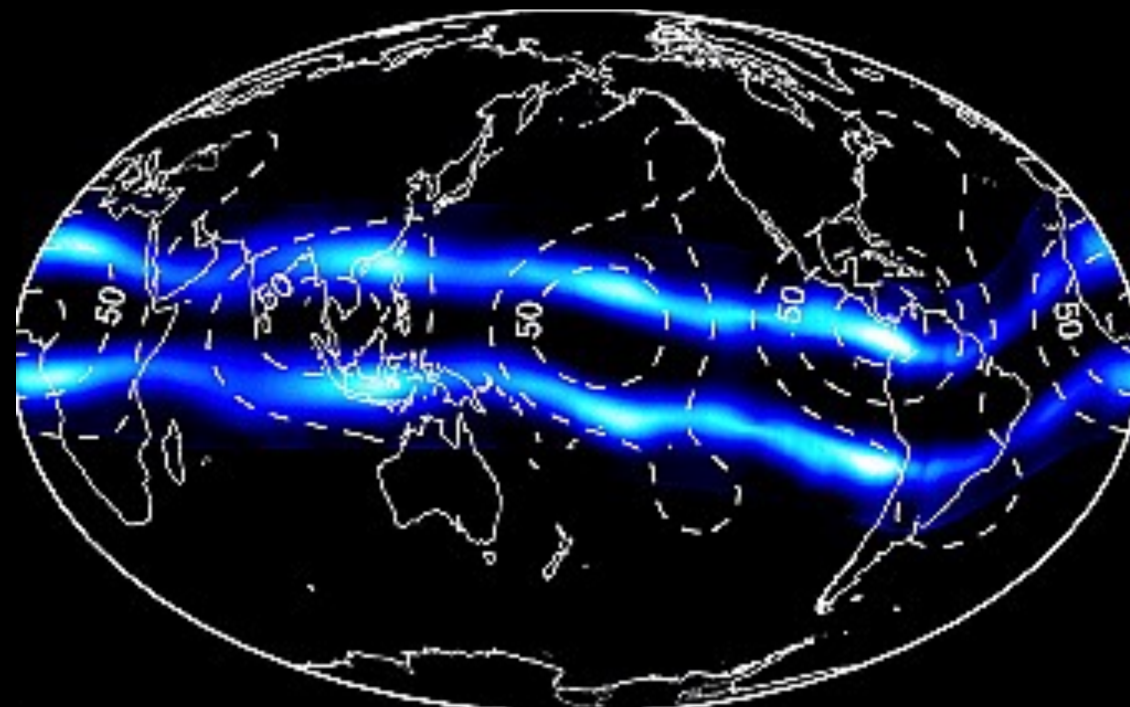
A Whole Earth System View for Heliophysics: A NASA/GSFC Perspective

F. Sassi

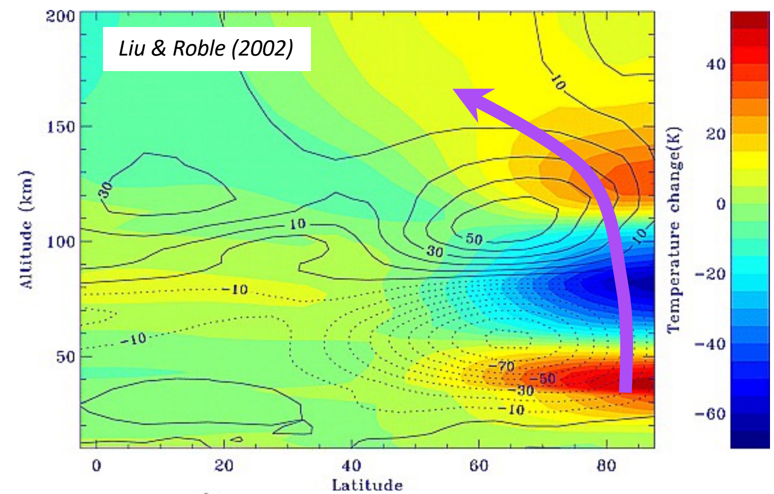
With contributions from: S. Pawson & R. Lieberman

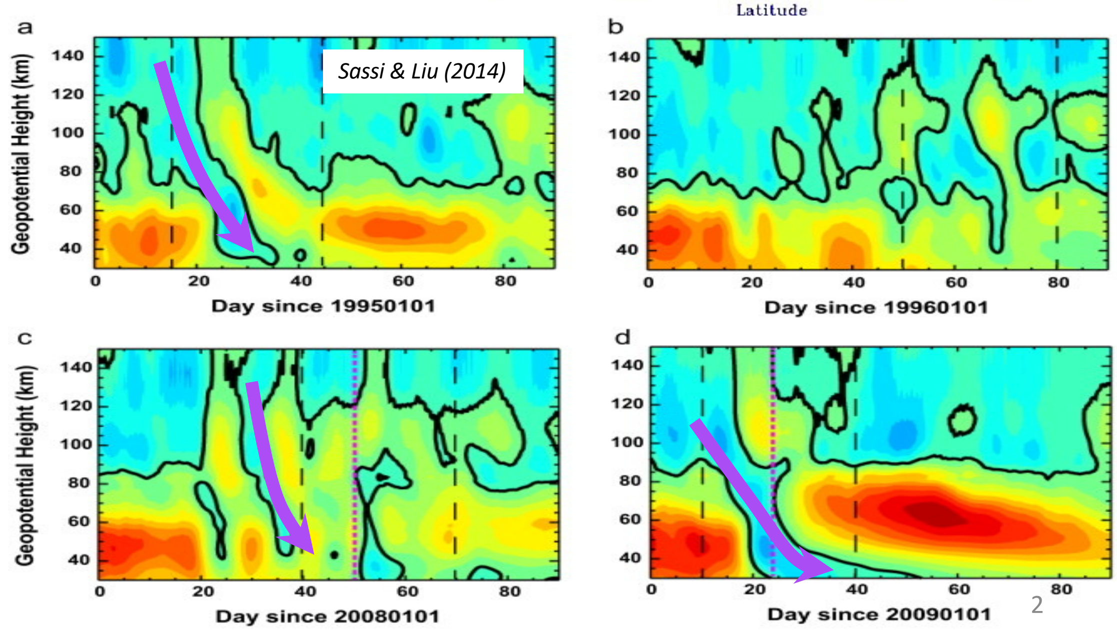


Immel et al., 2006

What is Whole Atmosphere Modeling?

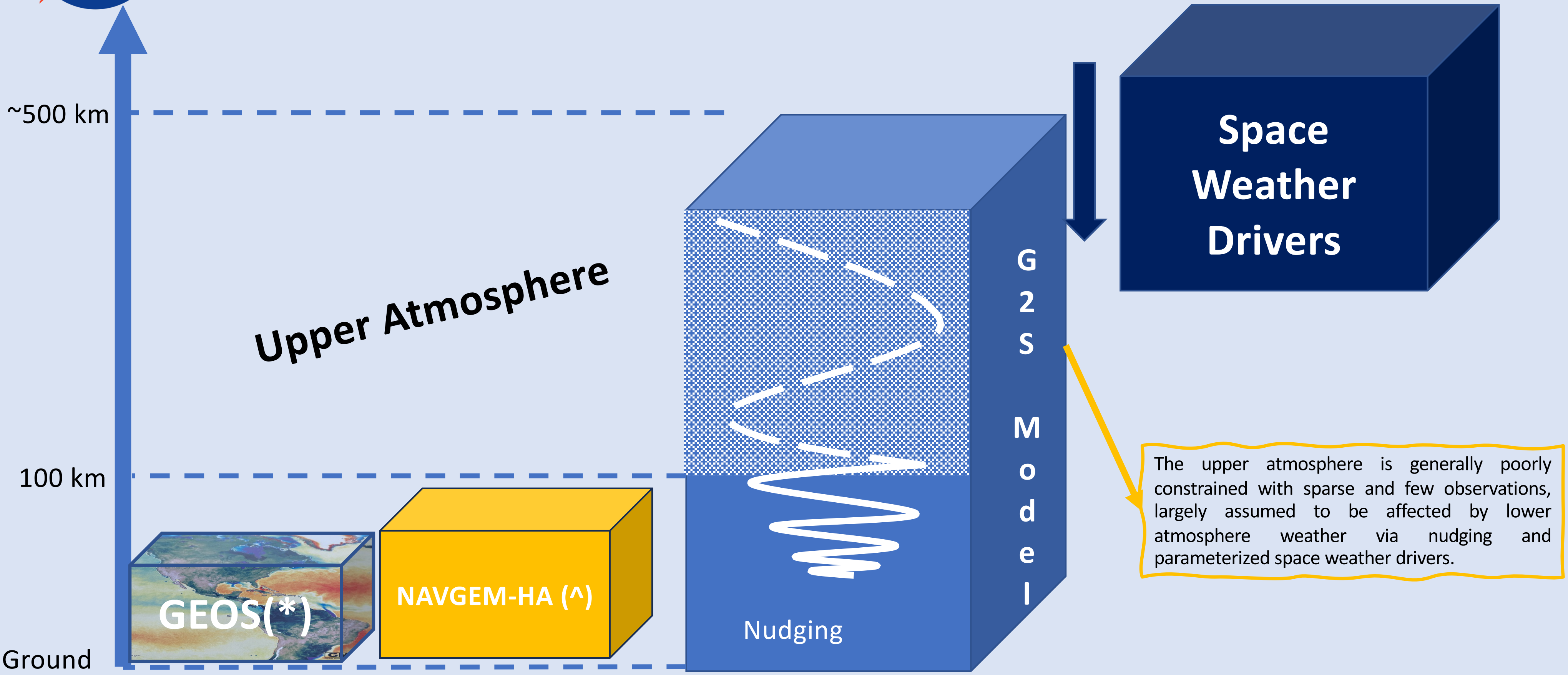
- It started with an idea of Roble in the late 1990s at NCAR
  - ➢ Coupling the NCAR lower atmosphere CCM3(*) and upper atmosphere TIME/GCM(**) models demonstrated that lower atmosphere weather influences the upper atmosphere
  - ➢ Prime demonstration during SSWs(^): upward and downward influences
- Whole atmosphere models have come out of age at NOAA, NRL, NCAR
  - ➢ NASA has been absent
- Understanding the whole atmosphere (from ground to space) is the biggest challenge we have right now to enable:
  - ➢ Efficient use of observations, models and tools by the heliophysics community
  - ➢ A new vision of "whole Earth system" as opposed to silos.
  - ➢ Scientific discoveries on short (space weather), medium (S2S), and long (climate) time scales.





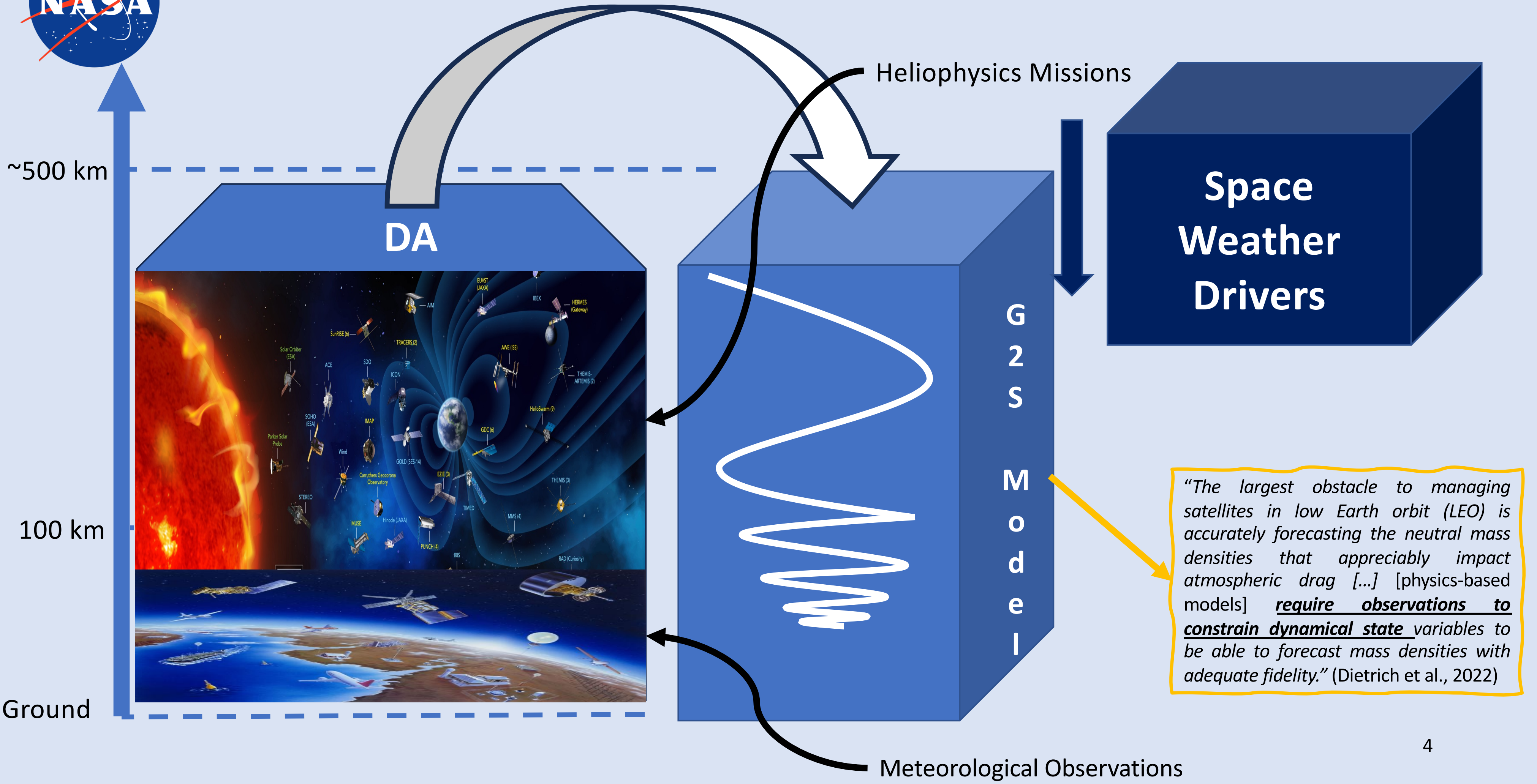
(*) Community Climate Model v3
(**) Thermosphere Ionosphere Mesosphere Electrodynamics/General Circulation Model
(^) Sudden Stratospheric Warming

Current State of the Art for Whole Atmosphere Modeling - 1



(*) Goddard Earth Observing System (^) Navy Global Environmental Model for High Altitudes

Current State of the Art for Whole Atmosphere Modeling - 2



"The largest obstacle to managing satellites in low Earth orbit (LEO) is accurately forecasting the neutral mass densities that appreciably impact atmospheric drag […] [physics-based models] ***require observations to constrain dynamical state*** *variables to be able to forecast mass densities with adequate fidelity."* (Dietrich et al., 2022)

Key Science and Mission Drivers

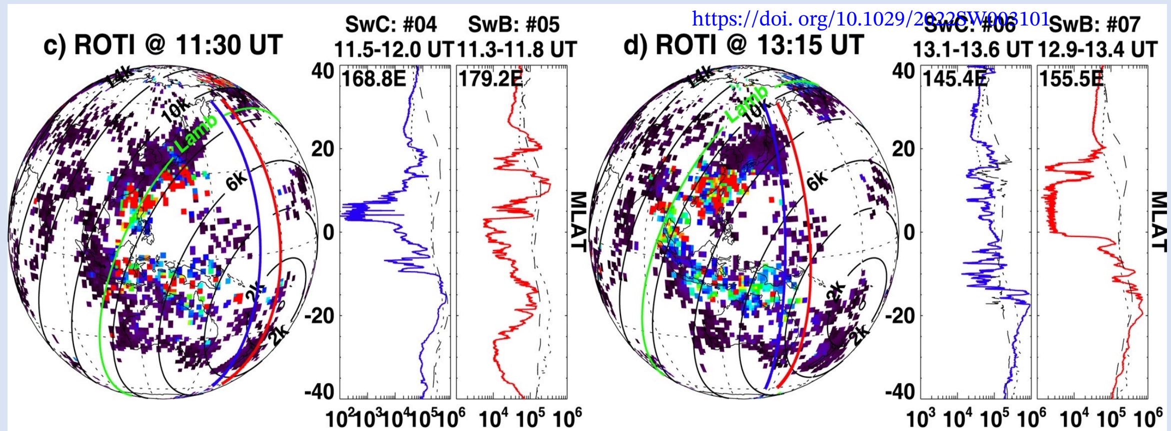
Natural Disasters

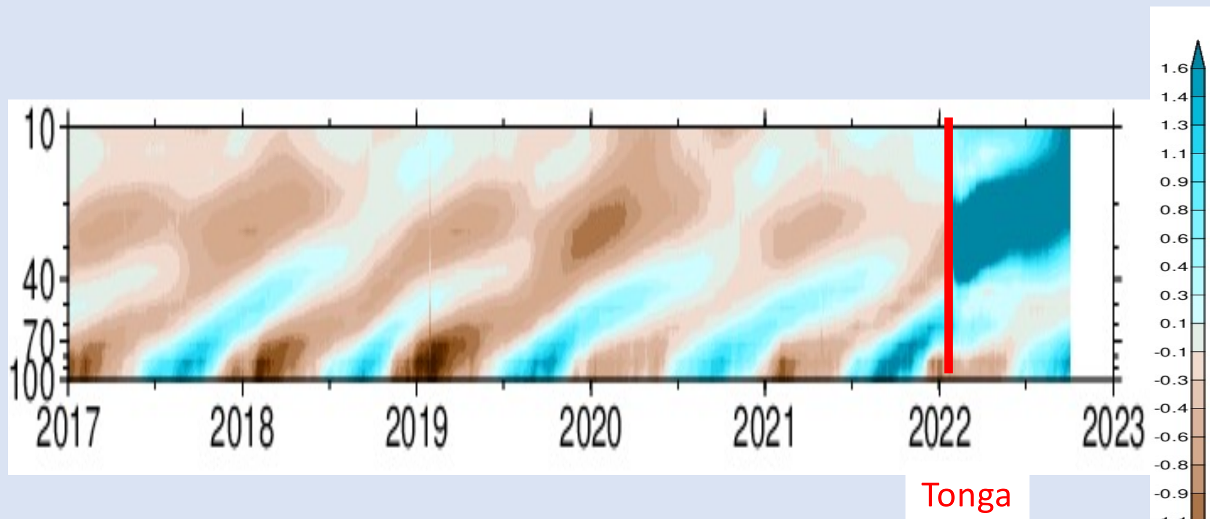
Explosive volcanic eruptions.

Not only Tonga but also Pinatubo and Krakatoa.

Climate impacts: Injection of water vapor (~58,000 Olympic-size pools) in the middle atmosphere affect radiative balance and chemistry. Because AOA is many years, it continues to this day.

Ground to geospace impacts: massive bite-outs of ionospheric densities driven by shock-acoustic wave-impulses.





H_2O anomalies as captured in the MERRA-2 Stratospheric Composition REanalysis of Aura MLS data (M2-SCREAM) of Wargan et al. (2023).

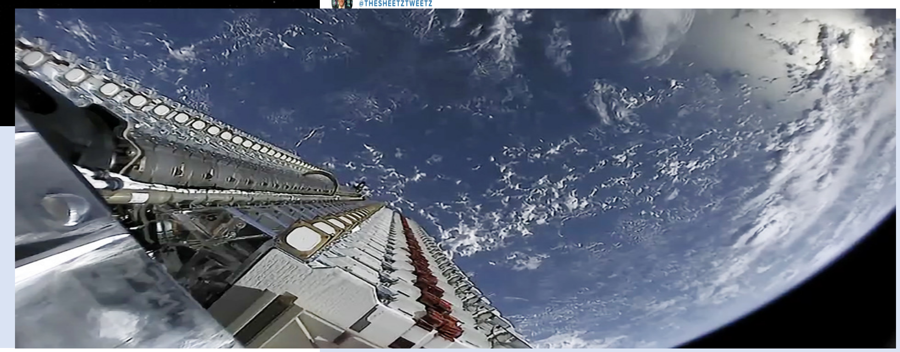
Space Traffic

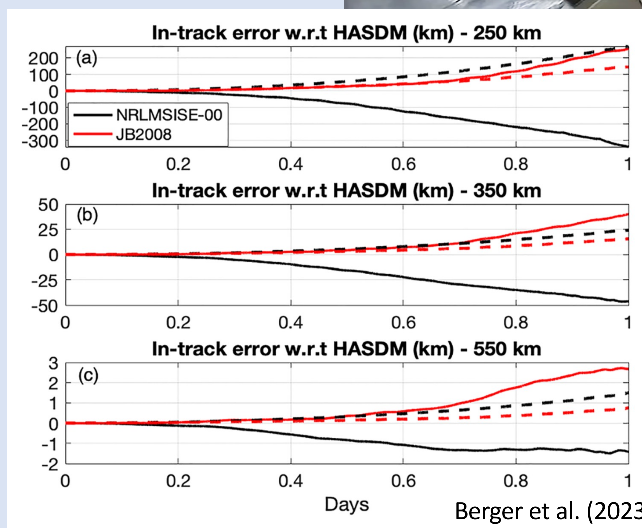
Space industry is fast growing, its revenues estimated to reach $1T by 2040

With increased space traffic in the coming decades, vehicles re-entry and management is critical

Berger et al. (2023): “We conclude that full-physics, data assimilative […] are needed to prevent similar—or worse—orbital system impacts during future geomagnetic storms.

The coupled physics of a system of systems (from magnetosphere to atmosphere) is poorly understood.





Berger et al. (2023)

In-track positional error incurred over 1 day when using the MSISE-00 (black) or JB08 (red) models with respect to HASDM as the reference density model during G1 and G5 geomagnetic storms for a “Starlink-type” satellite in low-drag configuration at (a) 250 km; (b) 350 km; and (c) at 550 km. Results for a G5 geomagnetic storm (solid lines) and a G1 geomagnetic storm (dashed lines) are shown. Note that the underlying thermosphere model for HASDM is the JB08 model; the curves for JB08 error relative to HASDM shown thus reflect the correction of JB08 errors due to data assimilation at any storm level.

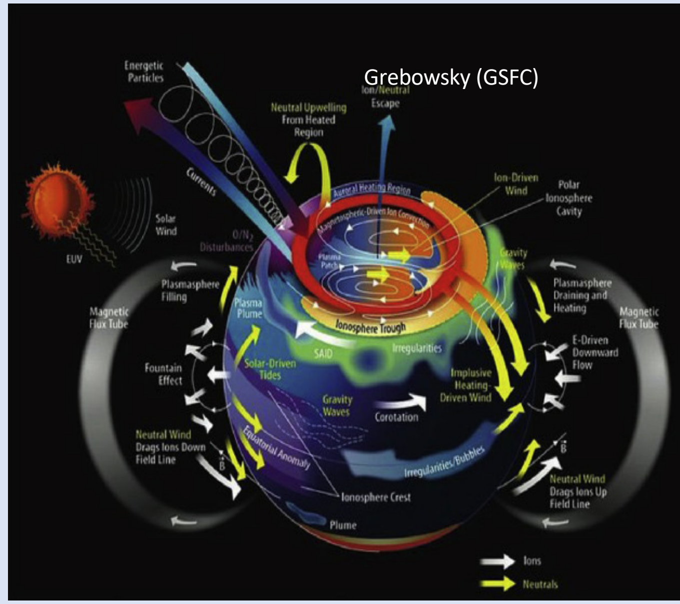
Space Weather

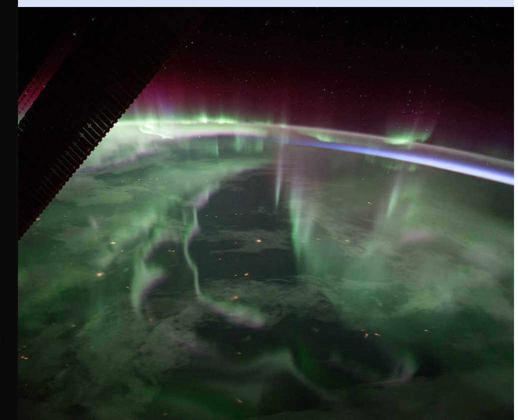
Magnetosphere ionosphere (MI) coupling: auroras are its visible effect.

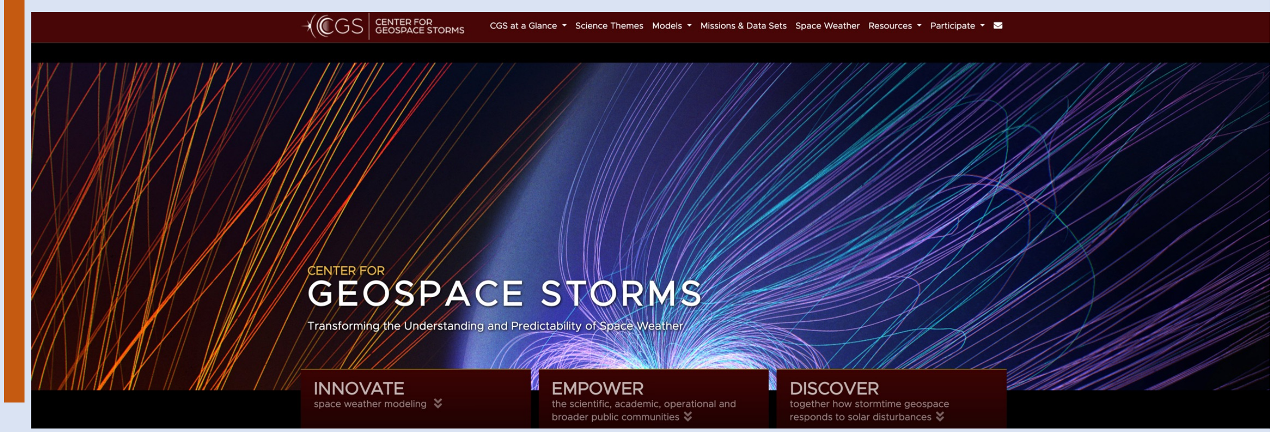
Modeling space weather and its interactions with ITM are mostly *ad hoc.*

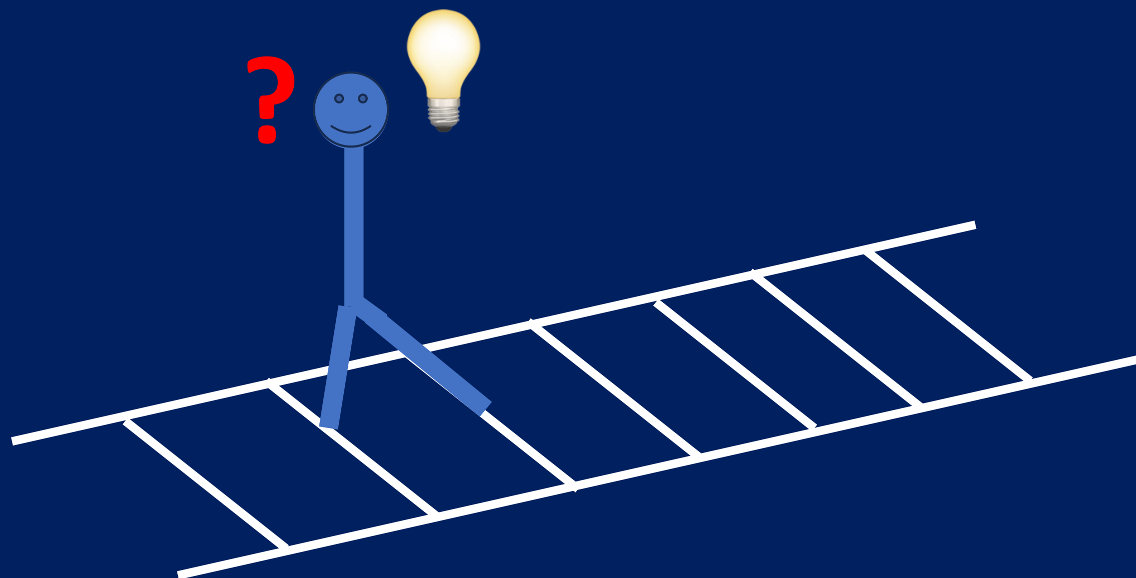
New frontiers are explored at CGS (https://cgs.jhuapl.edu/).

<u>Energetic inputs from the Sun require novel formulation of algorithms to handle numerically disruptive perturbations</u>.









Challenges → Opportunities

1. Define achievable goals
2. Identify necessary resources
3. Establish willing partnerships

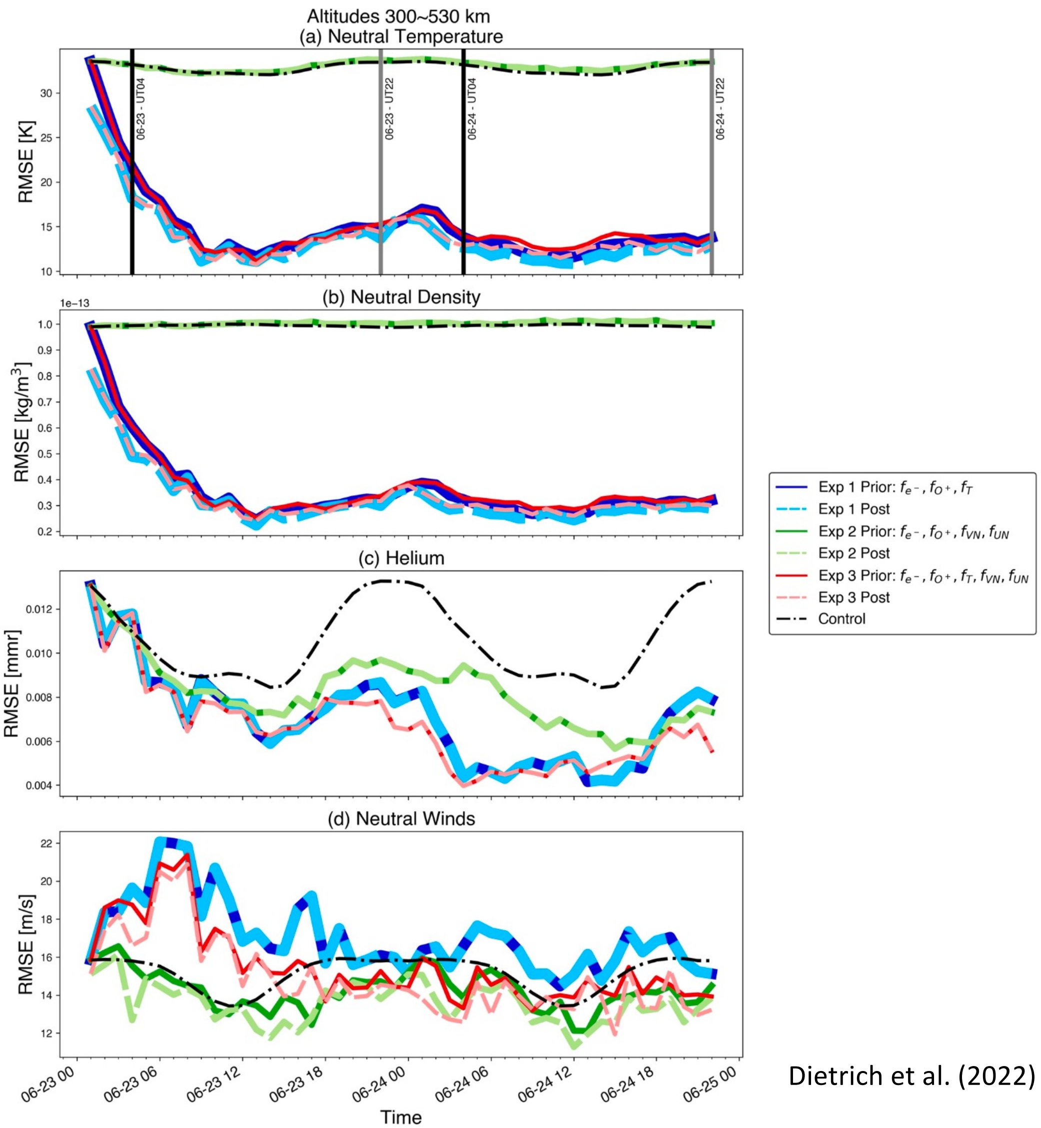
Integration of heliophysics observations with successful Earth system modeling and data assimilation is an economical and effective way to advance understanding of the upper atmosphere and enable science breakthroughs

Lack of Observations - Data Assimilation

Observations of neutral properties in the thermosphere will remain sparse and few for at least the next 10 years.

Dietrich et al. (2022) have shown that orbit error reduction is predominantly achieved through the estimation of neutral densities over neutral winds and drag coefficients using RO data.

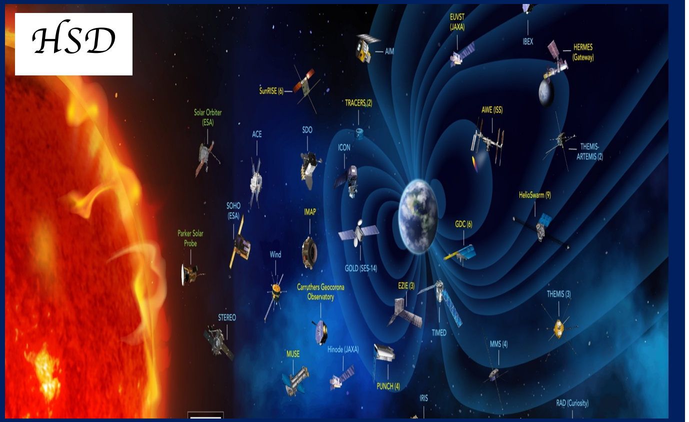
These results demonstrate the potential benefits of using ionospheric data with strongly coupled data assimilation and physics-based modeling.



Dietrich et al. (2022)

Why NASA – Why Now

- NASA's Heliophysics provides a suite of upper atmospheric observations
- NASA's GEOS(*) analyses and predictions capture space-time atmospheric dynamics that is a key driver of the upper atmosphere; it values each type of observation in context of multiple other observations
- A vertical extension of the GEOS system will bring NASA's Heliophysics observations into the same analysis framework as other "Earth observations"
- Impacts for basic research using mission observations
- Opportunity to create synergies with other Agencies (e.g., NOAA)
- Upcoming spaceflight opportunities (AWE, EZIE, GDC, DYNAMIC) require a strategic investment in ITM modeling and coupling with space weather models



(*) GEOS: Goddard Earth Observing System, a configurable suite of models for global analysis and prediction of atmosphere, ocean, land and ice

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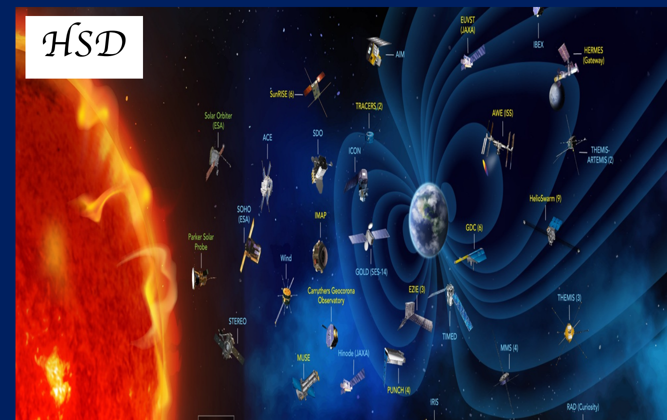

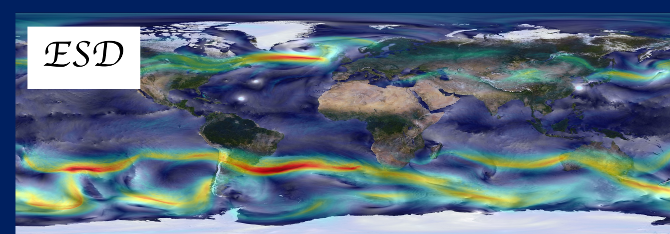

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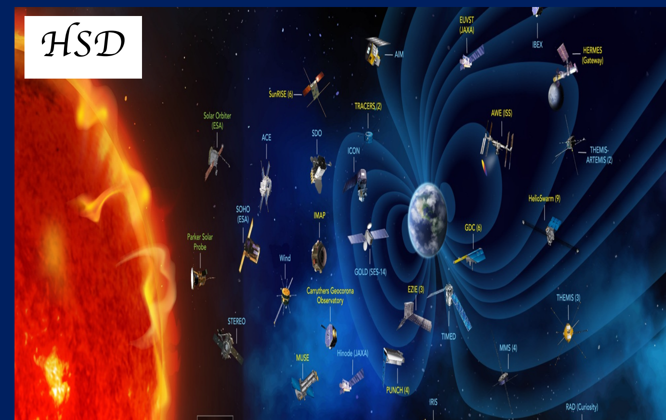

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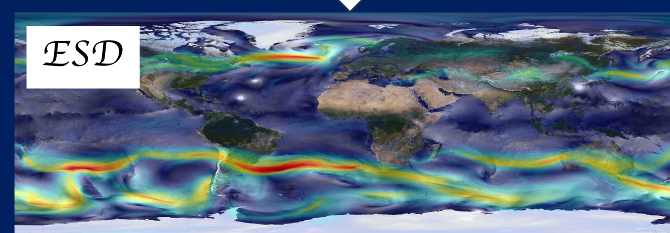

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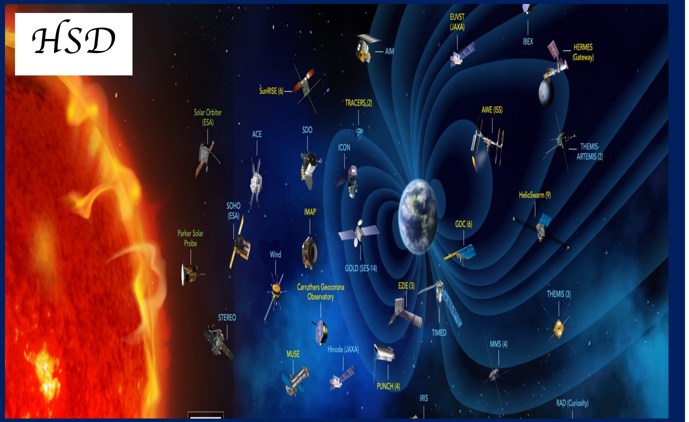

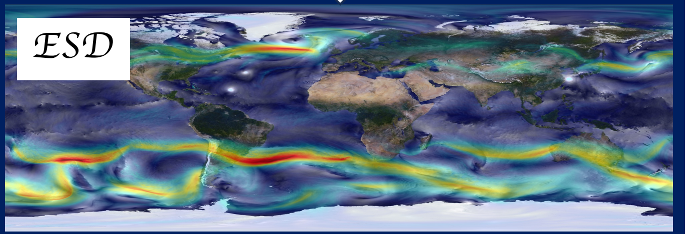

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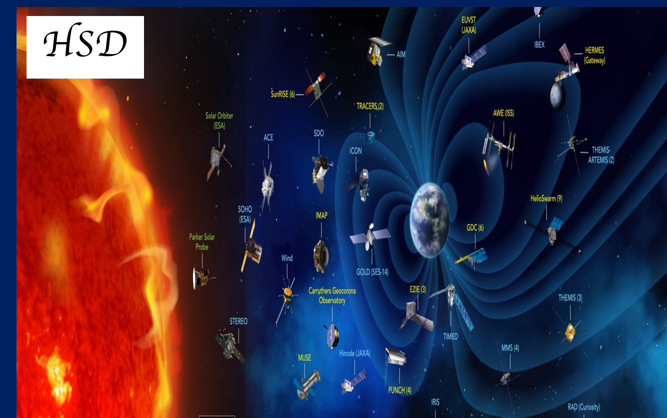

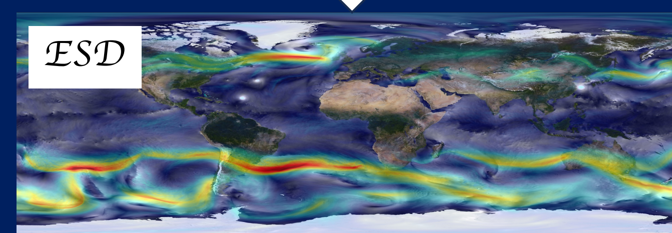

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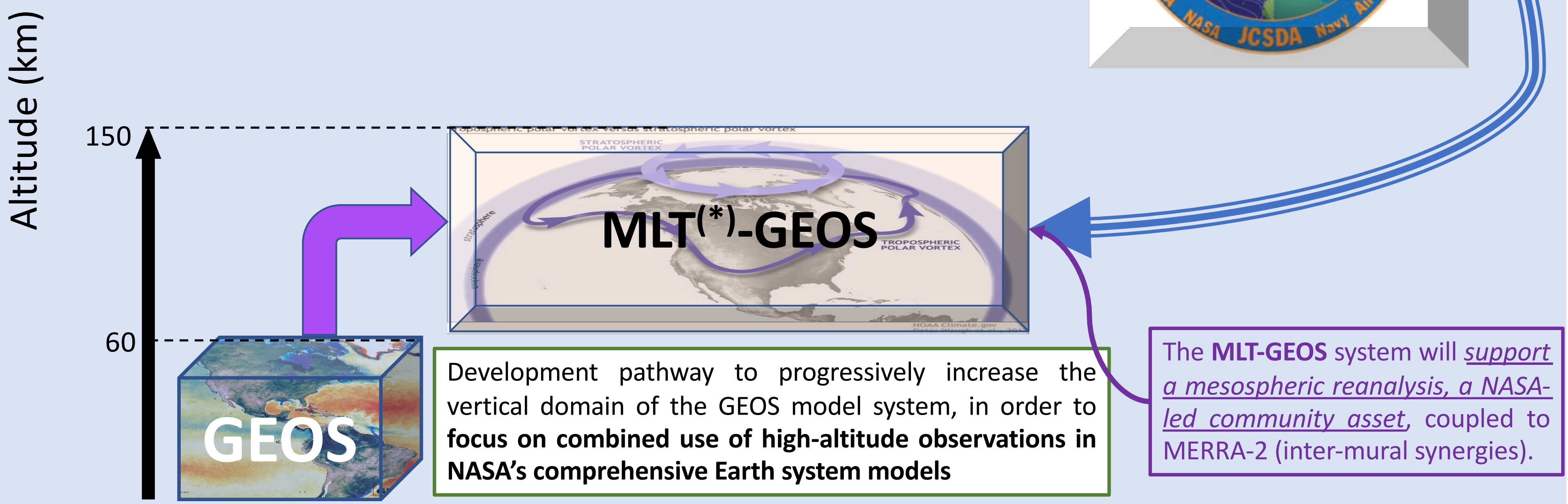

(*) MLT = Mesosphere & Lower Thermosphere
(**) HA = High Altitude

Overall goal: Combining capabilities developed separately in the Earth and Heliophysics domains, this phased project will lead to a whole-atmosphere modeling and analysis activity that maximizes the science impact of NASA's existing and future observations of the mesosphere and thermosphere.

Altitude (km)

350

150

60

Building on the development of MLT-GEOS, **HA-GEOS** *will provide mission planning and support for NASA space programs*, and a testbed for testing novel physics and data assimilation in the thermosphere.

Development pathway to progressively increase the vertical domain of the GEOS model system, in order to **focus on combined use of high-altitude observations in NASA's comprehensive Earth system models**

The **MLT-GEOS** system will *support a mesospheric reanalysis, a NASA-led community asset*, coupled to MERRA-2 (inter-mural synergies).

(*) MLT = Mesosphere & Lower Thermosphere

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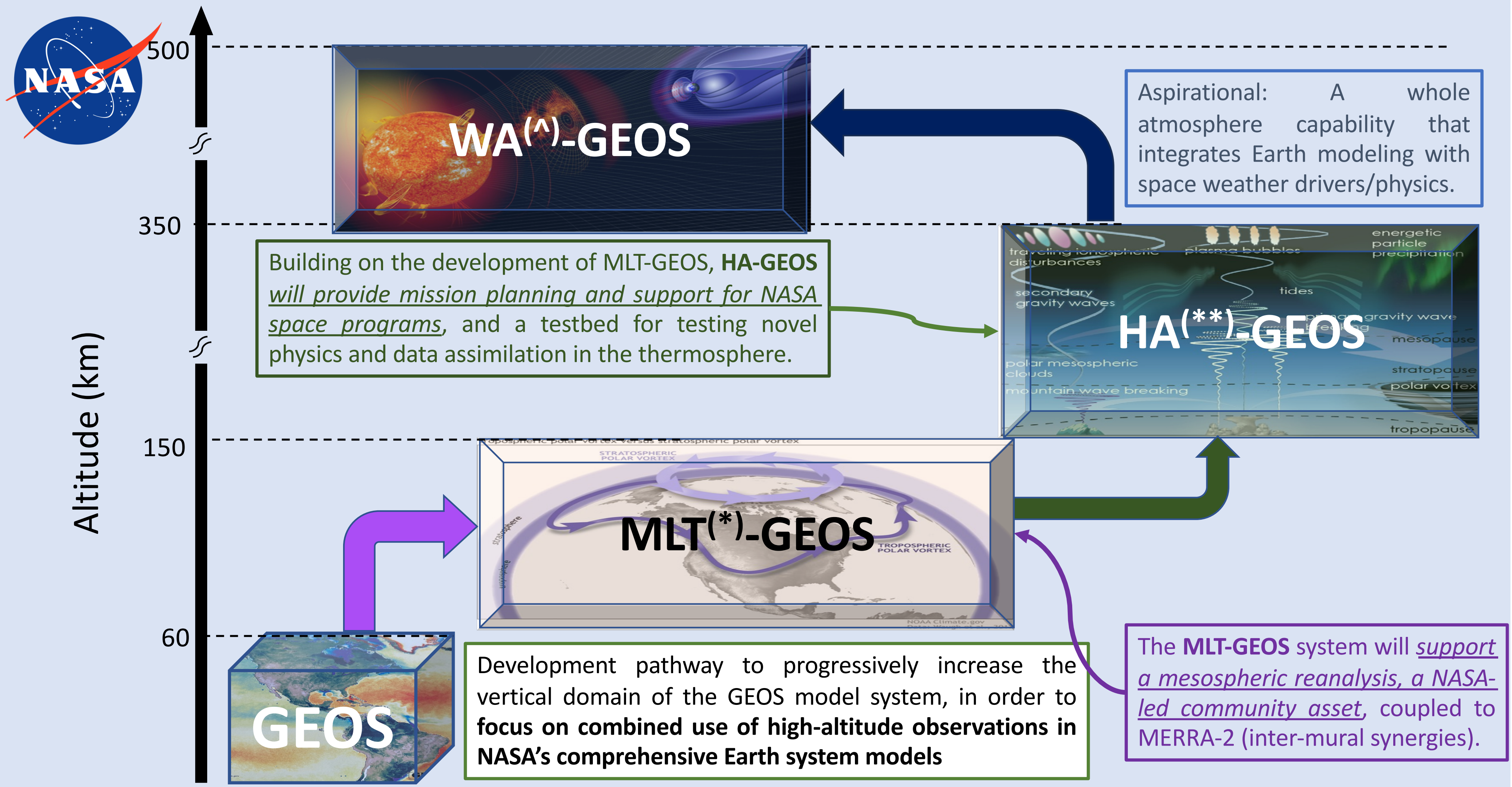

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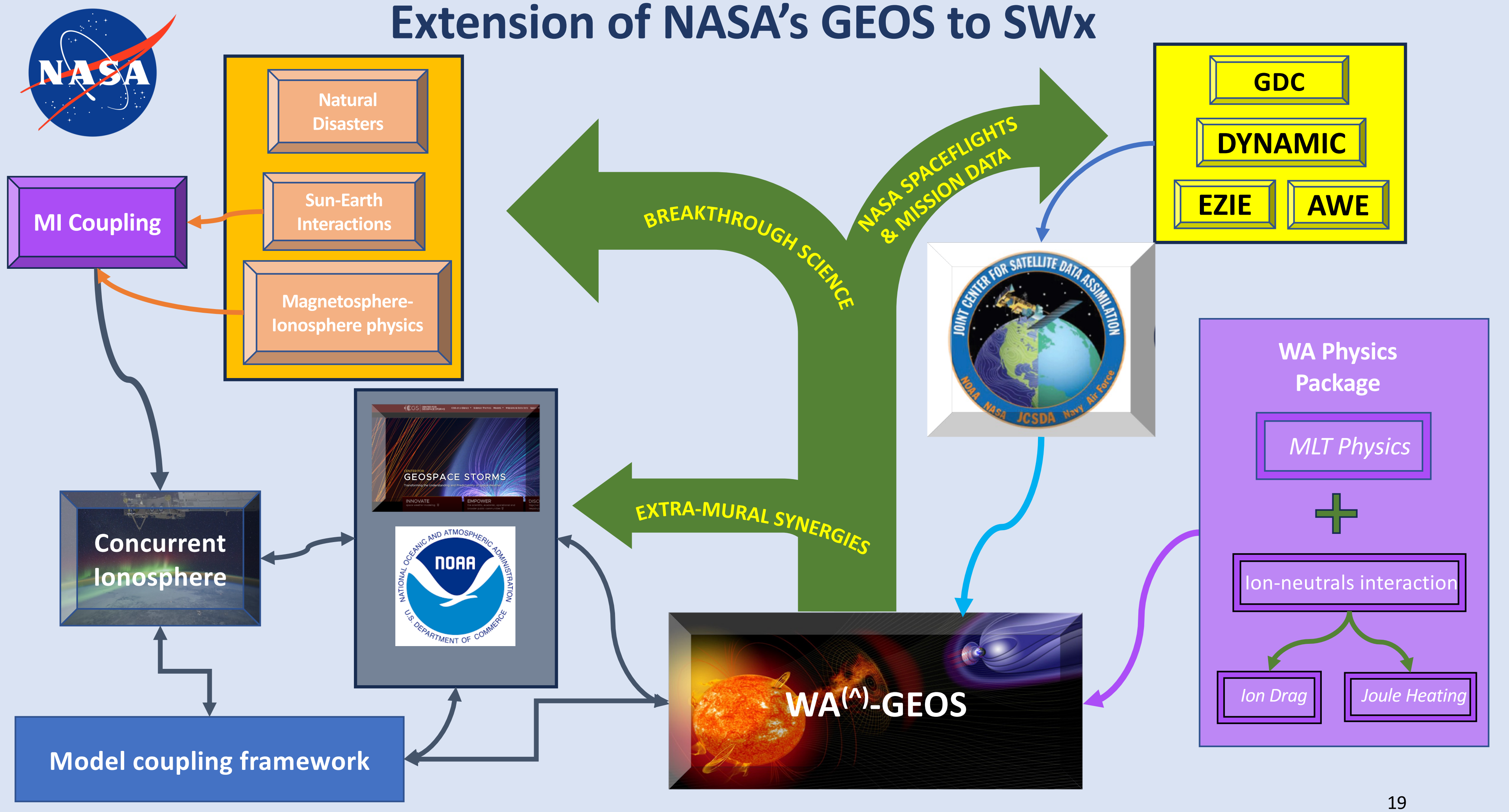
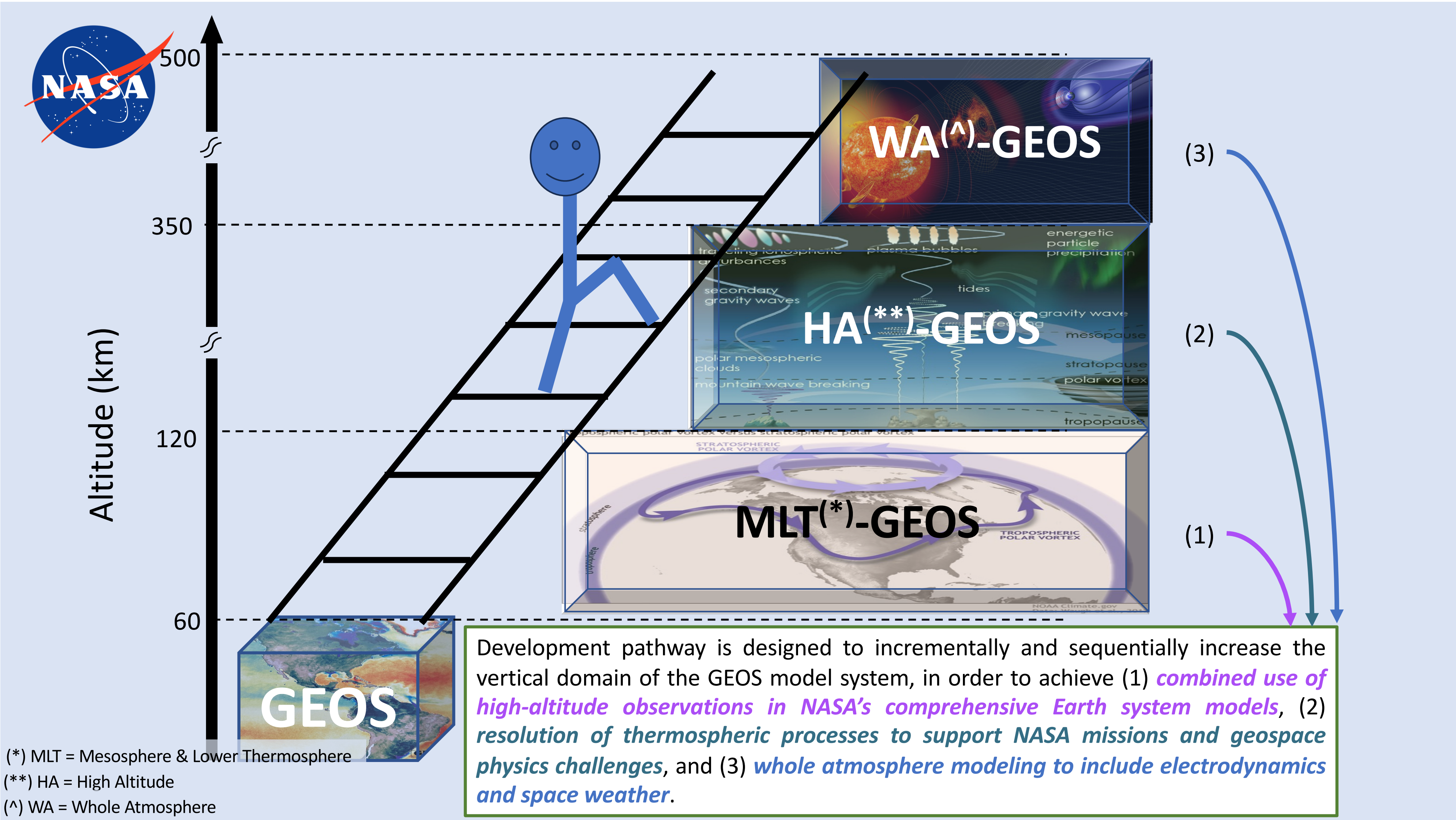
Extension of NASA's GEOS to SWx

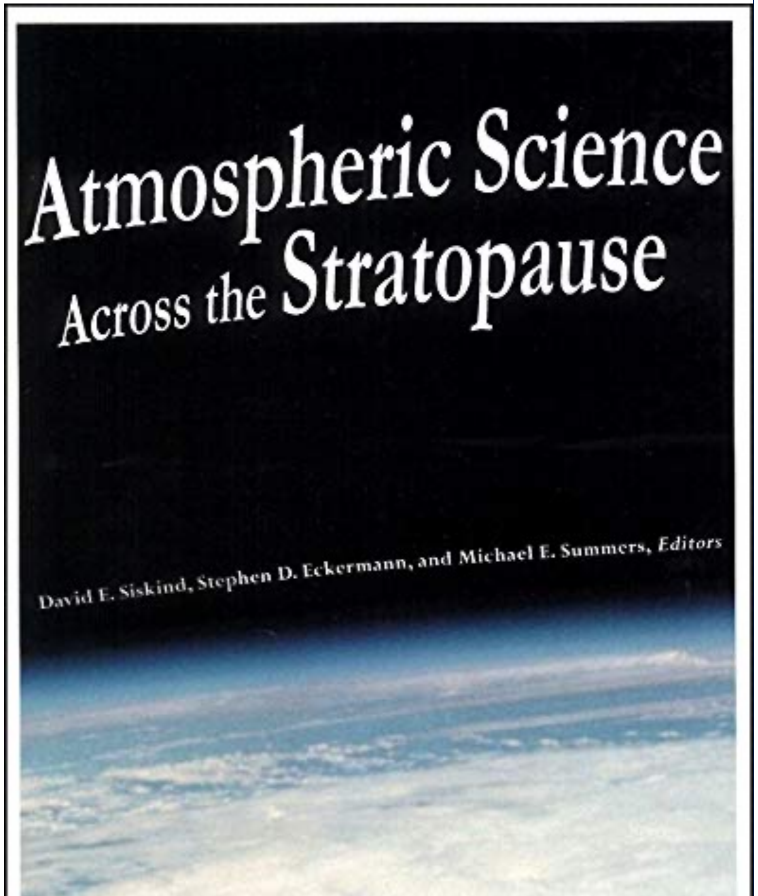


(^) WA = Whole Atmosphere


500
350
120
60
Altitude (km)
WA(^)-GEOS
HA(**)-GEOS
MLT(*)-GEOS
GEOS
energetic particle precipitation
plasma bubbles
tides
secondary gravity waves
mesopause
polar mesospheric clouds
stratopause
mountain wave breaking
polar vortex
tropopause
STRATOSPHERIC POLAR VORTEX
TROPOSPHERIC POLAR VORTEX
(3)
(2)
(1)
(*) MLT = Mesosphere & Lower Thermosphere
(**) HA = High Altitude
(^) WA = Whole Atmosphere
Development pathway is designed to incrementally and sequentially increase the vertical domain of the GEOS model system, in order to achieve (1) *combined use of high-altitude observations in NASA's comprehensive Earth system models*, (2) *resolution of thermospheric processes to support NASA missions and geospace physics challenges*, and (3) *whole atmosphere modeling to include electrodynamics and space weather*.

Closing Remarks

- Holistic approach to Whole Earth System (WES), from mud to space, is needed.
- Great advances have been made since the early 2000s.
- An outstanding problem is the paucity of observations in the upper atmosphere ➔ Ionospheric observations can/should be used.
- A WES requires:
  - Integration of data assimilation, helio-observations and theory
  - Adopt/combine new and old tools, DA & ML
- A WES enables science at the cutting edge, a NASA priority.
- Other Agencies have already started along this road.
- NASA/ITM & /GMAO to work with NOAA:
  - ➢ Same dynamical core
  - ➢ Similar physics
  - ➢ Same model coupling
- ITM/GMAO collab to include TIMED/SABER in GEOS assimilation (FY24 - proposed)
  - ➢ ITM developing know-how (FY23 – ongoing)



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Thank you for your attention

Other questions: fabrizio.sassi@nasa.gov