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Modeling the Upper Thermosphere / Lower Exosphere

September 8, 15

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High-Altitude Satellite Drag

Background & Motivation

Accurate nowcasts of satellite drag are critical in the upper register of the thermosphere for:

- Performing **accurate** conjunction assessments
- Providing satellite operators with actionable information (i.e. to maneuver or not to maneuver)
- Realistic uncertainty calculations as orbit is propagated

Why 500—1000 km??

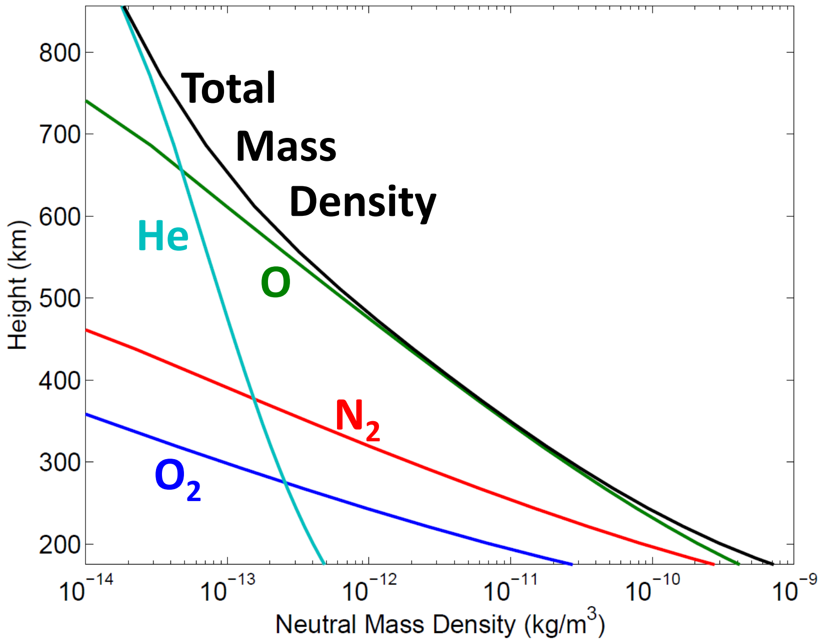
- It's one of the most crowded orbital regimes
- The need for precise orbit determination/prediction trumps the exponential decay of density w/ height

Modeling Neutral Helium

Behavior in the Upper Atmosphere

- Helium has very a small concentration from the ground thru the turbopause
- Diffusive separation above the turbopause causes the mixing ratio to increase, approaching unity in the upper thermosphere
- Seasonal variation termed **“Winter Bulge”** due to helium’s preference for the high latitudes in the winter hemisphere
- Local time preference prior to ~8:00 LT
- Helium’s inverse scale height is less sensitive to solar cycle variations (i.e. temperature changes) than are other species

TIE-GCM Solar Max. Profile (21 Dec. 2008)



Modeling Neutral Helium

Composition of the Major Species

Vector Diffusion Equation:

$$\tau\frac{g\,m_{N2}}{p_0\,\overline{m}}\left(\frac{T}{T_{00}}\right)^{0.25}\boldsymbol{\alpha}\mathbf{W} = \mathbf{L}\boldsymbol{\Psi}$$

Vector Continuity Equation:

$$\frac{\partial\boldsymbol{\Psi}}{\partial t} = -\mathrm{e}^z\frac{g}{p_0}\frac{\partial}{\partial z}\mathbf{W} - \left(\nabla\cdot(\boldsymbol{\Psi}\mathbf{V}) + \mathrm{e}^z\frac{\partial}{\ } \quad \right) + \mathbf{s}$$

If you're interested, details can be found in Sutton et al. [2015, JGR, in review]

Dickinson et al., [1984]:

molecular diffusion

$$\frac{\partial\boldsymbol{\Psi}}{\partial t} = -\mathrm{e}^z\tau^{-1}\frac{\partial}{\partial z}\left[\frac{\overline{m}}{m_{N2}}\left(\frac{T_{00}}{T}\right)^{0.25}\boldsymbol{\alpha}^{-1}\mathbf{L}\boldsymbol{\Psi}\right]$$

$$+\mathrm{e}^z\frac{\partial}{\partial z}\left(K(z)\mathrm{e}^{-z}\left(\frac{\partial}{\partial z} + \frac{1}{\ }\frac{\partial\overline{m}}{\ }\right.\right.$$

$$\left(\mathbf{V}\cdot\nabla\boldsymbol{\Psi} + \omega\frac{\partial}{\partial z}\boldsymbol{\Psi}\right) + \mathbf{s}$$

mass fraction time rate-of-change

Eddy di

vertical advection

horiz. advection

chemical source

$$\mathbf{W} = \begin{bmatrix}\rho_{O2}w_{O2}\\ \rho_O w_O\\ \rho_{He}w_{He}\end{bmatrix}$$ is the vector mass fluxes (wrt. momentum-weighted motion)

$$\boldsymbol{\Psi} = \begin{bmatrix}\psi_{O2}\\ \psi_O\\ \psi_{\ }\end{bmatrix}$$ is of mass fractions and $\psi_{N2} = 1 - \psi_{O2} - \psi_O - \psi_{He}$

$$\left(\frac{\partial}{\partial z} - 1 + \frac{m_i}{\overline{m}} + \frac{1}{\overline{m}}\frac{\partial\overline{m}}{\partial z} + \frac{\alpha_{Ti}}{T}\frac{\partial T}{\partial z}\right)$$ is the diagonal matrix differential operator specifying normalized pressure

otes: (1) See last slide for full definition of terms. (2) Eddy diffusion is neglected in the above Vector Diffusion Eq. for brevity.

Modeling Neutral Helium

Upper Boundary Conditions

- **Non-Escaping Flux** of Helium atoms with ballistic trajectories in collisionless exosphere as approximated by Hodges and Johnson [1968] and Hodges [1973]:

  $\Phi = -\nabla^2(n\,\dot{v}\,H^2P)$, where

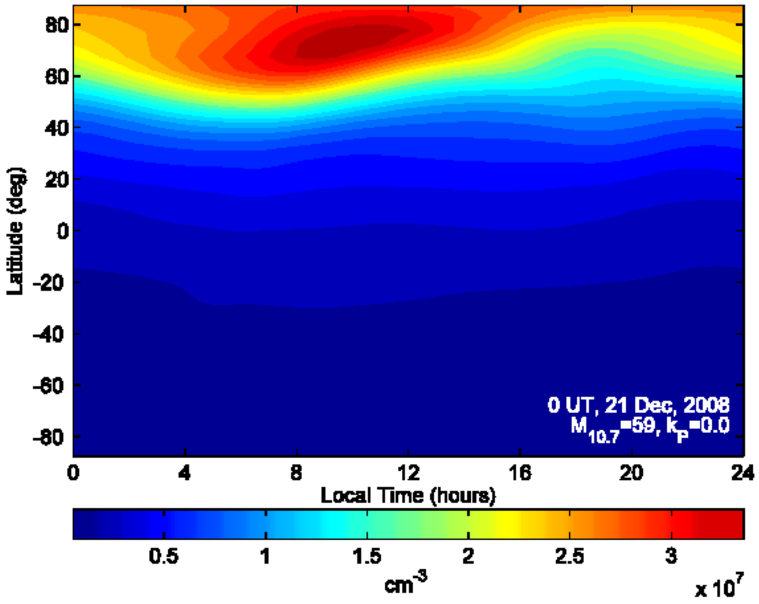
  n, $\dot{v}$, and H are the number density, mean thermal speed, and scale height of helium

  P is an integral quantity from the references above with small temp. dependence

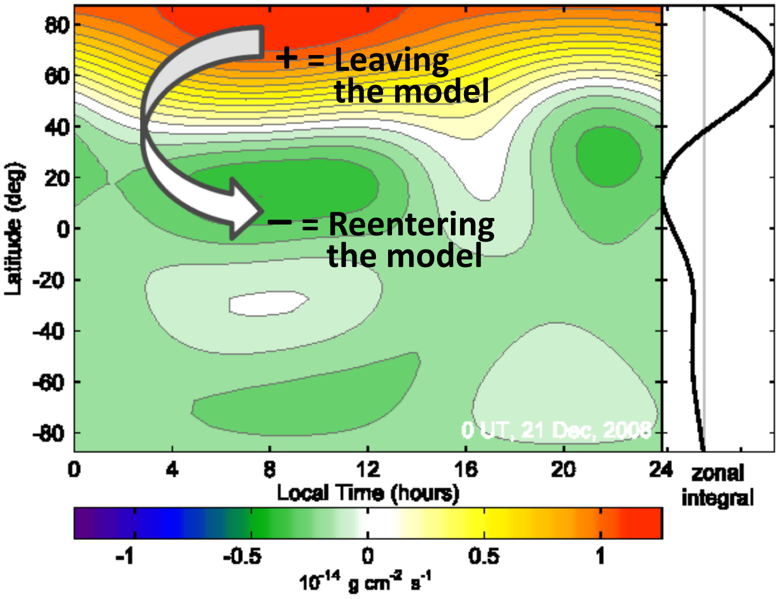
- Imposed as a diffusive flux at the model's top level using the vector diffusion equation (previous slide)

Typical Example during solstice (21 Dec., 2008)

Helium Number Density @ 250 km



Exospheric Transport Flux: $-m_{He}\nabla^2(\rho\,\bar{v}\,H^2P)$

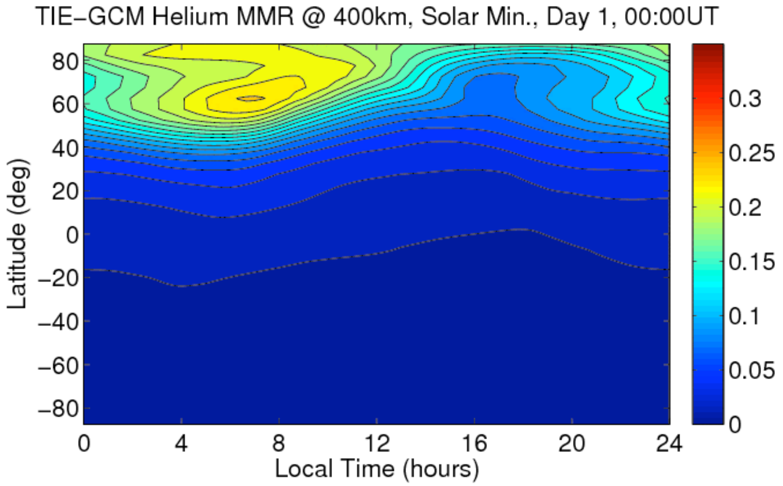


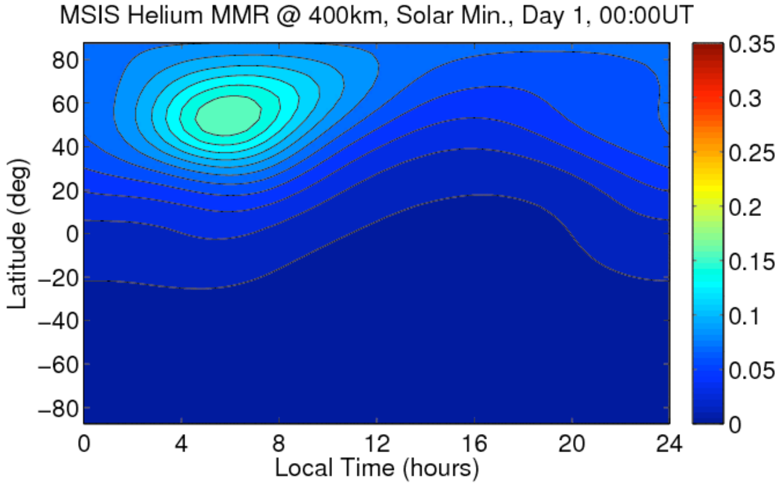
Seasonal Characteristics

Movie(?)

Seasonal/latitudinal evolution during Solar Min.:

- Winter Helium Bulge seen during solstices
- Early local time preference during equinox
- Modulated by diurnal forcing (not shown here, 00 UT only)
- Geomagnetic activity causes short-scale "flashes"





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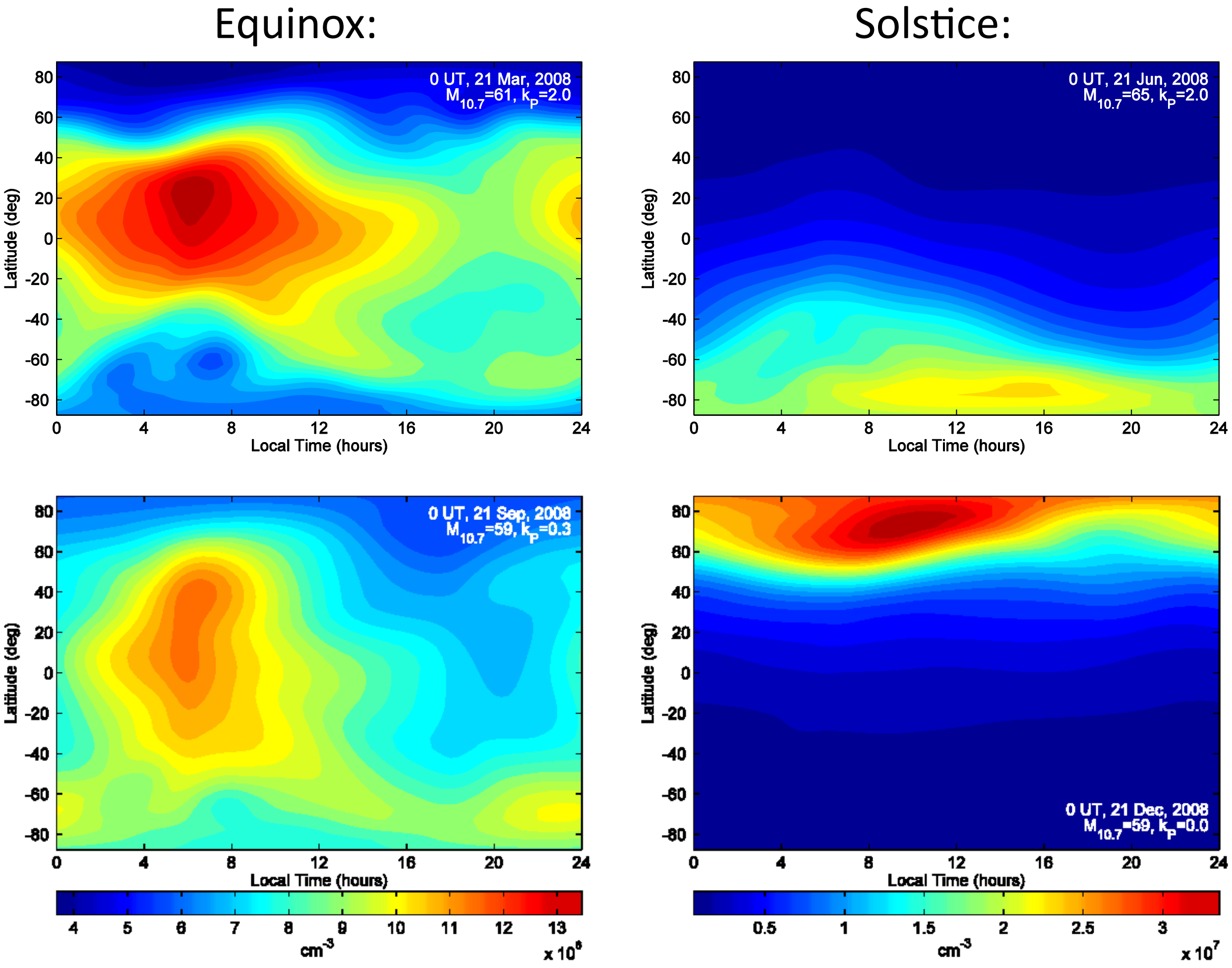
Seasonal Characteristics

TIE-GCM

- The “winter helium bulge” is clearly seen in both solstice plots
- Early local time preference is evident at low- to mid-latitudes during equinox and solstice
- Helium distributions at high latitudes are influenced by the location of the auroral zones, thus a longitude/UT periodicity is present (not shown)
- Sensitivity to geomagnetic activity: slightly elevated Kp levels (in upper plots) correspond to helium being shifted to lower latitudes

TIE-GCM Helium number densities @ 250 km during solar minimum



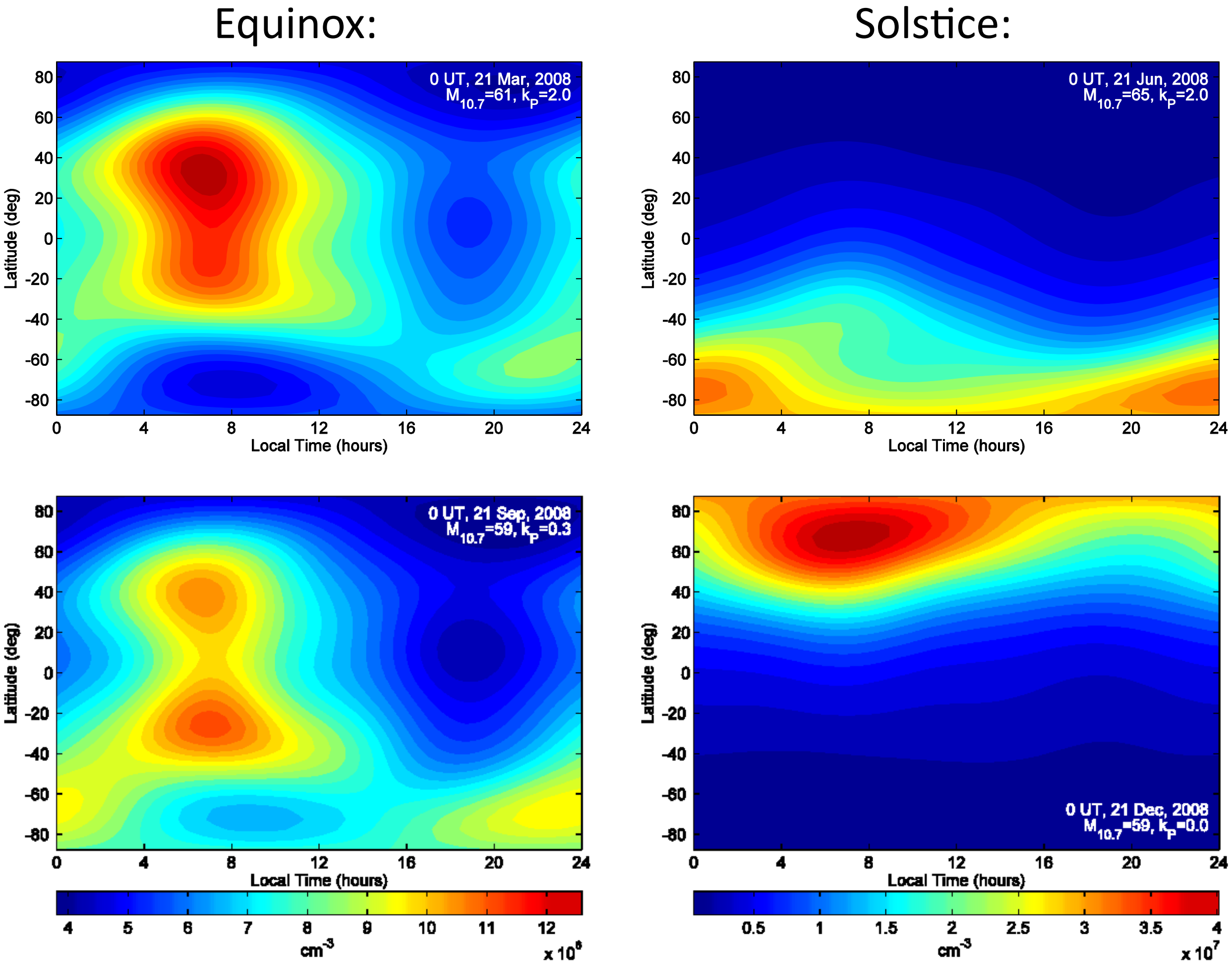
notes: Equinox plots share a common color scale, as do solstice plots

Seasonal Characteristics

MSIS

- Helium behavior as simulated by TIE-GCM shows excellent qualitative (and reasonably good quantitative) agreement with MSIS

MSIS Helium number densities @ 250 km during solar minimum



notes: Equinox plots share a common color scale, as do solstice plots

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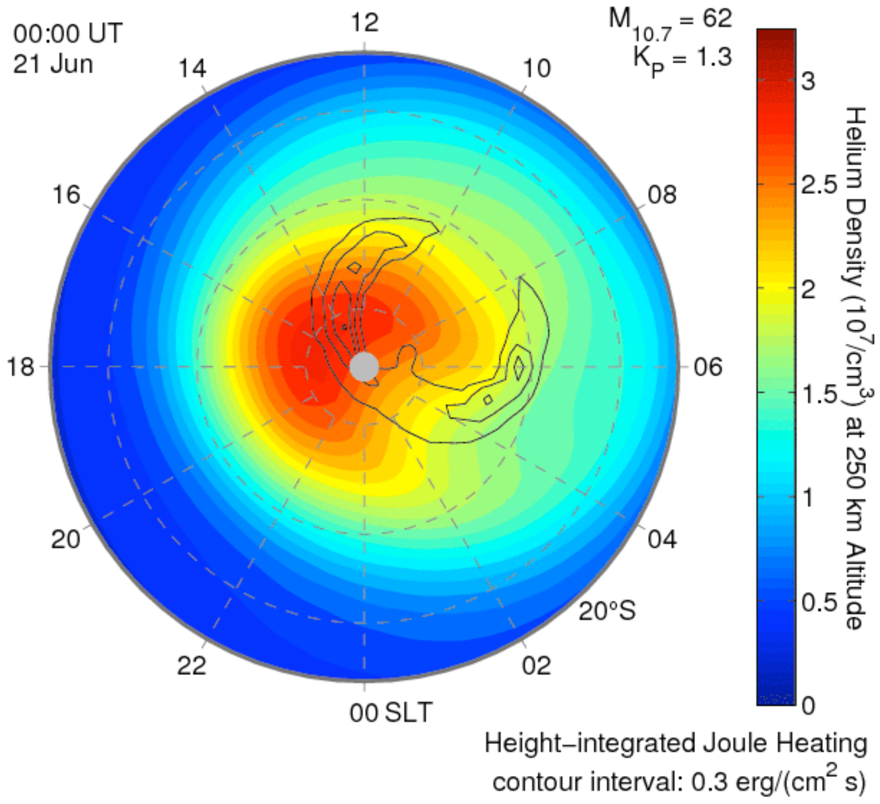
Diurnal Motion at High Latitudes

Movie(?)

Diurnal movement of the winter helium distribution:

- Southern Hemisphere, June Solstice
- Constant external forcing parameters
- Early local-time preference is modulated by the divergence/ upwelling associated with auroral heating



Height–integrated Joule Heating contour interval: 0.3 erg/(cm^2 s)

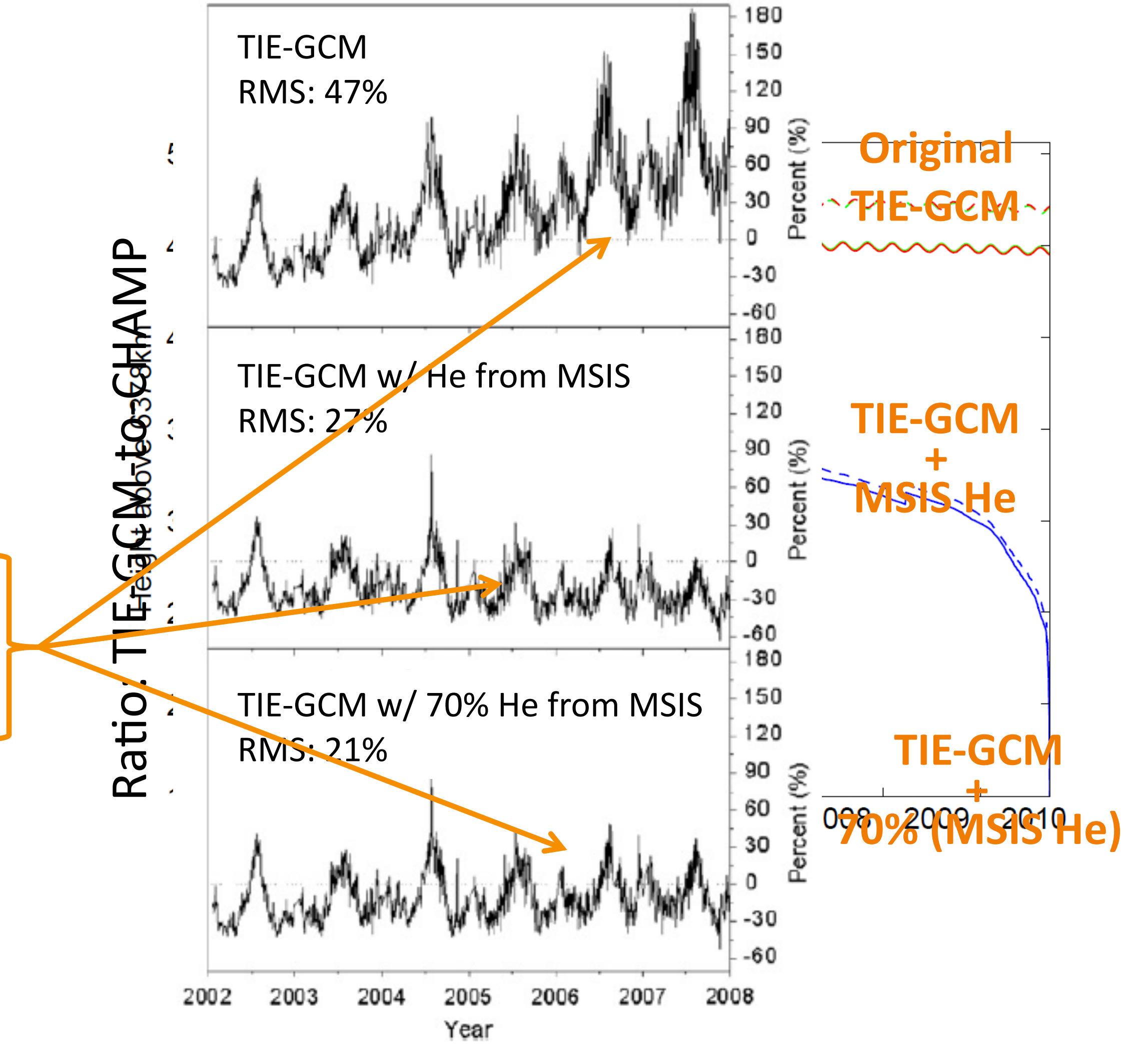
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Model/Data Comparison

Mass density from CHAMP satellite

Previous study by Kim et al. [2012, JASTP]:

- Ad hoc addition of MSIS Helium to TIE-GCM
- Modified thermodynamic properties
- Large differences seen in model densities sampled on CHAMP's orbit
- (note: everything has been normalized to 400 km using MSIS)



Original TIE-GCM

TIE-GCM + MSIS He

TIE-GCM + 70% (MSIS He)

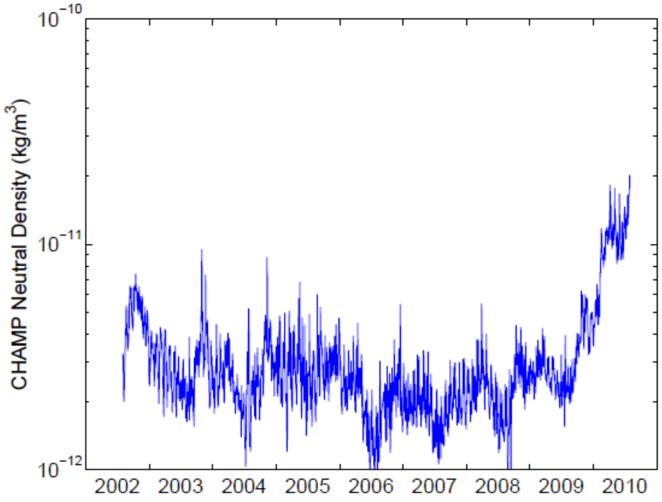
Model/Data Comparison

Mass density from CHAMP satellite

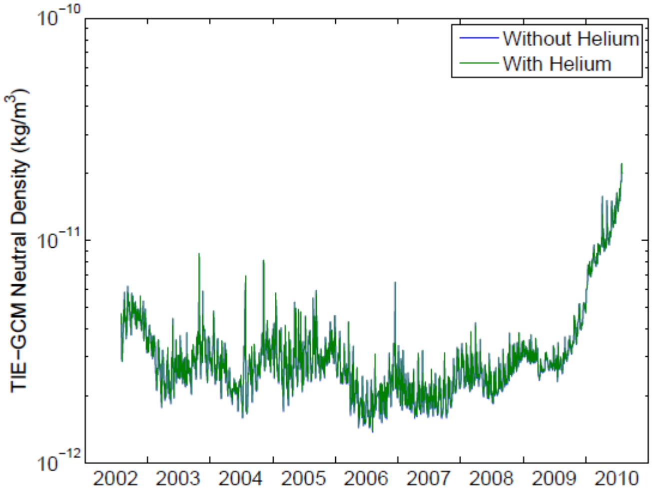
With our new self-consistent model, we have:

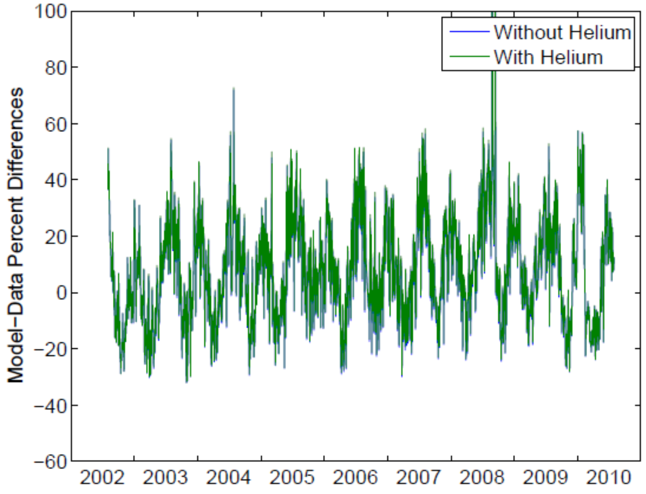
- Simulated the previous solar cycle, w/ and w/out helium
- Sampled these models on CHAMP, GRACE and other satellite orbits

CHAMP Density (at sat. alt.)



TIE-GCM w/ and w/out helium (at sat. alt.)





Model-to-Data Ratios

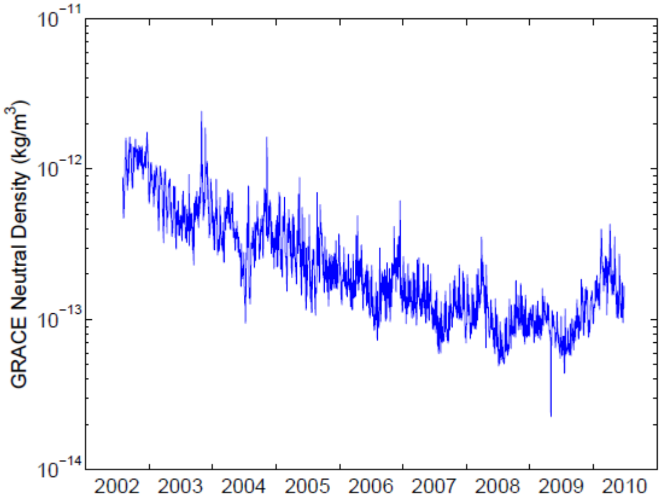
Model/Data Comparison

Mass density from GRACE satellite

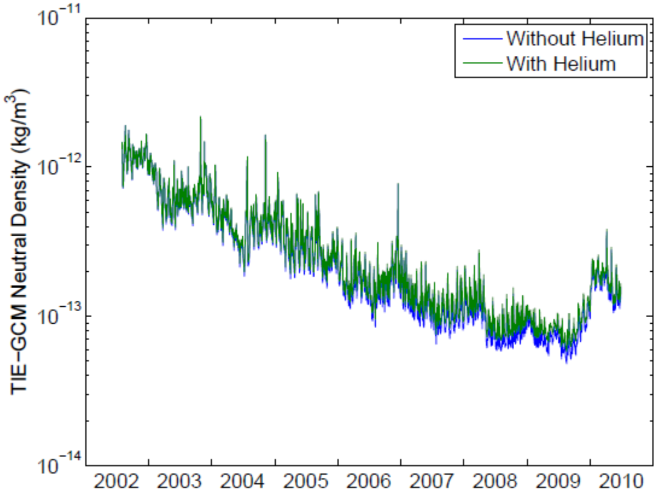
With our new self-consistent model, we have:

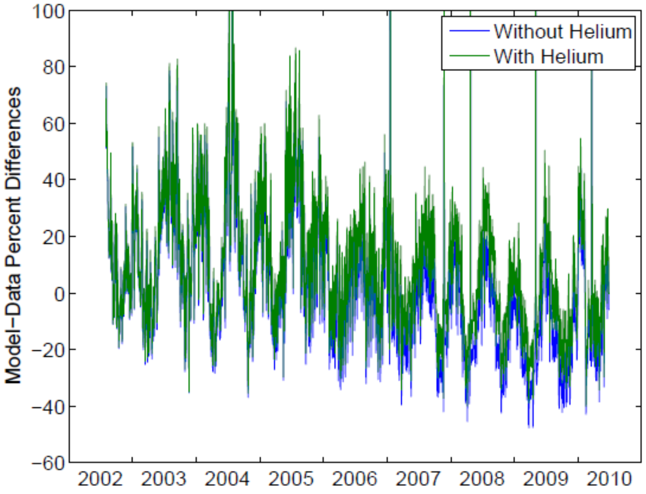
- Simulated the previous solar cycle, w/ and w/out helium
- Sampled these models on CHAMP, GRACE and other satellite orbits

GRACE Density (at sat. alt.)



TIE-GCM w/ and w/out helium (at sat. alt.)



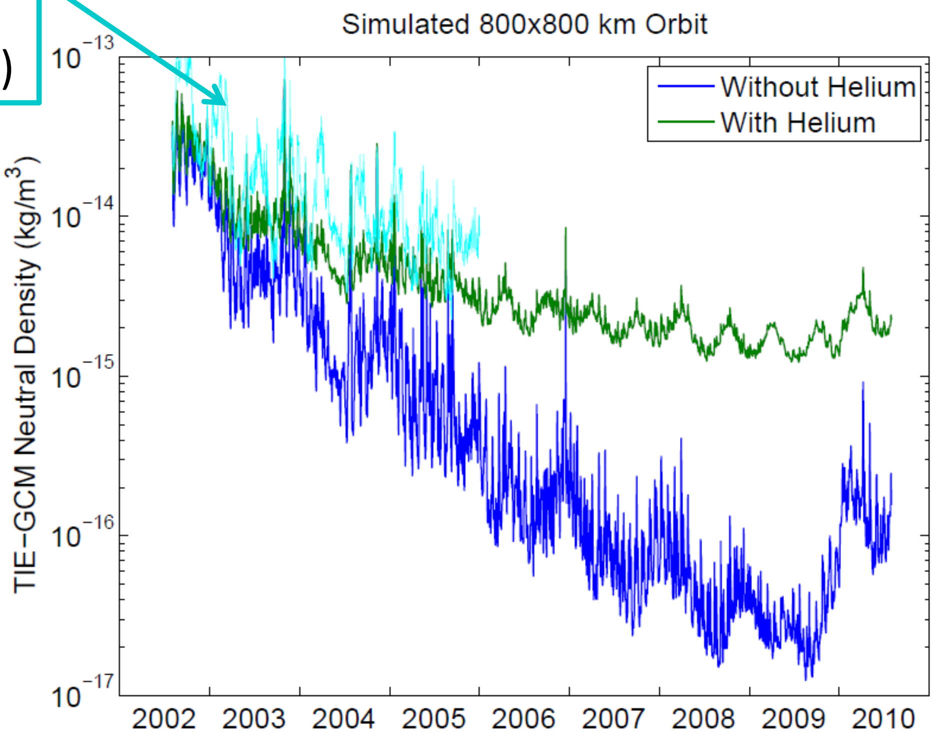


Model-to-Data Ratios

Model/Data Comparison

Mass density around 800 km

Rigidsphere 2 (LCS 4):
Satellite 05398
@ 788 x 853 km
(Credit: Bruce Bowman)



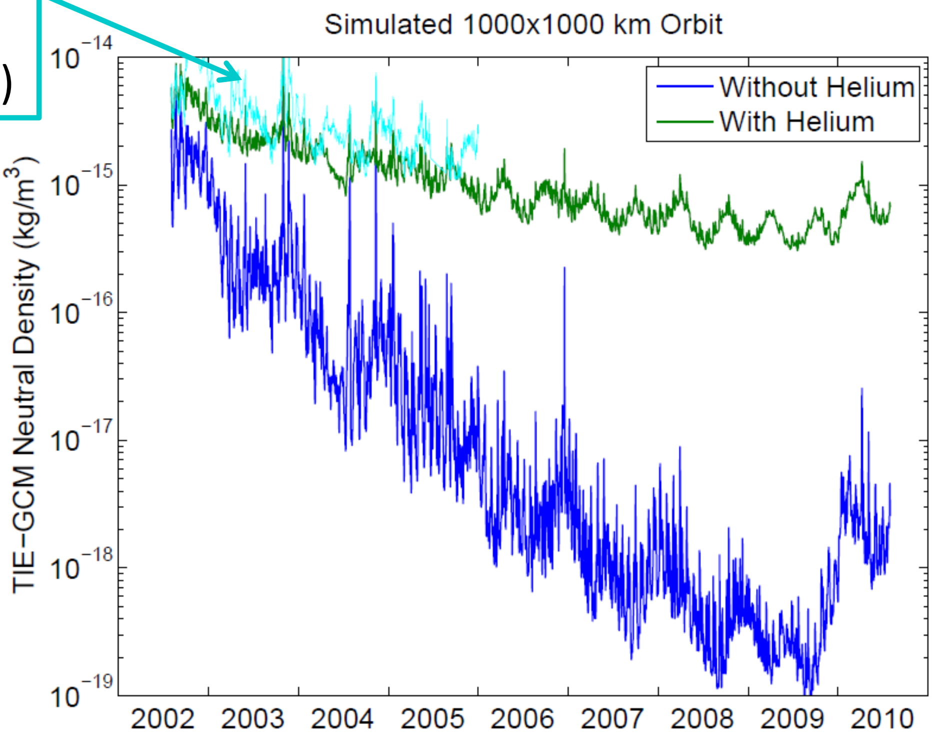
With our new self-consistent model, we have:

- Simulated the previous solar cycle, w/ and w/out helium
- Sampled these models on CHAMP, GRACE and other satellite orbits
- As a first step, we have assumed diffusive equilibrium to govern above TIE-GCM's upper boundary

Model/Data Comparison

Mass density around 1000 km

Calsphere 1:
Satellite 00900
@ 1007 x 1047 km
(Credit: Bruce Bowman)



With our new self-consistent model, we have:

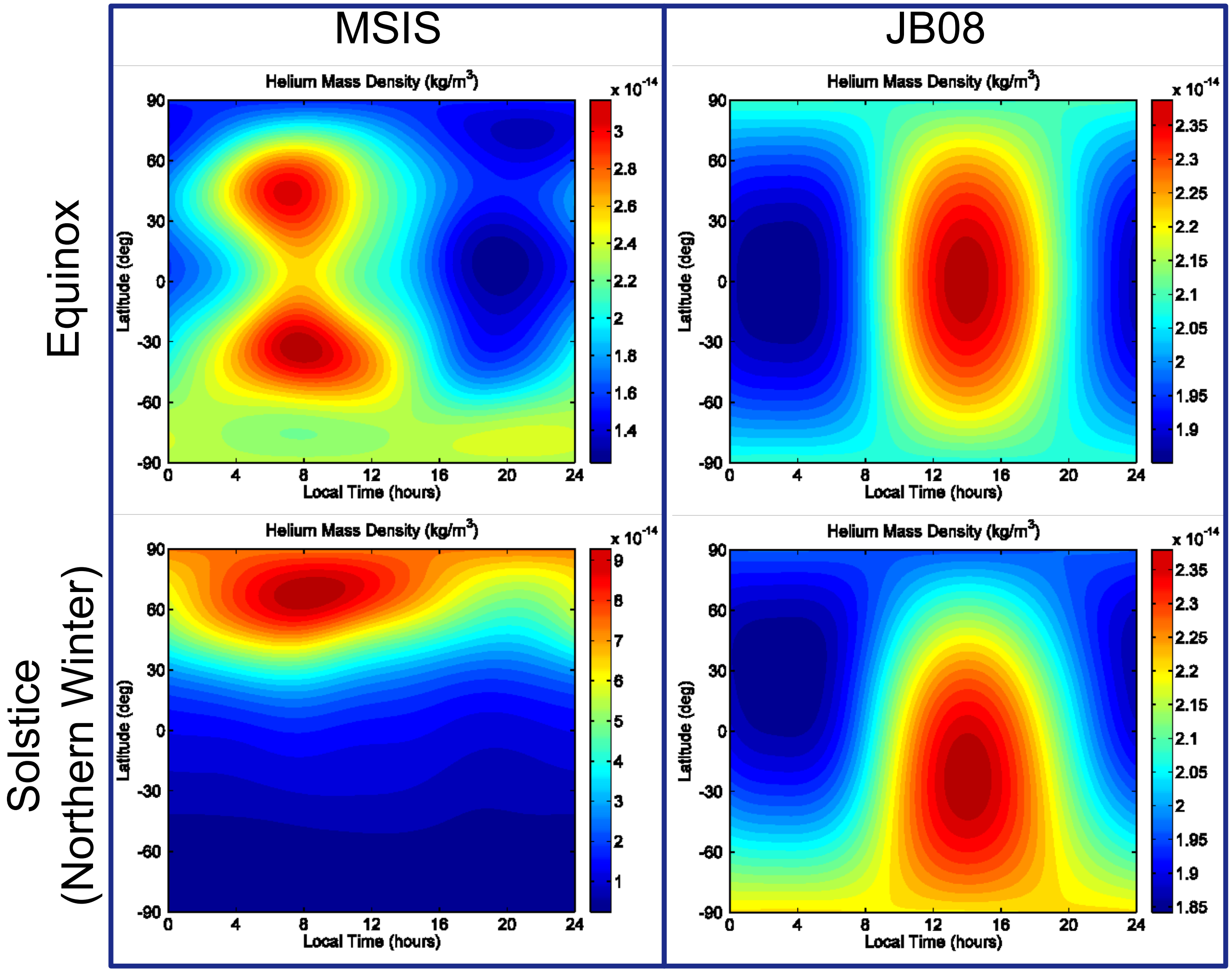
- Simulated the previous solar cycle, w/ and w/out helium
- Sampled these models on CHAMP, GRACE and other satellite orbits
- As a first step, we have assumed diffusive equilibrium to govern above TIE-GCM's upper boundary

Modeling Neutral Helium

Behavior in Empirical Models

- MSIS (left) is driven by mass spectrometer data, i.e. its helium distribution should be reasonably accurate
- Jacchia models are based on satellite drag data, ignoring Mass Spec. data and winter helium bulge (J77 uses an *ad hoc* method to account for helium seasonality).
- Jacchia-Bowman (right) model is currently the operational Sat. Drag model used by the U.S. Air Force

Models Run @ 400 km with F10.7=80



Summary

- **Satellite drag in the lower exosphere (~500-1000 km) is extremely sensitive to helium content, and therefore, to the dynamics in the middle thermosphere (~150-250 km)**
- **Including Helium** as a major species **in TIE-GCM** has significant implications on the:
  - Vertical structure,
  - Mass Density,
  - Geopotential height,
  - Winds, and
  - Seasonal and Local Time variations in the upper thermosphere
- **Potential application of the Helium model:**
  - Satellite drag modeling
  - Using Helium as a tracer for dynamic phenomena
  - Studies of the Exosphere and topside ionosphere

References & Nomenclature

References:

Dickinson, R. E., E. C. Ridley, and R. G. Roble (1984), Thermospheric general circulation with coupled dynamics and composition, *J. Atmos. Sci.*, *41*, 205–219, doi:10.1175/1520-0469(1984)041<0205:TGCWCD>2.0.CO;2.

Hodges, R. R., Jr., and F. S. Johnson (1968), Lateral transport in planetary exospheres, *J. Geophys. Res.*, *73*, 7307, doi:10.1029/JA073i023p07307.

Mayr, H. G., I. Harris, and N. W. Spencer (1978), Some properties of upper atmosphere dynamics, *Reviews of Geophysics and Space Physics*, *16*, 539–565, doi:10.1029/RG016i004p00539.

Newton, G. P., D. T. Pelz, and W. T. Kasprzak (1973), Equatorial thermospheric composition and its variations, in *Space Research XIII*, edited by M. J. Rycroft and S. K. Runcorn, pp. 287–290.

Picone, J. M., A. E. Hedin, D. P. Drob, and A. C. Aikin (2002), NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, *J. Geophys. Res.*, *107*, 1468, doi:10.1029/2002JA009430.

Reber, C. A., and P. B. Hays (1973), Thermospheric wind effects on the distribution of helium and argon in the Earth's upper atmosphere, *J. Geophys. Res.*, *78*, 2977, doi:10.1029/JA078i016p02977.

Richmond, A. D., E. C. Ridley, and R. G. Roble (1992), A thermosphere/ionosphere general circulation model with coupled electrodynamics, *Geophys. Res. Lett.*, *19*, 601–604, doi:10.1029/92GL00401.

Nomenclature:

g	gravitational acceleration
K	Eddy diffusion coefficient
$\mathbf{L}$	normalized force matrix
$m_i, \overline{m}$	molecular mass of ith component, mean molecular mass
p, p_0	pressure, reference pressure
$\mathbf{s}$	chemical source/sink matrix
T, T_{00}	neutral temperature, S.T.P. temperature
$\mathbf{V}$	horizontal wind vector [= $[u \ \ v]^T$]
w_i	deviation of vertical velocity of ith component from mean velocity

$\mathbf{W}$	vector containing the first N-1 components of $\rho_i w_i$
z	log-pressure coordinate [=$\ln(p_0/p)$]
$\boldsymbol{\alpha}$	normalized diffusion matrix
α_{Ti}	thermal diffusion coefficient for ith component
ρ_i, ρ	mass density of ith component, total mass density
τ	characteristic time constant
Φ_G	geopotential height
ψ_i	relative density of ith component
$\boldsymbol{\Psi}$	vector containing the first N-1 components of ψ_i
ω	vertical motion relative to log-pressure coordinate [=dz/dt]

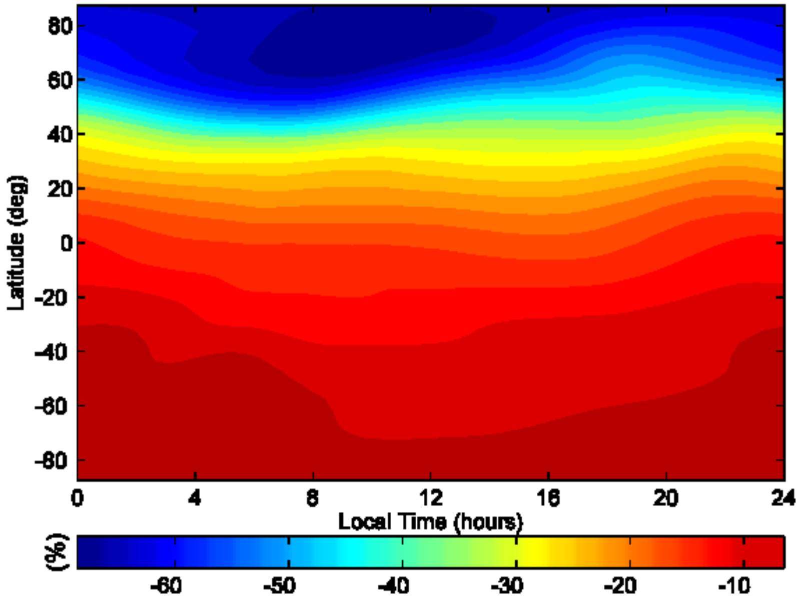
Backup Slides

Model Differences

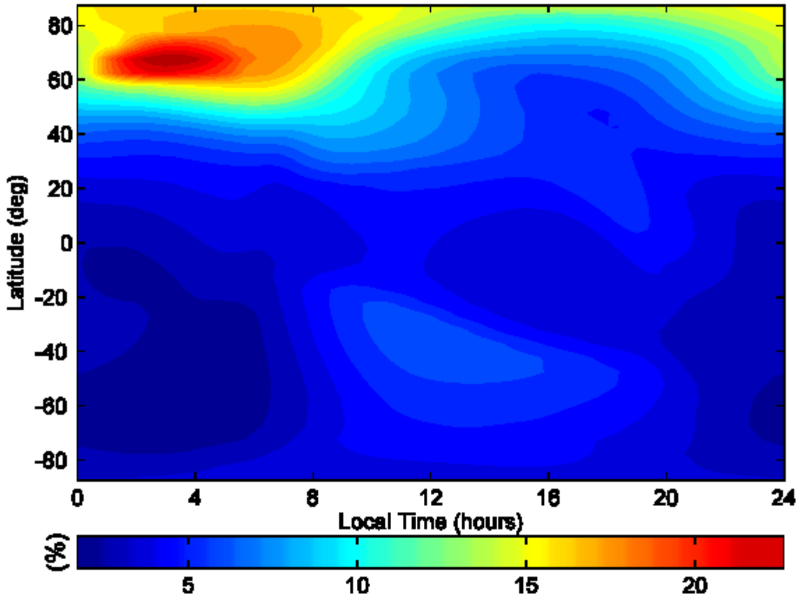
Mass Density

With vs. without Helium

At a constant pressure level: Z_P=7.25



At a constant altitude: 400 km



On an isobaric surface, density is proportional to the mean mass and indirectly proportional to temperature:

$$\rho \propto \bar{m}/T$$

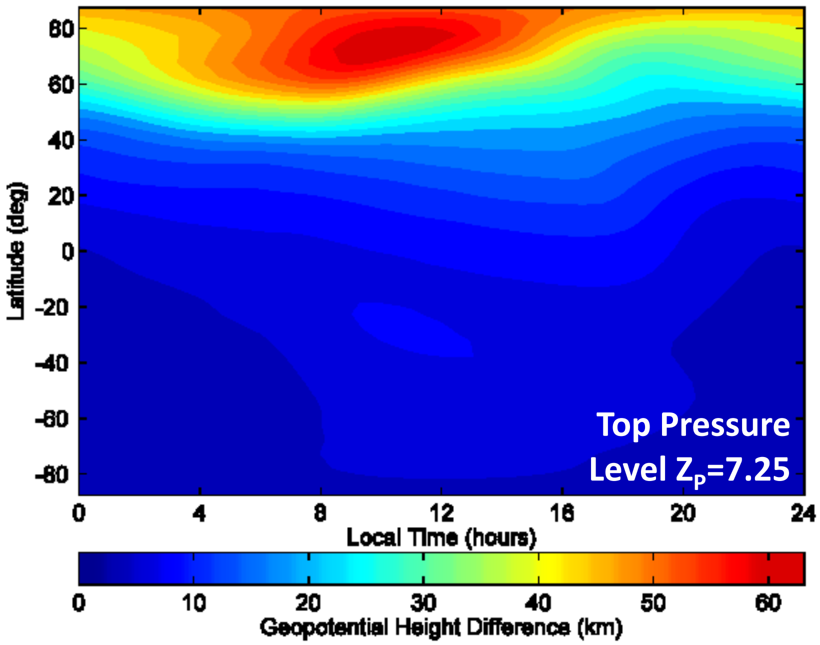
The competing factors of $\bar{m}$ and the increasing height of isobaric surfaces causes smaller densities at lower altitudes and larger densities at higher

Model Differences

Geopotential & Winds

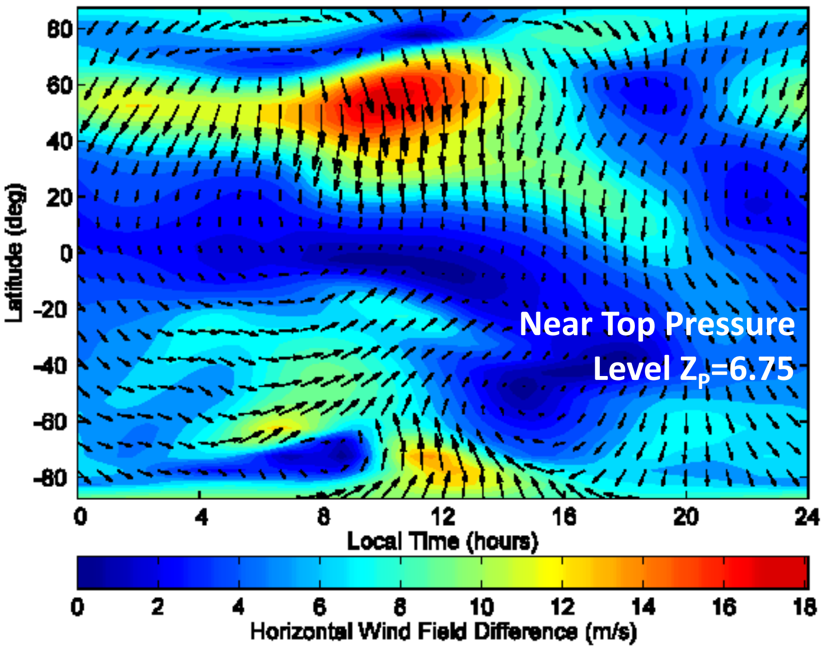
With vs. without Helium

Geopotential Difference



Top Pressure Level Z_P=7.25

Horizontal Wind Difference



Near Top Pressure Level Z_P=6.75

Increases in the height of isobaric surfaces occur in response to the lighter mean mass:

$$\frac{\partial}{\partial z}\Phi_G = \frac{RT}{\overline{m}}$$

$\Rightarrow$

These changes further couple to the momentum equations, modifying the horizontal winds:

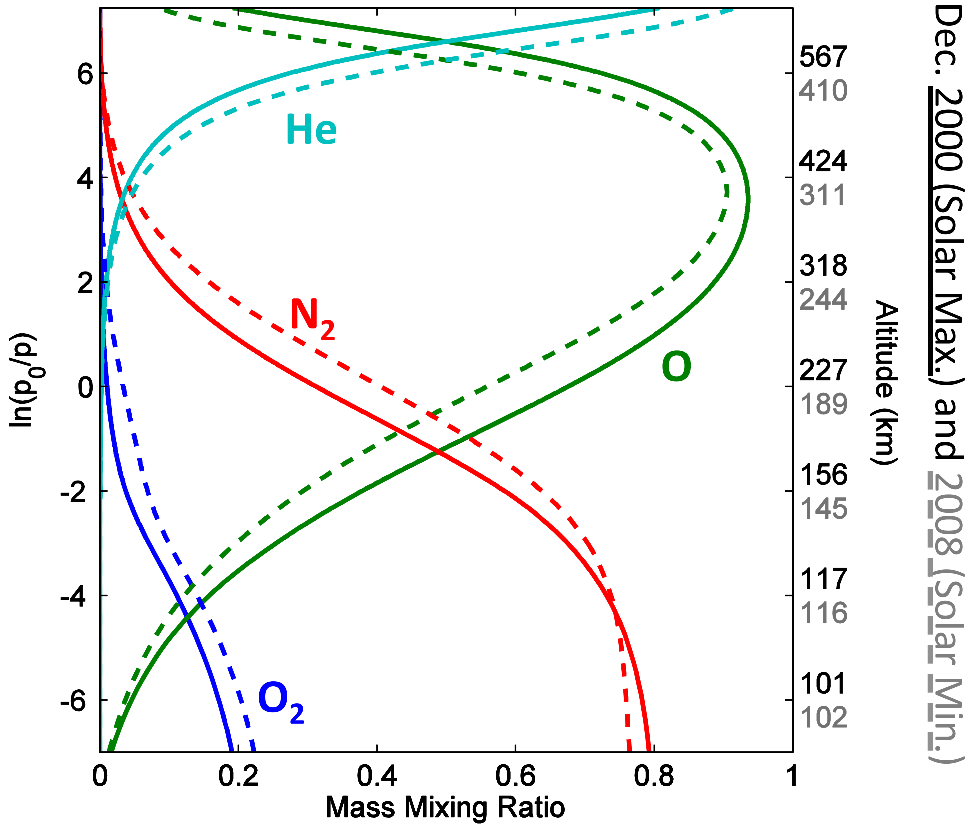
$$\frac{\partial}{\partial t}\mathbf{V} = -\nabla\Phi_G + \cdots$$

Modeling Neutral Helium

Behavior in the Upper Atmosphere

- Helium has very a small concentration from the ground thru the turbopause
- Diffusive separation above the turbopause causes the mixing ratio to increase, approaching unity in the upper thermosphere
- Seasonal variation termed **"Winter Bulge"** due to helium's preference for the high latitudes in the winter hemisphere
- Local time preference prior to ~8:00 LT
- Helium's inverse scale height is less sensitive to solar cycle variations (i.e. temperature changes) than are other species

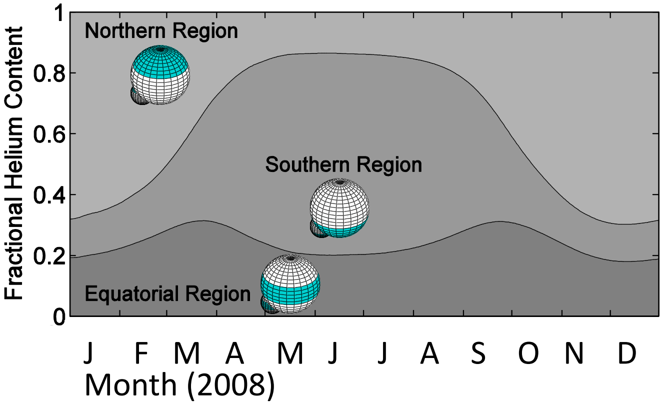
MSIS profile in the vicinity of the Winter Bulge

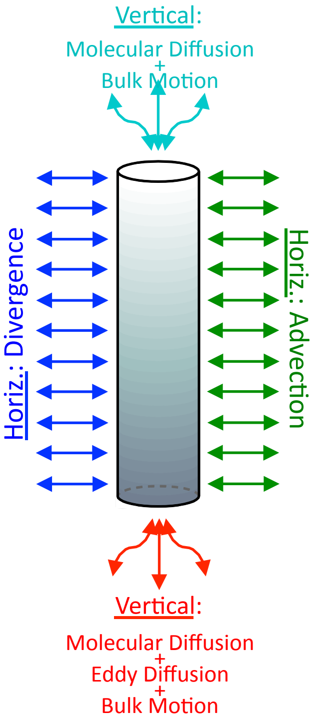


Helium Phenomenology

Regional Accumulation

- We divide the model domain into three regions of roughly equal volume
- The fraction of global helium content in each region has a strong seasonal component
- The contributions of each transport mechanism to the seasonal behavior are isolated in the far-right plots
- The divergence term accumulates helium into the winter polar region, beginning in the fall
- All other terms act to oppose this behavior, essentially reacting to the buildup of helium
- A quasi steady state is attained by early winter, when the divergence term is approximately balanced by the other terms

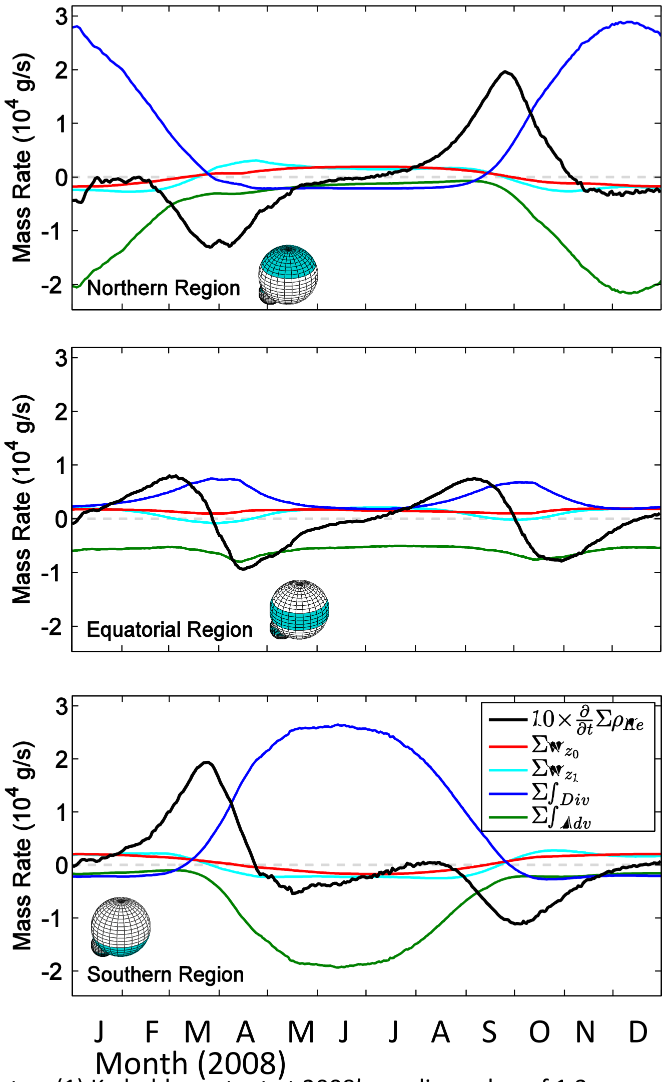



Vertical:
Molecular Diffusion + Bulk Motion

Horiz.: Divergence

Horiz.: Advection

Vertical:
Molecular Diffusion + Eddy Diffusion + Bulk Motion



notes: (1) Kp held constant at 2008's median value of 1.3

(2) black lines scaled by a factor of 10

Helium Phenomenology

What causes the Winter Helium Bulge?

- A longstanding disagreement exists regarding the relative importance of vertical advection (Reber & Hays, 1973) vs. horizontal transport (Mayr et al., 1978) – both in the presence of a diffusively separated atmosphere – in the creation and sustainment of the winter helium bulge
- In order to track the transport and redistribution of a constituent, we introduce an equation for mass conservation of species i within a log-pressure column:

$$\boxed{\begin{aligned}\frac{\partial}{\partial t}\Sigma\rho_i = {} & \phi_i(z_1) \\ & -\phi_i(z_0) \\ & -\frac{p_0}{g}\int_{z_0}^{z_1} \mathrm{e}^{-z} V\cdot\nabla\psi_i\, dz \\ & -\frac{p_0}{g}\int_{z_0}^{z_1} \mathrm{e}^{-z}\psi_i \nabla\cdot V\, dz\end{aligned}}$$

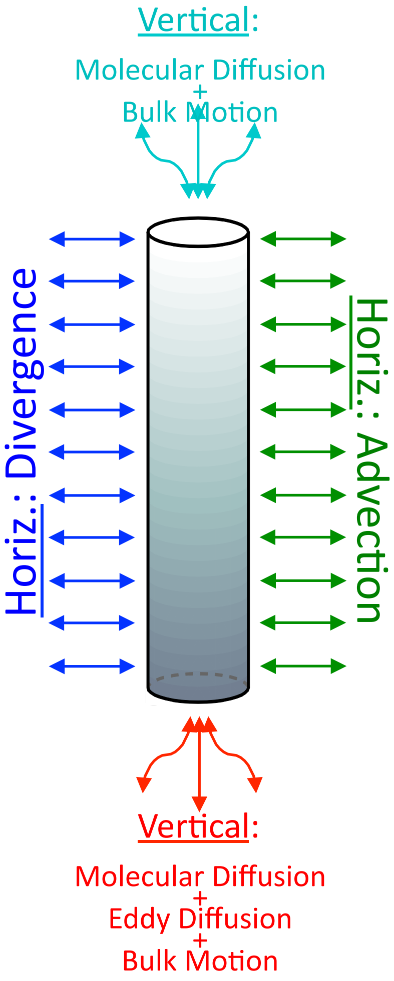
Mass flux of i through the top boundary

Mass flux of i through the bottom boundary

Horizontal advection – corresponds directly to the horiz. advection term in the composition equation

Horizontal divergence – considered implicitly by the composition equation

- This equation is formulated by vertically integrating the ith component of the vector continuity equation given on slide 4 from the bottom (z_0) to the top (z_1) log-pressure level



Vertical:
Molecular Diffusion
+
Bulk Motion

Horiz.: Divergence

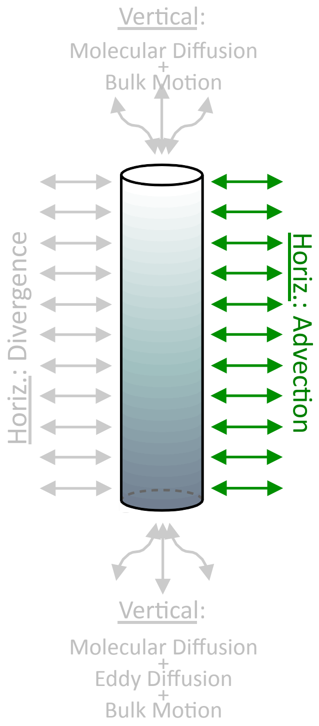
Horiz.: Advection

Vertical:
Molecular Diffusion
+
Eddy Diffusion
+
Bulk Motion

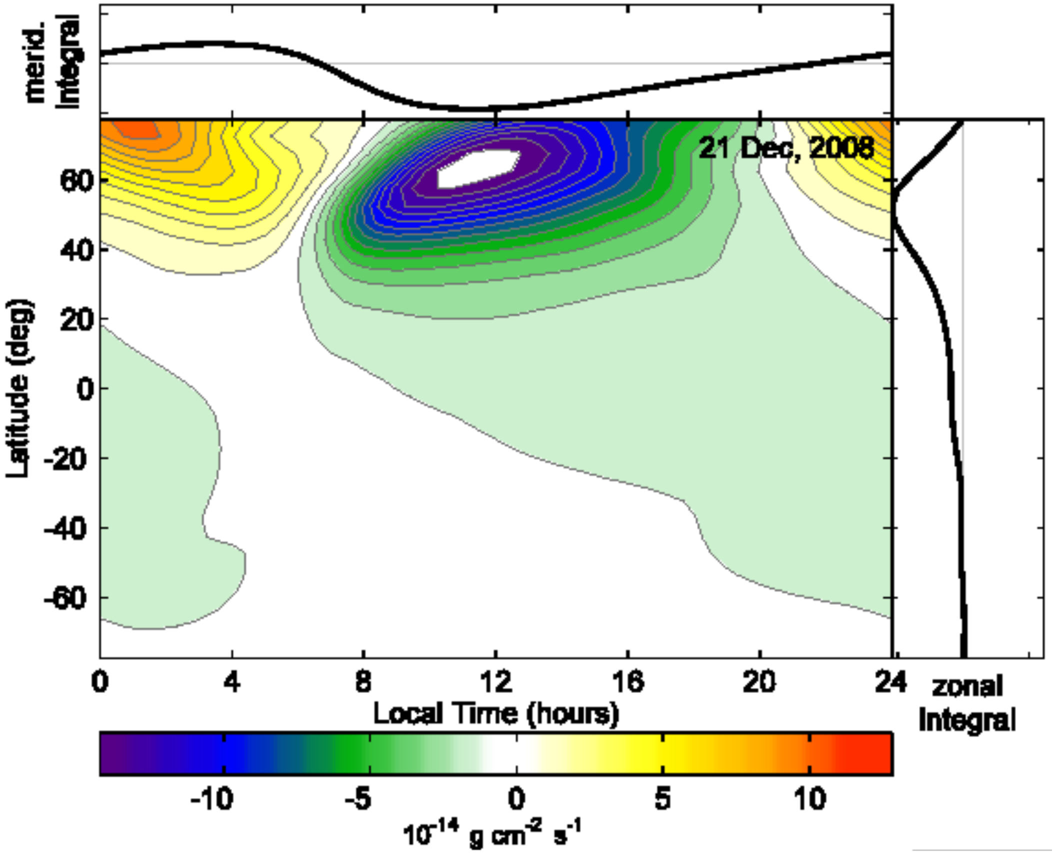
Helium Phenomenology

Horizontal Processes: Advection

- The advection term opposes the build-up of helium in the winter hemisphere
- Builds-up (depletes) helium in pre-(post-)sunrise local times during solstice



Rate of Mass Accumulation within a Column



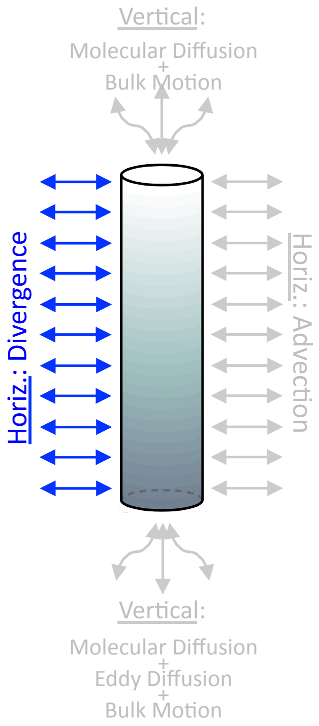
notes: (1) Mass rates are averaged over the course of a day

(2) All equinox plots for slides 11-13 share common color and axis scales, as do all solstice plots

Helium Phenomenology

Horizontal Processes: Divergence

- The divergence term accumulates helium in the winter hemisphere
- Builds-up (depletes) helium in pre-(post-)sunrise local times during all seasons



Vertical:
Molecular Diffusion
+
Bulk Motion

Horiz.: Divergence

Horiz.: Advection

Vertical:
Molecular Diffusion
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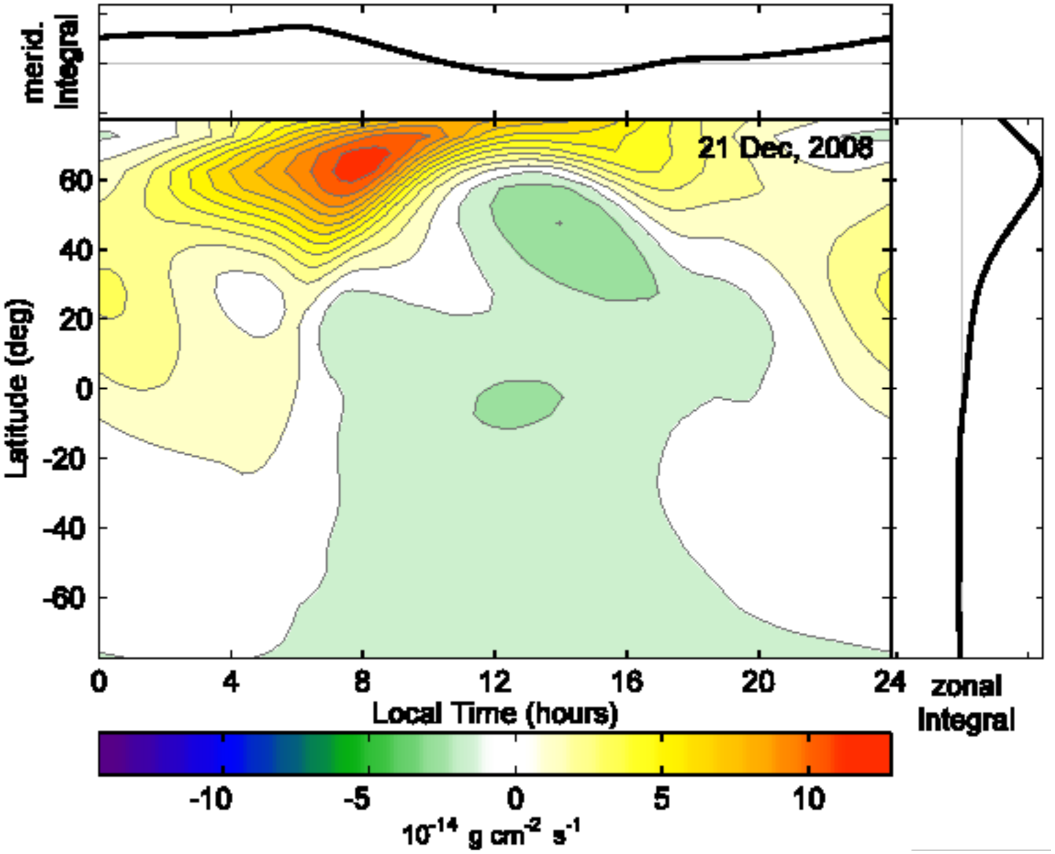
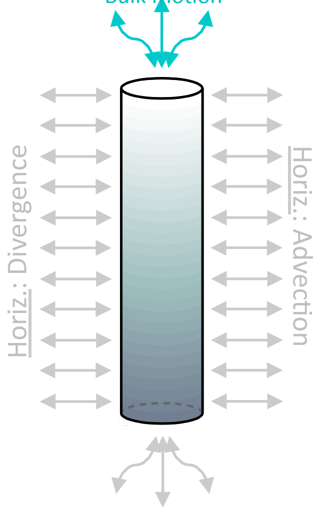
Rate of Mass Accumulation within a Column



notes: (1) Mass rates are averaged over the course of a day
(2) All equinox plots for slides 11-13 share common color and axis scales, as do all solstice plots

Helium Phenomenology
Vertical Processes

- Vertical motion depletes column helium content in the winter hemisphere
- Helium flux is dominated by lower bulk motion (upper molecular diffusion) at equinox (solstice)



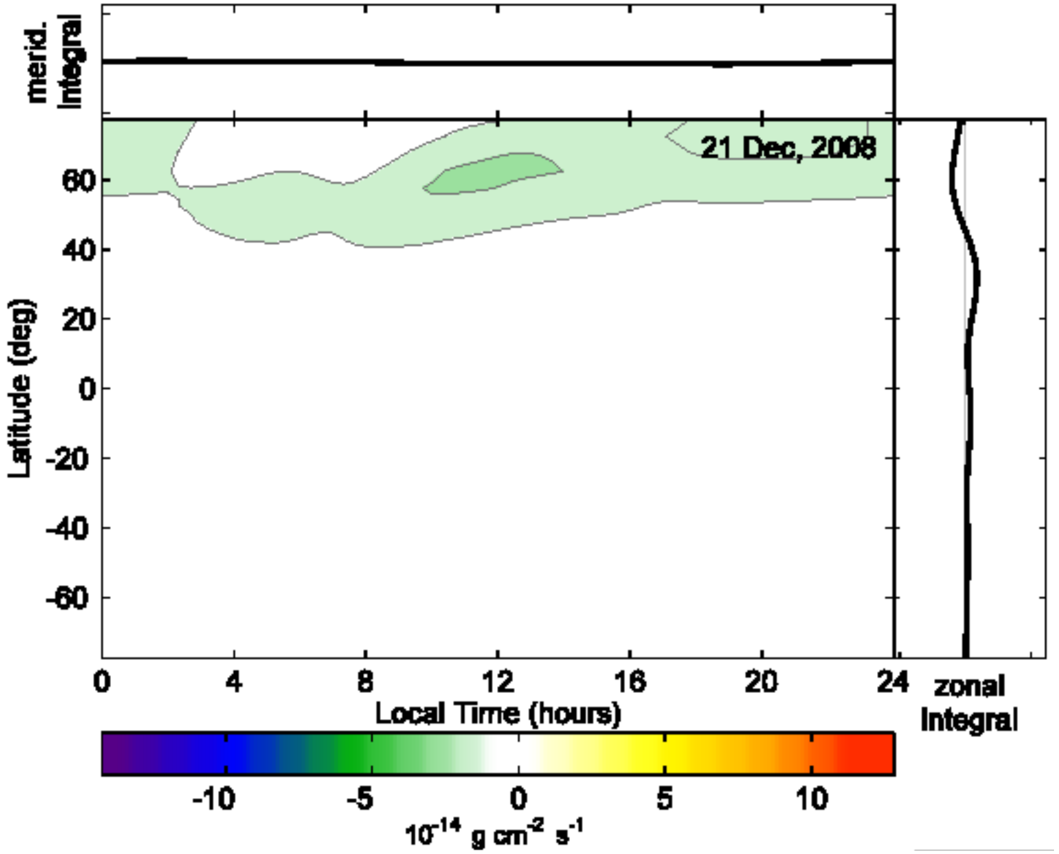
Vertical:
Molecular Diffusion
+
Bulk Motion

Horiz.: Divergence

Horiz.: Advection

Vertical:
Molecular Diffusion
+
Eddy Diffusion
+
Bulk Motion

Rate of Mass Accumulation within a Column

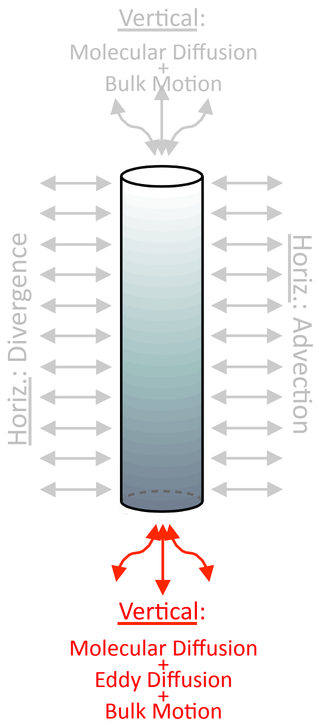


notes: (1) Mass rates are averaged over the course of a day
(2) All equinox plots for slides 11-13 share common color and axis scales, as do all solstice plots

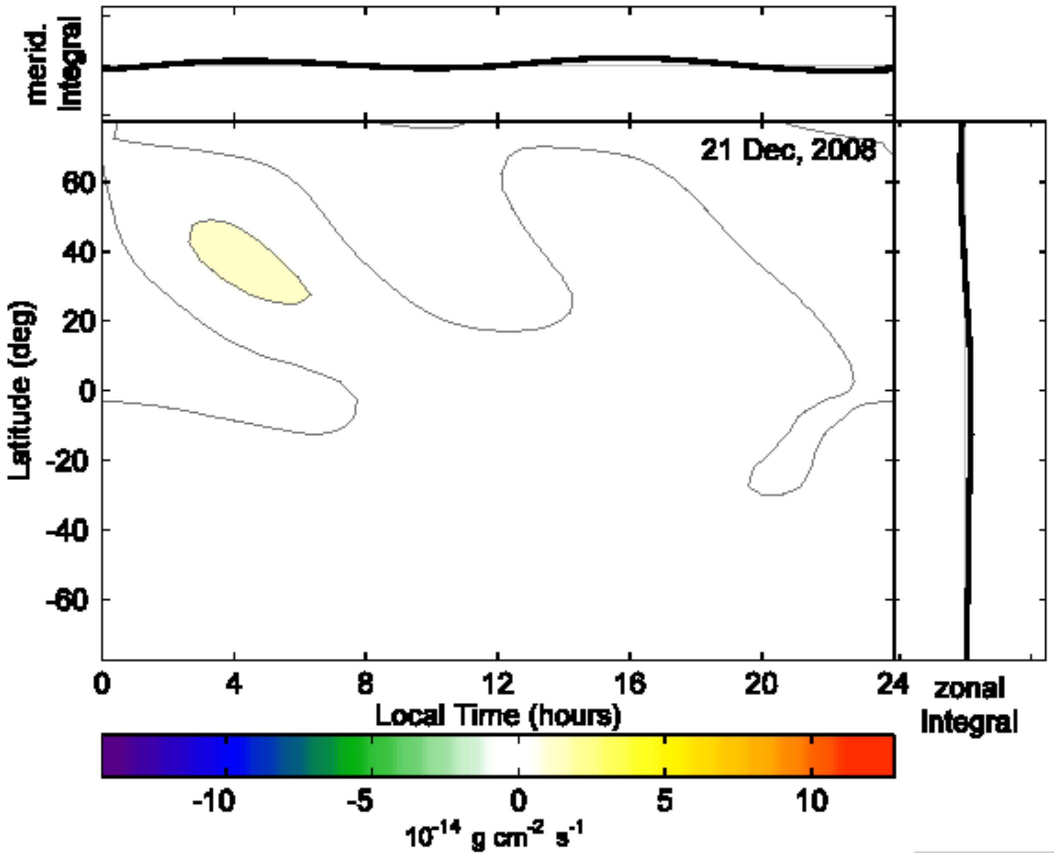
Helium Phenomenology

Vertical Processes

- Vertical bulk circulation has a small depleting effect on helium content in the winter hemisphere



Rate of Mass Accumulation within a Column



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Abstract

The TIE-GCM was recently augmented to include helium and argon, two approximately inert species that can be used as tracers of dynamics in the thermosphere. The former species is treated as a major species due to its large abundance near the upper boundary. The effects of exospheric transport are also included in order to simulate realistic seasonal and latitudinal helium distributions. The latter species is treated as a classical minor species, imparting absolutely no forces on the background atmosphere. In this study, we examine the interplay of the various dynamical terms – i.e. background circulation, molecular and Eddy diffusion – as they drive departures from the distributions that would be expected under the assumption of diffusive equilibrium. As this has implications on the formulation of all empirical thermospheric models, we use this understanding to address the following questions: (1) how do errors caused by the assumption of diffusive equilibrium manifest within empirical models of the thermosphere? and (2) where and when does an empirical model's output disagree with its underlying datasets due to the inherent limitations of said model's formulation?

Outline

- Background and Motivation
- Past and Current Implementation of Helium in TIE-GCM
- Upper Boundary Conditions
- Salient Features
- Thermodynamic Effects of Helium
- Conclusions and Future Work

Brief History of Helium

- First discovered from anomalous Solar emission line (c. 1868)
- Arises in Earth's crust and mantle from radioactive decay:

$$\begin{gathered}\mathrm{Th}^{232} \rightarrow \mathrm{Pb}^{208} + 6\,\mathrm{He}^{4} \\ \mathrm{U}^{235} \rightarrow \mathrm{Pb}^{207} + 7\,\mathrm{He}^{4} \\ \mathrm{U}^{238} \rightarrow \mathrm{Pb}^{206} + 8\,\mathrm{He}^{4}\end{gathered}$$

- Outgassing at a rate of 2.5e6 atoms*cm-2s-1 produces atmospheric abundance of ~5.24 ppmv at ground levels
- Non-thermal escape at the top of the atmosphere balances in-flux at ground levels, over a certain time scale. He+ outflow is currently thought to be responsible [Lie-Svendsen & Rees, 1996]

see Kockarts [1973]

Helium in T*-GCM

Helium was initially **solved as a minor constituent** in various versions of T*GCMs [Roble et al., 1988; Richmond et al., 1992; Roble and Ridley, 1994]:

- E. C. Ridley developed the framework to solve for helium as a minor species using an iterative (implicit) solver to include the non-escaping helium flux

It's my understanding that:

- At some point, a switch in software libraries caused the minor He code to stop working
- The upper boundary of T*GCM was raised from zp=5 to zp=7
- Afterward, Helium has been difficult to re-implement as a minor species

Major Species Composition Equation

The alpha matrix from Dickinson et al., [1984]:

$$\boldsymbol{\alpha} = -\begin{bmatrix} \phi_{O_2,N_2} + (\phi_{O_2,O} - \phi_{O_2,N_2})\psi_O & (\phi_{O_2,N_2} - \phi_{O_2,O})\psi_{O_2} \\ (\phi_{O,N_2} - \phi_{O,O_2})\psi_O & \phi_{O,N_2} + (\phi_{O,O_2} - \phi_{O,N_2})\psi_{O_2} \end{bmatrix}$$

The alpha matrix after inclusion of Helium as a major species:

$$\boldsymbol{\alpha} = -\begin{bmatrix} \phi_{O_2,N_2} + \sum_{k=\{O,He\}} (\phi_{O_2,k} - \phi_{O_2,N_2})\psi_k & (\phi_{O_2,N_2} - \phi_{O_2,O})\psi_{O_2} & (\phi_{O_2,N_2} - \phi_{O_2,He})\psi_{O_2} \\ (\phi_{O,N_2} - \phi_{O,O_2})\psi_O & \phi_{O,N_2} + \sum_{k=\{O_2,He\}} (\phi_{O,k} - \phi_{O,N_2})\psi_k & (\phi_{O,N_2} - \phi_{O,He})\psi_O \\ (\phi_{He,N_2} - \phi_{He,O_2})\psi_{He} & (\phi_{He,N_2} - \phi_{He,O})\psi_{He} & \phi_{He,N_2} + \sum_{k=\{O_2,O\}} (\phi_{He,k} - \phi_{He,N_2})\psi_k \end{bmatrix}$$

- When solving for He as a minor species, the major constituents are considered fixed and some of these terms are neglected, i.e. terms that describe the behavior of O1, O2, and N2 diffusing through He
- When solving for O1, O2, and N2, only an upper 2x2 is used

Modifications to TIE-GCM

Changes made in order to add Helium as a Major Component:

$$\boldsymbol{\Psi} = \begin{bmatrix} \psi_{O2} \\ \psi_{O1} \end{bmatrix} \quad \Rightarrow \quad \boldsymbol{\Psi} = \begin{bmatrix} \psi_{O2} \\ \psi_{O1} \\ \psi_{He} \end{bmatrix}$$

$$\psi_{N2} = 1 - \psi_{O2} - \psi_{O1} \quad \Rightarrow \quad \psi_{N2} = 1 - \psi_{O2} - \psi_{O1} - \psi_{He}$$

$\boldsymbol{L} = \delta_{ij}\left(\frac{\partial}{\partial z} - 1 + \frac{m_i}{\overline{m}} + \frac{1}{\overline{m}}\frac{\partial \overline{m}}{\partial z}\right)$ is expanded

$\boldsymbol{\alpha}$ matrix and TriDiagonal solver (inline code in comp.F) is expanded to include Helium diffusion terms and other related terms (note: now inverting a [3x3] matrix, instead of a [2x2], which is still efficient using direct methods)

MISC.: Added thermal diffusion; added Helium to calculation of geopotential, density, mbar, cp, kt, km, and several related quantities; Constant MMR at L.B.; extensive U.B. work (to be covered).

Upper Boundary Conditions

Thermal Escape

Diffusive Equilibrium for O_2 and N_2 (as in original TIE-GCM):

$$\left(\frac{\partial}{\partial z} - 1 + \frac{m_i}{\overline{m}} + \frac{1}{\overline{m}}\frac{\partial \overline{m}}{\partial z}\right)\boldsymbol{\psi}_i = 0$$

For $i = \{O_2, N_2\}$

Thermal Escape mass flux:

$$n_{He} m_{He} w_{He} = p_0 e^{-z} \frac{\psi_{He} \overline{m} v_p}{2\sqrt{\pi} RT} (1 + \lambda_c) \underbrace{\exp(-\lambda_c)} \approx 0,$$ where $\lambda_c = v_e^2 / v_p^2$

$v_e \approx 10.7$ km/s

$v_p \approx 1.8$ km/s

→

$\exp(-\lambda_c) = 4.5\text{e-}16$

Exponential term ensures that thermal flux is orders of magnitude too low to affect the global Helium content

Upper Boundary Conditions

Non-Escaping Flux

Non-Escaping Flux of Helium atoms with ballistic trajectories in collision-less exosphere as approximated by Hodges and Johnson [1968] and Hodges [1973]:

$\Phi = -\nabla^2 (n\langle v \rangle H^2 P_2)$, where

$n, \langle v \rangle, H^2$ are number density, mean thermal velocity, and scale height for helium

P_2 is an integral quantity from the references above, with small temp. dependence

Imposed as a diffusive flux at the top of the atmosphere using the vector diffusive flux equation:

$$\underbrace{\boldsymbol{W} = \begin{bmatrix} 0 \\ \dfrac{p_0 e^{-z}}{g^2} \sqrt{\dfrac{8}{\pi} \dfrac{R^3}{m_{He}^5}} \nabla^2 \left(\overline{m} \boldsymbol{\psi}_{He} T^{3/2} P_2 \right) \\ -\dfrac{p_0 e^{-z}}{g^2} \sqrt{\dfrac{8}{\pi} \dfrac{R^3}{m_{He}^5}} \nabla^2 \left(\overline{m} \boldsymbol{\psi}_{He} T^{3/2} P_2 \right) \end{bmatrix}}_{\text{Vector of mass flow rates}} = \tau^{-1} \frac{p_0 \overline{m}}{m_{N2} g} \left(\frac{T_{00}}{T} \right)^{0.25} \boldsymbol{\alpha}^{-1} \boldsymbol{L} \boldsymbol{\Psi}$$

Upper Boundary Conditions

Non-Escaping Flux

The non-escaping flux U.B.C. can be implemented in a couple of ways:

- Implicitly, using finite differences (slow, but stable)
- Explicitly, using finite differences (unstable, needs filtering)
- Explicitly, using a truncated spectral approximation (filtering is globally consistent if a triangular truncation is used)

Upper Boundary Conditions

Non-Escaping Flux

Non-Escaping Flux:

$$\Phi = -\nabla_h^2 (n\langle v\rangle H^2 P_2)$$

Treated explicitly. The function $n\langle v\rangle H^2 P$ is represented using a non-aliasing, truncated spectral approximation:

$$f(\theta_i, \phi_j) = \sum_{n=0}^{N} \sum_{m=0}^{n} \bar{P}_n^m(\theta_i)(a_{n,m} \cos(m\phi_j) + b_{n,m} \sin(m\phi_j))$$

using an efficient quadrature transform of the form [Swarztrauber, 1979, SINUM]:

$$a_{n,m} = \sum_{i=0}^{N}{}'' \bar{Z}_n^m(\theta_i) a_m(\theta_i)$$

$$\bar{Z}_n^m(\theta_i) = \frac{2}{N} \sum_{k=0}^{N}{}'' \cos k\theta_i \int_0^{\pi} \cos(k\theta) \bar{P}_n^m(\theta) \sin\theta \, d\theta.$$

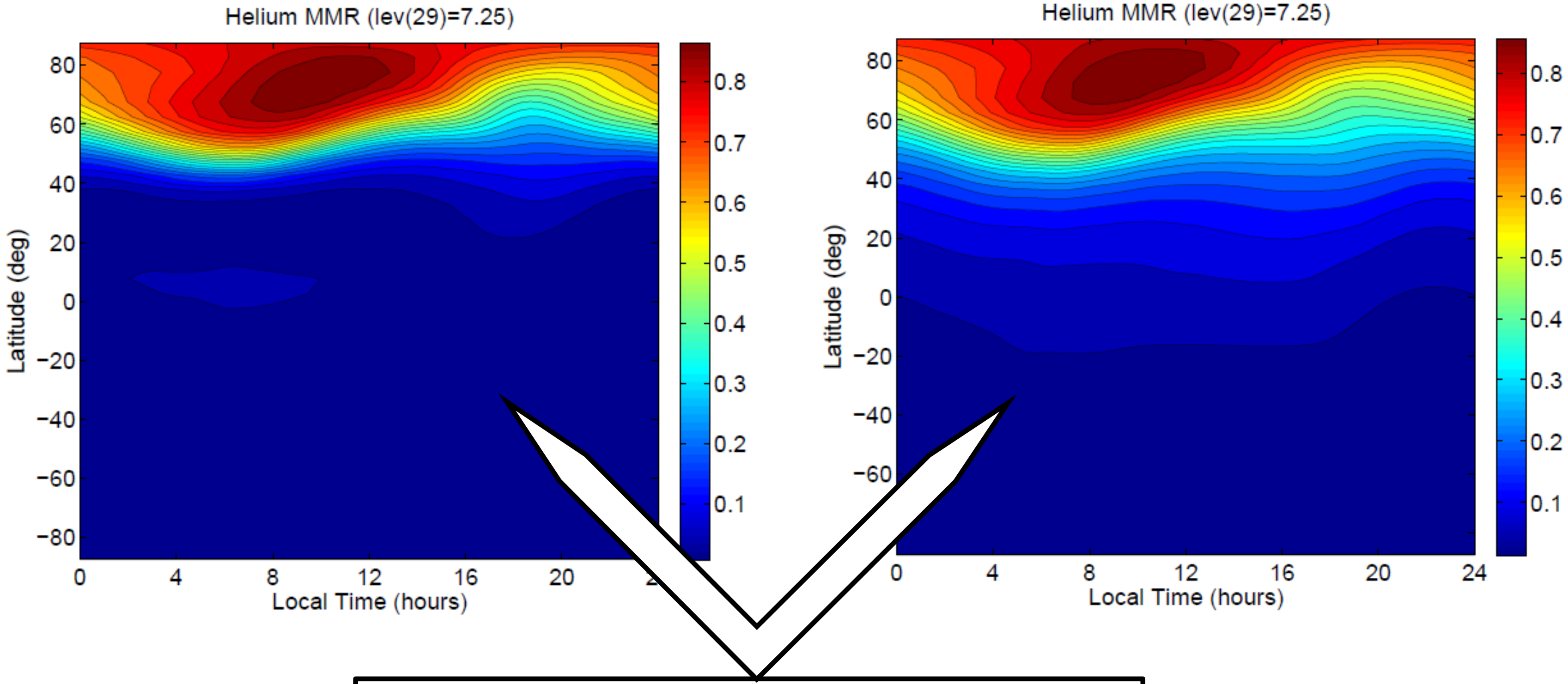
$$\bar{Z}_n^m(\theta_i) = \frac{2}{N} \sum_{k=1}^{N-1} \sin k\theta_i \int_0^{\pi} \sin(k\theta) \bar{P}_n^m(\theta) \sin\theta \, d\theta.$$

The Laplacian is then synthesized using the well-known relation:

$$\nabla_h^2 \left\{ \overline{P}_n^m(\theta) \left(a_{n,m} \cos m\varphi + b_{n,m} \sin m\varphi \right) \right\} =$$
$$-n(n+1) \overline{P}_n^m(\theta) \left(a_{n,m} \cos m\varphi + b_{n,m} \sin m\varphi \right)$$

Upper Boundary Conditions

Non-Escaping Flux



Zero Diffusive Flux UBC:

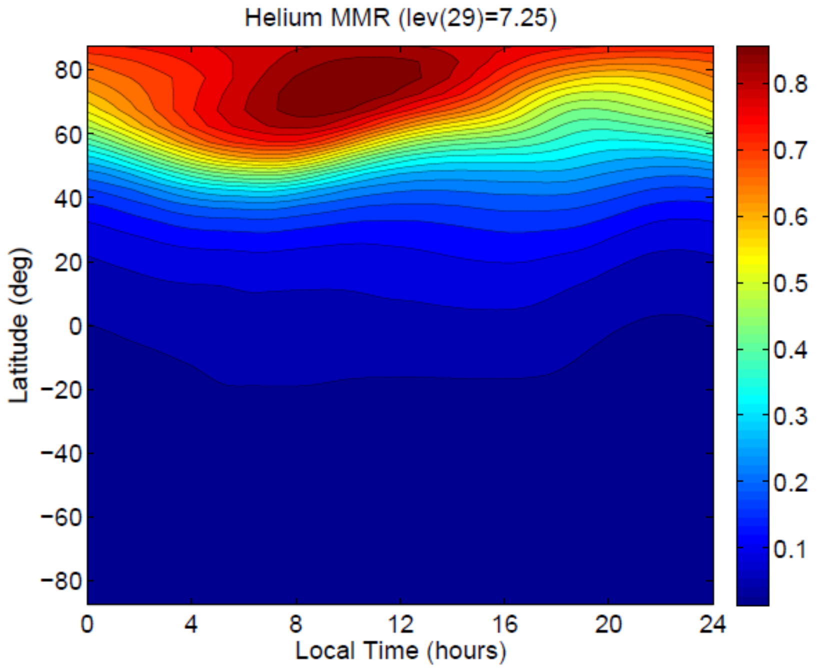
Accounting for Non-Escaping Flux:

Exospheric return flow accounts for increased Helium away from the Winter Bulge region; gradients are smoothed.

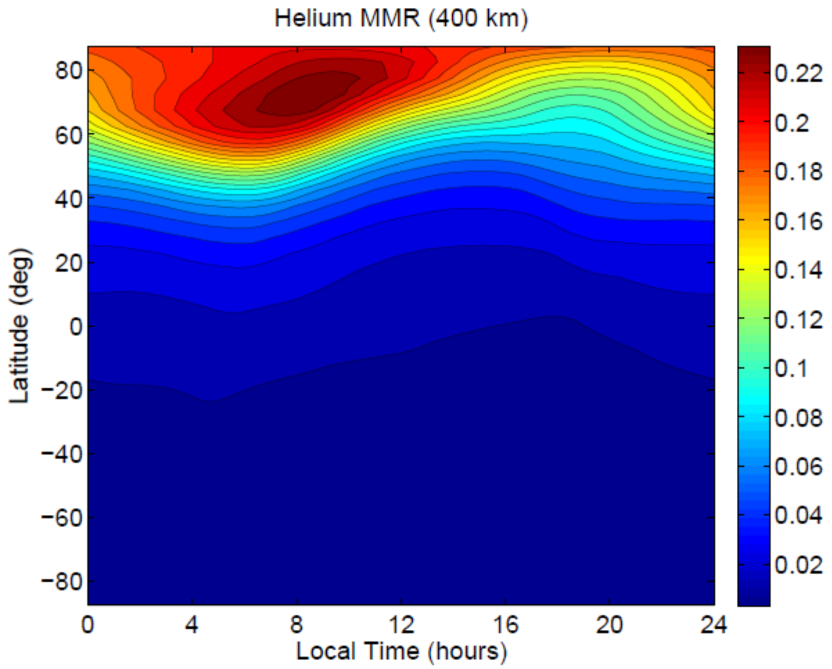
Helium Mass Mixing Ratio

Dec. 2008

Top Pressure Level ZP=7.25



Constant Altitude: 400 km



On a constant pressure level, MMR reaches >0.8 in the winter hemisphere
Note: the geopotential is much higher here because Helium increases the scale height

At 400km, the MMR is reasonably consistent with MSIS

Model Comparison

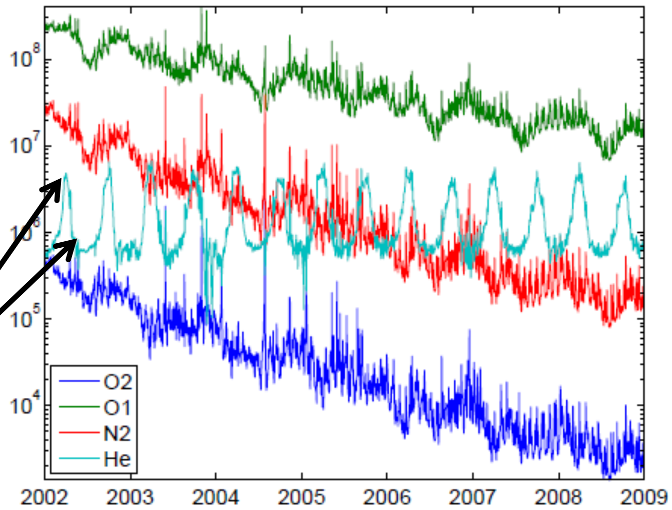
2008

Helium Movie

Solar Cycle Comparison (near equator)

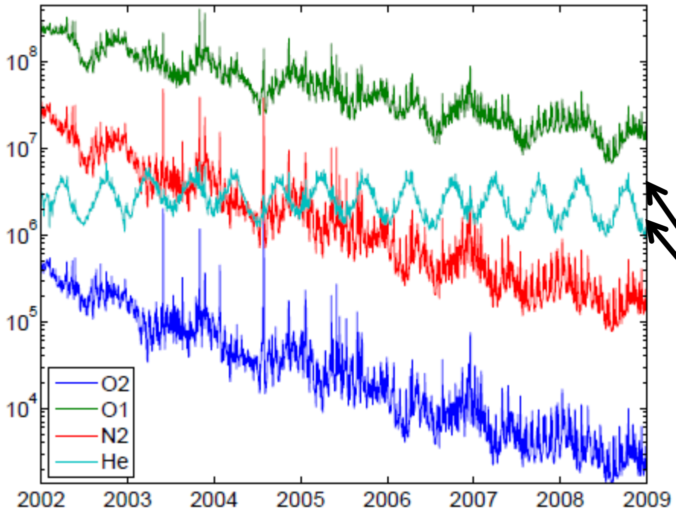
Zero Diffusive Flux UBC:

TIE–GCM Number Densities, 400 km, 2.5° lat, 0° lon, 00 UT



Steep Peaks during equinox, Low valleys during solstices

TIE–GCM Number Densities, 400 km, 2.5° lat, 0° lon, 00 UT

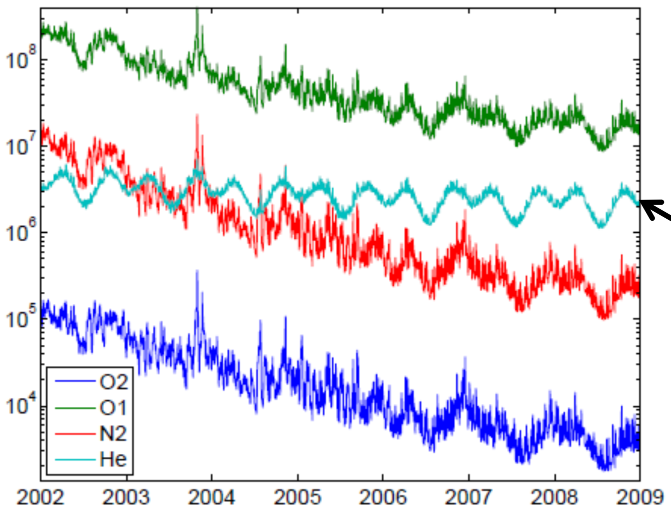


Non-Escaping Flux UBC:

Less dramatic Peaks/Valleys. More consistent w/ MSIS

MSIS

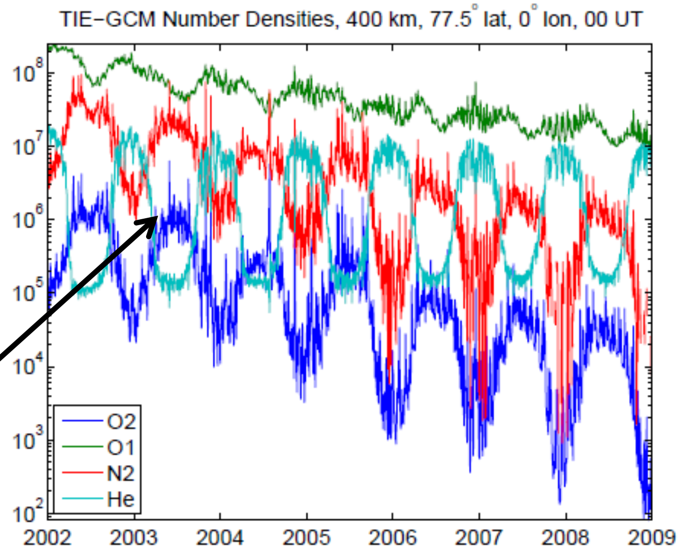
MSIS Number Densities, 400 km, 2.5° lat, 0° lon, 00 UT



Large annual oscillation in MSIS is not apparent in either version of TIE-GCM

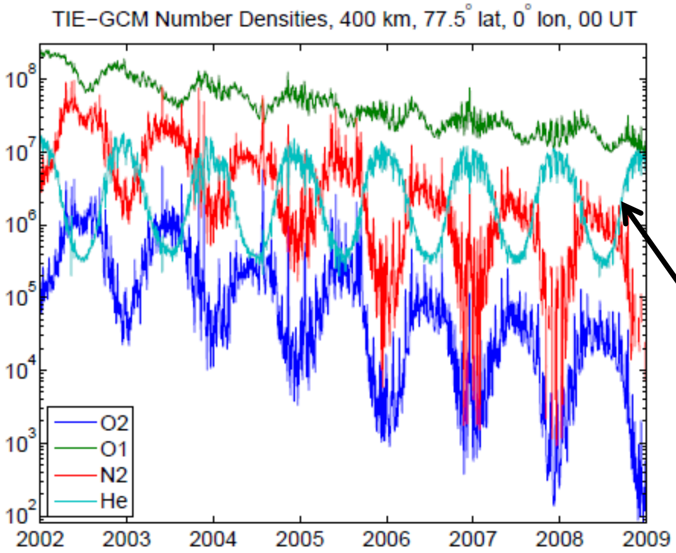
Solar Cycle Comparison (near north pole)

Zero Diffusive Flux UBC:


TIE−GCM Number Densities, 400 km, 77.5° lat, 0° lon, 00 UT

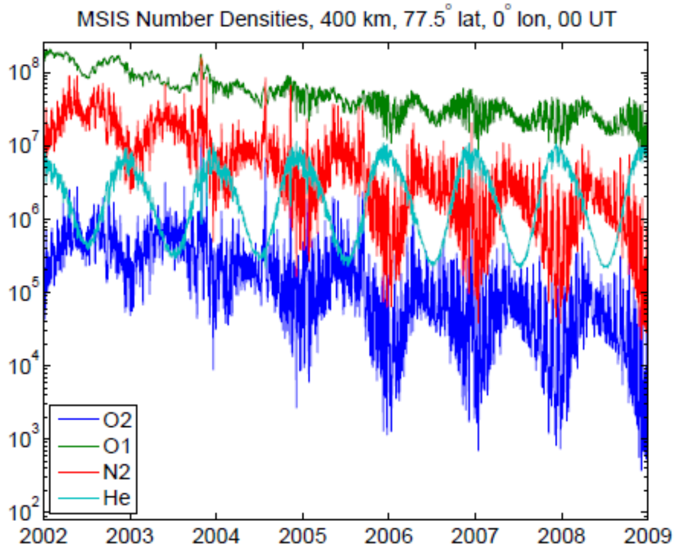
Quick/steep transition during equinox

Non-Escaping Flux UBC:


TIE−GCM Number Densities, 400 km, 77.5° lat, 0° lon, 00 UT

Slope is much more consistent w/ MSIS

MSIS

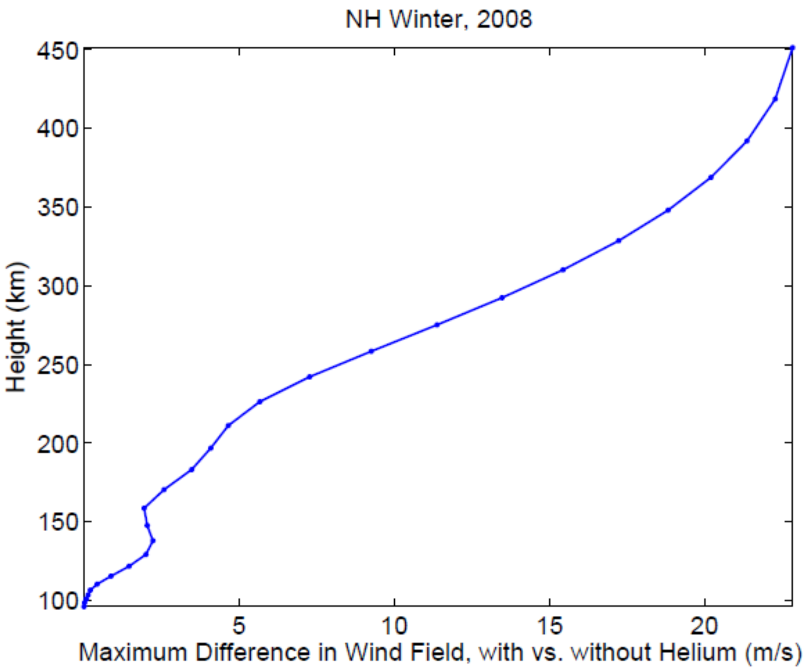

MSIS Number Densities, 400 km, 77.5° lat, 0° lon, 00 UT

Global Max. Difference in Winds

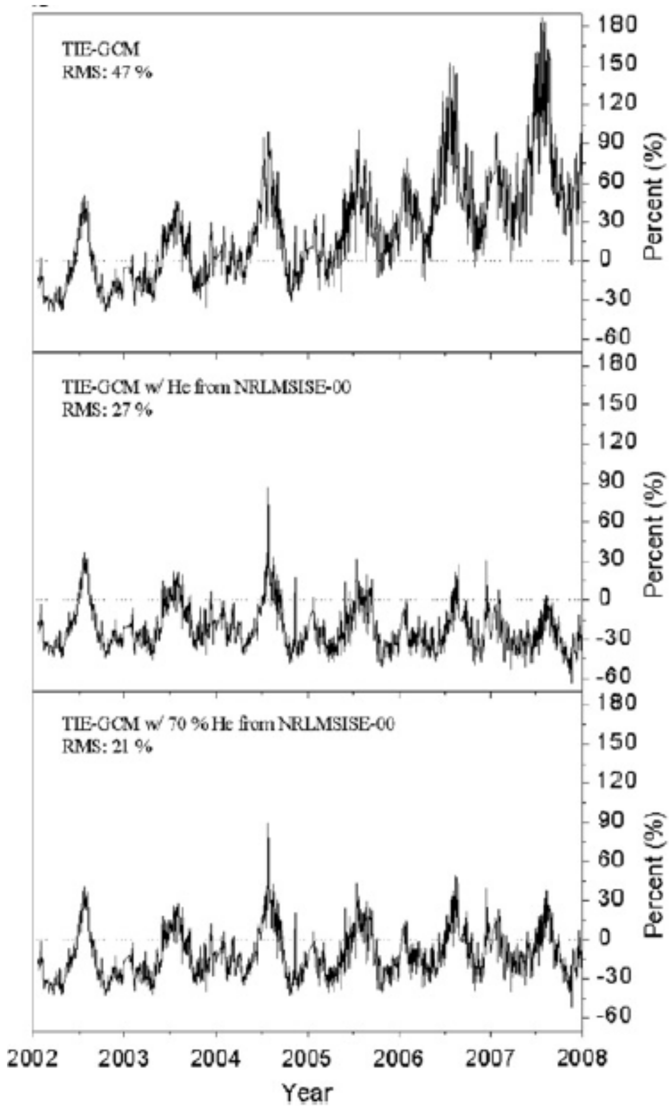
Dec. 2008

Helium sets up a general winter-to-summer perturbation wind at high altitudes:

- 5 m/s @ 200km altitude
- 15-25 m/s above 300km altitude



Revisit of Kim et al. [2011] Study

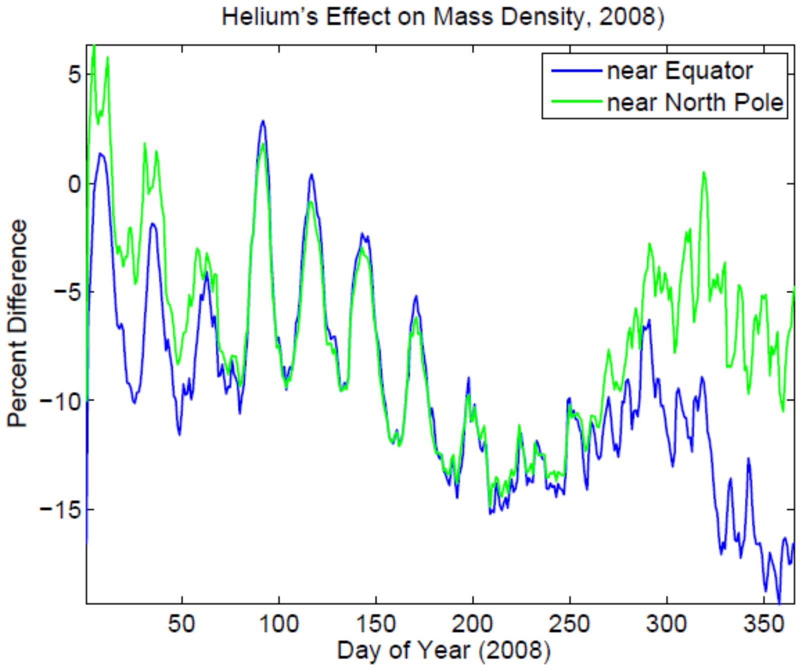


Premise:
Using MSIS Helium, specific heat, thermal conductivity, and molecular viscosity is updated within TIE-GCM

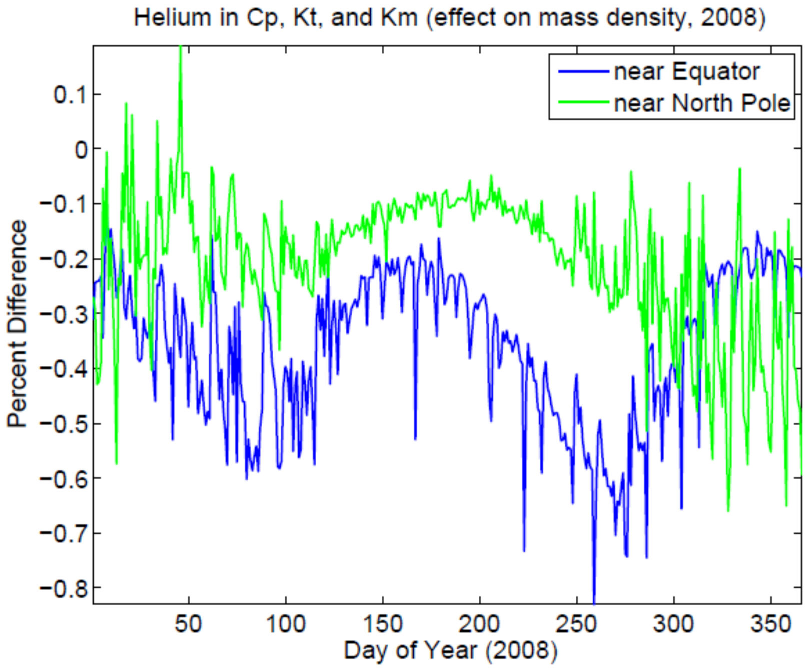
Outcome:
RMS error with CHAMP density measurements improves from 47% to 21%

Revisit of Kim et al. [2011] Study

Recalculating Mass Density after adding the effect of Helium on the mean mass (@ 400 km)



Recalculating Mass Density after adding the effect of Helium on Cp, Kt, Km (@ 400 km)



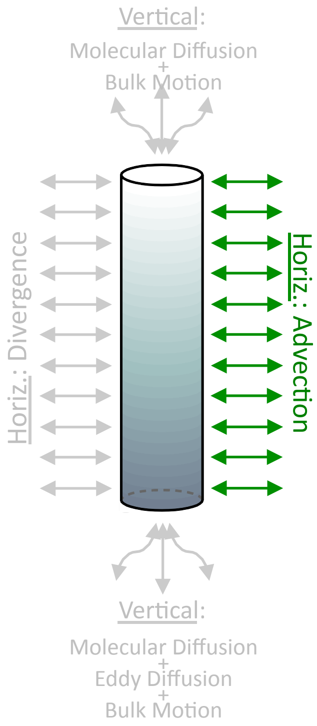
Largest Effect:
Helium's effect on mass density via changes in mean mass/scale height are responsible for most of the differences

Smaller Effect:
Helium's effect on mass density via changes thermodynamic properties are an order of magnitude less effective

Helium Phenomenology

Horizontal Processes: Advection

- The advection term opposes the build-up of helium in the winter hemisphere
- Builds-up (depletes) helium in pre-(post-)sunrise local times during solstice

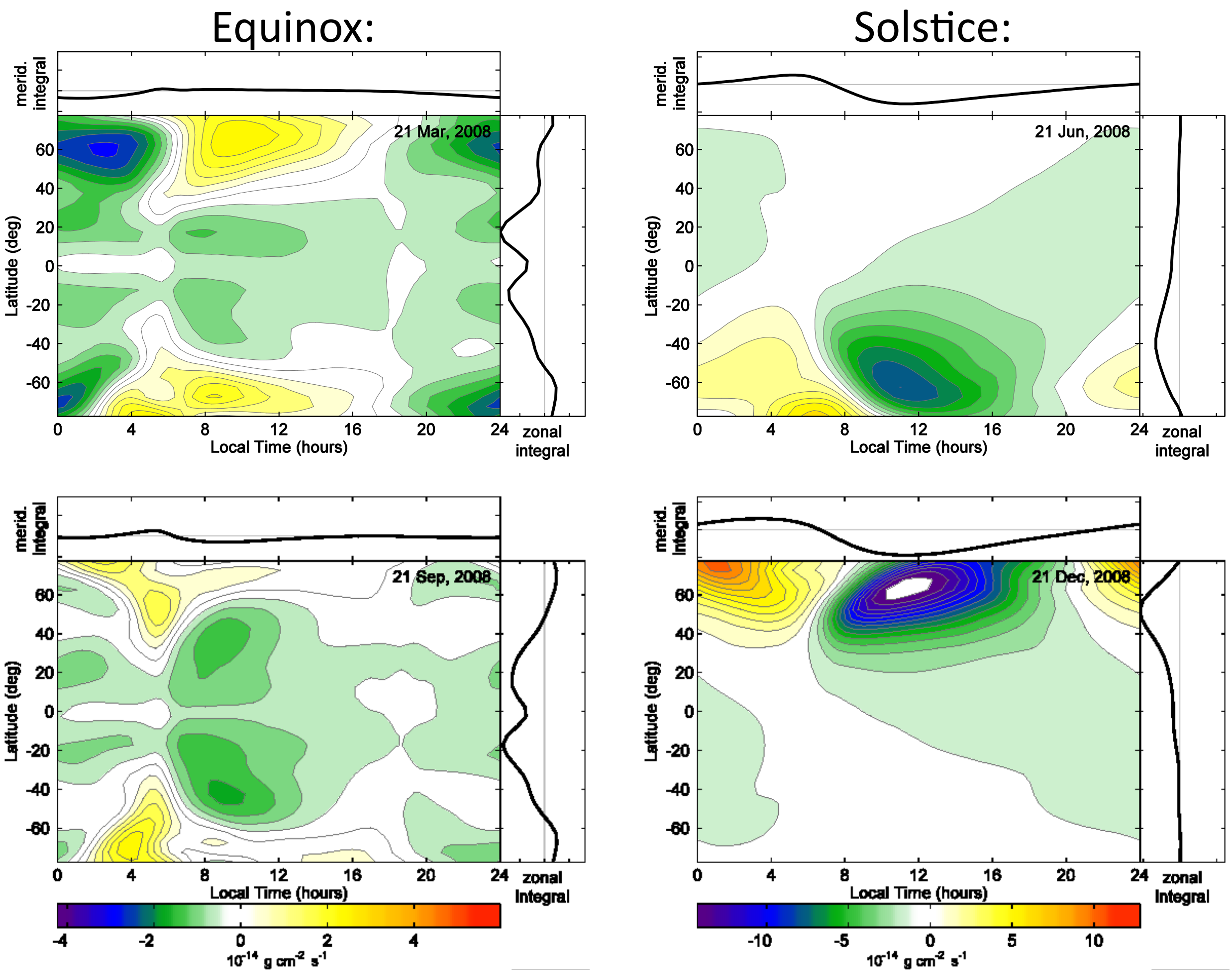

Vertical:
Molecular Diffusion
+
Bulk Motion

Horiz.: Divergence

Horiz.: Advection

Vertical:
Molecular Diffusion
+
Eddy Diffusion
+
Bulk Motion

Rate of Mass Accumulation within a Column


Equinox:

Solstice:

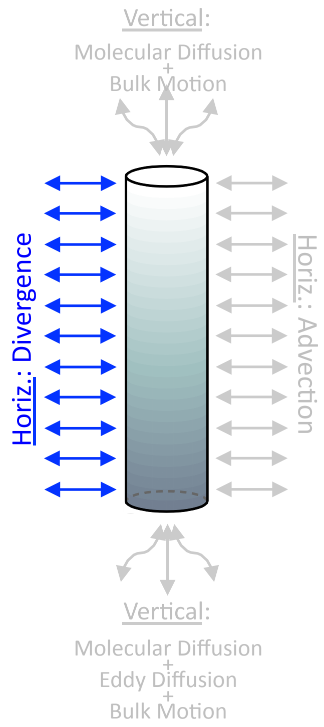
notes: (1) Mass rates are averaged over the course of a day

(2) All equinox plots for slides 11-13 share common color and axis scales, as do all solstice plots

Helium Phenomenology

Horizontal Processes: Divergence

- The divergence term accumulates helium in the winter hemisphere
- Builds-up (depletes) helium in pre-(post-)sunrise local times during all seasons



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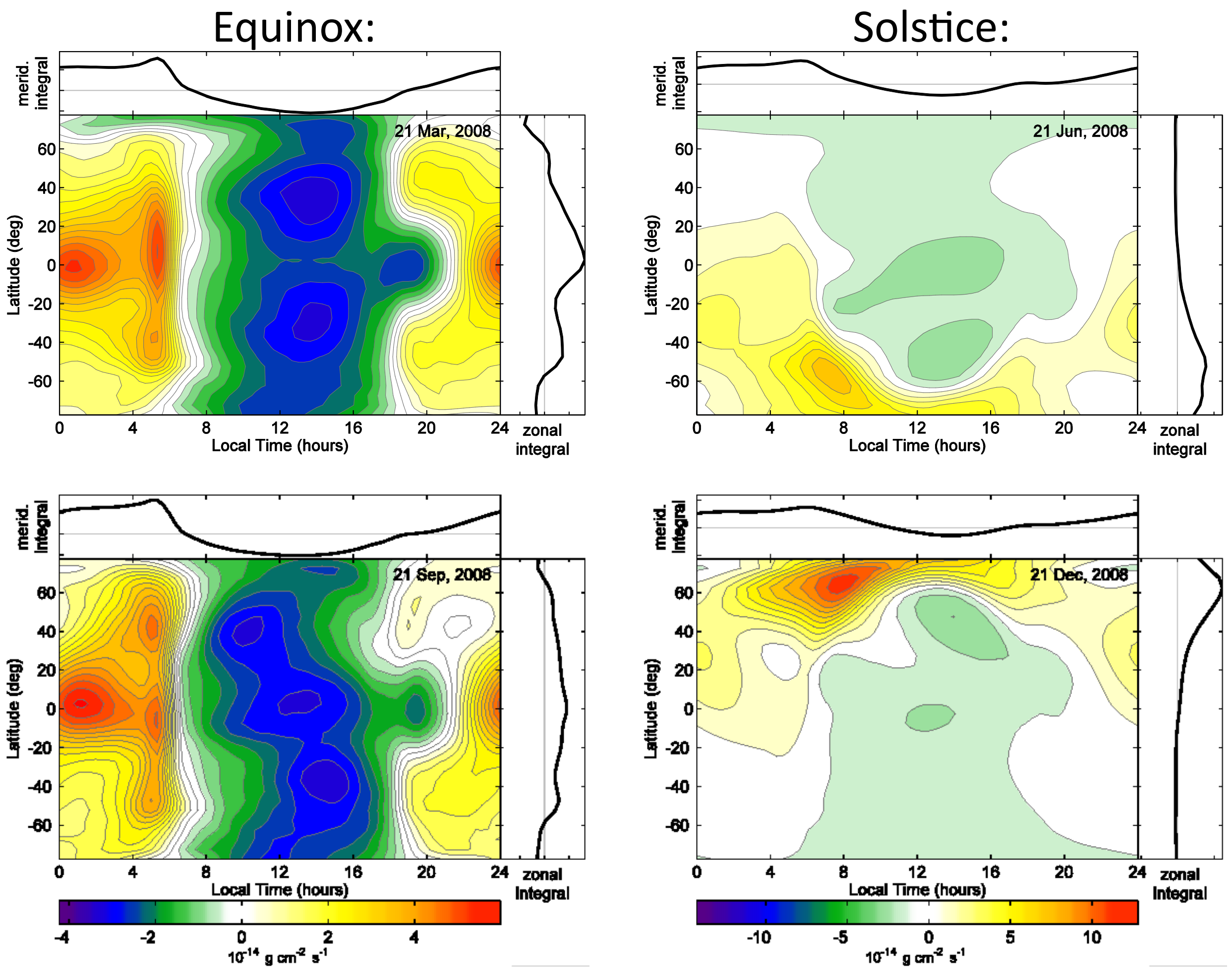
Equinox:

Solstice:

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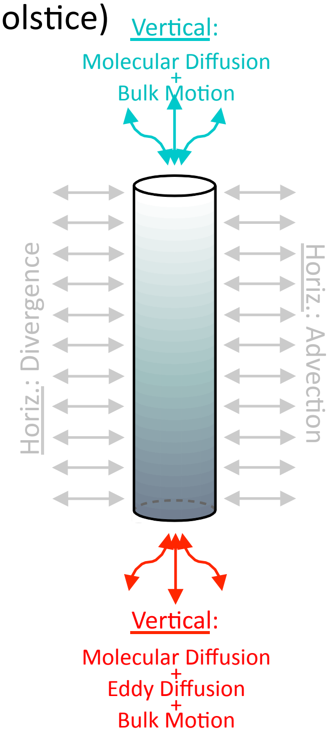
Helium Phenomenology

Vertical Processes

- Vertical motion depletes column helium content in the winter hemisphere
- Helium flux is dominated by lower bulk motion (upper molecular diffusion) at equinox (solstice)



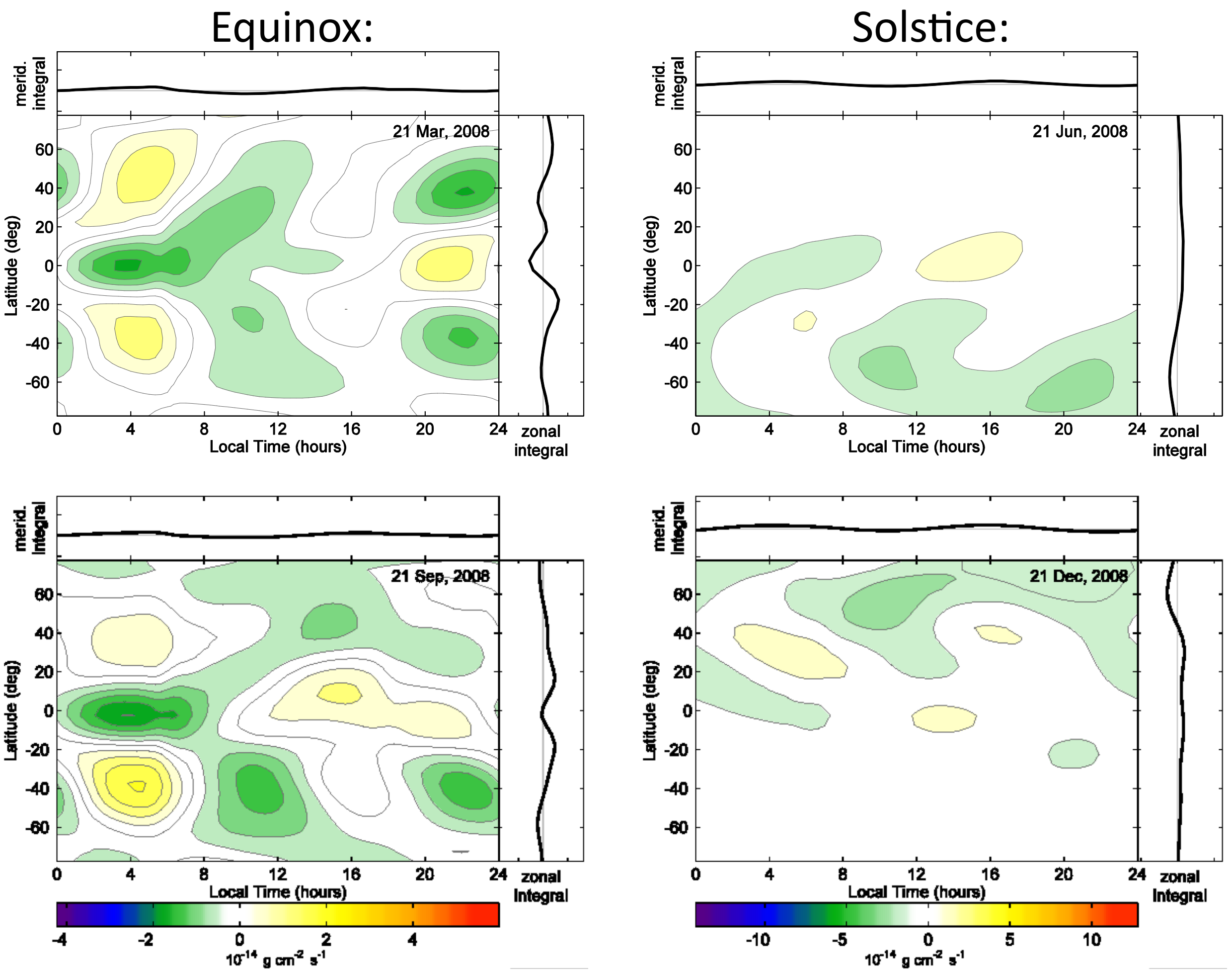
Vertical:
Molecular Diffusion
+
Bulk Motion

Horiz.: Divergence

Horiz.: Advection

Vertical:
Molecular Diffusion
+
Eddy Diffusion
+
Bulk Motion

Rate of Mass Accumulation within a Column



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Solstice:

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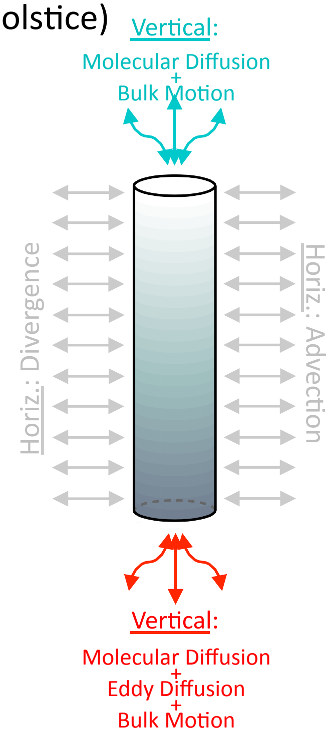

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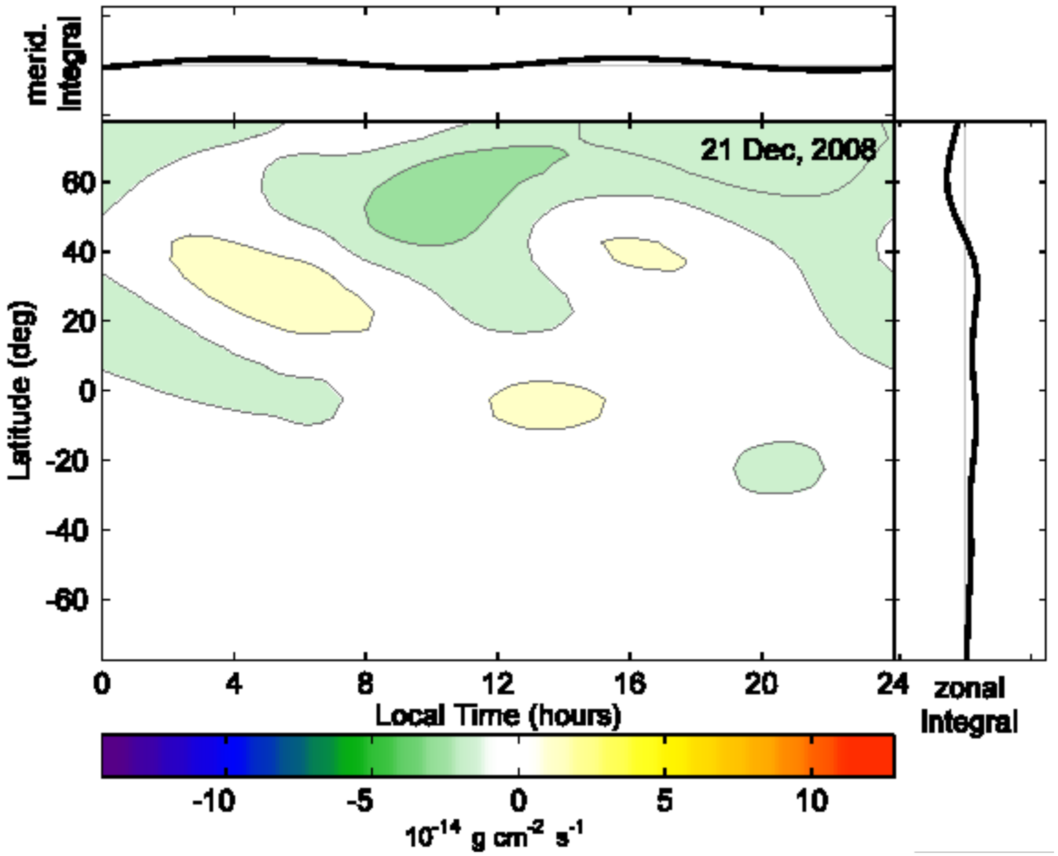

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Conclusions

- Including Helium as a major species in TIE-GCM has significant implications for the upper thermosphere:
    - Vertical structure
    - Mass Density
    - Geopotential height/pressure profile
    - Winds
    - Seasonal/Local Time
- Horizontal and vertical transport of a species entrained within the background circulation are equally important and directly linked
- Horizontal divergence – a term considered implicitly by the composition equation – is responsible for the seasonal helium distribution
    - Formation of the winter bulge is a direct result of interhemispheric transport, and cannot be accomplished through vertical motion alone

Future Development

Features to include/remedy:

- Update photo-absorption and photoionization of Helium
  - Currently treated as excess N_2 by qrj.F (i.e., qrj.F is unmodified)
  - Change n2, and 1e-5 to ‘small’ (make ‘small’ global)
  - Quenchfactor=factor/(mbar*tn)
- Check for n2 (elden.F)
- Check slant column/n2/mbar (chapman.F)
- Check (settei.F) for n2 calculations
- Update ion/neutral conductivities (lambdas.F?)
- Update O+ ambipolar diffusion (diffuse subroutine?)
- Check comp_n2d.F for mbar calculation
- Check dt.F for n2/mbar calculations
- Check aurora.F for n2

Future Development (con't)

Features to include/remedy:

- Add Production/Loss terms for Helium
- Add minor neutrals/ions: He^+, metastable $He(2^3S)$, others?
- Add effects of helium to the time-dependent minor species equation (i.e. N(4S) and NO)
- N_2 near upper boundary suffers from artificially low values during solstices in vicinity of winter helium bulge
- Add ability to use MPI
- Check for compliance with NCAR software standards
- Start branch for TIE-GCM-Helium code
- Validation

Questions?