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Highlights

- The northern polar mesospheric region above 8 km was warmer than normal in 2002
- Heating of the summer mesopause was accompanied by heating in the winter polar stratosphere
- The global temperature anomalies appear to develop and fade away nearly simultaneously

Inter-hemispheric Coupling during Northern Polar Summer Periods of 2002-2010 using TIMED/SABER Measurements

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Abstract

It has been found that for more than one polar summer season between 2002–2010, the northern polar mesospheric region near and above about 80 km was warmer than normal. The strongest warming effect of this type was observed to occur during northern summer 2002. Theoretical studies have implied that these “anomalies” were preceded by unusual dynamical processes in the southern hemisphere. We have analyzed temperature distributions measured by the SABER limb scanning infrared radiometer aboard the NASA TIMED satellite between 2002–2010 at altitudes from 15 to 110 km and for latitudes between 83°S to 83°N. We describe the approach to trace the inter-hemispheric temperature correlations demonstrating the global features that were unique for the “anomalous” northern polar summers. From our analysis of SABER data from 2002–2010, the anomalous heating for the northern mesopause region during northern summer was accompanied by stratospheric heating in the equatorial region. In the winter hemisphere it is accompanied by heating in the lower stratosphere and

mesopause region, and cooling in the stratopause region. Also, all the elements of the temperature anomaly structure appear to develop and fade away nearly simultaneously, thereby suggesting either a global influence or a rapid exchange.

Keywords: inter-hemispheric-coupling, polar summer, stratospheric warming

1 Introduction

In July, 2002, the MaCWAVE/MIDAS rocket program (Goldberg et al., 2004) was conducted at Andøya Rocket Range, Norway (ARR, 69.3°N, 16°E) to study the influence of gravity waves on the polar summer mesosphere. As part of that program, a large number of falling sphere MET payloads were launched to obtain the atmospheric temperature in the mesopause region. These data led to the conclusion that the mesopause temperatures were abnormally high above 80 km when compared to the mean value profiles for prior years. This was further evidenced by a reduced polar mesospheric summer echo (PMSE) occurrence rate as shown in their Fig. 4 of Goldberg et al. (2004). This is to be expected since the echoes are thought to be caused by charged ice particles with diameters in the nanometer range, with concentrations that decrease as the temperature heats up to the frost-point. Becker et al. (2004) proposed that this heating effect was a consequence of Rossby-wave forcing arising from the southern polar winter, particularly in the troposphere and stratosphere. Later, Becker and Fritts (2006) expanded on this theoretical concept with a more refined model. More recently, Karlsson et al. (2009) have argued that the variability in the summer polar mesosphere is caused by the planetary wave flux entering the winter stratosphere. This was accomplished by using the Canadian Middle Atmosphere Model (CMAM). It involves cross-equatorial flow caused by a stratospheric warming in the southern winter hemisphere.

In this work, we use temperature results from the TIMED/SABER instrument to demonstrate that the cross-equatorial transfer of atmospheric heating did occur for the mesospheric heating event first observed locally during the MaCWAVE/MIDAS rocket program. Also, this unusual heating of the polar summer mesosphere seemed to occur nearly simultaneously with a stratospheric warming in the winter polar stratosphere of the southern hemisphere. Furthermore, the effect was global rather than local in its occurrence and effect. The experimental evidence for these results is presented in the following sections.

2 Background

The TIMED (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics) Satellite was launched by NASA on December 7, 2001, and has been operating continuously to the present time. The SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) instrument in TIMED provides profiles of kinetic temperature, pressure and density, as well as minor constituents such as CO_2, NO, O_3, H_2O, etc. To enable measurement of the polar region in both hemispheres, the SABER instrument goes through a yaw cycle, wherein it points into the northern hemisphere for two months alternating by a shift to the southern hemisphere during the ensuing two months. Temperatures obtained in each polar region are a major part of this study.

Measurements at ARR from meteorological rocket falling sphere payloads, showing the warm polar summer in the northern hemisphere above 80 km altitude during MaCWAVE/MIDAS, were reported by Goldberg et al. (2004, Fig. 3) and Rapp et al. (2004, Fig. 1d). Further evidence for this behavior was also observed from synoptic studies of polar mesospheric summer echoes (PMSEs) in Goldberg et al. (2004, Fig. 4). A more recent display of PMSEs measured at Andøya (Latteck, personal communication, 2008) is shown in Fig. 1. The PMSE figures both show that the frequency of occurrence of PMSEs and the duration of the season for occurrence were significantly less during 2002 than for years before or following the 2002 season. Figure 2 is a schematic to help explain why this is an important indicator for polar mesospheric warming. The occurrence of PMSEs relies on the temperature to be below the frost–point temperature. The figure defines the altitude region where PMSEs and polar mesospheric clouds (PMCs) would occur. Clearly, a warming of this region would reduce the extent and possible occurrence of such phenomena. Further evidence regarding the warm polar summer of 2002 has been reported by Karlsson et al. (2009) and Feofilov and Petelina (2009), who showed a reduction in PMCs for the northern polar summer of 2002, using OSIRIS data from the Swedish ODIN satellite.

The evidence above indicates that anomalous warming of the polar summer hemisphere can and does occur. The major questions are still how frequently and in which hemisphere such warmings are likely to appear, how global the events are when they occur, and to what mechanism we can attribute their cause. These questions will be addressed in this work using nine years of SABER data.

3 Instrumentation and Approach

3.1 The SABER Instrument onboard the TIMED satellite

The TIMED satellite was launched on December 7, 2001 into a 74.1° inclined 625 km orbit with a period of 1.7 hours. The TIMED mission is focused on the energetics and dynamics of the mesosphere-lower thermosphere region (60–180 km) (Yee et al., 1999). SABER is a 10-channel broadband limb-scanning infrared radiometer covering the spectral range from 1.27 μm to 17 μm (Russell et al., 1999). SABER provides vertical profiles of kinetic temperature, pressure, ozone, carbon dioxide, water vapor, atomic oxygen, atomic hydrogen and volume emission rates in the NO (5.3 μm) and OH Meinel and $O_2(^1\Delta)$ bands. The vertical instantaneous field of view of the instrument is approximately 2.0 km at 60 km altitude, the vertical sampling interval is ~0.4 km, and the atmosphere is scanned from below the surface to 400 km tangent height. The instrument performs one complete up- and down scan every 53 sec. The instrument has been performing near-continuous measurements since January 25, 2002. The latitudinal coverage is governed by a 60-day yaw cycle that allows observations of latitudes from 83°S to 52°N in the South viewing phase or from 53°S to 82°N in the North viewing phase. It is important to note that the latitudinal coverage is consistent for all years: during the summer period in the Northern hemisphere SABER changes from North viewing phase to South viewing phase on day 194.

3.2 Peculiarities of non-LTE temperature retrievals and retrieval errors

In this work we utilized the most recent version (V1.07) of SABER data available online (http://saber.gats-inc.com/, last accessed on the 11-Mar-2012). The detailed analysis of the quality of this dataset is given by Remsberg et al. (2008). Here we quote the root-mean-square error estimates for different altitudes provided there.

In Table 1, $\Delta T_{\mathrm{polar}}$ refers to polar summer temperature distributions and $\Delta T_{\mathrm{regular}}$ represents error estimates at all other seasons and latitudes. As one can see, the errors in the polar summer mesopause region grow more rapidly above 85 km. This is linked with the mechanism of 15 μm CO_2 radiance forming and ratios between the components contributing to pumping the $CO_2(\nu_2)$. In the lower atmosphere the frequency of inelastic molecular collisions is sufficiently high, so that these collisions overwhelm other population/depopulation mechanisms of the molecular vibrational levels. This leads to a local thermodynamic equilibrium (LTE), and the populations follow the Boltzmann distribution governed by the local kinetic temperature T_{kin}. In the upper atmosphere, where the frequency of inelastic collisions is much lower than at lower altitudes, and other processes can influence the population of CO_2 vibrational levels. These include: a) the direct absorption of solar radiance by the CO_2 vibrational-rotational bands in the 2.0, 2.7, and 4.3 μm spectral region;

b) absorption of the 15 μm radiance coming from the warmer and denser lower atmosphere; c) vibrational-translational (V–T) energy exchanges by collisions with molecules and atoms of other atmospheric constituents; d) collisional vibrational-vibrational (V–V) energy exchange with other molecules. As a result, LTE no longer applies in this altitude region and the populations must be found by simultaneously solving the self-consistent system of kinetic equations that express the balance relations between various excitation/de-excitation processes and the radiative transfer equation. The polar summer temperature profile can be characterized by a steep gradient in the stratopause-mesopause region and extremely low (100–130 K) mesopause temperatures. Hence, the local thermal component of the $CO_2(\nu_2)$ level pumping is low in comparison with radiance coming from below, the populations of these levels are in non-LTE starting at 72 km (Kutepov et al., 2006) and the temperature retrieval errors become larger. We will demonstrate, however, that the temperature anomalies we observe exceed these errors. Moreover, since the uncertainties in the non-LTE rates that are responsible for the uncertainty of temperature retrievals from SABER measurements (Garcia-Comas et al., 2008) do not depend on the season or latitude, they do not introduce any bias in summer-to-summer correlative analysis performed in this work.

4 Results and Discussion

As a first step we show the difference maps of monthly averaged SABER temperatures during the summers of 2002–2010 (Fig. 3). To extend the latitude coverage we have selected days 182–212, the period of time that included the yaw maneuver. This selection makes the averages consistent with those shown by Espy et al. (2010) that will be used below. The plots in Fig. 4 show temperature deviations from 83°S to 82°N. Latitudes 53°S–53°N were observed for the whole considered time interval, while 53°N–82°N and 83°S–53°S areas were observed only during days 182–194 and 194–212, respectively. Both day- and night-time temperatures were zonally averaged and binned with a 5 degrees latitude step and a 1 km altitude step. We identified "normal", "cold" and "warm" years with respect to the polar summer mesospheric area and built the differences of temperature distributions (Fig. 3). Fig. 3a shows the temperature difference map for 2002, the warmest year, in comparison to averaged (2003+2004+2005+2006+2008+2009)/6 temperature distribution. This panel demonstrates the pattern that can also be seen in other panels in Fig. 3: a warmer than usual polar mesopause area; a warmer tropical atmosphere in the approximate 65–75 km altitude range; and finally, warmer mesopause, colder stratopause and warmer lower stratosphere areas at high latitudes in the winter hemisphere. Temperature differences can reach 12 K in warm areas and 20 K in the cold area. Besides 2002, the summers of 2007 and 2010 also demonstrated similar patterns (see Fig. 3b and Fig. 3c, correspondingly). Finally, Fig. 3d shows the temperature difference between the three warmest years versus the three coldest years. To further study the development of the patterns seen in Fig. 3 for 2002 we have split the period of June and July into one-week intervals and traced the changes on this timescale. The nine panels in Fig. 4 demonstrate how the "anomalous" structure progressed from almost non-existent during the first week of June to its maximum in the June 28 – July 4 period and then started fading after July 25. The dashed lines with arrows in Fig. 4 help track the behavior of temperature anomalies at different locations. It is important to note here that all the important elements of temperature anomaly structure seen in Fig. 3 and Fig. 4 appear to develop ***simultaneously***. We now try to identify if these phenomena are linked, if changes in one region induce changes in the other, and if there is any periodicity in the observed anomalies.

Next, we consider geopotential height difference as a tracer for polar vortex breakup. To test the hypothesis of sudden stratospheric warming (SSW) in the winter hemisphere affecting upper mesosphere/lower thermosphere in both hemispheres (Becker et al., 2004; Becker and

Fritts, 2006; Mbatha et al., 2010) initiating the warming of both hemispheres we chose the 10 hPa geopotential height difference at one altitude, Δh_{geopot}(10 hPa) as a tracker of a SSW. This approach follows from a typical behavior of geopotential height distribution during and after polar vortex breakdown followed by SSW: both in the case of vortex displacement and vortex splitting SSWs the 10 hPa isosurface shows distinctive maxima and minima located approximately at one latitude. The stronger the breakdown, the larger the difference of geopotential heights. Figure 5 demonstrates the behavior of Δh_{geopot}(10 hPa) for all nine years and for all latitudes. The alternating coverage of the geopotential height is caused by the yaw of the TIMED satellite every 60 days, as discussed earlier. The $\Delta \mathrm{h}_{geopot}$(10 hPa) values shown in Fig. 5 were located for each day in 10 degrees wide latitudinal belts. One can see that 2002 was, indeed, a unique year with respect to Δh_{geopot}(10 hPa): the difference between maximal and minimal values of h_{geopot}(10 hPa) reached 4 km at 70°S on day 240. The other years demonstrated lower values of Δh_{geopot}(10 hPa) and one can see that there is no correlation between this parameter and "warm"/"cold" years (see discussion of Fig. 4 above). Moreover, even in 2002 the main effects of polar vortex breakup in the Southern hemisphere began after day 200 while the strongest warming in the polar summer mesosphere occurred during days 175–185 (Fig. 4), ***well before*** the critical warming event in the Southern hemisphere. Consequently, the SSW in the winter hemisphere cannot be considered as the cause of the warming in the polar summer mesosphere under study in 2002. SSW's in the Southern hemisphere appear to have also occurred in 2005, 2007, and possibly 2009, but always too late to affect the summer polar mesosphere in the northern hemisphere.

Another approach to temperature anomaly analysis is made by comparing the average summer temperatures at "turning points"; i.e. at the tropopause, which is at the lower boundary of SABER measurements, and at the stratopause and mesopause. The latitudes for this analysis should represent high latitudes both in Southern and Northern hemispheres as well as tropical latitudes to trace the cross-equator correlations if they do exist. For this activity, the whole SABER V1.07 dataset was processed and zonal average temperature values for days 182–212 were calculated for the mesopause (T_{mesop}), stratopause (T_{stratop}), and tropopause or the lowest point in SABER altitude scan (T_{tropop}). These were obtained for the 40°S–55°S, 5°S–5°N, and 65°N–75°N latitude belts. A linear fit to the corresponding temperature values was made and subtracted to remove the long term trends. The remaining temperature anomalies for all nine years analyzed are shown in Fig. 6. One can see that the temperature anomaly amplitudes are different for the atmospheric areas shown in Fig. 6; i.e., they vary from ±0.3 K for T_{stratop} in the summer hemisphere to ±4.0 K for T_{stratop} in the winter hemisphere. To analyze the year-to-year variability we have selected the polar summer T_{mesop} to be the "Reference". Fig. 6 illustrates how the average temperatures for days 182–212 correlate with other parts of the atmosphere. We have built linear correlation coefficients, k_{corr}, for each of the temperature anomalies shown in Fig. 6 with the reference T_{mesop} anomaly and put the k_{corr} values in the corresponding panels of Fig. 6. As one can see, the largest correlation coefficients are for the combination of polar summer T_{mesop} with: tropical T_{mesop} (+0.83) and mid-latitude T_{tropop} (+0.91), T_{stratop} (–0.85), and T_{mesop} (+0.92). These observations are consistent with the temperature differences seen in Fig. 3 and discussed earlier in this section. They are also consistent with the work of Karlsson et al. (2009), but expand that work to more regions of the atmosphere.

Since the correlation coefficients can be quite large, we will refer now only to the polar summer T_{mesop} that is shown in Fig. 7. This figure provides an expanded view of the polar summer T_{mesop} anomaly (line with circles) supplemented with the 30 hPa zonal wind anomaly curve (http://www.cpc.ncep.noaa.gov, last accessed on 11 March 2012) to test the recent hypothesis of Espy et al. (2010) regarding the QBO modulation of inter-hemispheric summer mesospheric temperatures coupling in years 1991–2000. Indeed, the temperature anomaly seen in Fig. 7 demonstrates periodic behavior. However, one can see that the period of the polar summer T_{mesop} anomaly curve in 2002–2010 does not match that of the QBO curve (~26-28 months, Baldwin et al., 2001; Fischer and Tung, 2008). Analysis of the QBO period from 2002 to 2010 shows a period of 26.4 months, nearer the lower limit of the 26-28 month period. However, our analysis shows that we can match the observed behavior of the polar summer T_{mesop} anomaly using a periodic function with a 31-month period. The correlation coefficient for the sine function in this case is 0.97. This would tend to negate the QBO as the principal driver of the effect, at least between 2002–2010.

5 Concluding Remarks

The SABER pressure/temperature dataset for 2002–2010 was analyzed based on the MaCWAVE/MIDAS discovery of a warm summer polar mesosphere above approximately 83 km during 2002. Similar temperature anomalies in the northern polar mesosphere were also observed for the summers of 2007 and 2010. For 2002, there was a large sudden stratospheric warming in the southern hemisphere, but it followed rather than preceded the mesospheric warming in the northern hemisphere. An earlier stratospheric warming, which did not lead to a polar breakup, did occur in the southern hemisphere during May 2002. In fact, all three critical years had a major warming in the southern hemisphere, which followed rather than preceded the mesospheric warming in the northern polar mesosphere.

We also studied the nine-year period statistically (Fig. 6) and found that the behavior of the southern polar winter tropopause and mesopause correlated well with the equatorial stratopause and the northern polar summer on an annual basis. Furthermore, there was very little evidence for much of a lag between the onset of a stratospheric warming in the southern hemisphere and a gradual transition to warming in the northern polar mesopause region, as had been suggested by the inter-hemispheric movement of waves or another form of energy transfer. Instead, the change into a summer mode appeared to occur in both hemispheres simultaneously.

In the work of Espy et al. (2010) it was suggested that the process was governed by the QBO, which they claim had a period for their decade of study (1990–2000) of about 24.5 months. Our study for 2002–2010 occurred during a period when the QBO exhibited a period of about 26-28 months. This is seen by conducting a Fourier analysis on QBO data for the current decades (Fig. 7). Furthermore, this period seemed to be correct for at least the previous 50 years. However, the period of the temperature anomaly was very close to 31 months (Fig. 8), which does not appear to be directly influenced by the QBO. The explanation appears to require either a varying time lag or a beating against another oscillation not yet defined.

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Table 1. Temperature uncertainties for SABER V1.07 dataset (from Remsberg et al., 2008)

Alt. [km]	15	20	30	40	50	60	70	80	85	90	95	100
$\Delta T_{regular}$[K]	1.4	1.3	0.8	1.6	2.0	2.1	1.6	2.3	3.8	5.4	6.5	8.4
ΔT_{polar}[K]	1.4	1.3	0.8	1.6	2.0	2.1	1.6	5.3	8.2	10.4	16.4	25.8

Figure Captions

Fig. 1. Occurrence frequency of PMSE at ALOMAR from 2002 to 2008.

Fig. 2. Schematic illustrating how the frost point temperatures exceed the polar summer temperatures in the upper mesosphere thereby permitting formation of PMCs and PMSEs.

Fig. 3. Temperature anomalies between 2002-2010 as seen by TIMED/SABER. Panels a, b, and c are difference maps of the strongest anomaly years minus the average of the six weakest years. Panel d is the three strongest-year average minus the three weakest-year average.

Fig. 4. The $T - T_{ave}$ sequence as seen weekly during June-July 2002. The dashed lines track the persistence in space and time of each warm event.

Fig. 5. Annual plots of shifts in geopotential height (Δh_{geopot}) designating a polar breakup causing a SSW.

Fig. 6. Correlations of $\underline{T}_{mesop}$, $\underline{T}_{stratop}$, and $\underline{T}_{trop}$ for DOY 182-212 for each year from 2002-2010. The correlations are referenced to the $\underline{T}_{mesop}$ in the northern hemisphere. The southern hemisphere correlations are for lower latitudes due to the geographic sampling of the SABER instrument..

Fig. 7. Fitting the polar summer mesospheric temperature anomaly for k_{corr} = 0.97. The blue curve is the anomaly occurrence, red is a fit to 31 months, and green the QBO phase as reported by the U. S. National Climate Center.

Fig. 8. The oscillation period for the temperature anomaly at the northern mesopause. Note the tight correlation with 31 months, also shown.

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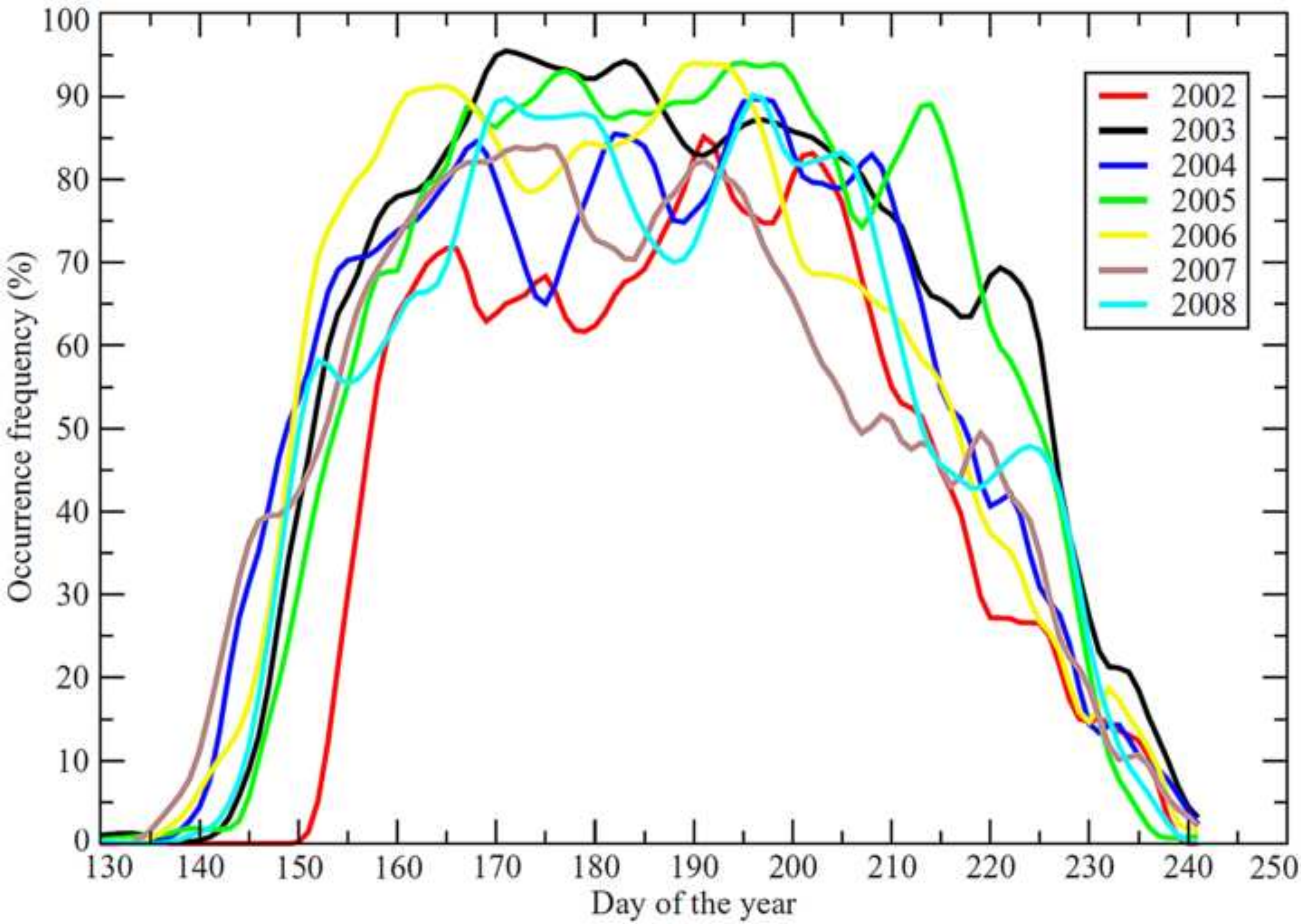

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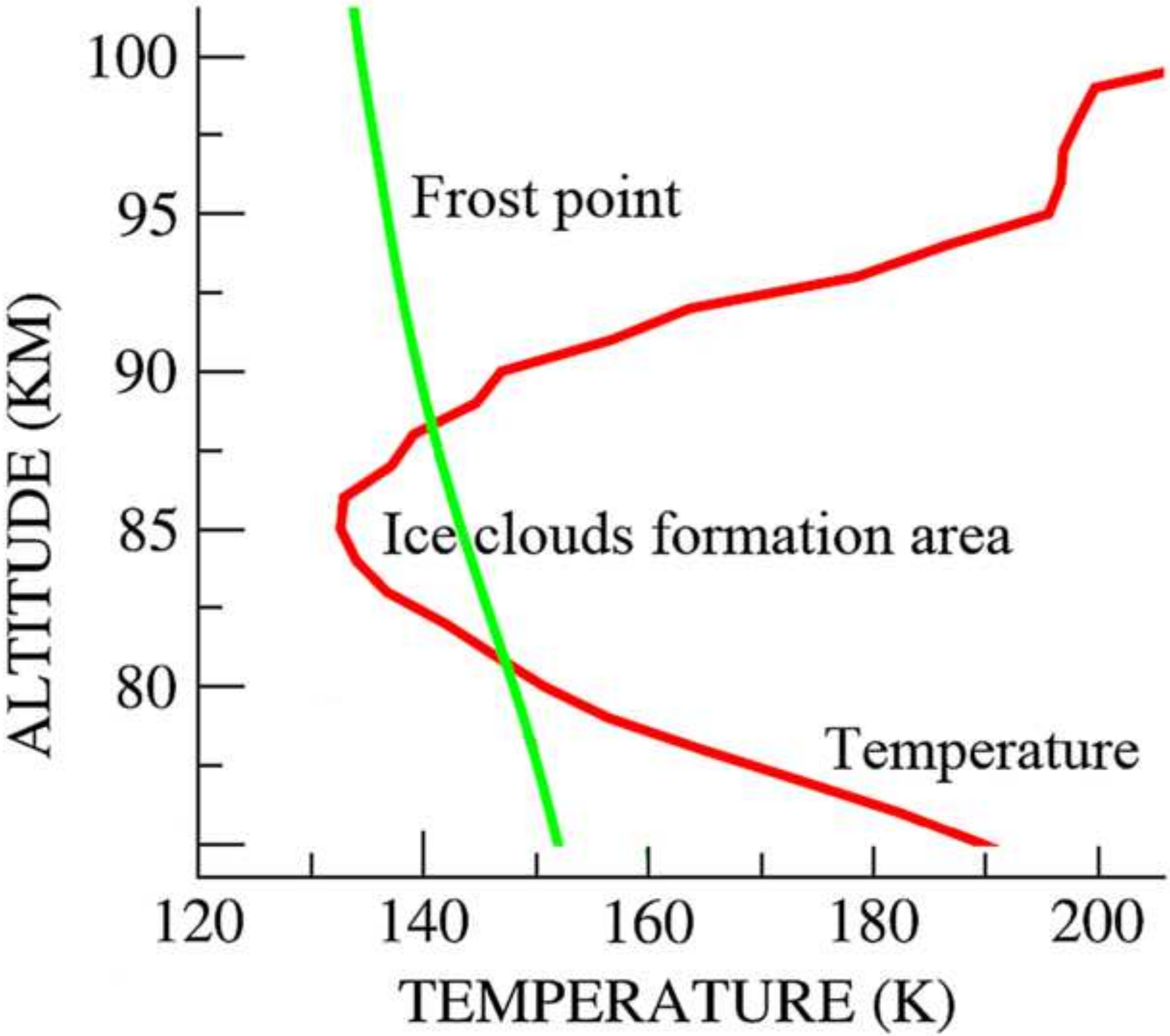

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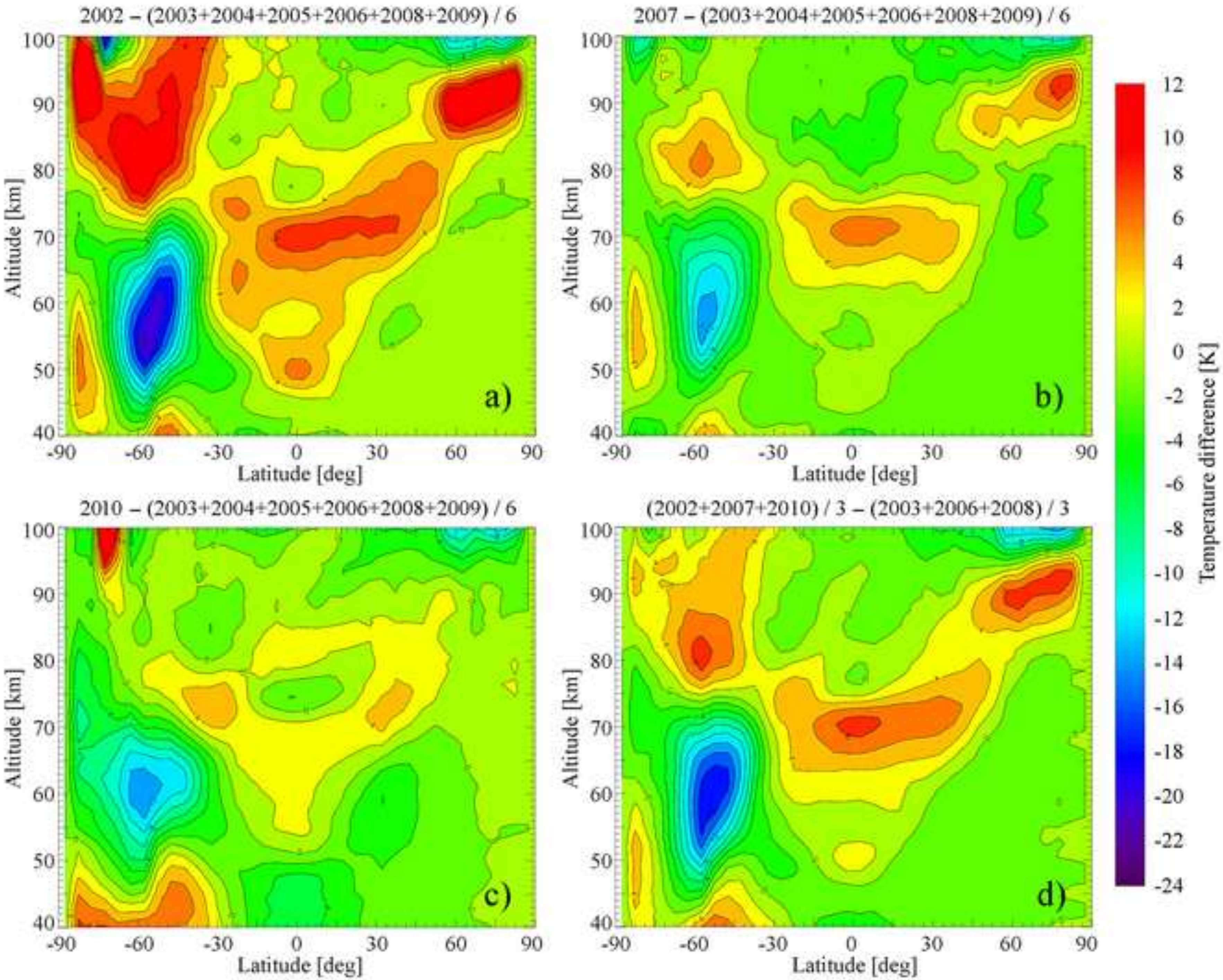

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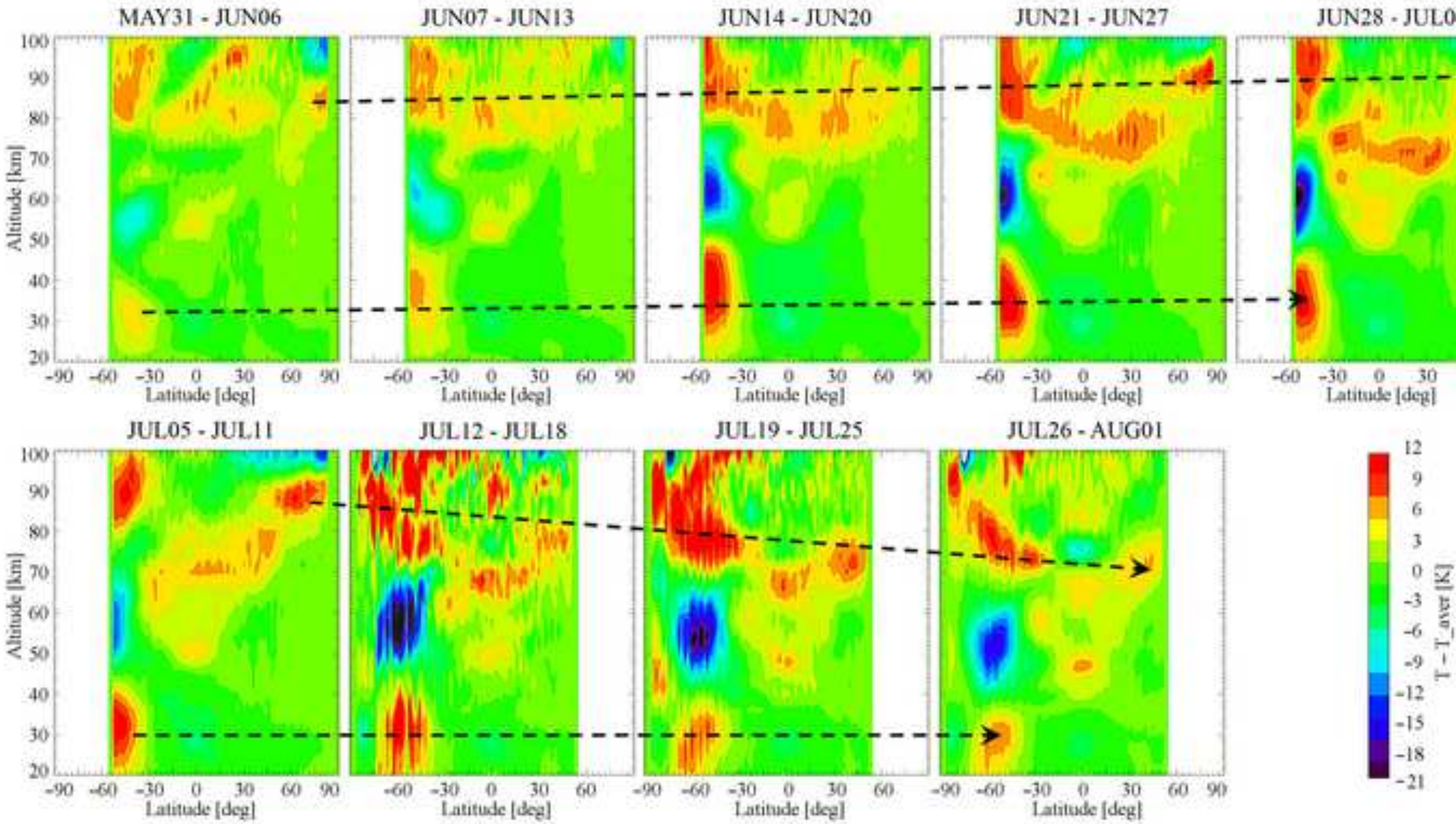

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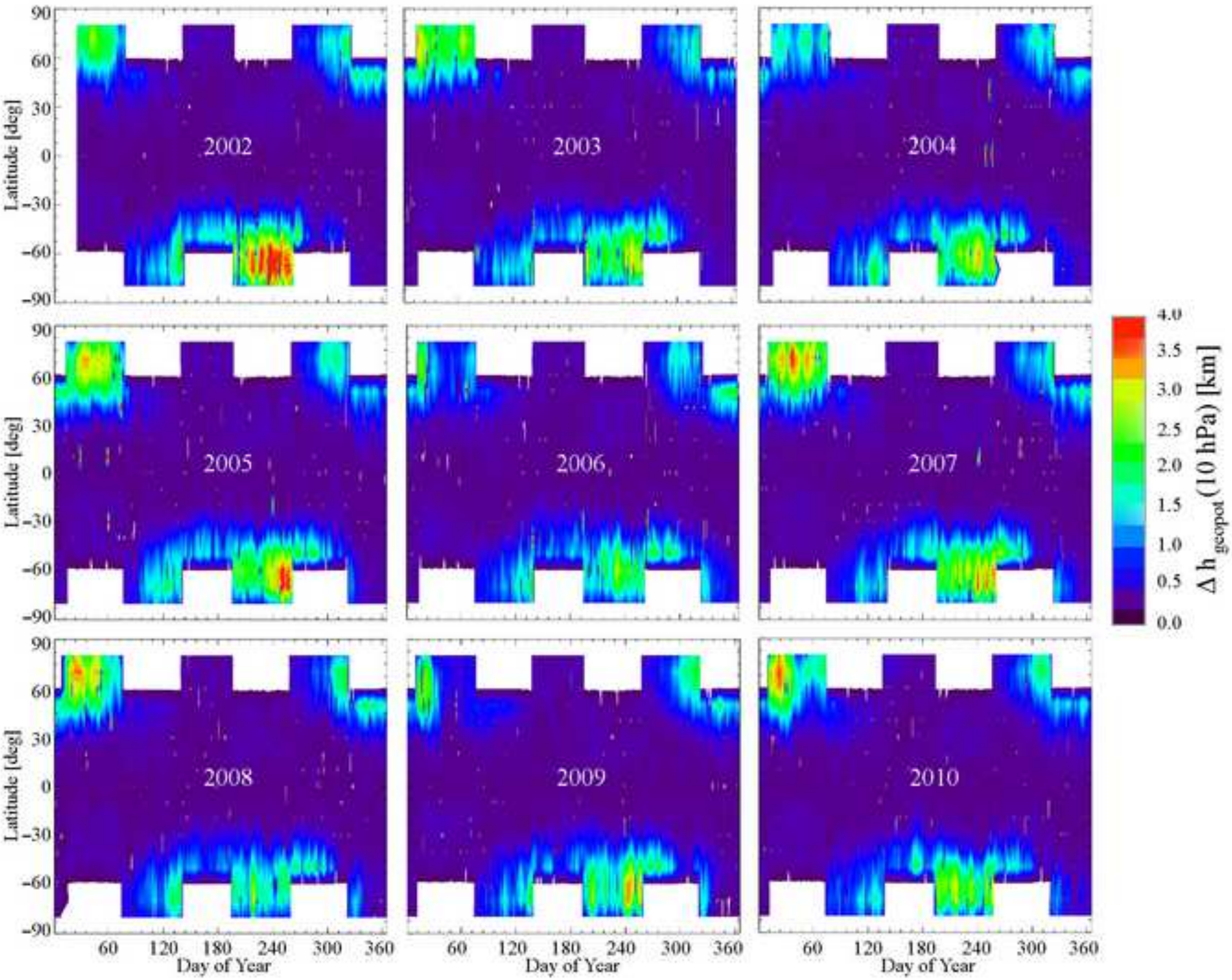

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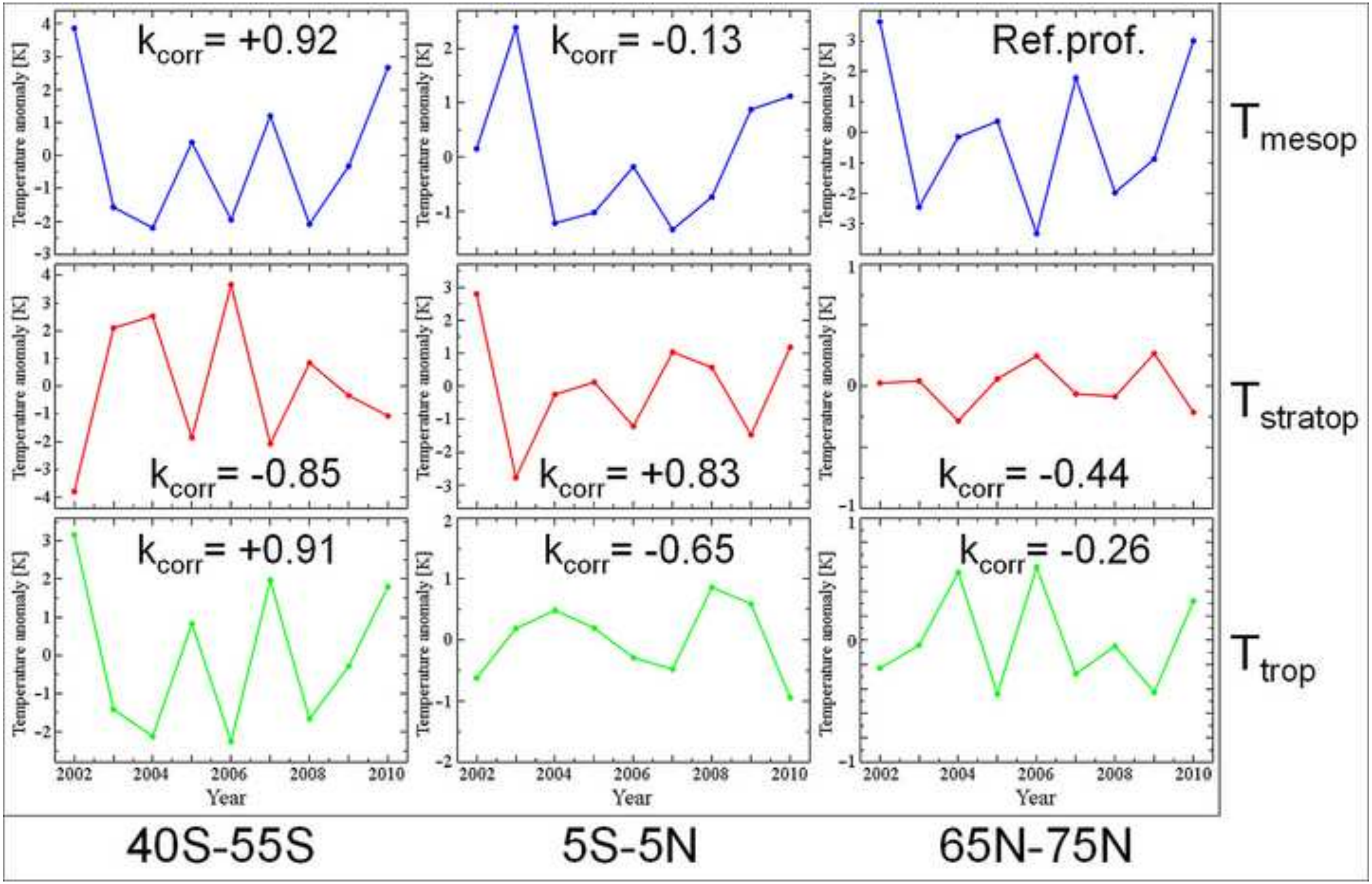

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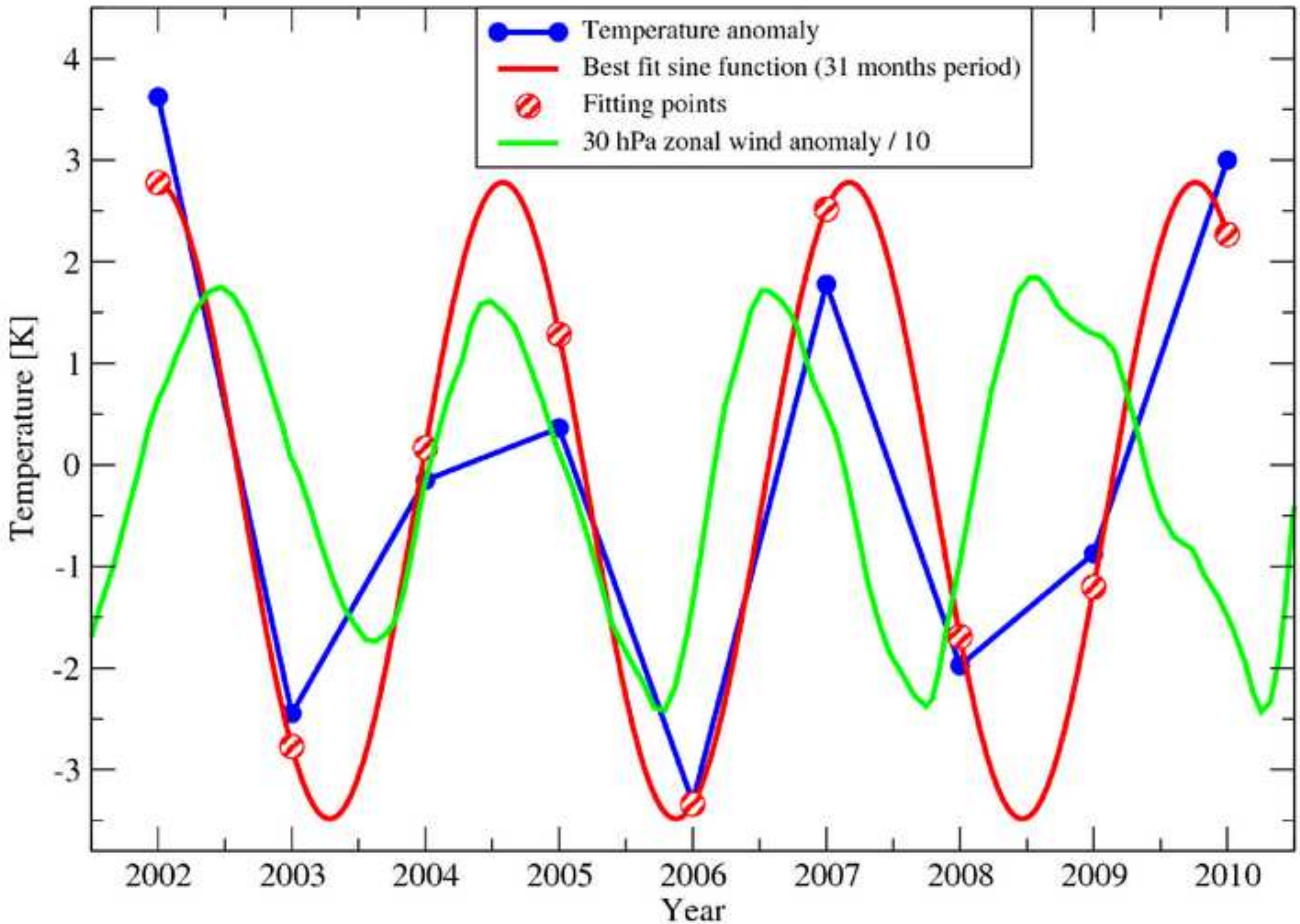

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