Coupling Fluid and Particle Atmospheric Models to Simulate the Thermosphere-Exosphere Transition Region

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I. Background and Objective

Background: The atmosphere becomes exponentially less dense with altitude. In the transition region of the upper thermosphere and lower exosphere, collisions between atoms and molecules cannot be ignored, but the gas is no longer in a continuum state [3]. Changes in the physics of the atmosphere near the exobase necessitate a change in the way we model these regions.

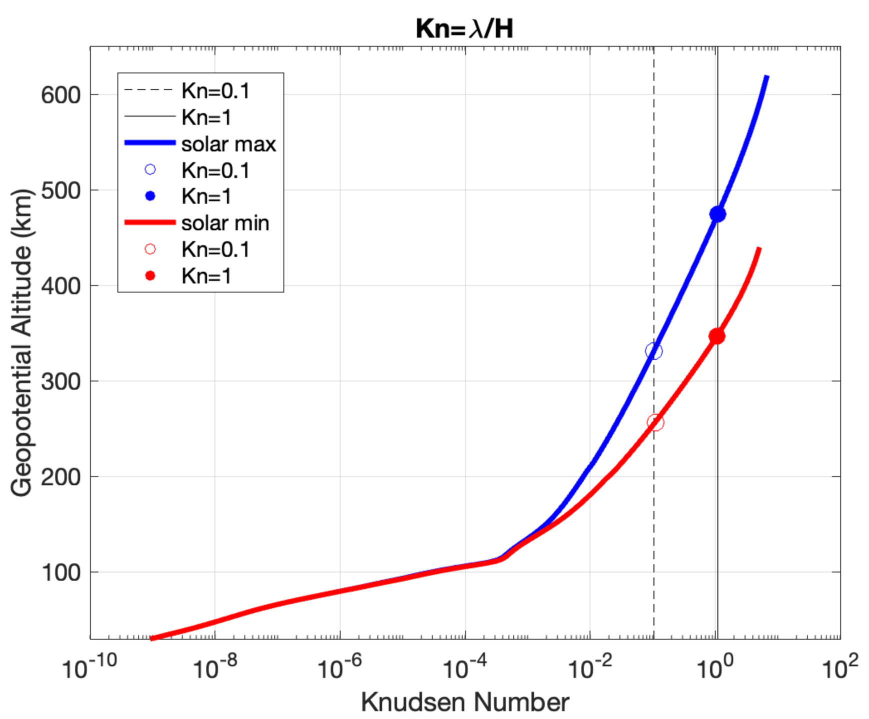


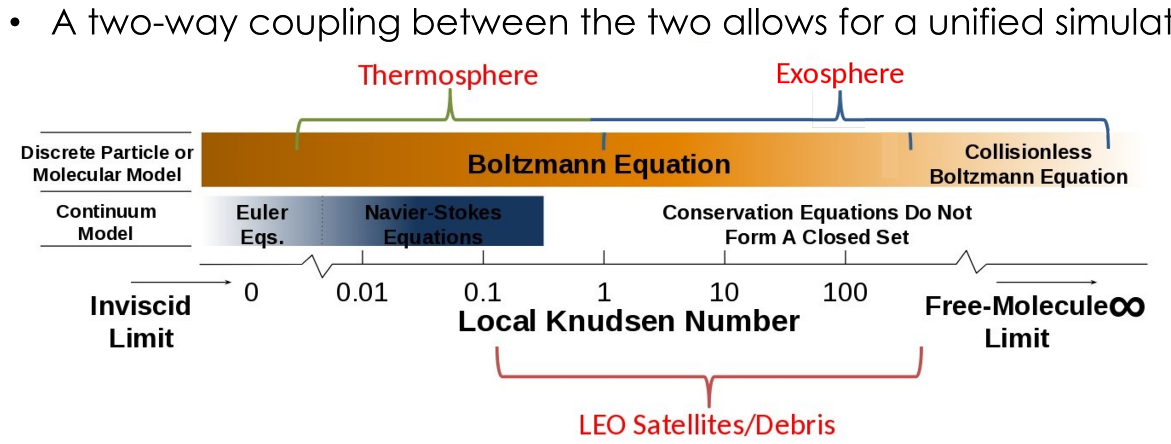
Fig 1. The Knudsen number (Kn), mean free path divided by density scale height, for different solar conditions. The transition region ($0.01 < Kn < 10$), where infrequent collisions disrupt the equilibrium of the gas, encompasses the upper thermosphere through the lower exosphere.

Problem: As the atmosphere becomes increasingly less collisional, fluid approximations used to describe these regions begin to break down

- Adding higher order terms to the fluid equations becomes complex and computationally expensive
- A direct simulation Monte Carlo (DSMC) scheme can model gas dynamics in all atmospheric regimes, but is limited by computational expense in dense regions [4]

Approach: Create coupled fluid-particle model of the atmosphere extending from 30 km through the exosphere

- A DSMC simulation is used to model the dynamics of the exosphere
- A fluid simulation models the dynamics of the thermosphere and below
- A two-way coupling between the two allows for a unified simulation



Left: Fig 2. Applicability of equation sets to an atmospheric regime based on Knudsen number. Modified from [2].

II. Significance

- Significantly increases the range of altitudes that can be simulated
- Improves understanding of fluctuations in atmospheric density that can affect the trajectories of spacecraft in LEO [8]
- Removes the need for simplifying assumptions about the dynamics of the thermosphere / exosphere transition (e.g., a Maxwellian velocity distribution directly below the exobase and a collisionless state directly above [5])

III. Models

TIME-GCM [6]

- Solves differential momentum, continuity and energy equations using finite differencing
  - Neutrals and ions
  - Assumption of hydrostatic equilibrium
- Output on constant pressure levels
- Grid: 2.5-degree resolution
- Altitude range: 32 to ~400-800 km, depending on solar cycle

MONACO

- DSMC model for individual particles using variable hard sphere collisional model
  - Neutral species H, He, N2, O
  - Gravity, Coriolis and centrifugal forces
- Output on constant altitude
- Grid: cubed sphere (variable resolution)
- Altitude range: 400 to 20,000 km

Visualization

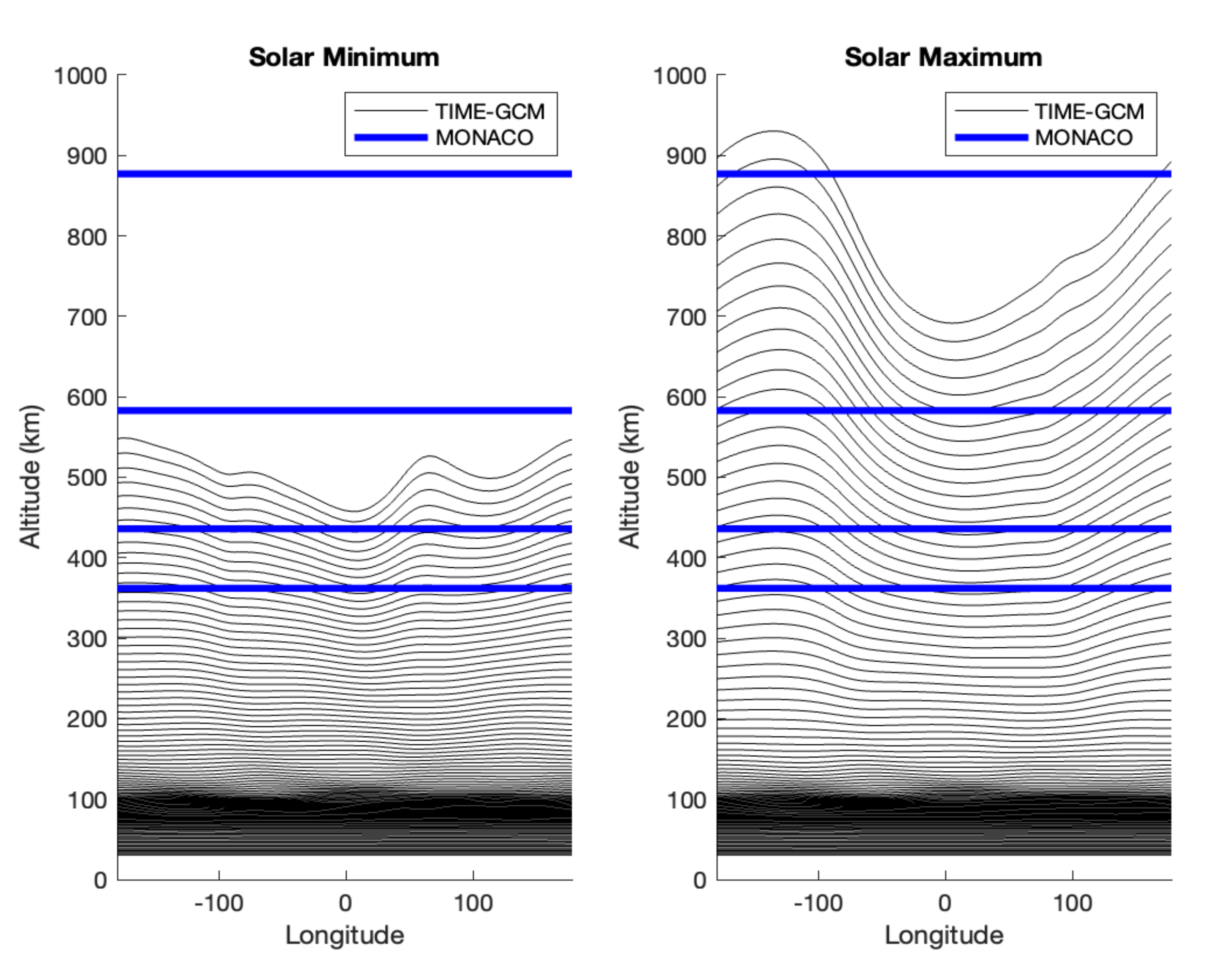


Fig 3. Vertical grids for TIME-GCM and MONACO from 0-1000 km; upper levels of MONACO not shown

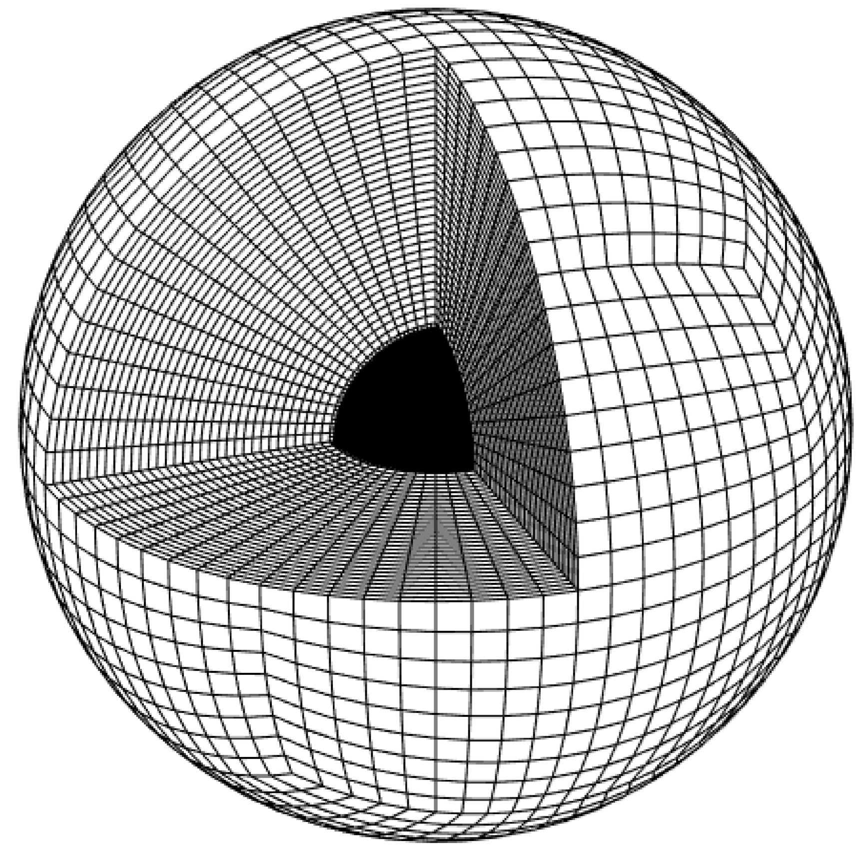


Fig 4. A "cubed-sphere" grid forms each layer of cells (Sutton 2023).

IV. Coupling

TIME-GCM delivers atmospheric state (wind, density, temperature) at 362 km → Output converted H, He, O and N_2 particle densities and velocities → MONACO lower boundary set using initialized particles

TIME-GCM → MONACO Coupling Implementation

- TIME-GCM used to calculate temperatures, winds and number densities for MONACO lower boundary

MONACO delivers hydrogen flux at location of TIME-GCM upper boundary → Output converted into spherical harmonic expansion → TIME-GCM upper boundary condition set using SH expansion of flux output

MONACO → TIME-GCM Coupling Implementation

- Replace analytical escape flux at TIME-GCM upper boundary with H flux from MONACO

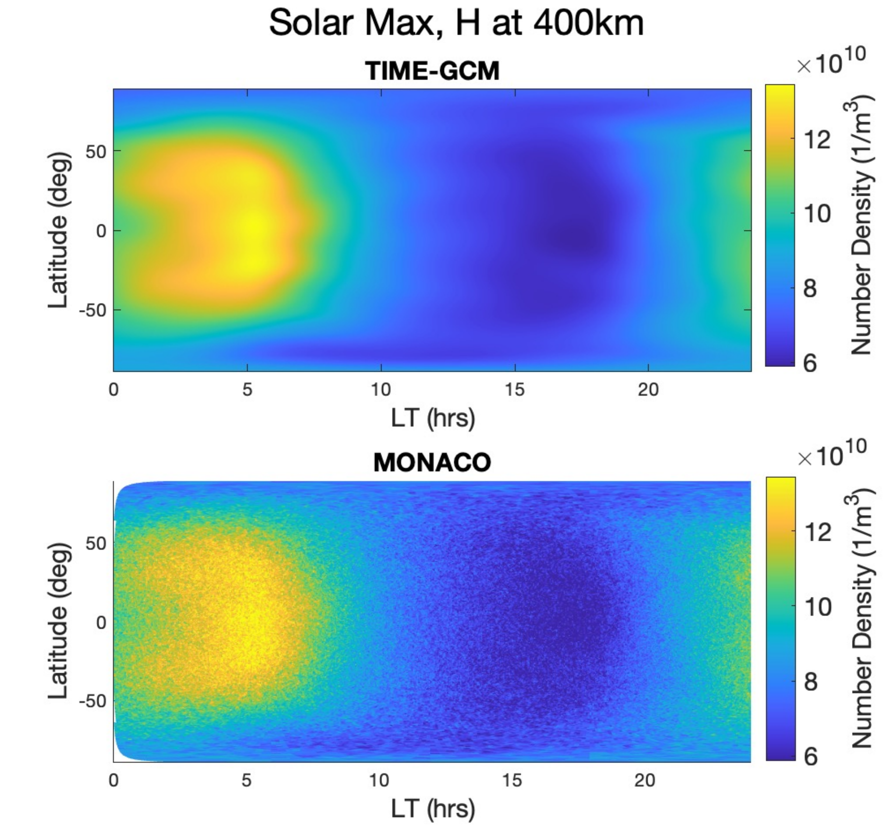
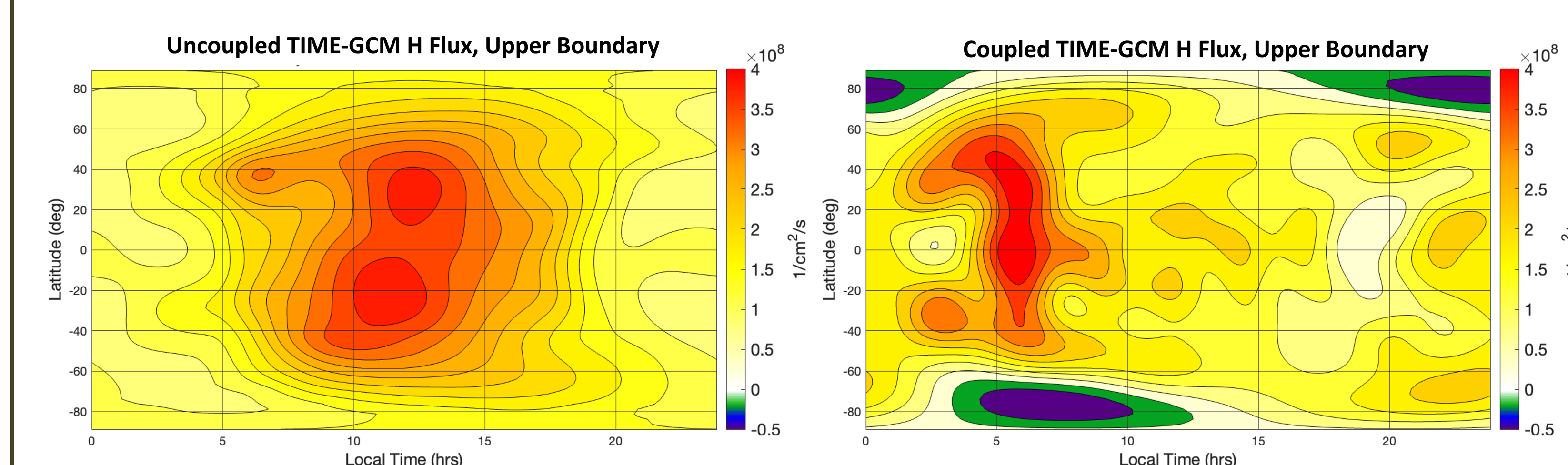


Fig 5. Hydrogen number densities at 400 km for TIME-GCM (top) and MONACO (bottom)

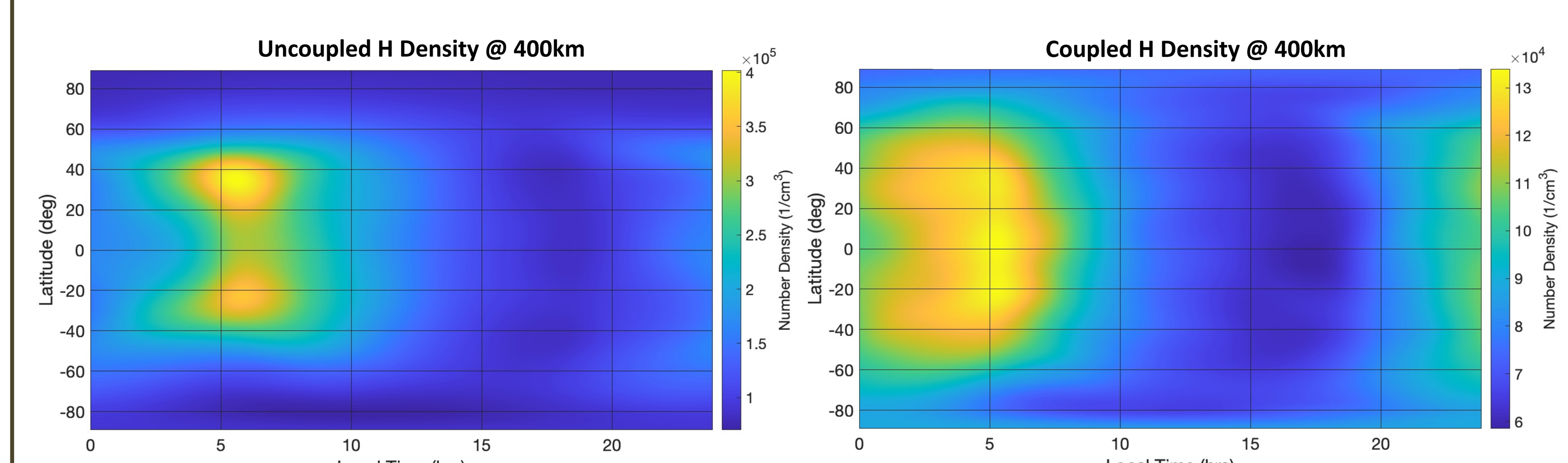
V. Findings and Coupling Impacts



1. Coupling allows TIME-GCM to account for effects of lateral H transport

- Coupled TIME-GCM upper boundary flux reflects lateral transport of H near exobase, which is necessary to accurately simulate H density [7]
- Magnitude of flux remains similar
- Peak flux moves to earlier local time

Left: Fig 6. H flux through TIME-GCM upper boundary for solar max, March equinox. Left: uncoupled. Right: 2-way coupling.



2. Equilibrium between exosphere and thermosphere models forces change in spatial distribution of H from thermosphere through exobase

- Peak H density in coupled model decreases, becomes more diffuse due to lateral transport
- Greater relative H concentration towards equator

Left: Fig 7. H number density for solar max, March equinox. Left: uncoupled. Right: 2-way coupling. Notice differing color scales.

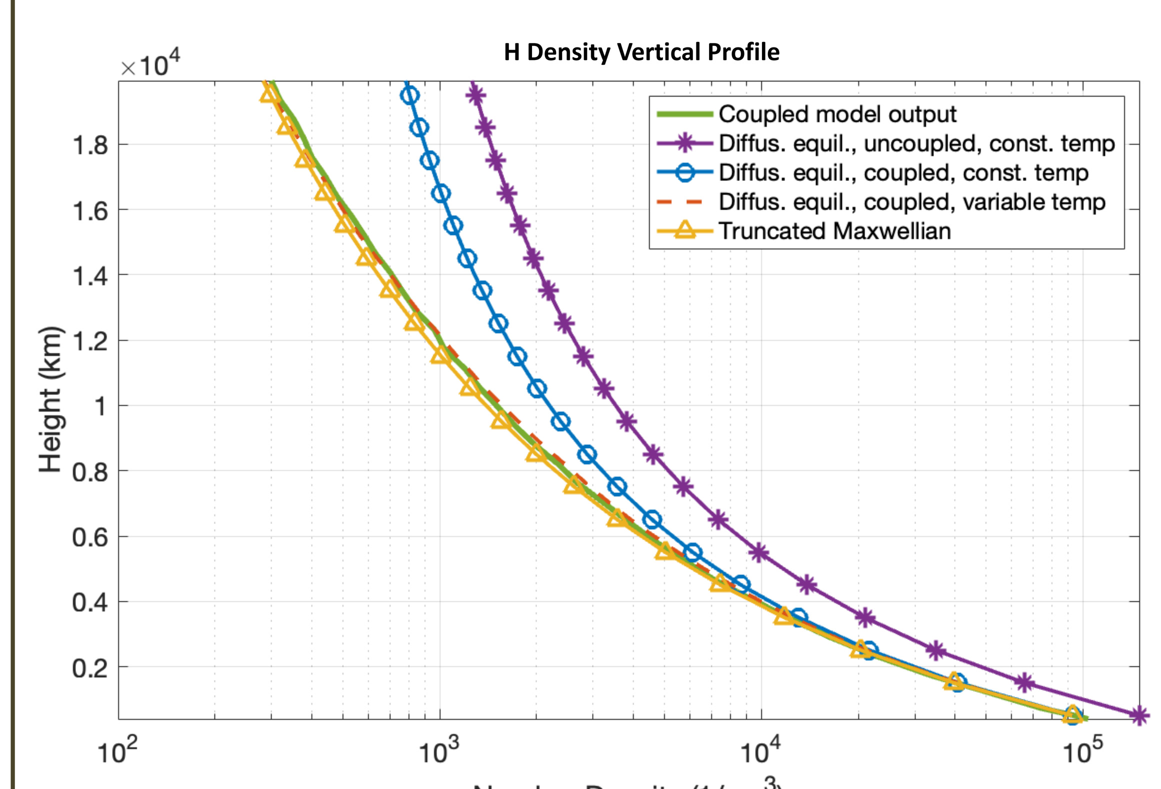


Fig 8. Vertical distribution of H density 500-20,000 km (latitude = 0°, local time = 0 hr)

3. Self-consistent exobase H density distribution necessary to predict vertical H profile

In reference to fig. 8:

- **Green line**: vertical profile of exospheric H density from coupled model
- **Purple stars**: diffusive equilibrium extrapolation using uncoupled model exobase density and constant temperature assumption
  - Ranges 40-80% higher than coupled H density profile over altitudes in figure
- **Blue circles**: diffusive equilibrium extrapolation using coupled model exobase density and constant temperature assumption
  - Diverges from coupled H density profile with altitude
- **Red dashes**: diffusive equilibrium extrapolation using coupled model exobase density and coupled model height-varying temperature
  - Closely follows coupled H density profile
- **Yellow triangles**: a population of ballistic and escaping particles calculated with a truncated Maxwellian velocity distribution [1] using coupled model exobase density and constant temperature
  - Closely follows coupled H density profile

VI. Acknowledgements

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VII. References

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