2.000E+00}

\textbf{CONTOUR INTERVAL = 1.000E+00}

\textbf{CONTOUR INTERVAL = 1.000E+00}

\textbf{CONTOUR INTERVAL = 1.000E+00}
V: Northward Wind
Jan.

NON-MIGRATING

MIGRATING SEMIDIURNAL

STANDARD HEIGHT (km)

CONTOUR INTERVAL = 2.000E+00

CONTOUR INTERVAL = 2.000E+00

CONTOUR INTERVAL = 1.000E+01

CONTOUR INTERVAL = 1.000E+00

CONTOUR INTERVAL = 1.000E+00
Fig.(4.1.2) Latitude dependence of total forcing which includes latent heating, heating due to dry convection, eddy thermal conduction and insolation absorption by water vapor in the troposphere and ozone absorption heating in the middle atmosphere for $S = +1$, (a), and $S = -1$, (b).
Chapter 4: Sources of Forcing

Fig. (4.1.3) As in Fig. (4.1.1) except for $s = +2$, (a), and $s = -2$, (b).
Linear model result by the GCM heating. (Ekanayake et al. 1997)

GCM result
number \( s=1 \) becomes large in the summer season at the north and south polar MLT regions. Two different possible excitation mechanisms of the non-migrating semidiurnal tide are suggested (Forbes et al., 1995; Portnyagin et al., 1998). One is non-migrating heating in the troposphere associated with latent heat release. The other is nonlinear interaction between the migrating semidiurnal tide and a stationary planetary wave with zonal wavenumber \( s=1 \). In this section the latter mechanism is investigated using the output data of the MACMKU.

3-1. Source of excitation

The idea of the nonlinear interaction forcing is as follows. The nonlinear interaction terms in the governing equation system expressed by the pressure coordinate system in the MACMKU are given by the advection terms. The nonlinear forcing terms due to a planetary wave and the semidiurnal tide are given by

\[
F_h = \frac{u_{pl}}{a \cos \theta} \frac{\partial u_{pl}}{\partial \lambda} + \frac{v_{pl}}{a \cos \theta} \frac{\partial}{\partial \theta} (u_{pl} \cos \theta) + \omega_{pl} \frac{\partial u_{pl}}{\partial \rho},
\]

\[
F_\theta = \frac{u_{pl}}{a \cos \theta} \frac{\partial v_{pl}}{\partial \lambda} + \frac{v_{pl}}{a \cos \theta} \frac{\partial v_{pl}}{\partial \theta} + \omega_{pl} \frac{\partial v_{pl}}{\partial \rho} + \omega_{pl} \frac{(2u_{pl}^2)}{a} \tan \theta,
\]

\[
F_r = \frac{u_{pl}}{a \cos \theta} \frac{\partial T_{sd}}{\partial \lambda} + \frac{v_{pl}}{a \cos \theta} \frac{\partial T_{sd}}{\partial \theta} + \omega_{pl} \frac{\partial T_{sd}}{\partial \rho} - \frac{R}{c_p T_{sd}},
\]

\[
+ \frac{u_{pl}}{a \cos \theta} \frac{\partial T_{pl}}{\partial \lambda} + \frac{v_{pl}}{a \cos \theta} \frac{\partial T_{pl}}{\partial \theta} + \omega_{pl} \frac{\partial T_{pl}}{\partial \rho} - \frac{R}{c_p T_{pl}}.\]

Semi-diurnal forcing with \( s=1 \) and \( s=3 \) (westward moving)
Result of a linear response model with $\bar{u}$ of GCM.
Linear response model

AMPLITUDE V
January S:W. S=3

CONTOUR INTERVAL = 2.000E+00

GCM (MACMKU)
Effects of background mean zonal winds

\( \bar{u}(\theta, z) \): mean zonal winds

Doppler shift of tidal frequency \( \omega \)

\[
\frac{\partial}{\partial t} + \frac{\bar{u}}{a \cos \theta} \frac{\partial}{\partial \lambda} = i(\omega + s\bar{u})
\]

\( S \): zonal wave number

\( \theta \): Latitude
Dynamic coupling between the lower and upper atmosphere

DOPPLER SHIFTED FREQ. = CORIOLIS FREQ.

Fig. 12. Location where Doppler shifted frequency is equal to Coriolis Frequency for $W_6$ (—) and $E_6$ (—) waves. Lower latitude region than the location indicates internal region.

Miyakawa et al. (1993)
Non-migrating semidiurnal tide South Pole, January

Semidiurnal westward moving $S=1$, $v$(m/s) $z = 108$ km, S. H.
Semidiurnal tides, Southern Hemisphere, January

Semidiurnal tides $S=0$ to $7$, $v$(m/s) $z = 108$ km, S. H.
Diurnal tides, Southern Hemisphere, January

0 UT
Jan. Diurnal S=0 to 7 \( v \) (m/s)
CONTOUR INTERVAL = 5.000E+00

6 UT
Jan. Diurnal S=0 to 7 \( v \) (m/s)
CONTOUR INTERVAL = 5.000E+00

12 UT
Jan. Diurnal S=0 to 7 \( v \) (m/s)
CONTOUR INTERVAL = 5.000E+00

18 UT
Jan. Diurnal S=0 to 7 \( v \) (m/s)
CONTOUR INTERVAL = 5.000E+00

Diurnal tides S=0 to 7, \( v \) (m/s) \( z = 108 \) km, S. H.
Concluding remarks:

- Migrating tides
- Non-migrating tides
- Both tides exist in the MLT region
- Confirmed by observations and numerical simulations

Excitation mechanism?

Migrating tides:
- $\text{H}_2\text{O}, \text{O}_3, \text{O}_2$ heating

Non-migrating tides
- Moist convective heating
- Tide-planetary waves interactions

Longitudinal variation of tidal amplitudes
- Interference between migrating and non-migrating tides

Need more observations
- TIMED mission