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Very Long Period Oscillations in the Atmosphere (0-110 km), Part 2: Latitude/Longitude comparisons and trends

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Key Points:

- oscillations in the period range 5-200 years likely to be self-excited (internal)
- oscillations very similar at four widely different latitudes and longitudes
- long-term climate changes difficult to distinguish from long-period oscillations.

Abstract

Measurements of atmospheric temperatures show a variety of long-term oscillations. These can be simulated by computer models, and exhibit multi-annual, decadal, and even centennial periods. They extend from the ground up to the lower thermosphere. Recent analyses have shown that they exist in the models even if the model boundaries are kept constant with respect to influences of the sun, ocean, and greenhouse gases. Therefore, these parameters appear not responsible for the excitation of these oscillations, i.e. the oscillations might be rather self-excited. However, influences of land surface/vegetation changes had not been enrirely excluded. This is studied in the present analysis. It turns out that such influences might be active in the lowermost atmospheric levels.

Long-term trends of atmospheric parameters as the temperature are important for the understanding of the ongoing climate change. Their study is mostly based on data sets that are one to a few decades long. The trend values are generally small, and so are the amplitudes of the long-period oscillations. It can therefore be difficult to disentangle these structures, especially if the interval of trend analysis is comparable to the period of the oscillations. If the oscillations are self-excited, there may be a non-anthropogenic contribution to the climate change which is difficult to determine. Long-term changes of the Cold-Point-Tropopause are analyzed here as an example.

Short Summary

Atmospheric oscillations with periods between 5 and more than 200 years are believed to be self-excited (i.e. non-anthropogenic) in the atmosphere, except at the lowest altitudes. They are found at altitudes up to 110 km, and at four very different geographical locations (75°N, 70°E; 75°N,280°E; 50°N,7°E; 50°S,7°E). Therefore, they hint to a global oscillation mode. Their amplitudes are on the order of present day climate trends and it is, therefore, difficult to disentangle them.

I Introduction

Long-period temperature oscillations have been observed in atmospheric measurements, and –surprisingly- in very similar form in general circulation models (e.g. Meehl et al., 2013; Deser et al., 2014; Lu et al., 2014; Dai et al., 2015; Dijkstra et al., 2006; for further references see Offermann et al. (2021)). The latter authors have reported decadal to even centennial oscillation periods that existed not only at the surface but extended from the ground to the lower thermosphere. It was shown that they were not excited by the sun, the ocean, or greenhouse gases. The amplitudes of these oscillations are not large (i.e fractions of 1 Kelvin). Nevertheless they may be important if long-term trends of temperatures are analyzed, as such trends are on this order of magnitude. Hence, these oscillations may be difficult to disentangle from the trends. This is especially important if the oscillations are part of the internal variability of the atmosphere. Internal and naturally forced variability for instance on decadal time scales is being discussed by Deser (2020) and in the IPCC Climate Change 2021 report (Eyring et al., 2021).

The analyses of Offermann et al (2021) show very long period oscillations that appear to be of internal (self-excited) origin, but whose detailed nature is as yet unknown. Therefore that paper collected a number of characteristic structures which may help to clarify that question. This approach is further followed here by a comparative study of four locations in the Northern and Southern Hemisphere (at 50°N vs 50°S , both at 7°E; and at 70°E and 280°E, both at 75°N; coordinates are approximate).

The long-period oscillations of Offermann et al. (2021) were not excited by influences from the sun, ocean, and greenhouse gases. Therefore, self-excitation had been considered as a possibility. However, doubts remained as to a possible excitation by "land-surface"-atmosphere interactions (see their Section 2.2). We therefore compare here locations and occasions with very different surface structures. The location 50°N is in middle of the European land mass. The location 50°S is about 15° south of the tip of South Africa in the Southern ocean. The polar locations are in northernmost Canada and Siberia. Concerning land-surface/atmosphere interaction these locations should behave fairly different. In a further comparison two different seasons (summer/winter) at 50°N, 7°E are considered.

The results of Offermann et al. (2021) had been derived from several atmospheric computer models with special runs whose boundary conditions had been kept constant. In the present analysis we again use two of these: HAMMONIA (38123) and ECHAM6 (for details see that paper). The models showed multi-annual, multi-decadal, and even centennial oscillation periods. These periods were found in a large altitude range, from the ground up to the lower thermosphere. The period values were about constant in this regime. The vertical profiles of oscillation amplitudes and phases, on the contrary, varied substantially. These variations were surprisingly similar for the different oscillation periods. An example of these vertical profiles is shown in Fig.1. The amplitudes vary between maxima and minima. The phases show steps of about 180° which occur at the altitudes of the amplitude minima. For details see Offermann et al. 2021 (their Fig.1). The pronounced vertical structures of the oscillations can possibly help to understand their nature proper.

Long period oscillations may have important influences on the analysis of long-term trends, for instance of temperature. Such trends in the lower and middle atmosphere have been discussed frequently. They are positive or negative, depending on altitude. Recent analyses for the troposphere and stratosphere have been presented, for instance, by Steiner et al. (2020) based on numerous measured data. Such analyses generally cover only a few decades. Therefore, the changes are usually small and often comparable to the oscillation amplitudes mentioned. It can sometimes be difficult to analyze them.

Of special interest are temperature changes near the tropopause, as the tropopause is influenced by many parameters and is believed to show a robust "finger print" of climate change (Santer et al., 2004; Pisoft et al., 2021). Tropopause trend analyses have been presented several times (e.g.Zhou et al., 2001; Gettelman et al., 2009; Hu and Vallis, 2019). Long-term changes of tropopause and stratopause altitudes have been analyzed by means of measured and modeled data by Pisoft et al. (2021). They find important changes, such as an increase in tropopause height and a contraction of the stratosphere which they attribute mainly to long-term increases of greenhouse gases. The temperature at the tropopause is frequently studied as the "Cold Point Tropopause" (CPT), i.e. the lowest temperature between troposphere and stratosphere. It is influenced by various atmopheric parameters and therefore discussed as a climate indicator (Hu and Vallis, 2019, Gettelman et al., 2009).

Long term changes of the CPT are of specific interest. They have been analyzed in the tropics several times. Zhou et al. (2001) find a negative trend of –0.57±0.06 K/decade in the time interval 1973-1998. RavindraBabu et al. (2020) find a trend of –1.09 K/decade in the time interval 2006-2018. Tegtmeier et al. (2020) report trends from –0.3 to –0.6 K/decade from reanalysis data in the time frame 1979-2005. However, positive trends of tropopause temperatures have also been discussed (Hu and Vallis, 2019). Positive as well as negative trends in the range –0.94 to +0.54 K/decade have been reported by Gettelman et al. (2009) in measured and model data. It is an open question what the reason for these differences and discrepancies in sign might be.

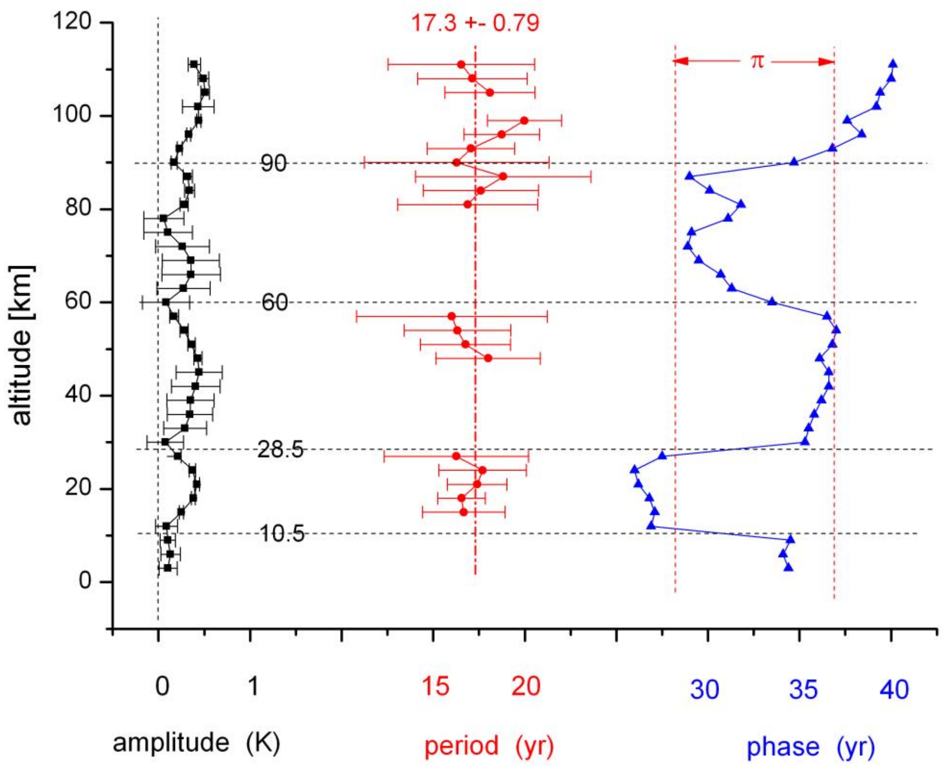

Fig. 1 Vertical structures of long-period oscillations near 17.3 ± 0.8 yr from HAMMONIA temperatures.

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The present paper is organized as follows: Section II shows analyses from a HAMMONIA model run (Hamburg Model of the Neutral and Ionized Atmosphere, 34 years) with fixed boundaries for solar radiation, ocean, and greenhouse gases. Atmospheric oscillations at northern and southern locations are compared in terms of their periods and amplitudes. The periods are between 5 and 28 years. Section III shows corresponding results from a 400 year long run of the ECHAM6 model (ECMWF/Hamburg), also with fixed boundaries. Longer periods from 20 to 206 years are analyzed here. Four locations at different latitudes and longitudes are compared. Section IV discusses the results. A possible self-excitation of the atmospheric oscillations is considered again. Furthermore the implications of the oscillations for the analysis of long-term trends is shown. As an example, the behaviour of the Cold Point Tropopause is discussed. Section V summarizes the results.

II HAMMONIA model (Hamburg Model of the Neutral and Ionized Atmosphere)

The HAMMONIA model (Schmidt et al., 2006) is based on the ECHAM5 general circulation model (Röckner et al.,2006), and extends vertically to 110 km. The simulation analyzed here was run at a spectral resolution of T31 with 119 vertical layers. A 34 year run of the model (38123) has been analyzed here for long-period oscillations at Wuppertal (50°N, 7°E). Model details and harmonic oscillation analysis have been descibed in Offermann et al. (2021). Model boundaries with respect to the sun, ocean, and greehouse gases were held constant. Nine long-period oscillations with periods between 5 and 28 years have been detected (see Tab.1). They were discussed in terms of self-excited (internal) atmospheric oscillations. Doubts concerning the self-excitation remained , however, because a possible land-surface/ atmosphere interaction could not be excluded. We therefore perform a corresponding analysis here for a conjugate geographic point at 50°S, 7°E. This location is about 15° south of the southernmost tip of South Africa in the middle of the ocean. Hence , the surface/atmosphere interaction should be quite different here from that in the middle of Europe. In case such an interaction plays a role, we hope to see this by comparing various atmospheric parameters. The analysis procedures in the North and the South are exactly the same.

Following Fig.1 we study periods and amplitudes of the long-period oscillations. The Figure shows that there are altitude ranges where a period could not be detected. This is attributed to the fact that the oscillation was not excited here, or that it was too strongly damped to be detected (see Offermann et al., 2021). At these altitudes the mean period value of the other altitudes is used as a proxy (vertical dashed red line, 17.3 ± 0.79 yr in Fig.1). The proxy is entered into the harmonic analysis and yields estimated values for amplitudes and phases of the oscillation at these altitudes. Details are given by Offermann et al. (2021). The statistical significance of the period values presented in this paper has been analyzed in the preceeding paper of Offermann et al. (2021, Section 3.2).

1) Periods

The above- mentioned nine periods found by Offermann et al. (2021) are repeated in Tab.1 together with their standard deviations (STD). At 50°S our analysis obtains seven oscillations, that are also shown in Tab.1. They all find a correspondence in the northern values. A close agreement is found, that is well within the combined standard deviations in all but one case, and is even within single standard deviation in most cases. These case are indicated by red print in Tab.1.

Table 1 holds a twofold surprise: First, it is interesting to see that long-period oscillations exist in the Southern hemisphere as well as in the Northern hemisphere. Second , it is surprising that the values of the periods are so nearly the same. We would not expect this if the surface/atmosphere interaction did play a significant role. This is apparently not the case. Our data rather appear to hint to a global oscillation mode that shows up in several periods.

2) Amplitudes

The vertical amplitude profile in Fig.1 shows a pronounced structure. This offers a valuable tool for our North/South comparison. Offermann et al. (2021) showed that vertical amplitude profiles of the different oscillations periods were surprisingly similar at the northern location. Their maxima occurred at about the same altitudes , and so did the minima. (See the accumulated amplitudes in Fig.11 of that Paper.) As a consequence the temperature standard deviations can be used as proxies for the accumulated amplitudes. This is done for the location 50°N, 7°E in Fig.2 (black squares). For the southern location at 50S, 7°E we do the same for a comparison to the North (Fig.2, red dots).

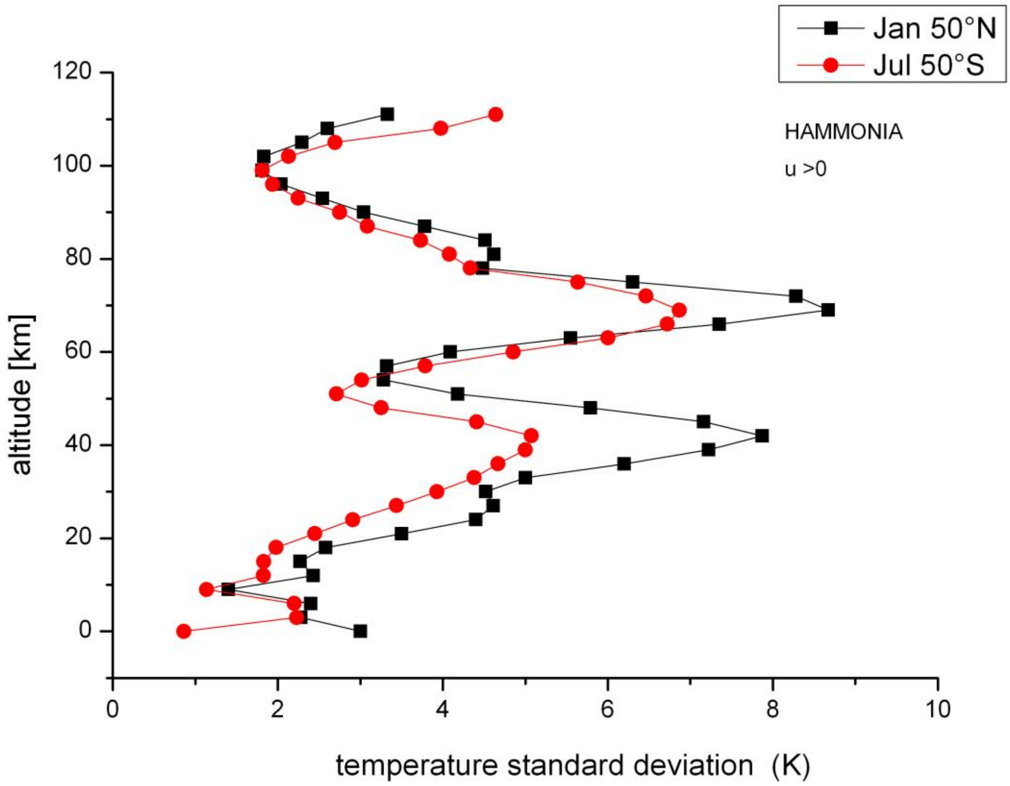

Fig.2 Temperature standard deviations as proxies for oscillation amplitudes in winter. Data for January at 50°N (black squares) are compared to July at 50° S (red dots).

In the Paper of Offermann et al. (2021) it was shown that the occurrence of the long-period oscillations was clearly dependent on the direction of the zonal wind: strong oscillation activity was **not** observed for easterly (westward) winds. In the middle atmosphere the zonal wind at solstices is opposite in the Northern and the Southern hemisphere. Hence, comparison of annual mean amplitudes at 50°N and 50°S could be misleading. We therefore compare here data of the same season: January 50°N to July 50°S (Fig. 2, zonal wind is eastward), and July 50°N to January 50°S (Fig.3, zonal wind is westward).

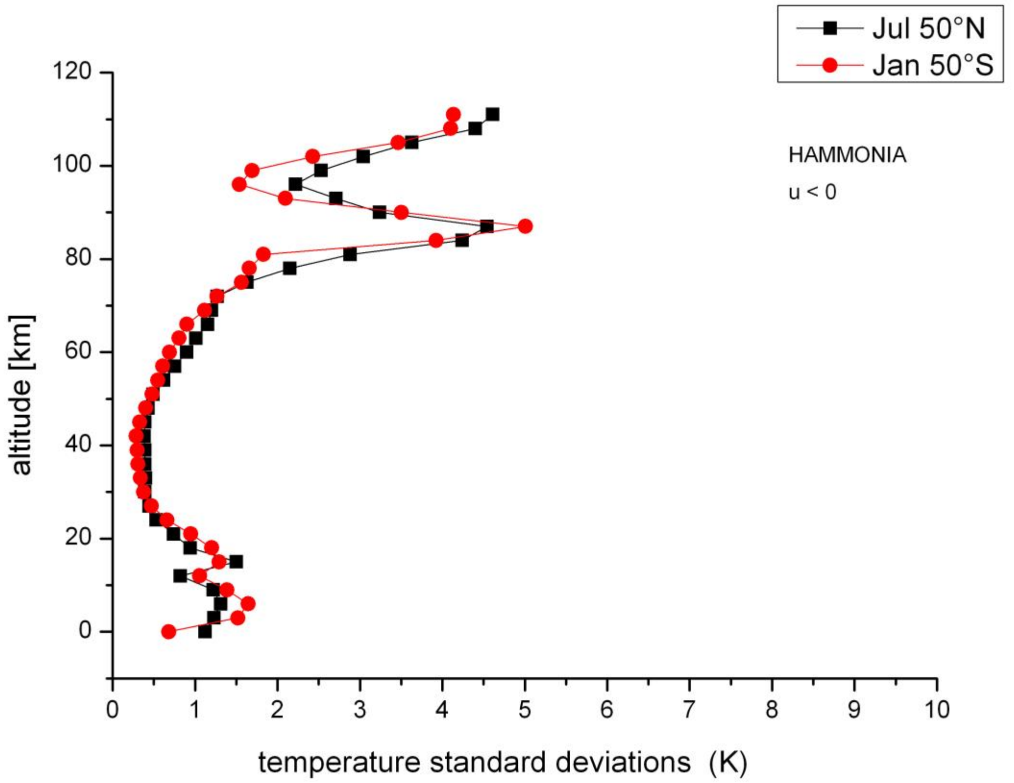

Fig.3 Temperature standard deviations as proxies for oscillation amplitudes in summer. Data are for July at 50°N (black squares) and for January at 50°S (red dots).

As expected, a comparison of the two pictures shows a large difference of the profiles between summer and winter at a given latitude, because of the opposite wind directions. The profiles in the same season, however, are surprisingly similar at 50°N and 50°S.

Taking together the results of periods and amplitudes it appears that we see essentially the same atmospheric behaviour at 50°N and 50°S. We see no evidence of a possible interaction between the land surface and the atmosphere in the excitation of the oscillations as the corresponding profile are so similar. We therefore tend to believe that these oscillations are self-excited (internal). A deviation from this similarity occurs, however, at the lowest altitude in Fig.2 and Fig.3.This will be discussed in Section IV below.

III ECHAM6 model (ECMWF/Hamburg)

Much longer periods than those in HAMMONIA were found in the ECHAM6 model (Offermann et al., 2021). ECHAM6 is the successor of ECHAM5 (Stevens et al., 2013). As the atmospheric component of the Max-Planck-Institute Earth System Model (MPI-ESM, Giorgetta et al., 2013) it has been used in a large number of model intercomparison studies related to the Coupled Model Intercomparison Project phase 5 (CMIP5). The ECHAM6 simulation analyzed here was run at T63 spectral resolution with 47 vertical layers). For more details see Offermann et al., 2021.

Our analyses were based on a 400 year run of the ECHAM6 model. In the long-period range seventeen oscillations were observed between 20 years and 206 years (Table 2). They offer further North/South comparisons in the multi-decadal range and beyond.

1) Periods

A harmonic analysis of the 400 yr run at 50°S, 7°E is performed in the same way as described in Offermann et al. (2021) for the North. Sixteen periods can be identified here, with periods between 20 years and 160 years. These are compared to the Northern values in Tab.2. (In some places of Tab.1-4 periods (counterparts) are missing. It is believed that in these cases the amplitudes were too small to be detected, as mentioned)

We find corresponding oscillation values ("North/South pairs") in all cases except one (206.7 yr in the North). The last but one column of Tab.2 shows the pair differences, the last column shows the combined standard deviations. An agreement of periods within the combined standard deviations is found in 12 cases (in red print). In the remaining five cases the periods agree within twice the standard deviations. This close agreement of the N-S-pairs is similar to that given in Tab.1. It is very remarkable that this close correspondence exists at these much longer periods, too. Together with the HAMMONIA results this again suggests some kind of a three dimensional global oscillation mode.

The HAMMONIA data show substantial differences of oscillation amplitudes between summer and winter. The oscillation periods of HAMMONIA and ECHAM6 in Tab. 1 and 2 , respectively, are annual values. As North and South are opposite in season the good agreement of the corresponding period pairs suggests that seasonal differences of the periods should not be large. We verify this using the larger set of ECHAM6 data. We compare annual mean oscillation periods to January and July (mean) values, respectively (Tab.3).

The comparison of the results at 50°N between annual periods and corresponding periods in the January data at 50°N yields 16 coincidences which agree within the combined standard deviations.The corresponding analysis of the annual 50°S data (Tab.2) and the July data at 50°S give 13 coincidences, 12 of which agreed within the combined standard deviations. (One agrees within the double standard deviations.) Hence, there is no essential difference between the annual and the summer and/or winter oscillation periods.

2) Amplitudes

Amplitudes of the long-period oscillations found in ECHAM6 are analyzed in terms of temperature standard deviations as it has been done for the shorter periods of the HAMMONIA model. Also here, large seasonal differences are expected. Therefore, a North/South comparison is performed for corresponding seasons, i.e January North is compared to July South as an example for winter. July

North and January South are compared correspondingly for summer. This is shown in Fig. 4 and 5, respectively.

Large seasonal differences are seen, indeed, and are similar to those at the shorter periods in Fig. 2 and 3. North and South profiles are, however, very similar if the same seasons are considered, as is observed for the shorter periods. Again, similarity is clearly lost at the lowest altitude.

It is also remarkable that the maxima near 40 km and 70 km agree so well in Fig.2 and 4.

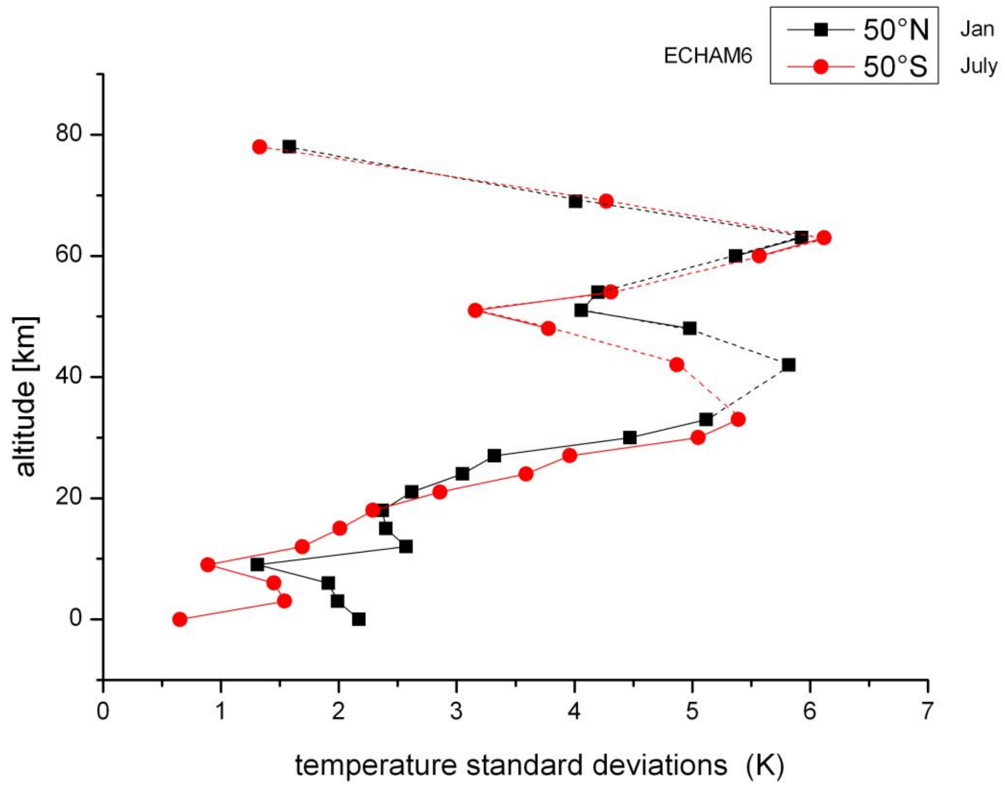

Fig.4 Comparison of ECHAM6 temperature standard deviations in winter. January 50°N (black squares) and July 50°S (red dots) are given as examples

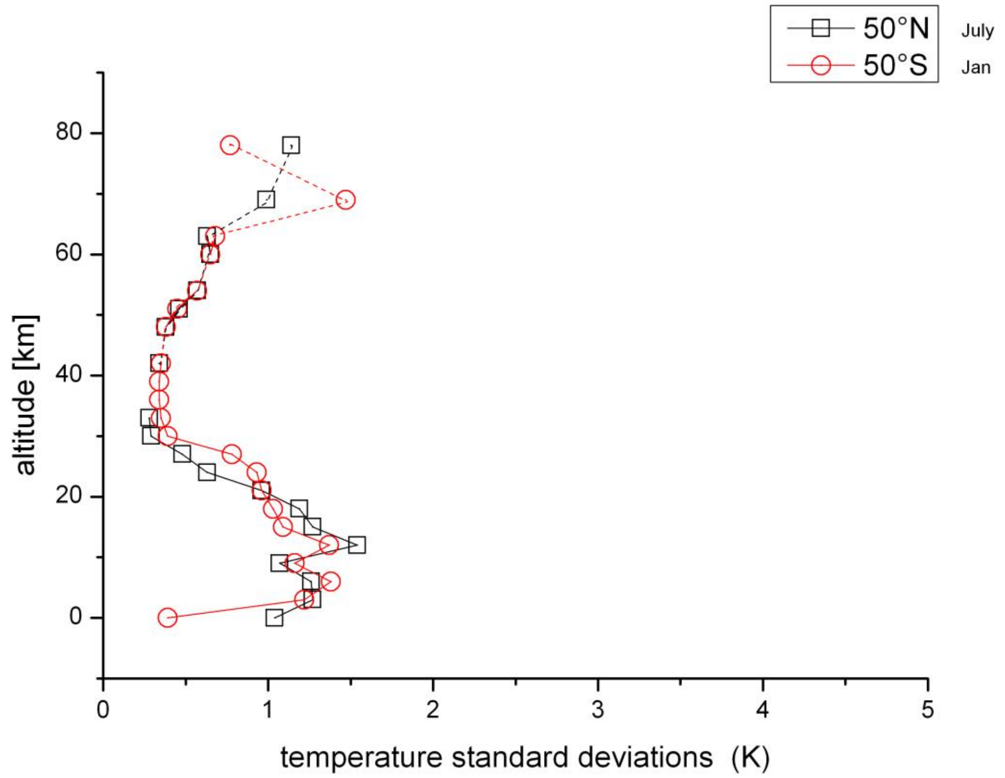

Fig. 5 Comparison of ECHAM6 temperature standard deviations in summer. July 50°N (black squares) and January 50°S (red circles) are given as examples

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3) Seasonal Differences

If there were an appreciable influence of land surface/ vegetation on the excitation of the long-period temperature oscillations in the atmosphere, one would expect a difference of the oscillations in season at a given location. Such an analysis is in part implicitly contained in the North/South comparisons given above. We repeat it here in more detail. Oscillation periods in January (northern hemispheric winter) and July (northern hemispheric summer) are analyzed in the ECHAM6 model at 50°N, 7°E. Seventeen pairs of oscillation periods can be identified at values similar to those of the annual analysis shown in the first column of Tab.2. This is shown in Tab.3. Standard deviations (STD) of the periods are also given. A period near 48 yr could not be found in July.These results are compared to the annual values of Tab.2. The second to last column in Tab.3 shows the differences of the periods in January and July. The last column shows the sum of their standard deviations. A close agreement of the January and July periods is found: in 14 cases, the periods agree within the combined standard deviations, which is indicated in red in Tab.3 (12 cases agree even within single standard deviations). In three cases, the periods agree within double standard deviations. The agreement of the monthly periods with the annual ones (first column in Tab.3) is similarly close.

Given the close agreement of the monthly periods, it is interesting to compare their amplitudes. These are shown in Fig. 6. Accumulated amplitudes are shown, i.e. the sum of all oscillation amplitudes obtained at a given altitude. The amplitudes could not be derived for each altitude. Hence, the curves shown in Fig.6 are approximate. The two curves are quite different. The January curve has high values, is highly structured, and closely resembles in shape the winter temperature standard deviation profiles in Fig. 4. The values of the July curve are much smaller and resemble in shape the summer curves of the standard deviations given in Fig.5. These agreements again justify the use of temperature standard deviations as proxies of the oscillation amplitudes.

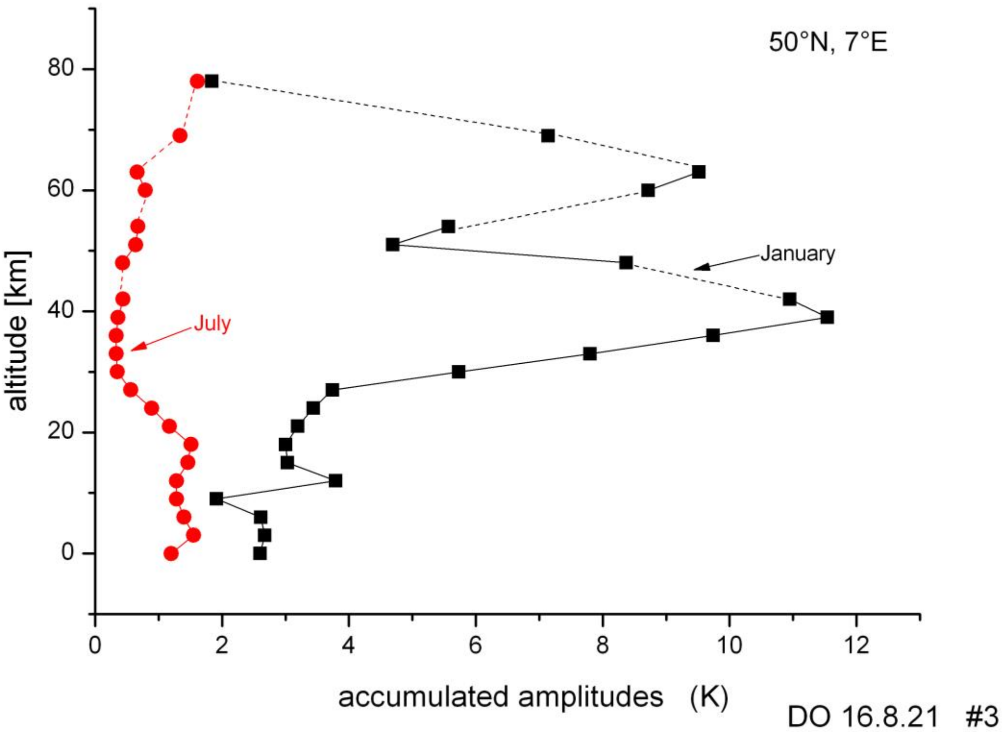

Fig. 6 Long-period temperature oscillations in the ECHAM6 model at 50°N, 7°E. Accumulated amplitudes are shown vs altitude for the periods given in Tab.3. Black squares are from monthly mean January data. Red bullets are from July.

The large difference in amplitudes in summer and winter in the stratosphere and mesosphere may be attributed to the opposite direction of zonal winds in the middle atmosphere in these seasons. It is surprising that in spite of these large differences the periods of the oscillations are so nearly the same. This demonstrates that the oscillation period is a robust parameter, as has been discussed by Offermann et al. (2021).

4) High Latitudes

Considerable land surface/vegetation differences might also be expected at polar latitudes. We have therefore analyzed ECHAM6 temperatures at 75°N, 70°E (Northern Siberia) and 75°N, 280°E (Northernmost Canada). Winter temperatures (January) have been searched for long period oscillations in the same way as described above. The results are shown in Tab. 4. For comparison January data at 50°N from Tab.3 are also given.

The results are quite interesting. The periods found at the two polar locations are very similar. Seventeen periods have been found at either station, and 16 of these agree within the combined standard deviations (12 agree even within single standard deviations). The periods at high latitudes are quite similar to those at mid latitudes (50°N, 7°E). The 18 periods seen at 50°N find 16 counterparts in either high latitude station. Of these 15 (14) agree within the combined standard deviations for the 70°E (280°E) station. Eleven periods even agree within single standard deviations in either case. Hence, the comparison of middle to high latitudes does not show an influence on periods, either.

Deser et al. (2012) showed in their analysis that the variability of surface temperatures at high (Northern) latitudes was considerably larger than that at mid and low latitudes. A similar result is obtained in the present data set for the upper atmosphere. We have caltulated the temperature standard deviations at the two polar locations (75°N) and show them in Fig. 7. The results at the 70°E and 280°E longitudes are fairly similar. However, as suspected, they are significantly larger than the mid-latitude values shown in Fig.4.

The profile forms shown in Fig. 7 are fairly different from those in Fig.4. They are smeared and the extrema occur at different altitudes. It appears that the profiles for different oscillation periods can be different for different latitudes as well as for different longitudes. A detailed analysis is, however, beyond the scope of this paper.

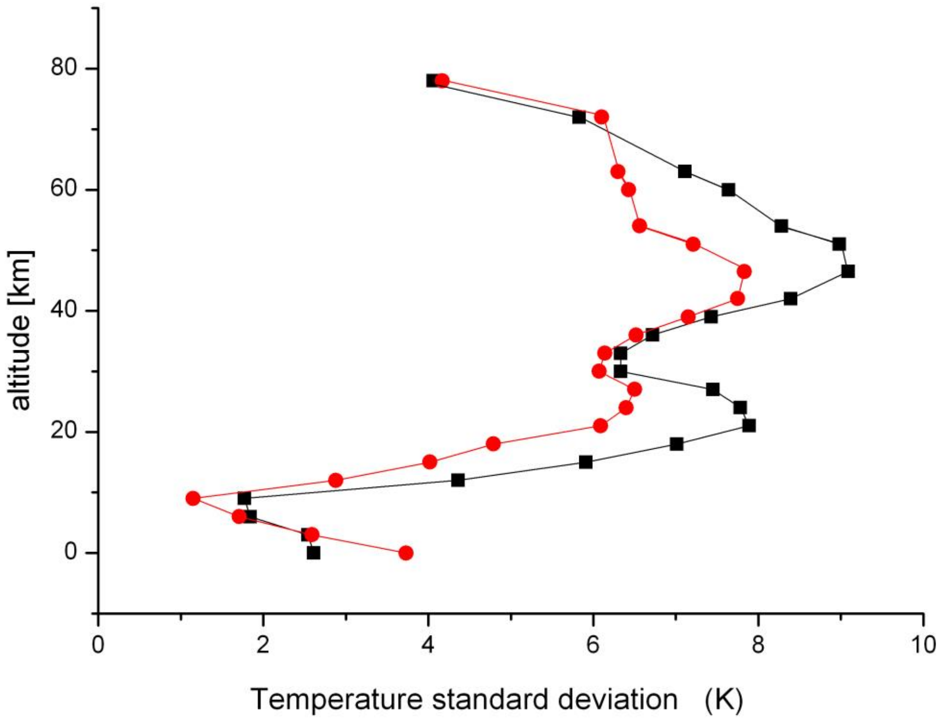

Fig.7 Temperature standard deviations at polar latitudes 75°N, 280°E (black squares) and 75°N,70°E (red dots) in January

IV Discussion

1. Internal oscillations

The boundary conditions of the computer model runs used by Offermann et al.(2021) and in the present analysis were kept constant. This concerned solar irradiation, the ocean, and greenhouse gases. Nevertheless, the atmospheres in the models showed pronounced and consistent oscillations. It was therefore suggested that these oscillations were self-excited or internal in the atmosphere. Land surface/vegetation changes as external influences, however, were not completely excluded in the earlier paper. To check such possible influences the models are analyzed here at times and locations that have different land surface/vegetation conditions. These are on the one hand two corresponding locations in the Northern and Southern hemisphere (50°North and South at 7°East). On the other hand two different seasons are compared at the same location (50°North, 7°East). Finally, two polar locations (75°N at 70°E and 280°E, respectively) are compared to the middle latitudes.

The results for all northern and southern locations/occasions are very similar as concerns the oscillation periods. Pairs of oscillations at two different locations are compared and show nearly the same values in many cases.. Also the amplitudes are found to be similar when comparing the corresponding seasons. However, amplitudes at different seasons (summer/winter) at the same location are quite different. Despite this discrepancy, their periods are very similar. We conclude from these various similarities that the long-period oscillation are not likely to originate from land surface/vegetation processes in most part of our high vertical profiles. However, the similarity is lost at the lowest altitude, as mentioned above.

The large summer/winter difference in amplitudes (standard deviations) is shown here for one pair of North/South locations (50°N/S, 7°E), only. Deser et al. (2012) have shown global surface analyses which indicate , however, that this may be a global phenomenon (their Fig.16). This is seen if their December-January data are compared to our January data: Northern values are much larger than Southern values. It thus appears that our North/South difference is part of an extended (global) structure.

However, there is a seeming disagreement between our data and those of Deser et al. in July: theses authors do not see much difference between 50°N and 50°S, whereas here in Fig 2-5 the Northern values are much smaller than those in the South if the entire profiles are considered.

The discrepancy disappears if only the lowest altitudes in our data are considered . Our North and South profiles are fairly similar at all altitudes except the bottom values: at the lowest altitude all of our Southern amplitudes (given as standard deviations) are much smaller than their Northern counterparts (Fig. 2-5). It needs to be emphasized that this difference is limited to the lowermost altitude , and disappears at about the next higher level (3 km). This applies to the two different models HAMMONIA as well as ECHAM6. The difference of the two lowermost levels is surprising, It is, however, significant as the statistical error of the standard deviations is 12% for HAMMONIA and 3.5% for ECHAM6. In numbers Fig. 2-5 yield the following results. The January values are high in the North (2.2-3.0 K) and small in the South (0.39-0.68 K). Contrary to this, the July values are comparatively low as well in the North (1.04-1.12 K) as in the South (0.65-0.86 K). This is qualitatively similar to the results of Deser et al. (2012).

Desai et al. (2022) mention that land-atmosphere interactions should occur essentially in the lowest 1-2 km of the atmosphere (boundary layer). It thus appears interesting to interpret the large deviations from profile similarity at the lowermost levels of Fig.2-5 as an indication of land-atmosphere interaction at these levels. The deviations are large and significant. They quickly disappear at the higher levels. This suggests that excitation of long-period oscillations by land suface-atmosphere interactions would be limited to the lowermost atmosphere.

Internal variability in the atmosphere has been discussed several times in the literature (see Deser (2020) and references therein). This is thought to be caused by the chaotic dynamics of the atmosphere and oceans, and to be generally unpredictable more than a few years ahead of time. It remains to determine how this is related to our internal oscillations.

2. Implications of internal oscillations

a) Temperature trends

Long-term temperature changes are part of the on-going climate change, as well in the troposphere as in the upper atmosphere (Eyring et al., 2021). It is important to know whether there is a relation between these trends and the internal (non-anthropogenic) atmospheric variability. We study this question by ECHAM6 data in the lower stratosphere, as the boundary values of the model runs were kept constant, and therefore the model variability is believed to be internal.

New long-term temperature trends in the troposphere and stratosphere have recently been presented by Steiner et al. (2020). Data cover about four decades (1980 – 2020). These authors find trends on the order of -0.2 K/decade in the lower stratosphere (near- global averages, their Fig. 8). For comparison, we show ECHAM6 data for 50° N, 7°E at 18 km altitude in our Fig.8. These data are annual mean residues, i.e. the mean value has been subtracted from the annual data set. The series has been smoothed by a 16 point running mean. The Figure shows trend-like increases or decreases of 0.2 K/dec or even steeper over 4 decade intervals.This is indicated by the slant red lines that give an increase of 0.2 K/dec.

The comparison with Steiner et al. (2020) is approximate because our data are local (50°N, 7°E), whereas Steiner et al. give global means. Such means tend to smooth all variability to some extent. Nevertheless, the results suggest that the long-term trends derived by Steiner et al. (2020) may contain some contribution of internal (i.e. non-anthropogenic) variability. This confirms a corresponding result of these authors saying that "…there may be a nonnegligible internally generated component to the larger stratospheric trends…" (see their Section 5).

Care must therefore be taken if deriving climate trends from data sets of limited length (4 decades). A similar caveat applies if internal oscillations with periods on this order are excited in the atmosphere.

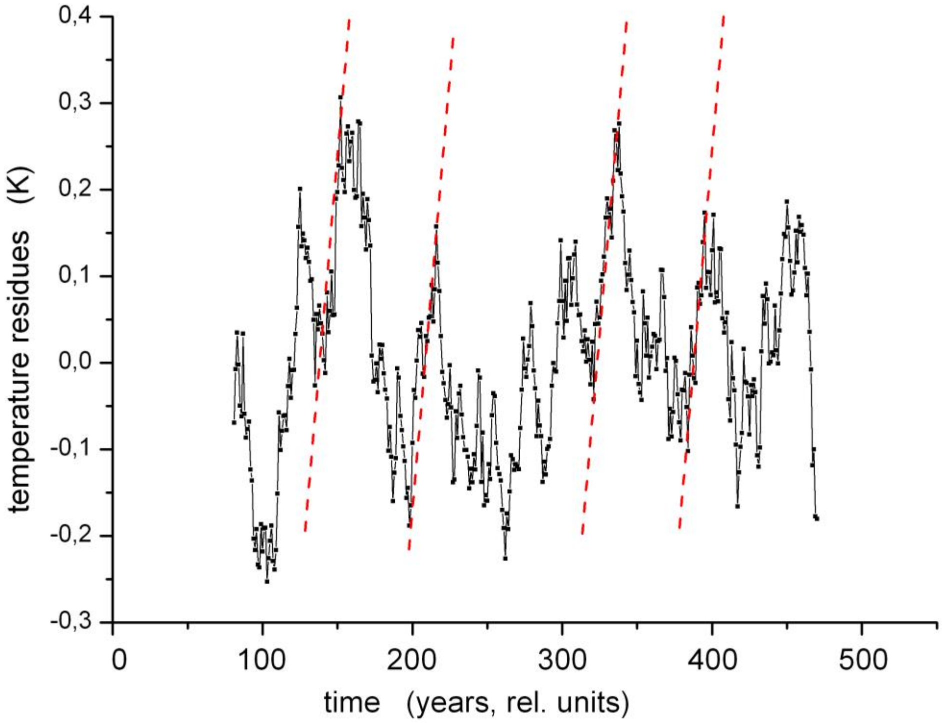

Fig.8 ECHAM6 annual temperature residues at 50°N, 7°E, 18 km altitude. Data have been smoothed by a 16 point running mean. Time is in relative units. Inclined dashed (red) lines have a gradient of 0.2 K/decade.

b) Cold Point Tropopause.

The Cold Point Tropopause (CPT) is frequently discussed as a climate indicator (see e.g. Hu and Vallis, 2019; Gettelman et al., 2009; Han et al., 2017). A similar parameter is the Lapse Rate Tropopause (LRT), which we do not discuss here as it is generally close to and behaves similarly as the CPT (Pan et al., 2018; RavindraBabu et al., 2020).

We analyze long-term changes of the Cold Point Tropopause (CPT) in the ECHAM6 model with fixed boundaries at 50°N, 7°E and the corresponding Southern Hemisphere location (50°S, 7°E) as part of our North/South comparison. The lowest temperatures are found in this model at 11.5 km (208.67 hPa) and 12.4 km (181.16 hPa) (this is the altitude resolution of the data). We have selected the lowest temperature at these two altitudes and thus formed a data set that approximates the Cold Point Tropopause, considering our limited altitude resolution.

The results are shown in Fig.9. The figure compares our CPT data at the two locations. To study data that are corresponding, winter values are shown, i.e January data in the Northern hemisphere and July data in the Southern hemisphere. The data have been smoothed by a 16 point running mean to suppress the short term variability that is large (5 K pp). The picture shows that the Southern CPT are somewhat lower than the Northern ones. Most interesting is the strong variability in either data set, including some apparent periodicity. The latter is indicated by the vertical dashed lines at 60 year intervals.

On time scales of decades, positive and negative trends are seen. The positive trends are comparable to the dashed (blue) straight lines that have a gradient of 1 K/dec. The picture shows that such gradients or even steeper ones are not uncommon in the data. The decreasing branches show similar (negative) gradients.

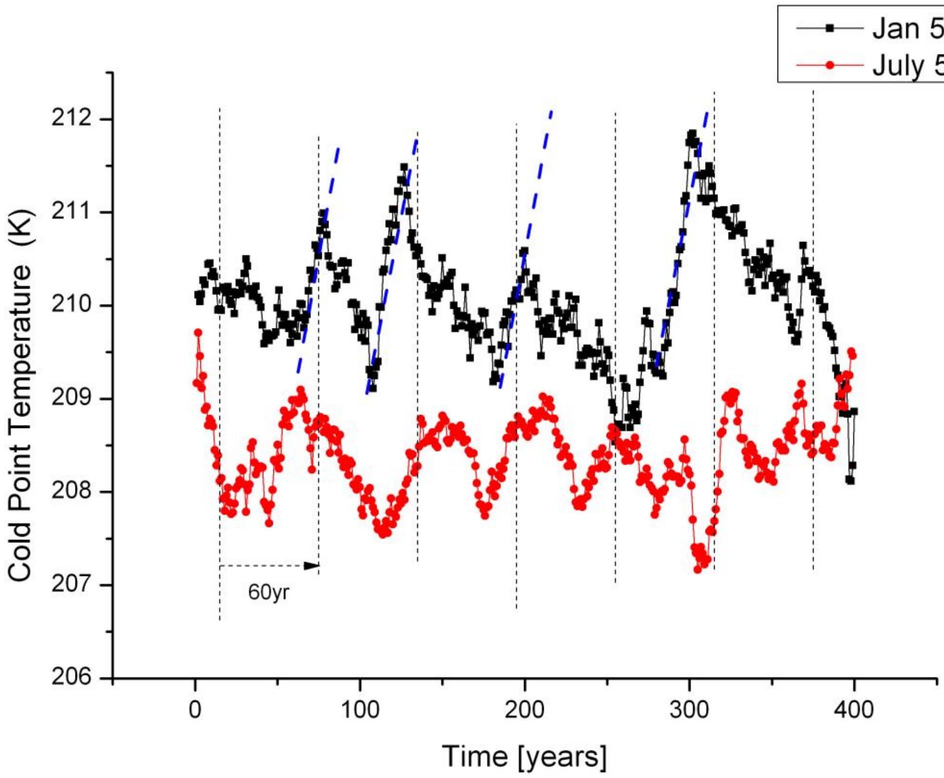

Fig.9 Cold Point Tropopause temperatures in ECHAM6.
Winter data are shown for 50°N, January (black) and 50°S, July (red). Dotted vertical lines (black) indicate a 60 yr periodicity. Inclined dashed lines (blue) show a trend of 1 K per decade. Time is in relative units.

Gradients on this order of magnitude are reported in the literature. Amazingly, positive as well as negative values are found, as mentioned in Section I. Recently, negative and positive trends in two subsequent 20 year time intervals (1980-2000;2001-2020) have been discussed by Konopka et al. (2022). Figure 9 shows that this may not be surprising, but may occur quite naturally depending on the time interval chosen for the trend determination. The quasi-periodic behaviour of the CPT plays a role here and suggests a possible connection to the internal oscillations of the atmosphere.

We therefore perform harmonic analyses of the CPT data similarly as described above for annual temperatures in Tab.2. The CPT data are monthly data of January and July, respectively. It was shown above that there is little difference between annual and monthly oscillation periods, and it was checked that this applies here, too.

The harmonic analyses of the data yield a number of internal oscillation periods in the period range of Tab.2, indeed. The results at the Northern and Southern locations are compared in Tab.5. The table shows that the periods in the North and South form pairs similarly as in Tab.1 and 2. Eleven coincidences are obtained. Seven of these agree within the combined standard deviations (red in the last two columns of Tab.5). Four agree within the double standard deviations (black in Tab.5). All periods listed in Tab.5 also find a counterpart in the corresponding (North or South) columns of Tab.2. Also, these pairs agree within combined standard deviations (except one). It thus appears that the Cold Point Tropopause is at least partly controlled by the internal atmopheric oscillations. This applies to the North as well as to the South, i.e. the North/South symmetry shown above is also found in this parameter.

The amplitudes of the CPT oscillations are found quite variable with period (not shown here). The Northern and the Southern data both show strong amplitude peaks near 60 years. This fits to the data shown in Fig.8.

Low frequency oscillations (LFO) in the multi-decadal range (50-80 years) have frequently been discussed for surface temperatures. They have, for instance, been interpreted as internal Atlantic

Multidecadal Variability or Pacific Decadal Oscillations/Interdecadal Pacific Oscillations (e.g. Meehl et al., 2013, 2016; Lu et al., 2014; Deser et al, 2014; Dai et al., 2015). It appears that internal oscillations play a role also here as contributors to the CPT variations in either hemisphere. Great caution is therefore advised when interpreting tropopause changes in the context of the anthropogenic long term climate changes (e.g. Pisoft et al., 2021).

V Summary and Conclusions

1) Self-excitation of oscillations

Present day sophisticated atmospheric computer models exhibit long period temperature oscillations in the multi-annual, decadal, and even centennial year range. Such oscillations may be found even if the model boundaries are kept constant concerning the influences of solar radiation, the ocean, and the variations of greenhouse gases (Offermann et al., 2021). A possible influence of land surface/ vegetation changes, however, was undecided yet. Therefore, in the present analysis oscillation periods are compared at locations/occasions with different land surface/vegetation behaviour, hoping to see possible differences in oscillation periods. Three cases are studied: First, a location in the Northern hemisphere (50°N, 7°E) and its counterpart in the Southern hemisphere (50°S, 7°E) are considered. The Northern location is in the middle of Europe, whereas the Southern location is 15° south of the tip of South Africa in the middle of the Southern ocean. Second, two different seasons are compared in the Northern location (January and July). Third, two polar latitude locations are studied at 75°N, 280°E and 75°N, 70°E. The land surface/vegetation conditions are quite different in all of these cases. Two models are studied (HAMMONIA, ECHAM6) for medium and long oscillation periods (5 to beyond 200 years). The periods obtained for the contrasting cases are all found very similar.

The same holds for the vertical profiles (up to the mesopause) of the oscillation amplitudes at most altitudes. It is therefore concluded that the oscillations most likely are internally excited in the atmosphere.

There is, however, one exemption. Land-atmosphere interactions should mainly occur in the lowermost atmophere (boundary layer). We therefore considered especially the lowest atmospheric levels. Here, indeed, the vertical amplitude profiles showed peculiar structures that we tentatively attribute to land-atmosphere interactions. The peculiarities quickly disapper at higher altitudes. Hence we obtain the preliminry picture of self-excited oscillations in the upper atmosphere, and possible land surface excitation at the lowest levels.

2) Trends and long periods

Long- term trends in atmospheric parameters are frequently analyzed in the context of the ongoing climate change. Trend values are mostly small, and it is sometimes difficult to determine whether or to what extent they are anthropogenic in nature. In this context internal oscillations can play a role even if their amplitudes are small. If the oscillation period is on the order of the interval used for the trend analysis it may become difficult to disentangle trend and oscillation. It is unimportant here, whether the oscillations are self-excited or not.

As an example the Cold Point Tropopause (CPT) in the 400 year run of the ECHAM6 model with fixed boundaries is analyzed at two North/South locations. Strong trend-like increases or decreases of CPT values are seen on decadal time scales (order of 30 years). They are on the order of the trend values discussed in the literature. They are, however, not of anthropogenic origin, as is frequently assumed in the literature. Harmonic analysis of the CPT values yields oscillation periods that are very similar for the North and South location, and are similar to the values otherwise given in this analysis. Apparently these internal oscillations are important contributors to the CPT variations observed.

Data Availibility

The HAMMONIA and ECHAM6 data are available from Hauke Schmidt, MPI Meteorology, Hamburg.

Author Contribution

DO performed the data analysis and prepared the manuscript with the help of all co-authores.

JW managed the data collection and preparation.

ChK helped with the geographical analysis.

R.K provided interpretation and editing the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

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Table 1 Oscillation periods and their standard deviations at 50°N, 7°E vs 50°S, 7°E (HAMMONIA model)

	Period (yr) 50°N	STD	Period (yr) 50°S	STD	difference of periods	combined STD
1	5,34 ±	0,1	5,61±	0,15	-0.27	0.25
2	6,56	0,24				
3	7,76	0,29	7,42	0,28	0.34	0.57
4	9,21	0,53	9,24	0,45	-0.03	0.98
5	10,8	0,34	10,7	0,18	0.1	0.52
6	13,4	0,68	13,2	0,86	0.2	1.54
7	17,3	1,05	16,5	1,3	0.8	2.35
8	22,8	1,27	--	--		
9	28,5	1,63	30,3	4,6	-1.8	6.23

Table 2 Oscillation periods and their standard deviations at 50°N, 7°E vs 50°S, 7°E (ECHAM6 model)

.

	Period (yr) 50°N	STD	Period (yr) 51°S	STD	difference of periods	combined STD
1	20	±0,35	20,1	±0,4	-0,1	0,75
2	20,9	0,15	21,8	0,37	-0,9	0,52
3	22,1	0,23	23,2	0,33	-1,1	0,56
4	23,8	0,42	24,3	0,41	-0,5	0,83
5	25,3	0,46	26,1	0,44	-0,8	0,9
6	27,3	0,41	28,6	0,44	-1,3	0,85
7	30,2	0,49	31,8	0,58	-1,6	1,07
8	33,3	0,84	34,5	0,58	-1,2	1,42
9	36,9	1,17	38,3	1,05	-1,4	2,22
10	41,4	0,97	43	1,52	-1,6	2,49
11	48,4	1,73	49,7	1,78	-1,3	3,51
12	58,3	1,77	60,3	2,33	-2	4,1
13	64.9	2.98	66.5	2.5	-1.6	5.48
14	77.5	3.94	84.8	4.74	-7.3	8.68
15	95.5	5.86	110.9	10.9	-15.4	16.76
16	129.4	14.5	160.2	8.88	-30.8	23.38
17	206.7	16.3				

Table 3 Temperature oscillation periods (yr) at 50°N,7°E, standard deviations (std), and column differences

	Period Annual	STD	Period January	STD	Period July	STD	difference Jan-July	STD sum Jan+July
1	20	0,35	19,6	0,33	19,8	0,52	-0,2	0,85
2	20,9	0,15	20,8	0,32	21	0,18	-0,2	0,5
3	22,1	0,23	22,4	0,33	22,2	0,38	0,2	0,71
4	23,8	0,42	24,1	0,19	24,1	0,31	0	0,5
5	25,3	0,46	25,3	0,49	26,1	0,21	-0,8	0,7
6	27,3	0,41	27,8	0,76	27,7	0,17	0,1	0,93
7	30,2	0,49	30,3	0,62	30,2	0,76	0,1	1,38
8	33,3	0,84	33,1	1,03	33,7	0,55	-0,6	1,58
9	36,9	1,17	37,5	1,05	38,1	1,3	-0,6	2,35
10	41,4	0,97	41,5	1,49	44,3	1,23	-2,8	2,72
11	48,4	1,73	48,3	1,69	--	--	--	--
12	58,3	1,77	57,9	0,53	53,3	1,77	4,6	2,3
13	64,9	2,98	63,5	2,7	66,2	1,92	-2,7	4,62
14	77,5	3,94	77,1	2,5	79,1	5,11	-2	7,61
15	95,5	5,86	97,6	7,81	103,8	5,4	-6,2	13,21
16	129,4	14,5	130,1	9,03	121,1	9,32	9	18,35
17			169,3	10,55	183,4	7,51	-14,1	18,06
18	206.7	16.3	239	15,3	216,2	14,67	22,8	29,97

Table 4 Temperature oscillation periods (yr) and their standard deviations (STD) at 50°N, 7°E; 75°N, 70°E; and 75°N, 280°E in January.

	50°N, 7°E	STD	75°N, 70°E	STD	75°N, 280°E	STD
1	19.6	0.33	19.6	0.44	19.2	0.26
2	20.8	0.32	21	0.19	20.7	0.32
3	22.4	0.33	22.8	0.4	22.6	0.32
4	24.1	0.19	24.4	0.2	24.4	0.3
5	25.3	0.49	25.8	0.55	25.3	0.27
6	27.8	0.76	28.9	0.34	26.7	0.29
7	30.3	0.62	30.9	0.66	29.9	0.7
8	33.1	1.03	33.1	0.51	32.6	0.69
9	37.5	1.05	35.8	0.93	37	0.6
10	41.5	1.49	40.5	0.9	39.7	0.8
11			44.7	1,25	43.9	1.29
12	48.3	1.69	51.1	2.22	50.9	2.49
13	57.9	0.53				
14	63.5	2.7	61.4	1.75	64.4	2.73
15	77.1	2.5	76.7	4.04	82.2	2.16
16	97.6	7.81	95.8	5.97	91.2	5.91
17	130.1	9.03	149.4	9.95	139.4	10.99
18	169.3	10.55				
19	239	15.3	232.5	13.1	244.5	22.8

Table 5 Cold Point Tropopause oscillations in winter at 50°N and 51°S, standard deviations, and column differences

	CPT period (yr) Jan 50°N	STD	CPT period (yr) July 51°S	STD	difference of periods	combined STD
1	19.8	0.27	20.2	0.56	-0.4	0.83
2	21.1	0.44	22.2	0.38	-1.1	0.82
3	24.9	0.32	24.1	0.38	0.8	0.7
4	28.8	1.26	26.2	0.32	2.6	1.58
5	31.3	1.84	32.8	0.6	-1.5	2.44
6	42.3	1.64	39.8	1.33	2.5	2.97
7	48.3	3.22	47.1	3.22	1.2	6.44
8	58	2.22	65.5	2.14	-7.5	4.36
9	75.1	4.45	81.8	5.6	-6.7	10.05
10	107.7	6.64	96.4	8.7	11.3	15.34
11	179.3	13.3	171.5	21.7	7.8	35

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