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# Past Antarctic summer temperature revealed by total air content in ice cores

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**Abstract.** Seasonal temperature reconstructions from ice cores are missing over glacial-interglacial timescales, preventing a good understanding of the driving factors of Antarctic past climate changes. Here the total air content (TAC) record from an Antarctic ice core is analyzed over the last 440 thousand of years (ka). While the water isotopic record, tracer for annual mean surface temperature, exhibits a dominant ~100 ka cyclicity, the TAC record is associated with a dominant ~40 ka cyclicity. Our results show that the TAC record is highly correlated with the mean insolation over the local astronomical half-year summer. It also shows for the first time that it is highly correlated with local summer temperature simulated with an Earth system model of intermediate complexity. This suggests that the Antarctic TAC records could be used as a proxy for local summer temperature changes. Also, our simulations show that local summer insolation is the primary driver of Antarctic summer surface temperature variations while changes in atmospheric greenhouse gas concentrations and northern hemisphere ice sheet configurations play a more important role on Antarctic annual surface temperature changes.

## 1 Introduction

The analysis of Antarctic ice cores provides paramount information to reconstruct and understand the climate dynamics of the past 800 ka. Amongst the key climatic parameters that can be inferred from these deep ice cores are the local mean annual temperature reconstructed from the isotopic composition of ice, e.g. δD (Dome Fuji Ice Core Project Members, 2017; Jouzel et al., 2007), and past atmospheric greenhouse gas (GHG) concentrations measured on air trapped in the air bubbles (Bereiter et al., 2015; Loulergue et al., 2008; Lüthi et al., 2008). However, the climate during local summer, which is a critical season for polar regions especially in terms of solar energy received, is seldomly discussed, except through the highlighting of local insolation signatures of $O_2/N_2$ ratio of trapped gas (Bender, 2002; Kawamura et al., 2007; Landais et al., 2012) and air content (Eicher et al., 2016; Epifanio et al., 2023; Lipenkov et al., 2011) in ice core records. In particular, there is no suitable proxy of

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the local summer temperature. Moreover, a debate remaining in Antarctica climate study is related to whether the Antarctica temperature variations on orbital time scale are controlled by the Northern Hemisphere (NH) insolation or by local insolation (Huybers and Denton, 2008). As the insolation over Antarctica is received mostly during summer, having a proxy of summer temperature would therefore be essential for helping to decipher the role of NH versus local insolation as well as the role of other glacial boundary conditions such as the changes in atmospheric GHG concentrations and in ice sheet configuration.

Concerning the local insolation signature of air content, during the transformation by compaction of the low-density snow accumulating at the surface of the ice sheet, first to firn, a material still with a porosity open to the atmosphere, and then to ice, an air tight material, air bubbles close-off from the surrounding atmosphere and they become trapped in ice. In the absence of surface melting, which is the case at the EPICA Dome C (EDC) site (75°06" S, 123°21" E; 3233 m a.s.l.) on the high plateau of East Antarctica and according to the ideal gas law, the amount of air (V) of the bubbles at close-off depends on their physical volume ($V_c$) and on the pressure ($P_c$) and temperature ($T_c$) of the air contained in $V_C$ at the enclosure time (Martinerie et al., 1992). In first approximation, $T_c$ is equivalent to the mean annual temperature prevailing at the surface of the ice sheet, which is estimated from the isotopic composition of the ice.

Then, V can be defined as the total volume of air in unit mass of ice, measured at standard temperature $T_0$ and pressure $P_0$, and $V_c$ is the pore volume per unit mass at close-off:

Equation (A) $V=V_C\ P_c/T_c \times T_0/P_0$

Furthermore, the porosity at close-off, Vc, is related to temperature.

During previous works V (for air content) and TAC (for Total Air Content) have been indifferently used for designating the same property. In this work we are using TAC, which is usually used in the recent works.

More recently long-term high resolution studies of TAC records obtained from several deep ice cores in central Antarctica (Kawamura et al., 2001; Lipenkov et al., 2011; Martinerie et al., 1994; Raynaud et al., 2007) revealed a long-term large variability that cannot be explained by changes in $T_c$ or $P_c$. In particular at EDC, about 85% of the variance observed in the high-resolution V record covering the last 440 ka can be explained neither by $P_c$, nor by $T_c$ changes. This led to consider that other properties, beside the mean annual temperature and barometric pressure at the surface, may also influence TAC. By using continuous wavelet transform (CWT) analysis, Raynaud et al. (2007) found that the TAC record at EDC shows significant power in the obliquity and precession bands, with a dominant obliquity signal which have been assumed to reflect orbitally-driven changes in local summer insolation.

To account for the observed anti-correlation between local summer insolation and TAC, a mechanism has been proposed (Lipenkov et al., 2011; Raynaud et al., 2007) where the local summer insolation, by controlling the near-surface snow temperature and temperature gradients during summertime, affects the near-surface snow structure and consequently the porosity of the firn pores at close-off, i.e. the total air content of air bubbles (Lipenkov et al., 2011; Raynaud et al., 2007). Based on such assumption, TAC was used as an orbital dating tool to constrain ice core chronologies. TAC-based age markers have been used for the latest official chronologies for polar ice cores, AICC2012 (Bazin et al., 2013; Veres et al., 2013) and AICC2023 (Bouchet et al., 2023). However, the exact physical processes that lead to an imprint of the local summer insolation

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in the TAC record are unclear. In particular, uncertainties remain regarding the link between TAC and the surface climatic parameters such as local temperature.

In this study, we use the TAC record measured in the EDC ice core covering the last 440 ka (Raynaud et al., 2007). We compare it with a new local insolation index and with transient simulations performed with the Model LOVECLIM1.3 to explore the link between insolation, Antarctic summer temperature and TAC, as well as the related mechanisms. Finally, we compare the TAC record with the EDC δD record to understand the major driving factors of the summer and annual mean temperature changes in Antarctica.

## 2 Method

### 2.1. TAC measurements

TAC measurements have been performed at the Institute of Environmental Geosciences (Grenoble, France) using an original barometrical method implemented with an experimental setup called STAN (Lipenkov et al., 1995). Results of the numerical data of the measurements versus depth along the EDC ice core can be found in the appendix in Raynaud et al. (2007). The TAC data shown on Fig.1 are displayed on the AICC2023 ice age chronology (Bouchet et al., 2023).

### 2.2. Model and simulations

The model used in this study is LOVECLIM1.3, a three-dimension Earth system Model of Intermediate Complexity, with its atmosphere (ECBilt), ocean and sea ice (CLIO) and terrestrial biosphere (VECODE) components being interactively coupled. The model setup is the same as the one used in ref. (Yin et al., 2021) and detailed description can be found there.

We first performed a transient simulation with 10x acceleration covering the last 800 ka, which allows to compare the simulated local summer temperature with the TAC record over the entire last 440 ka. In this simulation the variations of orbital forcing and GHG were considered, and the global ice sheets were fixed to their pre-Industrial condition. Using the same model, it has been shown that 10x acceleration has a significant impact on deep ocean temperature, but it has no major impact on surface temperature (Yin and Berger, 2015). This is further confirmed in our study where the Antarctica summer temperature of the 10x acceleration simulation is matching well with that of the non-accelerated simulations (not shown).

We further performed transient simulations without acceleration for some glacial-interglacial episodes of the last 440 ka to investigate the relative effects of insolation, GHG and NH ice sheets (see section 5 for simulation periods and results). For each episode, it includes three simulations. The first two simulations, Orb and OrbGHG, were performed in Yin et al. (2021) and detailed description of experiment setup can be found there. Here we only give some brief introduction. In the Orb simulation, only the change of orbital forcing (Berger and Loutre, 1991) was considered, with the GHG and ice sheets being fixed to their pre-industrial condition. In the OrbGHG simulation, the change of GHG (Loulergue et al., 2008; Lüthi et al., 2008; Schilt et al., 2010) was additionally considered. In the third simulation, OrbGHGIce, the change of NH ice sheets (Ganopolski and Calov, 2011) was additionally considered, but the Southern Hemisphere ice sheets remained fixed to the pre-

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Industrial condition. The initial conditions were provided by a 2000-year equilibrium experiment with the NH ice sheets, GHG concentrations and astronomical parameters at the starting date of the simulated period. In the presence of land ice, albedo, topography, vegetation and surface soil types corresponding to ice-covered condition were prescribed at corresponding model grids in LOVECLIM1.3. Detailed description of the ice sheet setup can be found in Wu et al. (2023).

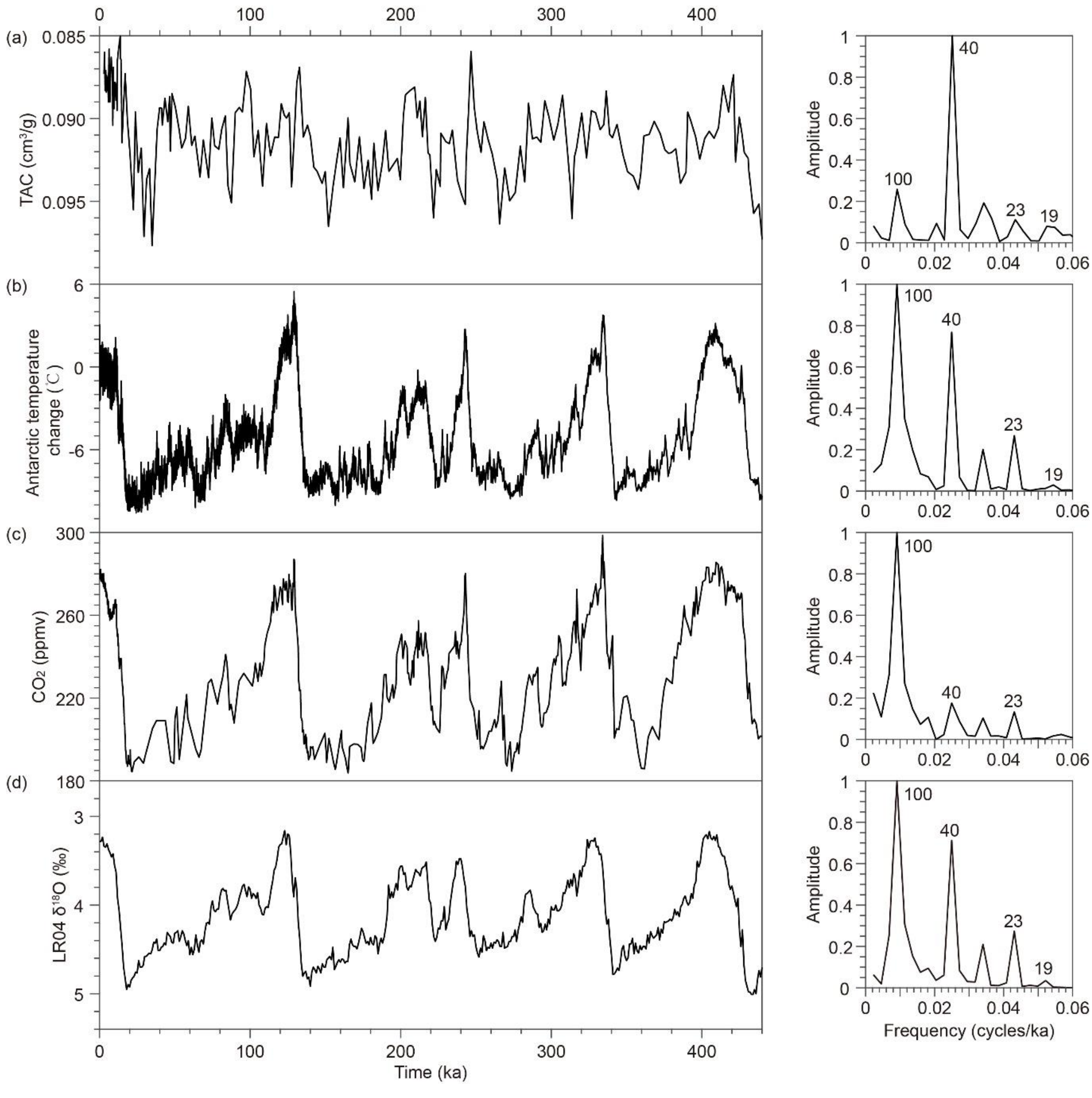


**Figure 1. Variations and spectra over the past 440 ka of (a) TAC record (raw data, Raynaud et al. 2007), (b) Antarctic annual temperature reconstructed from the EDC δD record (Jouzel et al., 2007), (c) $CO_2$ concentration (Lüthi et al., 2008) and (d) benthic $\delta^{18}O$ (Lisiecki and Raymo, 2005). The major periodicities in ka are indicated. The EDC TAC record, local annual temperature reconstruction and $CO_2$ concentrations are displayed on the AICC2023 chronology (Bouchet et al., 2023).**

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## 3 EDC TAC changes vs. Local summer insolation variations over the past 440 ka

The spectral analysis of the TAC record shows that its variations over the last 440 ka are dominated by the 40-ka cycle (Fig. 1), which corresponds to the main periodicity of obliquity. It also shows the 100-ka cycle as well as the 23-ka and 19-ka cycles which correspond to the precession cycles (Berger, 1978), but their amplitude in the power spectrum is much weaker. This spectral characteristic illustrates that the variations of TAC are strongly driven by the astronomical forcing and could be linked to insolation changes (Lipenkov et al., 2011; Raynaud et al. 2007).

When comparing a proxy record with insolation, it is not necessarily straightforward to decide which insolation to choose, because different types of insolation exist and their relationship with climate is not always clear (Berger et al., 2010; Berger et al., 1993). In a previous study presenting the EDC TAC record over the past 440 ka (Raynaud et al., 2007), an Integrated Summer Insolation index (also referred as ISI) was established and compared with the TAC record in order to find the ISI curve with variations that would resemble the most the changes recorded in the TAC record. The ultimate objective of such exercise was to identify an insolation target to infer dating constraints from TAC based on orbital tuning. The most appropriate orbital tuning target was found by tuning the precession-to-obliquity amplitude ratio of the insolation index on the corresponding spectral signature of the TAC record. It corresponds to the so-called ISI 380 record that was obtained by summing over the year, the daily insolation above a threshold of 380 $W.m^{-2}$. Hence, this orbital tuning heavily relies on (1) the tuning of the relative amplitudes of the precession and obliquity in the power spectra and as a consequence (2) the selected insolation threshold value. It is also based on the assumption of a time-linear (constant) response of TAC to the selected insolation threshold. To avoid these assumptions, we propose to use a simpler and independent insolation index in the present work: the mean insolation over the astronomical half-year summer at 75°S.

The astronomical half-year summer in the Southern Hemisphere (SH), which corresponds to the half-year winter in the NH, is defined as the time interval during which the Earth travels from fall equinox to spring equinox on the ecliptic (Berger and Loutre, 1994; Berger and Yin, 2012). The advantage of using astronomical season is to allow for the change of the length of seasons. The half-year astronomical summer in the SH is the main interval during which the southern polar regions (regions within the Antarctic Circle) receive solar radiation over a year. The length of this half-year summer is varying in time and is only a function of precession (Berger and Loutre, 1994; Berger and Yin, 2012). Over the last 440 ka, it varies between 171.3 and 194.0 days. The total solar radiation received over the half-year astronomical summer is only a function of obliquity (Berger et al., 2010). Therefore, the mean summer insolation at 75°S, which is calculated by dividing the total irradiation received during the half-year summer by its length, is both a function of obliquity and precession with obliquity being dominant. Compared to the total summer insolation or the integrated insolation above a threshold (ISI), the mean insolation of the astronomical half-year summer (it is referred as mean summer insolation hereafter) considers not only the total amount of energy received during the summer, but also the length of the summer which could also be important.

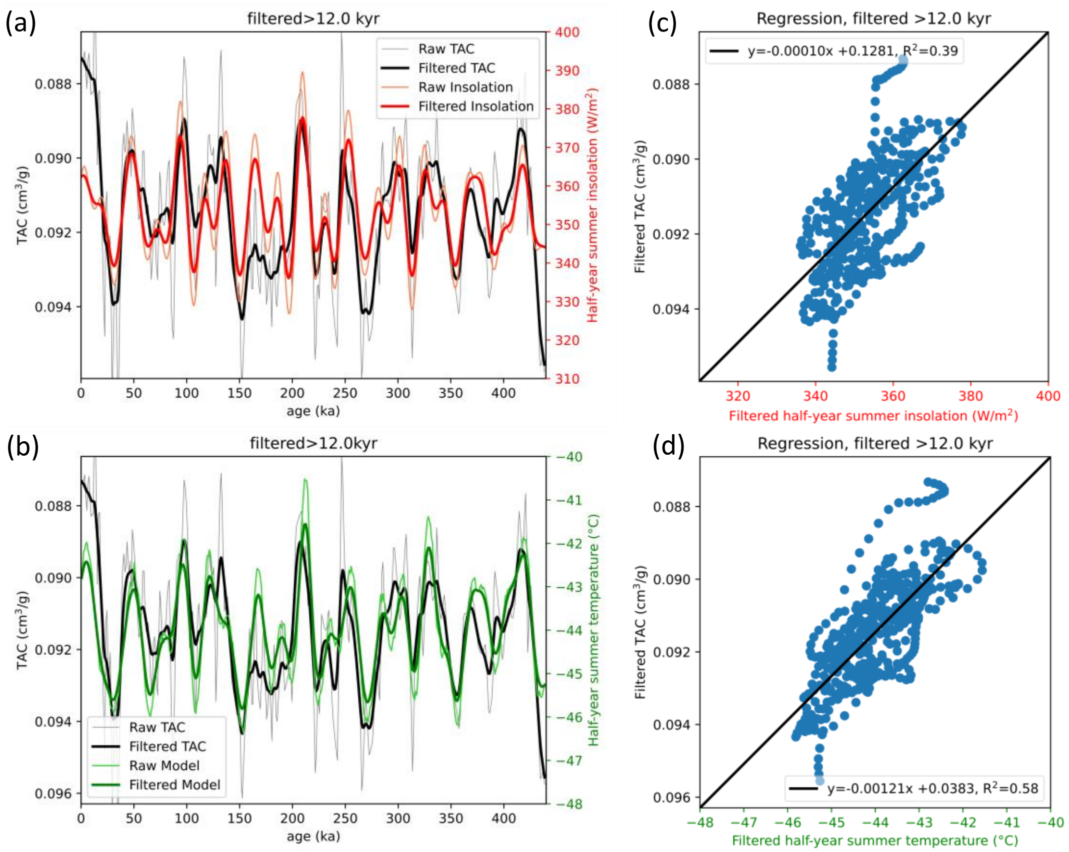


**Figure 2. Comparison of TAC record with (a) mean insolation during astronomical half-year summer at 75°S calculated using the solution of ref. (Berger and Loutre, 1991) and with (b) simulated mean half-year summer (October to March) temperature at EDC. Their corresponding linear regression analyses are shown in (c) and (d). Low-pass filtered >12 ka is applied on the TAC, insolation and summer temperature raw data before comparison. Note that the TAC axis is reversed on the left panels to ease the visual comparison.**

Fig. 2 shows the comparison between TAC and the mean summer insolation. Since we focus here on the orbital-scale variations, a low-pass filter (> 12 ka) has been applied to the TAC data before the comparison in order to eliminate the high-frequency signals. A good resemblance in term of temporal structure and amplitude is observed between the two variables and the two datasets appear well correlated with a $R^2$ correlation coefficient of 0.39 (Fig. 2). This comparison is surprisingly good, especially if we note that TAC could also be influenced by other factors. The high correlation between TAC and the mean summer insolation indicates that TAC can be considered as a proxy primarily driven by the mean local summer insolation. This new result implies that for dating purposes the mean summer local insolation is more appropriate than the ISI 380 curve (Raynaud et al., 2007) to be used as an orbital dating target. Indeed, it appears preferable to favor the mean summer insolation record as it is fully independent from the TAC record compared to ISI 380 although the degree of correlation with the TAC record is of similar relevance. While this is beyond the scope of this study to discuss in details the implications for the definition of TAC-based age markers to constraint the EDC ice core dating (Bouchet et al., 2023), we present in Fig. 3, a

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comparison of the two insolation indexes over the past 440 ka. We observe a strong resemblance in term of the relative amplitude and timing of changes in the two records. Following the approach described in Raynaud et al. (2007), we calculate the evolution of the phase delay between the two records filtered in the 15-46 ka band to provide a quantification of the age differences that could be generated from the use of one curve or the other for orbital dating purposes. On average, the age difference is of about 260 years and never above 650 years. These age differences should be considered as minimal as they do not account for other sources of age uncertainties when building a TAC-based orbitally-tuned chronology e.g. our ability to define precisely the tie points between the TAC data and the insolation index also depends on the quality of the visual resemblance between TAC and the insolation target. These matters will be fully discussed in a subsequent study.

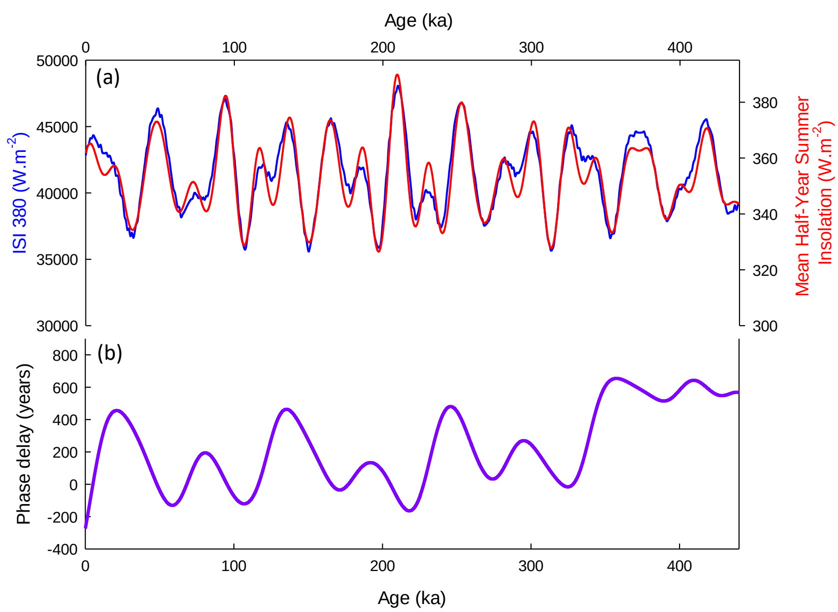

**Figure 3. (a) Comparison of ISI 380 (blue) with the mean insolation during astronomical half-year summer (red), (b) evolution of the phase delay (purple) between the two insolation curves filtered in the 15-46 ka band.**

## 4 EDC TAC changes vs. local summer temperature changes simulated by the LOVECLIM1.3 model

While it appears that the EDC TAC record is correlated with the local mean summer insolation, its relationship to seasonal surface temperature reconstructions has not been investigated yet. Recently, a quantitative reconstruction of the seasonal temperature changes in West Antarctica has been produced throughout the Holocene (Jones et al., 2023), but to our knowledge no seasonal temperature reconstructions in Antarctic ice cores are available over the longer glacial-interglacial timescale. Hence, we propose to compare the EDC TAC record with the local summer temperature changes obtained from transient simulations performed with LOVECLIM1.3.

We observe that the EDC TAC values increase when the modeled local summer temperatures decrease. Fig. 2 also shows there is a high and positive correlation between the simulated summer temperature and the mean summer insolation.

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Linear regression analysis shows that TAC and the simulated summer temperature are highly and negatively correlated. The linear coefficient of determination ($R^2$=0.58 if a low-pass filter > 12 ka is applied on the TAC data) indicates that about 58% of the TAC variability observed on the EDC ice core over the last 440 ka is explained by the half-year summer temperature at EDC, which suggests that summer temperature variations in the central part of East Antarctica can be considered as the main driving forcing of TAC. The slope of the regression shows an increase of 0.00121 $cm^3$ of TAC per gram of ice for a cooling of 1°C of the mean half-year summer local temperature at EDC. The regression analysis has been also evaluated by using the raw TAC data and a low-pass filter of > 6 ka. The good correlation between TAC and the summer temperature is not altered although the regression slope is slightly affected with an increase of about 0.0011 $cm^3$ of TAC per gram of ice for a cooling of 1°C. These are information of interest when discussing the mechanisms linking summer insolation and TAC (see section 6). As proposed in previous studies (Lipenkov et al., 2011; Raynaud et al., 2007), local summer insolation could affect the near-surface snow structure and consequently the porosity of the firn pores at close-off, i.e. the total air content, by controlling the near-surface snow temperature and the vertical temperature gradients in snow. The good correlation between the two independent climate variables, TAC measured from ice cores and summer temperature simulated by a model, indicates that the TAC record in the ice cores can be used as a proxy for local summer temperature.

Wavelet analysis (Fig. 4) shows that the variations of both TAC and the simulated summer temperature are dominated by the ~40-ka cycle throughout the last 440 ka, indicating the major role of obliquity. They also contain a ~20-ka cycle, but this cycle is not stable in time, with an amplitude which is relatively strong for instance around 100 and 200 ka in both TAC and simulated summer temperature but weak during other periods. This may be related to the amplitude modulation of eccentricity on precession (Berger and Loutre, 1991). The eccentricity at ~100, 200 and 300 ka was large, leading to large variations of precession and thus stronger effect of precession around these time intervals than during other times. However, the power of obliquity is generally more important than the one of precession when considering the past 440 ka, in particular around 400 ka and during the last 50 ka when eccentricity was small leading to small variations of precession. The 100-ka periodicity is also observed in both TAC and the simulated summer temperature but with a weak amplitude. This weak signature of the 100-ka cycle in both the TAC and the mean half year summer temperature must arise from the glacial-interglacial boundary condition changes which are characterized by a major periodicity of 100 ka (see section 5).

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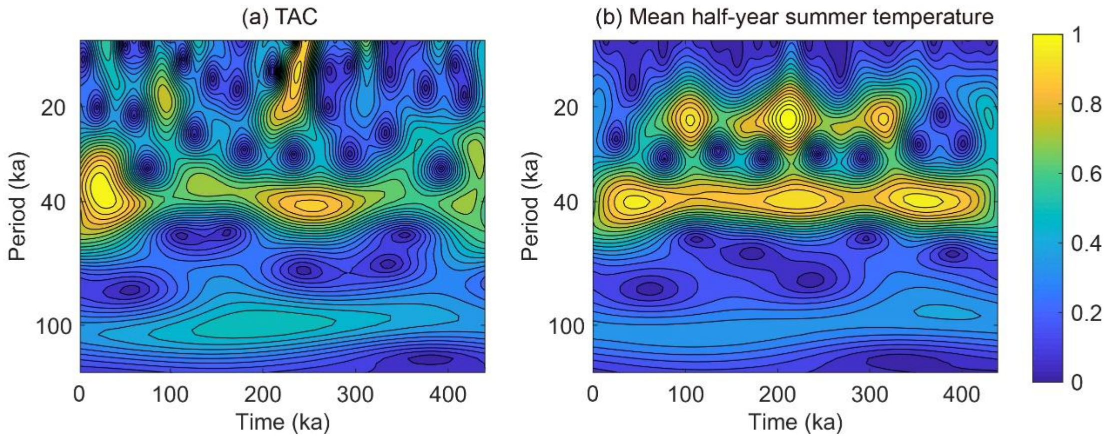


**Figure 4. Continuous wavelet transforms of (a) the low-pass (> 12 ka) filtered TAC record and (b) simulated mean half-year summer temperature of the past 440 ka.**

## 5 Deciphering the driving forcing of past Antarctic summer and annual temperature changes

The δD record from Antarctic ice has been widely used as an important proxy for mean annual temperature over Antarctica (Jouzel et al., 2007; Stenni et al., 2010), although it has also been suggested to be biased toward winter temperatures (Laepple et al., 2011). We use it in the present work as a record of the EDC mean annual temperature.

Different from the TAC record which is dominated by the 40-ka cycle, the EDC δD record is dominated by the ~100-ka cycle (Fig. 1). The difference in the dominant periodicities between the TAC and δD records suggests that the major driving factors for the summer and annual mean temperatures are different. As showed above, TAC is strongly linked to local summer temperature which is mainly controlled by the local summer insolation. However, the dominant 100-ka cycle in the δD record suggest that the annual mean temperature is mainly controlled by the glacial-interglacial boundary conditions such as global ice volume and GHG which are dominated by strong 100-ka cycle (Fig. 1).

To investigate the response of the Antarctica climate to insolation, GHG and ice sheets, the three sets of transient simulations, Orb, OrbGHG, and OrbGHGIce (see section 2) which cover the last five interglacial-glacial episodes, are analyzed here (Fig.5). We first compare the δD temperature reconstruction with the simulated annual mean temperature of OrbGHGIce. Fig. 5 shows that this comparison is quite good over the simulation periods in terms of climate variation pattern, showing the capacity of the model to simulate the orbital-scale climate variations at the EDC site. One may also note that the magnitude of the temperature change between glacial and interglacial is significantly underestimated in the model as compared to the reconstruction. In our simulation, the Antarctica ice sheet as well as the sea level are kept invariant, which could contribute at least partly to the underestimated amplitude of temperature change in the model. However, a recent study using borehole thermometry and firn properties suggests that the temperature reconstruction using water-stable isotopes calibrated against modern spatial gradients could generate a too large amplitude of glacial-interglacial temperature change (Buizert et al., 2021).

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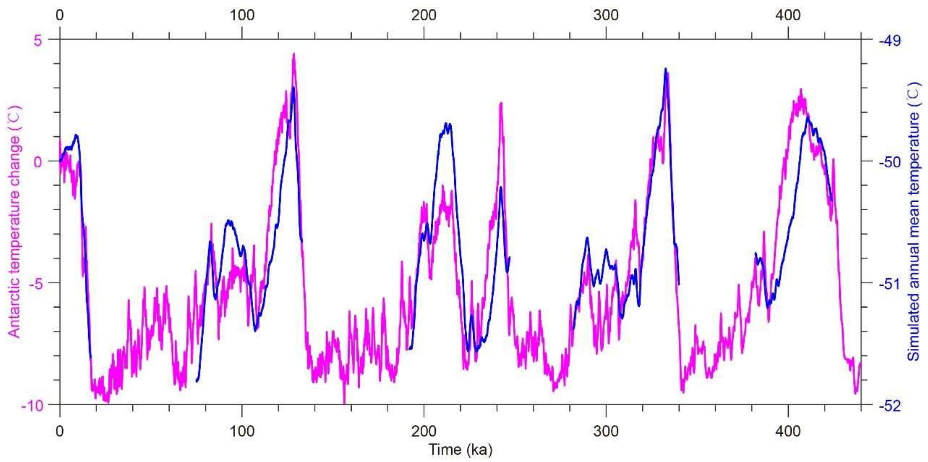


**Figure 5. Comparison of the EDC mean annual temperature record (pink line, Jouzel et al. 2007) with the simulated annual mean temperature of the OrbGHGIce experiments (blue line, this study).**

For example, at EDC, the LGM (26-18 ka) temperature relative to the Pre-Industrial time is about -9°C according to the δD-based reconstruction (Jouzel et al., 2007), but it is only -4.3±1.5°C in the more recent reconstruction (Buizert et al., 2021). In our simulation, the EDC annual temperature at 17 ka is -1.7°C relative to the Pre-Industrial era, and the simulated largest glacial-interglacial amplitude is ~3°C, which is within the uncertainty of the recent reconstruction (Buizert et al., 2021). Nevertheless, such small glacial-interglacial difference found in our study seems difficult to be explained taking into account the relationship between snow accumulation rate and surface temperature from the saturation vapor relationship (Cauquoin et al., 2015). However, what is essential for our study is that the model could capture the orbital-scale variability of the reconstructed temperature.

To investigate the relative effect of insolation, GHG and NH ice sheets on the summer and annual temperature at EDC, we take the 133-75 ka period, which includes the last interglacial period and the glacial inception, as an example to compare the Orb, OrbGHG and OrbGHGIce experiments. As expected, the annual and summer temperatures at Dome C are reduced in response to reduced GHG and increased NH ice sheets (Fig. 6b-c), with the impact of GHG being larger than the NH ice sheets for both temperatures. As far as the summer temperature is concerned, the variation pattern of OrbGHG and OrbGHGICE is very similar to the one of Orb (Fig. 6b), showing the minor effect of GHG and NH ice sheets on the temporal variations of summer temperature. Over this period, the largest summer temperature change caused by insolation is 4.4°C while it is 1°C for GHG and 0.3°C for ice sheets. However, when annual temperature is considered (Fig. 6c), its variation pattern is largely altered in response to changes of GHG and NH ice sheets. Over this period, the largest annual temperature change caused by insolation is 1.2°C while it is 1°C for GHG and 0.5°C for ice sheets. These clearly show that as compared to insolation, GHG and NH ice sheets have weaker effect on the summer temperature but they have stronger effect on annual mean temperature. This, at least partly, explains why the TAC and δD records display different dominant periodicities over long timescales.

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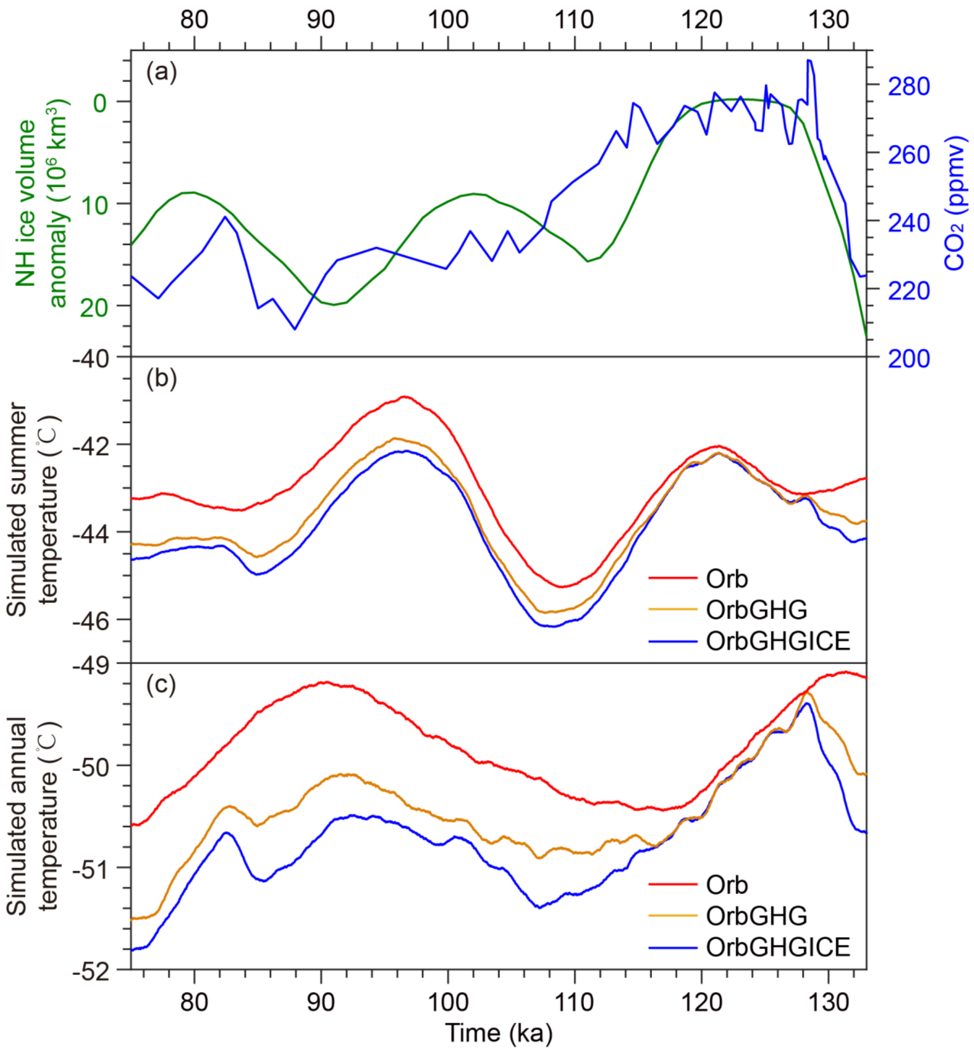


**Figure 6. LOVECLIM1.3 transient simulation without acceleration for the period 133-75 ka. The effect of insolation, GHG and NH ice sheets on the summer and annual temperature at Dome C. (a) $CO_2$ concentration (blue, Lüthi et al., 2008) and NH ice volume anomaly as compared to pre-industrial (green, Ganopolski and Calov, 2011), (b) simulated mean half-year summer temperature and (c) simulated annual mean temperature from the Orb, OrbGHG and OrbGHGICE experiments.**

## 6 Possible mechanisms linking TAC and local summer temperature

The possible mechanism by which summer temperature and near-surface temperature gradients can affect the pore volume at close-off, $V_c$, has been proposed assuming a homogenous firn column and neglecting the sealing effect on the total amount of air trapped in ice (Lipenkov et al., 2011; Raynaud et al., 2007). This simplification seems to be reasonable for low-accumulation sites such as EDC, Vostok, Dome Fuji, because at those sites: (1) the horizontal extent of snow layers

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characterized by different physical properties, as a rule, does not exceed a few meters, which suggests a patchy pattern of their spatial distribution on and below the ice sheet surface (Ekaykin et al., 2023; Fujita et al., 2009), (2) the variability of density (Hörhold et al., 2011) and microstructural properties (Gregory et al., 2014) of firn is relatively low, as is the stratigraphic-scale variability of the air content of ice (Lipenkov et al., 2011; Lipenkov et al., 1997). In addition, the firn can be affected by layering, pore closure in denser layers occurs at a shallower depth compared to the pore closure for layers that are less dense. However, in sites with low-accumulation it was shown that regardless of their density (denser or less dense), $V_c$ and hence, $V$ is similar in both types of layers (Fourteau et al., 2019).

The snow metamorphism on the cold Antarctic Plateau is essentially a summertime phenomenon. It speeds up when the temperature of the uppermost layers of snow rises well above the mean annual temperature, thus increasing both the equilibrium concentration of water vapor in the snow pores and the temperature gradients in the near-surface snow. Elevated temperatures and strong temperature gradients promote the rapid growth of snow grains and the formation of a coarse-grained snow structure. Small-scale stratigraphic variations in the snow structure, which are typical in the upper few meters of snow column, progressively disappear with depth (Alley, 1980), while the average grain size remains related to temperature conditions prevailing at the time of snow diagenesis near the ice sheet surface.

According to the model proposed by ref. (Arnaud, 1997) for the Antarctic ice sheet, TAC is increasing with the mean annual surface temperature through the competing densification mechanisms of snow and firn, and the critical density at the transition between snow and firn ($D_0$) is also increasing with the mean annual temperature. Our work (see section 5) shows no (poor) correlation and large spectral differences between TAC and mean annual surface temperatures. In contrast we observe a strong anti-correlation between TAC and the mean surface summer temperature records. This observation suggests the existence of another factor, beside the mean annual temperature, which could affect negatively the critical density. Indeed, TAC increases with the number of pores per grain at close-off. This latter parameter depends on the critical density of the snow, $D_0$, which corresponds to the transition between grain-boundary sliding (GBS) and power law creep (PLC) as the dominant densification mechanism: the higher the critical density of snow, the greater the number of pores per grain and therefore the larger TAC value at close-off (Arnaud, 1997). Since GBS decreases for larger grains (Alley, 1987), while PLC does not depend much on the grain size, $D_0$ should also decrease when the grains are big.

Thus, time periods with a warmer summer temperature (high insolation) promote a coarser-grained snow structure and hence lower critical density of snow and reduced TAC at pore closure, and vice versa. This mechanism is proposed here to explain the strong anti-correlation observed here between TAC and the mean summer surface temperature. A numerical model, which takes into account the successive mechanisms involved between the surface snow and the closure of pores, is still required.

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## 7 Conclusions

The lack of seasonal temperature reconstruction on Antarctica hampers a good understanding of the forcing and mechanism of climate changes over this climatically sensitive region. We revisit here the TAC record measured from the ice core at EDC covering the last 440 ka, which is dominated by the 40-ka cycle and is highly correlated with the local mean insolation over the astronomical half-year summer, showing the major role of local summer insolation on the TAC record. In this study we show that the high correlation between two independent variables, the TAC measured from ice cores and the summer temperature simulated by a climate model, indicates that the TAC record can be used as a unique proxy for local summer temperature. The anti-correlations between local summer insolation/temperature and TAC can be explained by assuming that local summer insolation is controlling the near-surface snow temperature and temperature gradients during summertime, which would affect the near-surface snow structure and consequently the porosity of the firn pores at close-off, i.e. the TAC of air bubbles (Lipenkov et al., 2011; Raynaud et al., 2007).

The comparison between TAC and δD records indicates that the major driving factors for the summer and annual mean temperatures are different at Dome C. TAC is strongly linked to local summer temperature, while the annual mean temperature is strongly controlled by the glacial-interglacial boundary conditions like the global ice volume and GHG. We show that the LOVECLIM1.3 model could capture the orbital-scale variability of the δD-based temperature reconstruction. Our transient simulation which allows to investigate the relative effect of insolation, atmospheric greenhouse gas concentrations and NH ice sheet volume changes, shows that as compared to insolation, greenhouse gases and NH ice sheets have weak effect on the summer temperature, but strong effect on annual mean temperatures. This model result confirms the hypothesis made from the spectral characteristics of the TAC and δD records, explaining why these two records display different orbital periodicities.

## Author contributions

DR and QY designed the research. QY, ZW and AB performed the research related to the LOVECLIM1.3 simulations. DR, FP, EC and VL performed the research based on the EDC TAC record. QY, DR and EC wrote a draft of the paper with subsequent inputs from all the other authors.

## Competing interests

At least one of the (co-)authors is a member of the editorial board of Climate of the Past.

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**Data availability:** The data used in this study will be uploaded to https://zenodo.org once the paper is accepted for publication.

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