Observations of Polar Mesospheric Clouds from Space and Their Scientific Implications

Presented by

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This talk discusses what we know about a minor constituent in Earth’s atmosphere – Noctilucent Clouds – and how and why they form and vary.

It is not about processes or mechanisms that could affect global warming.

It is a story that describes how the Sun and processes in our vast atmosphere are coupled, even on small scales, in such a way as to affect a thin layer of clouds on the edge of space.

In the end, the story could be a description of the atmospheric equivalent of the “Miner’s Canary” of global change.
Scientific Implications of NLCs Outline

- Description of Noctilucent Clouds
- The environment where they form
- Why it is important to study these clouds
- How they are changing
- Current fundamental questions
- What could be causing the long-term changes
- Satellite instruments and missions
- Description of the AIM mission
- The role of T, H2O and dynamics in cloud variability
- Cosmic smoke observations
- Factors potentially affecting long-term NLC changes
Noctilucent Clouds are beautiful, iridescent, intriguing and of great scientific interest

- Heliophysics
- Earth Science
- Space Science
- Planetary Science

Tom Eklund, July 28, 2001, Valkeakoski, Finland
Ground-based observers refer to the clouds as Noctilucent or “night shining” Clouds (NLCs)
Satellite observers refer to the clouds as Polar Mesospheric Clouds

Tom Eklund, July 28, 2001, Valkeakoski, Finland
Noctilucent Cloud Background

- Polar summer
- ~ 83 km altitude
- Water ice crystals
- 30 nm to 80 nm size
- Coldest spot on Earth
- > 50° latitude N and S
- First observed in 1885
- Changes are occurring
- Possible connection with global change

NH Season: mid-May to mid-August
SH Season: mid-November to mid-February

Tom Eklund, July 28, 2001, Valkeakoski, Finland
What is the environment where noctilucent clouds form?

- Temperature is $-220^\circ F$
- Pressure is 100,000 times less than at the surface
- Air is 100,000 to a million times drier than Saharan desert air

Earth's Atmosphere

- Mesopause
- Mesosphere
- Stratopause
- Stratosphere
- Tropopause
- Troposphere

Temperature

Altitude (km)

$-80$ $-60$ $-40$ $-20$ $0$ $20$ $40$ $60$ $80$ $100$

$0$ $20$ $40$ $60$ $80$ $100$

$-80$ $-60$ $-40$ $-20$ $0$ $20$ $40$ $60$ $80$ $100$

Jim Russell - Aspen GCI
June 12 - 17, 2010
Why is it important to study Noctilucent Clouds?

- NLCs are influenced by
  - Solar changes
  - Cosmic smoke input to the atmosphere
  - Coupling by atmospheric dynamics from below
  - Coupling by the meridional circulation across hemispheres
  - Atmospheric temperature and H₂O changes

- The relatively narrow altitude region where NLCs form harbors information on key processes affecting our entire atmosphere

- Because the Sun has an important effect on NLC change as does temperature and H₂O; long-term measurements are needed to understand NLC variability
NLCs are changing in ways we do not understand

- Have been getting brighter and occurring more frequently over the last 27 years

DeLand, Shettle, Thomas, and Olivero (JGR, vol. 112, D10315, 2007)
NLCs seem to be occurring at lower latitudes than in the past

NLCs observed over Omaha, NE (41°N) on July 14, 2009
Mike Hollingshead
AIM observed low latitude PMCs on July 15, 2009
- Why do these clouds form and vary?
- Why are long-term changes occurring?
- Is there a connection with global change?
Three things are needed for PMC formation

- Water vapor
- Presence of particles
- Cold temperatures
While unproven, the most plausible causes for long-term PMC change are CO$_2$ and CH$_4$ increases.

- CO$_2$ increases in the lower atmosphere cause the atmosphere to warm.
- The same increases at 83km cause cooling.
- CH$_4$ increases lead to more water vapor in the atmosphere.
- Both effects make conditions more favorable for NLCs to form.
Atmospheric CO$_2$ and CH$_4$ are increasing dramatically

- **CO$_2$ versus time**: Colder mesosphere temperatures?
- **CH$_4$ versus time**: More mesospheric water vapor?
### WACCM inputs for estimated trends 2000 -2050

**IPCC A1b**
- SSTs from CCSM3 IPCC A1b simulation
- Fixed mean solar conditions; no QBO
- Trends in trace gases from IPCC A1b scenario:
- PMC effect on H$_2$O not included

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2050</th>
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<tbody>
<tr>
<td>CO$_2$</td>
<td>369 ppmv</td>
<td>532 ppmv</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>1760 ppbv</td>
<td>2400 ppbv</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>316 ppbv</td>
<td>350 ppbv</td>
</tr>
<tr>
<td>CFC-11 $^*$</td>
<td>262 pptv</td>
<td>104 pptv</td>
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<tr>
<td>CFC-12 $^*$</td>
<td>540 pptv</td>
<td>350 pptv</td>
</tr>
<tr>
<td>CFC-11 $^*$</td>
<td>82 ppt</td>
<td>46 pptv</td>
</tr>
</tbody>
</table>

$^*$ WMO (2003) Scenario Ab

Rolando Garcia,
December, 2009
WACCM Estimated Temperature and H$_2$O trends
Arctic (70°N, -90°) 2000-2050 (JJA)

Large trend in H$_2$O, small trend in T near summer mesopause

PMC effect on H$_2$O is not included

Rolando Garcia, December, 2009
Satellite instruments/missions that have observed or are observing PMCs

- **SBUV series** 1978 - present
- **SME** 1981 - 1986
- **HALOE** 1991 - 2005
- **SNOE** 1998 – 2003
- **OSIRIS** 2001 - present
- **SCHIAMACHY** 2002 - present
- **OMI** 2004 – present
- **SHIMMER** 2007 - 2009
- **AIM** 2007 - present
AIM was launched from VAFB by a Pegasus XL rocket

- Launched April 25, 2007 at 1:26:03 PDT
- Near perfect 600 km orbit
  - 596 km perigee, 601 km apogee
  - Ascending node equatorial crossing time only 47 seconds off
SOFIE: Solar Occultation for Ice Experiment

A 16-band differential absorption radiometer (UV to IR) to simultaneously measure cloud properties and the PMC environment

- Operates over 0.3\(\mu m\) to 5.3 \(\mu m\) range
- T, NLCs, CO\(_2\), H\(_2\)O, CH\(_4\), NO, O\(_3\), aerosols, cosmic smoke
- 2 km vertical resolution
High SOFIE sensitivity allows subvisible ice to be measured; suspected from radar echos, but never observed before AIM.
Four CCD cameras image PMCs at ~ 83 km

- $\lambda = 0.265 \, \mu m$; 1 X 2.5 km pixel size
- Cloud morphology and particle sizes
Four CCD cameras image PMCs at ~ 83 km
CIPS image shows detailed structure and ice voids.
What is the role of temperature and water vapor in the formation of PMCs?
The PMC season turns on and off abruptly like a geophysical light bulb.

The season start and end times are highly variable in the south.
Temperature is in dominant control at the season start and end. H$_2$O is in control during the season.
Temperature is a factor in PMC variability even during the season.

CIPS PMC frequency at 77° latitude and SABER temperature

Merkel et al., 2007
Mesopause temperature is a driver for PMC peak altitude formation.

SOFIE PMC altitude and SABER mesopause minus 3.5 km (circles) for 2007 - 2008 NH/SH seasons

Russell et al., JGR, 2010
How do planetary waves and gravity waves affect PMC formation and destruction?
NRL NOGAPS model and SOFIE data show that dynamics can extend the length of the PMC season.

Temperature wavelet amplitudes (grey and black)

Observed SOFIE clouds for ice >30 ng/m³ (white dots)

The atmospheric 5-day wave modulates PMC occurrence and can effectively extend the period of PMC occurrence by providing many days of localized regions of saturated air in the trough of the wave.

Nielsen et al., 2009
Gravity waves cause PMCs to dissipate. SABER Ts suggest that GWs lead to local heating.

GW and PMC correlation: -0.94
GW and SABER temperature correlation: 0.72

Chandran et al., 2009
Is it caused by a steady H₂O increase that amplifies PMC growth during the cooling phase and buffers sublimation during warming?
CIPS PMC frequency shows a bifurcation during the cooling and warming phases of the season.

Is it caused by a steady H$_2$O increase that amplifies PMC growth during the cooling phase and buffers sublimation during warming? Or is it dynamics?

[CIPS wave events [Taylor et al., 2010]]

Cooling

Warming

July 2007
What are the mechanisms leading to hemispheric coupling effects on PMC formation?
What is the mechanism for teleconnection? Stratospheric winter T and PMC radius anomalies

Based on analysis of ODIN OSIRIS data

Correlation coefficient = -0.95
Zonal Mean Temperature Field in January
Less planetary wave activity in stratosphere (cold)
Less planetary wave activity in stratosphere (cold) → More net gravity wave drag
Less planetary wave activity in stratosphere (cold) → More net gravity wave drag → Stronger circulation in mesosphere
Less planetary wave activity in stratosphere (cold) → More net gravity wave drag → Stronger circulation in mesosphere → Colder summer mesopause.

- Larger NLC particles
- Drag
- -T
AIM NH PMC data and MLS SH Temp show summer and winter hemisphere coupling.

CIPS NH frequency of PMC occurrence

Karlsson et al., 2009
What is the role of cosmic dust in PMC formation?
AIM is addressing key PMC formation science

SOFIE NH cosmic smoke

Three nucleation source theories

- Cosmic smoke (Hunten, 1980)
- Sulfate particles from below (e.g. Mills, 2009)
- Proton-hydrate ions (Witt, 1962; Reid, 1989)

Air is upwelling during the PMC season. SOFIE has collected thousands of such profiles to study PMC and smoke correlations.
Northern Hemisphere smoke versus time for Sept 30, 2008 to Sept. 14, 2009

8 arcmin solar lockdown once a month
SOFIE Southern Hemisphere smoke time series

a) 0.5 hPa

Relative extinction

Jul 07  Jan 08  July 08  Jan 09  Jul 09

SOFIE CHEM2D WACCM

b) 0.01 hPa

Relative extinction

Jul 07  Jan 08  July 08  Jan 09  Jul 09

SOFIE CHEM2D WACCM

55 km

82 km
Factors potentially affecting long-term PMC changes

- CH$_4$ increases leading to increased mesospheric H$_2$O
- CO$_2$ increases leading to a colder mesosphere
- Changes in Lyman - $\alpha$ over the solar cycle (definite effect)
- Global temperature increases could alter lower altitude gravity wave source activity and vertical propagation
- A warming lower atmosphere could change planetary wave activity and hence meridional coupling
- Long-term changes in cosmic smoke?
Backup
Effect of temperature change on season length

![Graph showing the relationship between temperature change (T change in K) and start day from solstice for early and late seasons, with warm and cold temperature conditions.]
Effect of water vapor change on season length

![Graph showing the effect of water vapor change on season length. The x-axis represents H2O change (factor), with values ranging from 0.1 to 10.0. The y-axis represents the start day from solstice, with values ranging from -20 to -50. The graph is divided into two sections: 'Early' and 'Late'. The 'Early' section has 'dry' and 'wet' categories, while the 'Late' section shows a clear trend of decreased day count with increased H2O change.]
SBUV & WACCM-PMC: Northern Hemisphere

Red = DeLand, 2007
Black = this analysis

Marsh, NCAR, 2010, private communication
PMC science is directly driven by the Sun

- The first 6 seasons of AIM observations occurred during a prolonged solar minimum
- We know PMCs are affected by solar changes but we do not know why
- A warming atmosphere could change temperature and dynamical influences on PMC formation

The next step needed to understand why PMCs form and vary is to collect data over a wide range of solar conditions

Study of a global change connection requires measurements over a solar cycle (PMCs, T, H₂O, CO₂, CH₄, O₃, NO, aerosols and cosmic smoke)
NH PMC frequency of occurrence observed by the SOFIE instrument on the AIM satellite
PMC frequency and brightness have been increasing over the last 28 years.

Long-term frequency trends observed by the SBUV series of satellite instruments [Shettle et al., 2009]
PMC frequency and brightness have been increasing over the last 28 years.

Long-term brightness trends observed by the SBUV series of satellite instruments [Deland et al., 2007]
SOFIE and SABER temperature comparisons for July 1 – 15, 2007
SOFIE and ACE H$_2$O comparisons for the NH summer
SABER and SOFIE H$_2$O comparisons on May 29, 2007
Methane (CH$_4$)

CH$_4$ accounts for 20% of the global warming effect.

**Natural sources of CH$_4$:**
- produced as a result of microbial activity in the absence of oxygen.
  - Natural wetlands or bogs
  - Termites

**Anthropogenic sources of CH$_4$:**
- Rice paddies
- Cattle
- Drilling for oil
- Landfills
- Biomass burning
- Coal mining.

Anthropogenic sources account for 70% of the methane produced annually.

Methane oxidization: one CH$_4$ $\rightarrow$ 2 H$_2$O
$CO_2$ accounts for 55% of the global warming effect.

**Natural sources of $CO_2$:**

- Respiration: all living organisms respire and give off carbon dioxide.
- Decomposition of organic material

**Anthropogenic sources of $CO_2$:**

- Fossil fuel burning (65%)
- Deforestation and burning of rain forest
- Land-use conversion
- Cement production

Anthropogenic sources account for most of the $CO_2$ produced annually.
Why is the summer mesosphere colder than the winter?

Summer polar region
Rising, expanding air → Cooling

Winter polar region
Descending, compressing air → Heating
1. Southern Winter Zonal Winds travel West-East

2. Upward flowing gravity waves disrupt winds, pulling air down and increasing the meridional flow

3. Rising air expands and therefore cools, producing a cold summer mesosphere
AIM PMCs and SABER temperatures show presence of 5-day and 2-day planetary waves

June 1 to July 15, 2007

First evidence of eastward 2 day wave [Merkel et al., 2009]
NH and SH clouds exhibit different properties

CIPS images for one month after solstice in both hemispheres