Challenges for Upper Atmosphere Research

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Contents
Mesosphere structure and features
Ozone distribution
Solar proton events
NLC
Summary
Structure and features

Atmospheric layers

Lutgens and Tarbuck’s *The Atmosphere*, 2001
Mesospheric phenomena

- protons, electrons
- photons
- gravity waves
- tides
- chemistry
- emissions
- meteor dust
- shuttle exhaust

Non-LTE - vertical transport and diffusion

Mesospheric circulation - atoms, ions

Gravity waves - emissions
Temperature distribution: January

Sources: ECMWF (z<45 km), MSIS90 (z>45 km)
Temperature distribution: March
Temperature distribution: June

ECMWF temperature June

Altitude (km)

Latitude

ESA AATC Oxford 2008 Upper Atmosphere - Erkki Kyrölä
Factors affecting mesosphere

**Gravity wave breaking:** -> Meridional circulation from the summer pole to the winter pole
- Climate change may change the wave intensity and breaking
- Distribution of long-lived constituents
- Adiabatic cooling and warming

**Tides:** Winds, vertical transport, temperature variations

**Increase of GHG:** CO2, H2O and CH4
- Cooling of the mesosphere

**Ionization by particles:** Solar proton events -> local and non-local changes in chemistry

**Ionization by photons:** solar EUV, Lyman alpha
Observing mesosphere

Only 1/10000 of ozone is in mesosphere
99% of neutral density is below 40 km

GOMOS: UV absorption
MIPAS: IR (non-LTE) emission
SCIAMACHY: UV limb scattering and emissions
OSIRIS: UV limb scattering and emissions
SABER: IR (non-LTE) emission
MLS: microwave emission

EISCAT: incoherent scattering, electron density
Sounding rockets
Ozone distribution
Ozone distribution

Ozone GOMOS-MIPAS comparison

From Verronen et al., Adv. Space Res., 2005
Figure 2. Comparison of nighttime SABER and GOMOS ozone density for data within 10° longitude, 5° latitude and 0.5 hour local time. Left shows average (solid) SABER 9.6 μm and (dashed) GOMOS densities on a linear scale. Right gives the (solid) mean and (dashed) rms differences. Units are 10^8 cm\(^{-3}\).
Stratosphere: O3 number density in 2003 ($10^{12}$ cm$^{-3}$)
Stratospheric ozone chemistry

Ozone generation and loss

- O + O₂ → O₃
- O₃ + hv → O + O₂

Catalytic O₃ destruction

- Cl + O₃ → ClO + O₂
- NO + O₃ → NO₂ + O₂
- Br + O₃ → BrO + O₂

Reservoirs

- ClO + NO₂ → ClONO₂
- ClO + O → Cl + O₂

Polar stratospheric clouds

- T < -85°C

Extra chlorine from CFCs

- CFC + hv → Cl

Liberation of chlorine

- Cl + Cl → Cl₂
- Cl₂ + hv

Heterogenous chemistry

- ClONO₂ + HCl → ClO + NO₂
- Cl₂ + HNO₃
Brewer-Dobson meridional circulation explains the latitudinal and seasonal distribution of ozone.
Mesospheric ozone number density \( (10^8 \text{cm}^{-3}) \) in 2003
Mesosphere: $\log_{10} O_3$ mixing ratio in 2003
Zoom to ozone minimum
Ozone number density \(10^8\text{cm}^{-3}\) (30 day median)
Ozone mixing ratio

Lat=50

Altitude
100 90 80 70 60 50 40 30 20

Time
03 04 05 06 07 08

Lat=0

Altitude
100 90 80 70 60 50 40 30 20

Lat=-50

Altitude
100 90 80 70 60 50 40 30 20
Total ozone column at 80 km
Mesospheric ozone chemistry

Ozone generation and loss

- $O + O_2 + M \rightarrow O_3$ \hspace{1cm} $k_1$
- $O_3 + h\nu \rightarrow O + O_2$ \hspace{1cm} $J$
- $O + O_3 \rightarrow 2O_2$ \hspace{1cm} $k_2$

Catalytic $O_3$ destruction

- $H + O_3 \rightarrow OH + O_2$ \hspace{1cm} $k_3$
- $OH + O \rightarrow H + O_2$

Day

\[
[O_3] = \frac{k_1 [O][O_2][M]}{J}
\]

Night

\[
[O_3] = \frac{k_1 [O][O_2][M]}{k_2 [O] + k_3 [H]}
\]
Mesospheric ozone at night

\[
[O_3] = \frac{k_1[O][O_2][M]}{k_2[O] + k_3[H]}
\]

\[
k_1 = 6 \cdot 10^{-34} \left( \frac{300}{T} \right)^{2.4}
\]

\[
k_2 = 1.4 \cdot 10^{-10} e^{-\left(\frac{470}{T}\right)}
\]

\[
k_3 = 8 \cdot 10^{-12} e^{-\left(\frac{2060}{T}\right)}
\]

If T decreases, k1 increases, k2 and k3 decreases:
O3 increases

O3 and T anticorrelation!
**Mesospheric ozone at night**

\[
[O_3] = \frac{k_1[O][O_2][M]}{k_2[O] + k_3[H]}
\]

\[k_1 = 6 \cdot 10^{-34} \left( \frac{300}{T} \right)^{2.4}\]

\[k_2 = 1.4 \cdot 10^{-10} e^{-\frac{470}{T}}\]

\[k_3 = 8 \cdot 10^{-12} e^{-\frac{2060}{T}}\]

Diffusion + tides

Transport

You really need a chemical transport model to understand the situation.
Ozone production

H + O₃ → OH + O₂
OH + O → H + O₂

Winter

Stratopause

Long lived: O₃

Summer

H₂O

GW

Ozone production
Meridional circulation
Solar Proton Events

With contributions from
A. Seppälä, FMI
P. Verronen, FMI
Movies from http://sohowww.nascom.nasa.gov/  EIT
Movies from http://sohowww.nascom.nasa.gov/  

LASCO
Energetic particles and their sources

- Cosmic rays: ions
  100MeV-10GeV

- Solar Energetic Particles: p, e
  10MeV-100MeV

- Radiation belt particles: e, p
  1MeV-100MeV

- Auroral particles: e, p
  100eV-100keV
Modelling mesosphere

- Background atmosphere (MSISE-90)
- Protons, electrons, GCR

Sodankylä Ion Chemistry A 1-D Model

- Neutral gas concentrations
- Electron and ion densities
- Production and loss rates for each process

Incl. 400 chemical reactions
Solves: 63 ions + 13 neutrals
Altitude range: 20-150 km
Steady-state/Time-dependent
Vertical transport (diffusion)
Sodankylä Ion Chemistry model

- coupled 1D neutral-ion chemistry model
- time-dependent concentrations

- 79 constituents as unknowns
  - 36 positive ions
  - 28 negative ions
  - 15 neutral species
- altitudes from 20 to 150 km

- neutral chemistry included
  - odd oxygen
    - O + O₃
  - odd nitrogen
    - N + NO + NO₂
  - odd hydrogen
    - H + OH + HO₂

(from P. Verronen, 2006)
SIC model
negative ions
Energetic Particles and the Atmosphere

Charged particles precipitate in the polar areas producing $\text{HO}_x$ and $\text{NO}_x$ gases in mesosphere and stratosphere

$\text{HO}_x (\text{H} + \text{OH} + \text{HO}_2)$
Short lifetime
$\text{HO}_x$ cycle, upper-stratosphere + lower-mesosphere
$\text{OH} + \text{O}_3 \rightarrow \text{HO}_2 + \text{O}_2$
$\text{HO}_2 + \text{O} \rightarrow \text{OH} + \text{O}_2$
Net: $2\text{O}_x \rightarrow 2\text{O}_2$

$\text{NO}_x (\text{N} + \text{NO} + \text{NO}_2)$
Loss: photodissociation $\rightarrow$ longlived during night $\rightarrow$ transported to stratosphere and lower latitudes
$\text{NO}_x$ cycle, upper-stratosphere
$2(\text{NO} + \text{O}_3) \rightarrow 2(\text{NO}_2 + \text{O}_2)$
$\text{NO}_2 + h\nu \rightarrow \text{NO} + \text{O}$
$\text{NO}_2 + \text{O} \rightarrow \text{NO} + \text{O}_2$
Net: $2\text{O}_3 \rightarrow 3\text{O}_2$
A. Seppälä, FMI
GOMOS NO\textsubscript{2} 2003-2004 winter (movie)

Aika 15.10.2003 - 16.10.2003

A. Seppälä, FMI
Northern polar regions NO$_x$ from GOMOS

A. Seppälä, FMI
Solar Proton Events - Jan 2005 SPE and the Tertiary Ozone Maximum

• TOM first reported by Marsh et al. 2001
• Occurs ~72km near the polar night terminator
• Result of decreased O$_x$ loss by catalytic HO$_x$ cycles after decreased HO$_x$ production with reduced UV radiation. (Less UV ->Less HO$_x$ from H$_2$O photolysis -> Less catalytic O$_x$ loss)
Third ozone peak in January
GOMOS $O_3$ observations and model results

Seppälä et al., Geophys. Res. Lett. 2006
Solar proton events and odd H ozone loss
P. Verronen, FMI
Noctilucent clouds
Photograph taken by Mika Yrjölä in August 2003. This image portraits a bright noctilucent cloud over Lake Saimaa.
NLC movie

14-Jul-2004
23:00 UT

J. Stegman, MISU
GOMOS photometer measurements
OSIRIS
B. Karlsson
D. Degenstein
etc.
RESEARCH CHALLENGES FOR THE MESOSPHERE

• Waves, wave breaking
• General mesospheric circulation
• Tides
• Particle events
• Solar EUV variation
• Increased GHG, cooling
• NLC
Summary and references

- Mesosphere is sensitive to external natural forcings and climate change. There is a need to understand the different components of change.
- Measurements are difficult and rare. Need for new measurements.
- Modelling of mesosphere is difficult. Modelling needs to include neutral and ion chemistry and meridional circulation.

Review: A. Smith: Physics and chemistry of the mesopause region, J. Atmospheric and Solar-Terrestrial Physics, 66. 839, 2004

A. K. Smith and D. R. Marsh: Processes that account for the ozone maximum at the mesopause, JGR,110, D23305, 2005
Thank you. You have been a wonderful audience!