

## Seasonal Variations of Stratospheric Age Spectra in GEOSCCM

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### Popular Summary

There are many pathways for an air parcel to travel from the troposphere to the stratosphere, each of which takes different time. The distribution of all the possible transient times, i.e. the stratospheric age spectrum, contains important information on transport characteristics. However, it is computationally very expensive to compute seasonally varying age spectra, and previous studies have focused mainly on the annual mean properties of the age spectra. To date our knowledge of the seasonality of the stratospheric age spectra is very limited.

In this study we investigate the seasonal variations of the stratospheric age spectra in the Goddard Earth Observing System Chemistry Climate Model (GEOSCCM). We introduce a method to significantly reduce the computational cost for calculating seasonally dependent age spectra. Our simulations show that stratospheric age spectra in GEOSCCM have strong seasonal cycles and the seasonal cycles change with latitude and height. In the lower stratosphere extratropics, the average transit times and the most probable transit times in the winter/early spring spectra are more than twice as old as those in the summer/early fall spectra. But the seasonal cycle in the subtropical lower stratosphere is nearly out of phase with that in the extratropics. In the middle and upper stratosphere, significant seasonal variations occur in the subtropics. The spectral shapes also show dramatic seasonal change, especially at high latitudes. These seasonal variations reflect the seasonal evolution of the slow Brewer-Dobson circulation (with timescale of years) and the fast isentropic mixing (with timescale of days to months).

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12

## Abstract

12

13

14 The stratospheric age spectrum is the probability distribution function of the transit times  
15 since a stratospheric air parcel had last contact with a tropospheric boundary region.  
16 Previous age spectrum studies have focused on its annual mean properties. Knowledge  
17 of the age spectrum's seasonal variability is very limited. In this study, we investigate  
18 the seasonal variations of the stratospheric age spectra using the pulse tracer method in  
19 the Goddard Earth Observing System Chemistry Climate Model (GEOSCCM). The  
20 relationships between the age spectrum (also called Transit-Time Distribution, or TTD)  
21 and the Boundary Impulse Response (BIR) are reviewed and a simplified method to  
22 reconstruct seasonally varying age spectra is introduced. The age spectra in GEOSCCM  
23 have strong seasonal cycles, especially in the lowermost and lower stratosphere and the  
24 subtropical overworld. These changes reflect the seasonal evolution of the Brewer-  
25 Dobson circulation, isentropic mixing, and transport barriers. We also investigate the  
26 seasonal and interannual variations of the BIRs. Our results clearly show that computing  
27 an ensemble of seasonally dependent BIRs is necessary in order to capture the seasonal  
28 and annual mean properties of the stratospheric age spectrum.

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32 **1. Introduction**

33

34 The mean age of stratospheric air is the average time for an air parcel to travel from a  
35 source region in the troposphere (or near the tropopause) to a sample region in the  
36 stratosphere [Hall and Plumb, 1994]. The mean age is a fundamental transport timescale  
37 that has been widely used in stratospheric transport studies, particularly in the evaluation  
38 of chemical transport models and chemistry-climate models (CCMs) [Hall et al., 1999a,  
39 b; Eyring et al., 2006]. However, the mean age only contains partial information of  
40 transit timescales. The complete information is included in the age spectrum, i.e., a  
41 probability distribution function of all the possible transit times since an air parcel had  
42 last contact with the tropospheric boundary source region [Hall and Plumb, 1994; Waugh  
43 and Hall, 2002]. Many studies have shown that the age spectrum is more useful than the  
44 mean age in diagnosing transport characteristics, e.g., the relative importance of different  
45 transport pathways into the lower stratosphere [Andrews et al., 2001; Bonisch et al.,  
46 2009], the seasonal variations of stratospheric transport [Andrews et al., 1999; Reithmeier  
47 et al., 2008; Bonisch et al., 2009], and the horizontal recirculation rate in the tropical pipe  
48 region [Strahan et al., 2009].

49

50 The age spectrum is a kind of boundary propagator. By definition, the boundary  
51 propagator  $G(r,t|\Omega,t')$  is a Green's function that solves the continuity equation for the  
52 mixing ratio of a conserved and passive tracer  $\chi(r,t)$  [Hall and Plumb, 1994]. This  
53 solution can be expressed by the following integration

54 
$$\chi(r,t) = \int_{-\infty}^t \chi(\Omega,t') G(r,t|\Omega,t') dt'$$

55 where  $\Omega$  is the boundary source region,  $r$  is the sample region,  $t'$  is the source time or the  
 56 time the tracer had last contact with  $\Omega$ , and  $t$  the field time or the time the tracer is  
 57 sampled at  $r$ . In many cases the boundary propagator is easier to interpret if it is rewritten  
 58 as a function of the transit time  $\xi=t-t'$ , i.e.,

$$59 \quad \chi(r,t) = \int_0^{\infty} \chi(\Omega,t-\xi)G(r,t|\Omega,t-\xi)d\xi$$

60 where  $G(r,t|\Omega,t-\xi)d\xi$  represents the mass fraction of the air parcel at  $r$  and a specific field  
 61 time  $t$  that was last in contact with  $\Omega$  between  $\xi$  and  $\xi+d\xi$  ago [*Waugh and Hall, 2002;*  
 62 *Holzer et al., 2003; Haine et al., 2008*]. Here  $G(r,t|\Omega,t-\xi)$  is the age spectrum, and it is  
 63 called the Transit-Time Distribution (TTD) in tropospheric and ocean transport literatures  
 64 [e.g., *Holzer et al., 2003; Haine et al., 2008*]. In this paper we use TTD and age spectrum  
 65 interchangeably.

66

67 The age spectrum cannot be directly observed, and we rely almost solely on models to  
 68 compute the age spectrum. Two methods have been used to calculate the stratospheric  
 69 age spectrum, the pulse tracer method [*Hall et al., 1999b*] and the trajectory method  
 70 [*Schoeberl et al., 2003*]. The pulse tracer method is simpler and has been used more  
 71 commonly than the trajectory method. It does not need any additional software and can  
 72 be easily implemented. Put a pulse of a conserved and passive tracer in the boundary  
 73 source region  $\Omega$  at a specific source time  $t'$  and let it disperse throughout the interior area.  
 74 The time series of the mixing ratio of this tracer at any interior point  $r$ , which can be  
 75 expressed mathematically as  $G(r,t'+\xi|\Omega,t')$ , represents the model's time-evolving  
 76 response to a delta function boundary condition.  $G(r,t'+\xi|\Omega,t')$  is called the Boundary

77 Impulse Response (BIR, *Haine et al.*, 2008). Thus the direct product of the pulse tracer  
78 method is not the TTD, but the BIR. In general the BIR  $G(r, t' + \xi | \Omega, t')$  is not equal to the  
79 age spectrum (TTD)  $G(r, t | \Omega, t - \xi)$ , because the boundary propagator is a function of both  
80 field time  $t$  and source time  $t'$ . However, for a stationary condition the boundary  
81 propagator is only a function of the transit time  $\xi$ , i.e., for any  $t$  and  $t'$ ,  $G(r, t | \Omega, t - \xi) =$   
82  $G(r, t' + \xi | \Omega, t')$ . All the previous stratospheric pulse tracer age spectrum studies used this  
83 property to compute the BIR as the TTD [*Hall and Plumb*, 1994; *Hall et al.*, 1999a, b;  
84 *Schoeberl et al.*, 2005]. These studies assumed steady flow and performed a single  
85 realization of the BIR as an approximation of the annual-mean or time-averaged TTD.

86

87 The traditional stratospheric pulse tracer studies have greatly improved our understanding  
88 of the annual mean properties of the age spectrum [*Hall and Plumb*, 1994; *Waugh and*  
89 *Hall*, 2002; *Schoeberl et al.*, 2005], but their approach has disadvantages. By assuming  
90 steady flow and performing a single realization, their method cannot be used to  
91 investigate the seasonality of the stratospheric age spectra. Stratospheric transport has a  
92 strong seasonal cycle due to the seasonal variations of processes such as tropical  
93 upwelling, subtropical jets, and polar vortices [e.g., *Chen*, 1995; *Pan et al.*, 1997;  
94 *Rosenlof et al.*, 1997; *Ray et al.*, 1999; *Randel et al.*, 2001]. One would expect the  
95 stratospheric age spectra to have large seasonal variations. However our knowledge of  
96 the age spectrum's seasonality is very limited. To date the only work that investigated  
97 the seasonal variations of stratospheric age spectra was done by *Reithmeier et al.* [2008]  
98 using a trajectory method. *Reithmeier et al.* [2008] found that the age spectra in the  
99 ECHAM4 general circulation model (GCM) have strong seasonal cycles, and that the

100 shapes of the age spectra change significantly with latitudes. However, there are serious  
101 transport biases in ECHAM4. Specifically, the subtropical barrier is too weak and is  
102 located too far away from the Equator compared to observations. These biases could be  
103 related to the limitations of the version of ECHAM4 used in *Reithmeier et al.* [2008],  
104 which has a very coarse horizontal (6 degrees) and vertical (only 19 levels) resolution and  
105 a very low model top at 10 hPa. The model limitations and the poor transport  
106 performance cast doubts on the results of *Reithmeier et al.* [2008].

107

108 Another concern about the traditional pulse tracer method is whether a single BIR is a  
109 good approximation of an annual-mean age spectrum. Because in reality the stationary  
110 assumption does not hold, the single BIR approach implies that the seasonality of  
111 stratospheric transport has small impact on the annual mean properties of the age  
112 spectrum. *Hall et al.* [1999b] found that the mean age of a single BIR agrees reasonably  
113 well with the annually averaged clock tracer mean age. This was used as evidence that  
114 the annual mean properties of the age spectrum could be well captured by a single BIR  
115 realization. But no previous studies actually investigated the seasonal change of the BIR  
116 and the differences between the TTD and the BIR in the stratosphere.

117

118 The limits of the traditional stratospheric pulse tracer method can be addressed by  
119 performing an ensemble of time-dependent BIR simulations. *Holzer et al.* [2003] and  
120 *Haine et al.* [2008] described in detail a straightforward method to calculate the TTDs in  
121 unsteady flow using the pulse tracer. We will review their method in the next section.  
122 This method requires performing a large number of BIR experiments in different seasons

123 and years to reconstruct the time-varying TTDs, and therefore it is computationally  
124 expensive. We want to point out that the pulse tracer method produces a more internally  
125 consistent age spectrum than the trajectory method because it uses the full and same  
126 model transport operator, including processes such as parameterized mixing, diffusion,  
127 and entrainment that could not be accurately represented by other methods [*Holzer et al.*,  
128 2003].

129

130 In this study we investigate the seasonal variations of the age spectra in the Goddard  
131 Earth Observing System Chemistry-Climate Model (GEOSCCM) using the pulse tracer  
132 method. We introduce an approach to significantly reduce the computational cost for  
133 calculating seasonally varying age spectra based on the method of *Holzer et al.* [2003]  
134 and *Haine et al.* [2008]. Our main purpose is to understand the seasonality of the  
135 stratospheric age spectra. Another purpose is to clarify the differences between the BIR  
136 and the TTD. Our work broadens the usage of the pulse tracer age spectra. These results  
137 will improve the understanding of the transport characteristics in the GEOSCCM, which  
138 has been shown to produce realistic stratospheric transport by various diagnostics  
139 [*SPARC CCMVal*, 2010]. Our results could also be used by empirical studies as guidance  
140 for age spectrum's seasonal variability.

141

142 Our method for calculating the age spectra is described in Section 2. We review the  
143 relationship between the TTDs and BIRs and describe how to compute TTDs and BIRs in  
144 unsteady flow using a simplified version of the method of *Holzer et al.* [2003] and *Haine*  
145 *et al.* [2008]. We will also briefly introduce the GEOSCCM and the simulations.



146 Seasonal variations of the TTDs are presented in Section 3. This is followed by  
147 discussions of the seasonal and interannual variations of the BIRs in Section 4.  
148 Discussions and summary are given in Section 5. All results presented in this paper are  
149 zonally and monthly averaged and then interpolated to the isentropic coordinate.

150

## 151 **2. Method**

152

153 As introduced in Section 1, the TTD and the BIR are different kind of boundary  
154 propagators. They are orthogonal to each other and their relationship is illustrated in  
155 Figure 1a. The contours in Figure 1a are an example of the boundary propagator at 60°N  
156 and 420 K. The TTD is fixed in field time and increases toward older source time, i.e., a  
157 horizontal cut through the boundary propagator map from right to left. The BIR is fixed  
158 in source time and increases with field time, i.e., a vertical cut from bottom to top. For  
159 unsteady flow the boundary propagator is a function of both field time  $t$  and source time  
160  $t'$  and therefore TTD and BIR are not the same (Figure 1c). Only in steady flow TTD  
161 equals BIR.

162

163 The BIR can be easily computed from the pulse tracer experiment. Once the BIR is  
164 obtained, the TTD can be constructed from the BIR. For steady flow, this is simple  
165 because the TTD equals the BIR. And we only need to perform a single tracer  
166 experiment because the age spectrum for a stationary condition has no time dependence.  
167 But in reality, transport is not stationary and computing the TTD is more complicated.  
168 The most direct method is to construct a complete boundary propagator map with many

169 successive vertical BIR sections and then a horizontal cut through the map gives the TTD  
170 (Figure 1., also see Figure 1 of *Haine et al.* [2008] and Figure 2 of *Holzer et al.* [2003]).  
171 This method requires a large number of tracer experiments, so in practice some  
172 simplifications have to be made.

173

174 We first computed twelve BIRs with twelve pulse tracers released in each month of a  
175 given model year. The method of *Hall et al.* [1999b] is followed to compute the BIR.  
176 The boundary source region is set to be the tropical lower troposphere from 10°S to 10°N  
177 and between the surface and about 800 hPa. In order to approximate the delta function  
178 boundary condition, a pulse of artificial conserved and passive tracer is uniformly  
179 released in the source region. The tracer's mixing ratio is set to an arbitrary constant  
180 value for the first month of the experiment and then held as zero through the rest of the  
181 experiment in the source region. Each experiment runs for twenty years in order to  
182 account for the long tail of the stratospheric age spectrum [*Schoeberl et al.*, 2003]. Then  
183 the time series of the tracer's mixing ratio is the BIR. Twelve pulses were released at  
184 each month of a given year and each pulse tracer produces one BIR. Figure 1b shows an  
185 example of the calculated BIRs at 60°N and 420 K as a function of source time  $t'$  and  
186 field time  $t$ . Here the source time represents when the pulses are released at the tropical  
187 surface and the field time is when the mixing ratio of the tracer is sampled in the  
188 stratosphere.

189

190 The twelve BIRs form twelve vertical sections of the boundary propagator map, but they  
191 are not enough to reconstruct the TTDs. For a 20-year long TTD, a total of 240 pulse

192 experiments are needed. In practice it is not possible to run such a large number of  
193 experiments with the GEOSCCM. So we make an initial assumption that the BIR's  
194 interannual variability is sufficiently small compared to its seasonal variability that we  
195 can ignore age spectrum's interannual variations for the purpose of this study. We will  
196 show in section 4 that this is a reasonable assumption in GEOSCCM. Under this  
197 assumption, we construct the boundary propagator map by simply repeating the 12 BIRs  
198 every year for 20 years and shifting the source time accordingly, i.e., let  $G(r, t' + \xi | \Omega, t') =$   
199  $G(r, t' + \xi + n \times 12 | \Omega, t' + n \times 12)$ , where  $t' = \text{Jan, Feb, ... Dec}$  represents the source time of the  
200 pulse tracer experiments, and  $n = 1, 20$  are the repeating years. We then obtain the TTDs  
201 as horizontal cuts through the map (Figure 1a). In the next section we show evidence that  
202 our method is valid in a climatological mean sense, i.e., our calculation captures very  
203 well the seasonality of the climatological mean.

204

205 The pulse experiments were performed in a transient simulation using the GEOSCCM  
206 Version 2. GEOSCCM Version 2 is an update from GEOSCCM version 1 [Pawson *et al.*,  
207 2008]. It couples the GEOS5-GCM [Reineker *et al.*, 2008] with a comprehensive  
208 stratospheric chemistry package [Douglass *et al.*, 1996]. The model has 72 vertical levels  
209 with a top level at 1 Pa. The simulation was carried out on a horizontal resolution of  $2^\circ$   
210 latitude by  $2.5^\circ$  longitude. The twelve pulses were released in each month of model year  
211 2000 and ran for 20 years to 2019, where the model year represents the conditions of the  
212 external forcings. The simulation was forced with IPCC (2001) greenhouse gas (GHG)  
213 scenario A1b and WMO (2007) ozone depleting substance scenario A1. The sea surface  
214 temperature and sea ice contents were taken from an NCAR Community Climate System

215 Model 3.0 run in the A1b GHG scenario. The solar forcing was held constant in the  
216 experiments.

217

218 Results from GEOSCCM Version 2 have been extensively analyzed and evaluated using  
219 observation-based process-oriented diagnostics along with other CCMs in the SPARC  
220 CCMVal-2 project [*SPARC CCMVal*, 2010]. Overall GEOSCCM performs well in terms  
221 of the stratospheric dynamical and thermal structure, trace gas distributions, and their  
222 decadal changes in the recent past. GEOSCCM has quite realistic transport  
223 characteristics in the stratosphere. The tropical ascent rates, the lower stratospheric  
224 mixing rates, and the mean age compare well to observations. GEOSCCM has the best  
225 performance in mean age among all the CCMs that participated in the CCMVal-2. But  
226 GEOSCCM has a somewhat stronger subtropical barrier in the middle stratosphere and a  
227 stronger Antarctic polar vortex barrier than observed.

228

### 229 **3. Seasonal Variations of the Transient Time Distribution**

230

231 Three parameters that characterize aspects of the age spectra are the modal age  $\tau_M(r,t)$ ,  
232 the mean age  $\Gamma(r,t)$ , and the width  $\Delta(r,t)$  [*Waugh and Hall*, 2002]. The modal age is the  
233 most probable transit time, corresponding to the time of the spectral peak. The mean age

234 is the first moment of the age spectrum  $\Gamma(r,t) = \int_0^\infty \xi G(r,t|\Omega,t-\xi) d\xi$  and represents the

235 average transit time. The width is related to the second moment of the age spectrum

236  $\Delta(r|t) = \sqrt{\frac{1}{2} \int_0^\infty (\xi - \Gamma(r|t))^2 G(r,t|\Omega,t-\xi) d\xi}$ , which is a measure of the spread of the

237 spectrum. Among the three parameters, only the mean age can be derived from  
238 measurements and its seasonal variability has been studied before [*Andrews et al.*, 1999;  
239 *Reithmeier et al.*, 2008; *Bonisch et al.*, 2009]. Here we first show the seasonal variations  
240 of the mean age.

241

242 Figure 2 shows the mean age (contour) and its differences from the annually averaged  
243 mean age (color) as functions of latitude and potential temperature at two month  
244 intervals. The mean age has significant seasonal variations and these variations change  
245 with latitude and height (also see Figures 5a, 5d, and 5g which show the seasonal  
246 evolution of the mean age at the 360 K, 420 K, and 550 K isentropic surface). In the  
247 extratropical lower stratosphere (poleward of about 30° degrees latitude and below about  
248 the 500 K isentropic surface), the mean age has a strong annual cycle with the youngest  
249 air in summer and early fall and the oldest air in winter and early spring. Large seasonal  
250 change is also found in the subtropical lower stratosphere (between 10° and 30° degrees  
251 latitude and below about 450 K). Its magnitude is smaller than that in the extratropics in  
252 absolute value, but is comparable in relative change, which is up to 40% different from  
253 the annual-mean value. In winter/early spring and summer/early fall, the seasonal cycle  
254 in the subtropical lower stratosphere is nearly out-of-phase with that in the extratropics.  
255 In the middle and upper stratosphere above about 500 K the seasonal variability of the  
256 mean age is generally smaller than that in the lower stratosphere, and the largest seasonal  
257 variations are found in the subtropics.

258

259 Before discussing the seasonal variations of the TTDs in more detail, we conduct a  
260 consistency check within the model by comparing the TTD mean age and its seasonal  
261 cycle with the model clock tracer mean age. The clock tracer is a linearly increasing  
262 tracer whose source region is at the global surface. For the clock tracer, the mean age is  
263 simply calculated as the time lag between the stratospheric sample region and the  
264 reference region, defined here as the tropical surface in order to be consistent with the  
265 pulse tracer experiment. This consistency check can determine whether our calculated  
266 TTD mean age is correct and whether it is worth investigating further into the seasonality  
267 of the TTDs. Figure 3 shows the climatology of the monthly clock tracer mean age  
268 distribution. Comparing Figure 3 with Figure 2 clearly shows that the clock tracer and  
269 age spectrum have almost exactly the same mean age distribution and seasonal variations.  
270 Small differences are found in the tropopause region. It appears that the clock tracer  
271 mean age is a bit younger and its seasonal cycle is stronger than the age spectrum mean  
272 age in the extratropical tropopause region. Nevertheless, given the completely different  
273 methodology in the TTD and the clock tracer, the overall very similar mean age seasonal  
274 evolution in these two methods provides convincing evidence that our calculation of the  
275 TTD is valid, in the sense it represents very well the climatological seasonal variations of  
276 the age spectra.

277

278 The model simulated mean age seasonal variations agree well with the small number of  
279 observational studies that have been published to date. *Bonisch et al.* [2009] investigated  
280 this topic with mean age derived from in-situ measurements of SF<sub>6</sub> and CO<sub>2</sub> during the  
281 SPURT aircraft campaigns that were carried out in the upper troposphere/lower

282 stratosphere in the extratropics over Europe. They found that in the lowermost  
283 stratosphere bounded by the tropopause and the 380 K isentropic surface, the oldest air (>  
284 3 years) was observed in April and the youngest air (< 1 year) was observed in October.  
285 Our model results are consistent with *Bonisch et al.* [2009], although the oldest air occurs  
286 in March and the youngest air occurs in September in our model calculations (note there  
287 are no March and September data in *Bonisch et al.*, 2009). This agreement gives us more  
288 confidence in our calculations.

289

290 The seasonal change of the mean age reflects the seasonality of stratospheric transport.  
291 In a simplified view, the stratospheric transport is controlled by the integrated effects of  
292 the slow Brewer-Dobson circulation (with timescale of years) and the relatively fast  
293 isentropic mixing (with timescale of weeks to months). The Brewer-Dobson circulation  
294 is strongest in NH winter and weakest in NH summer [*Rosenlof*, 1995]. The seasonal  
295 variations of isentropic mixing are controlled by the seasonal evolution of the mixing  
296 barriers. There are three mixing barriers, which can be identified by the locations of the  
297 strongest gradients in Figure 2 (indicated by symbol X). The polar barrier, located at the  
298 edge of the polar vortex in winter and early spring, suppresses mixing between the polar  
299 old air and midlatitude young air. The subtropical barrier isolates the tropical pipe from  
300 the surf zone in the overworld and it is strongest in late winter/early spring and weakest  
301 in late summer/early fall. The tropospheric jet or tropopause barrier significantly limits  
302 cross-tropopause mixing between the tropical upper troposphere and the midlatitude  
303 lowermost stratosphere in winter. The seasonal variations of the mean age are  
304 determined by the relative importance of these processes.

305

306 The seasonal cycle of the mean age in the extratropical lowermost stratosphere (between  
307 about the tropopause and the 380 K isentropic surface) indicates that the fast isentropic  
308 mixing between the tropical upper troposphere or Tropical Tropopause Layer (TTL) and  
309 the midlatitude lowermost stratosphere is most important in summer/early fall and least  
310 important in winter/early spring [Bonisch *et al.*, 2009]. This is consistent with the  
311 seasonal cycle of the tropical jet and tropopause barrier [Chen, 1995; Pan *et al.*, 1997].  
312 The tropospheric jet is weak and the tropopause is high during the summer/early fall  
313 (Figures 4a and 4b), and the cross-tropopause isentropic mixing is strong. In winter/early  
314 spring the strong tropospheric jet and low tropopause height significantly suppress the  
315 cross-tropopause mixing. The strong wintertime and weak summertime Brewer-Dobson  
316 circulation descent might also play a role in determining the seasonal change of the mean  
317 age in the lowermost stratosphere.

318

319 A very similar cycle is found in the extratropical lower stratosphere between about the  
320 380 K and 500 K isentropic surface. Again this suggests that isentropic mixing has the  
321 largest impact and Brewer-Dobson circulation descent has the smallest impact in  
322 summer/early fall. In the polar stratosphere the seasonal evolution of the Brewer-Dobson  
323 circulation and the polar barrier determine the seasonal change of the mean age. In  
324 winter the strong descent brings old air to the polar region from higher altitudes. The  
325 polar barrier prohibits mixing between the old polar air and the young midlatitude air  
326 throughout the winter, resulting in the oldest air in the spring polar region. In summer



327 and early fall, mixing with the younger midlatitude air and weak descent result in the  
328 youngest polar air.

329

330 One interesting feature is the near opposite phase of the seasonal cycle of the mean age in  
331 the subtropical and midlatitude lower stratosphere below about the 450 K isentropic  
332 surface. This feature is most clearly seen in the NH in January, March and July,  
333 September in Figure 2 (also see Figures 5a and 5d). The seasonal change of the  
334 subtropical lower stratospheric mean age cannot be explained by that of the tropical  
335 upwelling. The strongest upwelling occurs in the subtropics of the summer hemisphere  
336 (Figure 4c), but the oldest subtropical air is found in the summer hemisphere. One  
337 possible explanation is that the opposite phase reflects the seasonal cycle of isentropic  
338 mixing in this region. The strong mixing in summer/early fall between the subtropics and  
339 midlatitudes leads to anomalously old subtropical air and young midlatitude air. And the  
340 weak isentropic mixing in winter/early fall leads to anomalously young subtropical air  
341 and old midlatitude air. It should be noted, however, that there are no observational  
342 studies on the mean age's seasonal variations in the subtropical lower stratosphere. Thus  
343 this model feature needs to be verified by observations of the mean age.

344

345 We also note the phase of the seasonal cycle of the subtropical mean age changes above  
346 the 450 K isentropic surface, which is most clearly seen in winter/early spring and  
347 summer/early fall. This suggests the base of the tropical pipe is located at about 450 K,  
348 consistent with observations [*Rosenlof et al.*, 1997]. The edge of the lower tropical pipe  
349 moves toward the equator in late winter/early spring and brings old air to the subtropical

350 lower stratosphere above 450 K. It moves away from the equator in late summer/early  
351 fall and the subtropical lower stratosphere is filled with more young tropical air.

352

353 The age spectra provide additional information on transit timescales. Figure 5 shows the  
354 seasonal evolution of the modal age, width and the mean age at the 360, 420, and 550 K  
355 isentropic surfaces. Outside the Tropics the 360 K isentropic surface represents the  
356 lowermost stratosphere. The 420 K isentrope is used to represent the tropically  
357 controlled transition region, which is bounded between approximately the 380 K and 450  
358 K isentropic surfaces [*Rosenlof et al.*, 1997]. And the 550 K is chosen to represent the  
359 overworld. The width is an important age spectrum parameter [*Hall and Plumb*, 1994].  
360 Physically it is a measure of the strength of the recirculation [*Strahan et al.*, 2009]. A  
361 stronger recirculation leads to a wider width, longer tail, and older mean of the spectra.  
362 Thus it is not surprising that the width has almost the same seasonal variations as the  
363 mean age.

364

365 The modal age represents the timescale of the most common path. Its seasonal change is  
366 similar to that of the mean age, but the modal age change is more abrupt. At 360 K the  
367 modal age is 1 month equatorward of 30°N and S for all seasons. But at high latitudes  
368 the modal age is younger in summer than other seasons. This summer shortcut can also  
369 be clearly seen at 420K, especially in the NH. For instance, it takes only two months to  
370 transport the spectral peak from the TTL to the NH high latitudes during Jun-Aug. But  
371 this fast path is shut off during winter/early spring, as illustrated by the strong gradients  
372 in the sub-polar latitudes. These large gradients, also seen in the mean age, show the

373 change of the relative importance of the fast isentropic mixing and the slow Brewer-  
374 Dobson circulation descent in winter/early spring due to the combined effect of the strong  
375 wintertime adiabatic descent and the polar barrier. The modal age at 550 K shows very  
376 dramatic seasonal variations at high latitudes. Interestingly the strongest gradient in the  
377 mean age occurs in the subtropics, representing the impact of the subtropical barrier that  
378 isolates the tropical pipe from the surf zone. However, the subtropical barrier is not clear  
379 in the modal age.

380

381 We now examine the seasonal cycle of the age spectra at some chosen latitudes at the  
382 360, 420, and 550 K isentropic surfaces. At 360 K and 20°N a narrow spectral peak at 1  
383 month characterizes the age spectra (Figure 6). The modal ages are the same for all  
384 seasons, but the width is wider in summer than in winter. At 46°N, the strongest spectral  
385 peaks and the youngest peak value (1 month) occur in August and September. The  
386 weakest peaks (about half that in fall) with the oldest peak values (3 months) occur in  
387 March and April, suggesting that the fast pathway evident during the summer is  
388 suppressed during the winter. Almost exactly the same seasonal variations are found at  
389 high latitudes. At 80°N, the fall age spectra have the youngest mean age and the  
390 strongest spectral peak. Their modal age of 4-5 months indicates that the spectral peaks  
391 leave the source region in late spring/early summer. The spring spectra have the oldest  
392 mean and model age, and their spectral peaks are traced back to fall of the previous year.  
393 These results are consistent with the wintertime tropospheric jet barrier in the lowermost  
394 stratosphere. The SH age spectra have very similar seasonal variability as their NH  
395 counterparts.

396

397 The overall seasonal change in the age spectra at the 420 K isentropic surface (Figure 7)  
398 is similar to that at 360 K. One feature in the 420 K age spectra not seen in the  
399 lowermost stratosphere is the large change in the modal age at high latitudes (also see  
400 Figure 5e). For instance at 80°S the modal age changes dramatically from about 0.75  
401 year in the February spectrum to about 4 years in the November spectrum. The sharp  
402 jump in the winter/early spring modal age is associated with significant changes in the  
403 spectral shape. For example, the February and March spectra at 80°N have three  
404 comparable peaks with transit time of about 1.2, 2.7 and 3.7 years, respectively. The  
405 second peak is a bit higher than the other two and that is the modal age by definition.  
406 Apparently the modal age is not a very useful parameter to characterize the spectral shape  
407 for this kind of spectrum. Note even the first peak is much older than the 0.5 year modal  
408 age of the summer spectra. Also the magnitude of the February-March peaks is about ¼  
409 of the July-August spectra. We interpret this as the seasonal change of the dominant  
410 pathway at high latitudes. In summer/early fall, isentropic mixing brings young TTL air  
411 directly to the polar region. In winter/spring, slow descent from high altitude dominates.  
412

413 The 550 K age spectra also show large jumps in modal age at high latitudes (Figure 8).  
414 The modal ages of the winter/spring spectra are much older (up to two times) than those  
415 of the summer spectra, but their magnitudes are stronger. This suggests that mixing  
416 between middle and high latitudes in summer, which is weak because of the summer  
417 stratospheric easterlies, leads to a younger although weaker spectral peak in the polar  
418 region. In winter/spring the mixing is prohibited and the spectral peaks represent solely

419 the descent of the Brewer-Dobson circulation. The younger and weaker summer spectral  
420 peak is a unique feature in the overworld high latitudes and it explains the relatively  
421 small mean age seasonal cycle in this region.

422

423 The change of the spectral shape from a single peak at low and middle latitudes to  
424 multiple peaks at high latitudes was first reported by *Reithmeier et al.* [2008], who  
425 calculated age spectra in the ECHAM4 GCM using the Lagrangian trajectory method. A  
426 major focus of *Reithmeier et al.* [2008] was to understand what causes the high latitudes  
427 multiple spectral peaks, which are 1 year apart and independent of height. They argued  
428 that these multi-modal polar spectra are caused by two processes: the seasonality of the  
429 tropical upwelling that generates single mode spectra at midlatitudes, and the  
430 summertime mixing between the polar and midlatitude air that leads to a superposition of  
431 the midlatitude single mode spectra with the polar spectra once a year and generates  
432 multiple annual peaks.

433

434 Although our TTDs show multiple peaks similar to those in *Reithmeier et al.* [2008],  
435 there are some differences. Figure 9 shows the March and September age spectra at 80°N  
436 and S at 420 K. The starts of the age spectra are shifted such that the x-axis reflects the  
437 season of the source time. The age spectra are plotted in the logarithmic scale to  
438 highlight the tail region. In both the NH and SH high latitudes, the annually repeating  
439 peaks last contacted the tropical surface during their respective summer season. This is  
440 not the case in *Reithmeier et al.* [2008] (see their Figures 5 and 9). These annual peaks  
441 are very clear in the tail region, suggesting they are caused by the annual cycle of the

442 recirculation into the polar stratosphere. Our results indicate that air parcels leaving the  
443 tropical surface in summer have a larger chance to be re-circulated into the polar  
444 stratosphere. Apparently the annual cycle of the Brewer-Dobson circulation and polar  
445 vortex barrier determine the annual cycle of the recirculation into the polar region, but the  
446 mechanism is not clear.

447

448 The tails of the age spectra, defined here as regions with transit time older than 4 years,  
449 decay exponentially with time. Thus the tails can be approximated by an exponentially  
450 decaying mode  $\Psi_0(r,t)\exp(-\frac{\xi}{\tau_0})$  (straight solid lines in Figure 9). This decay rate  $\tau_0$  is  
451 the eigentime of the lowest mode of the age spectra [*Hall et al.*, 1999a; *Ehhalt et al.*,  
452 2004]. It is a fundamental stratospheric transport diagnostic and remains nearly constant  
453 in different seasons and locations (2.77 years in GEOSCCM). Of course this does not  
454 mean that the tails are not seasonal dependent, because  $\Psi_0(r,t)$  changes with season and  
455 location.

456

#### 457 **4. Seasonal and Interannual Variations of the Boundary Impulse** 458 **Response**

459

460 A concern about the traditional pulse tracer approach is that it uses only a single BIR  
461 realization to approximate the annual-mean TTD. *Haine et al.* [2008] showed  
462 theoretically that the statistical properties of an ensemble mean of the TTDs are  
463 equivalent to those of an ensemble mean of the BIRs in unsteady flow. We have  
464 compared the annual-mean TTDs and BIRs in our model simulations and have found

465 they are nearly identical (not shown). This means if the seasonality of the BIR is small, a  
466 single BIR realization could be a good representation of an annual-mean TTD.

467

468 Our simulations show significant seasonal variations in the BIR. In order to illustrate  
469 the BIR's seasonality, Figure 10 plots the seasonal evolution of the BIR mean age, modal  
470 age, and width at 420 K. The seasonal change is small in the tropics, but becomes  
471 significant at high latitudes. For example, in the NH polar region, the mean age of the  
472 winter released BIR (about 2.75 years) is about 25% younger than the mean age of the  
473 summer released BIR (3.5 years). And the modal age of the spring BIR (5 months) is  
474 only half of the summer value (10 months). Clearly, the annual-mean properties of the  
475 age spectrum cannot be well captured by a single BIR in areas of large BIR seasonality  
476 such as the polar region.

477

478 We also want to emphasize that the seasonal change of the BIR, which is based on the  
479 source time, could be very different from the seasonal change of the TTD that is based on  
480 the field time. Our model results show that both the phase and magnitude of the BIR's  
481 seasonal cycle are different from those of the TTD's (compare Figure 10 with Figures 5d-  
482 5f). One striking difference is the shift of the phase in the extratropics between the BIR  
483 and TTD. The summer-released BIRs have the oldest mean age, modal age and the  
484 largest width, which is nearly out of phase with the TTDs whose youngest mean and  
485 modal age, and smallest width occur in the late summer/early fall. It can be also clearly  
486 seen that the seasonal change of the BIR is much smaller than that in TTD.

487

488 In order to help to understand the different seasonality in the BIR and the TTD the  
489 seasonal evolution of the BIRs at 80°N and 420 K is plotted in Figure 11. This is similar  
490 to Figure 1b, but only the first two years of the BIRs are shown. The most interesting  
491 feature is that the modal ages of the BIRs are seasonally locked to the summer field time.  
492 No matter when the pulse is released, its peak always reaches high latitudes during Jun-  
493 Aug. It takes about 6 months for the peaks of the winter-released pulse to arrive 80°N.  
494 The transport of summer-released BIRs into the polar lower stratosphere is strongly  
495 suppressed in winter and early spring by the vortex barrier. They do not penetrate into  
496 the high latitudes until the breakup of the polar vortex in late spring. This leads to the  
497 oldest and weakest spectral peaks, meaning that the summer-released BIRs have the  
498 smallest fraction of young air and thus oldest mean age. Furthermore, the summer/early  
499 fall peaks and winter/early spring valleys with respect to the field time means that the  
500 TTDs, which are horizontal cuts from right to left through the boundary propagator map,  
501 have the youngest mean age in summer/late fall and oldest mean age in winter/early  
502 spring (see Figure 7).

503

504 We made an initial assumption in this study that the BIR's interannual variations are  
505 smaller than its seasonal variations. We performed eight additional pulse experiments to  
506 verify that this assumption is valid. The eight pulses were released respectively in  
507 January and July in years 2001 to 2004. Since we already have the January and July BIR  
508 for year 2000, a total of five January-released and five July-released BIRs for 2000-2004  
509 were obtained. The mean and standard deviations of the five January (black) and July  
510 (red) BIRs at some chosen locations in the NH are shown in Figure 12. The SH has very



511 similar features and is not shown. In the subtropical lower stratosphere (20°N at 360 K  
512 and 420K) the interannual variations are very small such that the lines representing the  
513 standard deviation almost overlap with the mean BIR. In the midlatitude lower  
514 stratosphere the magnitude of the spectral peaks shows some interannual variations.  
515 Considerable interannual changes are found in the 550 K extratropics and polar lower  
516 stratosphere. Nevertheless, the seasonal differences between the January and July BIRs  
517 clearly stand out.

518

519 We have already shown that the TTD mean age agrees very well with the clock tracer  
520 mean age (Figures 2 and 3). We compared closely the mean age's seasonal change in the  
521 polar region where relatively large interannual variations occur, and found excellent  
522 agreements between the TTD and clock tracer mean age. These results suggest that the  
523 interannual variability of the BIR has only small impact on our calculations of the TTDs.

524

## 525 **5. Discussion and Summary**

526

527 The seasonal variations of the stratospheric TTDs are investigated in this study using the  
528 pulse tracer method in GEOSCCM. We have found that the TTDs have significant  
529 seasonal variations throughout the stratosphere. The largest seasonal changes occur in  
530 the lowermost and lower stratosphere and the subtropical overworld. Up to 40%  
531 differences between the individual month and annually averaged mean age are commonly  
532 found in these regions. The modal ages and spectral shapes demonstrate even bigger  
533 changes in the polar stratosphere. The seasonal variations of the TTDs reflect the

534 seasonal evolution and relative importance of the slow Brewer-Dobson circulation and  
535 the fast isentropic mixing.

536

537 The differences between the TTD and the BIR are known in tropospheric and ocean  
538 transport studies [*Holzer et al.*, 2003; *Haine et al.*, 2008], but the BIR is often used as the  
539 TTD in stratospheric transport [*Hall and Plumb*, 1994; *Hall et al.*, 1999a, b; *Schoeberl et*  
540 *al.*, 2005]. These studies perform a single pulse tracer experiment and the resultant BIR  
541 is used as an approximation of the time-averaged TTD. Here we show that the BIRs have  
542 significant seasonal variations. Thus it is problematic to use a single BIR realization to  
543 represent the annually averaged TTDs. Our model results also show that the phase and  
544 magnitude of the BIR's seasonal cycle are different from those of the TTD's. Clearly it  
545 is misleading to use BIRs to study the seasonality of the TTDs. On the other hand, *Haine*  
546 *et al.* [2008] showed theoretically that an ensemble-averaged BIR is equivalent to an  
547 ensemble-averaged TTD. This is confirmed by the nearly identical annually averaged  
548 BIR and TTD in our results (not shown). In summary, computing an ensemble of BIRs is  
549 needed in order to investigate either the seasonality or the annual-mean properties of the  
550 TTDs.

551

552 Several studies have used empirical age spectra to investigate stratospheric transport  
553 [*Andrews et al.*, 1999, 2001; *Bonisch et al.*, 2009]. They assumed an analytic solution for  
554 the age spectra and used in-situ trace gas measurements to constrain the empirical  
555 parameters. *Andrews et al.* [2001] proposed a bimodal spectral shape with two distinct  
556 peaks to represent respectively the fast quasi-horizontal mixing and slow Brewer-Dobson

557 circulation in the NH midlatitude lower stratosphere. *Bonisch et al.* [2009] adopted this  
558 bimodal concept and made important revision that the superposition of the two modes  
559 does not necessarily lead to two distinct spectral peaks. The age spectra in GEOSCCM  
560 show a single peak in this region (see Figures 6 and 7), which does not support the  
561 bimodal shape of *Andrews et al.* [2001]. Our results appear to be consistent with the  
562 conceptual model of *Bonisch et al.* [2009]. However, *Bonisch et al.* [2009] concentrated  
563 on the mean age and did not present the seasonal evolution of their empirical age spectra.  
564 Therefore we could not make direct comparisons with *Bonisch et al.* [2009]. We do find  
565 multi-modal spectral shapes at high latitudes, but the multiple spectral peaks are due to  
566 the annual cycle of air recirculation. As pointed out by *Reithmeier et al.* [2008], it is very  
567 challenging to apply this multi-modal spectral shape in empirical studies.

568

569 An importance implication of our results is on the long-term changes in the mean age.  
570 Chemistry climate models consistently simulate a decrease of the stratospheric mean age  
571 in the recent past and in the 21st century at a rate about 2-3%/decade [e.g., *Garcia and*  
572 *Randel*, 2008; *Oman et al.*, 2009]. The decrease in the mean age is consistent with the  
573 acceleration of the Brewer-Dobson circulation [*Austin and Li*, 2006; *Li et al.*, 2008].  
574 However, the acceleration of the Brewer-Dobson circulation is directly related to the  
575 decrease of the modal age, not the mean age [*Strahan et al.*, 2009]. Of course a younger  
576 modal age could result in a younger mean age, but other processes, such as a weakening  
577 of recirculation and/or a decrease in the long-term decay timescale, could also contribute  
578 to the decrease of the mean age. We will investigate the long-term changes in the  
579 stratospheric age spectra in a warming climate in a separate study.

580

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582

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587

588

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712

712 **Figure Captions**

713

714 Figure 1: Illustration of the relationship between the Transit-Time Distribution (TTD)  
715 and Boundary Impulse Response (BIR). Panel (a) is a boundary propagator map at 60°N  
716 and 420 K. This map is constructed from 252 vertical slices. Each vertical slice is a BIR,  
717 which is fixed in source time and increases with field time. The TTD is fixed in field  
718 time and increases towards older source time, i.e., a horizontal cut from right to left  
719 through the boundary propagator map. An example of the BIR and TTD is shown in  
720 panel (c). When constructing the boundary propagator map (a), we do not calculate all  
721 the 252 BIRs. Instead we only calculate 12 BIRs with source time in each month of a  
722 given year. These 12 BIR realizations (shown in panel b and in the black rectangle in  
723 panel a) are then repeated every year for 20 years to form the boundary propagator map.

724

725 Figure 2: Distribution of the TTD mean age (contour) and its difference from the  
726 annually averaged mean age (color) at two month intervals. The contour interval is 0.5  
727 yr. The red line is the tropopause. The symbol X in the January panel indicates the  
728 location of the transport barriers.

729

730 Figure 3: Same as Figure 2, but for the climatological mean (2000-2019) clock tracer  
731 mean age.

732

733 Figure 4: Seasonal cycle of (a) the zonal wind at 360 K; (b) the tropopause height; (c) the  
734 residual vertical velocity at 360 K.

735

736 Figure 5: Seasonal evolution of the TTD mean age, modal age, and width at 360, 420 and  
737 550 K. The contour interval is 0.25 year for the mean age and 0.2 yr for the width. The  
738 unit of the modal age is month and variable contour intervals are used in different levels:  
739 1 month at 360 K, 2 months (modal age < 1 yr) and 4 months (modal age > 1 yr) at 420  
740 K, and 4 months at 550 K.

741

742 Figure 6: Seasonal cycle of the TTDs at 20°, 46°, and 80° latitude north and south at 360  
743 K. The dotted line is the modal age and the solid line is the mean age. The colors in each  
744 panel are normalized by the maximum PDF shown in the caption.

745

746 Figure 7: Same as Figure 6, but for 420 K.

747

748 Figure 8: Same as Figure 6, but for 550 K.

749

750 Figure 9: The March (black) and September (red) TTDs at 80°N and S at 420 K. The  
751 starts of the age spectra are shifted (indicated by the thin dash lines) so that the x-axis  
752 represents the season of the source time. The vertical dotted lines correspond to January  
753 in source time.

754

755 Figure 10: Seasonal evolution of the BIR mean age, modal age and width at 420 K. The  
756 contour interval is 0.25 year for the mean age and 0.2 year for the width. The contour

757 interval for the modal age is 2 month (modal age < 1 year) and 4 month (modal age >  
758 1year).

759

760

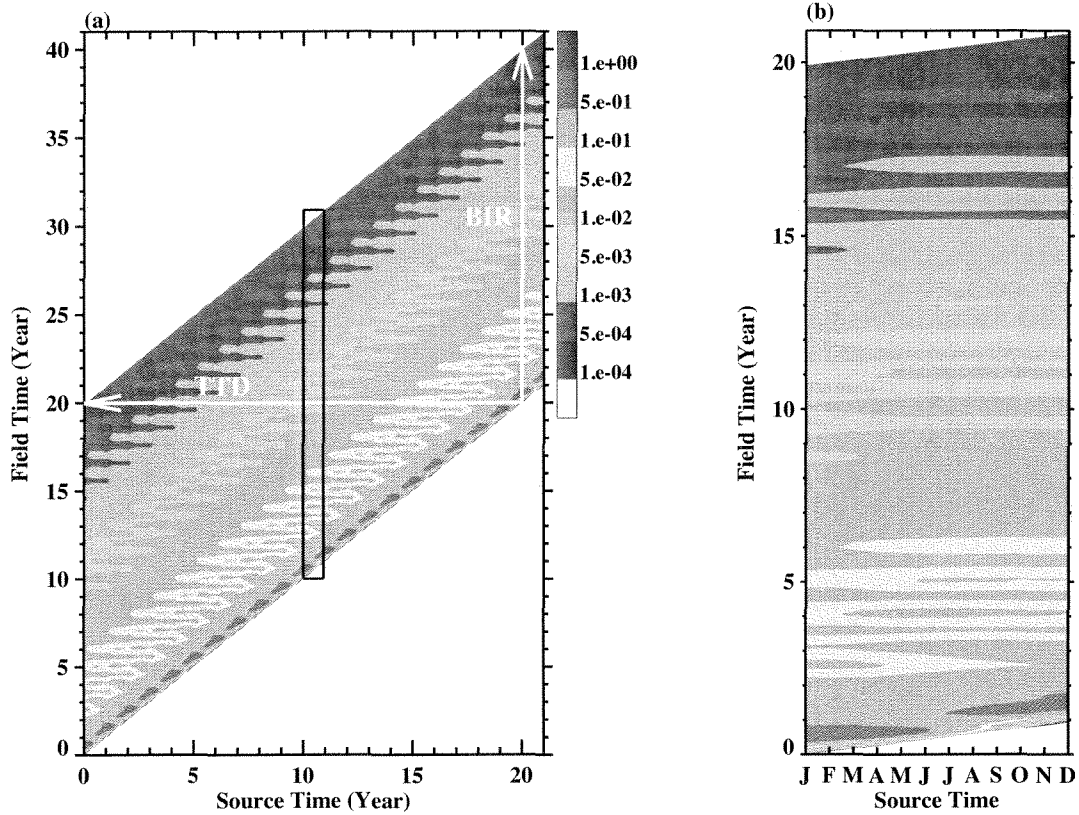
761 Figure 11: Seasonal evolution of the BIRs at 80°N and 420 K as a function of source  
762 time and field time.

763

764 Figure 12: Comparison of the January (black) and July (red) BIRs at some chosen  
765 locations in the Northern Hemisphere. The thick lines are the mean of five BIRs, which  
766 are released in January or July in 2000-2004. The thin lines are the standard deviations  
767 of the five BIRs.

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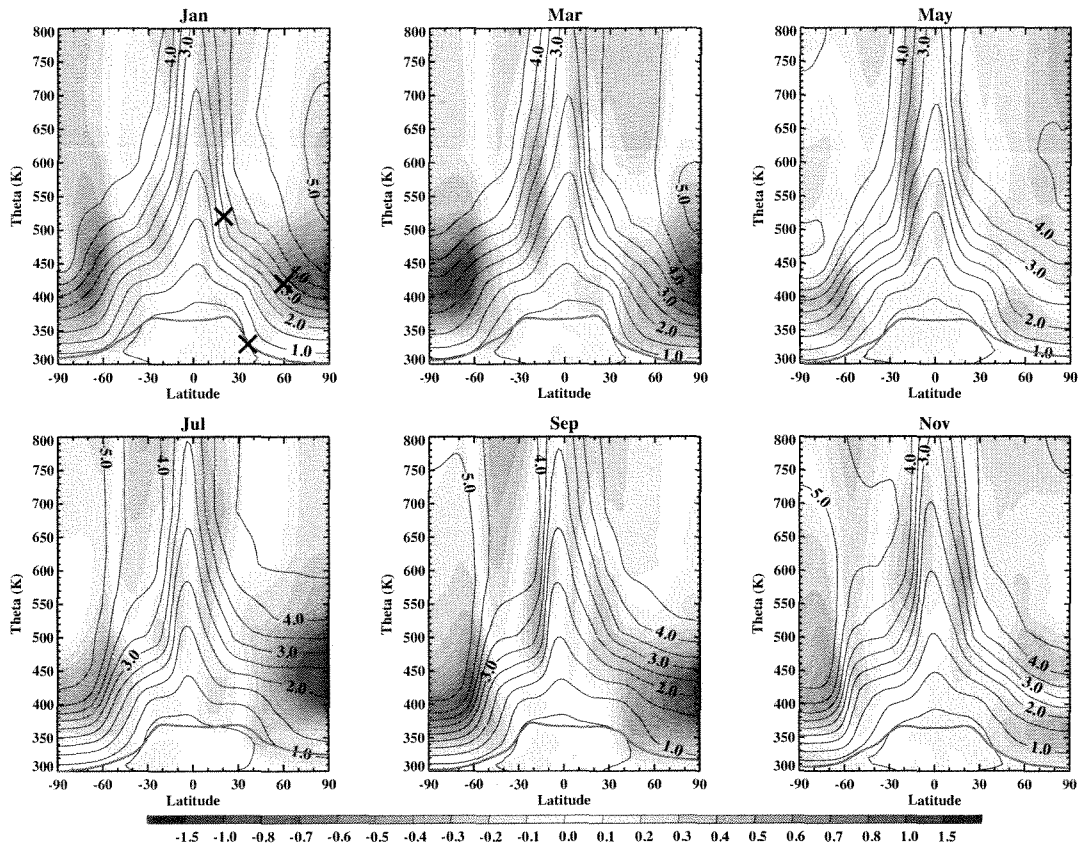
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772 Figure1: Illustration of the relationship between the Transit-Time Distribution (TTD)  
 773 and Boundary Impulse Response (BIR). Panel (a) is a boundary propagator map at 60°N  
 774 and 420 K. This map is constructed from 252 vertical slices. Each vertical slice is a BIR,

775 which is fixed in source time and increases with field time. The TTD is fixed in field  
776 time and increases towards older source time, i.e., a horizontal cut from right to left  
777 through the boundary propagator map. An example of the BIR and TTD is shown in  
778 panel (c). When constructing the boundary propagator map (a), we do not calculate all  
779 the 252 BIRs. Instead we only calculate 12 BIRs with source time in each month of a  
780 given year. These 12 BIR realizations (shown in panel b and in the black rectangle in  
781 panel a) are then repeated every year for 20 years to form the boundary propagator map.  
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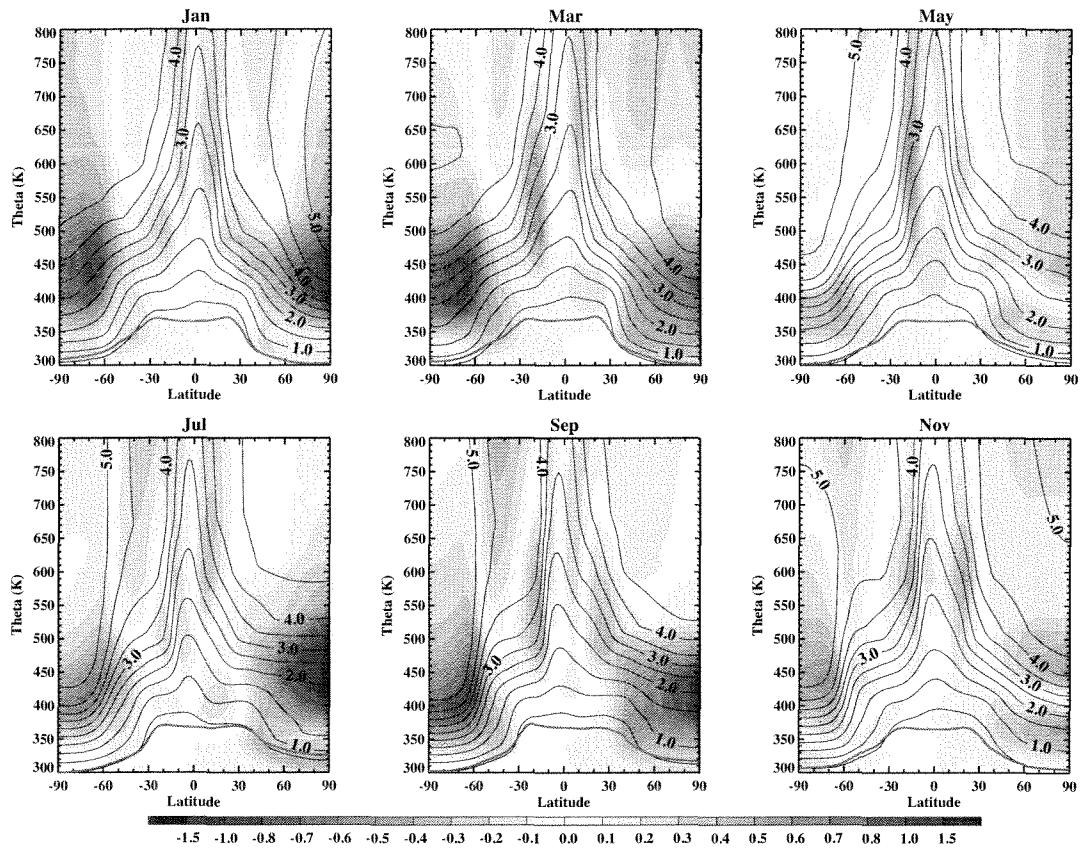
785 Figure 2: Distribution of the TTD mean age (contour) and its difference from the  
786 annually averaged mean age (color) at two month intervals. The contour interval is 0.5  
787 yr. The red line is the tropopause. The symbol X in the January panel indicates the  
788 location of the transport barriers.

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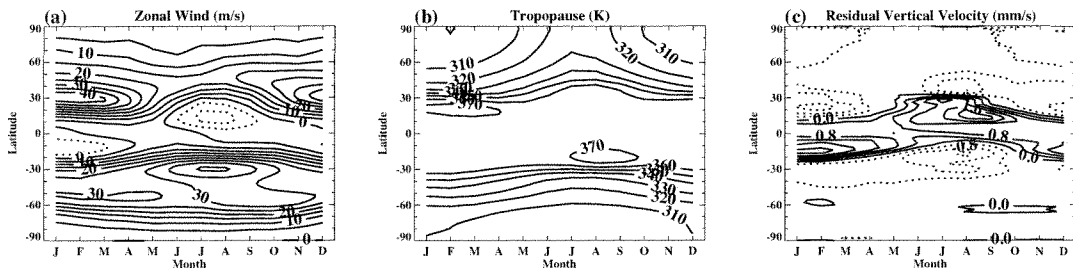
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793 Figure 3: Same as Figure 2, but for the climatological mean (2000-2019) clock tracer  
794 mean age.

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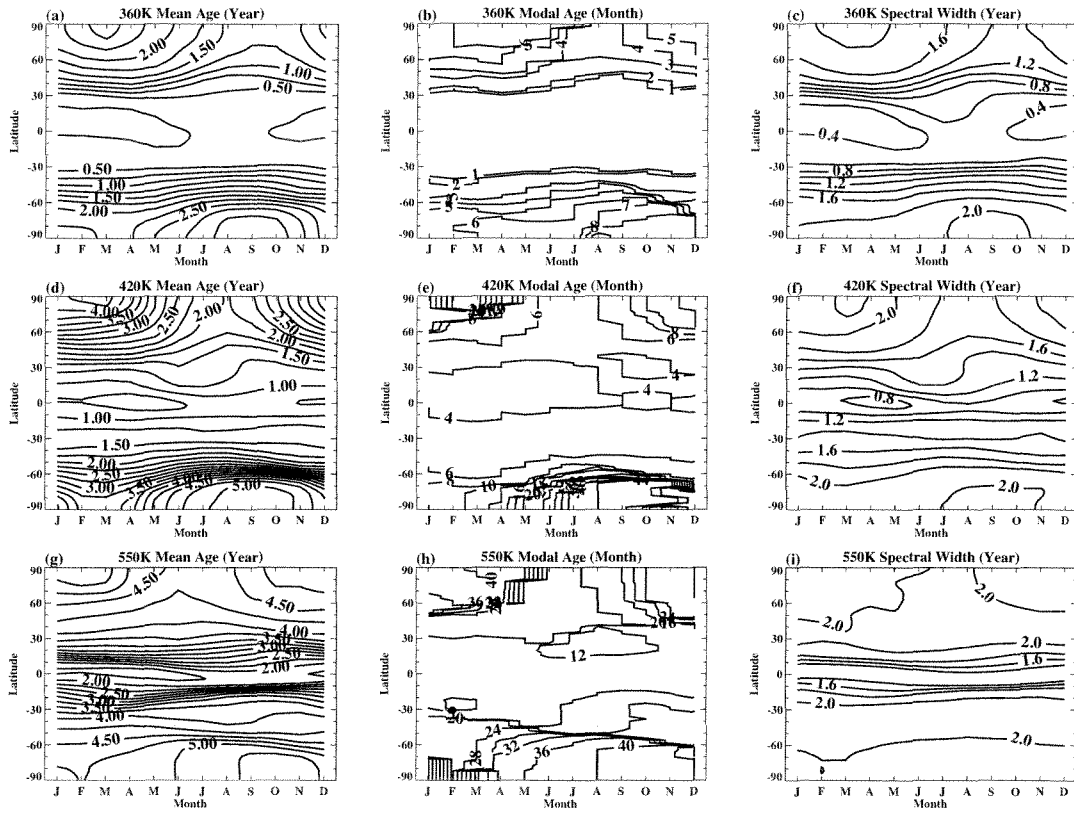
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798 Figure 4: Seasonal cycle of (a) the zonal wind at 360 K; (b) the tropopause height; (c) the  
799 residual vertical velocity at 360 K.

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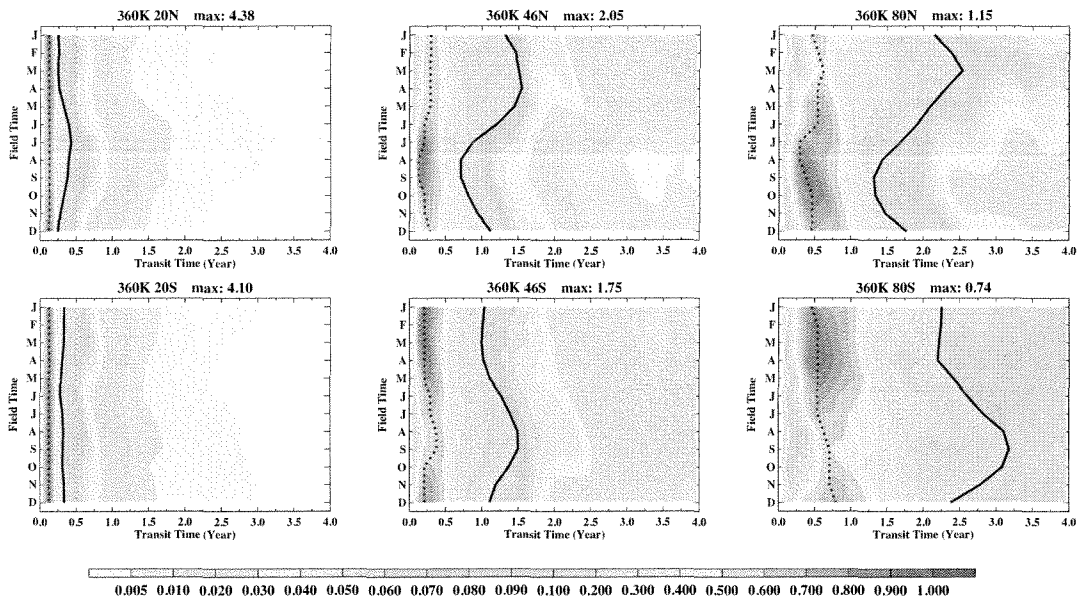
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804 Figure 5: Seasonal evolution of the TTD mean age, modal age, and width at 360, 420 and  
805 550 K. The contour interval is 0.25 year for the mean age and 0.2 yr for the width. The  
806 unit of the modal age is month and variable contour intervals are used in different levels:  
807 1 month at 360 K, 2 months (modal age < 1 yr) and 4 months (modal age > 1 yr) at 420  
808 K, and 4 months at 550 K.

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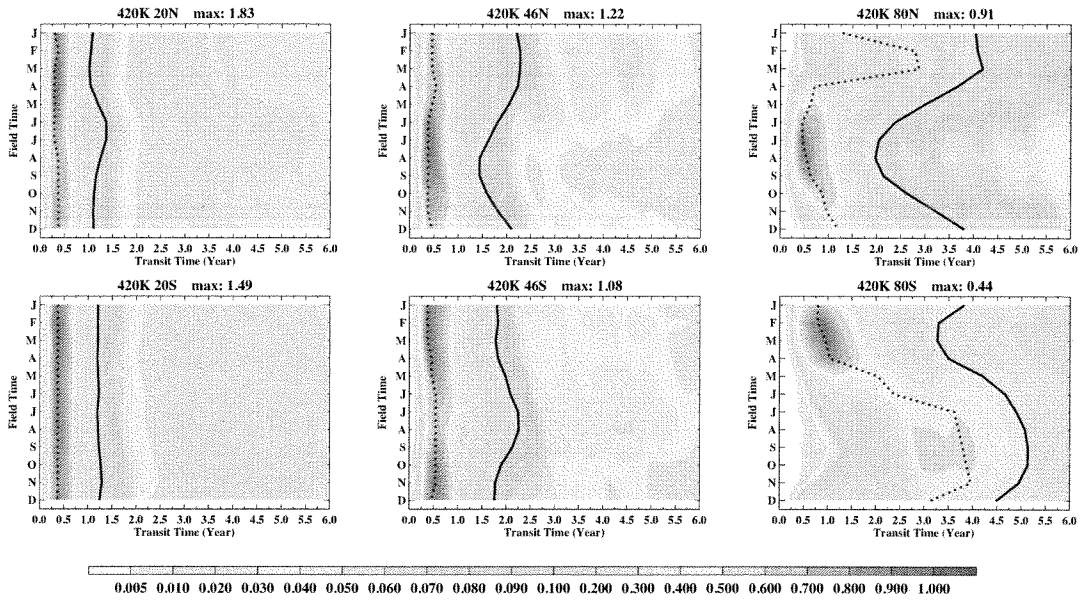
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812 Figure 6: Seasonal cycle of the TTD age spectra at 20°, 46°, and 80° latitude north and

813 south at 360 K. The dotted line is the modal age and the solid line is the mean age. The

814 colors in each panel are normalized by the maximum PDF shown in the caption.

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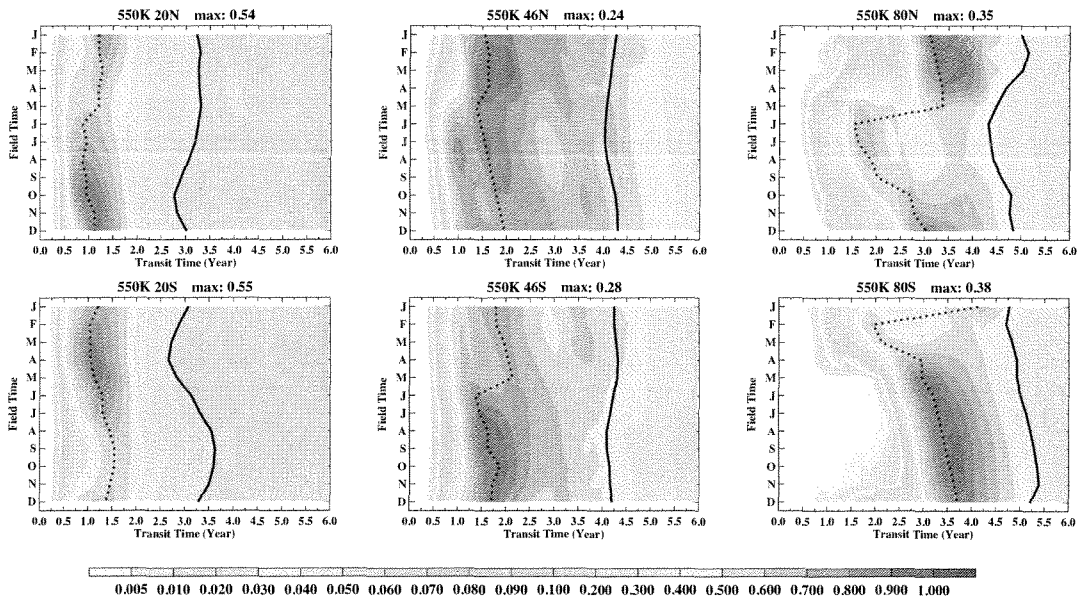
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818 Figure 7: Same as Figure 6, but for 420 K.

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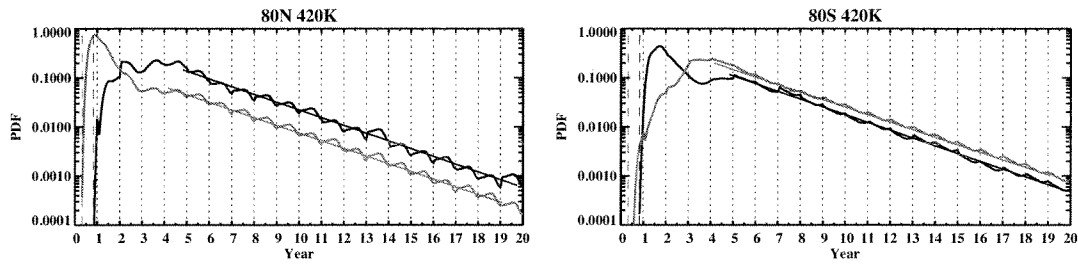
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822 Figure 8: Same as Figure 6, but for 550 K.

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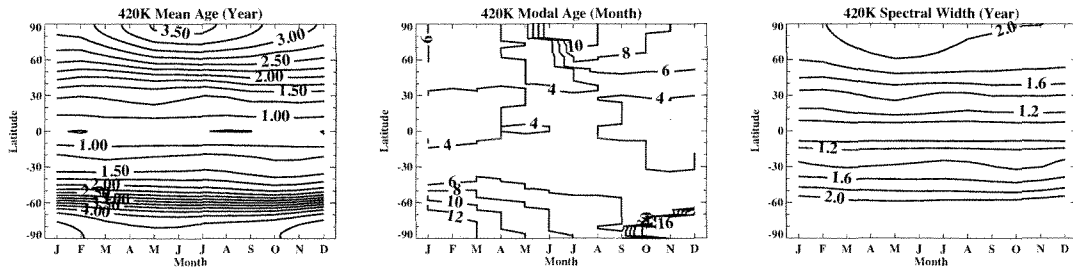
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826 Figure 9: The March (black) and September (red) TTD age spectra at 80°N and S at 420  
827 K. The starts of the age spectra are shifted (indicated by the thin dash lines) so that the x-  
828 axis represents the season of the source time. The vertical dotted lines correspond to  
829 January in source time.

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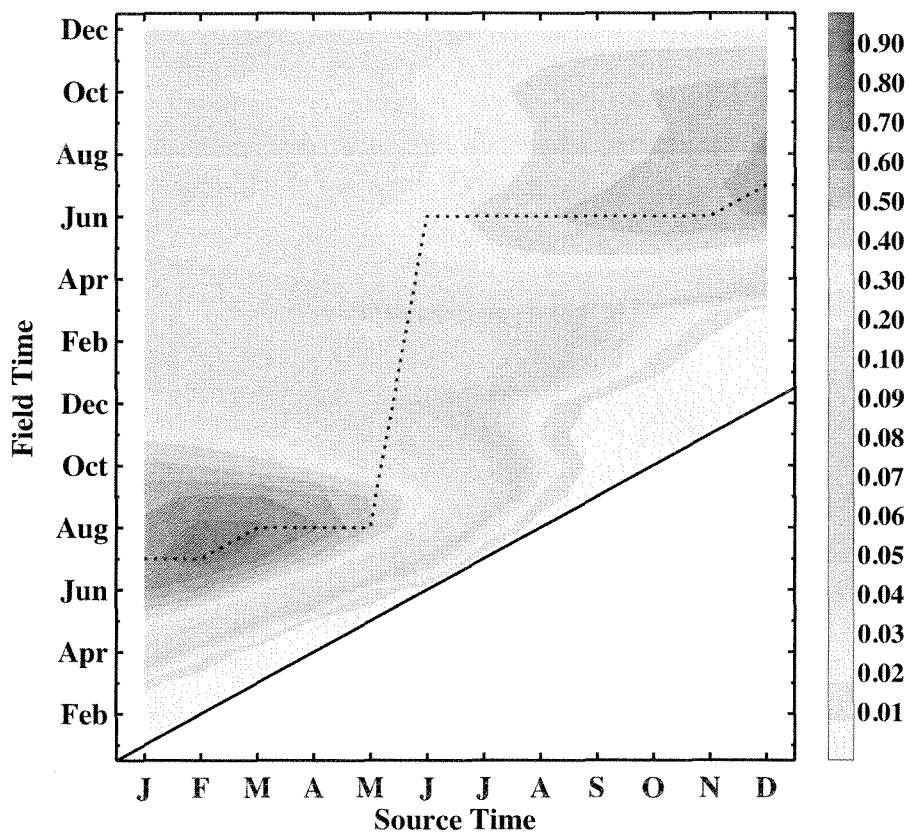
833 Figure 10: Seasonal evolution of the BIR mean age, modal age and width at 420 K. The  
834 contour interval is 0.25 year for the mean age and 0.2 year for the width. The contour  
835 interval for the modal age is 2 month (modal age < 1 year) and 4 month (modal age >  
836 1year).

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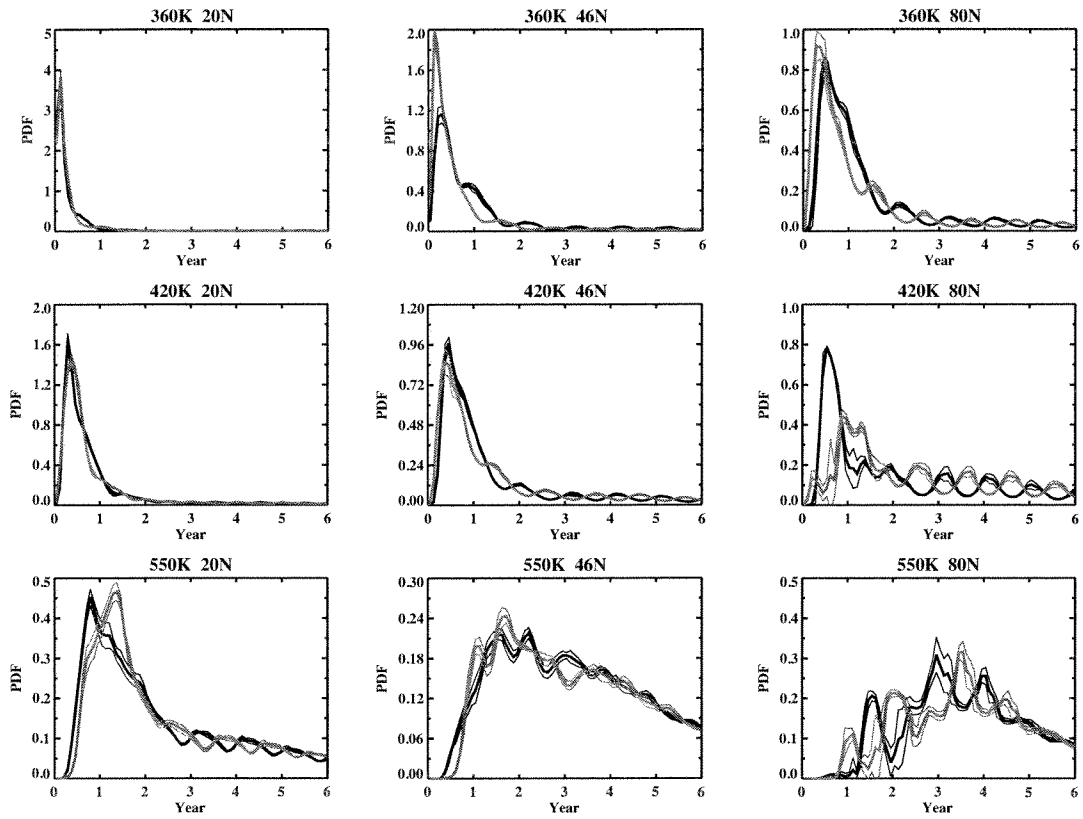
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841 Figure 11: Seasonal evolution of the BIR at 80°N and 420 K as a function of source time  
842 and field time.

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846 Figure 12: Comparison of the January (black) and July (red) BIRs at some chosen  
847 locations in the Northern Hemisphere. The thick lines are the mean of five BIRs, which  
848 are released in January or July in 2000-2004. The thin lines are the standard deviations  
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