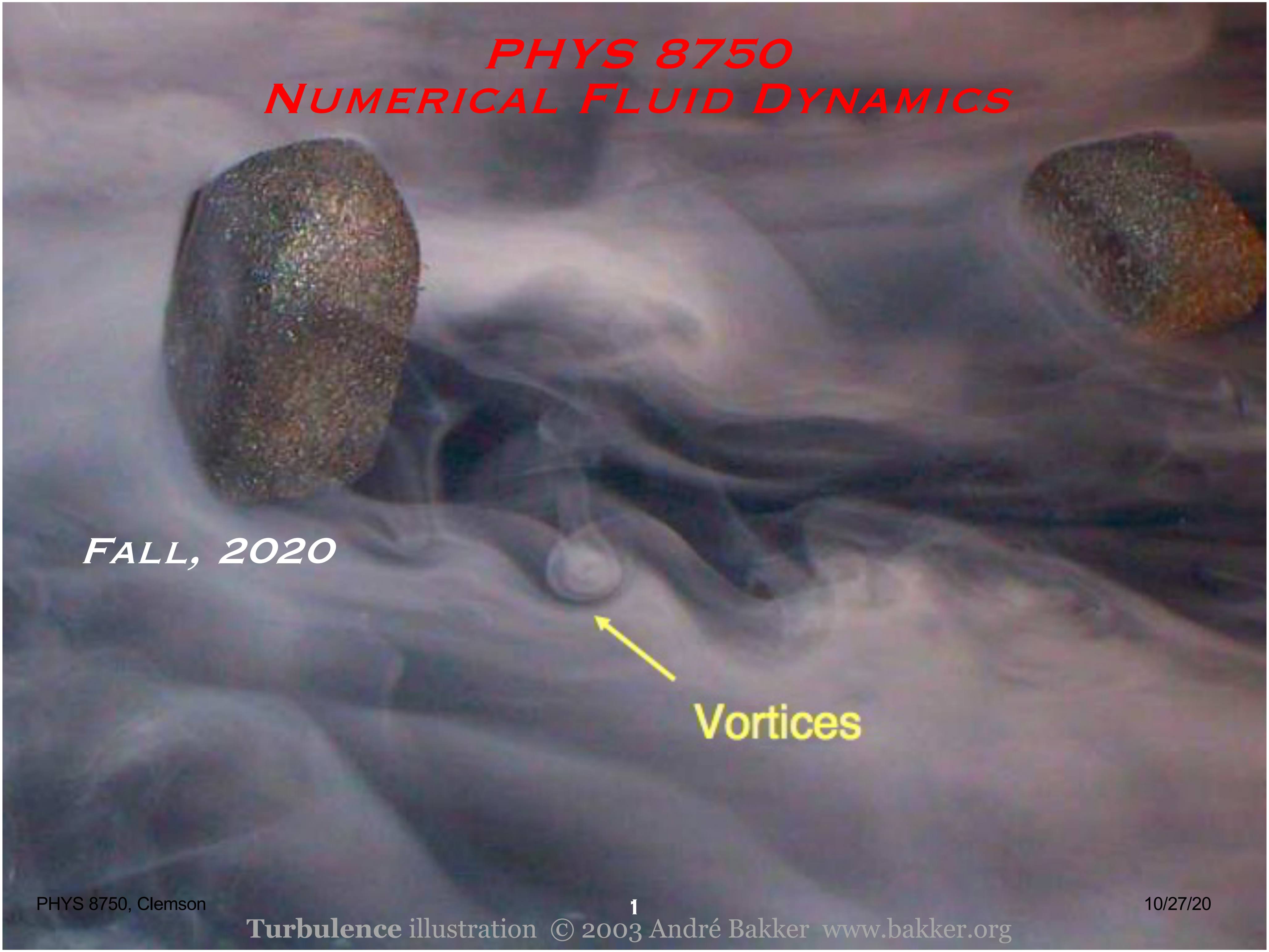
PHYS 8750
Numerical Fluid Dynamics

Fall, 2020



PHYS 8750

CLASS #18
ATMOSPHERIC MODELS

Class #17 (Chapter 5.5)

Finite Volume Method

Flux limiters

Outline

1. Atmospheric Models
2. Model types
   - Empirical models
   - Physics models
   - Data assimilative models
3. NRLMSIS and IRI
4. GSWM and CTMT

Atmospheric Models

- **Empirical Models (data based, mathematical, statistical)**

  Good for climatology and background atmosphere

  NRLMSIS, IRI, HWM

- **Physics Models (physical models)**

  - **Steady-state (external forcing or boundary condition)**

    GSWM, CTMT, Stationary Planetary Waves (week of Nov 17, 19)

  - **Time-evolving (initial condition)**

    General circulation models (TIEGCM, CESM, KMCM, CTIPe)

    Barotropic/baroclinic planetary wave model (week of Nov 17, 19)

    Gravity wave models (MAGIC)

- **Data Assimilative Models**

  Underlying Physics models + data assimilation

  WACCM-DART, ECMWF, MERRA

NRLMSIS

Naval Research Lab Mass Spectrometer Incoherent Scatter Model

NRLMSIS 2.0: A whole-atmosphere empirical model of temperature and neutral species densities

J. T. Emmert[1], D. P. Drob[1], J. M. Picone[2], D. E. Siskind[1], M. Jones Jr.[1], M. G. Mlynczak[3], P. F. Bernath[4,5], X. Chu[6,7], E. Doornbos[8], B. Funke[9], L. P. Goncharenko[10], M. E. Hervig[11], M. J. Schwartz[12], P. E. Sheese[13], F. Vargas[14], B. P. Williams[15], and T. Yuan[16]

NRLMSIS 2.0 is an empirical atmospheric model that extends from the ground to the exobase and describes the **average observed behavior** of temperature, 8 species densities, and mass density via a parametric analytic formulation. The model inputs are location, day of year, time of day, solar activity, and geomagnetic activity.

NRLMSIS

PARAMETRIC ANALYTIC FORMULATION + FITTING USING DATA

$$\frac{1}{T(\zeta)} = \begin{cases} \left\{T_{ex} - (T_{ex} - T_B)\exp\left[-\sigma(\zeta - \zeta_B)\right]\right\}^{-1} & ; \ \zeta \geq \zeta_B \\ \sum_{i=0}^{N_S-1} \alpha_i S_i(\zeta) & ; \ \zeta < \zeta_B \end{cases}$$

$T(\zeta)$	Temperature profile as a function of geopotential height
$\zeta_B = 122.5$ km	Bates profile reference height and joining height
T_{ex}	Exospheric temperature (fitting parameter)
$T_B = T(\zeta_B)$	Temperature at ζ_B (fitting parameter)
$\sigma = T'_B / (T_{ex} - T_B)$	Shape parameter
$T'_B = \left.\frac{dT}{d\zeta}\right\rvert_{\zeta=\zeta_B}$	Temperature gradient at ζ_B (fitting parameter)
$N_S = 24$	Number of B-spline basis functions
α_i	Coefficients on B-spline basis functions (fitting parameters)
S_i	Cubic B-splines with nodes at heights $\zeta_{S,i}$; $i = 0$ to $N_S + 3$

$$\zeta_{S,i} = \{-15, -10, -5, 0, 5, \ldots, 80, 85, 92.5, 102.5, 112.5, 122.5, 132.5, 142.5, 152.5\} \text{ km}$$

$$\ln n(\zeta) = \ln n_0 - \frac{g_0}{k}\int_{\zeta_0}^{\zeta} \frac{M(\zeta')}{T(\zeta')} d\zeta' - \ln\frac{T(\zeta)}{T(\zeta_0)} - Ce^{-(\zeta-\zeta_C)/H_C} + R\left[1 + \tanh\left(\frac{\zeta - \zeta_R}{\gamma(\zeta) H_R}\right)\right]$$

$n(\zeta)$	Number density of a particular species
$n_0 = n(\zeta_0)$	Reference density (defined below)
ζ_0	Reference geopotential height
g_0	Reference gravitational acceleration (see equation (A3))
k	Boltzmann constant
$M(\zeta)$	Effective mass profile (defined below)
C, ζ_C, H_C	Chemical loss term parameters
R, ζ_R, H_R	Chemical/dynamical correction parameters

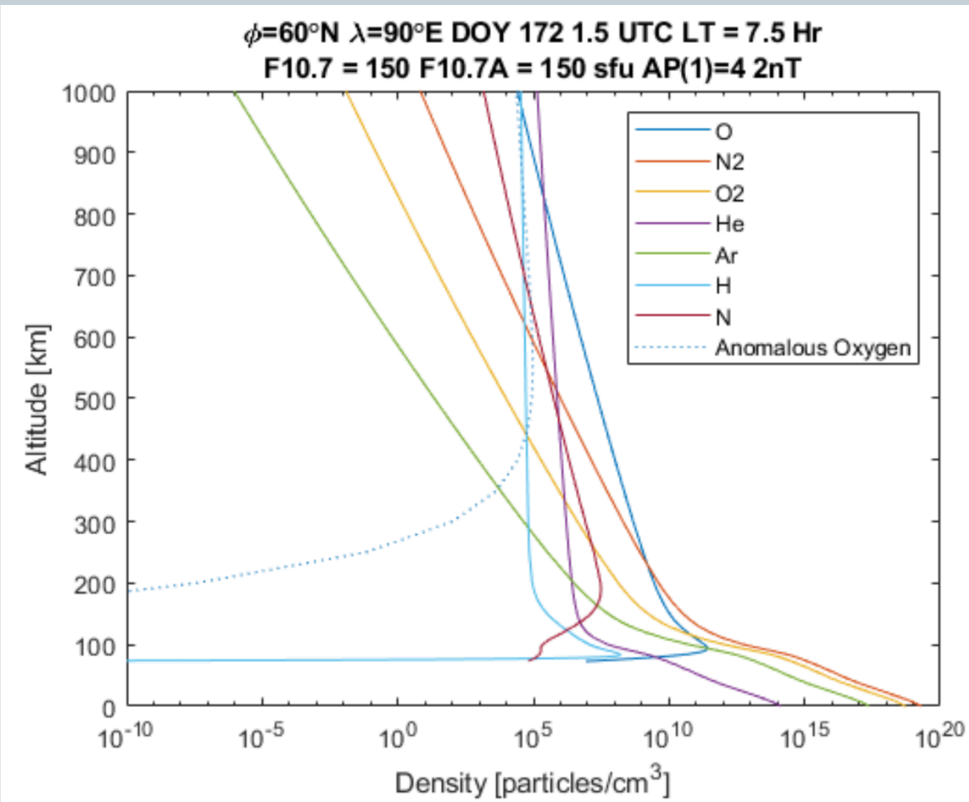
$$\gamma(\zeta) = \frac{1}{2}\left\{1 + \tanh\left(\frac{\zeta - \zeta_\gamma}{H_\gamma}\right)\right\}$$

$\zeta_\gamma = 70$ km

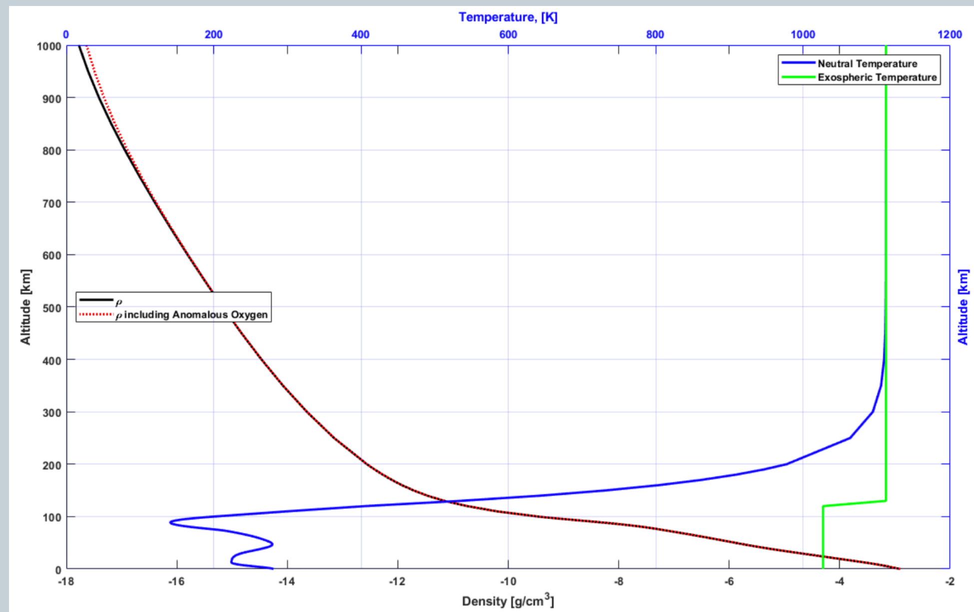
$H_\gamma = 40$ km

Outputs of NRLMSIS

Density of Species



Density & Temperature



IRI (International Reference Ionosphere)

The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI).

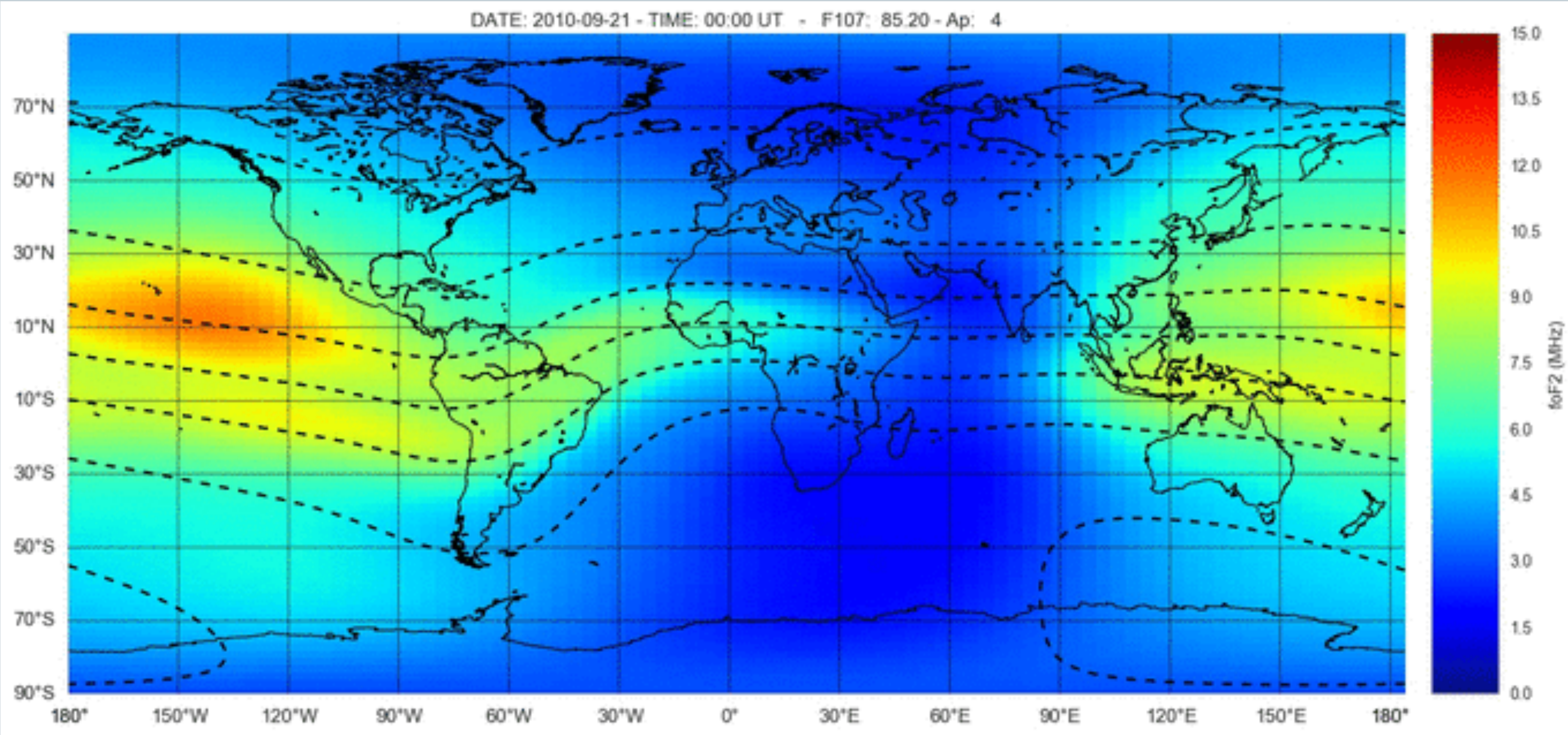
PARAMETERS:

Ne, Te, Ti, ion composition (O^+, H^+, He^+, N^+, NO^+, O^+_2, Cluster ions), equatorial VI, vertical TEC (vTEC), spread-F probability, auroral boundaries, effects of ionospheric storms on F and E peak densities.

INPUTS:

Required: solar indices (F10.7), ionospheric index (ionosonde-based IG index 12-month running mean), magnetic index (ap).

IRI Outputs


DATE: 2010-09-21 - TIME: 00:00 UT - F107: 85.20 - Ap: 4
70°N
50°N
30°N
10°N
10°S
30°S
50°S
70°S
90°S
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
180°
15.0
13.5
12.0
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0
foF2 (MHz)

Physics Models

- **Steady-State**

Mean values or waves amplitude do not change with time.

Large-scale Wave models

Tides: GSWM, CTMT

Planetary Waves: stationary wave model

Global Scale Wave Model

$$\frac{\partial u}{\partial t} - 2\Omega \sin\theta v + \frac{1}{a\cos\theta}\frac{\partial \Phi}{\partial \lambda} = 0 \qquad (1)$$

$$\frac{\partial v}{\partial t} + 2\Omega \sin\theta u + \frac{1}{a}\frac{\partial \Phi}{\partial \theta} = 0 \qquad (2)$$

$$\frac{\partial}{\partial t}\Phi_z + N^2 w = \frac{\kappa J}{H} \qquad (3)$$

$$\frac{1}{a\cos\theta}\left[\frac{\partial u}{\partial \lambda} + \frac{\partial}{\partial \theta}(v\cos\theta)\right] + \frac{1}{\rho_o}\frac{\partial}{\partial z}(\rho_o w) = 0 \qquad (4)$$

where

u	eastward velocity
v	northward velocity
w	upward velocity
Φ	perturbation geopotential
N^2	buoyancy frequency squared $= \kappa g/H$
Ω	angular velocity of Earth
ρ_o	basic state density $\propto e^{-z/H}$
z	altitude
λ	longitude
θ	latitude
κ	$R/c_p \approx 2/7$
J	heating per unit mass
a	radius of Earth
g	acceleration due to gravity
H	constant scale height
t	time

Forbes, 1995

By assuming the wave form

$$\{u, v, w, \Phi\} = \{\hat{u}, \hat{v}, \hat{w}, \hat{\Phi}\}\exp[i(s\lambda - \sigma t)] \qquad (5)$$

Then 4D problem becomes 2D

$$\frac{\partial}{\partial t} = -i\sigma, \frac{\partial}{\partial \lambda} = is$$

Separation of variable and solve for latitude and altitude directions

$$\hat{J} = \sum_n \dot{\Theta}_n(\theta) J_n(z) \qquad (7)$$

$$\hat{\Phi} = \sum_n \Theta_n(\theta) G_n(z) \qquad (6)$$

Global Scale Wave Model

Equation along altitude (z direction)

$$i\sigma H\left[\frac{1}{\rho_o}\frac{\partial}{\partial z}\rho_o\frac{\partial}{\partial z}G_n\right]+\frac{1}{\rho_o}\frac{\partial}{\partial z}(\rho_o\kappa J_n)=-\frac{i\sigma\kappa}{h_n}G_n \quad (12)$$

Equation along latitude (y direction)

$$\frac{d}{d\mu}\left[\frac{(1-\mu^2)}{(f^2-\mu^2)}\frac{d\Theta_n}{d\mu}\right]-\frac{1}{f^2-\mu^2}$$

$$\left[-\frac{s}{f}\frac{(f^2+\mu^2)}{(f^2-\mu^2)}+\frac{s^2}{1-\mu^2}\right]\Theta_n+\epsilon\Theta_n=0 \qquad (14)$$

For each tidal component, decompose heating term into different Hough modes, and solve for the tidal responses in different modes. The full solution is the superposition of all the Hough modes.

Global Scale Wave Model

Hough Modes

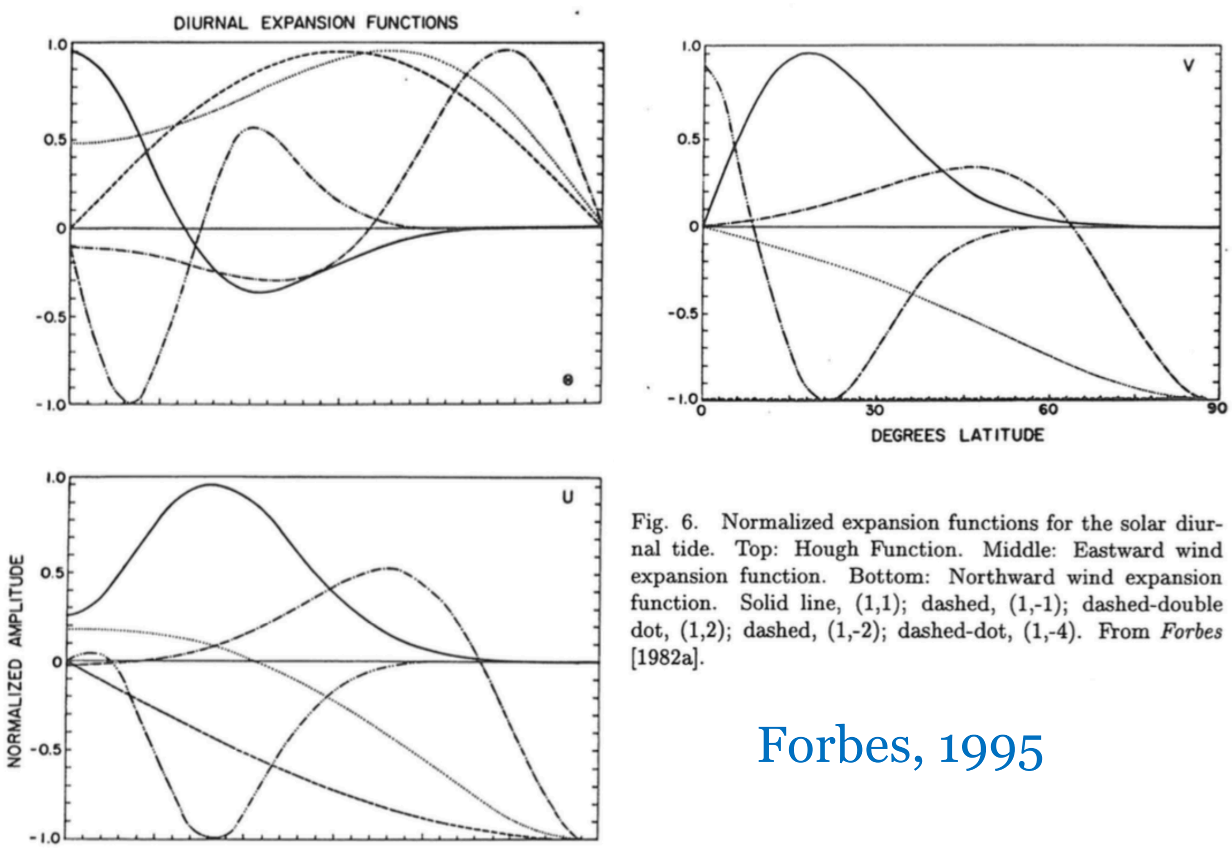
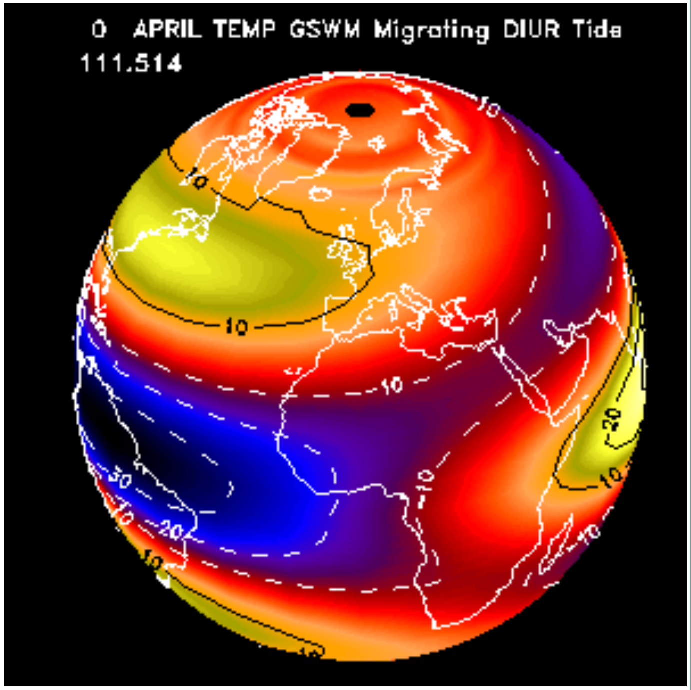


Fig. 6. Normalized expansion functions for the solar diurnal tide. Top: Hough Function. Middle: Eastward wind expansion function. Bottom: Northward wind expansion function. Solid line, (1,1); dashed, (1,-1); dashed-double dot, (1,2); dashed, (1,-2); dashed-dot, (1,-4). From *Forbes* [1982a].

Forbes, 1995

Temperature DW1



Spherical coordinate: Legendre functions

Climatological Tidal Model of the Thermosphere (CTMT)

Hough Mode Extensions

- Generalized form of Hough Modes; account for dissipation

Model concept

- Fit HMEs to TIMED tides in the MLT region; 2002-2008 averages
- Use fit coefficients to reconstruct the tides in the thermosphere, F10.7 = 110 sfu

Oberheide, J., J. M. Forbes, X. Zhang, and S. L. Bruinsma, Climatology of upward propagating diurnal and semidiurnal tides in the thermosphere, *J. Geophys. Res.*, *116*, *A11306*, *doi:10.1029/2011JA016784*, *2011*.

Climatological Tidal Model of the Thermosphere (CTMT)