Observations of Polar Mesospheric Clouds from Space and Their Scientific Implications

Presented by

James M. Russell III

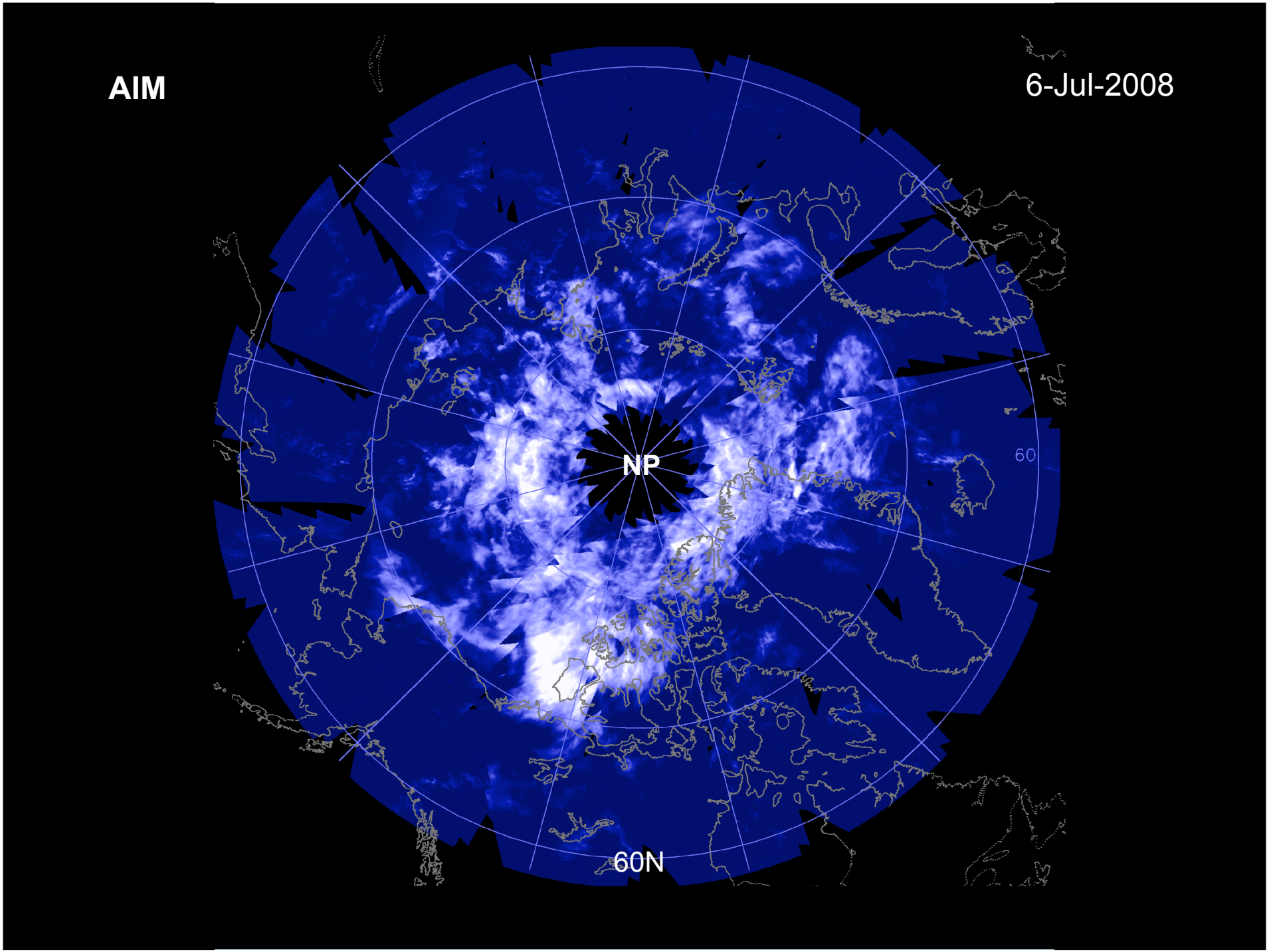
With Contributions from: Scott M. Bailey, Cora E. Randall, Mark E. Hervig, Matt DeLand and the AIM Science Team

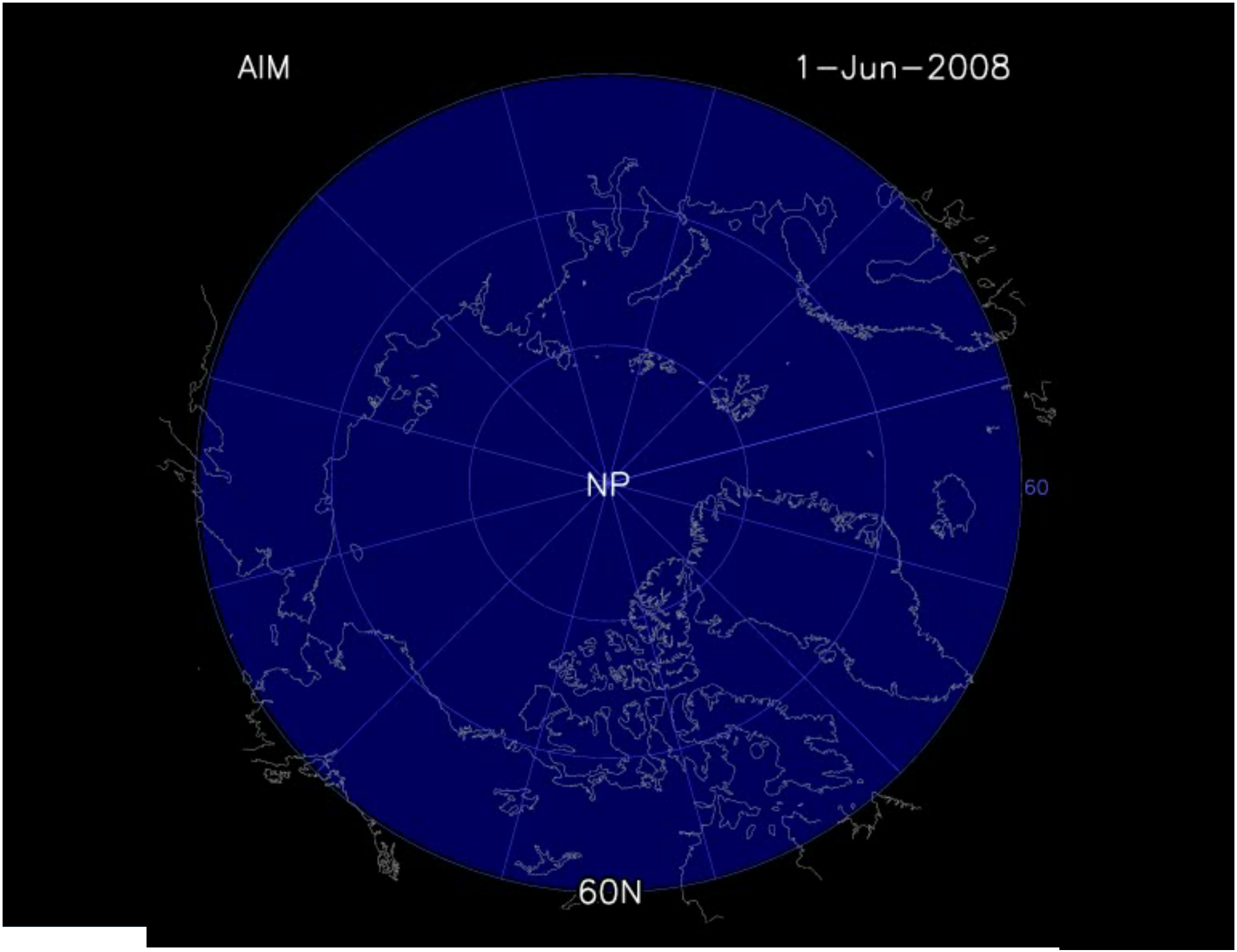
Global Change and the Terrestrial Environment
Aspen Global Change Institute

June 12 - 17, 2010

Scientific implications of Noctilucent Clouds (NLCs)

- 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


AIM
6-Jul-2008
NP
60
60N


AIM
1−Jun−2008
NP
60
60N

Scientific Implications of NLCs Outline

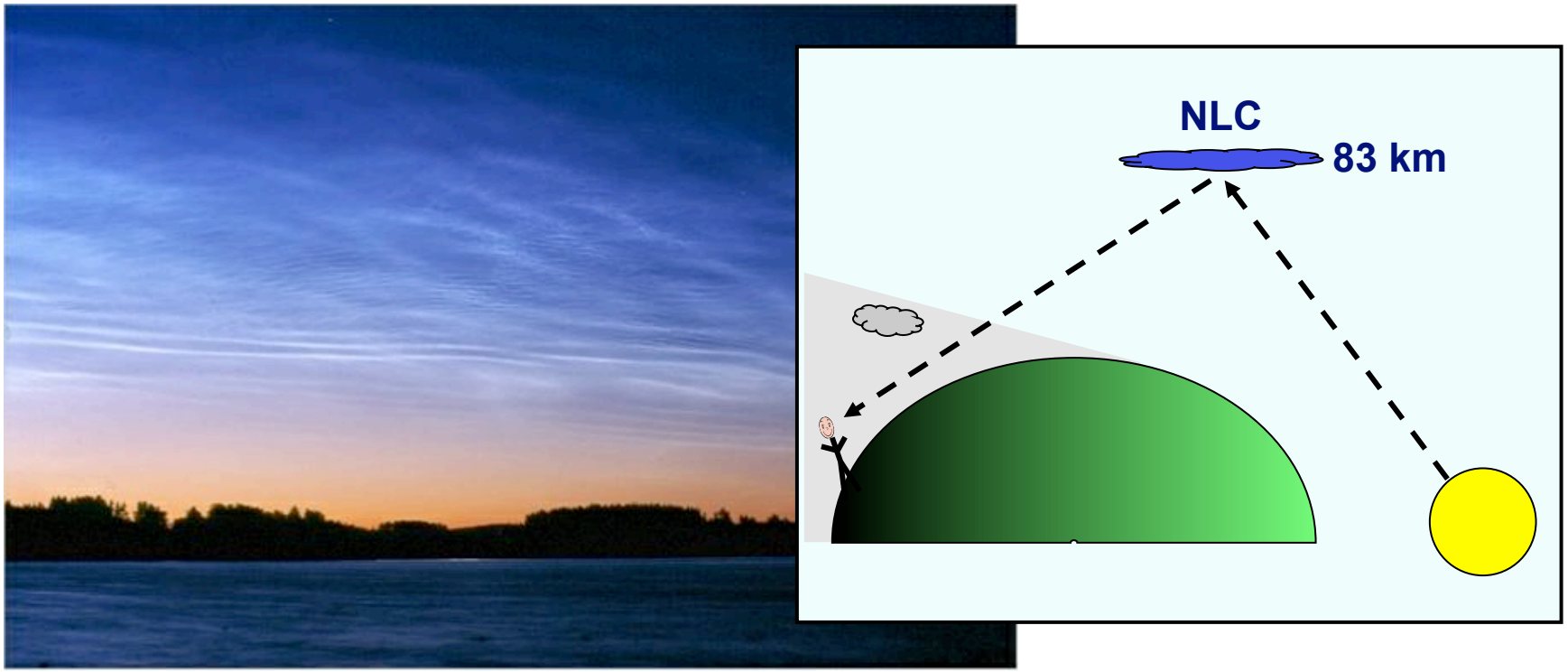
- Description of Noctilucent Clouds
- The environment where they form
- Why it is important to study these clouds
- How they are changing
- Current fundamental questions
- What could be causing the long-term changes
- Satellite instruments and missions
- Description of the AIM mission
- The role of T,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

Noctilucent Clouds are beautiful, irridescent, intriguing and of great scientific interest

Tom Eklund, July 28, 2001, Valkeakoski, Finland

- Heliophysics
- Earth Science
- Space Science
- Planetary Science

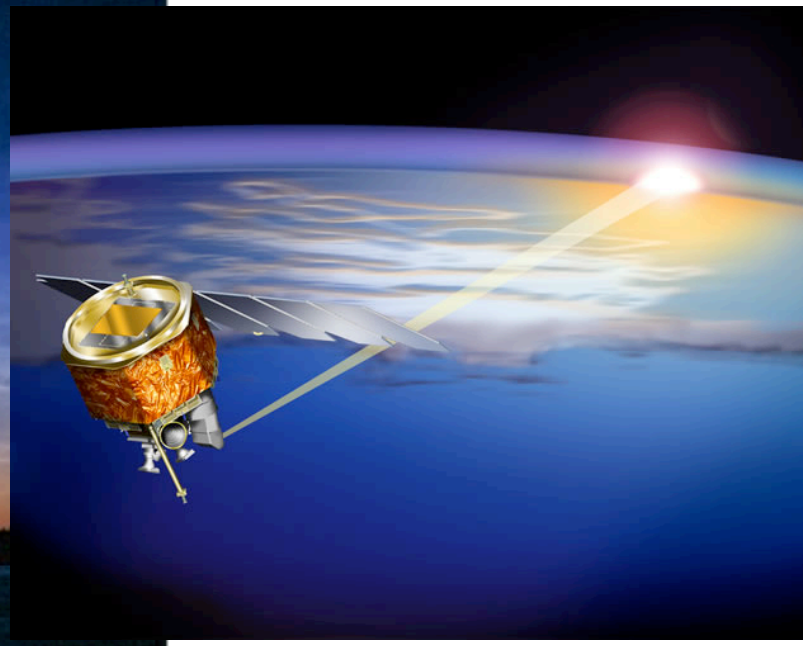
Noctilucent Clouds (NLCs)



Tom Eklund, July 28, 2001, Valkeakoski, Finland

- **Ground-based observers refer to the clouds as Noctilucent or "night shining" Clouds (NLCs)**

Polar Mesospheric Clouds (PMCs)



Tom Eklund, July 28, 2001, Valkeakoski, Finland

- **Satellite observers refer to the clouds as Polar Mesospheric Clouds**

Noctilucent Cloud Background

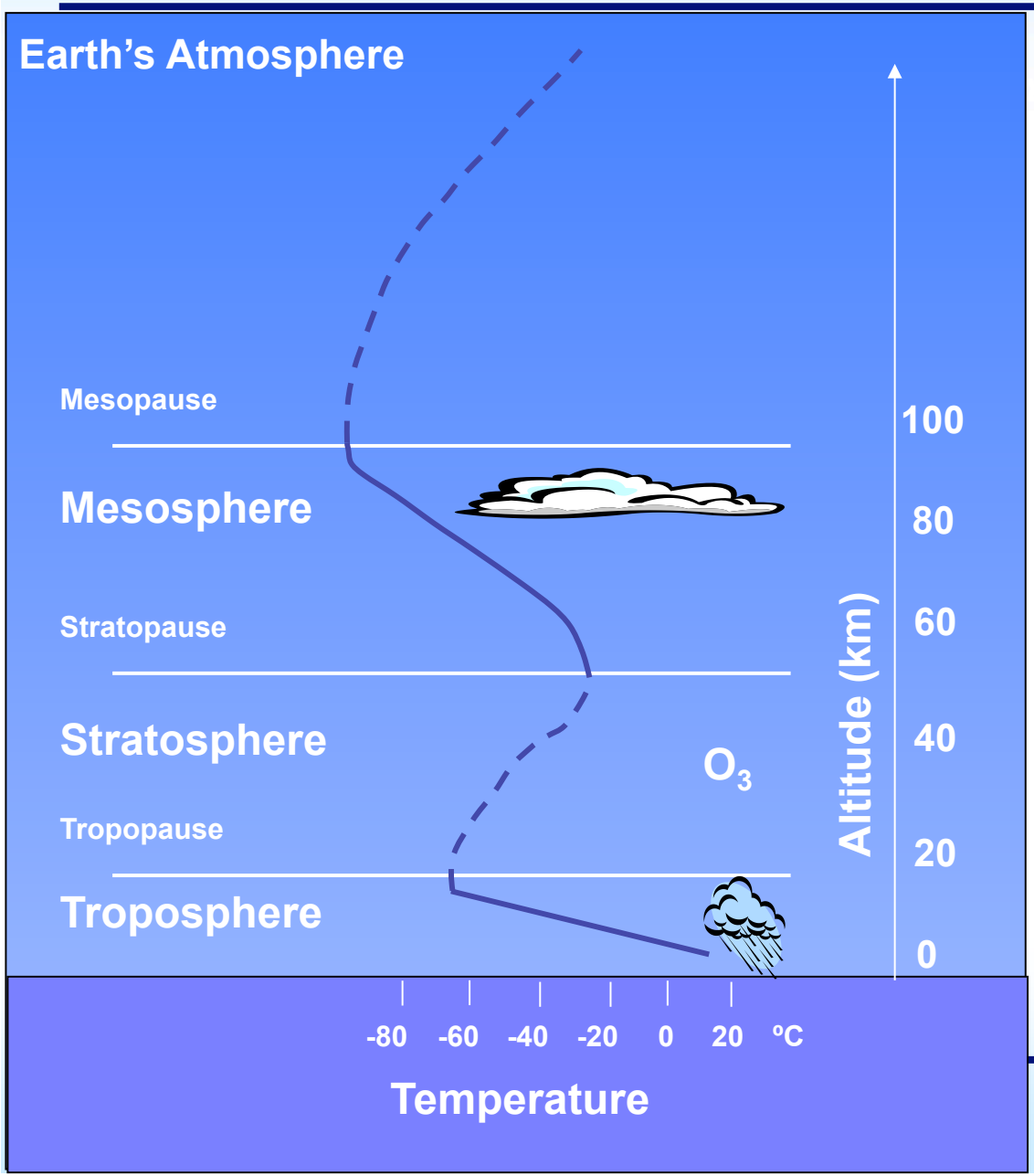
Tom Eklund, July 28, 2001, Valkeakoski, Finland

- 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

What is the environment where noctilucent clouds form?



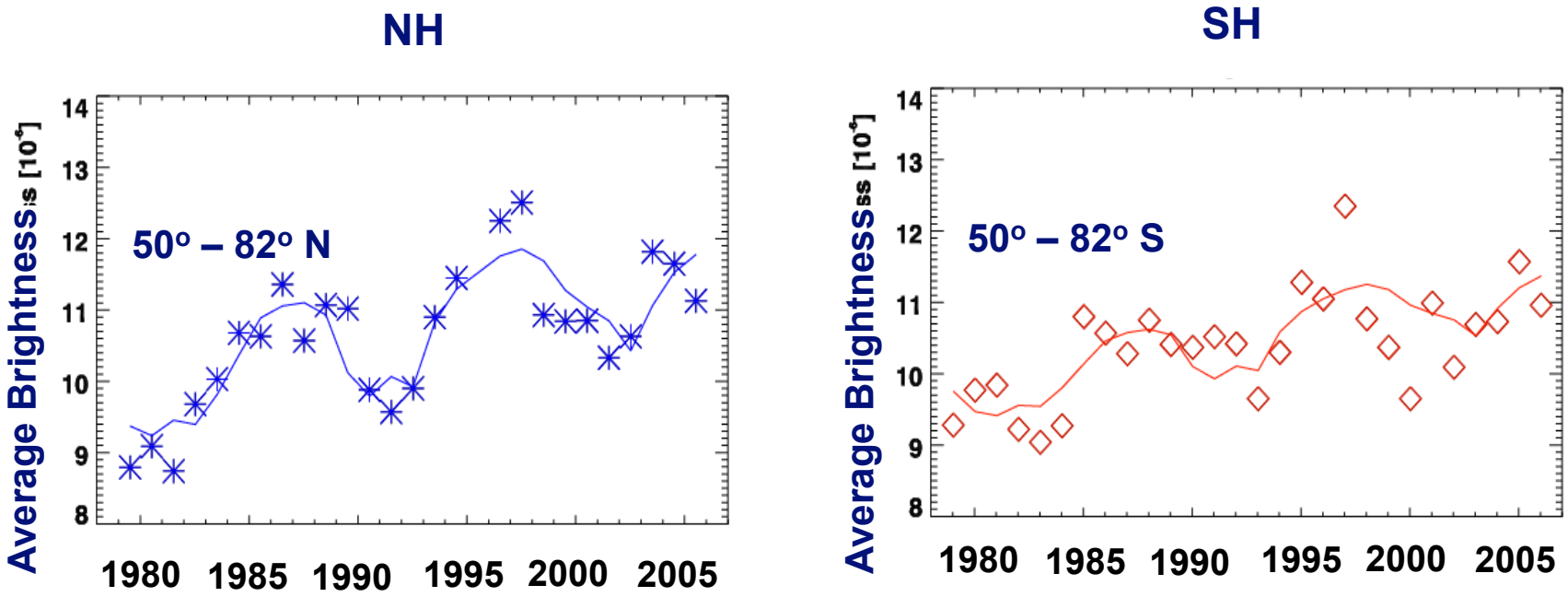
- Temperature is -220°F
- Pressure is 100,000 times less than at the surface
- Air is 100,000 to a million times drier than Saharan desert air

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 H_2O 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 H_2O; 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**

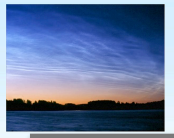


DeLand, Shettle, Thomas, and Olivero (JGR, vol. 112, D10315, 2007)

NLCs seem to be occurring at lower latitudes than in the past

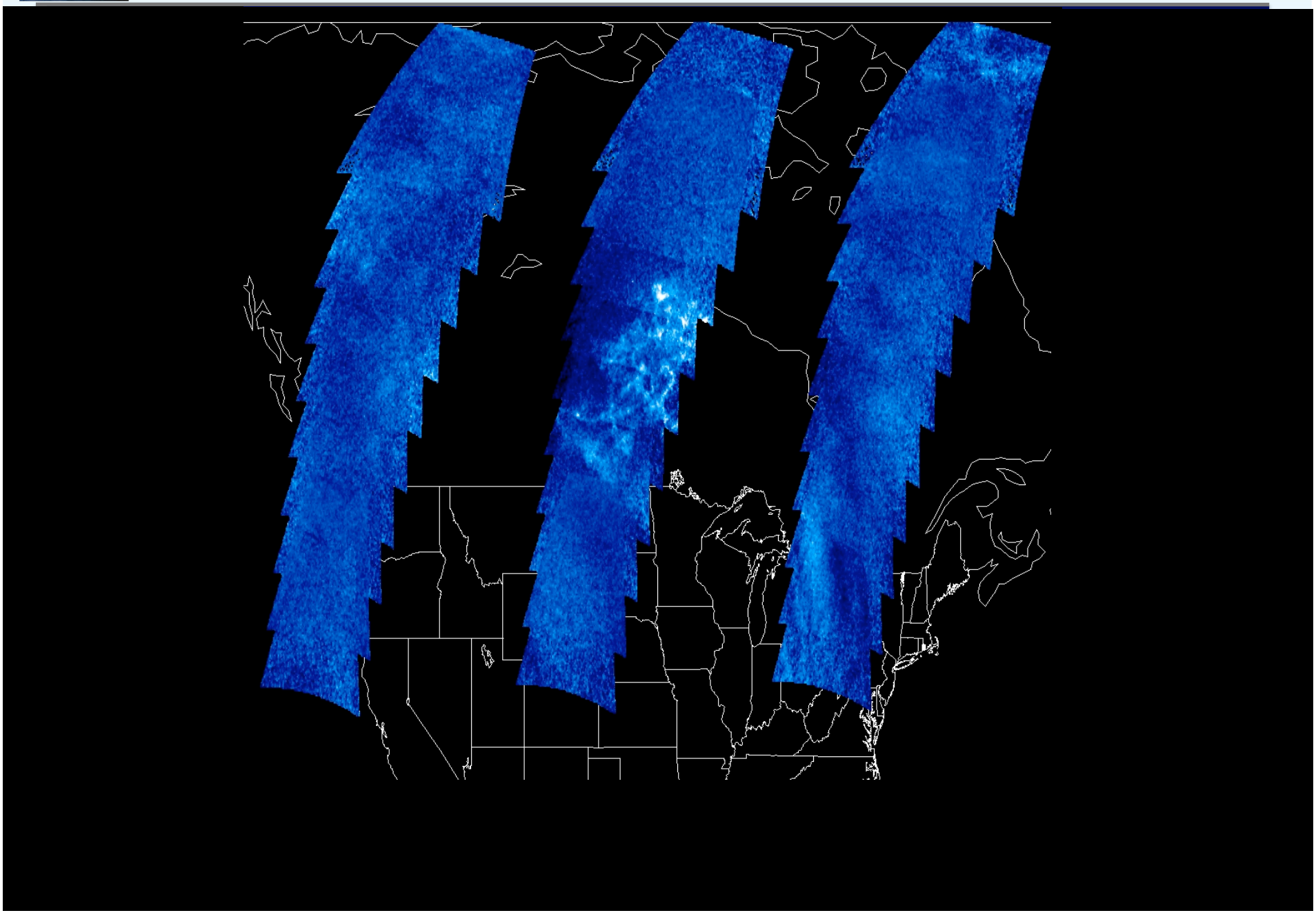
NLCs observed over Omaha, NE (41^0N) on July 14, 2009

Mike Hollingshead



Exploring Clouds at the Edge of Space

AIM observed low latitude PMCs on July 15, 2009



Exploring Clouds at the Edge of Space

Space Station PMC Photograph

Acquired by a Space Station Astronaut on January 30, 2010

Fundamental PMC questions

- Why do these clouds form and vary?
- Why are long - term changes occurring?
- Is there a connection with global change?

What could be causing the observed long-term PMC changes?

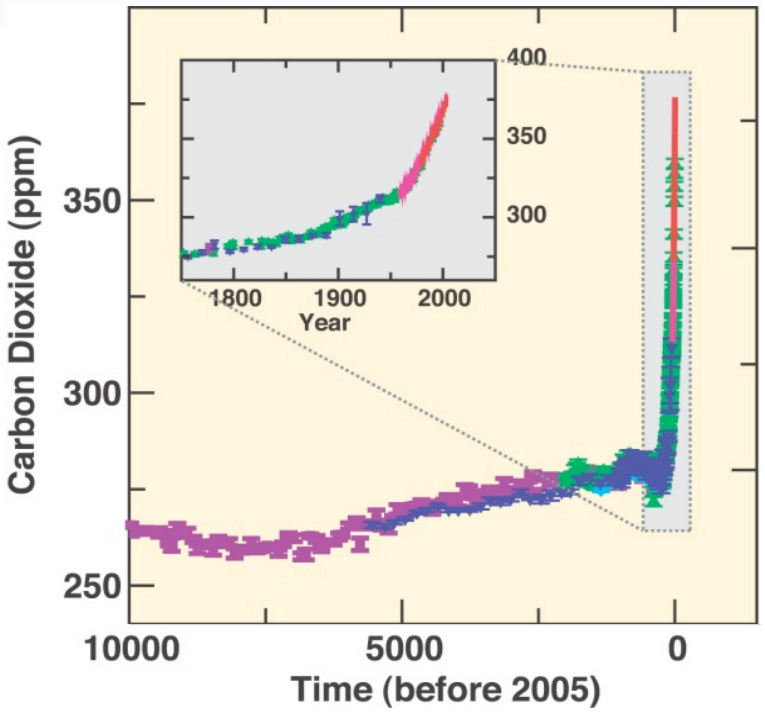
Three things are needed for PMC formation

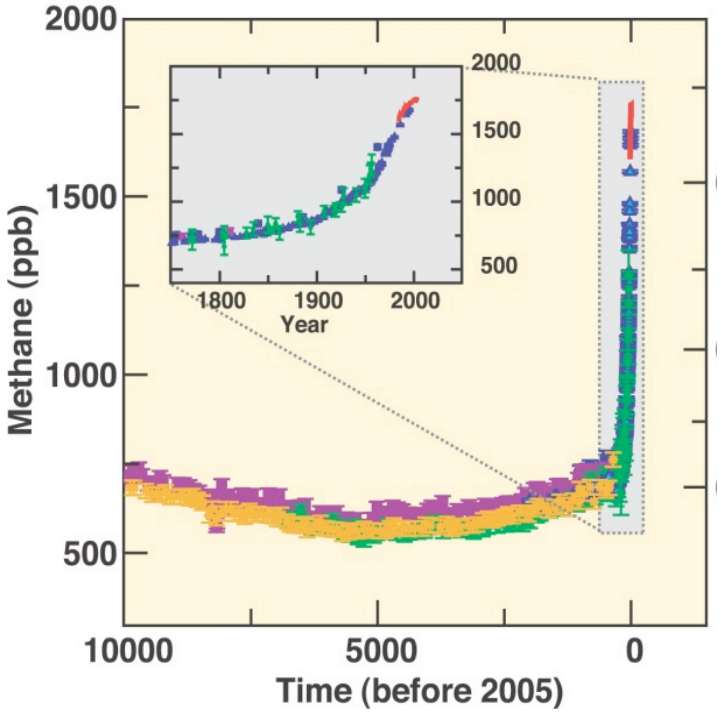
- Water vapor
- Presence of particles
- Cold temperatures

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 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

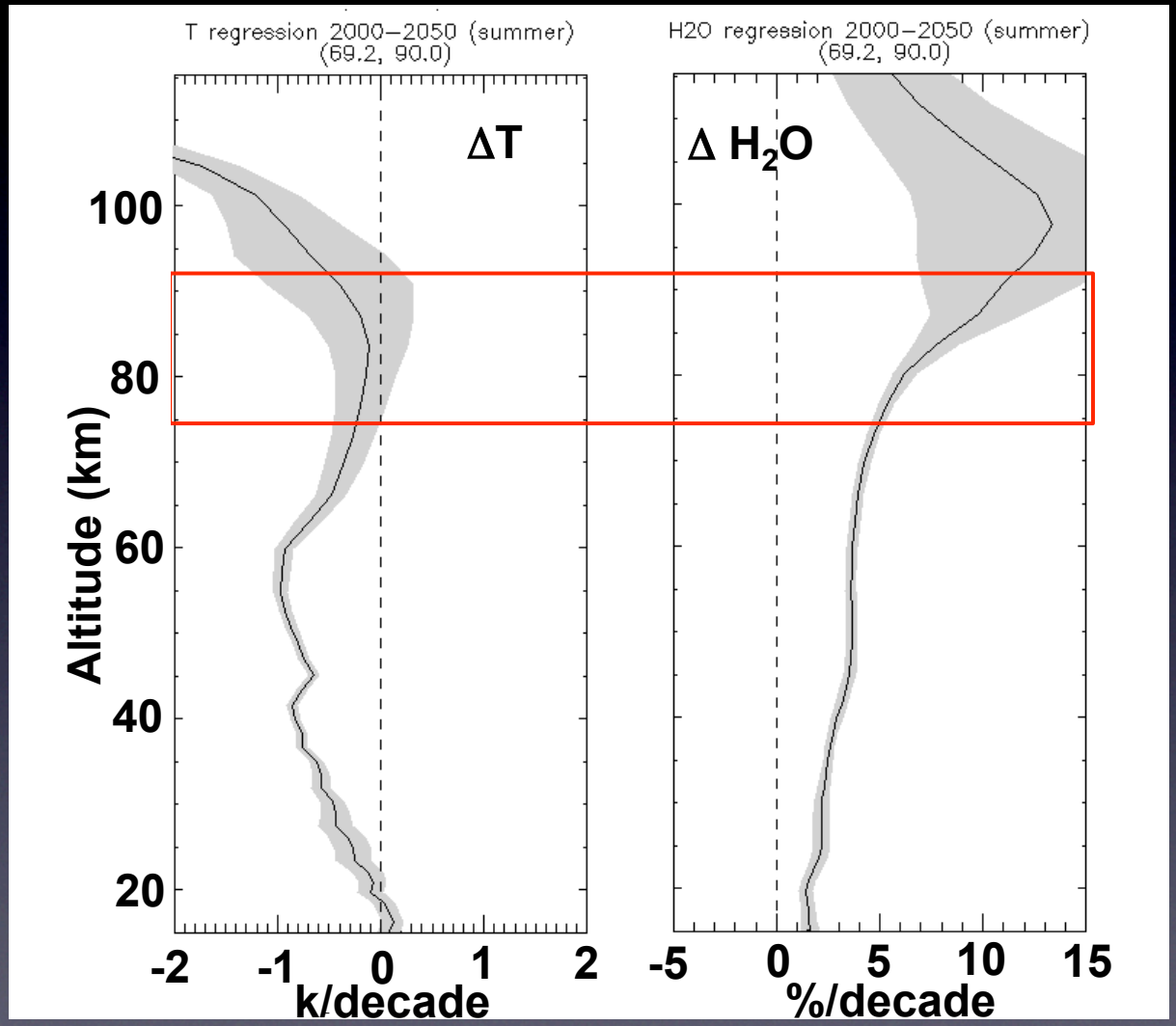
- SSTs from CCSM3 IPCC A1b simulation
- Fixed mean solar conditions; no QBO
- Trends in trace gases from IPCC A1b scenario:
- PMC effect on H_2O not included

	2000	2050
CO_2	369 ppmv	532 ppmv
CH_4	1760 ppbv	2400 ppbv
N_2O	316 ppbv	350 ppbv
CFC-11*	262 pptv	104 pptv
CFC-12*	540 pptv	350 pptv
CFC-113*	82 ppt	46 pptv

* WMO (2003) Scenario Ab

Rolando Garcia, December, 2009

WACCM Estmated Temperature and H_2O trends Arctic (70°N, -90°) 2000-2050 (JJA)



PMC effect on H_2O is not included

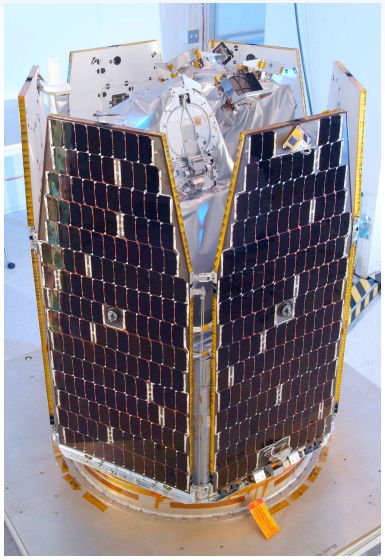
Large trend in H_2O, small trend in T near summer mesopause

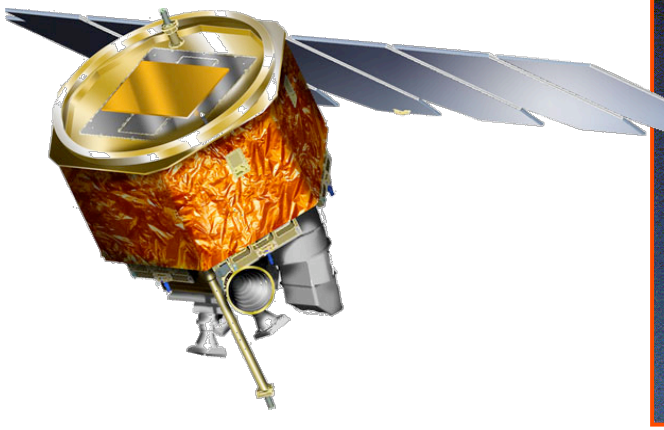
Rolando Garcia, December, 2009

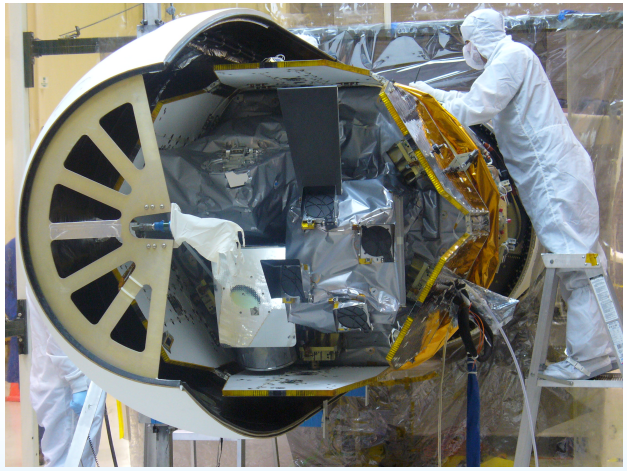
Satellite instruments/missions that have observed or are observing PMCs

• 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



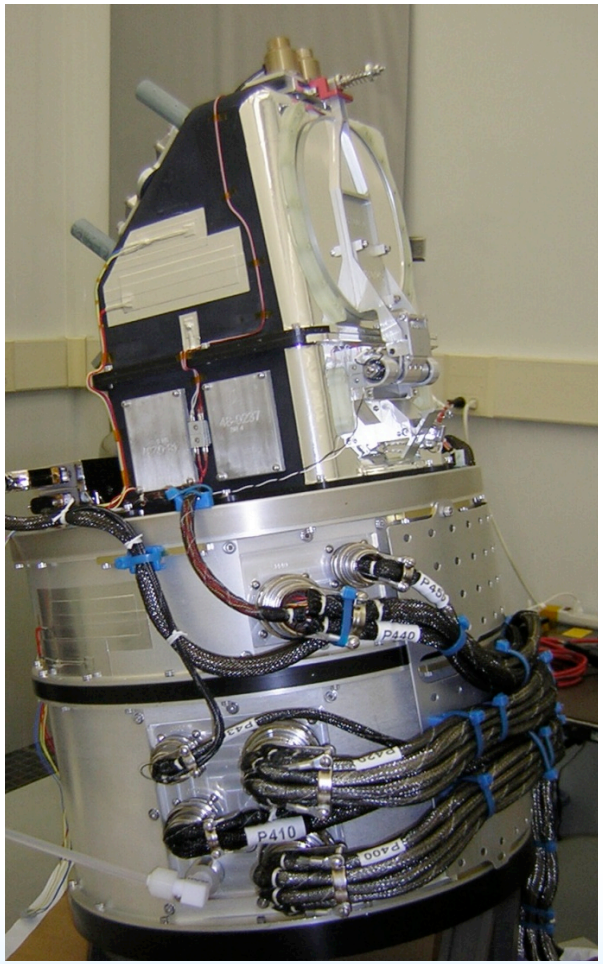




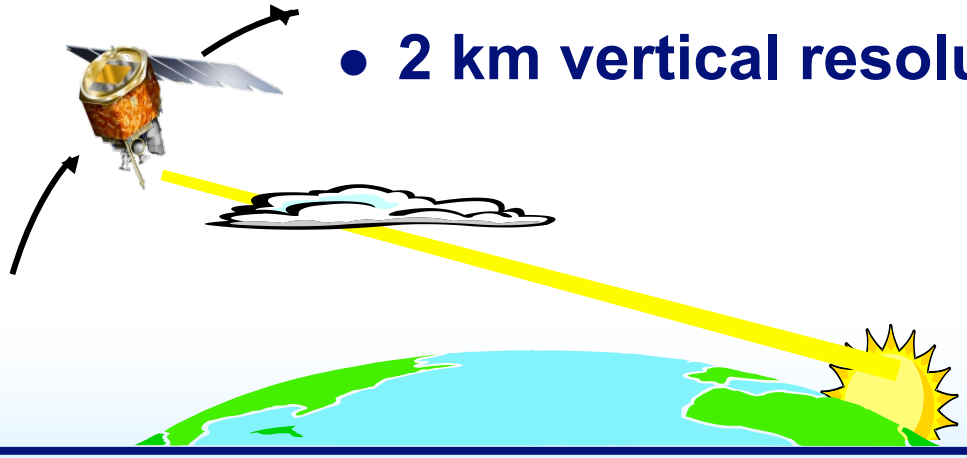
- Launched April 25, 2007 at 1:26:03 PDT
- Near perfect 600 km orbit
  - 596 km perigee, 601 km apogee
  - Ascending node equatorial crossing time only 47 seconds off

SOFIE: Solar Occultation for Ice Experiment

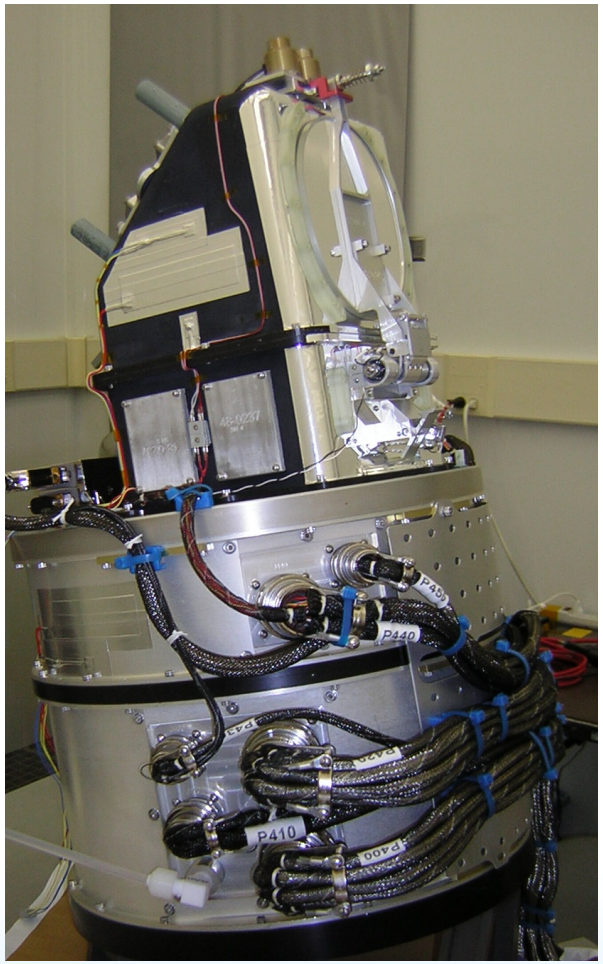
A 16-band differential absorption radiometer (UV to IR) to simultaneously measure cloud properties and the PMC environment

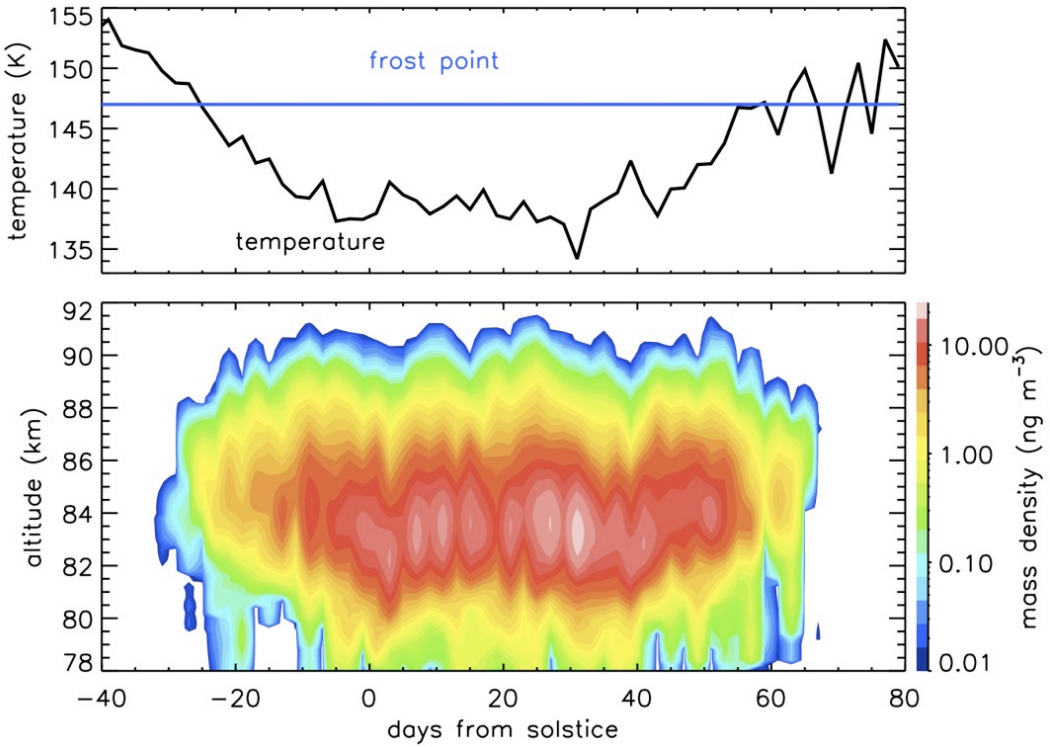


- **Operates over 0.3μm to 5.3 μm range**
- **T, NLCs, CO_2, H_2O, CH_4, NO, O_3, aerosols, cosmic smoke**
- **2 km vertical resolution**



SOFIE: Solar Occultation for Ice Experiment

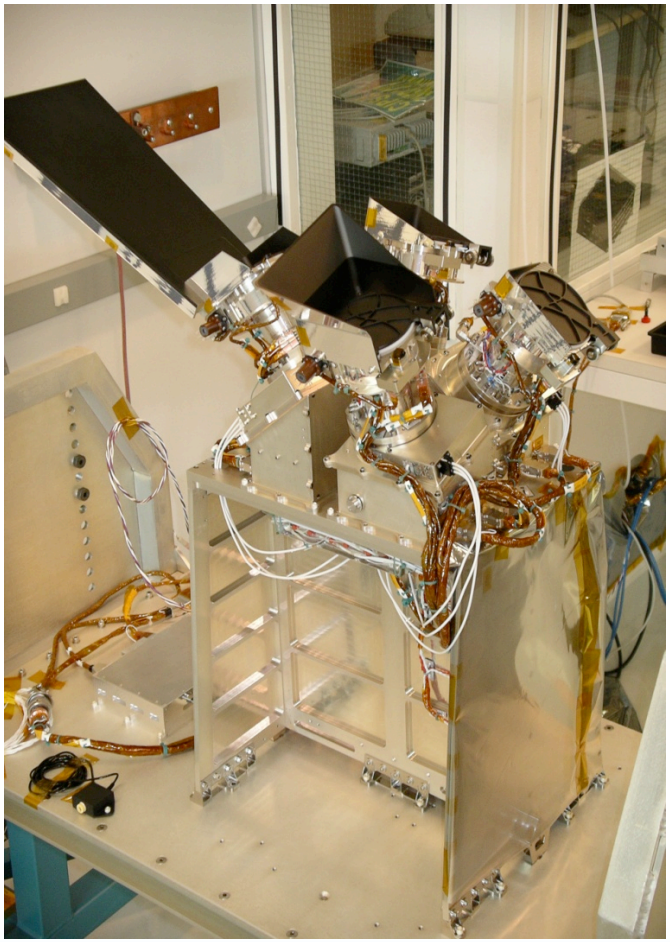




High SOFIE sensitivity allows subvisible ice to be measured; suspected from radar echos, but never observed before AIM

CIPS: Cloud Imaging and Particle Size Experiment

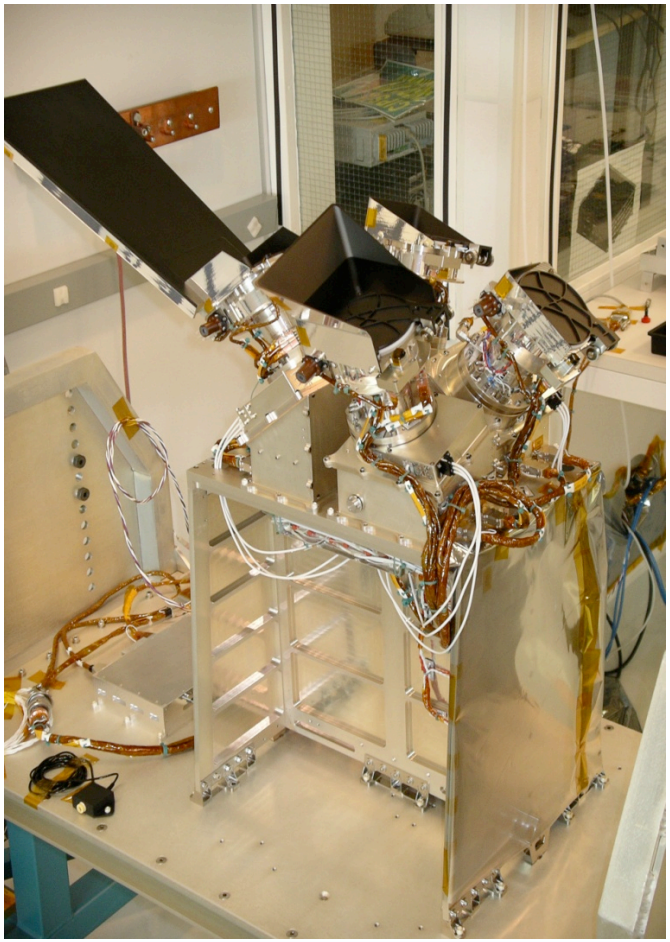
Four CCD cameras image PMCs at ~ 83 km

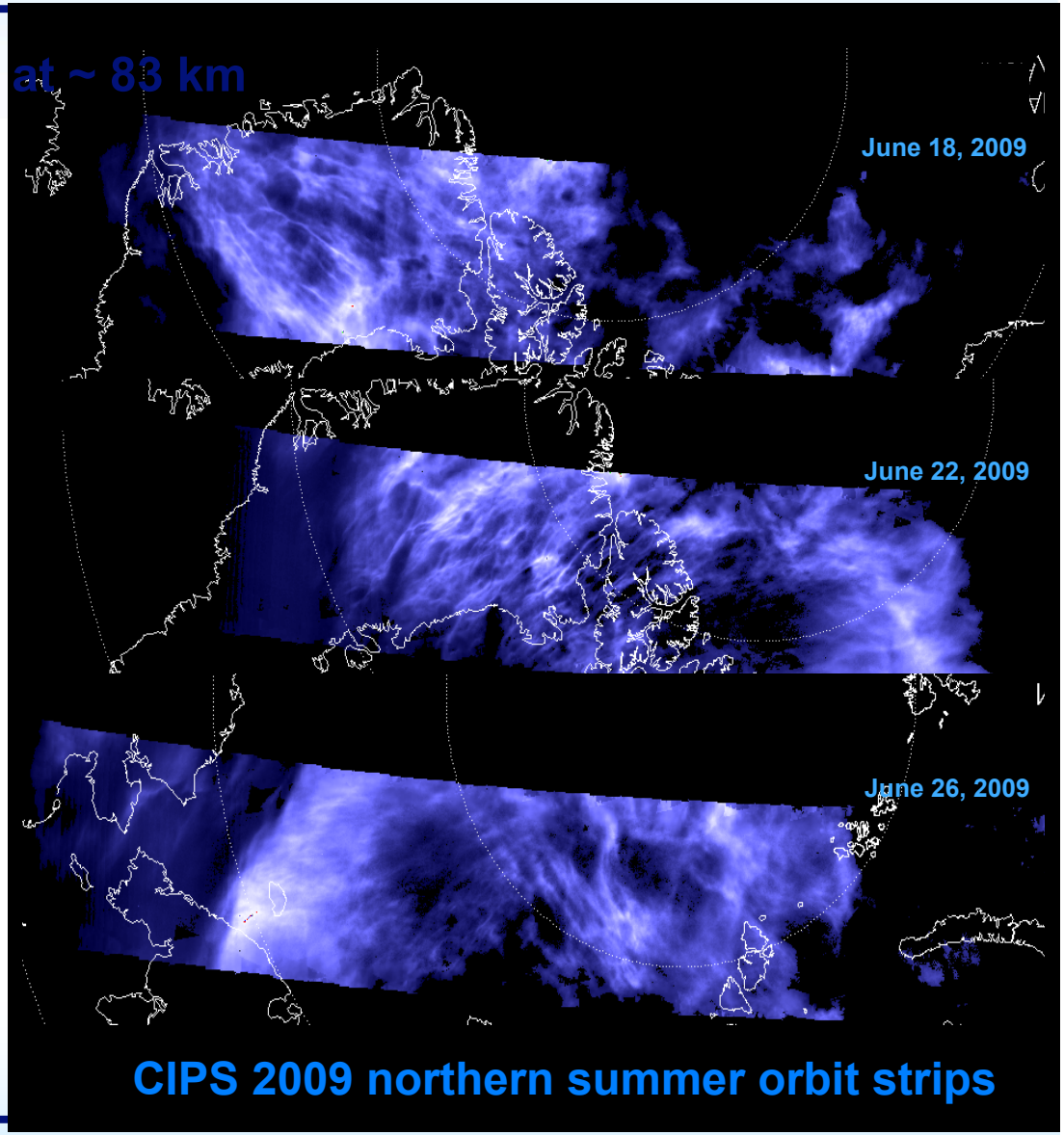


- λ = 0.265 μm; 1 X 2.5 km pixel size
- Cloud morphology and particle sizes

CIPS: Cloud Imaging and Particle Size Experiment

Four CCD cameras image PMCs at ~ 83 km

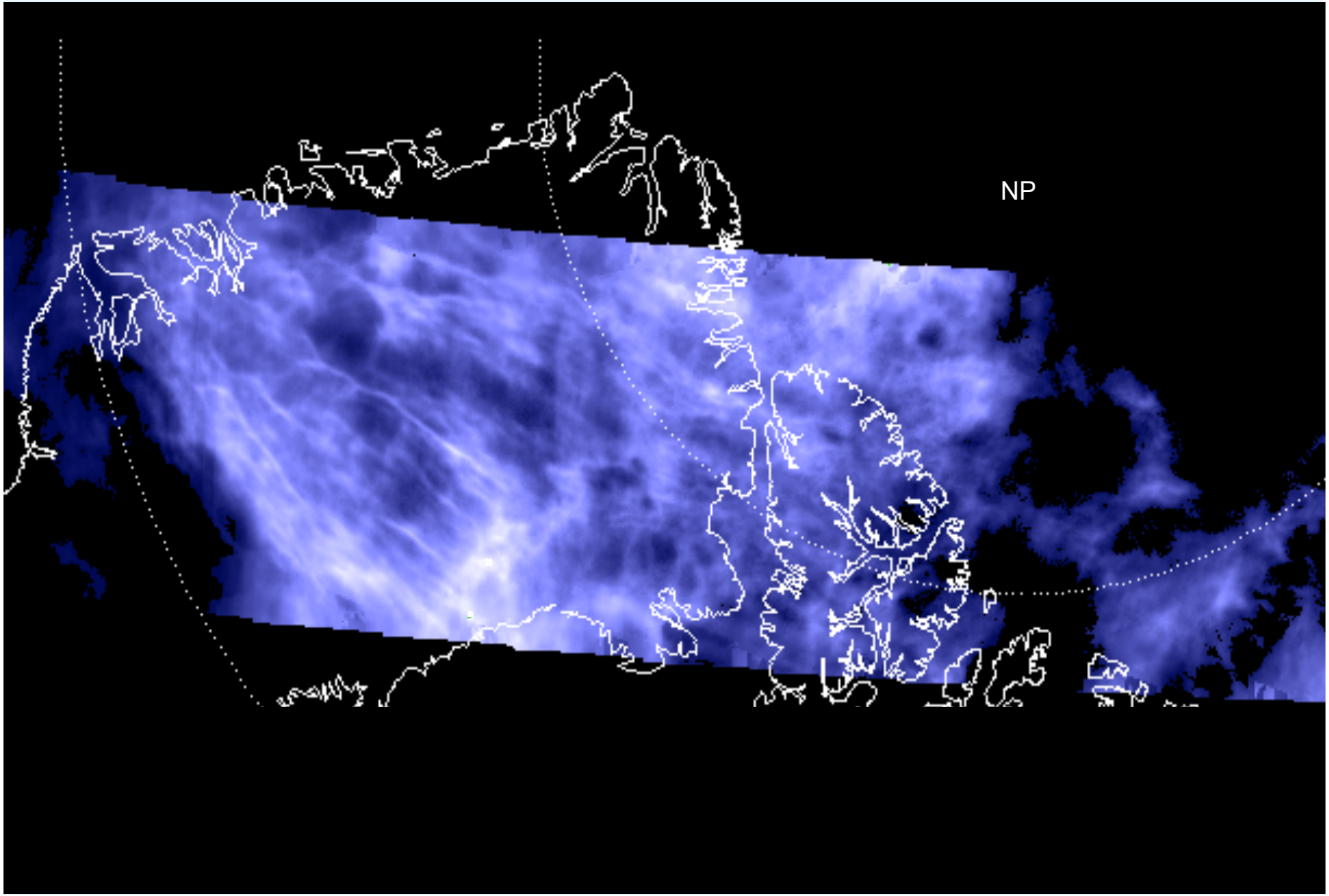


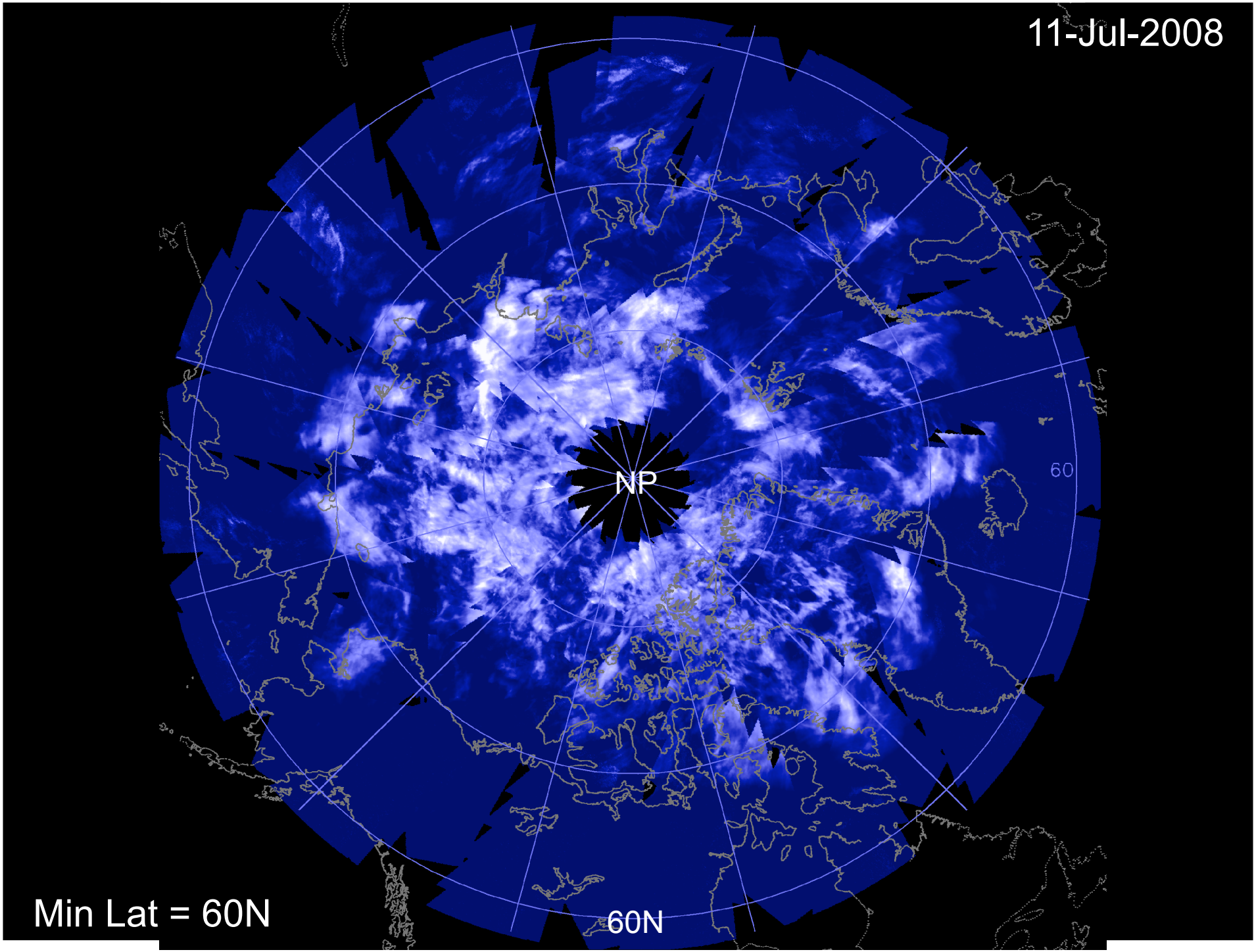


CIPS 2009 northern summer orbit strips

Exploring Clouds at the Edge of Space

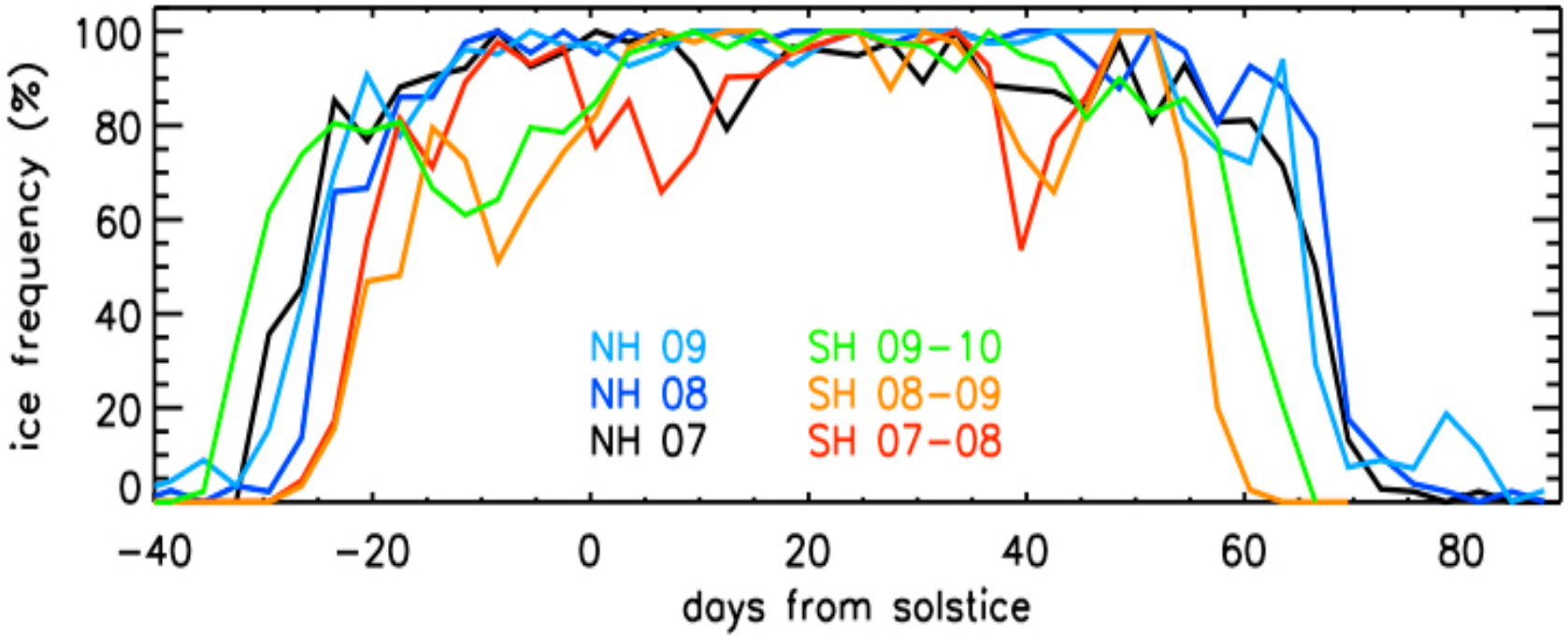
CIPS image shows detailed structure and ice voids




11-Jul-2008
NP
60
Min Lat = 60N
60N

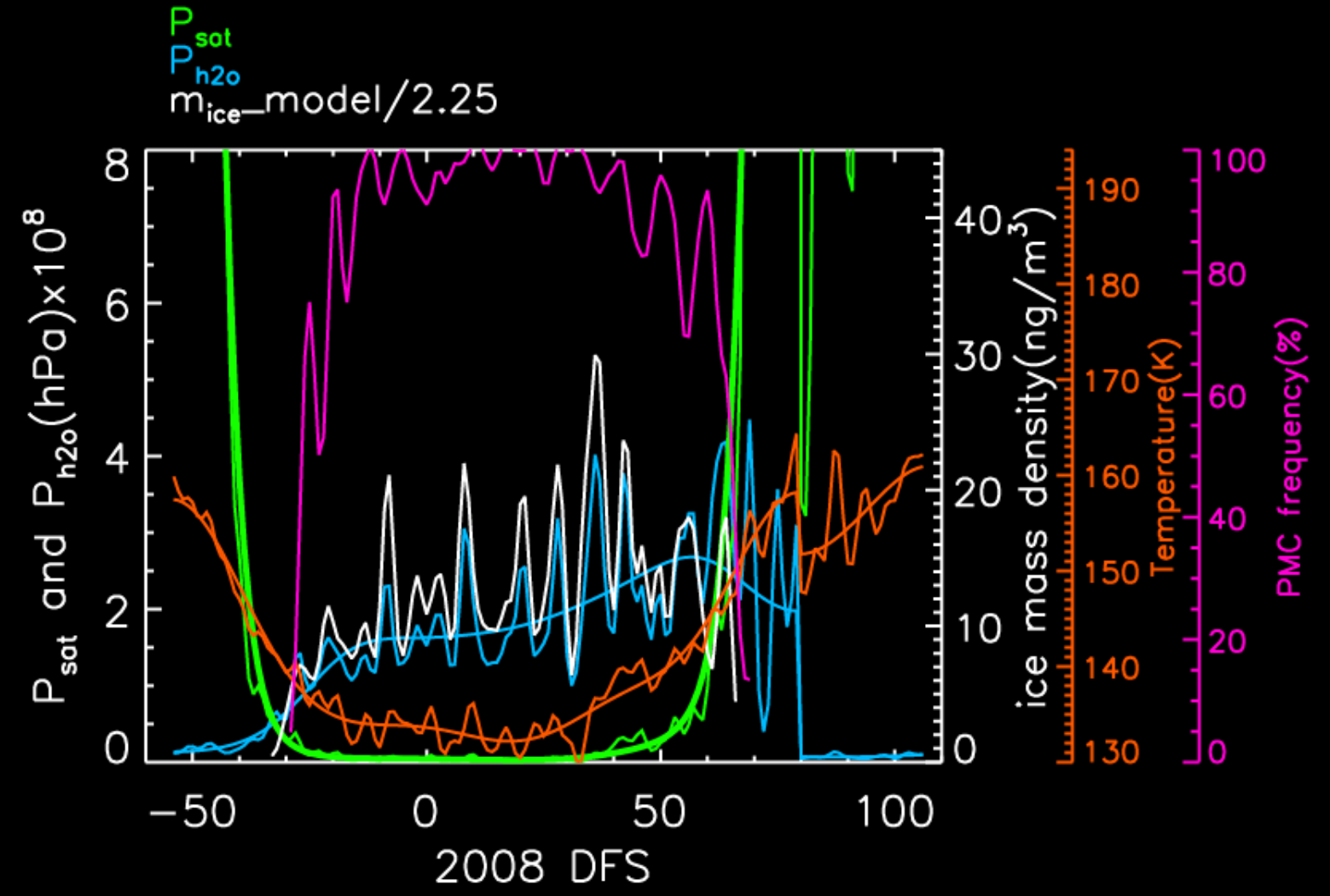
What is the role of temperature and water vapor in the formation of PMCs?

The PMC season turns on and off abruptly like a geophysical light bulb



The season start and end times are highly variably in the south

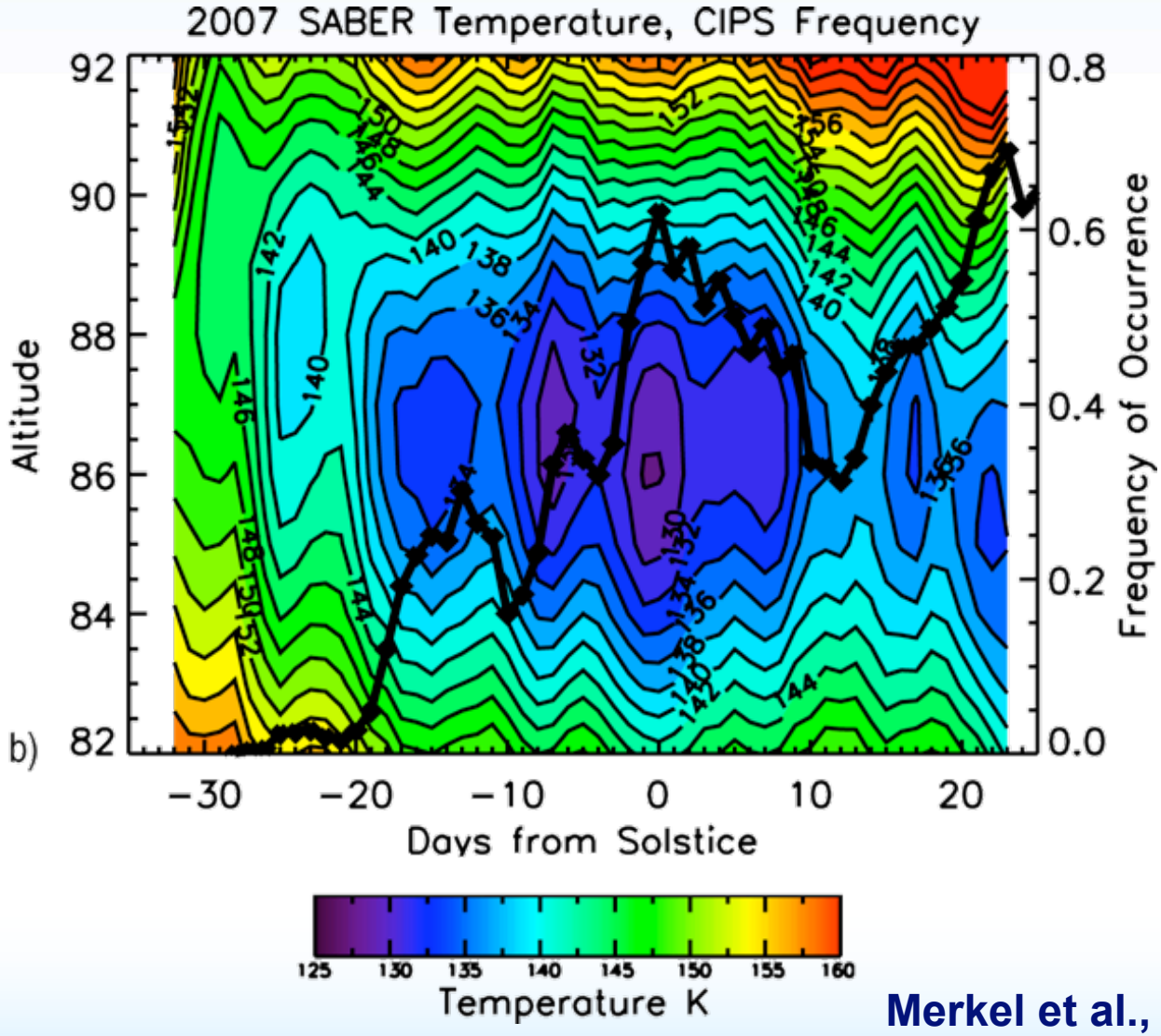
Temperature is in dominant control at the season start and end. H_2O is in control during the season.



Northern Hemisphere

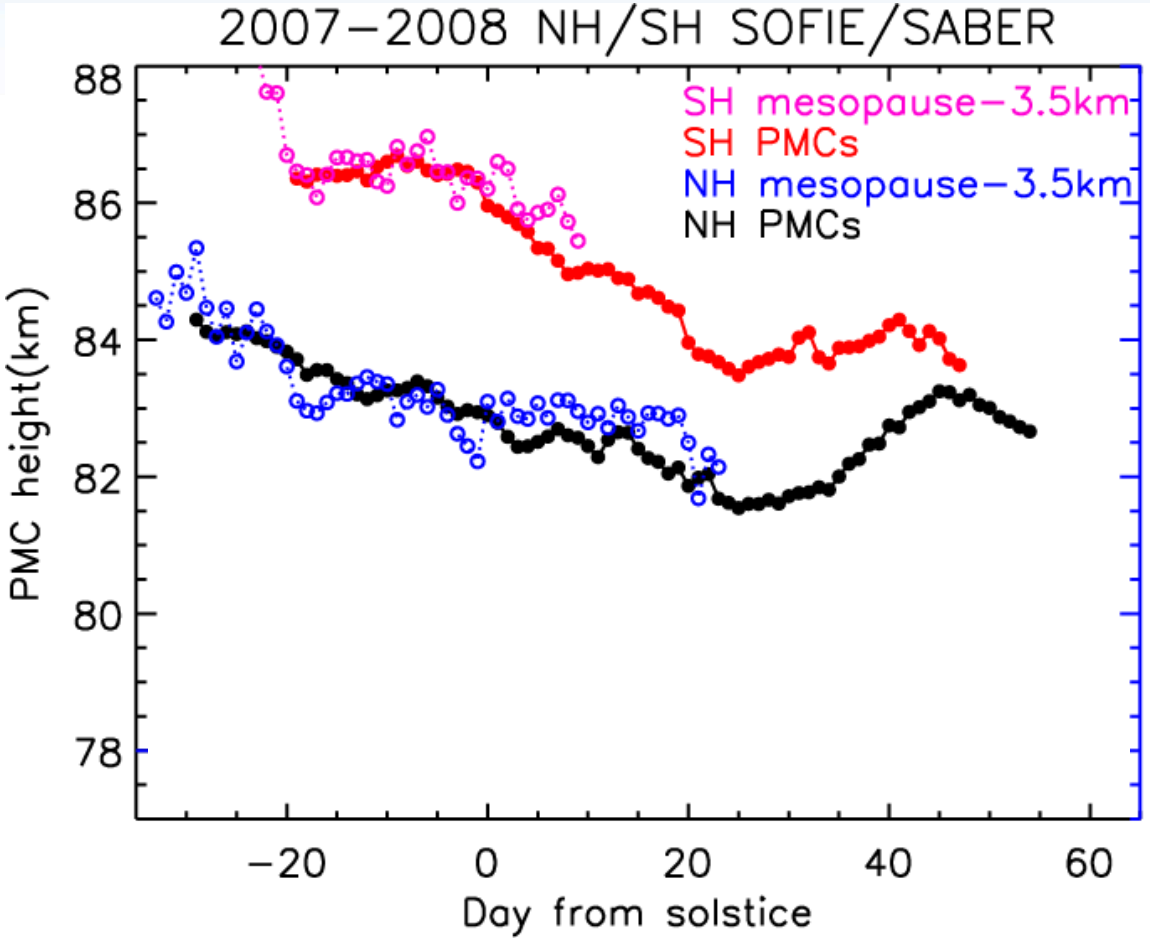
Temperature is a factor in PMC variability even during the season

CIPS PMC frequency at 77° latitude and SABER temperature



Merkel et al., 2007

Mesopause temperature is a driver for PMC peak altitude formation

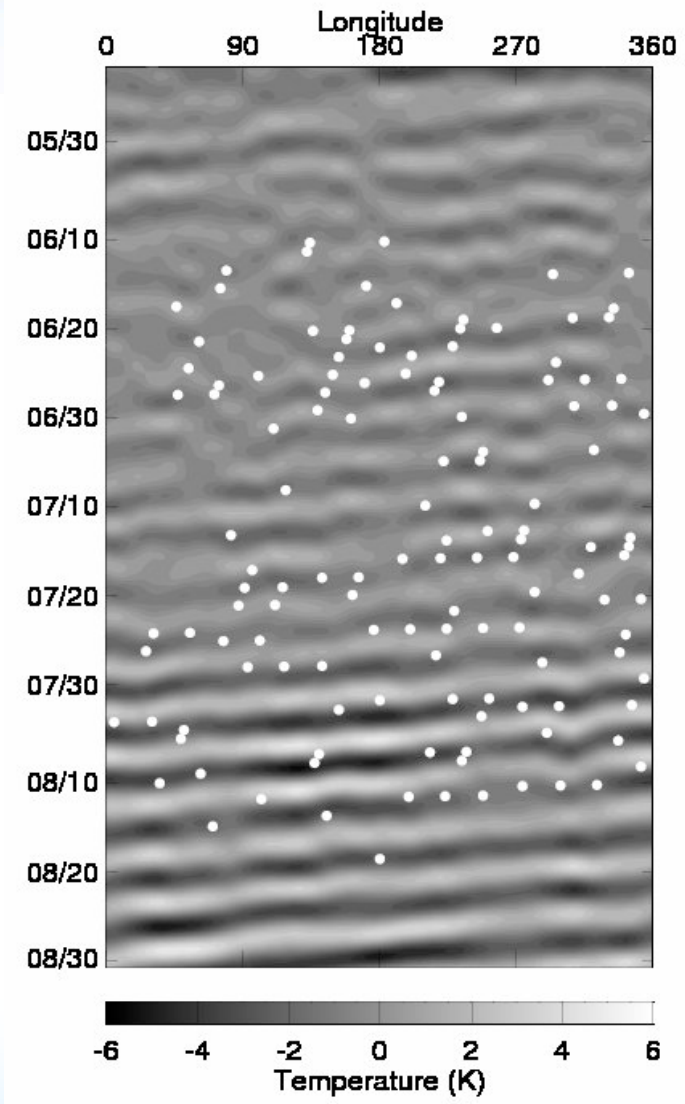


SOFIE PMC altitude and SABER mesopause minus 3.5 km (circles) for 2007 - 2008 NH/SH seasons

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

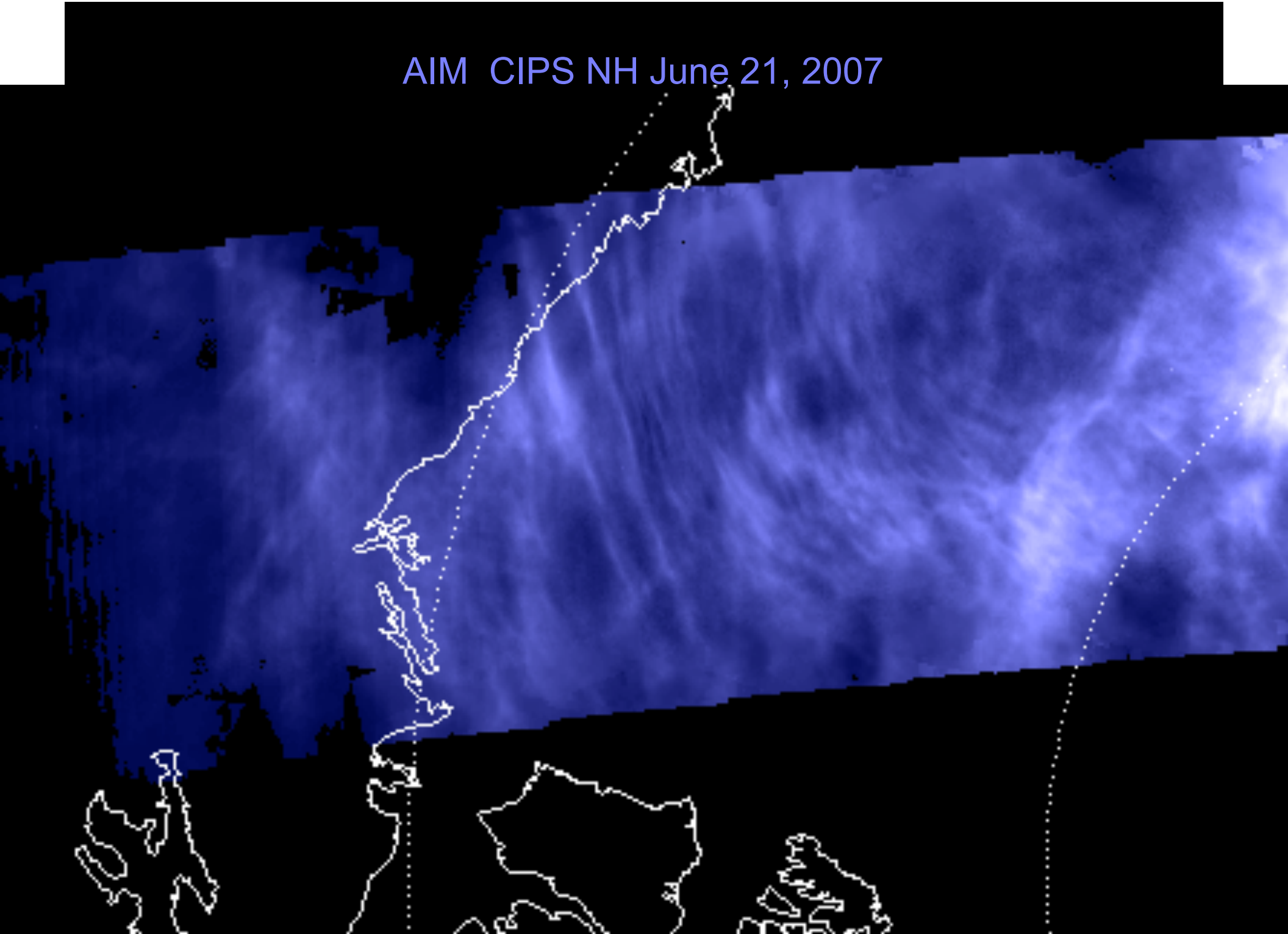


Temperature wavelet amplitudes (grey and black)

Observed SOFIE clouds for ice >30 ng/m^3 (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

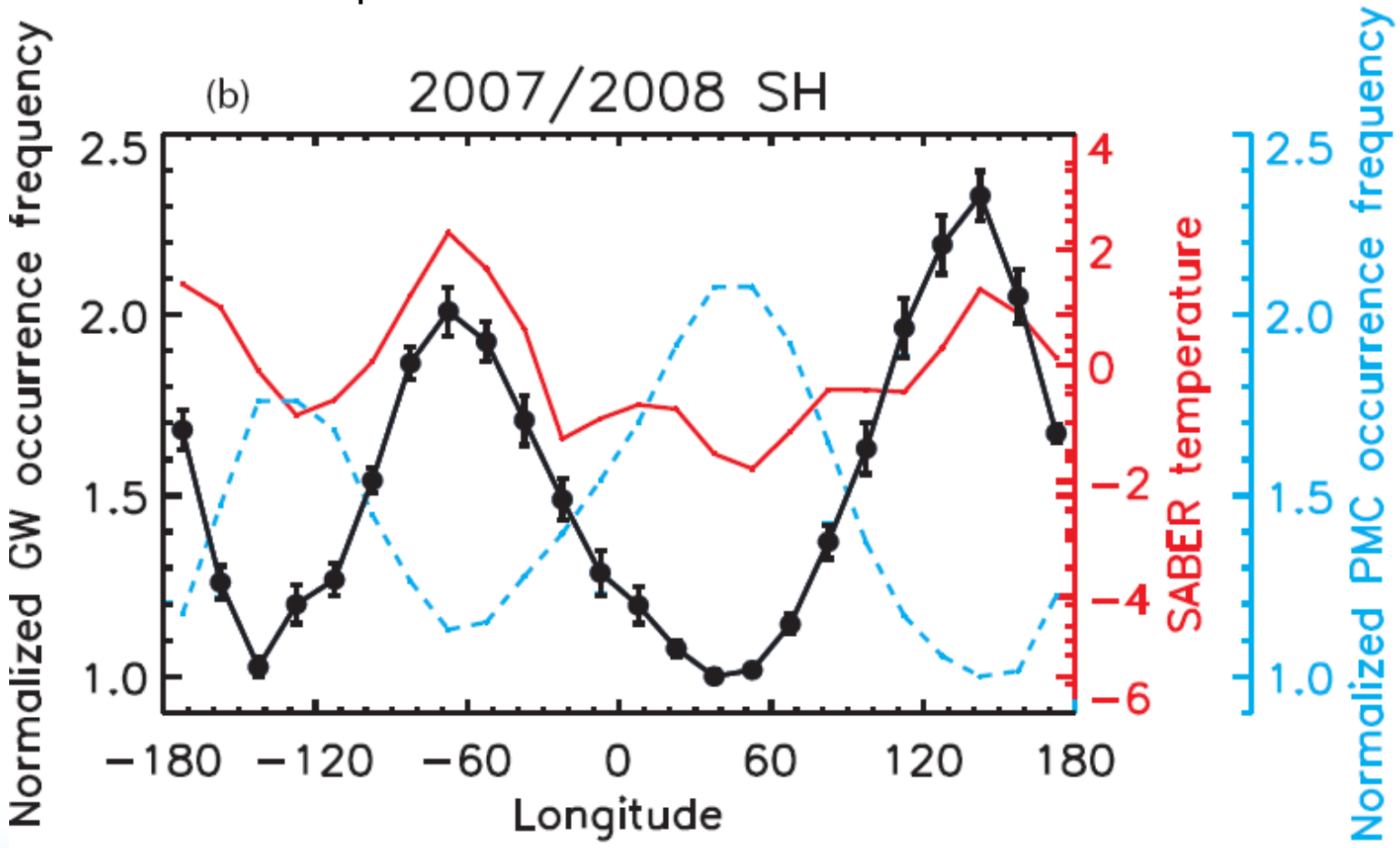

AIM CIPS NH June 21, 2007

Gravity waves cause PMCs to dissipate
SABER Ts suggest that GWs lead to local heating

GW and PMC correlation: **- 0.94**

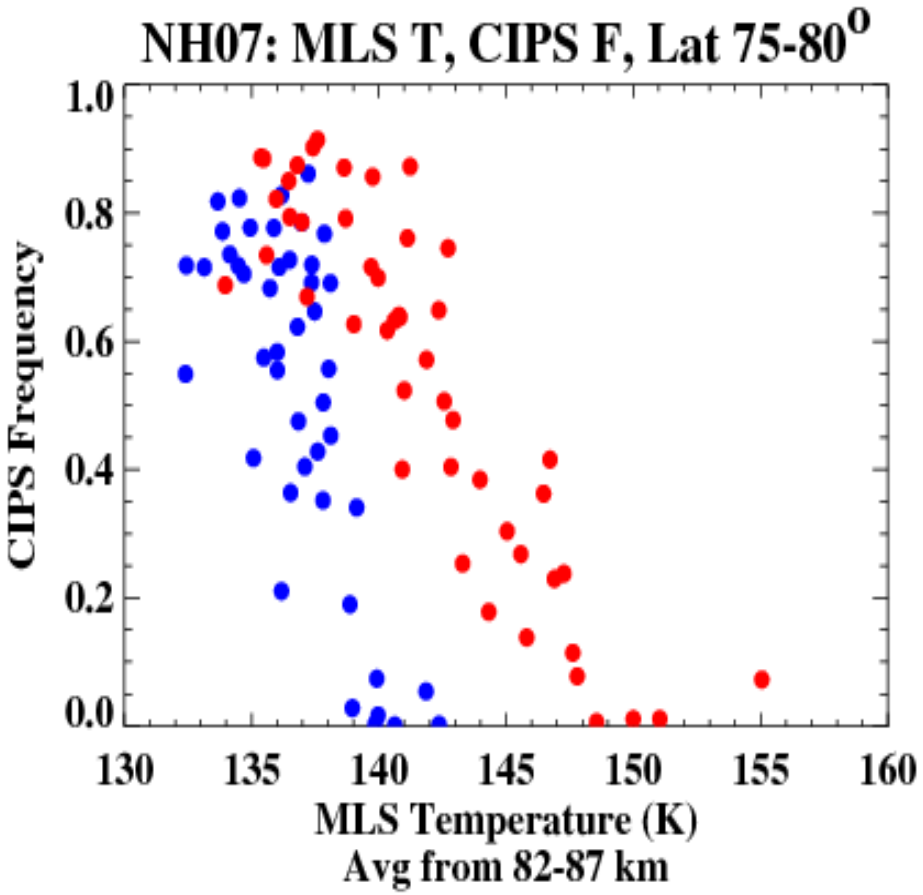
GW and SABER temperature correlation: **0.72**

70^0S -80^0S
± 10 DFS



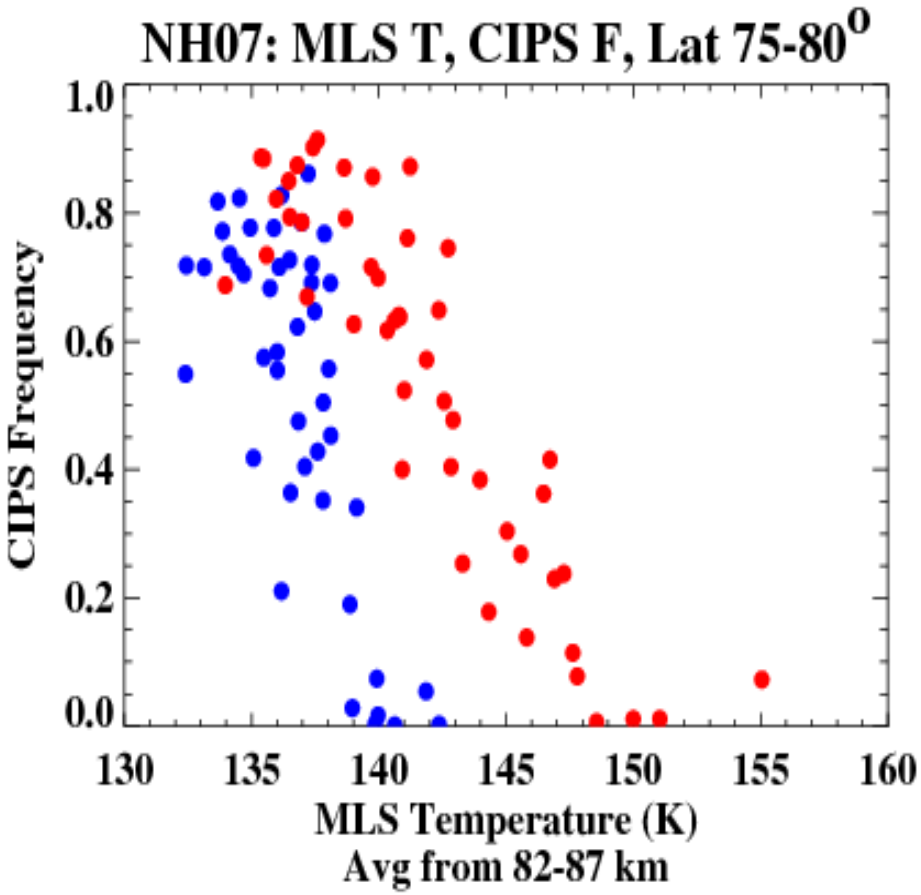
Chandran et al., 2009

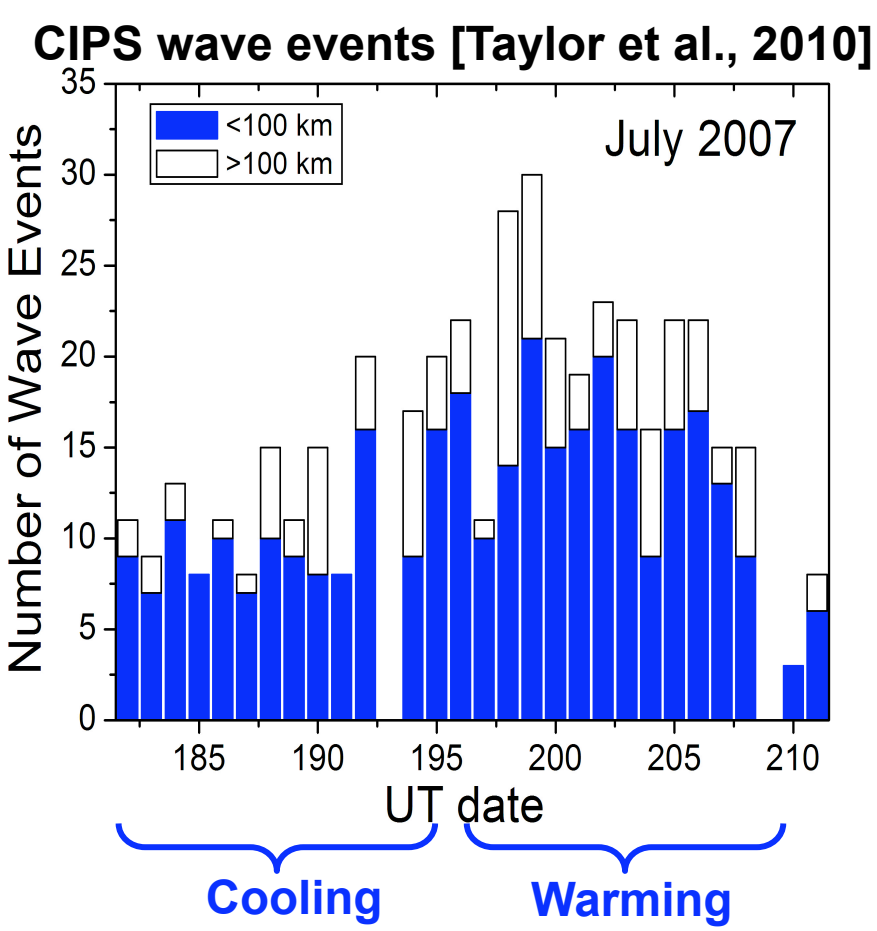
CIPS PMC frequency shows a bifurcation during the cooling and warming phases of the season



Is it caused by a steady H_2O 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

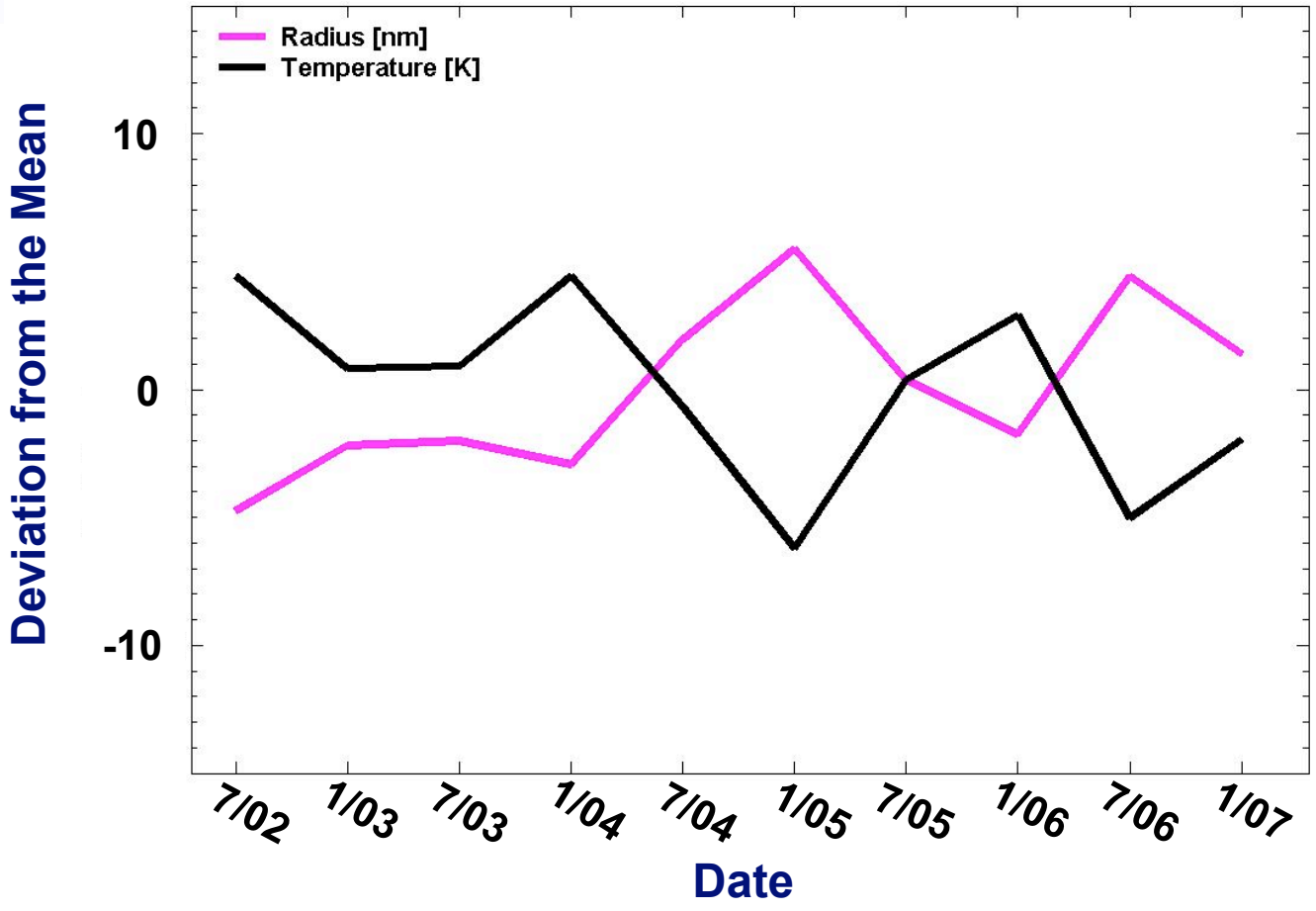




Is it caused by a steady H_2O increase that amplifies PMC growth during the cooling phase and buffers sublimation during warming? Or is it dynamics?

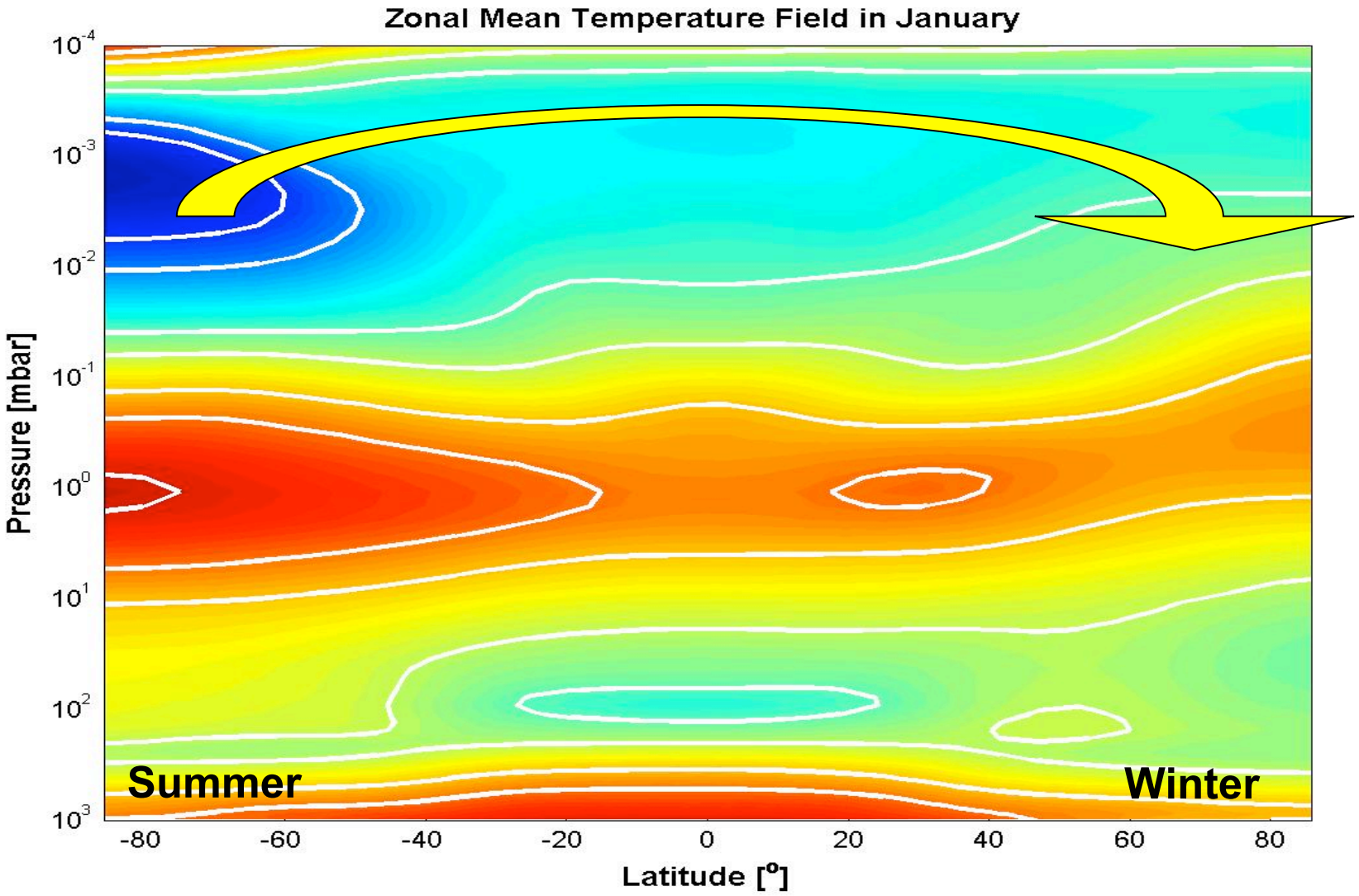
What are the mechanisms leading to hemispheric coupling effects on PMC formation?

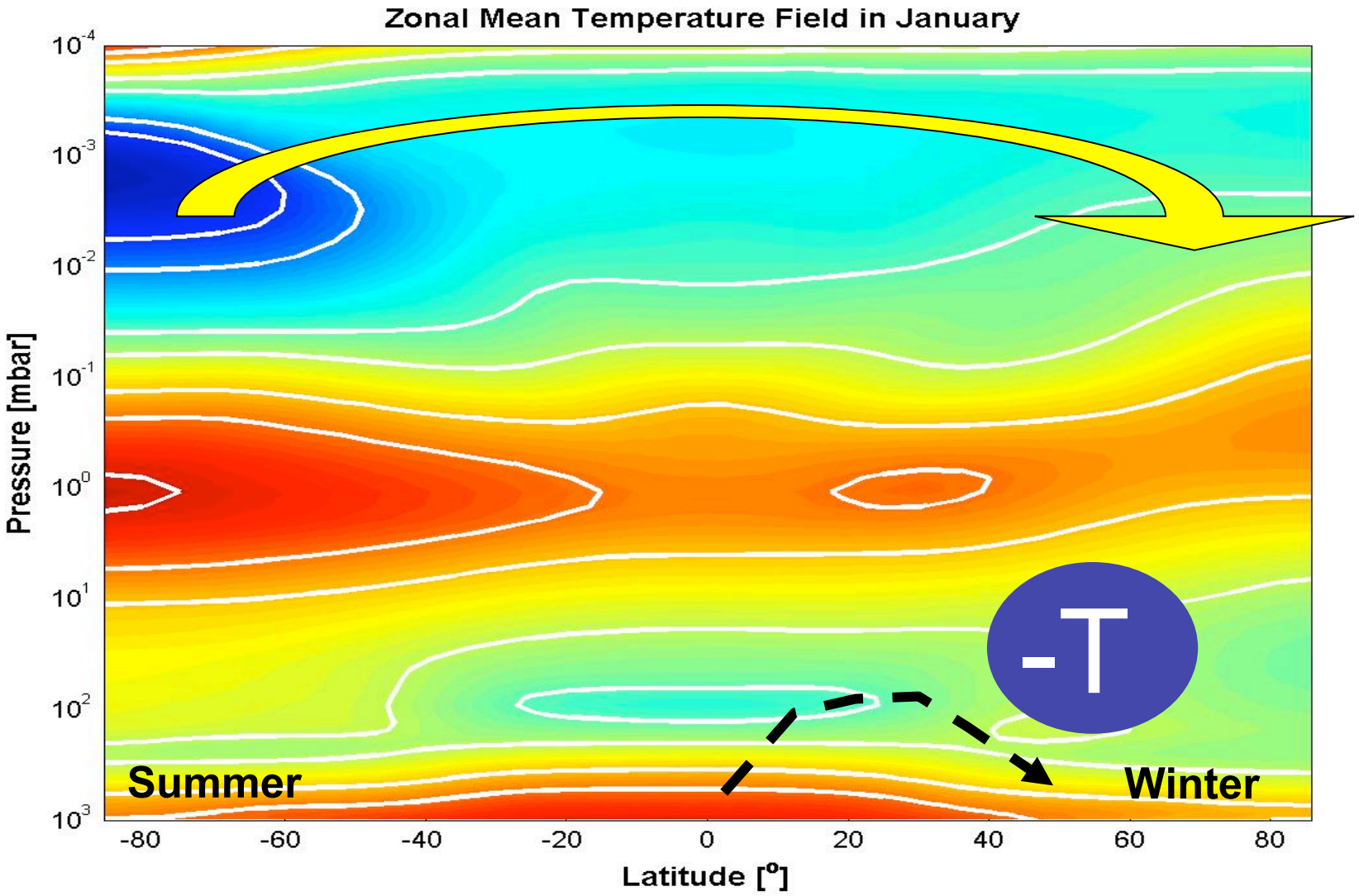
What is the mechanism for teleconnection? Stratospheric winter T and PMC radius anomalies



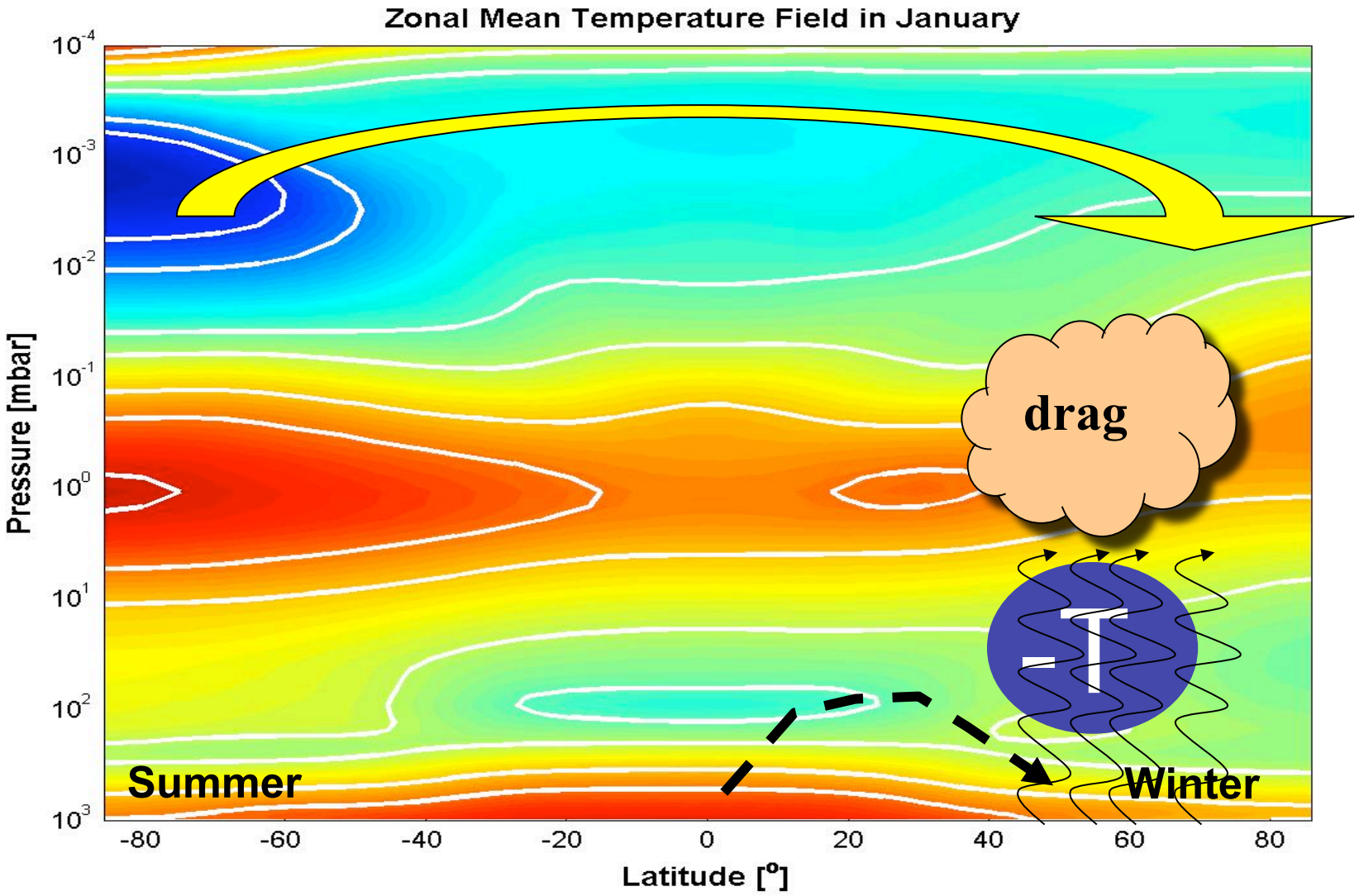
Correlation coefficient = - 0.95

Adapted from Karlsson et al, Geophys. Res. Lett., 34, 2007
Based on analysis of ODIN OSIRIS data

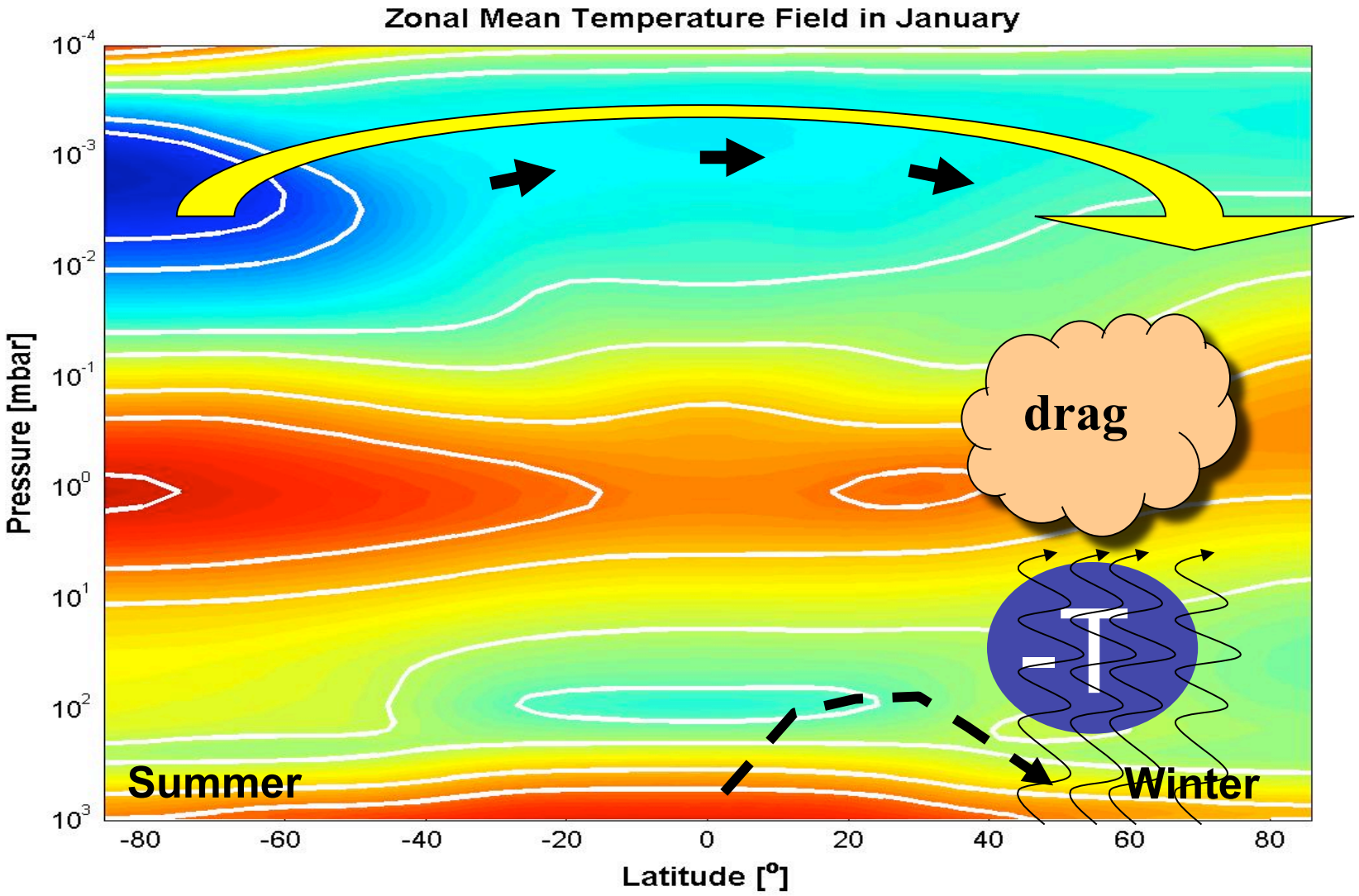

Zonal Mean Temperature Field in January
Pressure [mbar]
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
Summer
Winter
-80
-60
-40
-20
0
20
40
60
80
Latitude [°]



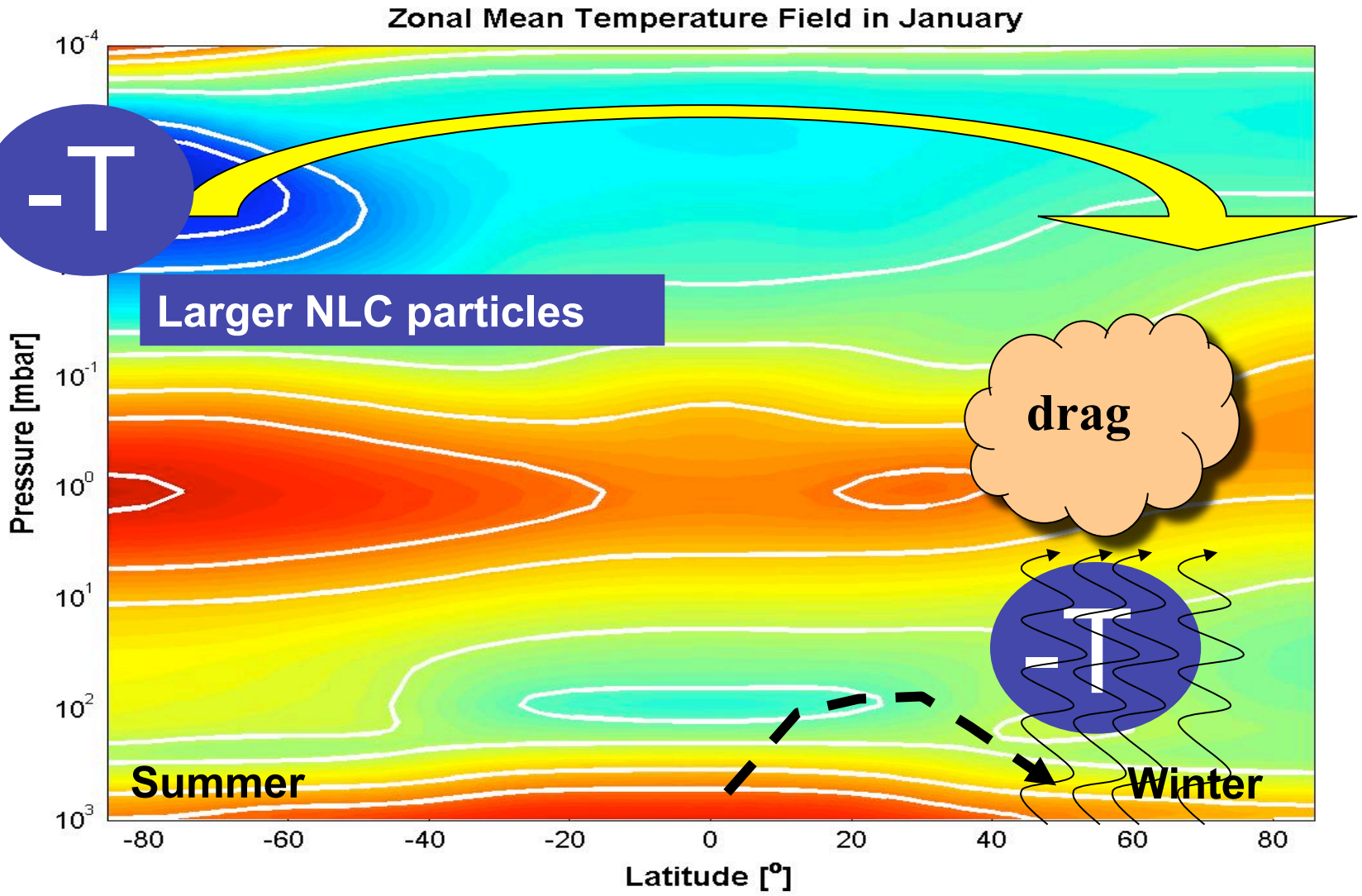
Less planetary wave activity in stratosphere (cold)



Less planetary wave activity in stratosphere (cold) → More net gravity wave drag

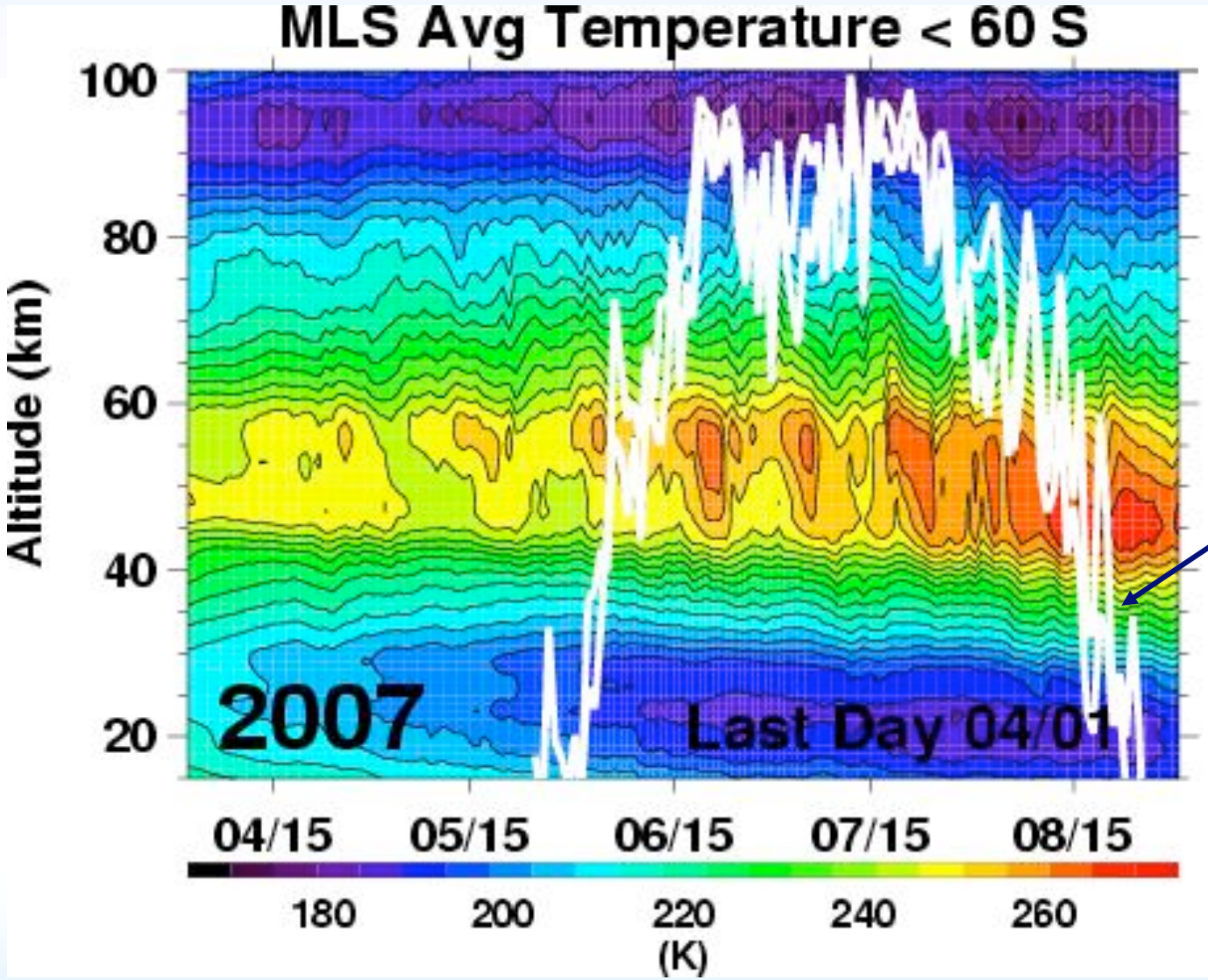


Less planetary wave activity in stratosphere (cold) → More net gravity wave drag → Stronger circulation in mesosphere



Less planetary wave activity in stratosphere (cold) → More net gravity wave drag → Stronger circulation in mesosphere → Colder summer mesopause

AIM NH PMC data and MLS SH Temp show summer and winter hemisphere coupling



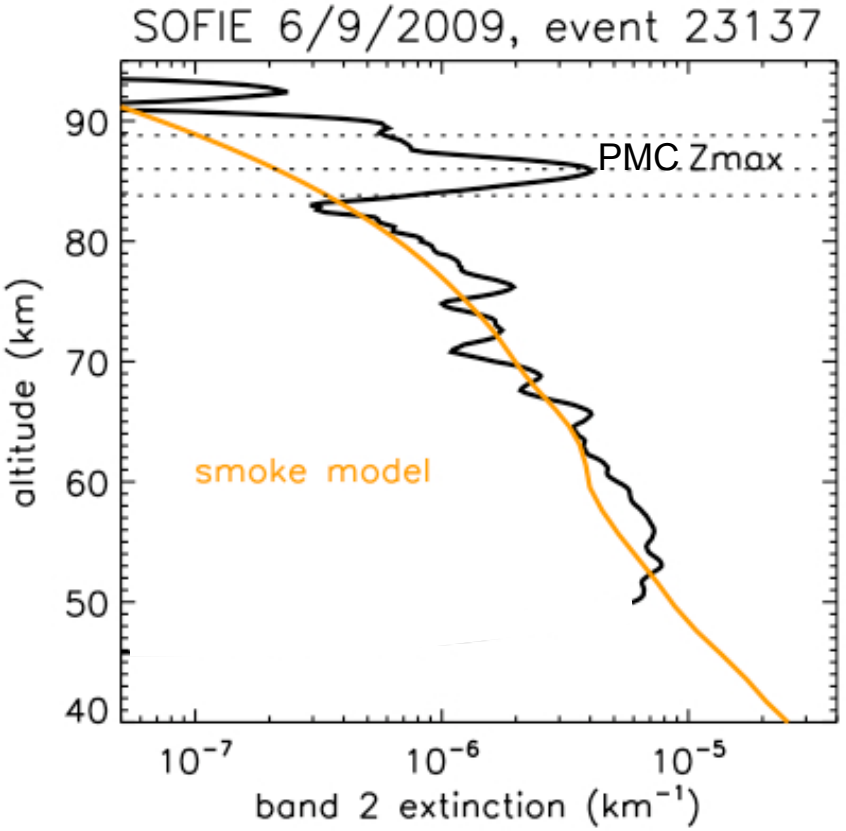
CIPS NH frequency of PMC occurrence

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

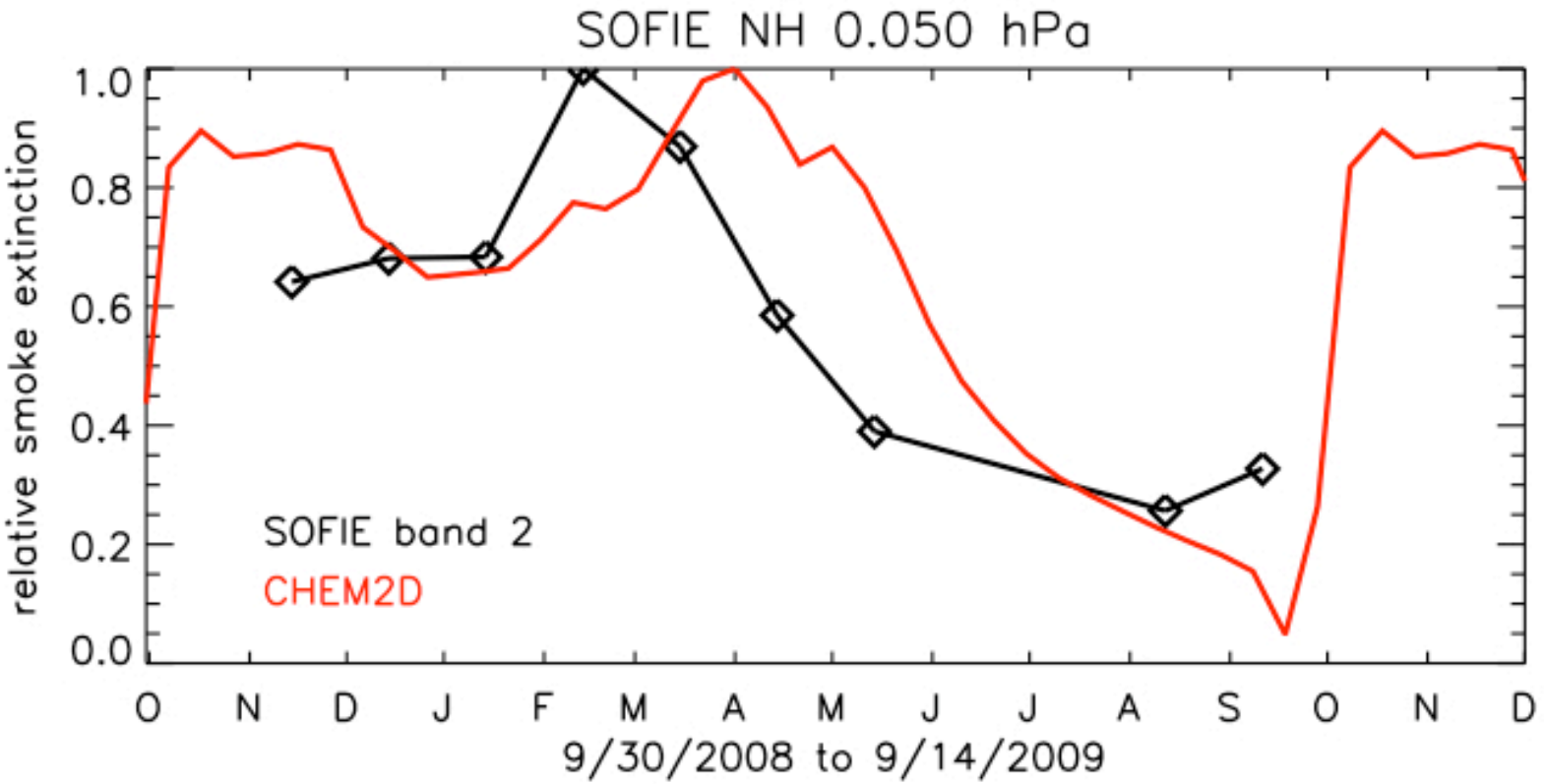


Three nucleation source theories

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

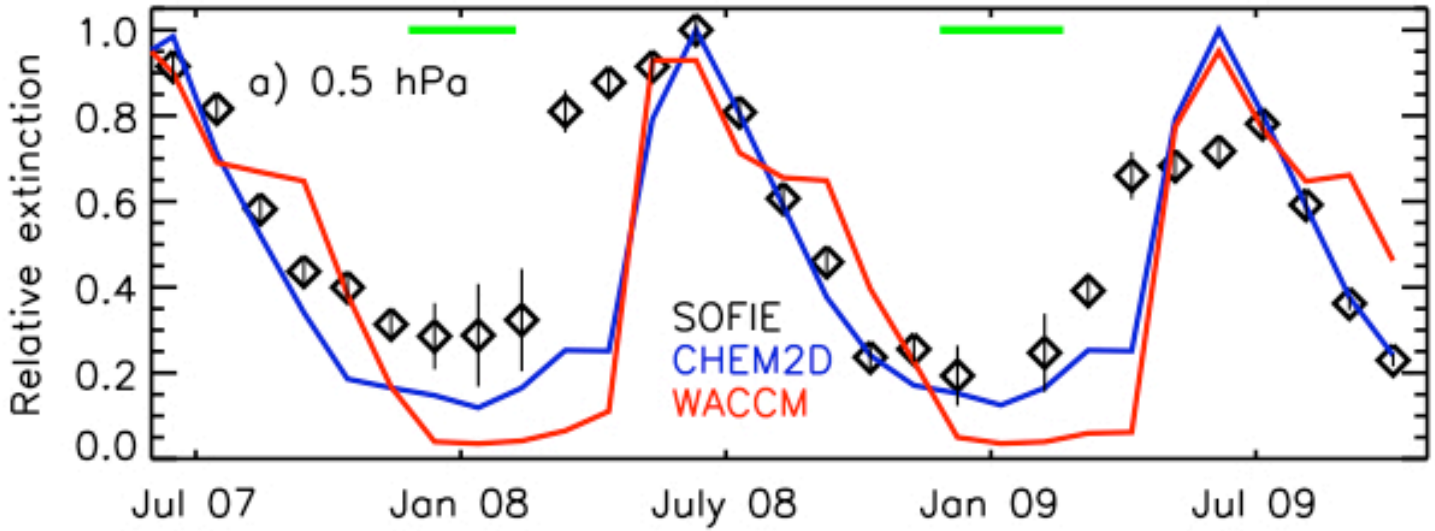
Air is upwelling during the PMC season. SOFIE has collected thousands of such profiles to study PMC and smoke correlations.

Northern Hemisphere smoke versus time for Sept 30, 2008 to Sept. 14, 2009

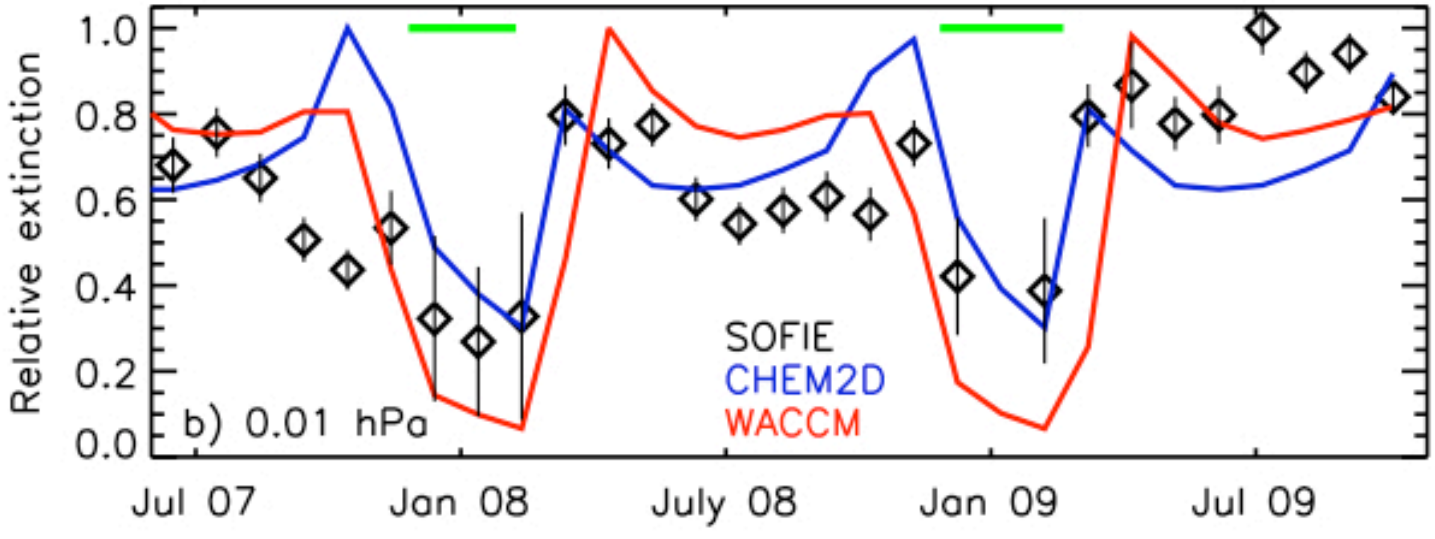


8 arcmin solar lockdown once a month

SOFIE Southern Hemisphere smoke time series



55 km



82 km

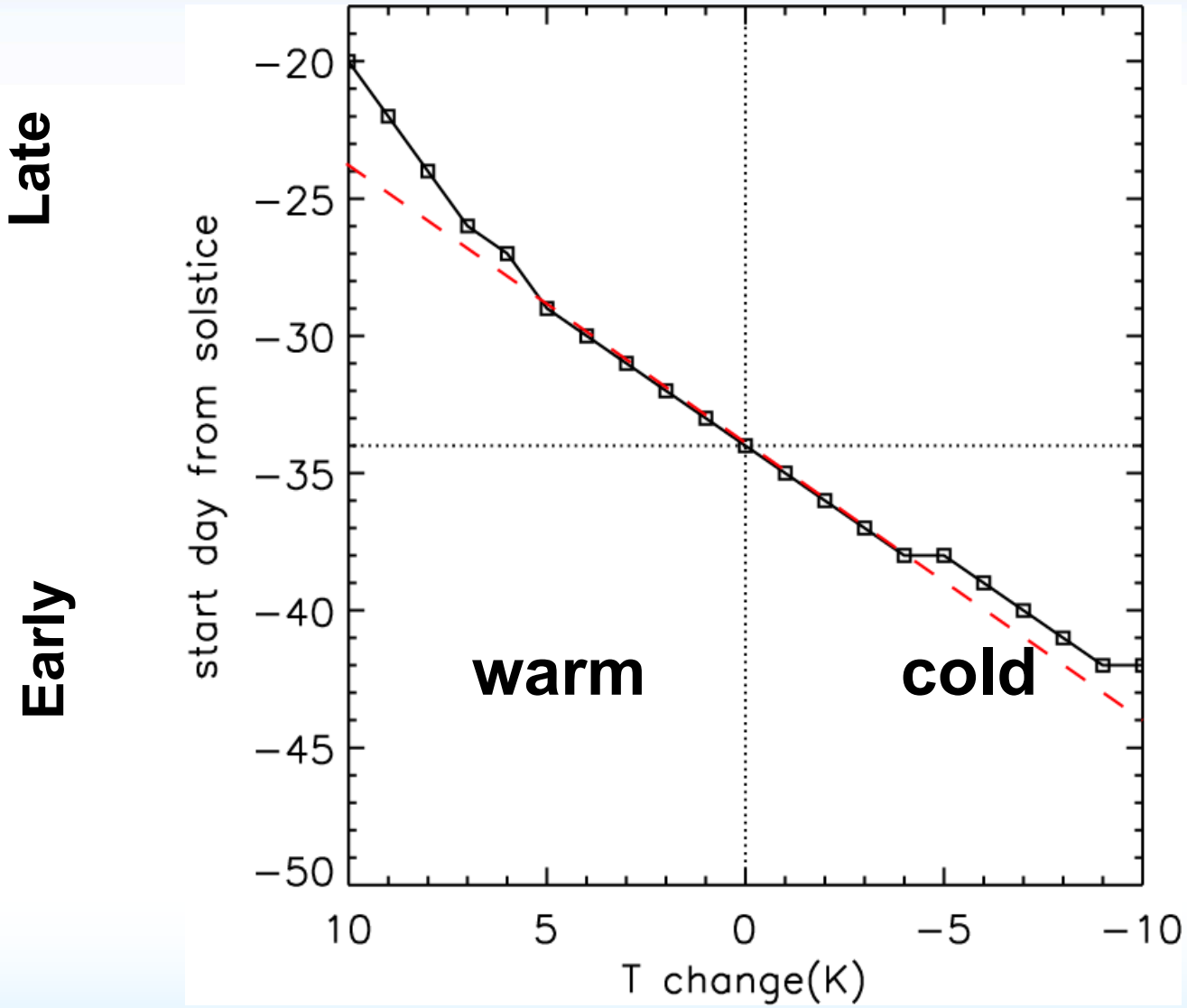
Exploring Clouds at the Edge of Space

Factors potentially affecting long-term PMC changes

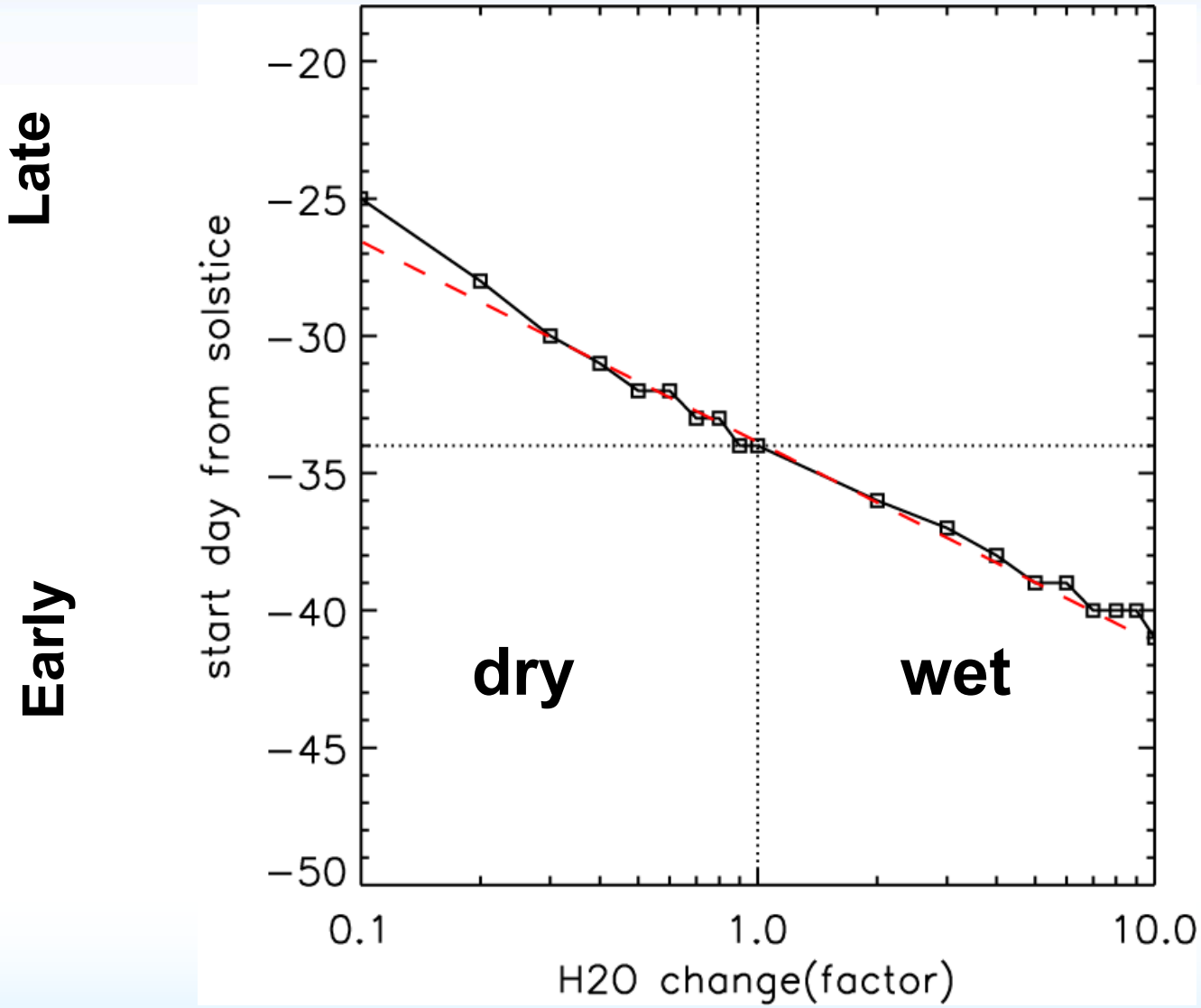
- CH_4 increases leading to increased mesospheric H_2O
- CO_2 increases leading to a colder mesosphere
- Changes in Lyman - α over the solar cycle (definite effect)
- Global temperature increases could alter lower altitude gravity wave source activity and vertical propagation
- A warming lower atmosphere could change planetary wave activity and hence meridional coupling
- Long-term changes in cosmic smoke?

Backup

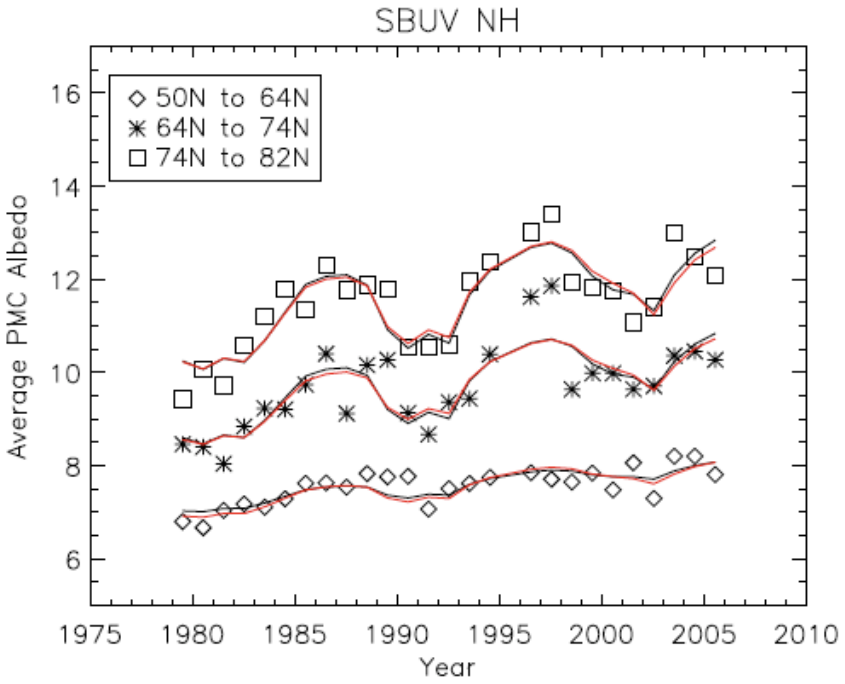
Effect of temperature change on season length

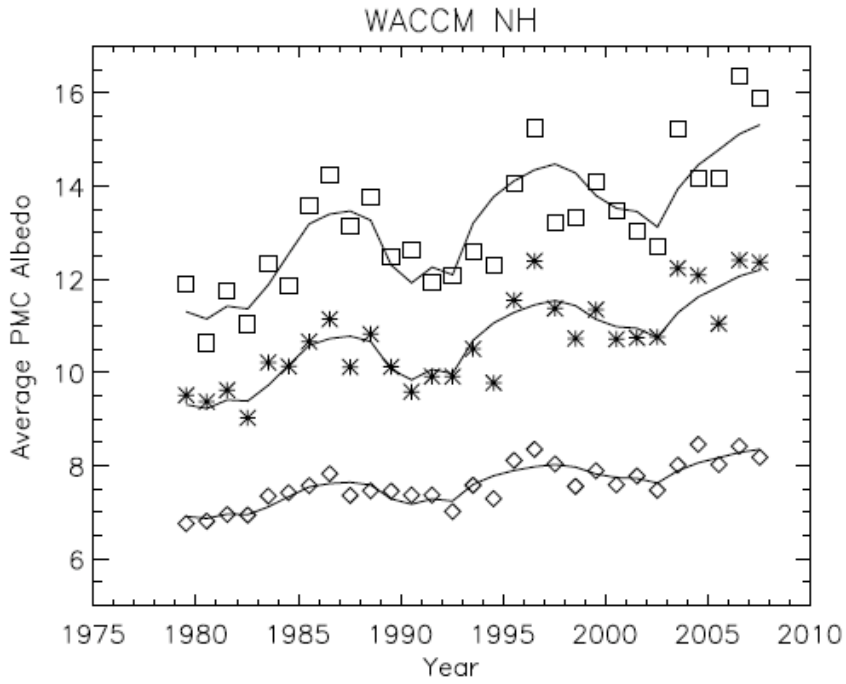


Effect of water vapor change on season length



SBUV & WACCM-PMC: Northern Hemisphere



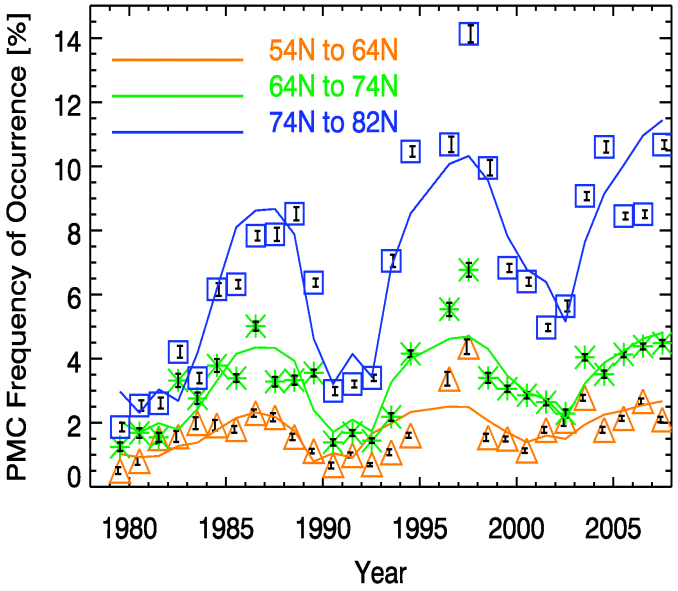


Red = DeLand, 2007

Black = this analysis

Marsh, NCAR, 2010, private communication

PMC science is directly driven by the Sun

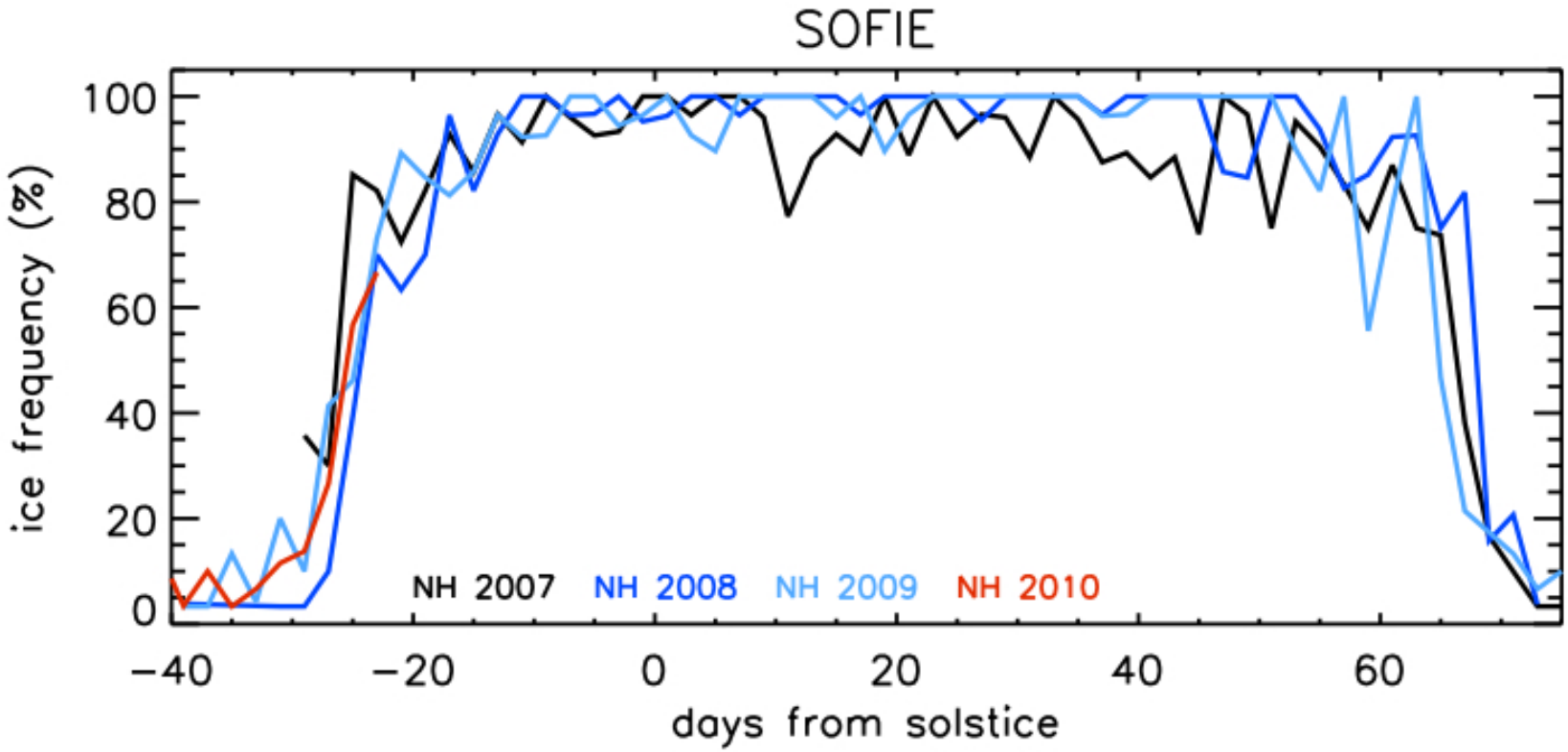


- The first 6 seasons of AIM observations occurred during a prolonged solar minimum
- We know PMCs are affected by solar changes but we do not know why
- A warming atmosphere could change temperature and dynamical influences on PMC formation

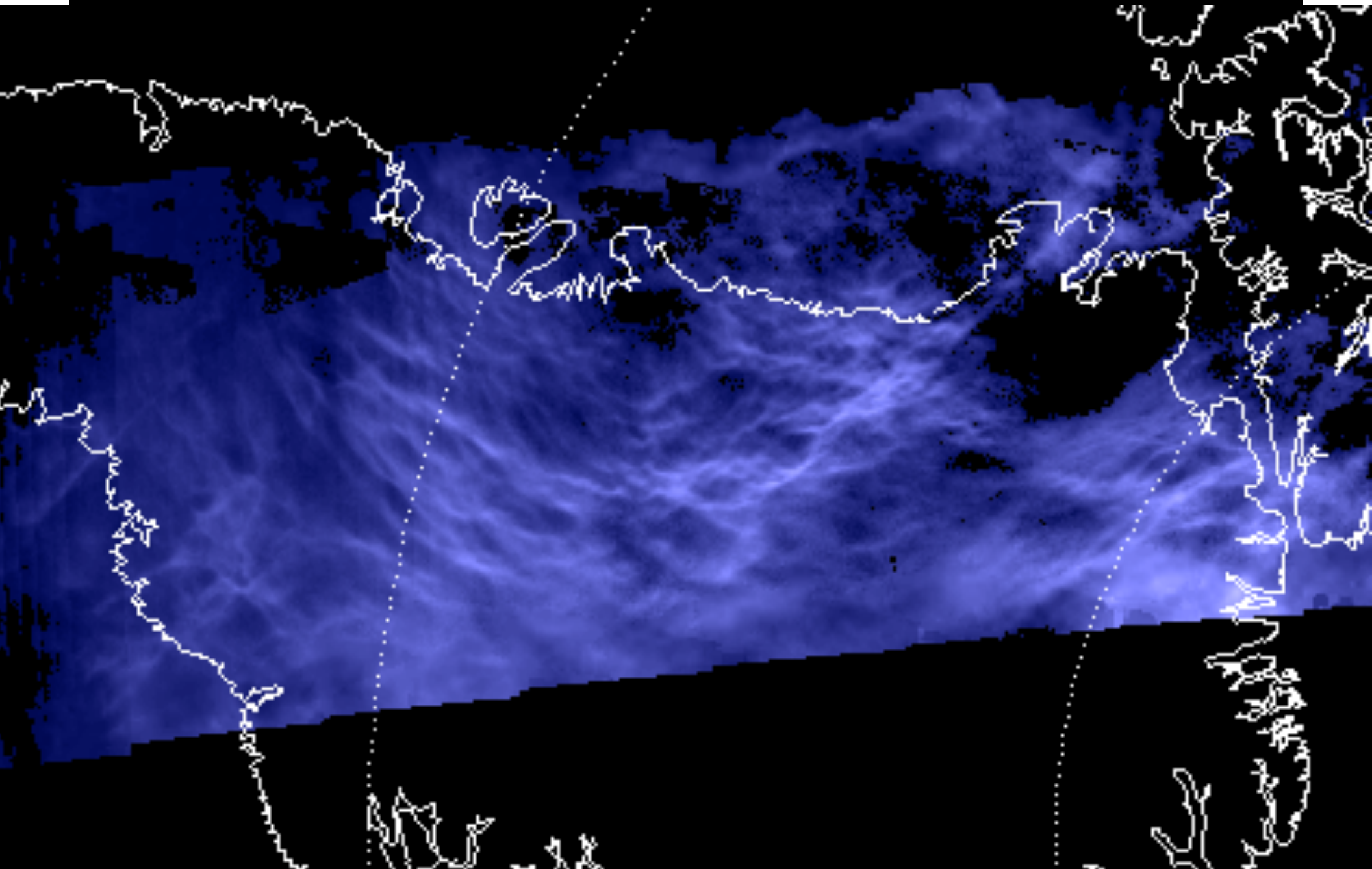
The next step needed to understand why PMCs form and vary is to collect data over a wide range of solar conditions

Study of a global change connection requires measurements over a solar cycle (PMCs, T, H_2O, CO_2, CH_4, O_3, NO, aerosols and cosmic smoke)

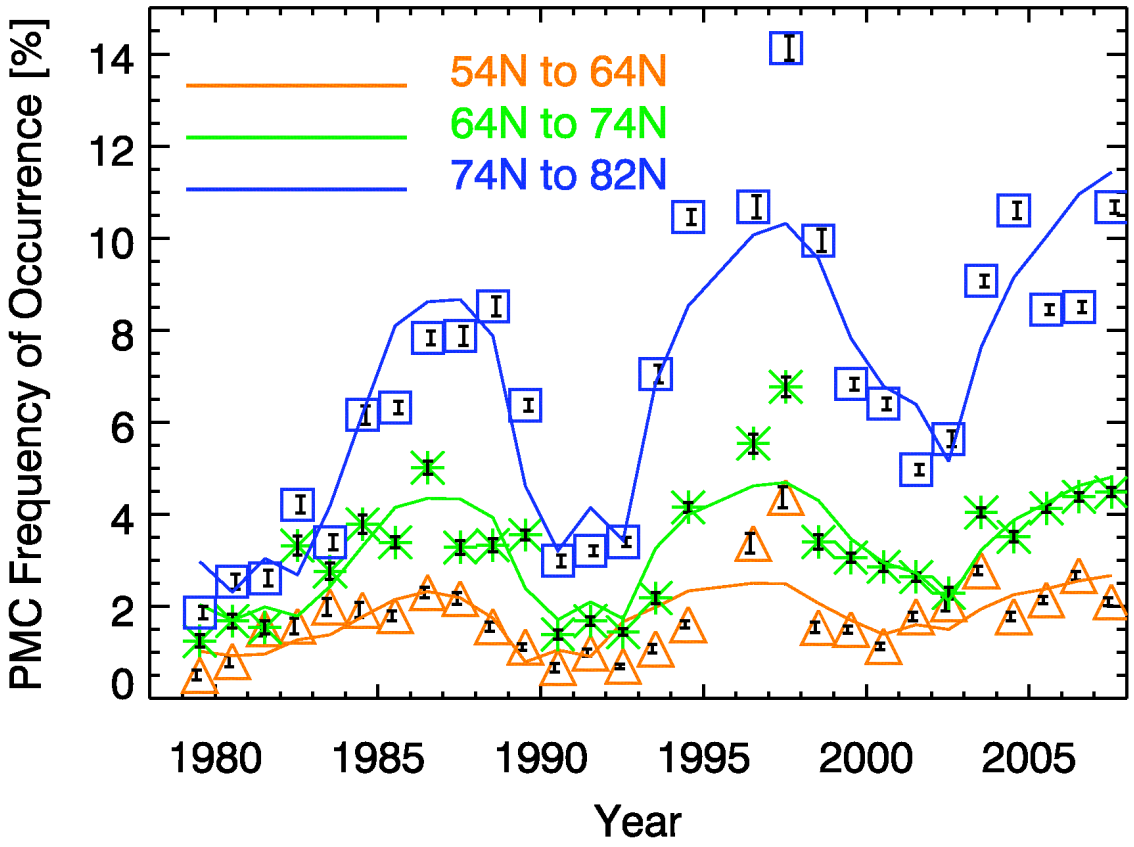
NH PMC frequency of occurrence observed by the SOFIE instrument on the AIM satellite



AIM CIPS NH June 22, 2007

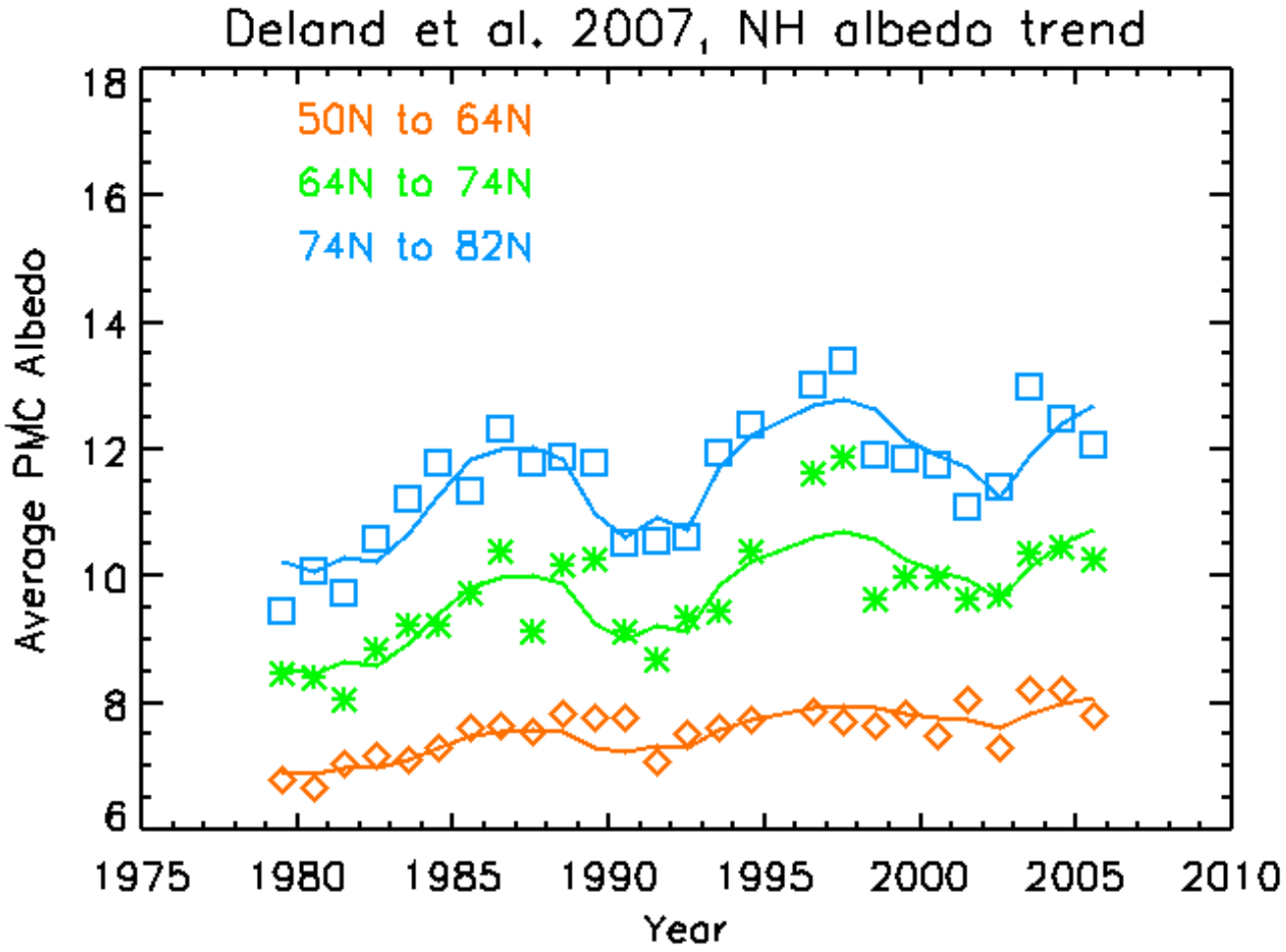


PMC frequency and brightness have been increasing over the last 28 years



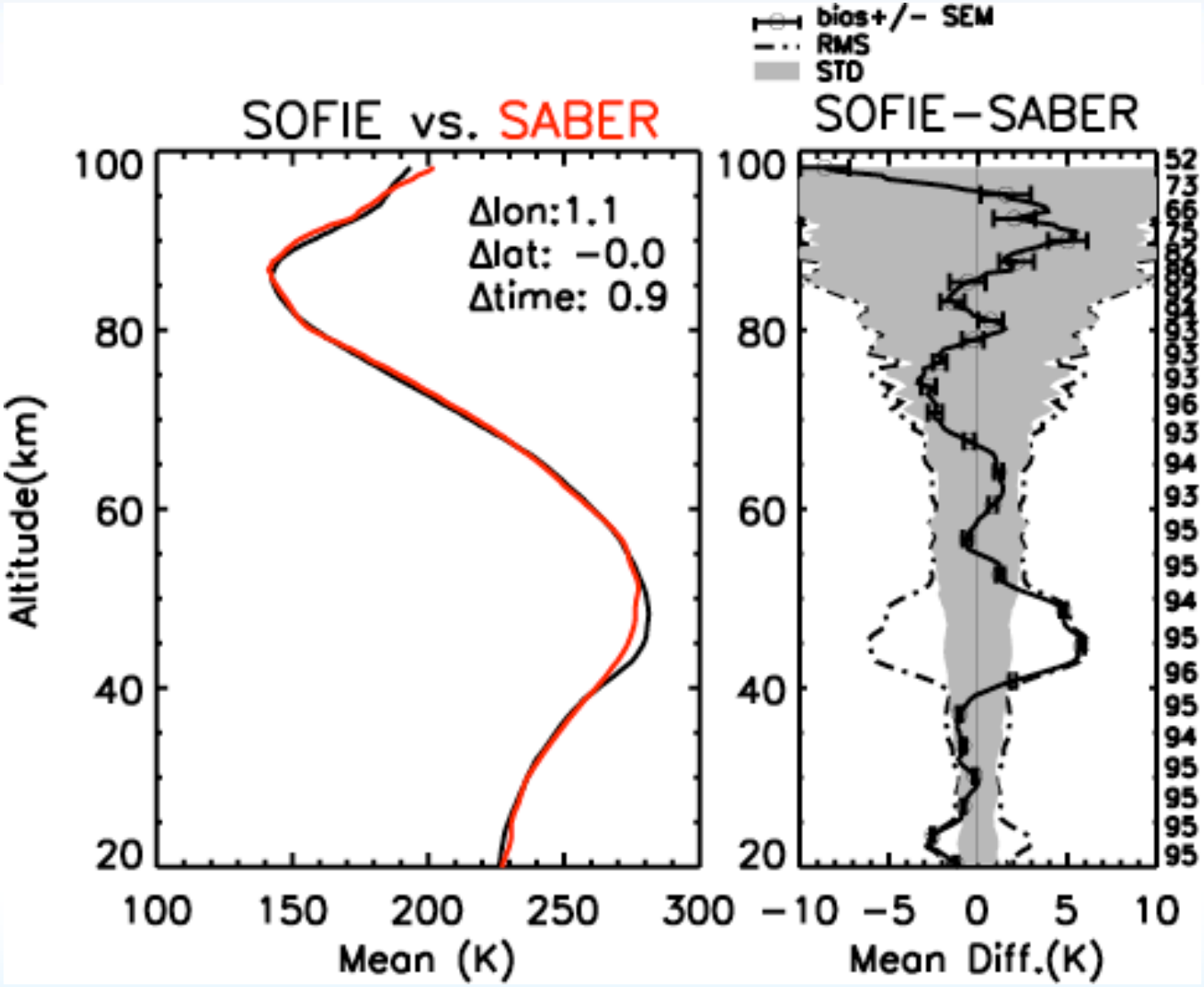
Long-term frequency trends observed by the SBUV series of satellite instruments [Shettle et al., 2009]

PMC frequency and brightness have been increasing over the last 28 years

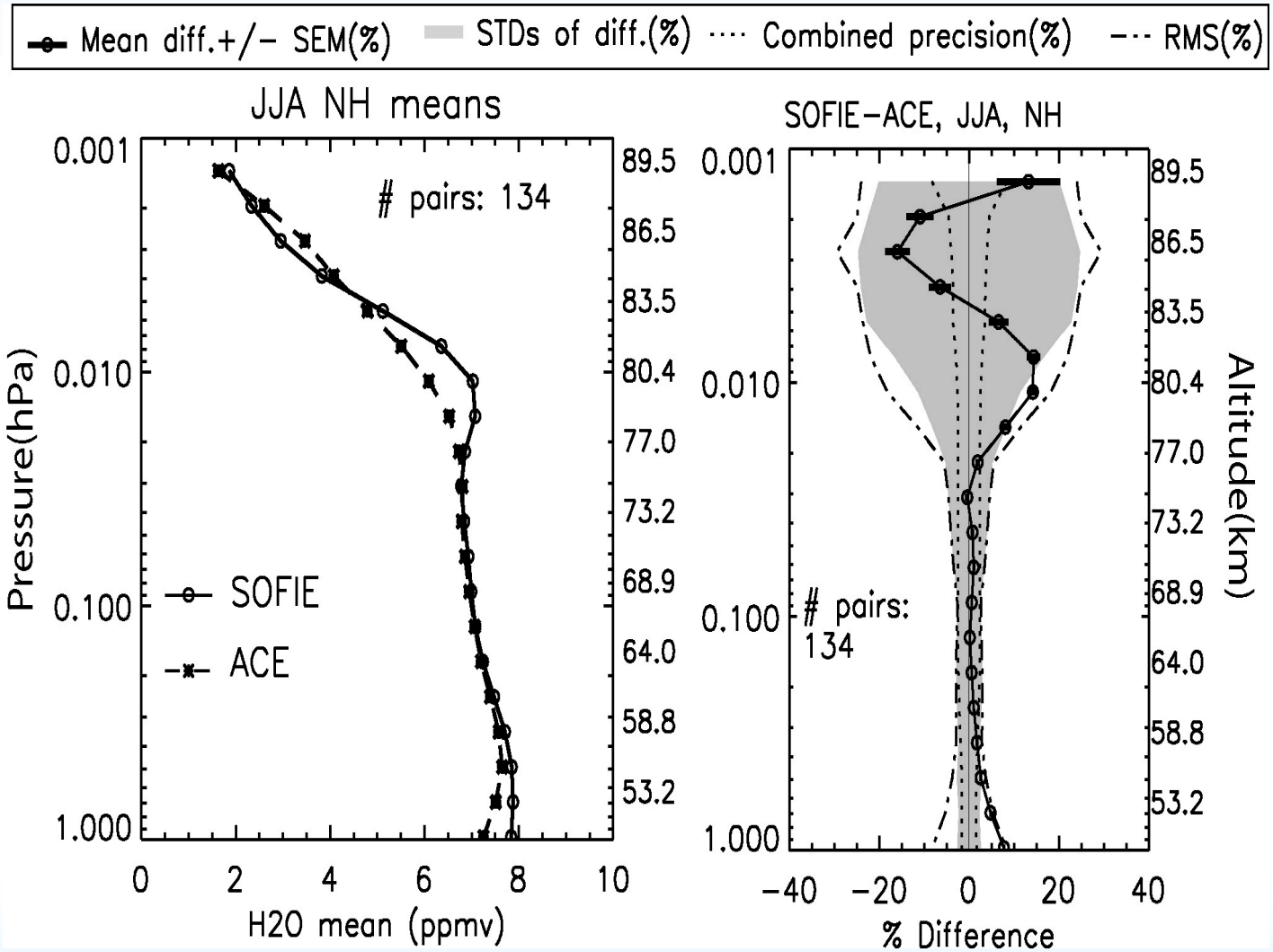


Long-term brightness trends observed by the SBUV series of satellite instruments [Deland et al., 200y]

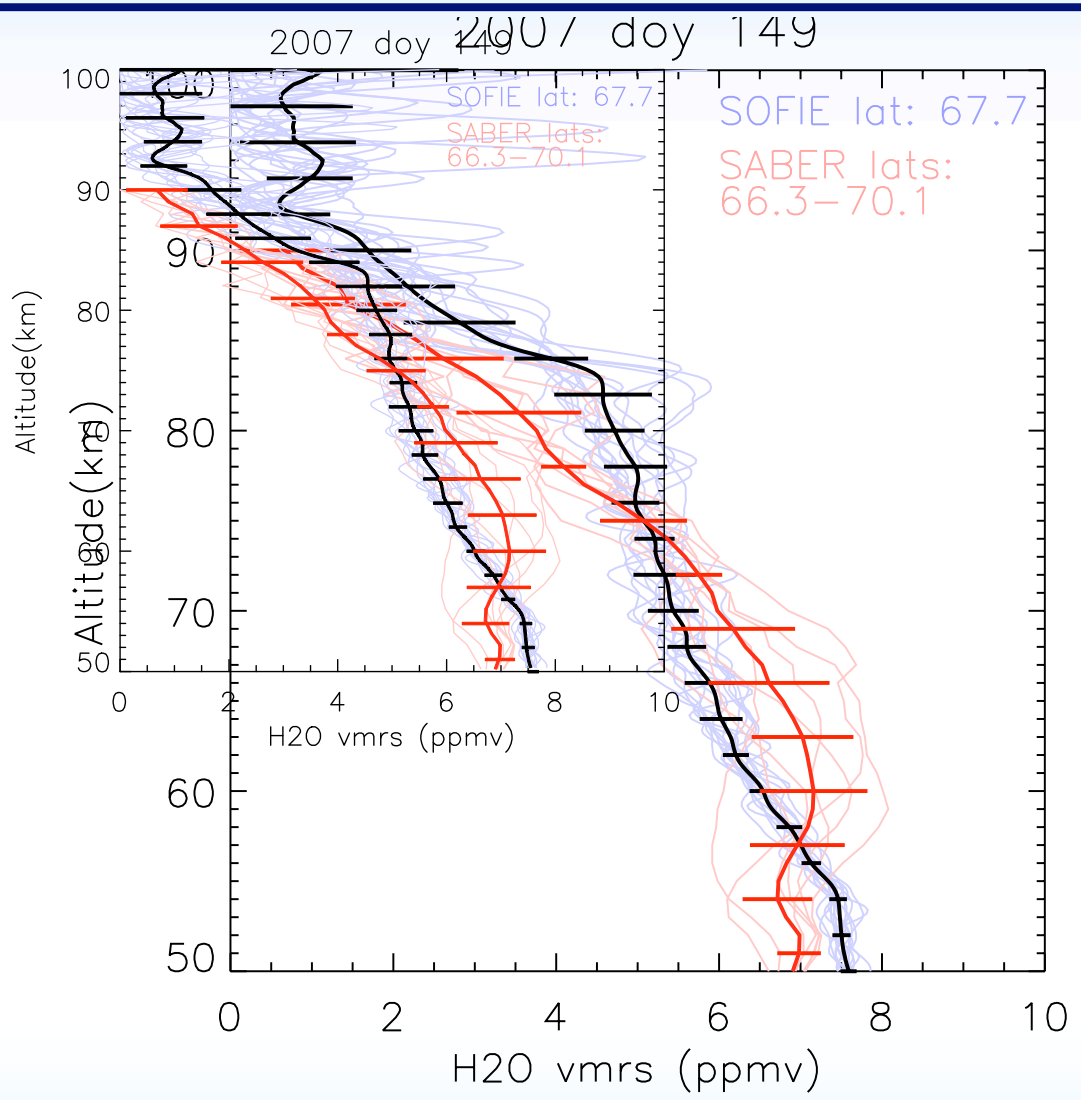
SOFIE and SABER temperature comparisons for July 1 – 15, 2007



SOFIE and ACE H_2O comparisons for the NH summer



SABER and SOFIE H_2O 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 $\longrightarrow$ 2 H_2O

Carbon Dioxide (CO_2)

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

The global atmosphere is coupled even on small scales!

1. Southern Winter Zonal Winds travel West-East

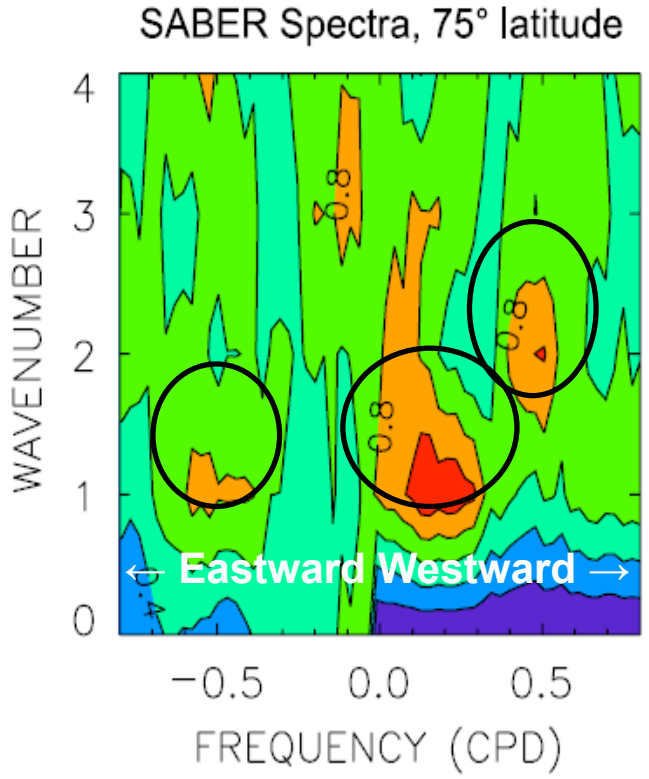
3. Rising air expands and therefore cools, producing a cold summer mesosphere

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

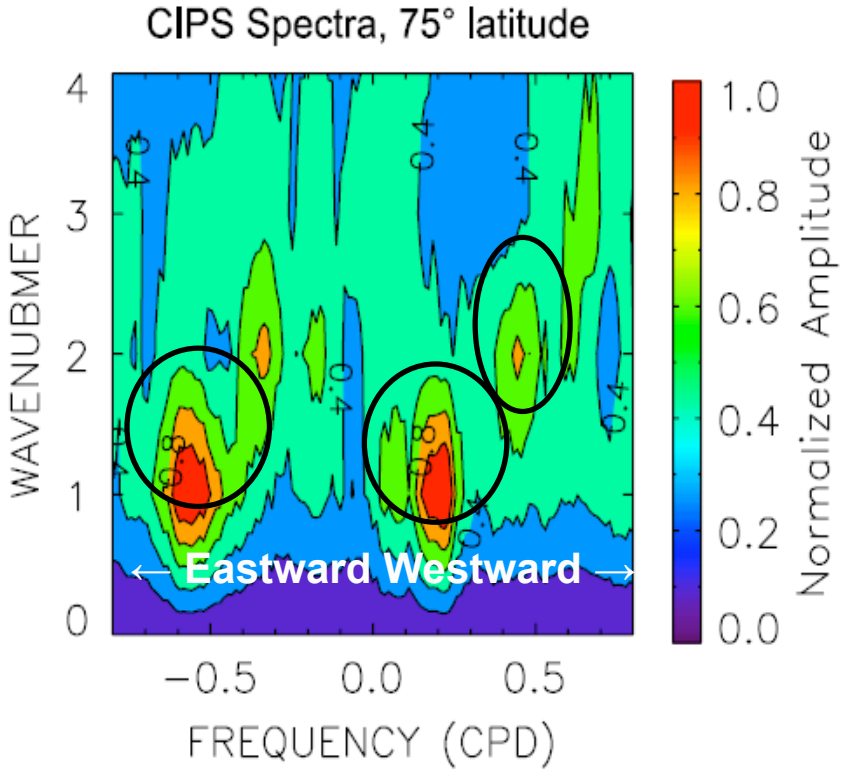
AIM PMCs and SABER temperatures show presence of 5-day and 2-day planetary waves

June 1 to July 15, 2007

Temperature

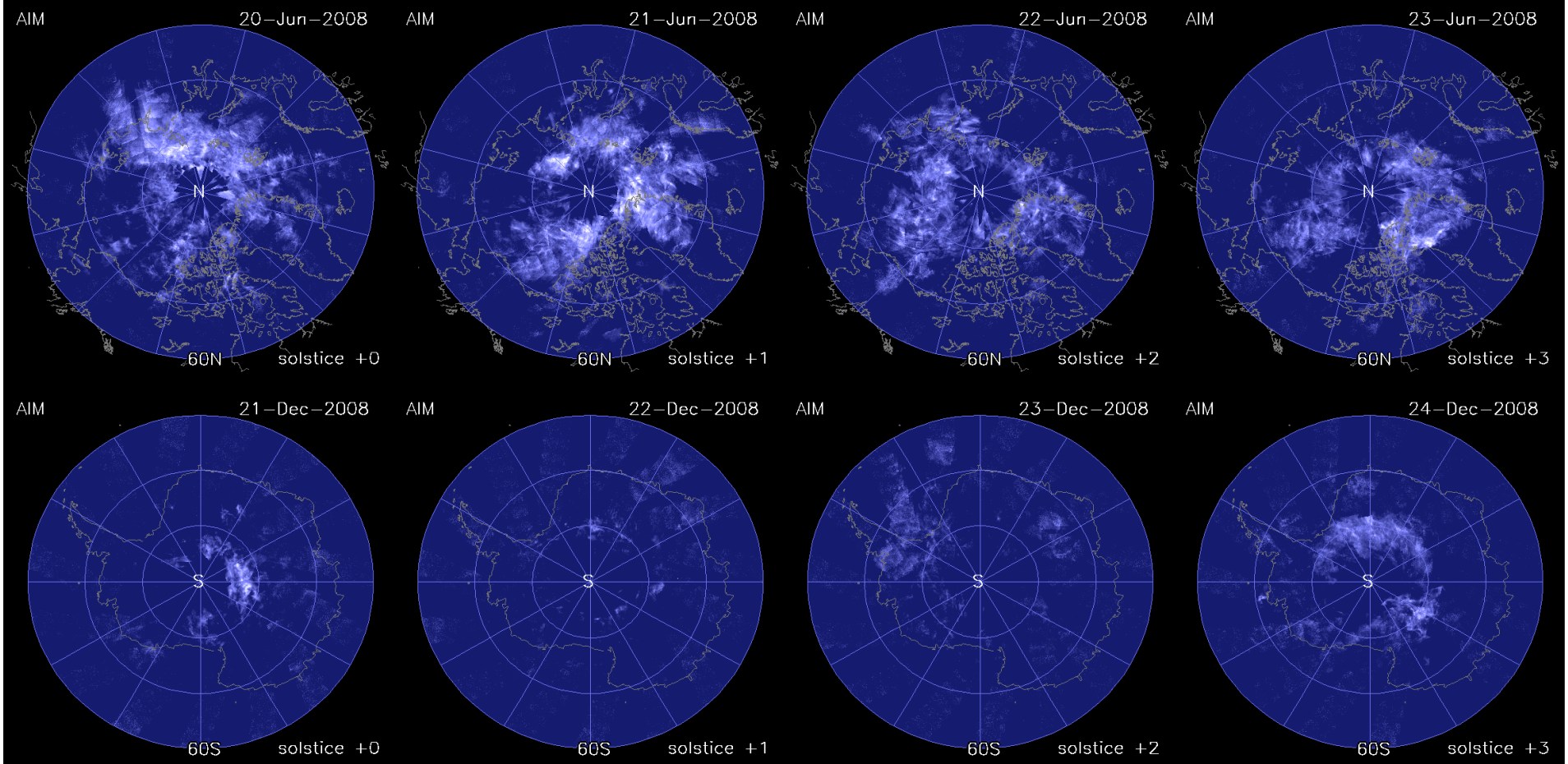


CIPS PMC Albedo



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