

# **On the Relationship Between the Brewer-Dobson Circulation and the Southern Annular Mode During Austral Summer in Coupled Chemistry-Climate Model Simulations**

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## **Popular Summary**

The Brewer-Dobson circulation (BDC) is the mean transport circulation in the stratosphere. It consists of an upwelling branch in the tropics, poleward flows from the tropics to the extratropics, and downward flows in the extratropics. The BDC plays a crucial role in the distribution of important stratospheric trace gases, such as ozone and water vapor. Therefore changes in the strength of the BDC under global warming could have significant impact on stratospheric ozone depletion and recovery. For example, all climate models that are used by the World Meteorological Organization to predict ozone evolution in the 21<sup>st</sup> century project a strengthening of the BDC that leads to ozone super-recovery in the mid-latitudes. On the other hand, ozone changes could also affect the strength of the BDC.

This work investigates an outstanding question: whether and how changes in the Brewer-Dobson circulation are connected to climate change in the troposphere, in particular, the annular modes. The annular modes are the leading variability in the extratropical troposphere, which describes a seesaw pattern of circulation fluctuations between the polar and middle latitudes. Using simulations from the Goddard Earth Observing System Coupled Chemistry Climate Model (GEOS CCM), we found the strengthening of the BDC in the summer Southern Hemisphere is strongly correlated with a shift of the Southern Hemisphere Annular Mode (SAM) toward its positive phase for the last 4 decades of the 20<sup>th</sup> century. This relationship is only present in model runs that simulate the stratospheric ozone depletion. Therefore it is concluded that the BDC-SAM relationship is driven by Antarctic ozone depletion. The ozone hole significantly cools the Antarctic stratosphere in late spring/early summer, which leads to a delayed breakdown of the polar vortex: strong circumpolar eastward flows that usually shift to westward winds in late spring. The prolonged persistence of stratospheric eastward flow enhances upward propagation of tropospheric waves into the stratosphere and strengthens the BDC. The increased wave flux in the stratosphere in turn drives a SAM trend toward its positive phase. Our results also show that the BDC-SAM relationship is robust on the interannual timescale.

1 **Relationships between the Brewer-Dobson circulation and the southern**  
2 **annular mode during austral summer in coupled chemistry-climate**  
3 **model simulations**

4

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## Abstract

13

14 The Brewer-Dobson circulation (BDC) is the mean meridional mass circulation in the  
15 stratosphere and the Southern Annular Mode (SAM) is the prime variability pattern of the  
16 Southern Hemisphere extratropical troposphere. Motivated by previous studies showing  
17 that both the strength of the BDC and the SAM have the largest trends in the austral  
18 summer in the recent past, this paper investigates the relationships between the BDC and  
19 the SAM using coupled chemistry-climate model simulations. The model results show  
20 that the strengthening of the BDC in the Southern Hemisphere during November-  
21 February (NDJF) is strongly projected onto the high index of the SAM. The BDC-SAM  
22 relationship is driven by Antarctic ozone depletion, which increases stratosphere-  
23 troposphere interactions through a delayed Antarctic vortex breakup. The prolonged  
24 persistence of stratospheric westerlies enhances upward propagation of tropospheric  
25 wave activity into the stratosphere and strengthens the BDC. The wave flux and westerly  
26 anomalies in the stratosphere in turn drives a SAM trend toward its high index. Model  
27 results also show that the BDC-SAM relationship is robust on the interannual timescale.

28

28 **1 Introduction**

29

30 The stratospheric mean meridional circulation, or the so-called Brewer-Dobson  
31 circulation (BDC), plays a crucial role in the distribution of ozone and other important  
32 trace species in the stratosphere [*Brewer 1949; Dobson 1956*]. The BDC consists of an  
33 upwelling branch in the tropics, poleward flows, and downwelling branches in the  
34 extratropics [*Andrews et al., 1987*]. The forcing of the BDC is from Rossby and gravity  
35 wave breaking in the extratropical stratosphere, which deposits westward momentum in  
36 the atmosphere that drives a poleward flow [*Holton et al., 1995*]. Because of mass  
37 continuity, poleward flow in the extratropical stratosphere induces rising motion in the  
38 tropics and sinking motion in the mid-to-high latitudes.

39

40 *Butchart and Scaife* [2001] were the first to predict a strengthening of the BDC in  
41 response to greenhouse gas (GHG) increase. Because an enhanced BDC has significant  
42 impacts on stratospheric transport, ozone recovery, and stratosphere-troposphere  
43 exchange, the strength of the BDC under global warming has been extensively  
44 investigated. Numerous middle-atmosphere model simulations have confirmed that an  
45 increase in the BDC is a robust model response to climate change [e.g., *Butchart et al.,*  
46 *2006*]. Model results indicate that the acceleration of the BDC is caused by a stronger  
47 stratospheric wave forcing with contributions from both model resolved waves and  
48 parameterized gravity waves [*Butchart et al., 2006; Li et al., 2008; Garcia and Randel,*  
49 *2008; McLandress and Shepherd, 2009*]. Several studies have linked the increase in the  
50 stratospheric wave driving to GHG increase, sea surface temperature change, and

51 stratospheric ozone depletion [*Butchart and Scaife, 2001; Li et al., 2008; Garcia and*  
52 *Randel, 2008; Omen et al., 2009*].

53

54 Despite extensive studies of the BDC, there are still some outstanding dynamical  
55 questions. One important issue is whether and how changes in the BDC are connected to  
56 climate change in the troposphere, in particular, the annular modes. The annular modes  
57 are the leading variability in the extratropical troposphere at intraseasonal, interannual,  
58 and decadal timescales [*Thompson and Wallace, 2000; Thompson et al., 2000*]. When  
59 the zonal-mean zonal wind in the stratosphere is weak westerly, the annular modes are  
60 coupled with the stratospheric circulation through active wave – mean flow interactions.  
61 During these active seasons, wind variability associated with the annular modes can  
62 modulate Rossby wave propagation into and within the stratosphere, and hence can  
63 modulate the strength of the BDC. On the other hand, increased wave – mean flow  
64 interactions in the stratosphere can affect tropospheric variability reflected as changes in  
65 the annular modes [*Hartmann et al., 2000*]. Previous work on the relationship between  
66 the annular modes and the BDC has focused on their interannual variations. For  
67 example, *Limpasuvan and Hartmann [2000]* and *Hartmann et al. [2000]* found that a  
68 high index of the Northern Annular Mode (NAM) is associated with a poleward shift of  
69 the tropospheric jet and a stronger polar vortex, which decreases the refractive index and  
70 leads to a reduction of the stratospheric wave drag and a weaker BDC. But this  
71 relationship appears to hold only on the interannual timescale [*Hu and Tung, 2002*]. In  
72 the Southern Hemisphere (SH), *Fogt et al. [2009]* found that the spring stratospheric  
73 wave driving is significantly correlated with the summer Southern Annular Mode (SAM),

74 suggesting a close relationship between the BDC and SAM on the intra- and inter- annual  
75 timescale.

76

77 At present, the relationship between the annular modes and the strength of the BDC over  
78 the decadal timescale is poorly understood. The motivation of this paper is the similar  
79 seasonality of the trends in the SAM and the BDC in the late 20<sup>th</sup> century, which suggests  
80 that the long-term trends in the SAM and the BDC could be closely related. The SAM is  
81 the dominant pattern of variability in the SH troposphere, which describes the  
82 fluctuations in geopotential height, temperature, zonal wind, and surface pressure with  
83 opposite signs in high and middle southern latitudes [*Thompson and Wallace, 2000*].  
84 Observational studies have identified a significant trend of the SAM toward its positive  
85 phase (or a high index) during the late 20<sup>th</sup> century, characterized by a strengthening of  
86 the Antarctic polar vortex and a poleward shift of the tropospheric jet with the largest  
87 seasonal trend occurring in the austral summer [*Thompson and Solomon, 2002; Marshall,*  
88 *2003*]. Similar seasonality in the trend of the BDC has been reported in a number of  
89 coupled chemistry-climate model (CCM) investigations [*Butchart et al., 2006; Li et al.,*  
90 *2008*]. *Li et al. [2008]* further showed that this seasonal structure in the BDC trend is  
91 mainly caused by large increases in the SH downwelling during the austral summer. In  
92 addition, previous studies have found that Antarctic ozone depletion has a significant  
93 impact on the seasonality of the trends in the SAM [*Cai and Cowen, 2007; Perlwitz et al.,*  
94 *2008*] and the BDC [*Li et al., 2008; McLandress and Shepherd, 2009; Oman et al.,*  
95 *2009*].

96

97 The purpose of this paper is to investigate whether and how trends in the SAM and the  
98 BDC are related in the austral summer by examining simulations from the Goddard Earth  
99 Observing System (GEOS) CCM. We focus on the BDC-SAM relationship over the  
100 decadal timescale, but we also address their link on the interannual timescale. The model  
101 and simulations used in this paper are described in the next section. Results are presented  
102 in Section 3. Conclusions and discussions are given in Section 4.

103

## 104 **2 Model and Simulations**

105

106 This study uses simulations with version 1 of the GEOSCCM. Details of the model can  
107 be found in *Pawson et al.* [2008]. The model is an extension of the GEOS-4 General  
108 Circulation Model with a comprehensive stratospheric chemistry module. It uses a flux-  
109 form semi-Lagrangian dynamical core and the physics are adapted from the NCAR  
110 CCM3. The stratospheric chemistry module is from the Goddard Chemical Transport  
111 Model [*Dougllass et al.*, 1996]. The model chemistry is coupled with the physical  
112 processes through the radiation code. The model has 55 vertical levels with a top at 0.01  
113 hPa. Simulations used in this study were performed with a horizontal resolution of 2°  
114 latitude by 2.5° longitude.

115

116 For this study, we present results from three simulations of the latter half of the 20<sup>th</sup>  
117 century (1960-2000). The first two experiments P1 and P2 are a two-member ensemble  
118 simulation (with different initial conditions) forced with observed, time-dependent sea  
119 surface temperature and sea ice amounts from HadISST, and the CCMVal REF1 scenario  
120 of GHGs and ozone-depleting substances (ODSs) [*Eyring et al.*, 2005]. The mean of P1

121 and P2 in this study is denoted as P12. The third run C160 is identical to the first two  
122 except that the halogen concentrations are fixed at 1960 levels. The purpose of C160 is to  
123 separate the impacts of GHG and ODS.

124

125 *Eyring et al.* [2006] evaluated simulations of temperature, trace species, and ozone for the  
126 period 1980-1999 from P1 and twelve other CCMs. *Pawson et al.* [2008] assessed  
127 ozone-temperature coupling in P1 and P2. Overall P1 and P2 results agree well with  
128 observations in terms of the stratospheric thermal structure and trace gas distributions.  
129 Long-term stratospheric temperature trend and ozone depletion in P1 and P2 are in  
130 reasonable agreement with observations. As with other CCMs, GEOSCCM has biases.  
131 One that is relevant to this study is that the Antarctic vortex is too persistent [*Pawson et*  
132 *al.*, 2008; *Hurwitz et al.*, 2009]. This will be discussed in Section 4.

133

### 134 **3 Model Results**

135

136 A key factor to understand the relationship between the trends in the BDC and SAM is  
137 their seasonality. This is illustrated by comparing the seasonal structure of trends in the  
138 net SH downward mass flux and the Antarctic geopotential height in the P12 simulations,  
139 which represent the seasonality of trends in the BDC and the SAM, respectively (Fig. 1).  
140 Here and for the rest of this study, the trend is calculated by a linear least-squares  
141 regression. The statistic significance of the trend is calculated using a two-tailed  
142 Student's t-test with the degrees of freedom reduced from a lag-1 autocorrelation of

143 regression residuals [*Santer et al.*, 2000]. The net hemispheric downward mass flux has  
144 been widely used as a measure of the strength of the BDC and is calculated by

145 
$$2\pi \int_{\varphi_t}^{pole} a\rho \cos\varphi \overline{w^*} d\varphi$$

146 where  $\overline{w^*}$  is the residual vertical velocity,  $\rho$  is the density,  $a$  is the Earth's radius, and  $\varphi_t$   
147 is the southern turnaround latitude where the tropical upwelling changes to extratropical  
148 downwelling [*Butchart et al.*, 2006]. The SAM characterizes the seesaw pattern of  
149 geopotential height changes between Antarctica and the middle latitudes, and thus the  
150 seasonal structure of the trend in the Antarctic geopotential height can illustrate the  
151 seasonality of the trend in the SAM [*Thompson and Solomon*, 2002]. Figure 1 shows that  
152 the net SH downward mass flux at 30 hPa (1a) and the Antarctic geopotential height at  
153 850 hPa (1b) have the largest and statistically significant (95% confidence level) trends in  
154 the austral late spring and summer (November - February). The increase in the net SH  
155 downwelling indicates an acceleration of the southern BDC, whereas the falling of the  
156 geopotential height indicates a trend of the SAM toward its positive phase. If we  
157 calculate the trends for the seasonal mean net downward mass flux, then both the summer  
158 (December-February) and winter (June-August) trends are statistically significant, but the  
159 summer trend is about 1/3 larger than the winter trend. Similar seasonal structure in the  
160 net SH downward mass flux is found in other lower stratosphere levels. For the  
161 geopotential height change over the Antarctic troposphere, Figure 1b shows smaller but  
162 statistically significant decreasing trend in April. This seasonal structure in the P12  
163 simulations agrees well with *Thompson and Solomon* [2002] who identified substantial  
164 decreasing trend in the tropospheric geopotential height over Antarctic in the austral  
165 summer and fall using radiosonde data.

166

167 Figure 2a shows the seasonal evolution of the Antarctic geopotential height trend for the  
168 period 1960-2000. In the stratosphere, the geopotential height within the polar cap  
169 decreases from October to May with the largest drop in late spring and early summer  
170 (statistically significant at the 95% confidence level). This large decrease in the  
171 stratospheric geopotential height from November to February is caused by a strong  
172 cooling in the Antarctic lower stratosphere that peaks in November and extends to  
173 February (Fig. 2b, recall that, assuming constant surface pressure, geopotential height

174 represents the vertical integral of temperature  $Z(p) = - \int_{p_{surf}}^p \frac{RT(p)}{g} d \ln p$ ). During

175 November-January, the geopotential height decrease extends from the stratosphere to the  
176 surface (Fig. 2a). These features agree very well with observations [*Thompson and*  
177 *Solomon, 2002*]. The cooling in the Antarctic lower stratosphere also produces a large  
178 westerly shift of the circumpolar flow in the stratosphere that is coupled with an  
179 enhanced westerly flow throughout the troposphere from November to January (Fig. 2c).

180

181 Several observational [*Thompson and Solomon, 2002*] and modeling studies [*Cai and*  
182 *Cowen, 2007; Perlwitz et al., 2008*] have suggested that the large summer SAM trend is  
183 related to Antarctic ozone depletion. Strengthening of the BDC during the austral  
184 summer in the recent past has also been largely attributed to Antarctic ozone depletion  
185 [*Manzini et al., 2003; Li et al., 2008; McLandress and Shepherd, 2008*]. In our  
186 simulations the role of Antarctic ozone depletion in driving trends in the BDC and the  
187 SAM can be clarified by comparing the P12 and C160 results. Again, C160 is same as  
188 P12 except that the halogen loading is fixed at 1960 levels, and therefore has no Antarctic

189 ozone hole. Without ozone depletion there is no significant trend in the 30 hPa net SH  
190 downward mass flux in December-February (Figure 3a) when the P12 simulations show  
191 the largest increase (see Fig. 1a for comparison). The trend in the Antarctic geopotential  
192 height at 850 hPa in Cl60 (Fig. 3b) also has totally different seasonal structures from that  
193 in P12 (see Fig. 1b). The lower tropospheric geopotential height over Antarctica actually  
194 increases (although not statistically significant) in late spring and early summer in Cl60  
195 (also see Fig. 4a), due to GHG-increase induced tropospheric warming (Fig. 4b).  
196 Comparing temperature changes in the Antarctic stratosphere between Cl60 and P12  
197 reveals that the strong lower stratosphere cooling and the significant middle stratosphere  
198 warming is driven by the ozone hole (Figs. 4b and 2b). Figure 4c shows that in Cl60 the  
199 circumpolar flow does not have a significant trend from November to February in the  
200 troposphere and stratosphere, in contrast to the strong westerly accelerations in the P12  
201 simulations. These different changes between the P12 and Cl60 simulations clearly show  
202 that the large summer SAM and BDC trends are driven by Antarctic ozone depletion.

203

204 The connection between Antarctic ozone depletion and the strengthening of the BDC in  
205 the SH is well understood [e.g., *Li et al.*, 2008]. Ozone hole cools the Antarctic lower  
206 stratosphere, increases the meridional temperature gradient in the sub-polar region, and  
207 strengthens the westerly circumpolar flow. As a result, the breakup of the Antarctic polar  
208 vortex is delayed from late spring to early summer. A direct consequence of the delayed  
209 polar vortex breakup is that the stratospheric planetary wave activity emanating from the  
210 troposphere can penetrate higher and stay longer in the stratosphere, causing an  
211 acceleration of the BDC. It should be noted that an underlying assumption of the above

212 argument is that the strengthening of the southern BDC can be accounted for by increases  
213 in the planetary wave forcing. Therefore we first need to verify whether this is indeed the  
214 case in the P12 simulations in order to apply the delayed polar vortex breakup mechanism  
215 to explain the seasonality of the BDC trend.

216

217 Figure 5 compares the evolution of the November-February (NDJF) 30 hPa net SH  
218 downward mass flux and the contributions from model resolved waves and parameterized  
219 gravity waves calculated from the downward control principle [Haynes *et al.*, 1991]. We  
220 choose NDJF because the net SH stratospheric mass flux increase and the lower  
221 tropospheric Antarctic geopotential height drop are largest during this four-month period  
222 (see Fig. 1). Figure 5 shows that the actual net SH mass flux agrees very well with the  
223 wave-driven mass flux from the downward control analysis. Model resolved waves and  
224 parameterized gravity waves account for, respectively, 72% and 28% of the net SH  
225 downward mass flux at 30 hPa, consistent with previous studies [e.g., Butchart *et al.*,  
226 2006]. The long-term and interannual variations of the mass flux driven by EP-flux  
227 divergence are in very good agreement with the actual mass flux with a correlation of  
228 0.97. We conclude that the strengthening of the SH extratropical BDC is mostly due to  
229 increase in the stratospheric planetary wave forcing.

230

231 Figure 5 also shows that the change of the net SH downwelling during NDJF is not a  
232 linear trend. There is an abrupt change around 1980 and the trend for the period 1981-  
233 2000 is much larger than that for the period 1960-1980. We found that the NDJF net SH  
234 downwelling is highly correlated with the October Antarctic total ozone ( $r=0.90$ ) (Fig. 6),

235 which suggests that the strength of the southern summer BDC is strongly affected by the  
236 severity of Antarctic ozone depletion. Similar temporal structures are also found in the  
237 evolution of the Antarctic geopotential height during NDJF in both the troposphere and  
238 the stratosphere (Fig. 6). The time series of the 30 hPa and 850 hPa geopotential height  
239 are highly correlated with each other ( $r=0.78$ ), and they are both strongly correlated with  
240 the October Antarctic total ozone ( $r=0.89$  and  $0.59$ , respectively) and the 30 hPa net SH  
241 downward mass flux ( $r=0.78$  and  $0.62$ , respectively). *Thompson and Solomon* [2002]  
242 identified strong correlations between Antarctic ozone depletion and the falling of the  
243 tropospheric and stratospheric geopotential height in the southern high latitudes using  
244 observational data and argued that these correlations suggest a significant impact of the  
245 ozone hole on the SAM trend. Our P12 results support their argument and also reveal a  
246 possible linkage between the BDC and SAM through their close connection with the  
247 Antarctic ozone hole.

248

249 The relationship between the changes in the southern extratropical BDC and SAM in the  
250 P12 simulations is investigated by comparing the trend of the residual circulation with the  
251 regression (or covariance) of the residual circulation on the SAM index. We follow the  
252 method of *Thompson et al.* [2000] to define the SAM as the first empirical orthogonal  
253 function (EOF) of the 850 hPa geopotential height southward of  $20^{\circ}\text{S}$ . The EOFs are  
254 calculated using NDJF mean time series for the period 1981-2000 and the standardized  
255 leading principal component time series are used as the SAM index. The calculated  
256 SAM index using this method is very similar to the inverted 850 hPa Antarctic  
257 geopotential height (see Fig. 6). Results presented in the following are not sensitive to

258 the definition of the SAM pattern and index. For example, we can use the circumpolar  
259 upper tropospheric zonal wind as the SAM index and obtain the same results. We focus  
260 on the 20-year period 1981-2000 because changes in the BDC and SAM are much larger  
261 than those in the period 1960-1980 (Fig. 6).

262

263 The linear trend of the residual vertical velocity in NDJF between 1981 and 2000 in P12  
264 is shown in Fig. 7a as a function of latitude and pressure. In the stratosphere, trend in the  
265 residual vertical velocity demonstrates an accelerated BDC with enhanced downwelling  
266 in the southern high latitudes (dashed contours) and increased upwelling in the mid-  
267 latitudes (solid contours). Very similar spatial patterns are found in the SAM regression  
268 map (Fig. 7b), showing that an anomalously strong BDC is associated with a high index  
269 of the SAM. The nearly identical patterns in Figs. 7a-b illustrate that the long-term  
270 change of the strengthening of the BDC is highly projected onto the trend of SAM toward  
271 its high index. The trend in the residual vertical velocity that is linearly congruent with  
272 the SAM index, obtained by multiplying the covariance with the linear trend of the SAM  
273 index, can be used to quantify the relationship between trends in BDC and SAM  
274 [Thompson and Solomon, 2002]. The SAM index has a linear trend of 0.90/decade for  
275 the period 1981-2000 in the P12 simulations, thus it can be inferred that more than 80%  
276 of increases in the Antarctic downwelling and mid-latitude upwelling are linearly  
277 congruent to the SAM index. Furthermore, almost all the tropospheric trend in the  
278 residual vertical velocity is linearly projected onto the SAM.

279

280 Although the BDC does not show a significant linear trend in NDJF in Cl60 (Fig. 3a), it  
281 is still worthy to examine whether the interannual variations of the BDC are related to  
282 those of SAM in Cl60. Figure 8a shows that the linear trend in the stratospheric residual  
283 vertical velocity is not statistically significant and does not resemble the SAM regression  
284 map. However, the SAM index regression map in Cl60 (Fig. 8b) has a nearly identical  
285 pattern to that for P12 (Fig. 7b). The magnitude of the regression coefficients is smaller  
286 in Cl60 than in P12, because the trends of the BDC and SAM in P12 yield larger  
287 covariance. When the covariance between the residual vertical velocity and the SAM in  
288 P12 is calculated using detrended data, the resulting regression coefficients have nearly  
289 the same magnitude as those in Cl60 (figure not shown). The similar regression patterns  
290 in P12 and Cl60 illustrate that, regardless of ozone depletion, a high SAM index is  
291 associated with anomalously strong polar downwelling and mid-latitude upwelling in  
292 austral summer on the interannual timescale. Without ozone depletion, this relationship  
293 only holds as year-to-year variability in Cl60. The impact of the Antarctic ozone hole is  
294 to drive a long-term trend in the BDC that is strongly congruent with the year-to-year  
295 SAM variations.

296

297 In order to understand why trends in the southern BDC are strongly reflected in the SAM  
298 index in the P12 simulations, we need to find out the cause for the acceleration of the  
299 BDC and its connection with the SAM. We have already shown in Fig. 5 that the  
300 strengthening of the BDC in the austral summer is mostly due to increase in the  
301 stratospheric planetary wave driving. Thus the question is how the enhanced planetary  
302 wave driving is related to the SAM. To answer this question, we examine the linear

303 trends in the NDJF zonal mean temperature, zonal wind, eddy momentum and heat flux  
304 between 1981 and 2000 and their SAM regression maps (Fig. 9). Temperature changes  
305 in the summer Antarctic stratosphere are marked by a vertical dipole structure (Fig. 9a)  
306 that has been reported in many model simulations [e.g., *Mahlman et al.*, 1994] and has  
307 been confirmed in radiosonde and reanalysis data [*Randel and Wu*, 1999]. The strong  
308 Antarctic lower stratospheric cooling increases the meridional temperature gradient and  
309 enhances the stratospheric westerlies over the high latitudes (Fig. 9b). In NDJF, a  
310 westerly shift of the SH stratospheric flow indicates a delay of the polar vortex breakup,  
311 which prolongs the period of weak westerlies in the lower stratosphere and increases the  
312 upward propagation of planetary wave activity into the stratosphere. This is illustrated in  
313 Fig. 9c showing a large increase in negative northward meridional eddy heat flux (an  
314 approximation of the vertical component of the EP flux) in the stratosphere poleward of  
315 about 50°S, which increases westward momentum deposition and strengthens the BDC.  
316 The westerly accelerations of the zonal wind in the SH high latitude stratosphere is  
317 coupled with increased westerlies in the troposphere centered at 60°S (Fig. 9b). The  
318 tropospheric zonal wind trend is characterized by a dipole structure, indicating a  
319 poleward shift of the tropospheric jet. This poleward shift is maintained by a similar  
320 displacement of the eddy meridional flux of zonal momentum in the upper troposphere  
321 (Fig. 9d).

322

323 The SAM regression maps of the temperature, zonal wind, and eddy heat and momentum  
324 flux are presented in Figs. 9e-h. Nearly identical patterns are found between the  
325 regression maps and the linear trends, indicating that trends in the tropospheric and

326 stratospheric circulations and wave activities are strongly projected onto the positive  
327 phase of the SAM. Multiplying the regression maps with the linear trend in the SAM  
328 index and comparing, we found that nearly all trends in the troposphere are congruent  
329 with the SAM index. More important for the purpose of this study, most of the  
330 stratospheric trends (about 80%) are congruent with the SAM index.

331

332 Figures 10a-d show that the in the C160 simulation that does not include ozone depletion,  
333 linear trends of the NDJF zonal wind, and eddy momentum and heat flux are not  
334 statistically significant. Although C160 simulates statistically significant temperature  
335 changes due to GHG increase, it does not reproduce the strong Antarctic lower  
336 stratosphere cooling and middle stratosphere warming. Comparing with the P12 results  
337 (Figs. 9a-d) clearly demonstrates that the trends in the P12 simulations are driven by the  
338 ozone hole. However, the SAM regression maps in C160 are very similar to those in P12,  
339 but with smaller covariance (Figs. 10 e-h). When we remove the trends in the P12 results  
340 and calculate the regression, we find that the regression coefficients have nearly the same  
341 magnitude in P12 and C160. This similarity indicates that the relationship between  
342 interannual variations of the summer stratospheric circulation and SAM are robust, with  
343 or without ozone depletion.

344

345 Our model simulated austral summer circulation changes and the SAM regression maps  
346 are in broad agreement with those calculated using the National Centers for  
347 Environmental Prediction (NCEP) Reanalysis 2 data. Figure 11 shows that the major  
348 features of the SH summer climate change agree qualitatively very well between the

349 NCEP Reanalysis and the P12 runs, including the Antarctic lower stratospheric cooling,  
350 the strengthened circumpolar flow, and the enhanced stratospheric wave flux. There are  
351 no direct observations of the BDC (or the residual vertical velocity), but the increases of  
352 eddy heat flux in the mid-high latitude stratosphere in the NCEP Reanalysis (Fig. 11c)  
353 support the modeled strengthening of the BDC. Figure 11 also shows that the trends  
354 resemble the regressions onto the SAM index, supportive of the BDC-SAM relationship  
355 in our model simulations. However, GEOSCCM over-predicts the trends and the  
356 covariances with the SAM index. In the next section, we discuss why the BDC-SAM  
357 relationship is amplified in the simulations.

358

359 The above analyses suggest that the key to understand the BDC-SAM relationship in the  
360 austral summer is to link the circumpolar westerly anomalies and enhanced wave activity  
361 in the stratosphere to a high index of the tropospheric SAM. There is growing  
362 observational evidence that such stratospheric anomalies induce tropospheric variability  
363 reflected as a positive phase of the annular modes [e.g., *Baldwin et al.*, 2003; *Thompson*  
364 *et al.*, 2005; *Fogt et al.*, 2009]. Therefore a possible mechanism to explain the link  
365 between the ozone hole, the strengthening of the BDC, and the SAM trend is this: the  
366 ozone hole increases the stratospheric wave driving and strengthens the BDC through a  
367 delayed vortex breakup, which in turn forces a SAM trend toward its high index. One  
368 way to test this hypothesis is to remove the SAM variability that is linear congruent with  
369 the stratospheric wave driving, and check the relationship between the SAM residual and  
370 the ozone hole. If the SAM residual is correlated with the ozone hole and has a  
371 significant trend, this would suggest that other processes in addition to stratospheric wave

372 driving are involved in linking the ozone hole with the tropospheric SAM trend. We  
373 found that after removing the part of SAM index that is congruent with the NDJF 30 hPa  
374 mass flux, the SAM index residual does not have a statistically significant trend and is  
375 not significantly correlated with the October total column ozone ( $r = -0.14$  after removal  
376 of trends) for the 1960-2000 period in the P12 runs (similar results are obtained for the  
377 period 1981-2000 with  $r = -0.20$ ). In comparison, as can be inferred from Figure 6, the  
378 NDJF SAM index is highly correlated with October total ozone ( $r = -0.52$  after removal  
379 of trends) and has a statistically significant trend. These results appear to support our  
380 hypothesis that Antarctic ozone depletion forces a summer tropospheric SAM trend  
381 almost entirely through changes in stratospheric wave driving.

382

#### 383 **4 Discussion and Conclusions**

384

385 The relationship between the BDC and the SAM in the austral summer is investigated  
386 with GEOSCCM simulations. In P12 that simulates ozone depletion, the southern BDC  
387 accelerates and the SAM has a trend toward its positive phase during NDJF in the latter  
388 half of the 20<sup>th</sup> century, and the strengthening of the BDC is strongly projected onto the  
389 high index of the SAM. In contrast, in C160 that does not simulate ozone depletion,  
390 neither the SAM nor the BDC has a significant trend during NDJF. These model results  
391 clearly demonstrate that Antarctic ozone depletion drives the BDC-SAM relationship on  
392 the decadal timescale. We suggest that the ozone-hole induced delay of the Antarctic  
393 vortex breakup is the key to link the strengthening of the BDC with the SAM during the  
394 austral summer. The delayed onset of easterlies in the Antarctic lower stratosphere

395 prolongs the period for dynamical stratosphere-troposphere interactions. A direct  
396 consequence of the persistent stratospheric westerlies is to strengthen the summer BDC  
397 by allowing more tropospheric planetary wave activity entering the stratosphere, as  
398 shown in Figs. 9 and 11. On the other hand, the enhanced stratospheric wave driving  
399 forces a SAM trend toward its high index. In summary, the BDC-SAM relationship is a  
400 result of increased stratosphere-troposphere coupling driven by ozone depletion.

401

402 Although the Cl60 simulation does not produce statistically significant trends in the BDC  
403 and the SAM during NDJF, it reproduces the same interannual relationship between the  
404 BDC and the SAM as that in the P12 simulations. And now the question is what drives  
405 the year-to-year variability of the summer SAM and BDC. *Fogt et al.* [2009]  
406 investigated intra-annual relationships between the Antarctic total column ozone, the  
407 SAM, and the stratospheric wave activity in the latter half of the 20<sup>th</sup> century using  
408 observations and the same GEOSCCM simulations analyzed in this study. They found  
409 that, in addition to the well-known negative correlation between the spring Antarctic  
410 ozone and the summer SAM, the spring stratospheric wave driving also plays an  
411 important role in determining the interannual variability of the summer SAM. The results  
412 of *Fogt et al.* [2009] suggest, based on the positive correlation between the summer SAM  
413 and BDC identified in this study, that the stratospheric wave activity (or BDC) in spring  
414 could significantly affect the wave activity in summer, and is important in driving the  
415 interannual BDC-SAM relationship. This is confirmed by the high negative correlation  
416 between the early spring BDC and the summer SAM ( $r = -0.56$  between October 30 hPa  
417 SH mass flux and the NDJF SAM index), and between the early spring BDC and late

418 spring/early summer BDC ( $r = -0.55$  between October and December/January 30 hPa mss  
419 flux) in the P12 simulations (correlation is calculated after removal of linear trends).

420

421 We suggest that the mechanism by which the spring stratospheric wave activity affects  
422 the interannual variability of the summer BDC and SAM is the same as that explaining  
423 how ozone depletion drives the decadal variations of the summer BDC and SAM, i.e.,  
424 through its impact on the persistence of the Antarctic vortex leading to changes in  
425 stratosphere-troposphere coupling. *Hurwitz et al.* [2009] showed that the Antarctic polar  
426 vortex breakup date is highly correlated with the spring stratospheric wave driving in the  
427 NCEP and ERA40 reanalysis data and in the simulations with a newer version of  
428 GEOSCCM. This relationship results from a 1-month lag correlation between the mid-  
429 latitude wave driving and the polar stratospheric temperature [e.g., *Austin et al.*, 2003].  
430 Anomalously weak eddy heat flux in early-middle spring leads to an anomalously cold  
431 polar stratosphere in late spring and a delayed vortex breakup, which extends the period  
432 of active stratosphere-troposphere dynamical coupling and causes a stronger summer  
433 BDC and SAM. However, it should be emphasized that the decadal trends of the summer  
434 BDC and SAM cannot be attributed to long-term changes in spring stratospheric wave  
435 driving. In the P12 simulations the BDC in October does not have a statistically  
436 significant trend (Fig. 1a). *Waugh et al.* [1999] found that in the NCEP reanalysis data  
437 the SH eddy heat flux at 100 hPa in early spring increases from 1979 to 1998, which  
438 cannot explain the prolonged persistence of the Antarctic vortex during this period.

439

440 It is interesting to compare the interannual BDC-SAM relationship identified in this paper  
441 to the BDC-NAM relationship reported in previous studies. *Limpasuvan and Hartmann*  
442 [2000] and *Hartmann et al.* [2000] found that a higher NAM index is associated with a  
443 weaker stratospheric wave driving, and hence a weaker BDC, in the NH high latitudes  
444 during the NH winter. This is opposite to the positive correlation between the BDC and  
445 SAM during the austral summer. The different relationships between the BDC and the  
446 annular modes in the NH and SH are due to the different seasonality of the SAM and  
447 NAM. The NAM is actively coupled with the stratosphere circulation in winter, whereas  
448 the SAM's active season is in late spring [*Thompson and Wallace, 2000*]. In the NH  
449 winter a high NAM index is associated with a stronger Arctic vortex and stronger  
450 circumpolar westerlies which decrease the refractive index and reduce wave activity  
451 entering polar stratosphere [*Limpasuvan and Hartmann, 2000; Hu and Tung, 2002*]. But  
452 in the SH summer a high SAM index is associated with a colder Antarctic lower  
453 stratosphere, which delays the breakdown of the Antarctic vortex and strengthens the  
454 BDC. From the above argument one expects that the BDC-SAM relationship would  
455 reverse during the austral winter, and this is confirmed in the GEOSCCM simulations  
456 (figure not shown).

457

458 There are no direct observations of the BDC, and hence the modeled BDC-SAM  
459 relationship could not be directly verified. *Stolarski et al.* [2006] found indirect evidence  
460 of a strengthened BDC from the observed ozone increase just above the ozone hole in the  
461 austral summer in satellite measurements, which supports our findings. More  
462 importantly, that the ozone-hole causes a delayed Antarctic vortex breakup leading to

463 increases in stratospheric wave flux, which is the key to understand the BDC-SAM  
464 relationship, is reasonable represented in the model simulations compared with the NCEP  
465 Reanalysis data. However, it is also apparent that the model over-predicts the BDC-SAM  
466 relationship and the austral summer climate change.

467

468 As briefly mentioned in Section 2, GEOSCCM has a “cold pole” bias in the spring  
469 Antarctic stratosphere, a common problem in middle atmosphere models [Eyring *et al.*,  
470 2006]. Because of the cold bias, the modeled Antarctic vortex is too persistent and  
471 breaks up about two weeks later than observed [Hurwitz *et al.*, 2009]. Fogt *et al.* [2009]  
472 found that, as a consequence of the later than observed Antarctic vortex breakup,  
473 GEOSCCM amplifies troposphere-stratosphere coupling and SAM persistence, and  
474 hence over-predicts the spring ozone – summer SAM relationship. These model  
475 deficiencies have important implications for the simulated BDC-SAM relationship  
476 reported in this study, because this relationship is driven by stratosphere-troposphere  
477 coupling. Therefore, while the simulated BDC-SAM relationship qualitatively agrees  
478 with the reanalysis data, this relationship is amplified in our model simulations. More  
479 generally, results presented here and those in Fogt *et al.* [2009] and Hurwitz *et al.* [2009]  
480 indicate that a too persistent model Antarctic vortex leads to over-predictions of the  
481 impacts of the ozone hole on the austral summer climate change in the late 20<sup>th</sup> century,  
482 which also implies that the model would unrealistically amplify the ozone recovery  
483 effects on climate change in the 21<sup>st</sup> century as well. Therefore, as pointed out by Fogt *et*  
484 *al.* [2009] and Hurwitz *et al.* [2009], improving the model presentation of the persistence

485 of Antarctic vortex is critical to correctly predict the interactions between ozone  
486 depletion, ozone recovery, and climate change in the troposphere and stratosphere.

487

488 Finally, the mechanism by which increased stratospheric wave activity drives a SAM  
489 trend, or more generally the mechanism for the stratospheric variability to affect the  
490 tropospheric circulation, is not clear. Currently there exist several hypotheses, including  
491 downward propagation of wind anomalies driven by eddy-mean flow interactions  
492 [*Christiansen, 2001*], amplification of tropospheric response to lower stratospheric wind  
493 anomalies [*Song and Robinson, 2004*], and increases of tropospheric eddy phase speed  
494 leading to a poleward displacement of the subtropical wave breaking zone [*Chen and*  
495 *Held, 2007*]. There is growing evidence that the stratosphere has impacts on the  
496 troposphere and understanding its dynamical mechanism is certainly an important  
497 research issue.

498

499

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640

640 **Figure Captions**

641

642 Figure 1: Seasonal cycle of linear trends in the period 1960-2000 for (a) 30 hPa net SH  
643 downward mass flux, and (b) 850 hPa Antarctic (65°S-90°S) geopotential height in the  
644 P12 simulations. Shading indicates that trends are statistically significant at the 95%  
645 confidence level.

646

647 Figure 2: Linear trends plotted as function of month and pressure in (a) Antarctic  
648 geopotential height (65°S-90°S), (b) Antarctic temperature (65°S-90°S), and (c)  
649 circumpolar zonal wind (55°S-70°S) in the P12 simulations. Shading indicates that trends  
650 are statistically significant at the 95% confidence level.

651

652 Figure 3: Same as Fig. 1, but for the Cl60 simulation.

653

654 Figure 4: Same as Fig. 2, but for the Cl60 simulation.

655

656 Figure 5: Time series of the NDJF mean net SH downward mass flux at 30 hPa (black).  
657 The red and blue lines are the wave-driven mass fluxes calculated from the downward  
658 control principle. The red lines show the results from model resolved waves (EP-flux  
659 divergence) only. The blue lines show the results including both resolved waves and  
660 parameterized gravity waves. The thick curves are 7-year running average mean.

661

662 Figure 6: Time series of (upper panel) October Antarctic total ozone; (middle panel) the  
663 negative of the NDJF mean net SH mass flux at 30 hPa; and (lower panel) NDJF mean  
664 geopotential height at 30 hPa (green, left axis) and 850 hPa (blue, right axis). Thick  
665 curves are 7-year running average mean.

666

667 Figure 7: (a) Linear trends of the NDJF residual vertical velocity in the period 1981-2000  
668 as a function of latitude and pressure. Shading denotes that trends are significantly  
669 different from zero at the 95% confidence level. (b) NDJF residual vertical velocity  
670 regressed on the standardized SAM index.

671

672 Figure 8: Same as Fig. 7, but for the Cl60 simulation.

673

674 Figure 9: Upper panels show linear trends for the period 1981-2000 as a function of  
675 latitude and pressure for the NDJF mean (a) temperature (K/decade), (b) zonal wind ( $\text{ms}^{-1}$ /  
676 decade), (c) northward meridional eddy heat flux ( $\text{Kms}^{-1}$ /decade), and (d) meridional  
677 eddy flux of zonal momentum ( $\text{m}^2\text{s}^{-2}$ /decade) in the P12 simulations. Shading denotes  
678 the 95% confidence level. Lower panels are the SAM regression maps for the NDJF  
679 mean (e) temperature (K/std SAM), (f) zonal wind ( $\text{ms}^{-1}$ /std SAM), (g) eddy heat flux  
680 ( $\text{Kms}^{-1}$ /std SAM), and (h) eddy momentum flux ( $\text{m}^2\text{s}^{-2}$ /std SAM).

681

682 Figure 10: Same as Fig. 9, but for the Cl60 simulation.

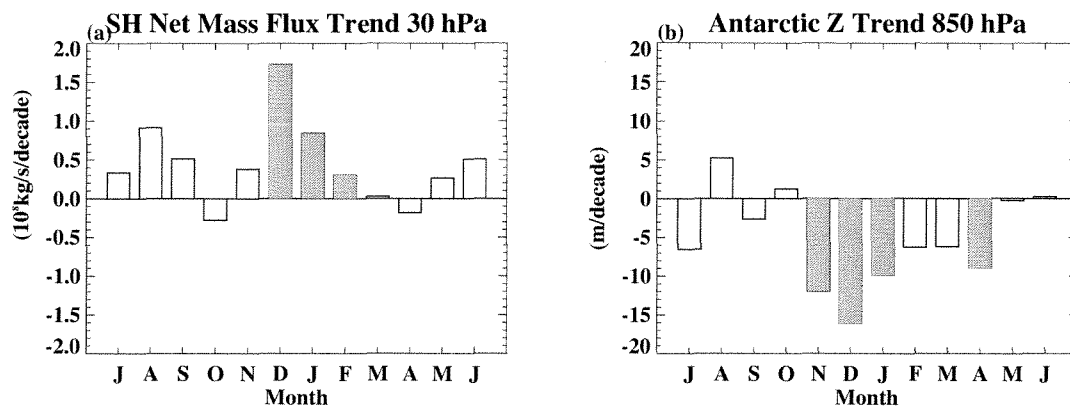
683

684 Figure 11: Same as Fig. 9 but calculated from the NCEP Reanalysis 2 data. The dark and  
685 light shadings denote 95% and 90% confidence levels, respectively. Note that the NCEP  
686 data are only available below 10 hPa.

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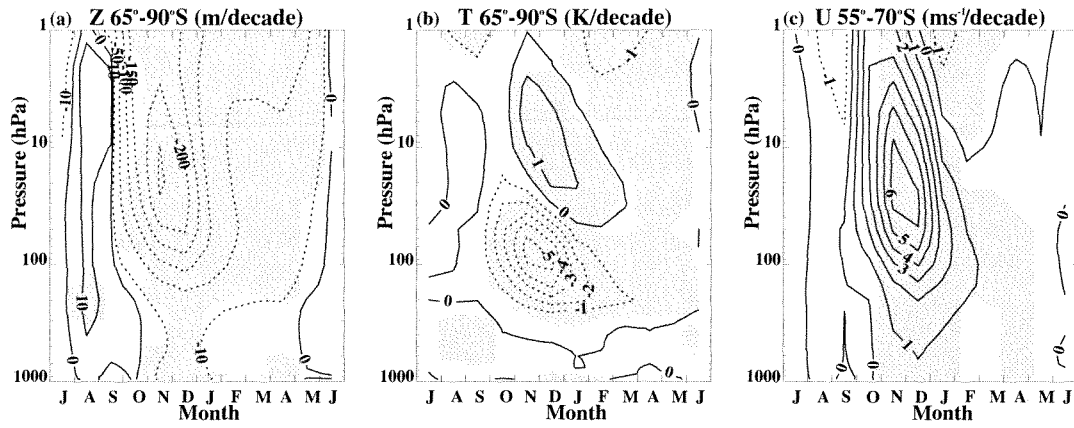
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694 confidence level.

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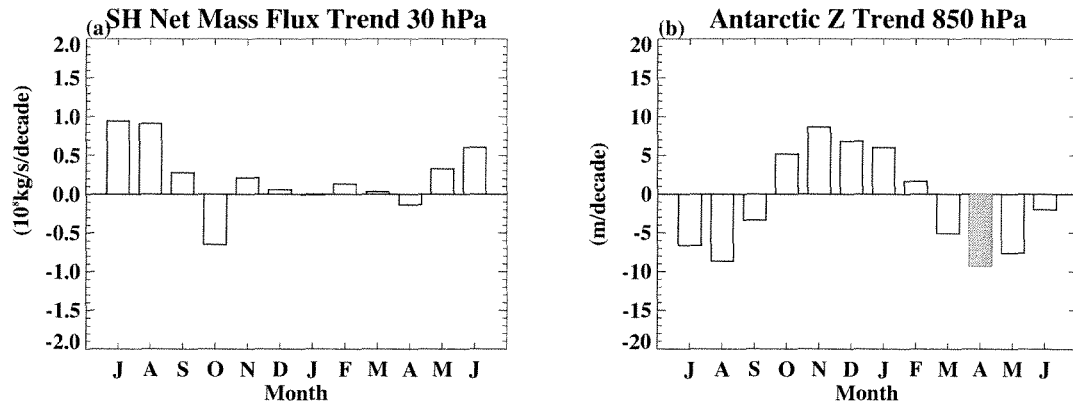
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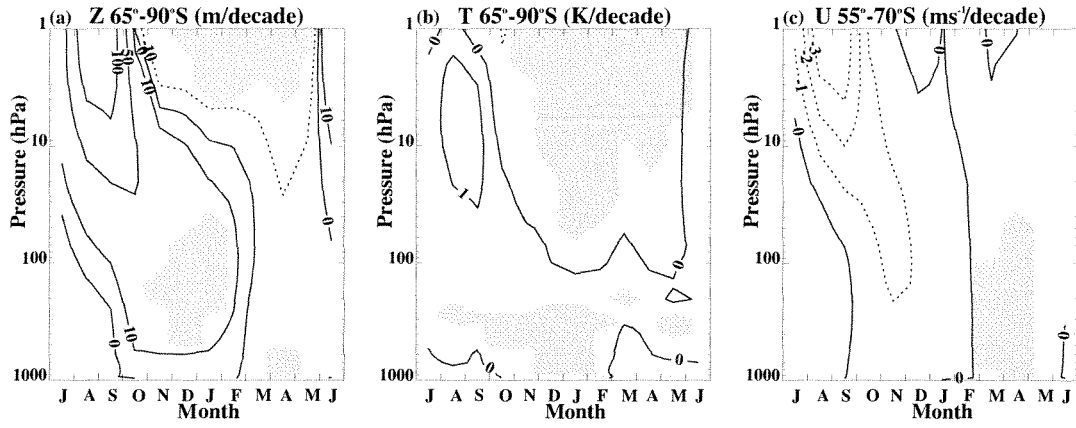
708

709 Figure 3: Same as Fig. 1, but for the Cl60 simulation.

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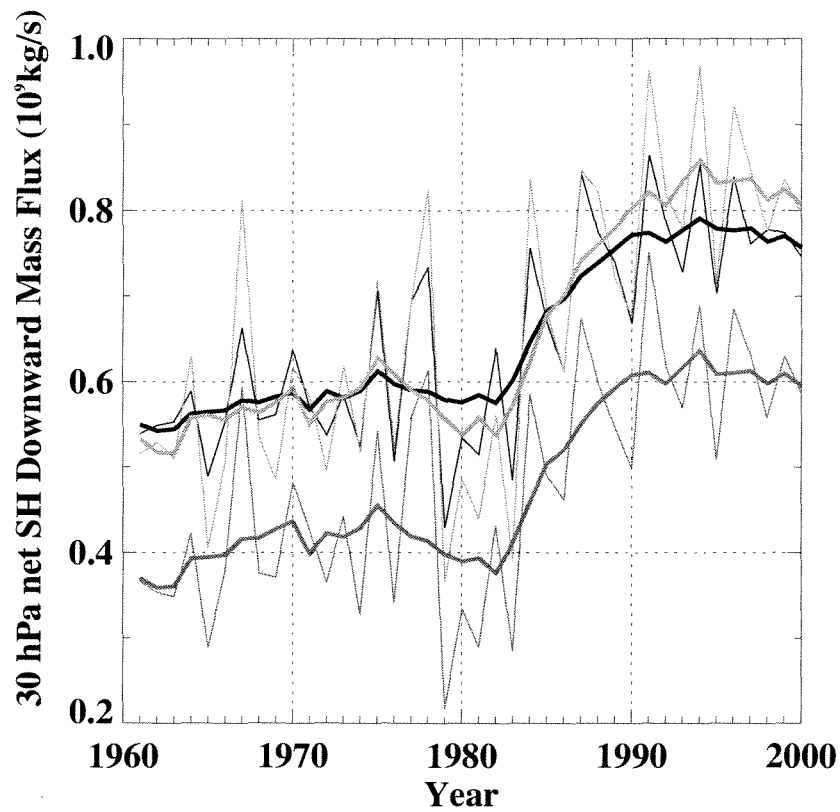
713

714 Figure 4: Same as Fig. 2, but for the CI60 simulation.

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720 Figure 5: Time series of the NDJF mean net SH downward mass flux at 30 hPa (black).

721 The red and blue lines are the wave-driven mass fluxes calculated from the downward

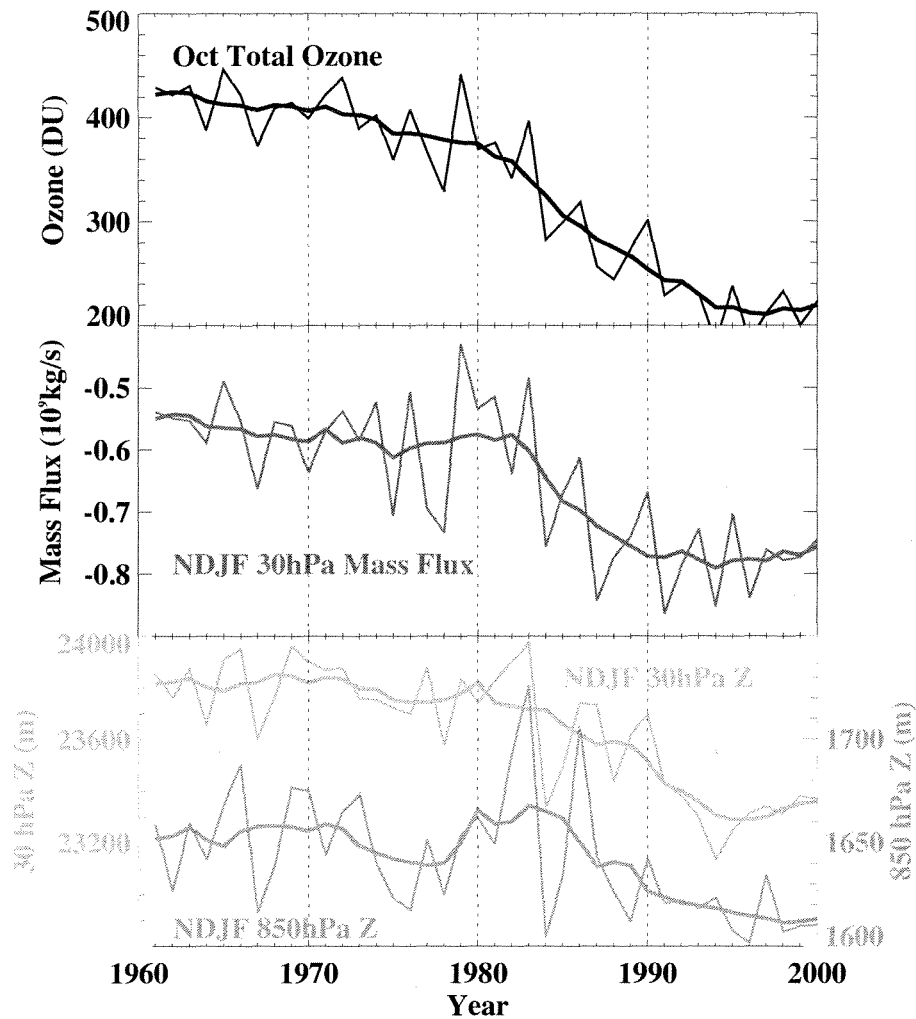
722 control principle. The red lines show the results from model resolved waves (EP-flux

723 divergence) only. The blue lines show the results including both resolved waves and

724 parameterized gravity waves. The thick curves are 7-year running average mean.

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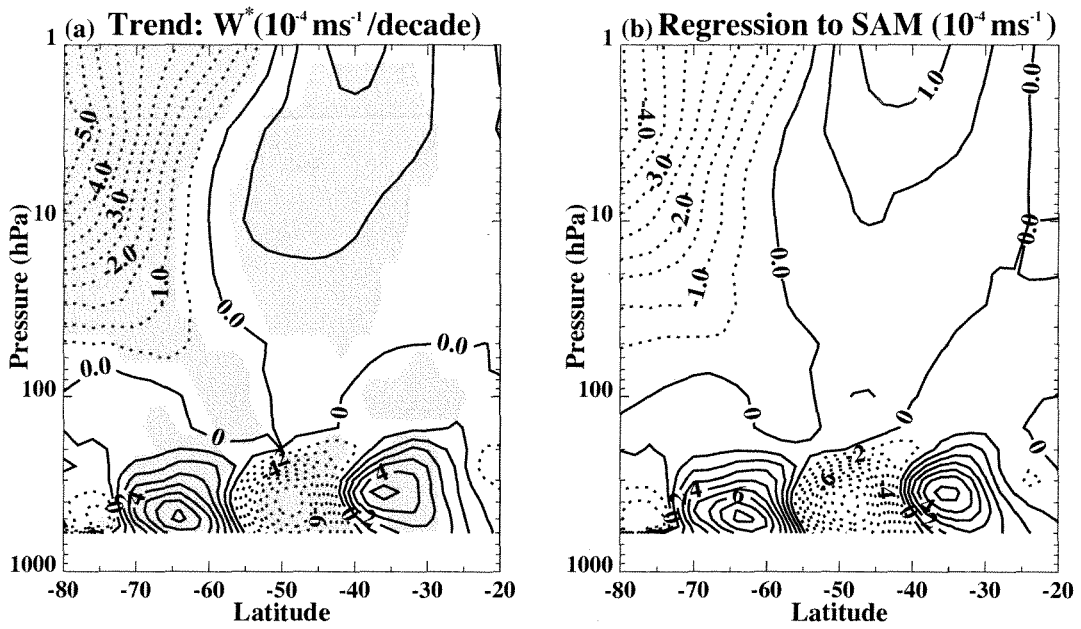
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729 Figure 6: Time series of (upper panel) October Antarctic total ozone; (middle panel) the  
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 732 curves are 7-year running average mean.

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737 Figure 7: (a) Linear trends of the NDJF residual vertical velocity in the period 1981-2000

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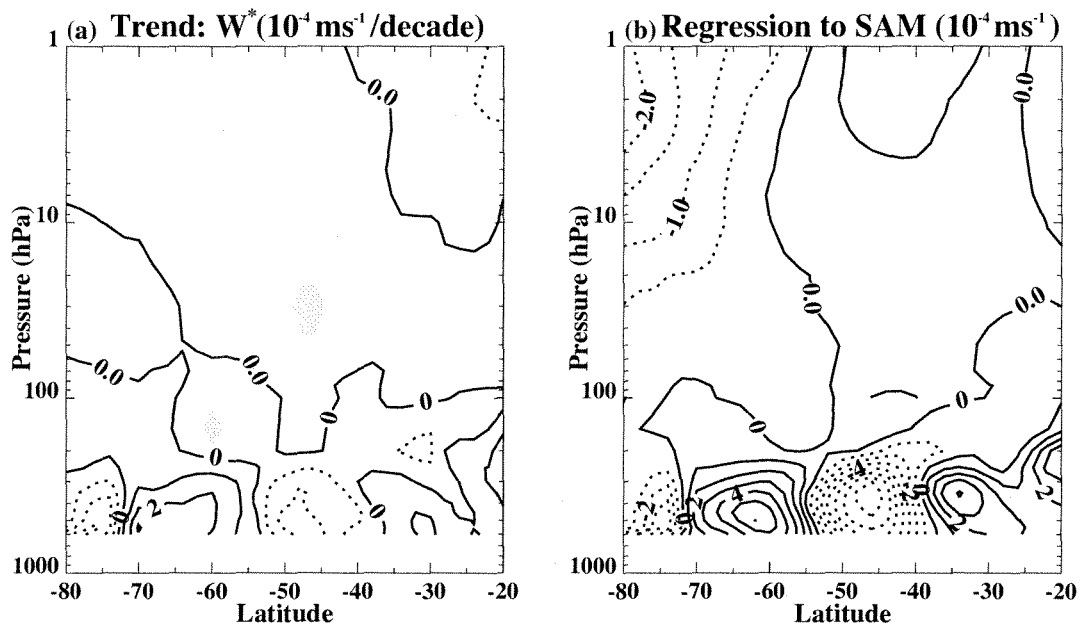
739 different from zero at the 95% confidence level. (b) NDJF residual vertical velocity

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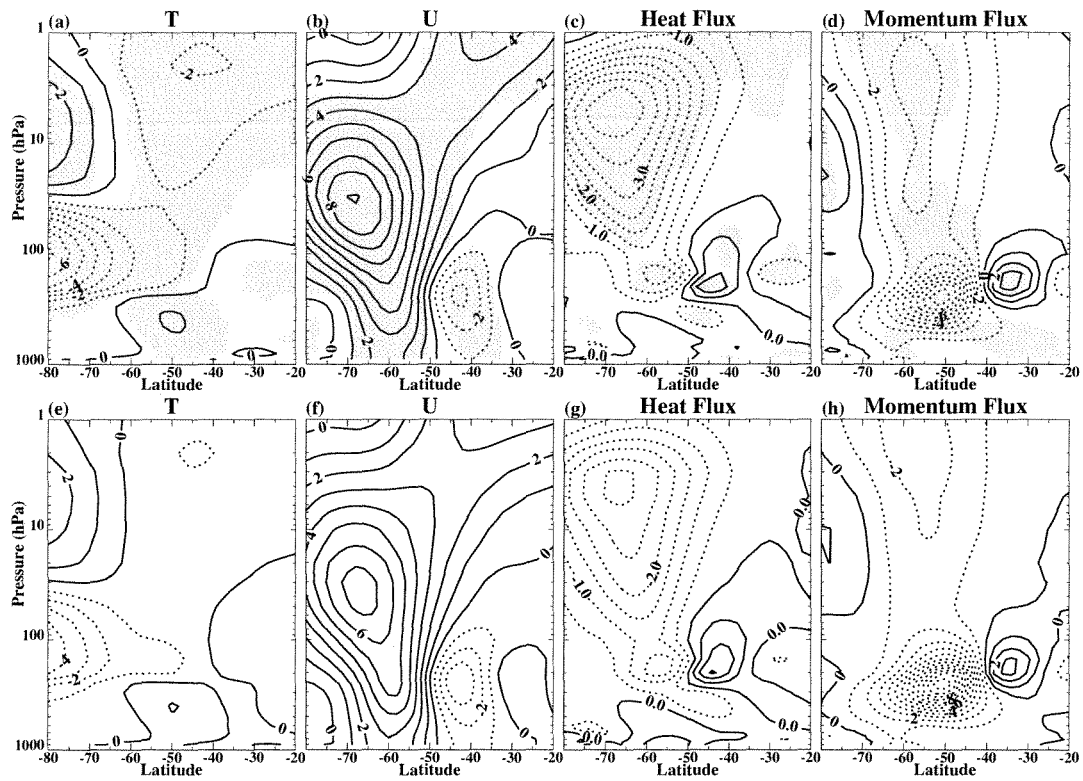
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745 Figure 8: Same as Fig. 7, but for the CI60 simulation.

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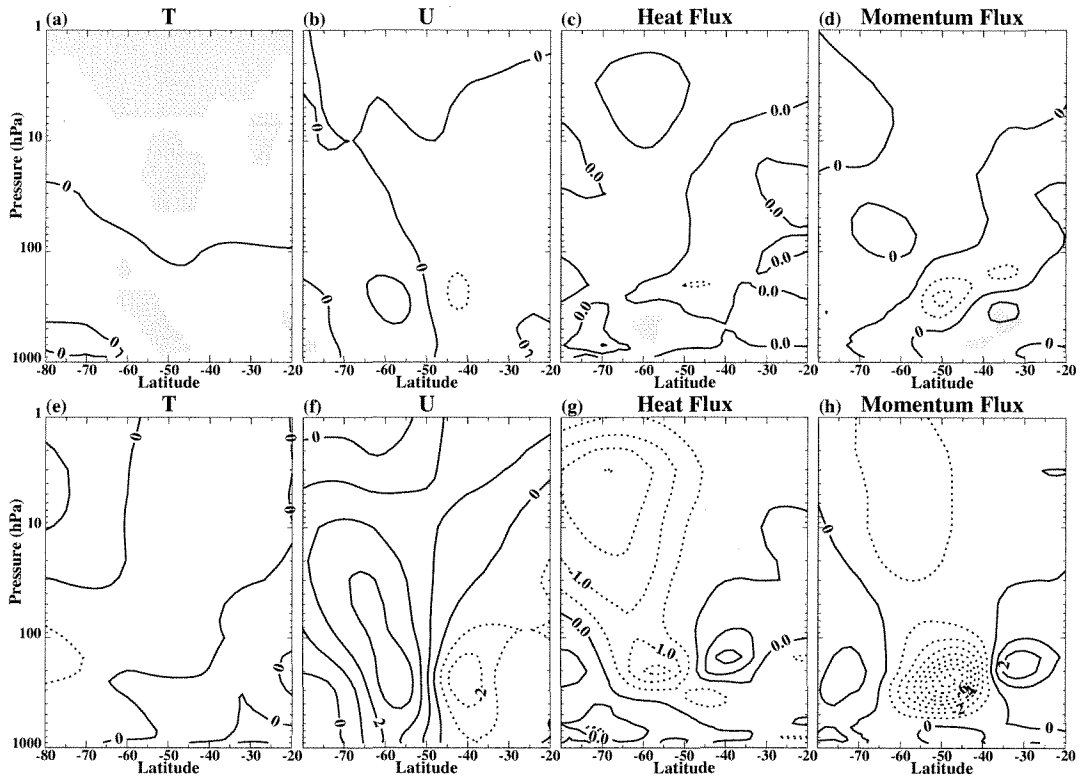
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750 Figure 9: Upper panels show linear trends for the period 1981-2000 as a function of  
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756 ( $\text{Kms}^{-1}$ /std SAM), and (h) eddy momentum flux ( $\text{m}^2\text{s}^{-2}$ /std SAM).

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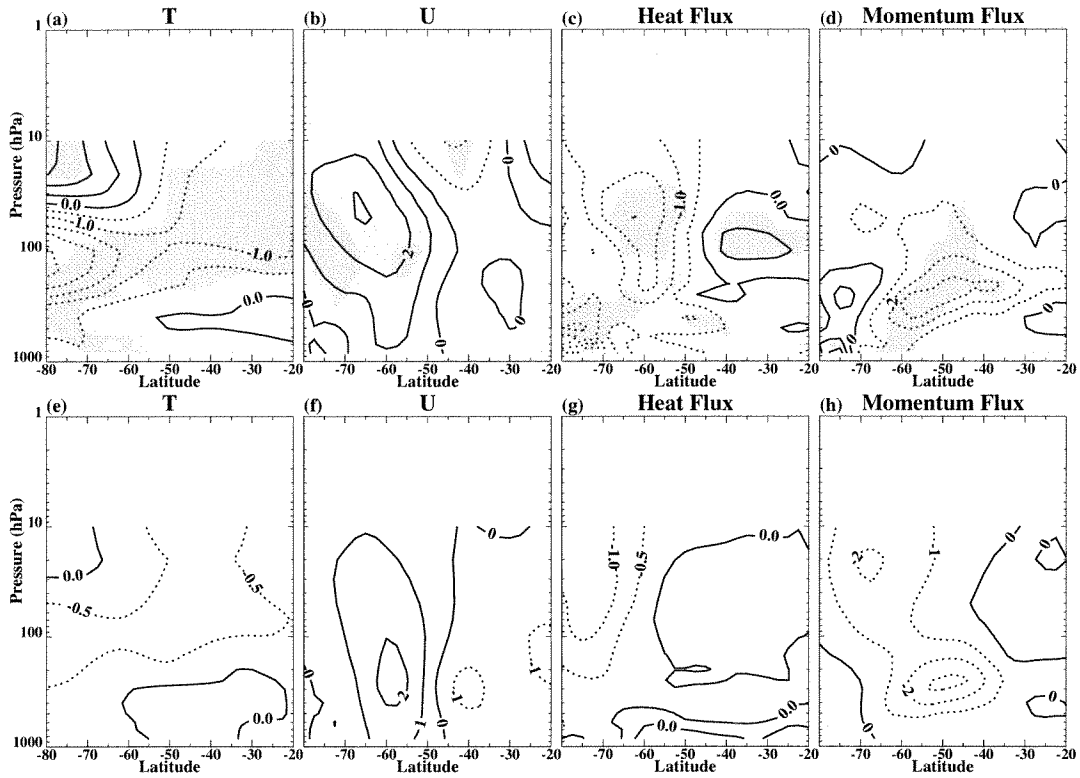
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761 Figure 10: Same as Fig. 9, but for the Cl60 simulation.

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766 Figure 11: Same as Fig. 9 but calculated from the NCEP Reanalysis 2 data. The dark and  
767 light shadings denote 95% and 90% confidence levels, respectively. Note that the NCEP  
768 data are only available below 10 hPa.