# An analysis of long-term trends in mesospheric temperatures from OH airglow spectra of Kiruna FTS and Sloan Digital Sky Survey


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## Abstract

We have analyzed mesospheric temperatures from OH airglow measurements with Fourier Transform Spectrometer (FTS) at Kiruna (67.9N, 21.1E) in the period of 2003 – 2012. We also derived mesospheric temperatures from rotational lines of the OH airglow (8-3) band in the sky spectra of Sloan Digital Sky Survey (SDSS), which operated at Apache Point Observatory (APO, 32°N 105°W) in the period of 2000 – 2014. We have found the seasonal variations, solar responses and long-term trends of mesospheric temperatures at both sites. FTS temperatures show signals of sudden stratospheric warming (SSW). The solar responses are 5.0 ±1.5 and 1.7 ±0.8 K/100SFU in FTS and SDSS temperatures, respectively. After removing the solar responses, the long-term trends are found to be –2.6 ±1.5 and –1.0 ±0.9 K/Decade over Kiruna and Apache Point, respectively. Our results indicate significant cooling trends at both latitude regions. Although both trends are comparable and consistent with other studies, the temperature trend from SDSS spectra should be regarded as unique contribution to global monitoring of climate change because the SDSS project is completely independent of climate studies. Finally we discuss our results by comparing with those of Microwave Limb Sounder (MLS) instrument on board Aura satellite.


## 1. Introduction

- Changes in mesospheric temperatures may be attributed to solar cycle effect and the variance of atmospheric ozone amount(Akmaev et al. [2006], Berger and Lübken [2015]), gravity waves(Hoffmann et al. [2011], Jacobi [2014]), and tropospheric climate changes(Nath and Sridharan [2014]).
- Especially, **enhancement of greenhouse gases such as $CO_2$ is supposed to induce a cooling of middle and upper atmosphere** (Berger and Dameris [1993], Portmann et al. [1995], Akmaev and Fomichev [1998, 2000]).
- **Offermann et al., [2010]** found that the **long-term trend** during 1988-2000 was insignificant but **turned into a cooling trend when using data of 1996-2008**.

| Location | Method | Reference | Heights (km) | Data duration | Solar response (K/100SFU) | Trend (K/decade) |
|---|---|---|---|---|---|---|
| 10°N-15°N | TIMED-SABER | Nath et al. (2014) | 85-87 | 2002-2012 | 4.314 (85km) | –1.86 |
| 41°N, 105°W | Na lidar | She et al. (2009) | 87 | 1990-2007 | 4 (W/O volcanic effect) | –0.28±1.32 |
| | | She et al. (2015) | 87 | 1990-2014 | | -1.0±1.0 |
| 51°N, 7°E | OH airglow | Offermann et al. (2010) | 87 | 1988-2000 | 3.5±0.21 (during 1988-2008) | -0.8 |
| | | | | 1996-2008 | | -3.4 |
| 56°N, 37°E | OH airglow | Perminov et al. (2014) | 87 | 2000-2012 | 3.5±0.8 | -2.2K±0.9 |
| 63.04°N, 129.51°E | OH airglow | Ammosov et al. (2014) | 87 | 1999-2013 | 4.24±1.39 7(25 months lag) | not significant |
| 78°N, 15°E | OH airglow | Sigernes et al. (2003) | 87 | 1980-2001 | not significant | not significant |
| 78°N, 16°E | Meteor radar | Hall et al. (2012) | 90 | 2001-2012 | 16±0.32 | -4±2 |
| | OH airglow | Holmen et al. (2014) | 87 | 1983-2013 | 3.6±4.0 | 0.2±0.5 |

**Table 1**. The solar responses and long-term trends published for the northern hemisphere.

## 2. Observations

### ➢ Kiruna FTS

- Korea Polar Research Institute(KOPRI) has operated the **Fourier Transform Spectroscopy(FTS) since October of 2001 to observe OH rotational temperatures over Kiruna, Sweden(67.90°N, 21.10°E)**.
- The FTS in Kiruna measures the spectrum of OH airglow with a range of **5000-10,000 $cm^{-1}$** with five selective spectral resolution of **1, 2, 4, 8, 16 $cm^{-1}$** (Won et al., [2004]).
- We used daily mean OH rotational temperatures for **November to next February during 2003-2014;** the temperature uncertainty is estimated to be less than 5%.

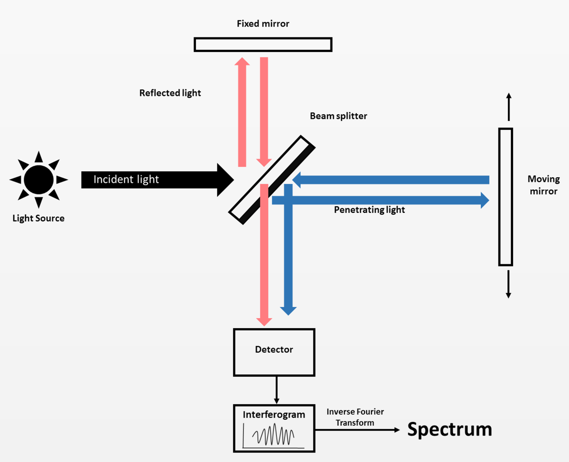


**Figure 1**. Schematic diagram of FTS.

| Kiruna FTS | | | |
|---|---|---|---|
| Year | Number of nights | Year | Number of nights |
| 2003/04 | 30 | 2008/09 | 52 |
| 2004/05 | 95 | 2009/10 | 68 |
| 2005/06 | 99 | 2010/11 | 59 |
| 2006/07 | 61 | 2011/12 | 80 |
| 2007/08 | 39 | 2012/13 | 71 |
| | | 2013/14 | 60 |
| TOTAL | | 723 | |

**Table 2**. Number of available FTS temperatures for each year.

### ➢ Sloan Digital Sky Survey(SDSS)

- Sloan Digital Sky Survey is an astronomical project which has been **observing images and spectra of celestial objects at Apache Point Observatory (APO, 32°N 105°W) since April 2000.**

| | SDSS- Ⅰ/Ⅱ | BOSS |
|---|---|---|
| Diameter of light fiber | 3'' | 2'' |
| Spectral range | 3800Å-9200Å | 3600Å-10400Å |
| Number of atmospheric spectra | At least 32 | At least 70 |

**Table 4**. Specifications of SDSS- Ⅰ/Ⅱ and BOSS spectrograph.

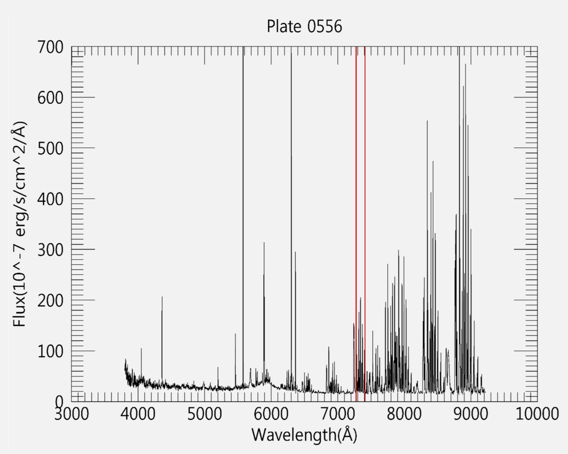


**Figure 2**. A sample SDSS atmospheric spectrum.

| SDSS | | | |
|---|---|---|---|
| Year | Number of nights | Year | Number of nights |
| 2000 | 62 | 2007 | 77 |
| 2001 | 96 | 2008 | 112 |
| 2002 | 103 | 2009 | 92 |
| 2003 | 112 | 2010 | 133 |
| 2004 | 86 | 2011 | 158 |
| 2005 | 76 | 2012 | 154 |
| 2006 | 77 | 2013 | 138 |
| | | 2014 | 69 |
| TOTAL | | 1545 | |

**Table 3**. Number of available SDSS temperatures for each year.

- SDSS spectrograph was connected to focal plane with light fibers.
- **SDSS- Ⅰ/Ⅱ spectrograph had been operating during 2000-2008**. Since **September 2009, BOSS spectrograph has been used**.
- The spectral data were obtained all year round except the maintenance period of **July to August (roughly, DOY 190-230)**
- OH rotational temperature can be calculated by equation (1) (Phillips et al. [2004]).

$$T = \left(\frac{hc}{k}\right)(F_b - F_a) / \ln\left[\frac{I_a A_b (2J_a' + 1)}{I_b A_a (2J_b' + 1)}\right] \quad \text{Eq. (1)}$$

- We selected **OH(8-3) P-branch lines** to derive the OH rotational temperatures from SDSS spectra.

| $P_1(3)$ | | $P_1(4)$ | | $P_1(5)$ | |
|---|---|---|---|---|---|
| Term | value | Term | value | Term | value |
| Central wavelength | 7343.4Å | Central wavelength | 7370.5Å | Central wavelength | 7404.6Å |
| Initial rotational energy state | 2 | Initial rotational energy state | 3 | Initial rotational energy state | 4 |
| $J_a'$ | 2.5 | $J_a'$ | 3.5 | $J_a'$ | 4.5 |
| $A_a$ | 0.225 | $A_a$ | 0.247 | $A_a$ | 0.263 |
| $F_a$ | 24009.51 | $F_a$ | 24093.34 | $F_a$ | 24201.45 |

**Table 5**. Properties of OH(8-3) $P_1(3)$, $P_1(4)$ and $P_1(5)$ emission lines(Langoff et al. [1987], Coxon and Foster [1982])

## 3. Results

- We here used the **daily mean MLS on board AURA satellite temperatures of 88.5km over 68°±5°N, 21°±5°E** to compare with FTS measurements.
- **9-day running average** of mean temperatures on same DOYs was defined as **seasonal variation**(Figure 3(l)), which was removed for the trend analysis (Holmen et al., 2014).
- Both temperatures show **their minima in January**. This is due to the distribution of central dates and recovery phases of **sudden stratospheric warming(SSW)**.
- Mesospheric temperature at high latitudes are affected by SSW (see figure4. (Walterscheid et al. [2000], Sigernes et al. [2003], Kurihara et al. [2010], Shepherd et al. [2010], Matthias et al. [2014]).

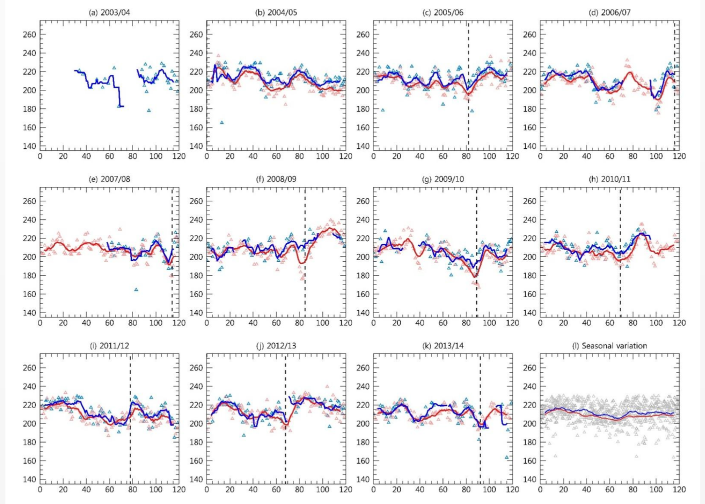

**Figure 3.** Time series(a-k) of Kiruna FTS(blue) and AURA/MLS(red) temperatures. Seasonal variation(l) was plotted by overlapping data of all years. X-axis and Y-axis indicate days passed from 01 Nov and temperatures(K), respectively. Central dates of SSW are marked by black dashed lines.

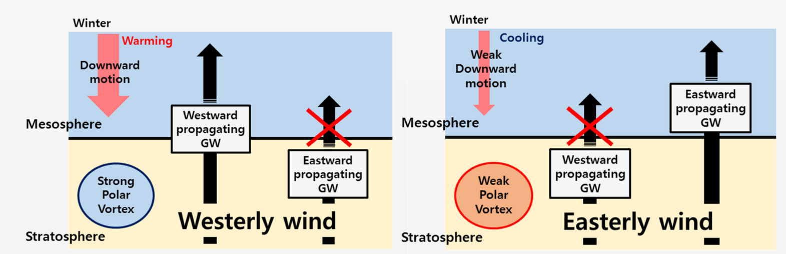


**Figure 4.** Schematic diagram of the Normal winter(left) and SSW(right) conditions in stratosphere and mesosphere.

- The **SSW signals in Kiruna MLS temperatures** appear **clearer** than in FTS temperatures.

- **We multiplied a 0.972561 of scale factor to the temperatures after 2009** to calibrate temperature bias due to the change of spectrograph in 2009. The scale factor was computed by comparing with MLS temperatures over **32°N±5°, 104°W±5° at night**
- The **seasonal variations of the temperatures over APO** are defined as **27-day running average** of mean temperatures on same DOYs and were removed for the trend analysis.
- High in winter and low in summer are evident in the SDSS seasonal temperature variation.

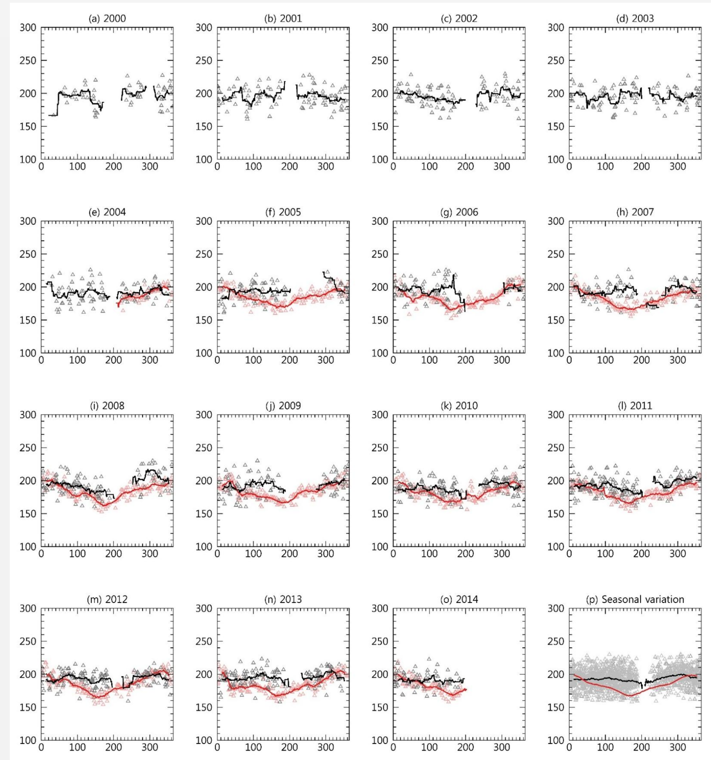

**Figure 5.** SDSS(black) and AURA/MLS(red) temperatures vs DOY during 2000-2014. Seasonal variation (p) is plotted by overlapping temperatures on the same DOY.

- **The temperatures over Kiruna and APO exhibit positive correlations with F10.7 indices**, in agreement with other studies.
- The solar responses over Svalbard(Hall et al., 2012, Holmen et al., 2014) are larger than those of Kiruna: Svalbard is at 10° higher latitude than Kiruna.
- Other solar response of mid-latitude region were typically within 3 -5 K/100SFU(She et al. [2009], Offermann et al. [2010], Perminov et al. [2014]). Their latitudinal coverage are at least about 10° higher than APO and they show larger value of solar responses.
- **Solar response tends to become larger at higher latitudes.**

| | Data duration | Location | Solar response ( /100SFU) |
|---|---|---|---|
| **Kiruna FTS** | 2003-2014 | Kiruna, Sweden (68°N, 21°E) | **5.0±1.5K** |
| **MLS (Kiruna)** | 2004-2014 | 68°±5°N, 21°±5°E | **4.1±0.1K** |
| **SDSS** | 2000-2014 | Apache Point Observatory (32°N 105°W) | **1.7K±0.8K** |
| **MLS (APO)** | 2004-2014 | 32°±5°N, 105°±5°W | **2.7K±0.6K** |

**Table 6.** Solar responses of the temperature over Kiruna and APO.

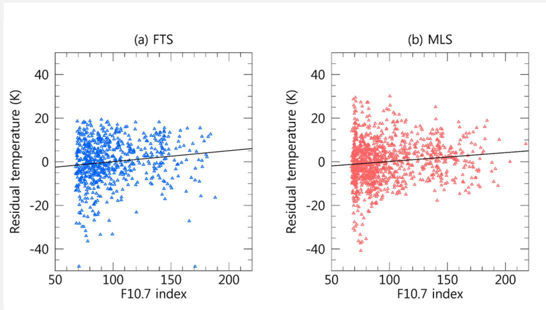

**Figure 6.** Solar responses of Kiruna FTS(a) and Kiruna MLS(b)

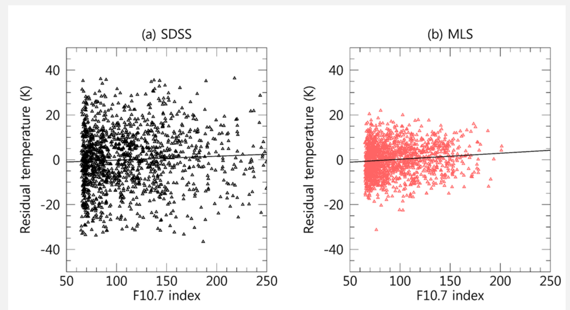

**Figure 7.** Solar responses of SDSS(a) and APO MLS(b)

- **Cooling trend** appears in **FTS temperatures** but **insignificant trend** in **Kiruna MLS** temperatures.
  → The discrepancy in long-term trends between Kiruna FTS and MLS may be due to the difference in SSW response of two instruments.
- **Both SDSS and MLS long-term trends** indicate **cooling** in mesosphere over mid-latitude.
- Our long-term trends are **consistent with other studies using data in 2000s**; the **trend change in mid 1990s** was reported in Offermann et al., [2010].

| | Data duration | Location | Long-term trend (/Decade) |
|---|---|---|---|
| **Kiruna FTS** | 2003-2014 | Kiruna, Sweden (68°N, 21°E) | **-2.6±1.5K** |
| **MLS (Kiruna)** | 2004-2014 | 68°±5°N, 21°±5°E | **0.6±1.2K** |
| **SDSS** | 2000-2014 | Apache Point Observatory (32°N 105°W) | **-1.0±0.9K** |
| **MLS (APO)** | 2004-2014 | 32°±5°N, 105°±5°W | **-1.4±0.7K** |

**Table 7.** Long-term trends of the temperature over Kiruna and APO.

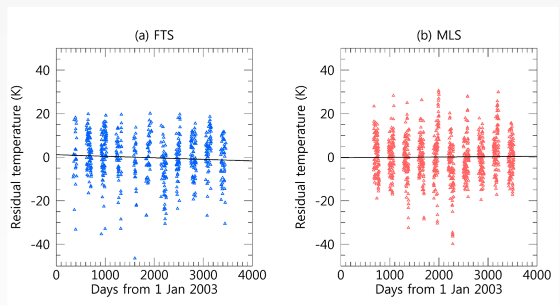

**Figure 8.** Long-term trends of Kiruna FTS(a) and Kiruna MLS(b)

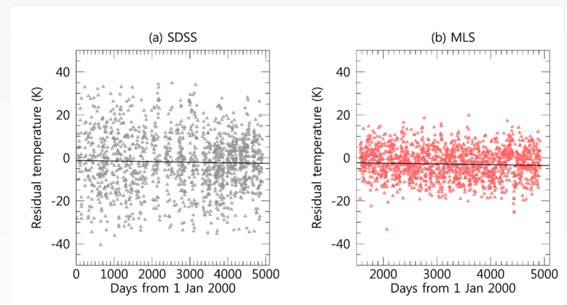

**Figure 9.** Long-term trends of SDSS(a) and APO MLS(b)

## 3. Summary

- The seasonal variation, solar response, and long term trend of mesospheric temperatures were derived from OH airglow temperatures observed by both **Fourier Transform Spectroscopy(FTS) at Kiruna(67.90°N, 21.10°E) during 2003 - 2014** and **Sloan Digital Sky Survey(SDSS) at Apach Point Observatory(APO, 32°N 105°W) during 2000–2014**.
- Both temperatures over Kiruna and APO are **positively correlated with solar activity** and the positive responses tend to increase with the latitude of observation site.
- **Cooling trend appears in FTS temperatures but insignificant trend in Kiruna MLS temperatures** probably due to their different SSW responses. Both SDSS and **MLS long-term trends over APO indicate cooling in mesosphere** at mid-latitudes.
- **The cooling trends found in this study are consistent with other studies that analyze data in 2000s afterward.**

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