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Reconstructing changes in Atlantic thermohaline circulation during the 20th century under two possible scenarios

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Atlantic thermohaline circulation (THC) is a key component of the Earth Climate System and identification of its changes during the 20th Century is critical to the understanding of its variation characteristics and the corresponding climatic impacts. Previous researches have been inconclusive, with the results varying depending on the approach used to measure THC. The results for the two established approaches for measurement of the phenomenon (direct observation and indirect reconstruction) are contradictive (weakening and non-weakening), and their credibility needs improving. Based on the tight relationship between THC anomaly and "see-saw" intensities of Sea Surface Temperature (SST) and Surface Air Temperature (SAT), we first diagnose their quantitative relationship in the model experiments, which is corresponding to its two possible scenarios, and then reconstruct the changes of THC during the 20th Century respectively with multiple observed datasets of SST and SAT. Model results show that THC anomaly and SST/SAT "see-saw" intensities are well correlated in timescales longer than 10/40 years under scenarios of weakening/non-weakening respectively. Two kinds of reconstructions here are consistent with each other, and we propose that THC has undergone a 2-cycle oscillation with inter-decadal scale since the Industrial Revolution with a magnitude of about 1 Sv. The transformation times of decadal trend are around the mid-1910s, the 1940s, and the mid-1970s. This research further validates the main results of previous reconstructions, and points out that THC does not have a long-term weakening during the 20th Century.

thermohaline circulation, 20th Century, reconstruction, "see-saw" phenomenon, SST, SAT

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Thermohaline Circulation (THC) is an oceanic deep circulation system on a global scale, playing an important role in the meridional heat transport of the earth's climate system between low and high latitudes [1–3]. THC is proposed to be critical to the regional climate formation and the global climate changes, based on the analysis of the 20th Century's observations [4], paleoclimate records [5], and model simulations [6]. THC is also regarded as an important source of

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inter-decadal changes of global climate [7]. Under the background of global warming, THC is also thought to be one important factor that could trigger abrupt climate change in future. As such, it has received increasing attentions in recent years [4, 8–10]. The identification of THC changes during the 20th Century (early stage of undergoing global warming) is the basis of the analysis of the mechanism controlling THC changes and the relative climatic impact and also to the projection of the future changes of THC and related climatic impacts [9].

Observation of THC during the 20th Century is rare because of its deep depth, low velocity, and large spatial scale [1–3]. Observations by Dickson et al. [11] and Curry et al. [12] show that the formation environment of THC in high latitude of the North Atlantic has changed significantly during the second half of 20th Century, indicating that THC may have had a robust weakening during this period. Based on five observations at 25°N section in the North Atlantic from 1957 to 2004, Bryden et al. [13] proposed a 30% weakening of THC during the corresponding period. Demonstrating the uncertainty of measuring THC, Cunningham et al. [14] reached conclusions in direct conflict with Bryden et al. [13]. Based on a continuous observation at nearby 26.5°N section of 2 years, Cunningham et al. [14] found that THC changes broadly in seasonal cycle (range 4.0–34.9 Sv, 1 Sv=10^6 m^3/s) . The data used by Bryden et al. [13] are for different seasons, inducing the direct comparison of these data is not suitable. Although a case can be made that THC may have a long term weakening trend during the 20th Century, the evidence is far from conclusive and so far, clear variation characteristics cannot be achieved.

Deriving from the diagnostic relationship in model simulations and physical processes, several researchers recently have tried to reconstruct the changes of THC during the 20th Century. Based on the negative relationship of intensities in THC and the North Atlantic Oscillation (NAO), as revealed by the model of LASG/IAP GOALS, Zhou et al. [15] reconstructed the changes of THC during the 20th Century with an observed NAO index and found a 4-stage variation feature that they labeled as "weak-strong-weak-strong". After that, Zhou et al. [16] validated previous results with observed Sea Surface Temperature (SST) and observed convection intensity in THC's origins in the North Atlantic. Based on the synchronous correlation of intensities of THC and SST "see-saw" phenomenon revealed by model MPI [17], Latif et al. [18] did a similar reconstruction with an observed SST difference between two key regions in the South and North Atlantic, and achieved similar results as Zhou et al. [15]. Based on the diagnostic link between THC and Atlantic Multidecadal Oscillation (AMO) revealed by model HadCM3, Knight et al. [19] completed an identical reconstruction with an observed AMO index. Knight et al.'s results point out the variation magnitude of THC of 0.5–1 Sv. Based on the meridional density gradient between the North Atlantic subpolar and subtropical gyres within the upper ocean and the results of three oceanic reanalysis datasets, Wang et al. [20] proposed a strengthening trend of THC during the second half of the 20th Century. These reconstructions all indicate that THC did not experience a long term weakening during the 20th Century and its fluctuation occurs primarily within an inter-decadal scale.

These works all suggest significant changes of THC during the 20th Century. However, several questions are still not fully addressed in these observations and reconstructions. For example, does THC response significantly to the global warming and show a long term weakening during this period? If the largely consistent results in multiple reconstructions approach reality, at what point during the 20th Century does the strengthening begin? A related but important unanswered question remains unanswered, that is, what is the magnitude of THC changes during the whole 20th Century? In short, the identification of the specifics of THC changes during the 20th Century is still a big challenge. This paper seeks to help fill this gap in our knowledge by providing further works in rare observations and the improvement of the reconstruction scheme, aiming to achieve a cross-evidenced result.

A common problem existing in the reconstructions outlined above is that their derived observation is almost always a single dataset, and their results are basically not cross-evidenced with multiple variables and in multiple observed datasets. This problem threatens the credibility of the results. We argue that one way to improve the reconstruction scheme is to ensure that collected data are based on more fundamental model characteristics and involve more observed datasets of multiple variables. Moreover, the new reconstructed result should be cross-evidenced with previous ones.

The pronounced climatic impact of THC changes is the bipolar "see-saw" phenomenon in air-sea interface temperature, which was identified in paleoclimate records and model simulations [5, 6, 10, 19, 21, 22]. The weakening of THC could induce the significant cooling in the extra-tropical Northern Hemisphere and warming in similar regions of the Southern Hemisphere, and vice versa. The mechanism of this phenomenon is that the changes of THC could induce the weakening or strengthening of the cross-equator heat transport in the Atlantic Ocean and then induce the heat redistribution in the Southern and Northern Hemispheres in ocean and atmosphere [22]. Air-sea interface temperature, including SST, and Surface Air Temperature (SAT) are two factors that are thought to respectively indicate the distribution characteristics of heat in ocean and atmosphere. Thus, except SST, SAT is another important factor which could indicate the redistribution of heat as "see-saw" phenomenon. The "see-saw" phenomenon has been identified in an observed SAT dataset during the 20th Century [23]. Model simulation shows that the intensities of "see-saw" phenomenon and THC anomaly are closely related [17]. Thus, we can reconstruct the THC changes during the 20th Century, based on the "see-saw" phenomenon with observed datasets of SST and SAT synchronously. This new scheme is similar to Latif's except the introduction to SAT and SST [18]. There are abundant observations of the air-sea interface temperature, and multiple datasets of SST and SAT are already formed [24–31], so we can include these SAT datasets into the new reconstruction scheme to improve the credibility of reconstruction results.

Research results about THC changes during the 20th Century mostly cover the second half of the century with scant attention paid to the beginning of the 20th Century [13, 20]. The reason for this is that direct observations of THC did not begin until the 1950s. Additionally, other related variables' observations used in reconstruction are more abundant and precise from this point forward. This is especially true for observations in the Southern Hemisphere since measurements for the first half of the 20th Century are notoriously rare and inaccurate. This means that Latif's scheme [18] is insufficient because the key regions they set in the South and North Atlantic rely on too small a data set to allow for results that could be considered valid and representative. To resolve this problem, the new scheme here includes the whole hemispheric data to calculate the "see-saw" intensities of SST and SAT, with an aim of availably and representatively use the rare data in the Southern Hemisphere during the first half of the 20th Century. This alteration of our new scheme is supported by the paleoclimate records and model simulations, such as the "see-saw" phenomenon in SST and SAT that actually occur on a global scale [6, 10, 19, 21, 22]. THC is an oceanic system with global scale, so its changes could induce the redistribution of the global oceanic heat and then of the atmospheric heat through air-sea interaction [1], which subsequently cause the inter-hemispheric "see-saw" phenomenon of SST and SAT.

The first step of our reconstruction scheme is the calculation of the diagnostic relationship between the THC anomaly and the SST/SAT "see-saw" intensities in model simulations [18]. Previous studies show that there are two possible change scenarios of THC during the 20th Century as weakening and non-weakening, which represented the situations of significantly and non-significantly effected by global warming respectively [32]. Which scenario dominated the THC changes during this period is not yet clear so far, since evidence is not plentiful, direct observations are relatively rare [13, 14], reconstructions suffer from credibility problems [15–20], and models are not easily simulated [9, 33]. So in the new reconstruction here, we consider these two possible scenarios synchronously in corresponding experiments, and compare their results to get a more credible conclusion. Idealized water-hosing and control experiments can be used to represent the changing scenarios of weakening and non-weakening respectively. The representation of water-hosing experiment to weakening scenario has the basis of paleoclimate observations and simulations, such as that robust global warming can induce the significant weakening of THC through recurring freshwater discharge into the North Atlantic [10, 21, 22].

Based on the analyses above, we first calculate the diagnostic relationship between the THC anomaly and SST/SAT "see-saw" intensities in two types of model experiments, and the averaged time series of SST/SAT "see-saw" intensities during the 20th Century within observations, and then reconstruct the THC changes during the 20th Century with model's diagnostic relationship and observed SST/SAT "see-saw" intensities under two possible scenarios.

1 Model experiments setting and data

The model employed here is the Community Climate System Model version 3 (CCSM3) with coarse resolution (T31_gx3v5). This is a fully coupled atmosphere-ocean-sea ice-dynamic vegetation climate model developed by the United States National Center for Atmospheric Research (NCAR) [34]. The atmospheric model is the CAM3 with a horizontal resolution of 3.75°×3.75° and 26 vertical hybrid coordinate levels. The land model is CLM3 with the same resolution as the atmosphere. The ocean model is the NCAR implementation of the POP with vertical z-coordinates and 25 levels. The longitudinal resolution is 3.6° and the latitudinal resolution varies, with finer resolution in the tropics and the North Atlantic. The sea ice model is the CSIM with the same resolution as the ocean model. The CCSM3 coarse resolution version has been used widely in equilibrium state simulations under different climate backgrounds and in sensitivity experiments [35, 36].

The control experiment integrates data for 400 model years under the climate background of Pre-Industrial (1860). Based on the control experiment, the water-hosing experiment applies a freshwater discharge into the North Atlantic of 50°–70°N with strength of 0.38 Sv and length of 300 model years, which weakens the THC to a nearly stopped state.

Each five long term datasets of SST and SAT are used here. Observed SAT datasets include ICOADS (NOAA, 1800/01–2010/03) [24], CRUTEM3 (Hadley Centre, 1850/01 to present) [25], GISS (NASA, 1880/01 to present) [26], NOAA (1880/01 to present) [27] and NCEP reanalysis (1948/01 to present) [28]. Among them, NCEP reanalysis dataset is an output of model combined with observations. Observed SST datasets include ICOADS (NOAA, 1800/01–2010/03) [24], HadISST (Hadley Centre, 1870/01 to present) [29], ERSST (NOAA, 1854/01–2008/12) [27], Kaplan Extended SST (NCEP, 1856/01 to present) [30] and OISST (NCEP, 1981/01–2007/12) [31].

2 Model experiments results

2.1 Water-hosing experiment

The THC intensity is defined as the maximum stream-function of Atlantic Meridional Overturning Circulation below the depth of 500 m. Intensities of SST/SAT "see-saw" are defined as the difference of each hemispheric mean (North minus South). The positive intensities of SST/SAT "see-saw" indicate that the Northern Hemisphere is warmer.

In the water-hosing experiment, accompanied by the weakening of THC with the magnitude of approximately 11 Sv in annual mean, SST/SAT "see-saw" phenomena become robust and the inter-hemispheric SST/SAT differences reach about 1.4°C/2.2°C, respectively (Figure 1). These indicate the model used here represent the SST/SAT "see-saw" phenomena well. The changes of THC anomaly and SST/SAT "see-saw" intensities show a significantly synchronous correlation.

The correlation of the three factors in Figure 1 is significant under long timescales but not when measured by timescales of brief duration (such as inter-annual scale). Therefore, the dependence of their correlation on timescales should be further detected. Here, we use the method of running mean to split the timescales of these three factors. Under different timescale ranges, we regress the THC anomaly with SST/SAT "see-saw" intensities (D_{sst}/D_{sat}) upon their diagnostic relationship, and then calculate the correlation coefficient between the regressed and simulated THC anomaly. The changes of these three factors in Figure 1 are robust in long timescales, which induces the correlation coefficients in Figure 2 all larger than 0.9 (with a 99% confidence level). When running mean scale increases, the correlation coefficient becomes higher. The running mean scale of 10 years is a critical value as for the changing rate of correlation coefficient in Figure 2. As a result, these three factors are only well correlated under the timescale longer than 10 years.

Based on the smoothed time series of the three factors with running mean scale of 10 years in water-hosing experiment, we give the diagnostic relationship as below:

$$\text{THC anomaly}=5D_{sst}+1.9D_{sat}. \qquad (1)$$

In eq. (1), the coefficient of D_{sst} is larger than that of D_{sat}. The reason relies on the reorganization of heat, which, induced by THC changes, primarily and directly occurs in the ocean, and then in the atmosphere through air-sea interaction.

In Figure 3, the regressed THC anomaly derived with Formula (1) (dashed line) is well correlated with the simulated one after smoothed with 10 years scale (solid line), and their correlation coefficient reaches 0.98, which means that the THC changes under the timescales longer than 10 years can be regressed well with the D_{sst} and D_{sat}.

2.2 Control experiment

In the control experiment, the changes of THC are dominated by its interior processes and the interaction with atmosphere, which represents the natural oscillation without external forcing (scenario of non-weakening). Dramatically different from the water-hosing experiment, the changes of THC and D_{sst}/D_{sat} in control experiment are not highly correlated, and the correlation coefficients all approach 0 (Figure 4). This indicates that the "see-saw" phenomena in SST and SAT are not dominated by the changes of THC under the non-weakening scenario. The difference with water-hosing experiment relies on two points: the mechanism

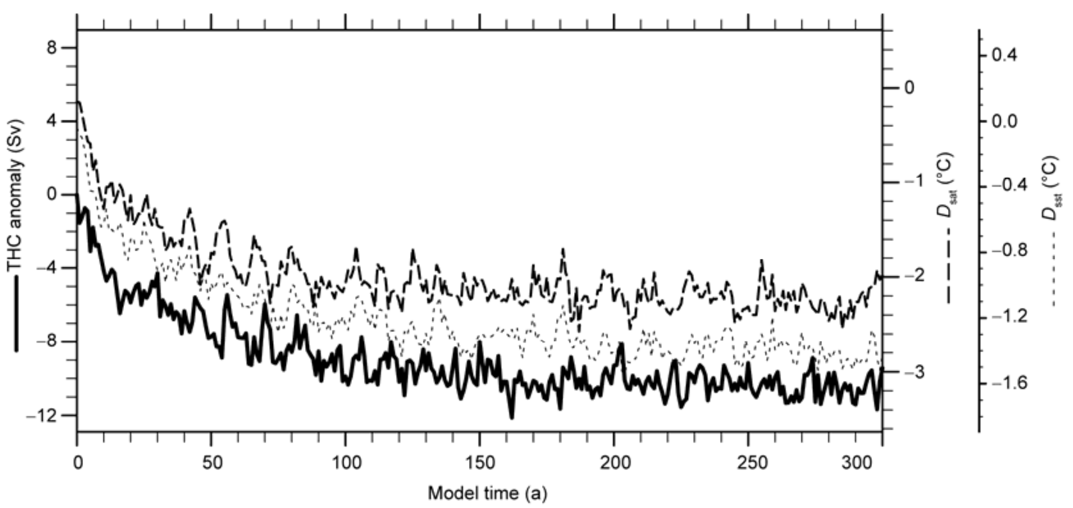

Figure 1 Time series of annual mean THC anomaly and SST/SAT "see-saw" intensities in water-hosing experiment. Thick solid/dashed/thin dotted lines represent the THC anomaly and the "see-saw" intensity of SST and SAT, respectively. The "see-saw" intensity of SST and SAT is represented with D_{sst}/D_{sat}, respectively.

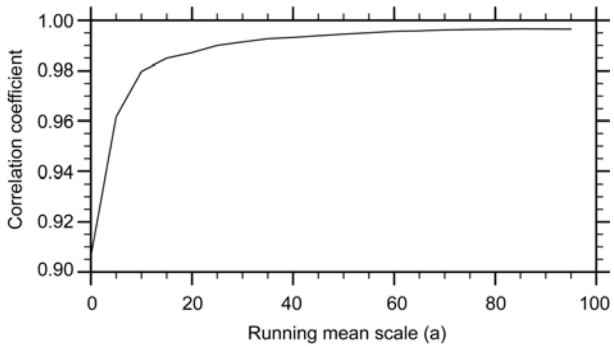

Figure 2 Correlation coefficients between simulated and regressed THC anomaly under different running mean timescales in water-hosing experiment.

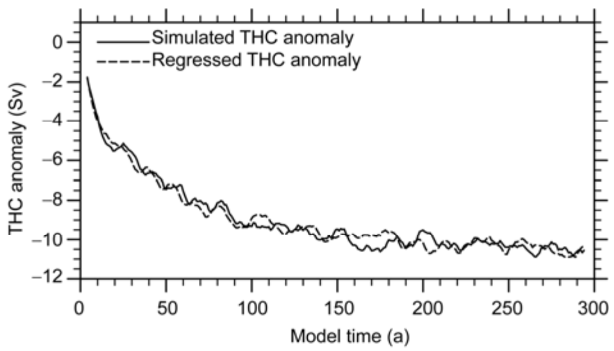

Figure 3 Comparison of regressed THC anomaly and simulated one under 10 years running mean in water-hosing experiment.

controlling the THC changes; and the magnitude of THC changes. Compared with the water-hosing experiment, there is not an external forcing in the control experiment and the magnitude of THC changes is small (annual mean maximum is just 2 Sv), which means the contribution of THC changes to "see-saw" phenomenon of SST and SAT is small as well.

In the control experiment, the analysis detailed in Figure 2 shows that the changes of THC under long timescales are significantly correlated with "see-saw" phenomena of SST and SAT too (Figure 5). With the increase of running mean scale in Figure 5, the correlation coefficient increases dramatically from around 0 to 0.8. The non-significant correlation under short timescales has been discussed in other studies. As shown in the control experiment with Norwegian BCM, the changes of THC under inter-annual scales are dominated by NAO [37, 38]. In general, under short timescales, the changes of THC are dominated by atmosphere; and under long timescales, the changes in atmosphere (including "see-saw" phenomenon) are dominated by THC.

When separating the timescale with the method of running mean, the resulted time series is shortened with a running mean scale. So, one important issue is how to choose a suitable running mean scale during establishing the diagnostic relationship as eq. (1) in the control experiment. The suitable running mean scale should keep the significance of regression and the length of reconstruction result of THC changes during the 20th Century hereinafter. According to Figure 5, we propose that the running mean scale of 40 years is suitable, with the correlation coefficient as 0.7 and satisfying the confidence level of 99.9%. The diagnostic relationship established with this running mean scale in control experiments is:

$$\text{THC anomaly}=10.7D_{\text{sst}}-5.3D_{\text{sat}}, \qquad (2)$$

Even when the correlation coefficient under running mean scale of 40 years reaches 0.7 (Figure 5), the evolutionary characteristics of THC anomaly and SST/SAT "see-saw" intensities are still significantly different (Figure 6). The large difference indicates that the relationship between THC

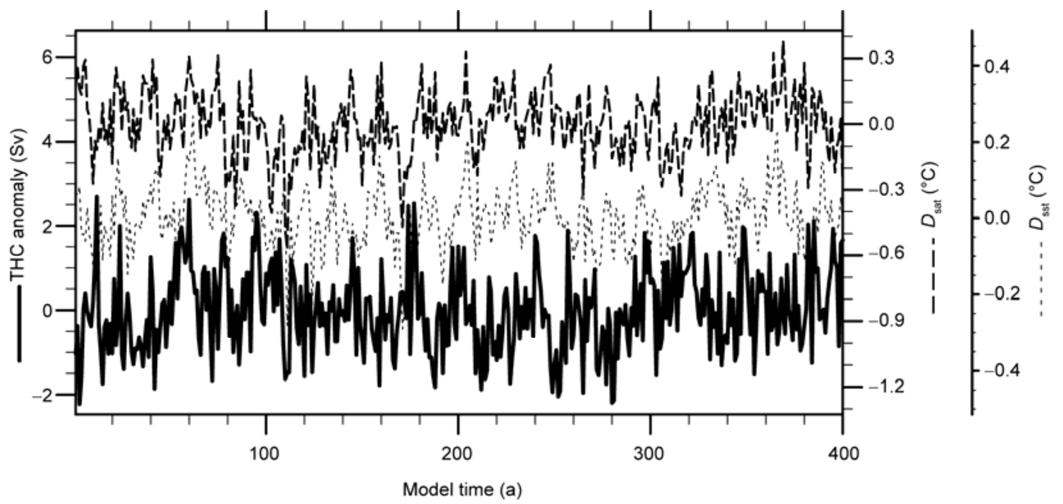

Figure 4 Time series of annual mean THC anomaly and SST/SAT "see-saw" intensities in control experiment.

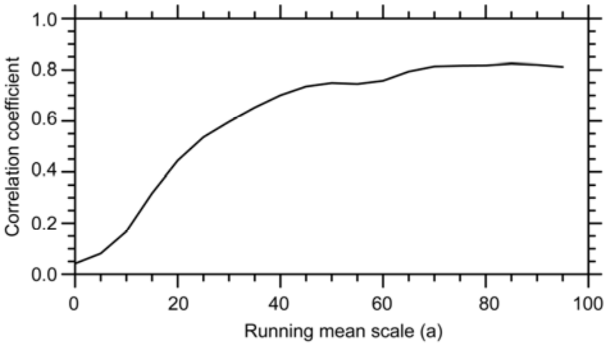

Figure 5 Correlation coefficients between simulated and regressed THC anomaly under different running mean timescales in control experiment.

anomaly and SST/SAT "see-saw" intensities under natural oscillation is complex. However, the regressed THC changes with eq. (2) are still well consistent with simulated one in Figure 7, which means that the diagnostic relationship of eq. (2) is representative under the timescale ranges longer than 40 years and it could be used to reconstruct the THC changes during the 20th Century with observed SST/SAT "see-saw" intensities.

Comparing these two experiments shows that the SST/SAT "see-saw" intensities both represent the changes of THC under different timescale ranges. Thus, we can reconstruct the THC changes during the 20th Century with observed SST/SAT "see-saw" intensities regardless of the scenario used. One important point that readers should note is that the corresponding timescale ranges in eqs. (1) and (2) are different. As a result, the regressed results with these two formulas will be different in timescale ranges.

SST and SAT are both considered when establishing diagnostic relationship in eqs. (1) and (2). One question is whether the regressed result with two factors is always better than the regressed result with one factor? As the results shown in Table 1, the answer is yes, especially for the control experiment. The increase of regressed results from one factor to two factors in water-hosing experiment is small, which indicates that responses of SST and SAT to THC large changes are basically consistent under long timescales. By contrast, the increase of regressed results from one factor to two factors in control experiment is robust. The experimental results indicate that there are some regularities within the different correlations between SST/SAT and THC (Figure 6), and it is helpful to heightening the regressed results significantly from one factor to two factors.

The reconstruction scheme with two factors is also better in the sufficient appliance of relative rare observations during the early 20th Century (especially for the Southern Hemisphere). Thus, the reconstruction of THC changes during the 20th Century involving the observations of these two factors allows researchers to achieve results that can explain a much higher degree of the observed variation.

3 "See-saw" phenomena in observations of the 20th Century

As shown in the analysis of model experiments, there are quantitatively diagnostic relationships between THC anomaly and "see-saw" intensities of SST/SAT with different timescale ranges under weakening and non-weakening sce-

Table 1 Correlation coefficients of simulated and regressed THC anomaly with single or double factor(s) in water-hosing and control experiments

Correlation factors	Water-hosing exp. (10 a running mean)	Control exp. (40 a running mean)
THC_{Dsst}–THC	0.977	0.252
THC_{Dsat}–THC	0.973	0.214
$THC_{Dsst,Dsat}$–THC	0.980	0.701

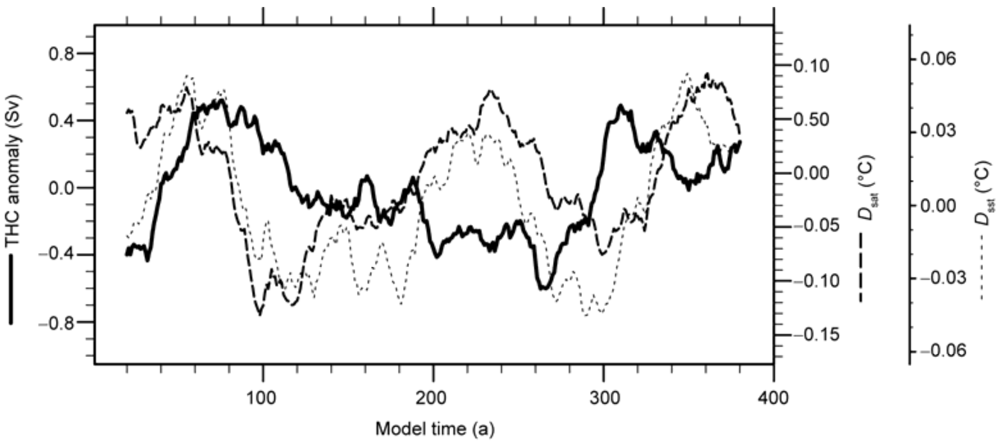

Figure 6 Time series of THC anomaly (thick solid line) and "see-saw" intensities of SST (thin dotted line) and SAT (dashed line) under running mean scale of 40 years in control experiment.

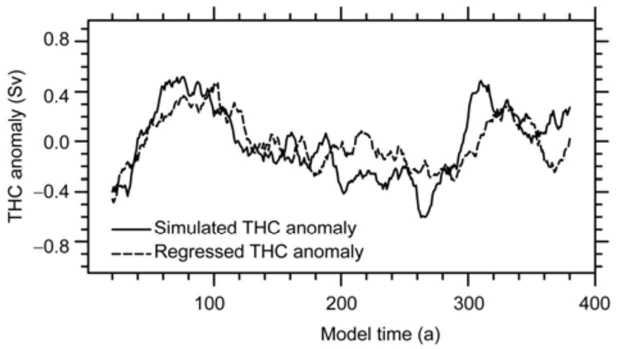

Figure 7 Comparison of regressed and simulated one THC anomaly in timescales of over 40 years in control experiment.

narios. According to the proposed reconstruction scheme in introduction section, another important question is whether all observations of SST and SAT have robust "see-saw" phenomenon. Even the result of ref. [23] supports this hypothesis in one SAT observation, but this question still needs to be tested in other observations of SST and SAT.

As shown in Figures 8 and 9 (a1)–(e1), the valid observations of each SST and SAT datasets are almost less in the Southern Hemisphere and less in the first half of the 20th Century. These spatial-temporal distributions of valid data confirm the consideration of new reconstruction scheme shown above.

The hemispheric means and "see-saw" intensities of SST and SAT are all processed to anomaly to remove the relative inconsistent mean in each SST/SAT dataset. Based on the analysis of our model experiment and other previous studies, the significant correlation between THC anomaly and SST/SAT "see-saw" intensities is over longer timescales. Thus, the hemispheric means (Figures 8 and 9(a2)–(e2)) and "see-saw" intensities (Figure 10(a), (b)) of SST and SAT of each observation are all smoothed with running mean scale of 10 years.

Hemispheric means in the south and north of each SST observation all indicate a robust warming trend, and the increasing magnitude has been all around 0.7°C since the

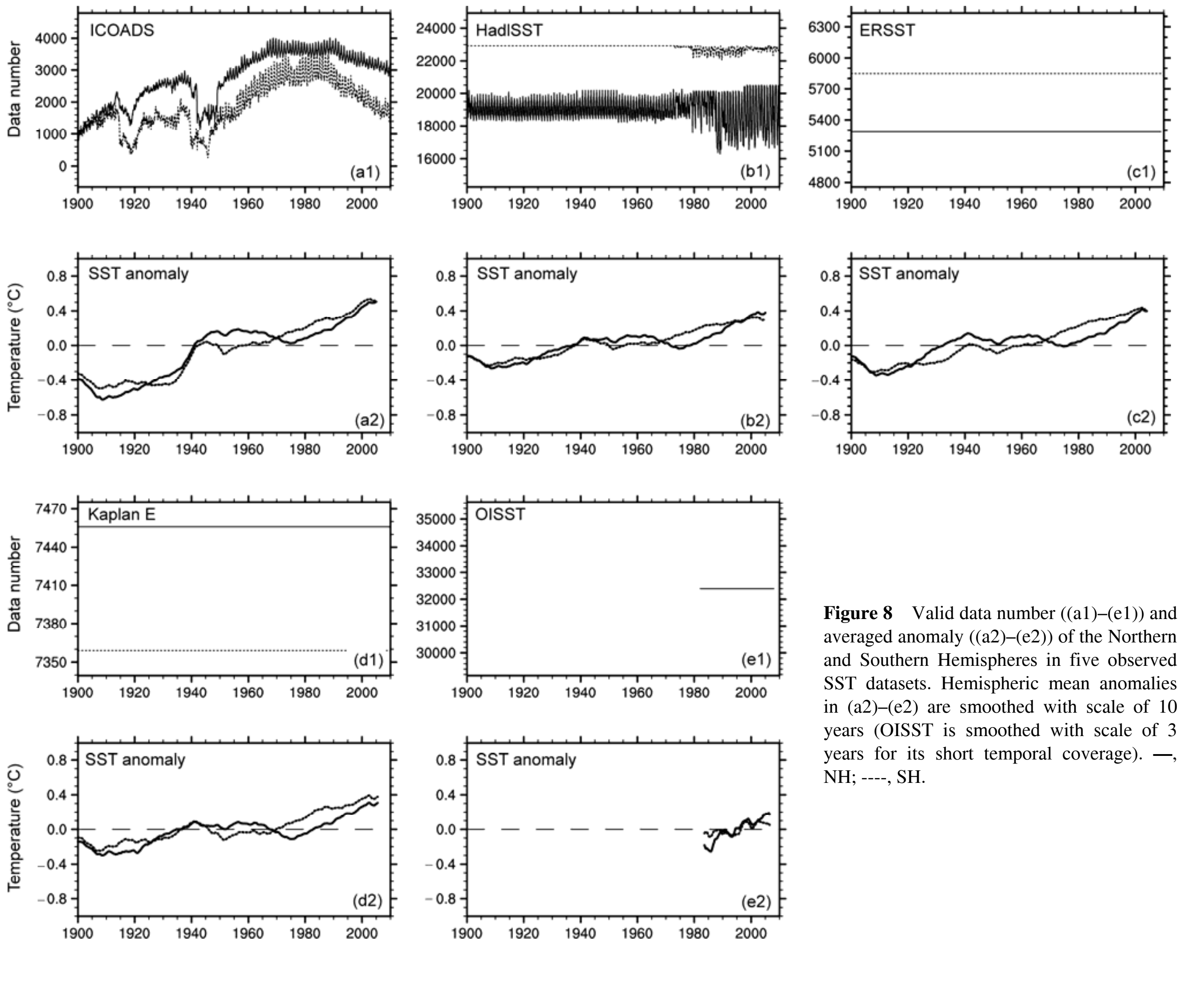

Figure 8 Valid data number ((a1)–(e1)) and averaged anomaly ((a2)–(e2)) of the Northern and Southern Hemispheres in five observed SST datasets. Hemispheric mean anomalies in (a2)–(e2) are smoothed with scale of 10 years (OISST is smoothed with scale of 3 years for its short temporal coverage). —, NH; ----, SH.

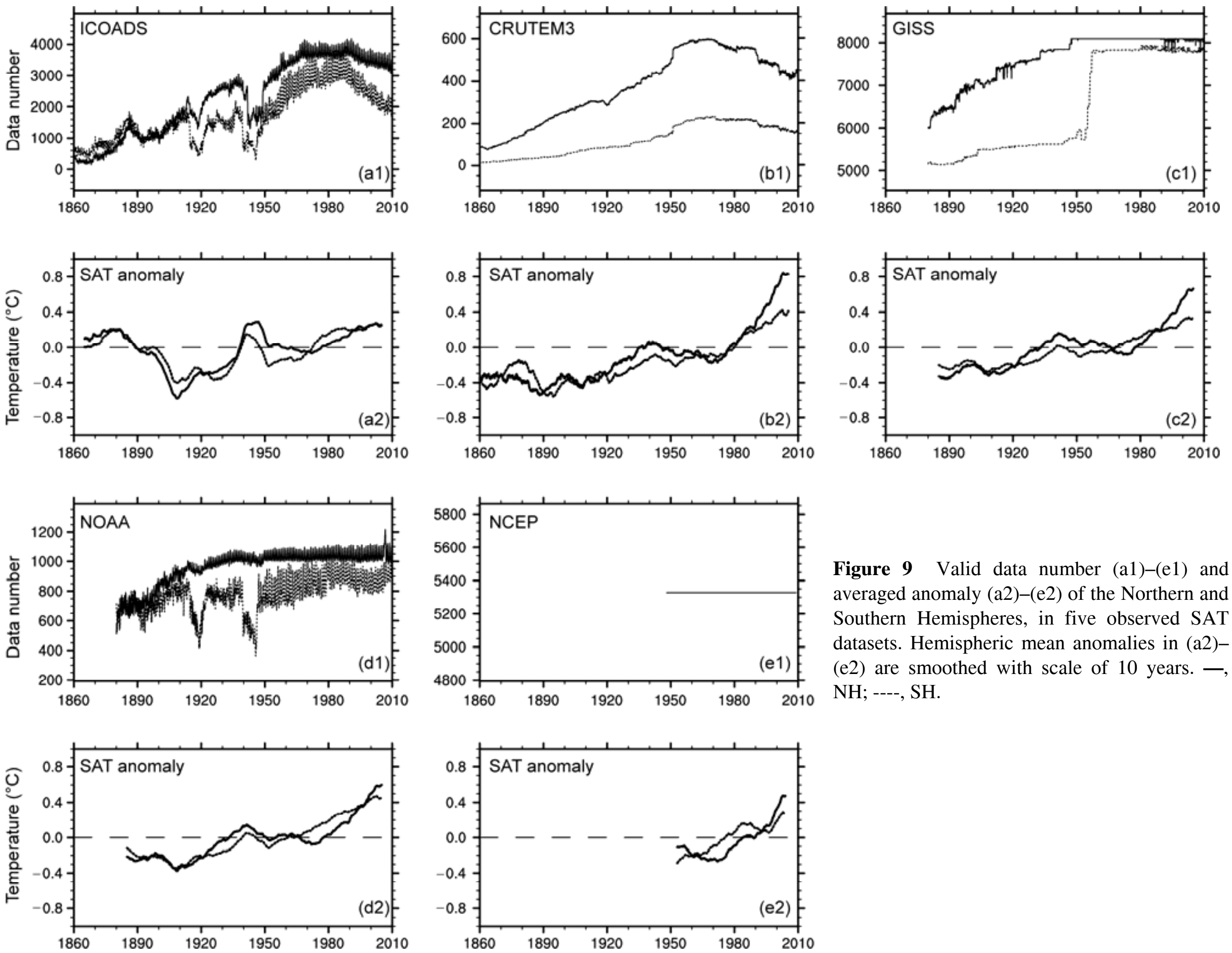

Figure 9 Valid data number (a1)–(e1) and averaged anomaly (a2)–(e2) of the Northern and Southern Hemispheres, in five observed SAT datasets. Hemispheric mean anomalies in (a2)–(e2) are smoothed with scale of 10 years. —, NH; ----, SH.

onset of the Industrial Revolution, which indicates that each SST observation is consistent with the other regarding global warming (Figure 8(a2)–(e2)). Overlying the warming trend, there are also differences in two hemispheric means of each SST observation with timescale of inter-decadal. For example, the Northern Hemisphere is warmer than the Southern Hemisphere around the 1950s and cooler around the 1980s. The difference indicates that "see-saw" phenomenon is common and distinctively consistent in each observation.

The evolutionary characteristics of SAT in each observation are similar to those of SST, indicating a warming trend with similar magnitude and an inter-decadal difference in each hemispheric means (Figure 9(a2)–(e2)). This demonstrates that each SAT observation can represent the "global warming" and "see-saw" phenomena.

As shown in Figure 10, the evolutionary characteristics and variation magnitudes of averaged SST and SAT "see-saw" intensities during the 20th Century are distinctively consistent (solid lines). The variations of SST/SAT "see-saw" intensities with inter-decadal scale are significant, such as the transformation from north warmer to south warmer during the periods of before the 1910s and between the 1940s and mid-1970s, and vice versa during other periods. The averaged variation magnitude in SST and SAT "see-saw" intensities is around 0.2°C, which is smaller than that of global warming trend (0.7°C since the Industrial Revolution). As a result, the "see-saw" phenomenon in SST and SAT during the 20th Century is robust but not dominant, so THC is just one of the key factors affecting the changes of SST and SAT during this period.

The averaged time series of SST "see-saw" intensity is well consistent with that of SAT after the 1910s, but not so well before the 1910s. Compared with SST, the consistence of each "see-saw" intensity series of SAT is relatively lower, especially before the 1910s. The differences of each observed "see-saw" intensity of SST or SAT rely on two points: first, the observed data involved are different, especially before the middle 20th Century; second, the methods of quality control and processing are different [24–31]. Not knowing the relative credibility of each datasets of SST and SAT, we have to choose the averaged series of SST and SAT (thick solid lines in Figure 10(a), (b)) as the basis of the reconstruction of THC changes hereinafter.

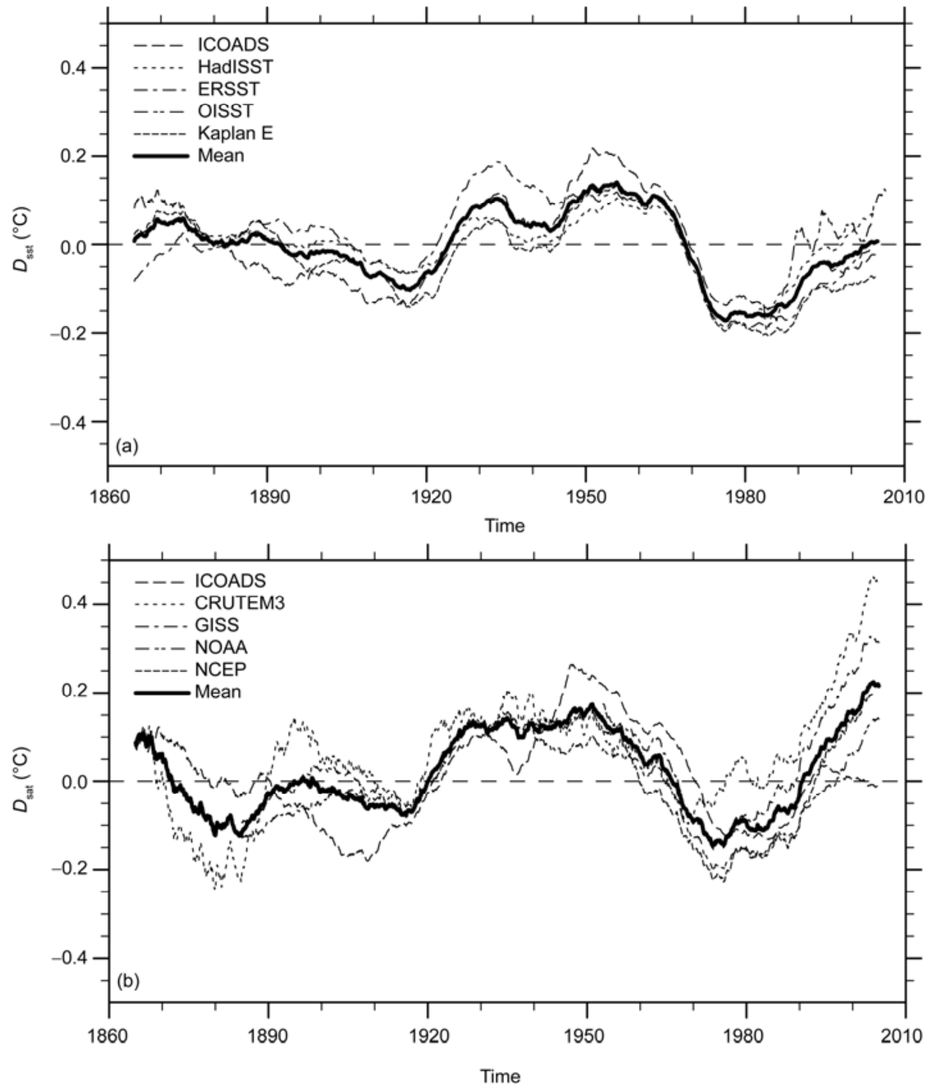

Figure 10 "See-saw" intensities (thin lines) and their mean (thick solid line) of SST (a) /SAT (b) in multiple observed datasets. Three years running mean is applied in NOAA OISST, but 10 years in the others.

4 Reconstruction of THC changes during the 20th Century

Based on the quantitatively diagnostic relationship between THC anomaly and SST/SAT "see-saw" intensities (eqs. (1) and (2)), and the observed SST/SAT "see-saw" intensities during the 20th Century (solid lines in Figure 10), we can reconstruct the changes of THC during the 20th Century. For the reasons that the SST/SAT "see-saw" intensities only represent the anomaly of THC, the following reconstruction just achieves the changes of THC and cannot get the mean intensity of THC during this period.

During the reconstruction, the corresponding timescale ranges of each diagnostic relationship are different. As a result, the timescale ranges of reconstructions under the weakening/non-weakening scenarios are different.

Figure 11 shows the reconstructed THC anomalies (solid lines) and corresponding confident intervals of 85% (between thin dashed lines) under the two scenarios studied. For the reasons of different timescale ranges of two reconstruction results, they cannot be compared directly. However, it is applicable to conduct a calculation of a set of smoothed reconstruction results under weakening scenario with the same timescale ranges as the non-weakening scenario (longer than 40 years, dotted line in Figure 11(a)). Comparing the dotted line in Figure 11(a) with the solid line in Figure 11(b), we found that their evolutionary characteristics and variation magnitude are largely similar. From this, it can be concluded that the reconstructions under the two scenarios are consistent with each other. Compared with the result of non-weakening scenario, the result of weakening scenario can provide more information as in the shorter timescales. Overall, the result of reconstruction suggests

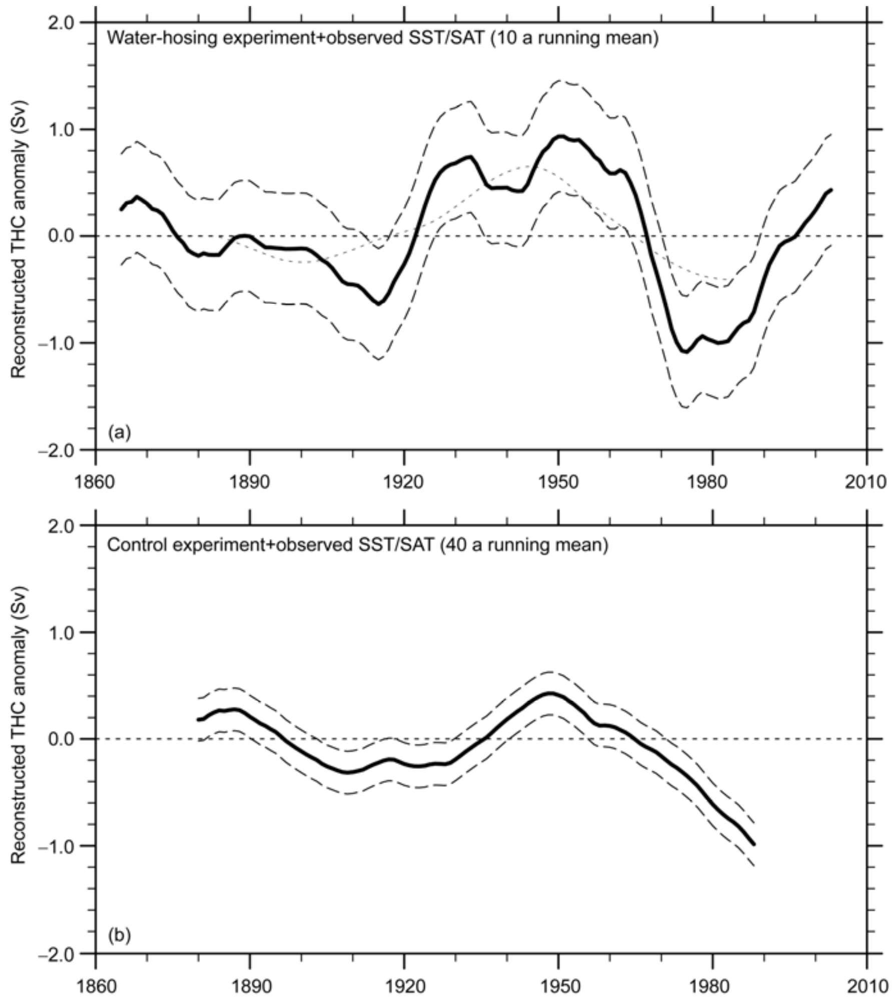

Figure 11 Reconstructed THC anomalies during the 20th Century under weakening (a) and non-weakening (b) scenarios. Thick solid line and dashed lines indicate reconstructed THC anomalies and 85% confidence intervals, respectively. Dotted line in subplot (a) is the result of 40 years running mean of its thick solid line. Confidence intervals are calculated with regressed and simulated THC anomalies in two experiments.

that THC undergoes a two-cycle oscillation with inter-decadal scale since the Industrial Revolution with magnitude of about 1 Sv. The transformation times of decadal trend are around the mid-1910s, 1940s and mid-1970s. The corresponding error range of 85% confidence intervals under weakening scenario (±0.52 Sv, Figure 11(a)) is larger than that in non-weakening scenario (±0.2 Sv, Figure 11(b)). The explanation is that the variation scales under former scenario are shorter and then the related THC changes are bigger correspondingly (Figures 1 and 3).

Some may question why the reconstruction result under the weakening scenario does not show a weakening trend (thick solid line in Figure 11(a)). The explanation is that the diagnostic relationship used in this reconstruction is derived from an experiment which indicates a weakening trend, but observed SST/SAT "see-saw" intensities used in this reconstruction does not have the weakening trend. Thus, the non-weakening reconstruction result does not contradict with its background basis and it confirms that the changes of THC during the 20th Century did not occur during a long-term weakening.

5 Discussion

Under two possible change scenarios of THC during the 20th Century, we develop a new reconstruction scheme based on the close relationship between THC anomaly and SST/SAT "see-saw" intensities. In the new reconstruction scheme, we first diagnose their quantitative relationship in the model experiments which corresponds to two possible scenarios, and then reconstruct the changes of THC with multiple observed datasets of SST and SAT. The introduction of methods of "hemispheric mean" and "double factors" in the establishment of diagnostic relationship and in the subsequent reconstruction has heightened the regression result significantly and applied the observations sufficiently. Also, the averaged SST and SAT "see-saw" intensities are used during the reconstruction, which are believed to be more reliable when the relative credibility of each dataset of

SST and SAT is not known. Compared with previous reconstruction schemes, the one presented in this paper is more precise since it involves two possible change scenarios and multiple observations, which means that the subsequent reconstruction results have a higher degree of validity and reliability.

Model results show that the THC anomaly and SST/SAT "see-saw" intensities are well correlated in timescales longer than 10 years under the scenario of weakening, and in timescales longer than 40 years under scenario of non-weakening. Two kinds of reconstruction results here are consistent with each other, and suggest that THC has undergone a two-cycle oscillation with inter-decadal scale since the Industrial Revolution with magnitude of about 1 Sv. The transformation times of decadal trend are around the mid-1910s, 1940s and mid-1970s. This work validates the main results of previous reconstructions, and points out that THC did not have a long term weakening during the 20th Century.

There are still several points where this reconstruction differs significantly from the previous reconstructions. One is the transformation time from decadal strengthening to weakening around the middle of the 20th Century. It should be noted that our results suggest this happens around the 1950s which is consistent with the findings of Zhou et al. [15, 16] and Knight et al. [19]. Our findings suggest this happens later than what Latif et al. [18] suggested. The start of recent decadal strengthening of THC in our results happens around the mid-1970s. This is consistent with the findings of Zhou et al. [15, 16], Latif et al. [18] and Knight et al. [19], but obviously later than that of Wang et al. [20]. Also, our result provides the inter-decadal variation magnitude of 1 Sv following Knight et al. [19], but this value is bigger than theirs.

Based on the analysis of model simulation results, two modes of THC changing are identified and their corresponding climatic impacts are different [39, 40]. The first is the mode within the whole THC system; the other is the mode within the North Atlantic Basin. It is unclear which mode best explains the changes of reconstructed THC and this should be studied in more depth.

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