Long Term Observations of Earth’s Upper Atmosphere

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SME
UARS
Aura
EnviSat
TIMED
Nimbus VII
SORCE
Outline

• The golden age of upper atmospheric science

• Some long-term observations in the stratosphere, mesosphere, and thermosphere

• After 40 years, what’s there left to do?

• The Atmospheric Coupling Explorer Mission

• Summary
The Golden Age of Upper Atmospheric Science
1975 - 2015

• Concerns over the ozone layer prompted development of satellite measurement of ozone, thermal structure, related chemistry, and dynamics

• Experimental techniques involve both limb and nadir observations
  – Limb sensors for both solar occultation and thermal emission
  – Nadir sensors for backscatter ultraviolet (e.g. SBUV, TOMS)

• Multiple U. S. and International instruments and missions flown over past 40 years to understand stratosphere, mesosphere, and lower thermosphere/ionosphere
Upper Atmosphere Satellite Instruments and Missions

- 1970’s -- LRIR, LIMS, AE, SAM
- 1980’s -- DE-1, DE-2, SAGE-II, SME
- 1990’s -- UARS, POAM
- 2000’s -- Aura, TIMED, Envisat, ODIN, SciSat, SAGE-III, SORCE, SMILES, AIM
- 2010’s -- SAGE III (2016); ICON; GOLD
- 2020’s -- ????
  - No missions in preparation for middle atmosphere science
Upper Atmosphere Satellite Instruments and Missions

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A gap in thermal structure and chemical composition measurements after 2020 seems inevitable
Selected Long-Term Observations

- Stratospheric Temperature 1978 – 2015
- Mesospheric Carbon Dioxide
- Thermospheric Infrared Radiation

Stratopause is ~ 9 K colder today than in 1978

LIMS & SABER Temperature Cosine(latitude) Weighted Mean

LIMS Nov 1978 - April 1979
SABER Nov 2014 - April 2015
LIMS-SABER Cosine-latitude Weighted Mean Temperature Difference, 50S to 50N

SC 23 Max

SC 24 Max

SC 23 Min

Mlynczak et al, GRL, in prep.
Upper Mesosphere and Lower Thermosphere CO$_2$

CO$_2$ trends are not consistent with model predictions

Yue et al., GRL, 2015
Global Radiative Cooling by CO$_2$ (W) 100 km to 140 km
2002 – 2015 : 5000 days of data

Radiative cooling responds on timescales from few days to decades

Mlynczak et al., 2003, 2005, 2010
Global Radiative Cooling by CO\textsubscript{2} (W) 100 km to 140 km
2002 – 2015 : 5000 days of data

Comparing Solar Maxima -- $\Delta E = 3.5 \times 10^{18}$ Joules
Global Radiative Cooling by NO (W) 100 km to 140 km
2002 – 2015 : 5000 days of data

Variability from daily to decadal scale
Due to combination of solar UV and geomagnetic variability
Global Radiative Cooling by NO (W) 100 km to 140 km
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Comparing Solar Maxima -- $\Delta E = 3.5 \times 10^{18}$ Joules

Mlynczak et al., 2003, 2005, 2010
Q: After 40 years, what’s left to do?

A: Understand in detail the explore the region between 100 and 200 km altitude

Q. Why?

A. Understanding the evolution of entire atmosphere above depends on it
Thermospheric IR Cooling by NO and CO$_2$

**CO$_2$** cooling dominant below 120 km
And at all altitudes during solar minimum

Mlynczak et al., JGR, 2010
How does increasing CO$_2$ cool the atmosphere above 140 km?
Overview of Energy Budget of Atmosphere above 100 km

Energy Input:
- Solar UV
- Solar Wind

Energy Redistribution:
- Heat Conduction
- Tides, Waves

Energy Loss:
- NO (5.3 μm)
- CO₂ (15 μm)
The 100 – 150 km Region is the Heat Sink for the Thermosphere

- External Energy Input
  - Solar UV
  - Solar Wind

- Energy Loss
  - NO (5.3 μm)
  - CO₂ (15 μm)

- Energy Redistribution
  - Heat Conduction
  - Tides, Waves

- Heat Sink

- Temperature (K)
- Altitude (km)

- Quiet Sun
- Active Sun

- Solar UV
- Solar Wind
- External Energy Input
- Energy Loss
Atmosphere Coupling Explorer Mission

- ACE is a mission to explore the thermosphere above 100 km
- ACE will continue legacy measurements from SABER

**MASTER Instrument**
- 35 kg, 35 W
- 100% SABER Heritage
- ½ mass, ½ power, 1/3 volume
- Identical radiometric performance

**TLS Instrument (S. Yee, APL)**
- T, O, winds – 100 to 160 km
- 15 kg
- 25 W
Existing Capability

Altitude (km)

CO$_2$, NO Cooling

T, O$_3$, CO$_2$, H$_2$O, O
Altitude (km)

15 50 100 150 200 250

Existing Capability

CO₂, NO Cooling

ACE Mission Capability

Heat Cond.

CO₂, NO Cooling

NO+

CO₂

CO
Summary

• Long, illustrious history of observations of Earth’s stratosphere, mesosphere, and thermosphere

• Presently facing a gap in measurements in near future

• Long term evolution due to CO₂ increase controlled by radiative cooling in the 100 – 150 km “heat sink”

• Technology now exists to measure T, O, 100 to > 160 km, and to study its coupling to above and below

• These measurements are a priority to understanding the future of satellite operations and climate change aloft
Beyond the Science: The Space Debris Hazard

Increasing CO₂ → Cooler, Less Dense Atmosphere
Increases Satellite Lifetimes
Increases Orbital Debris Lifetimes

Do We Understand the Energy Budget of the Atmosphere above 100 km?
Big Picture View of Space Debris

NASA Orbital Debris Program Office
Backups
What makes the Upper Atmosphere Interesting and Worthy of Study?

• Blend of classical photochemistry and aeronomy
  – Ozone is still the main radiative drive in the mesosphere and up to 90 km
  – Solar UV variability and particle precipitation influence thermal structure and composition

• Climate change
  – Expect M/LT to cool with increasing carbon dioxide

• Non-Equilibrium Radiative Transfer
  – ALL heating and cooling processes occur far removed from Local Thermodynamic Equilibrium (LTE) above ~ 65 km

• Atomic species become significant
  – Low density means long lifetimes for atomic oxygen and hydrogen
  – Remarkable influence on the energy budget of the 80-100 km region and above

• The E-region, 105-150 km, is the “heat sink” for the entire atmosphere up to the exobase – controls climate change in thermosphere/ionosphere
  – Ultimately determines density at satellite orbits
10^8 More Good Reasons!

- Softball size or larger (≥ 10 cm)
- Marble size or larger (≥ 1 cm)
- Ball-point pen tip (≥ 1 mm)

Total mass: 6,300 tonnes (2,700 tonnes in LEO)

Image Courtesy Hugh Lewis
U. Southampton, UK