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The Latitudinal Structure of Recent Changes in the Boreal Brewer-Dobson Circulation

by C. Shi et al.

Text is formatted as follows: **The referees' comments are written in bold.** *Responses to the remarks are written in italic.* Changes in the text of the manuscript are marked with apostrophes (" ").

A copy of the revised manuscript including all the track changes is appended.

Final response of the authors to the referees' remarks.

We thank all reviewers for their helpful comments and we followed their suggestions whenever possible. We feel that these changes have helped substantially to improve the manuscript.

Following our detail responses to the remarks of the referees

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Anonymous Referee #1: P1-P10; Anonymous Reviewer #2: P11-P17

Anonymous Referee #1: P1-P10

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General comment:

1) **At first: How the speed-up of the midlatitudinal downward branch results in an increase of HCl is not further explained. The authors write with respect to this: "Under the approximate conditions of no divergence and no horizontal**

HCl gradient, the strength of the local downwelling dominates the extratropical lower stratospheric HCl concentration by downward transport. Therefore, the increase in the mid-latitudes and decrease in the Arctic of HCl after 2006/07 can support the local speedup in mid-latitude and slowdown in the Arctic of the downwelling resulting from the narrowing equatorward of the downwelling branch of BDC." It is not clear to me what the authors really want to say with this statement. I might speculate that they wish to say that high HCl amounts from the higher atmosphere are transported downwards, but at the end I am left alone without any explanation.

Response: *We mean that air parcels with high HCl concentration are transported abnormally downward by the local speedup of downwelling branch in the mid-latitudes. More explanation is in the section 3.4 of the revision L257-L280.*

2) At second: The paper fully ignores all observational evidence that a positive trend of age of air has been found for the Northern mid-latitudes during the last decade (roughly 2002 - 2012), and, from single balloon observations, even for the last 30 years. This observational evidence comes not only from direct observations of age tracers, but also models driven by re-analyses like ERA-I produce increasing age of air over these years. It would be necessary to demonstrate how increasing age of air comes along with decreasing transport times within an accelerated mid-latitudinal BDC branch - one possibility would be significantly enhanced aging by mixing. The authors do not comment at all on these aspects and make no attempt to discuss their findings in the context of these earlier observations.

Response: *The age of air derived from dynamics only indicates the total slowdown of the BDC but cannot show the structural change of the BDC. Hence, there is not a contradiction between our opinions and theirs. This is expressed in detail in the revision, in L257-L280.*

3) At third: I am not able to follow the authors (and this might be my fault) with their numerical analysis that finally allows them to arrive at their conclusions, and at statements like the following: "The local acceleration of the mid-latitude downwelling results from the branch narrowing equatorward which is related to weak planetary wave activity and cold polar vortex enhancement." I am not aware of a mid-latitudinal downward branch of the BDC that is separated from the downward branch in the polar regions, so that I do not know how this narrowing can be caused, nor have I found any demonstration in the paper that the planetary wave activity was weak(er) or the cold polar vortex was enhanced (what exactly, was enhanced?).

Response: *We showed the basic facts in Fig.3a and discuss in section 3.2, in L169-L178.*

Specific comments:

4) Abstract, p24404, L6/7: "... decreasing extratropical middle-lower stratospheric HCl." I do not understand this statement. Weakening of the BDC would result in longer transport times and, thus, an increase of HCl due to longer exposure of CFCs to photolysis.

Response: *HCl increasing in the mid-latitude stratosphere is only caused by the strong downwelling because HCl was decreasing in the HCl source area when BDC is weakening during 2001-2011. They are expressed in detail in the revision, L268-L280.*

5) Abstract, p24404, L7-10: "However, the global ozone chemistry and related trace gas data records for the stratosphere data (GOZCARDS) show that the tropical lowermost stratospheric WV increased by 18%/decade during 2001–2011 and the boreal midlatitude lower stratospheric HCl rose 25%/decade after 2006." Is this your own analysis, or do you refer to

previous published material? In the latter case, a reference is required.

Response: *The specific trends are analyzed by ourselves and can be found in section 3.*

6) **Abstract, p24404, L11/12:"... a speedup of the mid-latitude downwelling." As above, I do not understand this conclusion, since, to my understanding, a slow-down of the BDC would indeed result in an increase of HCl in the extratropics.**

Response: *as in the revision, L268-L280.*

7) **p24405, L5-8:"In addition, in December, January, February and March (DJFM), a large proportion of WV transport into stratosphere over the Tropical Western Pacific (TWP) is known as “stratospheric fountain” (Geller et al., 2002; Bannister et al., 2004; Bonazzola et al., 2004). Thus, the variability of the BDC in the boreal winter affects the annual tropical lower stratospheric WV (Dessler et al., 2014)." The BDC is understood as a zonally averaged phenomenon. In this sense it is not correct to assign longitudinally restricted processes like the transport over the Western Pacific to the BDC.**

Response: *We deleted these redundant sentences in L51-L45.*

8) **p24405, L19/20: "However, the contrary HCl trends after 2006 in the mid-latitudes and the Arctic in boreal middle stratosphere (Fig. 2d and f) cannot be explained simply by the slowdown of the downwelling argued by Mahieu et al. (2014)." This is a bad organisation of the paper. Figs. 2d and f are referred to in the introduction that already show result of the analysis here - the introduction is not the correct place for this. Beyond this, Figures need to be referred to in the order of their appearance.**

Response: *This sentence is a comment on Malieu et al. So we deleted our figures here and revised to "However, the opposing HCl trends in the mid-latitudes and the Arctic in boreal middle stratosphere in Fig. 4a of Mahieu et al. (2014) cannot be explained simply by the slowdown of the downwelling.", in L66-L69.*

9) p24405, L26 and throughout the paper: "air age" - the term commonly used is "age of air" (in full: stratospheric mean age of air, abbreviated: AoA)

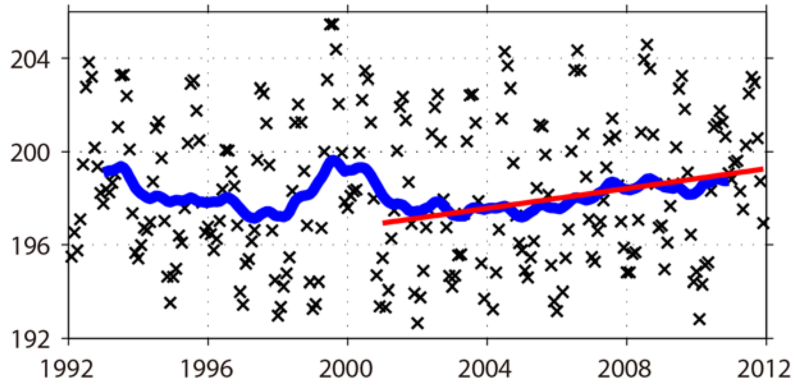
Response: *We revised all of them.*

10) p24406, L1/2: "Additionally, the HCl concentrations can be different in the air parcels with the same age but different transport pathways (Waugh et al., 2007)." This fact is accounted for in the concept of mean age of air by the age spectrum - indeed depends the mean age of air on the shape of the age spectrum since it is the first moment of the spectrum. Two air parcels with the same mean age but representing different transport pathways would have different age spectra that - only by chance - could have the same first momentum. Not impossible, but not very realistic. My impression is that the authors are not familiar with the concept of the age spectrum?

Response: *These tedious sentences in context were removed in L78-L80.*

11) p24408, L14-16: "During 2001–2011, the temperature near the tropical tropopause (10S–10N) (Fig. 1b) rises with a trend of 2.21 K/decade based on the GOZCARDSMERRA data." Is this consistent with other data sets, eg. SPARC temperature trend analysis? It seems to be a tremendous and unrealistically high amount!

Response: *A similar trend in ERA-interim is 2.13K/decade at 70 hPa. We did not find* *the temperature trend in the same location and period mentioned by other papers.*



12) **p24408, L19-22: "In addition, the decline of BDC during 2001–2011 was confirmed by air age increases in the boreal main stratosphere from Lagrangian transport models and observations (Ploeger et al.,2015; Mahieu et al., 2014; Stiller et al., 2012)." The increase and decrease of AoA shows a rather complicated pattern in these publications; I do not agree with this general statement made here; this argument mixes observations of AoA trends in the Northern mid-stratosphere with trends of uplift velocities in the tropical lower stratosphere.**

Response: *The redundant sentence was removed in L160-L163.*

13) **p24408, L24: "There is not only a shift of the BDC trend ..." What kind of shift? In what domain? There was no mentioning of any kind of shift before in the paper.**

Response: *The trend shift near 2000 in Fig. 1a is from increase to decrease.*

14) **p24409, L2: "... the flow would be accelerated if the flow pipe narrows" Where has it been shown that the "flow pipe" narrows? What is meant with the "flow pipe"? The tropical pipe?**

Response: *as in L174-L178, " If we regard the BDC as a flow pipe, the flow would be accelerated when the downwelling branch narrows following the principle of mass conservation. Fig.3a supports the pattern of the equatorward narrowing of the downwelling branch, a speedup in the mid-latitudes and a slowdown in high latitudes under the background of an enhanced polar vortex."*

15) p22409, L6-27: This entire paragraph is a mystery to me. I cannot follow where these structural changes in the BDC are deduced from.

Response: *We revised section 3.2, as in L169-L205.*

16) p22409, L13-15: "In other words, the downwelling branch narrowed equatorward and sank faster in the mid-latitudes (downward black thin hollow arrow in Fig. 1d)." I cannot follow at all. My understanding of the BDC is that BOTH in midlatitudes and polar latitudes downwelling is the predominant direction of the BDC; what do the authors want to say with their statement? That downwelling occurs only in the polar vortex regions?

Response: *as in comment 15. "According to the TEM momentum equation for the middle atmosphere, the weak wave activity may enhance the zonal flow (Fig. 2b) and weaken the BDC. Climatologically, the BDC downwelling branch is affected by zonal flow and is located throughout the stratosphere south of the jet axis and partly in the lower stratosphere under the jet core on the north of the jet (shading in Fig.3a). ", as in L169-L205.*

17) p22409, L15/16: "The regression of EPFp from Fig. 1a with temperature of DJFM in 2001–2011 (Fig. 1e) can ..." What has been plotted over what, and which kind of regression analysis has been done? I cannot follow what has been done here.

Response: *as in L194-L198, " Using single variable linear regression of temperature on the mean EPF (Fig.3b), the positive temperature anomalies (near 0.5K) in the middle latitudes and negative anomalies (near -2 K) in the Arctic can also support the latitudinal structural changes of the downwelling branch during the period, the equatorward narrowing of the downwelling branch, a local speedup of downwelling in the mid-latitudes and a slowdown in the Arctic. "*

18) p22410, L1-4: "The local acceleration of the mid-latitude downwelling results from the branch narrowing equatorward which is related to weak planetary wave activity and cold polar vortex enhancement." Again, I do not understand what is meant with "branch narrowing equatorward". Where has it been demonstrated that the planetary wave activity is weak, and where has the cold polar vortex enhancement been shown?

Response: *We revised section 3.2, as in L170-L210.*

19) p22410, L15-16: "Fueglistaler (2012) analyzed tropical stratospheric WV from HALOE and also found the trend after 2000." Since HALOE terminated its operation in 2005, the trend derived by Fueglistaler is certainly for another time period than the trend in this paper?

Response: *as in L228-L232. They was revised to " Randel et al. (2006) and Dhomse et al. (2008) indicated the opposite variation of WV during several years including 2000, a distinct mutational year (Fueglistaler, 2012). Here we extend the data series and discuss WV during 2001-2011 after the mutation."*

20) p22410/11, section 3.4: I understand this section as follows: since HCl vmr increases with altitude, a faster downward transport in mid-latitudes brings down higher HCl amounts from above, while in the Arctic, where the

downward transport is not accelerated according to the authors, the decrease of HCl continues in line with the decrease of CFCs. This interpretation is purely speculative. The authors fully ignore in their argumentation that there is independent observational evidence of increasing age of air in the Northern mid-latitudes. This is in clear contradiction to their result of accelerated downward transport in Northern midlatitudes. Even without this contradictory observational evidence, the claims of the authors would need to be manifested by some thorough assessments on the amount of HCl increase due to pure transport versus HCl decrease due to air becoming younger and less photolyzed. Besides this, faster downward transport does not necessarily mean that air from higher up in the atmosphere (where HCl vmr is larger) is transported down.

Response: *We revised this section, please refer to L257-L280.*

21) **p24411, L18/19: "The trends of boreal BDC tended to decrease and create latitudinal structural changes." Where has this been shown in this paper? Isn't this merely a summary of previous publications? By the way: do the authors really mean that the trend of the boreal BDC has changed, or the BDC itself?**

Response: *Fig.1a shows the negative trend of the BDC after 2000 and and Fig. 3a shows the structural changes. Refer to L169-L185.*

22) **p24411, L23: "...weaker planetary wave activity and the stronger polar vortex after 2000." Where exactly has this been shown in the paper?**

Response: *We revised this section. Please refer to L169-L216.*

23) p24411, L26/27: "The increasing HCl in the midlatitudes is caused by the local speedup of downwelling after 2006/07." This interpretation is in clear contradiction to the Mahieu et al. paper. The exact mechanism for this increase is not explained at any place in this paper. The reader might assume that the increased downward motion might bring higher HCl vmr from higher altitudes down to the middle stratosphere. However, the competing process of reduced photolysis during shorter transport times due to accelerated BDC has not been assessed. Without this assessment of competing processes the claim of the authors remain purely hypothetical.

Response: *We revised section 3.4, as in L257-L280.*

24) p24412, last para of the paper: The last para consists of a few random citations about possible future evolution of the BDC that does not help at all for the argumentation in this paper here.

Response: *The para was deleted in L300-L317.*

Technical comments:

25) Fig. 1: Is there any reason to squeeze all these panels within one single figure?

Response: *We reorganized the figures.*

Anonymous Referee #2: P11-P17

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General Comments:

In this study authors try to explain anonymous changes stratospheric HCl and H2O over last few years. Authors use observation-based GOZCARDS data and ERA-interim dynamical fields to argue that there are significant changes in the stratospheric circulation (or Brewer-Dobson (BDC) circulation). They argue that weakening on tropical upwelling caused by TTL warming (hence increasing trend in the stratospheric H2O) but enhanced downwelling caused increase in mid-latitude stratospheric HCl.

Some aspects of this study are quite good but overall authors fail to explain their results more clear way. There is no limit on number of figures or words. So authors should include detailed analysis of each aspect of their results. Most of the sections/sentences seem to combination of different ideas and there is no clear flow in their arguments. Presenting all the analysis in just couple of figures also does not help. Some references are cited just for sake of it and some are cited only after reading the abstract. Results presented in Mahieu et al (2014), clearly show increase in mid-latitude age of air throughout the NH stratosphere. Their analysis does not show any differences between the shallow branch and the deep branch circulation. Can you please explain why your results differ as you are also using ERA-interim data. Authors also forgot to include careful analysis of H2O trends presented in Hegglin et al., 2014. Overall I think this manuscript needs major revision before it is accepted to ACP.

Minor Comments

Page 24404

1. **Line 5-6 Confusing sentence: "Climatologically, a symmetric weakening BDC indicates increasing tropical lower stratospheric WV and decreasing**

extratropical middle-lower stratospheric HCl"

Response: *These were revised to "Therefore, a symmetric weakening BDC would increase the tropical lower stratospheric WV and decrease the extratropical middle-lower stratospheric HCl", in L19-L21.*

2. **Line 14-15: enhancing polar vortex? Do you mean strength of polar vortex? But when? early winter/mid-winter or late winter?**

Response: *as in L28-L32, "Results present that the enhancing polar vortex and weaken ing planetary wave activity leads to a downwelling branch narrowing equatorward and a local speedup of 24% at 20 hPa in the mid-latitudes." was revised to " Results present the accelerated winter mean Arctic circumpolar westerlies and the weakened planetary wave activity, which led to a equatorward narrowing of the downwelling branch and a local speedup of 24% at 20 hPa in the mid-latitudes.". The winter mean is in all DJF.*

3. **Line 16: What is regressive temperature increase? Where is your regression model. What terms are included?**

Response: *"there are regressive temperature increase of 1.5K near the tropical tropopause and that of 0.5K in the midlatitude middle stratosphere, " was revised to "Using a single variable linear regression of temperature on the mean EPF, the temperature anomalies show a positive 1.5K near the tropical tropopause and a positive 0.5K in the mid-latitude middle stratosphere" , in L32-L36*

4. **Line 23: aren't you contradicting yourself with Solomon et al., 2010?**

Response: *We agree with solomon, as in L42-L44, "In fact, WV decreased sharply near 2000 and then increased mildly in the tropical lower stratosphere. Solomon et al.*

(2010)…".

Page 24405

5. **line 21: Do you know why?**

Response: *The redundant sentence was deleted.*

Page 24406:

6. **line 2 and 3: Confusing link between Waugh et al., (2007) and deep BDC. Please revise**

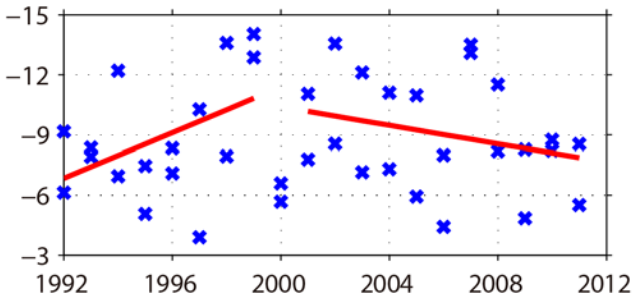
Response: *The tedious sentences in context were removed in L78-L81.*

7. **line 16-21: Can you please comment on various biases in GOZCARDS data. For careful and detailed analysis WV trend using satellite data, please see Hegglin et al., 2014 (Nature Geoscience)**

Response: *" The errors of the average GOZCARDS HCl and WV are less than 15% in most of the stratosphere (Froidevaux et al., 2015). Hegglin et al. (2014) merged other satellite data sets with the help of a chemistry–climate model and they determined there is a link between the trends of stratospheric WV and BDC during 1986-2010.", in L102-L106.*

8. **line 24-26: Using monthly mean data to calculate EPF and TEM is pointless. You should use daily fields and then calculate monthly mean values**

Response: *EPF trend from daily fields as the following figure is similar to the EPF trend from the monthly mean interim data as Fig.1a.*



page 24407

9. line 5: Which data are you using? NCEP or ERA-interim?

Response: *"EPF based on ERA-interim data", in L116.*

page 24408:

10. line 3: Linear regression is used to calculate correlation? why not simple rank-correlation. Give detailed expression for regression model.

Response: *"Linear regression is used to calculate the correlation between temperature and EPFp." was revised to " Using single variable linear regression of temperature on the mid-latitude lower-stratospheric EPF, the correlation between temperature and planetary wave activity is discussed.", in L139-L142.*

11. line 8: BDC increase in 1993 to 1999: This is not correct. We have some of the coldest winters during this period e.g. 1996, 1997. Overall scientific understanding is that ozone losses increased tropics-to-pole temperature gradient, hence Arctic vortex got stronger. Only two years 1998 and 1999 showed enhanced wave activity. Do you have any reference to support your argument?

Response: *EPF is seasonal mean in DJF in the figure, which may cover up the cold events in monthly or weekly scale. Furthermore, we focused on the period of*

2001-2011 in this paper and did not discuss the period of 1993-1999 in detail.

Page 24410

12. line 10-15: WV trends? Do you think Randel et al., 2006 or Dhomse et al., 2008 are incorrect to show increase BDC caused decrease in stratospheric water vapour after 2001?

Response: *in L228-L232, " Randel et al. (2006) and Dhomse et al. (2008) indicated the opposite variation of WV during several years including 2000, a distinct mutational year (Fueglistaler, 2012). Here we extend the data series and discuss WV during 2001-2011 after the mutation. "*

Figures

13. Figure 1a: For which years linear lines are fitted?

Response: *1993-1999 and 2001-2011*

14. Figure 1b: Why 25 month smoothing?

Response: *to remove seasonal and QBO signal.*

15. Why do you want to have all the analysis in two figures. Please separate EP flux analysis as a new Figure

Response: *We reorganized the figures.*

16. Can you please explain if the EP flux analysis shown in Figure 1 are from NCEP or ERA-interim. Do you use daily fluxes or just use monthly mean fields. Also I think better to use anomalies, not the absolute values.

Response: *"Time series of 45°N-75°N mean vertical EPF from ERA-Interim in DJF at 50hPa. The monthly mean fluxes have the similar trend to that from daily fields. Moreover, the anomalies and original values have the same trends.*

17. Plot U winds anomalies and EP flux anomalies separately.

Response: *U and EPF are usually plotted on one figure for analyzing their coordinated variations.*

18. Figure 1f and 1h- 3 and 5 year running means. I assume you are using earlier years from ERA-interim for pre-2001 time period but how are you truncation last 5 years. Those end points must be skewing the time series

Response: *We only used the years during 2001-2011 and the running mean value series does not occupy the start and the end points.*

19. Figure 2a: Can you please comment on quality of H2O data from GOZCARDS. As it is combination of SAGE/HALOE and MLS. But as soon as you add/remove satellite data, GOZCARDS seems to show strange behaviour. I think authors should carefully read GOZCARDS related document and should comment on those biases?

Response: *This data was widely used. Moreover, we can get similar figures to some other papers, analyzing the data we used. As in L102-L106, "The errors of the average GOZCARDS HCl and WV are less than 15% in most of the stratosphere (Froidevaux et al., 2015). "*

20. What residuals are almost similar to absolute values. Your regression model seems to have some problem. 21. Why do you use only solar term?

Response: *The residuals were added by constant terms. Thus they were similar to absolute values. The other terms even the solar term cannot pass a high statistical significance test. So, in the revision, we gave up the regression of HCl and only used the original values.*

The Latitudinal Structure of Recent Changes in the Boreal Brewer-Dobson Circulation

Chunhua Shi[1,2], Dong Guo [1,2], Jianjun Xu[2], Alfred M. Powell, Jr.[3], Ting Xu [1]

[1] Key Laboratory of Meteorological Disaster, Ministry of Education, Nanjing University of Information Science and Technology, Nanjing 210044, China.

[2] Global Environment and Natural Resources Institute, College of Science, George Mason University, Fairfax, VA, USA.

[3] Center for Satellite Applications and Research (STAR), National Oceanic and Atmospheric Administration (NOAA), College Park, MD, USA

Correspondence to:
Chunhua Shi (shich1997@gmail.com) or Jianjun Xu(jxu14@gmu.edu)

Abstract

The u~~U~~pwelling branch of the Brewer-Dobson Circulation (BDC) controls the tropical lower stratospheric water vapor (WV) through dynamic cooling near the tropopause. The d~~D~~ownwelling branch of BDC dominates the extratropical middle-lower stratospheric Hydrogen Chloride (HCl) by dynamic transport. ~~Climatologically~~Therefore, a symmetric weakening BDC would increase ~~indicates increasing~~ the tropical lower stratospheric WV and ~~decreasing~~ decrease the extratropical middle-lower stratospheric HCl. However, the global ozone chemistry and related trace gas data records for the stratosphere data (GOZCARDS) show that the tropical lowermost stratospheric WV increased by 18% decade^{-1} during 2001-2011 and the boreal mid-latitude lower stratospheric HCl rose 25% decade^{-1} after 2006. We interpret this as resulting from a slowdown of the tropical upwelling and a speedup of the mid-latitude downwelling. This interpretation is supported by composite analysis of the Eliasen-Palm Flux (EPF), zonal wind and regression of temperature on the EPF from the ERA-Interim data. Results present the accelerated winter mean Arctic circumpolar westerlies and the weakened planetary wave activity, which led to ~~that the enhancing polar vortex and weakening planetary wave activity~~

~~leads to~~ a equatorward narrowing of the downwelling branch~~ narrowing equatorward~~ and a local speedup of 24% at 20 hPa in the mid-latitudes. ~~Moreover, ~~Using a single variable linear regression of temperature on the mean EPF, the temperature anomalies show a positive 1.5K near the tropical tropopause and a positive 0.5K ~~there are regressive temperature increase of 1.5K near the tropical tropopause and that of 0.5K~~ in the mid-latitude middle stratosphere, which is also indicative~~es~~ of the tropical upwelling slowdown and the mid-latitude downwelling speedup during 2001-2011.

1 Introduction

It has recently been discovered that the stratospheric trace gases, such as Water Vapor (WV) and Hydrogen Chloride (HCl), tend to have anomalous trends since the beginning of the 21st century (Mahieu et al., 2014; Fueglistaler, 2012). In fact, WV decreased sharply near 2000 and then increased mildly in the tropical lower stratosphere. Solomon et al. (2010) suggested that decrease of the lower stratospheric WV near 2000 leads to a 25% reduction of the global warming rate~~ near 2000, which indicates that WV plays an important role in the balance of the global radiation~~. Mote et al. (1995) detected the 'tape recorder' effect on tropical WV above the tropopause and pointed out that the WV variability is dominated by dehydration based on the tropical Cold-Point Tropopause Temperature (CPTT). The tropical CPTT is connected with dynamic cooling of upwelling branch of Brewer-Dobson Circulation (BDC). ~~In addition, in December, January, February and March (DJFM), a large proportion of WV transport into stratosphere over the Tropical Western Pacific (TWP) is known as 'stratospheric fountain' (Geller et al., 2002; Bannister et al., 2004; Bonazzola et al., 2004). ~~Thus, the variability of the BDC in the boreal winter affects the annual tropical lower stratospheric WV (Dessler et al., 2014).

The principal source for Stratospheric HCl is the decomposition of chlorofluorocarbons (CFCs) in the upper stratosphere under intense ultraviolet radiation (UV). HCl is relatively long-lived in the stratosphere (Mohanakumar, 2008; Andrews et al., 1987) and is transported downward by the downwelling branch of the deep BDC. Due to the Montreal Protocol, the total atmospheric chlorine from~~of~~ CFCs decreased since 1992/1993 and stratospheric HCl declined after 1997 as shown from ground-based Fourier-transform infrared (FTIR) spectrometers and various satellite observations (Kohlhepp et al., 2011; Jones et al., 2011; Froidevaux et al., 2015.). When CFCs emission tends to be stable, HCl concentration in the upper stratosphere is dominated by ~~the~~ photochemical exposure which is also related to ~~deep~~ upwelling of BDC (Waugh et al., 2007). However, the ~~contrary~~ opposing HCl trends ~~after 2006~~ in the mid-latitudes and the Arctic in boreal middle stratosphere ~~(Fig.2d and Fig.2f)~~ in Fig. 4a of Mahieu et al (2014) cannot be explained simply by the slowdown of the downwelling ~~argued by Mahieu et al (2014)~~. There might be the ~~opposite~~ opposing trends of the local downwelling in the mid-latitudes and the Arctic.

Therefore, the combination of the variations of WV and HCl can be used to fully understand the change of the deep BDC which is abbreviated as BDC ~~in the~~ below. Recent studies found that the BDC has weakened since the beginning of the 21st century in the Northern Hemisphere (NH) according to ~~air age~~the age of air (Ploeger et al., 2015; Stiller et al., 2012). However, ~~the mid-latitude air age in the middle and lower stratosphere is not only dominated by the deep BDC but also by the shallow BDC. Furthermore, the deep BDC and the shallow BDC can vary independently (Garny et al., 2011; Gerber, 2012; Stiller et al., 2012). Additionally, the HCl concentrations can be different in the air parcels with the same age but different transport pathways (Waugh et al., 2007). Therefore, the deep BDC has direct and efficient influence on the stratospheric HCl and WV. Hence,~~ the mismatched~~ing~~ trends of the WV in the tropics and HCl in the extratropics in the recent observations allow one to deduce an abnormal latitudinal structural change in the BDC. This kind of latitudinal structure changes ~~have~~ has not been discussed before.

Hence, we focused on two points in this study: 1) the latitudinal structure of the recent boreal BDC; 2) the connections between the latitudinal structure of the BDC changes and the ~~mismatching~~ mismatched trends of WV and HCl. The data set is described in section 2. Section 3.1 and 3.2 present the trends of the boreal BDC and the latitudinal structural changes of the BDC. Section 3.3 shows the relationship between BDC and WV. Section 3.4 discusses the connection between BDC and HCl.

The conclusion is provided in section 4.

2 Data and methodology

2.1 Data

Monthly zonal average WV, HCl and temperature data are from Global OZone Chemistry And Related trace gas Data records for the Stratosphere (GOZCARDS Version 1.1, 1991 to 2012) satellite data set. WV data is derived from Level 2 satellite products by HALOE (1991-2005) V19, UARS MLS (1991-1993) V5, ACE-FTS (2004-2012) V2.2 and Aura MLS (2004-2012) V3.3. HCl data is derived from Level 2 products by HALOE (1991-2005) V19, ACE-FTS (2004-2012) V2.2 and Aura MLS (2004-2012) V3.3. Temperature data is derived from MERRA (1979-2012) V5.2.0. Details can be obtained from http://gozcards.jpl.nasa.gov. The errors of the average GOZCARDS HCl and WV are less than 15% in most of the stratosphere (Froidevaux et al., 2015). Hegglin et al. (2014) merged other satellite data sets with the help of a chemistry–climate model and they determined there is a link between the trends of stratospheric WV and BDC during 1986-2010.

European Centre for Medium-Range Weather Forecast (ECMWF) ERA-Interim reanalysis monthly mean data (Dee et al., 2011) with 1.5°×1.5° grid was used to calculate the Eliasen-Palm Flux (EPF) and Transformed Eulerian Mean (TEM) velocity.

2.2 Methodology

EPF of planetary waves (PWs, wave number 1-3) is expressed in equation (1) and TEM velocity (residual meridional circulation, ~~approximative~~ approximating the~~o~~ BDC) is expressed in equation (2) (Andrews et al., 1987). ~~In vector Figures of~~ EPF based on ERA-interim data~~, items are~~is normalized by 3.14×6378 km horizontally and by 1000 hPa vertically when in a vector figure. The units ~~is~~ are m^2s^{-2} (http://www.esrl.noaa.gov/psd/data/epflux/).

$$\begin{cases} F_{(\varphi)} = -r_0 \cos\varphi \overline{u'v'} & (1.a) \\ F_{(p)} = f r_0 \cos\varphi \dfrac{\overline{v'\theta'}}{\overline{\theta}_p} & (1.b) \end{cases}$$

$$\begin{cases} \bar{v}^* = \bar{v} - \dfrac{\partial}{\partial p}\left(\dfrac{\overline{v'\theta'}}{\bar{\theta}_p}\right) & (2.a) \\ \bar{\omega}^* = \bar{\omega} + \dfrac{\partial}{r_0 \cos\varphi \partial\varphi}\left(\dfrac{\overline{v'\theta'}\cos\varphi}{\bar{\theta}_p}\right) & (2.b) \end{cases}$$

~~Where o~~Overbars and primes denote zonal means and departures, subscripts without parentheses denote partial differentiation, p is the pressure, φ is the latitude, f is the Coriolis parameter, r_0 is the radius of the earth, θ is the potential temperature, u and v are zonal and meridional velocity, and ω is vertical velocity.

Deep BDC is driven by the breaking of PWs (EPF convergence) in the winter extratropical stratosphere~~ in winter as~~ known as the ‘downward-control principle’ (Haynes et al., 1991; Holton et al., 1995). ~~Due to t~~The vertical EPF expressed ~~as~~ in equation 1b (EPFp, the eddy heat flux) indicates the upward propagation of PWs mainly in the extratropical stratosphere.~~,~~ This implies the EPFp in the lower stratospheric~~e~~ region 45°N-75°N could be a proxy for the BDC (Newman et al., 2001; Li and Thompson, 2013). Generally, EPFp is negative. Thus, the absolute value of EPFp at 50hPa in 45°N-75°N ~~can~~ will represent the intensity of the BDC.

December-February (DJF) mean is used for boreal winter EPF, $\bar{\omega}^*$ and other dynamic variables. However, temperature is averaged from December to March (DJFM), because the influence of PW activities in DJF on stratospheric temperature will continue till March (Newman et al., 2001).

After using a 25-month moving average, the high-frequency signals are eliminated, the~~and~~ long-term (more than two years) interannual variability is left. Using single variable linear regression of temperature on the mid-latitude lower-stratospheric EPF, the correlation between temperature and planetary wave activity is discussed. ~~Linear regression is used to calculate the correlation between temperature and EPFp.~~

3 Results

3.1 Trends of the boreal BDC

The BDC proxy (EPFp at 50 hPa over 45°N-75°N in Fig.1a) in DJF from ERA-Interim shows that BDC in boreal winter tended to increase in 1993-1999 period. However, the BDC proxy tends to weaken with a trend of $2.21 \times 10^5 \ \text{pa} \cdot \text{m}^{-2} \cdot \text{s}^{-2} \cdot \text{decade}^{-1}$ (33% decade^{-1}) after 2000, which passes statistical significance test at the 90% confidence level. The change of upwelling in the BDC can affect the tropical CPTT by dynamic heating (i.e. less upwelling in the tropics implies less cooling and greater heating). Thus, the tropical lowermost stratospheric temperature can be used to test the long-term trend of the BDC. During 2001-2011, the temperature near the tropical tropopause (10°S-10°N) (Fig.1b) rises with a trend of 2.21 K decade^{-1} based on the GOZCARDS-MERRA data. A similar trend with 2.13 K decade^{-1} is also detected at 70 hPa in ERA-interim (figure not shown). The trend exceeds the significance test at the 99% confidence level. The tropical tropopause warming is consistent with the declining decline of the BDC observed in Fig.1a. Apparently, the result is similar to the ozone analysis in the tropical lower stratosphere (Aschmann et al., 2014) that where the BDC tends to decrease after 2000. In addition, the decline of BDC during 2001-2011 was confirmed by air age increases in the boreal main stratosphere from Lagrangian transport models and observations (Ploeger et al., 2015; Mahieu et al., 2014; Stiller et al., 2012).

3.2 The latitudinal structural changes of the BDC

There is not only a trend shift (near 2000 in Fig. 1a) of the BDC trend but also latitudinal structural changes of the BDC after 2000. BDC (red thick hollow arrow in Fig.1c2a and 3a) is a wave-driving net Lagrangian transport of mass through the middle atmosphere (Andrews and McIntyre, 1976). According to the TEM momentum equation for the middle atmosphere, the weak wave activity may enhance the zonal flow (Fig. 2b) and weaken the BDC. Climatologically, the BDC downwelling branch is affected by zonal flow and is located throughout the stratosphere south of the jet axis and partly in the lower stratosphere under the jet core on the north side of the jet (shading in Fig.3a). If we regard the BDC as a flow pipethe principle of mass conservation, the flow would be accelerated if where the flow pipe narrows following the principle of mass conservation. Fig.3a supports the pattern of the equatorward narrowing of the downwelling branch, a speedup in the mid-latitudes and a slowdown in high latitudes under the background of an enhanced polar vortex. Fig.1f 3c shows an acceleration of the downwelling (also as shown by 'downward black thin hollow arrow' in Fig.1d and 1e) on the south side of axis of the polar vertex axis (35°N about 65°N in Fig.1c2a) corresponding to the polar vortex enhancement (in Fig.1d) at 20 hPa. The 2007-2011 average TEM vertical speed of $4.02 \times 10^{-4}\ \mathrm{pa} \cdot \mathrm{s}^{-1}$ increased by 24-% over 2001-2005 average TEM vertical speed of $3.25 \times 10^{-4}\ \mathrm{pa} \cdot \mathrm{s}^{-1}$. In contrast, the downwelling was decelerated at 20 hPa on the north side of the polar vertex axis (Fig.3d). (in Fig.1f). Comparing to the averaged EPF (BDC proxy) and zonal wind in winter during the period of 2001-2011(Fig.1c), the differences of EPF and zonal wind between 2007-2011 and 2001-2005 show that the decline in the upward propagation of PWs could result in a negative anomaly of BDC (red thick hollow arrows in Fig.1d) accompanied by a polar vortex enhancement. It is suggested that the more powerful circumpolar westerly induced by weaker PWs would block the downwelling branch of the BDC outside the polar region. In other words, the downwelling branch narrowed equatorward and sank faster in the mid-latitudes (the equatorward side of the polar vortex). (downward black thin hollow arrow in Fig.1d). The regression of EPFp from Fig.1a with temperature of DJFM in 2001-2011 (Fig.1e) Using single variable linear regression of temperature on the mean EPF (Fig.3b), the positive temperature anomalies (near 0.5K) in the middle latitudes and negative anomalies (near -2 K) in the Arctic can also support the latitudinal structural changes of the downwelling branch during the period, . A negative center (near -2 K) in the Arctic implies an upwelling anomaly (upward black thin hollow arrow) which is validated by the weakening downwelling and shifting to upwelling (in Fig.1g) on the north side of axis of polar vertex (65°N-85°N) at 20 hPa. The anomalies of the temperature and TEM vertical velocity in the Arctic area indicate the equatorward narrowing of the downwelling branch was narrowing equatorward. The narrowing leads to , a local speedup of downwelling in the mid-latitudes and a slowdown in the Arctic. (Fig.1f and the downward black thin

~~hollow arrow in Fig.1e) which is also verified by a positive center (near 0.5K) in the middle stratosphere.~~ The positive center (near 1.5K in Fig.~~1e~~ 3b accounts for 62% of the total temperature increase in Fig.1b) is located in the lowermost stratosphere over tropics, from which the reduction of the upwelling of the BDC can be inferred ~~(downward red thick hollow arrow)~~.

To summarize, the reduction of the tropical upwelling, ~~and~~ the local strengthening in the middle latitudes and the decrease in the Arctic of the ~~mid-latitude~~ downwelling compose the latitudinal structural changes of the BDC after 2000. The decline of upwelling is in accord with the BDC weakening. The local acceleration of the mid-latitude downwelling results from the branch narrowing equatorward which is related to ~~weak planetary wave activity and cold~~the polar vortex enhancement.

3.3 Relationship between BDC and WV

The decline of the upwelling branch controls the increase of the tropical lower stratospheric WV. According to 'tape recorder' effect, the maximum warming of 1.5K (Fig.~~1e~~3b) in tropical lowermost stratosphere, ~~as~~ caused by the decline of ~~–~~upwelling in the weakening BDC, results in an increase of the tropical lower stratospheric WV by the dehydration of air crossing the cold-point tropical tropopause (Schiller et al., 2009) in 2001-2011. GOZCARDS data show that WV at 68hPa in 2001-2011 increased by the linear rate of 0.60 ppmv· decade^{-1} (~~17.5~~18% · decade^{-1}) which exceeds the significance test at the 99% confidence level (Fig.~~2a~~4a). WV at 46 hPa showed a similar trend of 0.27 ppmv· decade^{-1} (~~7.3~~7% · decade^{-1}) that passes statistical significance test at the 90% confidence level (Fig.~~2b~~4b). Randel et al. (2006) and Dhomse et al. (2008) indicated the opposite variation of WV during several years including 2000, a distinct mutational year (Fueglistaler, 2012). Here we extend the data series and discuss WV during 2001-2011 after the mutation.~~Fueglistaler (2012) analyzed tropical stratospheric WV from HALOE and also found the trend after 2000.~~

3.4 Relationship between BDC and HCl

There is a trend shift of boreal HCl in 2006/2007. GOZCARDS data at 32hPa show that mid-latitude (40°N-60°N) stratospheric HCl had a decreasing trend at a linear rate -0.40 ppbv· $decade^{-1}$ (-~~25.5~~26% · $decade^{-1}$) before 2006 and had an increasing trend of 0.38 ppbv · $decade^{-1}$ (~~24.7~~25% · $decade^{-1}$) after 2006 (Fig.~~2c~~4c). Both trends exceed the significance test at the 99% confidence level. ~~In order to show only the downwelling impacts, HCl regressed against the monthly solar 10.7cm flux (at the 99% confidence level) was removed from the monthly HCl data in Fig.2d. Trend shift of the residual HCl remains in 2006/2007. Trend after 2006 is 0.32 ppbv· $decade^{-1}$ and still passes statistical significance test at the 90% confidence level. HCl~~ At 46hPa in the mid-latitudes, HCl had similar trends of -0.15 ppbv· $decade^{-1}$ (-~~11.3~~11% · $decade^{-1}$) before 2006 and 0.33 ppbv· $decade^{-1}$ (~~24.5~~25% · $decade^{-1}$) after 2006 at 46hPa~~, -0.44 ppbv· $decade^{-1}$ (-24.8% · $decade^{-1}$) before 2006 and 0.17 ppbv· $decade^{-1}$ (9.8% · $decade^{-1}$) after 2006 at 22hPa~~ (pictures omitted), which was also noted by Mahieu et al. (2014). However, HCl in the Arctic (70°N-90°N) at 22 hPa continuously decreased after 2001 (Fig.~~2e~~4d) ~~. Declining trend is~~with -0.32 ppbv· $decade^{-1}$ which passes statistical significance test at the 95% confidence level. At the same time, the minimal HCl concentration in winter reduced faster after 2006 (in the ellipse in Fig.4d). ~~After removal of the solar cycle signals (Fig.2f), HCl reduced faster after 2006/2007 which is opposite to that in the mid-latitudes. It~~There is a similar declining trend of HCl at 15hPa~~ in the Arctic~~ (pictures omitted).

According to the atmospheric continuity equation, mass flux determines the local HCl concentration. Under the approximate conditions of no divergence and no horizontal HCl gradient, HCl transport is controlled by both vertical velocity and the vertical HCl gradient. The downward motion might bring higher concentration HCl from higher altitudes down to the middle stratosphere. HCl vertical gradient in the mid-latitude middle stratosphere is larger than that in high latitudes (in the black rectangle in Fig.5), which may enhance HCl downward transport and hence magnify the HCl positive trend in the middle latitudes caused by the speedup of downwelling in recent years. Similarly, the HCl decrease in the Arctic (in the ellipse in Fig.4d and

Fig. 4a of Mahieu et al., 2014) after 2006/2007 can support the local slowdown of downwelling.

The positive trend of the age of air for the northern mid-latitudes during the last decade (Ploeger et al., 2015; Mahieu et al., 2014; Stiller et al., 2012) can indicate the weakening of the BDC roughly (Fig.1a) but cannot show the structural change of the BDC (black thin hollow arrows in Fig.3a). The larger vertical gradient located in the mid-latitude middle stratosphere (Fig.5) where downwelling accelerated may be the key point for HCl but not for total air. The weakening of the BDC (not only the tropical upwelling but also the total extratropical downwelling) may increase HCl concentration due to air becoming older and more photolyzed. But HCl decreased near tropical stratopause (source region) during 2001-2011 (Froidevaux et al., 2015) with CFCs decreased, which can exclude the influence of an increasing HCl source by photolysis on the middle stratospheric HCl increase in the mid-latitudes. Therefore, from a dynamic point of view, the positive trend of mid-latitude HCl is better explained by the speedup of local downwelling. the strength of the local downwelling dominates the extratropical stratospheric local HCl concentration by downward transport. Therefore, the increase in the mid-latitudes and decrease in the Arctic of HCl after 2006/2007 can support the local speedup in mid-latitude and slowdown in the Arctic of the downwelling resulting from the narrowing equatorward of the downwelling branch of BDC.

4 Conclusion and Discussion

The trends of the boreal BDC tended to decrease and create latitudinal structural changes after 2000. The latitudinal structure of recent changes in the boreal BDC presented the reduction of the tropical upwelling and the local strengthening of the mid-latitude downwelling. The acceleration of downwelling in the mid-latitudes is caused by the equatorward narrowing of the BDC branch narrowing equatorward which is related to the a weaker planetary wave activity and the a stronger polar vortex.

In addition, the variation of WV in the tropics and HCl in the extratropics support the latitudinal structural changes of the BDC. The increasing lower tropical lower stratospheric WV results from the higher tropical CPTT which is mainly caused by the decline of the upwelling after 2000. The increasing HCl in the mid-latitudes is caused by the local speedup of downwelling after 2006/2007.

Numerous simulation studies (Eichelberger et al., 2005; Garcia and Randel, 2008; Butchart et al., 2010; Li et al., 2010; Fleming et al., 2011; Douglass et al., 2014) claimed that BDC will be stronger in the future. Those results are not consistent with the observations described in this paper. However, Winter and Bourqui (2011) found that mid-latitude zonal symmetric surface heating forcing, decreasing the meridional temperature gradient between the tropics and the mid-latitudes, results in a decline of the upward propagation of PWs in the polar region and enhances the polar vortex. Realistically, zonally asymmetric land-ocean warming is more likely to affect the PWs activity. Hu et al. (2014) confirmed that increasing the meridional temperature gradient of sea surface temperature (SST) could enhance the BDC and would be accompanied by increased PWs activity and a decline in the polar vortex. But in 2001-2011, the Pacific Decadal Oscillation (PDO) shifted from the warm phase to the cold phase. An increase of North Pacific SST weakened the meridional temperature gradient between the tropics and the mid-latitudes which was opposite to the simulation conditions of Hu et al. (2014). It appears the modification of the PDO in the meridional temperature gradient is a likely reason for the weaker PWs activity and the latitudinal structural changes in the boreal BDC in the beginning of the 21st century.

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Figures

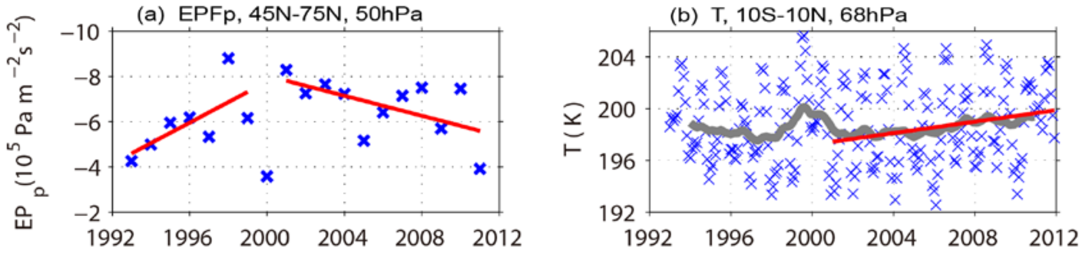

Fig.1 (a) Time series of 45°N-75°N mean vertical EPF from ERA-Interim in DJF at 50hPa, red lines show piecewise linear fits; (b) 10°S-10°N mean monthly temperature from GOZCARDS in DJFM at 68hPa, red thin line shows piecewise linear fit and the gray thick curve shows the 25-month running mean;

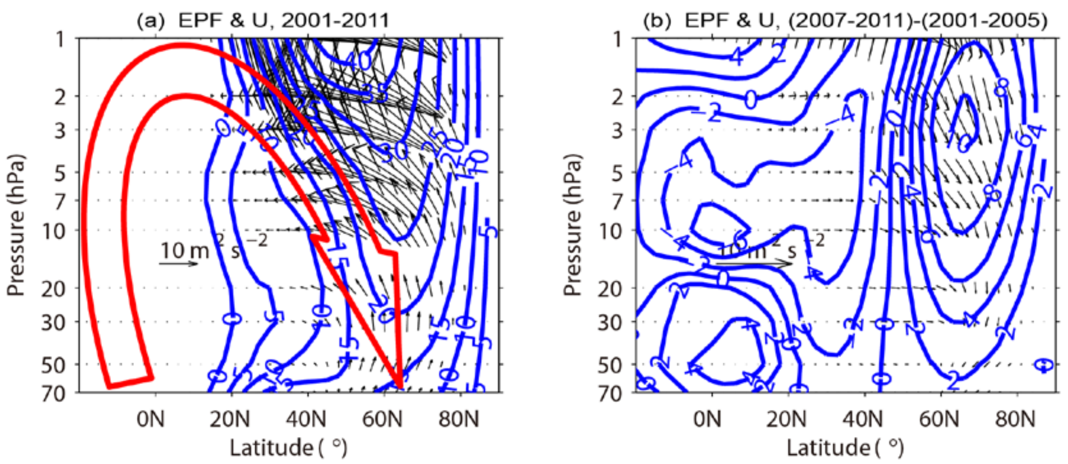

Fig.2 (a) Mean EPF (black thin arrows) of PWs and zonal wind (blue contours, $m\ s^{-1}$) in DJF of 2001-2011 from ERA-Interim, red thick hollow arrow indicates the mean BDC; (b) as in (a), but for the anomalies between 2007-2011 and 2001-2005;

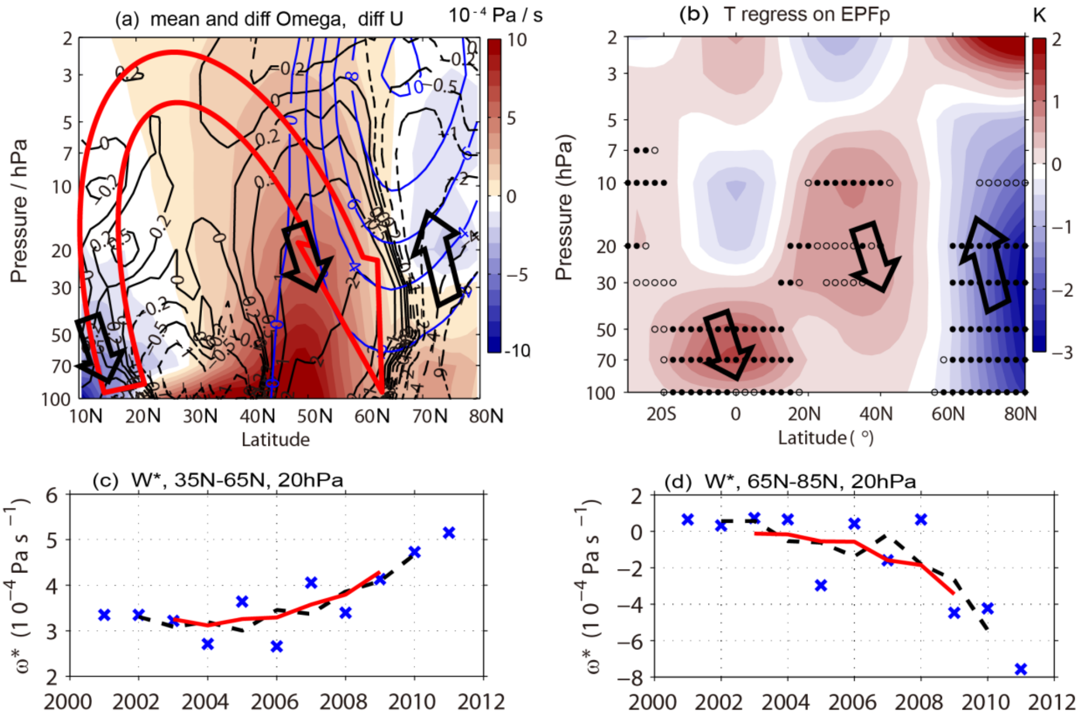

Fig.3 (a) Mean TEM vertical velocity (10^{-4} Pa s^{-1}, shading) in DJF of 2001-2011, the anomalies of vertical velocity (10^{-4} Pa s^{-1}, black contours) and zonal wind (blue contours, m s^{-1}) in DJF between 2007-2011 and 2001-2005, red thick hollow arrow indicates the mean BDC, black thin hollow arrows indicate the local BDC anomalies; (b) single variable linear regression of temperature (in DJFM, unit, Kelvin) on 45°N-75°N mean EPFp (in DJF at 50 hPa) in 2001-2011, Stippled regions passed the 90% (filled) and 85% (hollow) confidence test levels; (c) 35°N-65°N TEM vertical speed of BDC in DJF at 20hPa, black and red curves respectively indicate 3 and 5 year running means; (d) as in (c), but at 65°N-85°N.

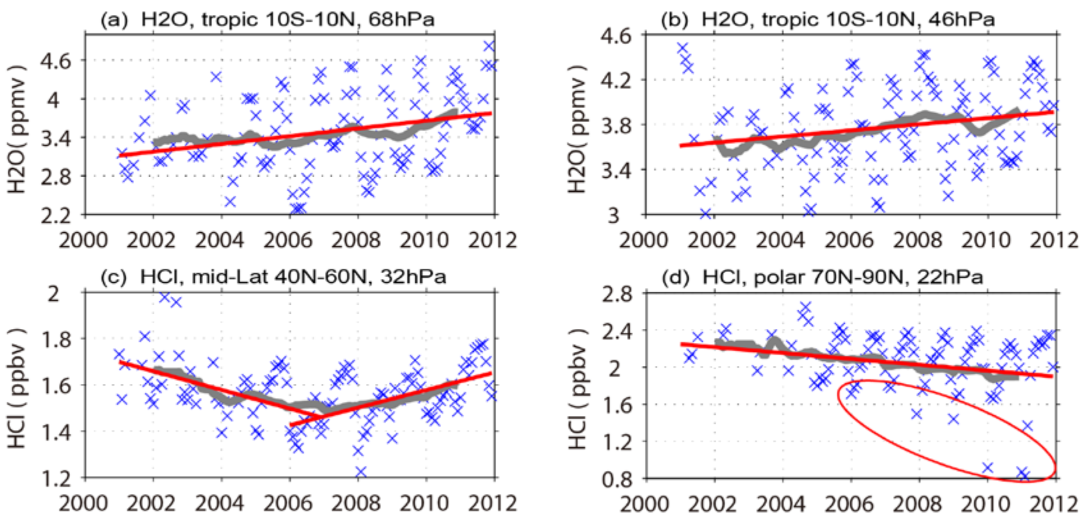

Fig.4 Time series of monthly H2O and HCl from GOZCARDS, thick gray curve for 25-month running mean and thin red line for piecewise linear fit; (a, b) H2O in tropics 10°S-10°N at 68hPa and 46hPa; (c) HCl in mid-latitude 40°N-60°N at 32hPa; (d) HCl in the Arctic 70°N-90°N at 22hPa;

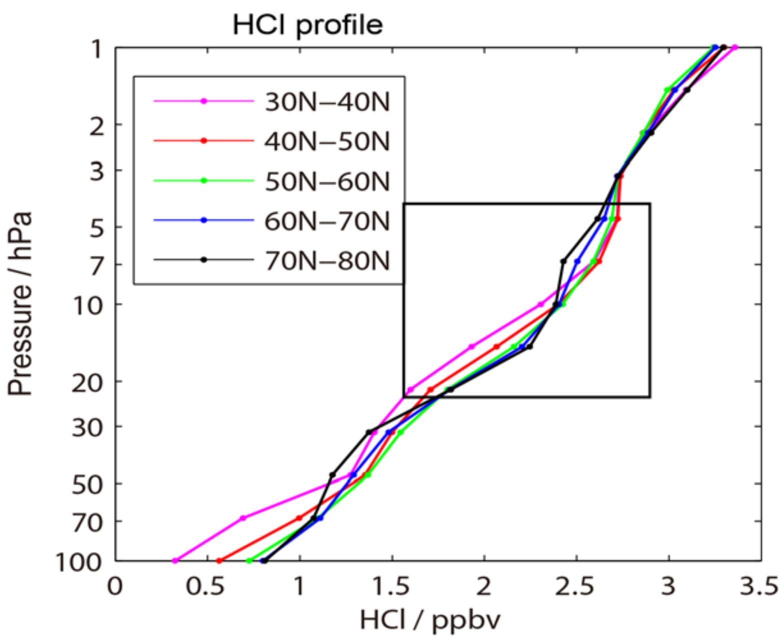

Fig.5 HCl profiles in DJF with different latitudes from MLS, decreasing vertical gradient with latitude in black rectangle.