

1 *This manuscript introduces a new climate index, the "Middle-latitude Indian
2 Ocean Dipole" (MIOD), and investigates its influence on the Southern
3 Hemisphere's middle and upper atmosphere. The study uses a multi-faceted
4 approach combining reanalysis, satellite data, and model simulations to build a
5 compelling narrative. The proposed physical mechanism links positive MIOD
6 events to enhanced planetary wave activity, which in turn drives significant
7 stratospheric and mesospheric changes. This mechanism is logical, well-articulated,
8 and represents a potentially significant contribution to our understanding of ocean-
9 atmosphere coupling. The finding of a strong asymmetry in the atmospheric
10 response between positive and negative MIOD events is particularly noteworthy.*

11 *However, the manuscript in its current form is undermined by several
12 methodological flaws and a lack of careful preparation that question the validity
13 and reproducibility of its core findings. Most central is the pre-removal of EESC
14 from SST prior to the EOF, which is unusual and risks biasing the MIOD pattern.
15 Second is event selection that is vulnerable to ENSO aliasing (e.g., 2016).
16 Furthermore, the statistical robustness is limited by a small sample size, and errors
17 in figure labels and captions detract from the paper's credibility. With stronger
18 methodological circumspection, a set of focused robustness checks, and cleaner
19 presentation, the paper can reach the level the idea deserves.*

20 *All my concerns are detailed below. I do not necessarily expect the authors to
21 address every point, but I do expect the critical issues to be dealt with convincingly
22 for the work to be credible.*

23 Major comments

24 1) SST preprocessing with EESC before the EOF

25 *The manuscript removes EESC from JJA SST prior to the EOF but largely treats this
26 as routine. It is not. EESC is a stratospheric halogen proxy : a direct, widely accepted
27 causal pathway to basin-scale SST variability is not established. Regressing out a
28 non-linear, parabolic-like trajectory from SST can reshape low-frequency variance
29 and therefore the EOF structures themselves. In other words, the MIOD pattern may
30 be sensitive to this step. If the intention is to isolate an SST pattern "untainted" by
31 ozone-related radiative trends, that needs a clear physical rationale. Otherwise, a
32 standard approach is to detrend SST (and, if desired, apply ENSO/SIOD partialing in
33 atmospheric fields, not in SST itself). At minimum the preprocessing must be made
34 prominent in the figure caption and methods, and the results shown to be robust to its
35 omission.*

36 **Response:** We thank the reviewer for this constructive comment. We agree that
37 regressing SST onto EESC is not a standard procedure and may unintentionally
38 reshape low-frequency SST variance. Our original intention was simply to isolate the

39 interannual SST variability associated with the MIOD pattern, but we recognize that
40 using a stratospheric halogen proxy is not physically justified for SST preprocessing.

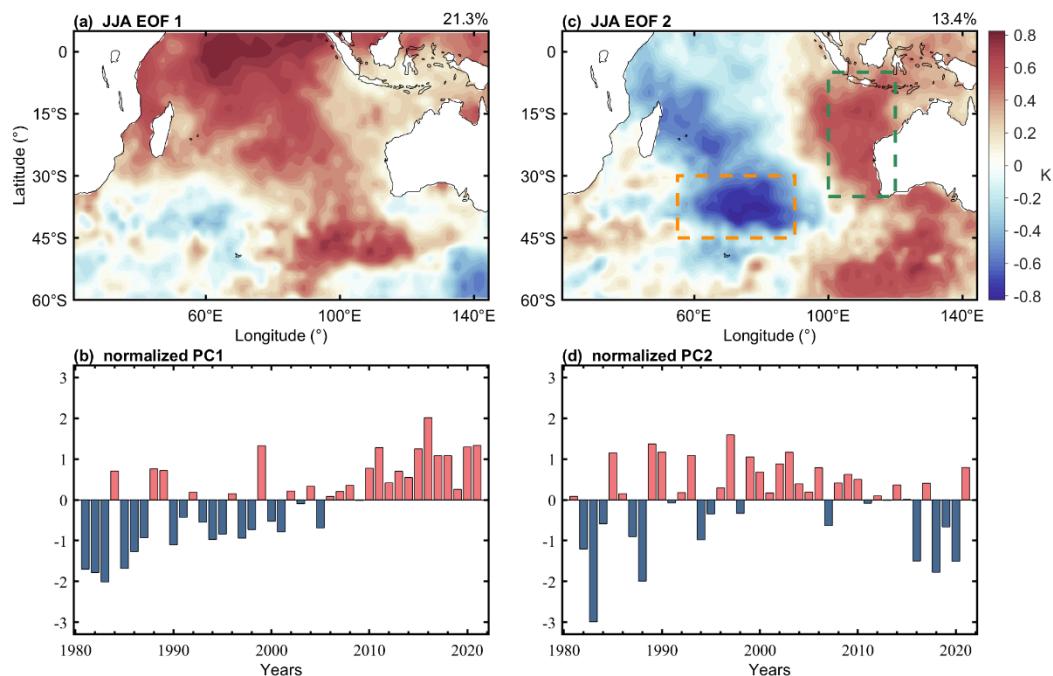
41 To avoid introducing any unnecessary assumptions, we have **completely**
42 **removed the EESC preprocessing step**. In the revised manuscript, the EOF analysis
43 is performed directly on JJA SST anomalies relative to the 1980–2020 climatology,
44 which represents the standard approach for examining interannual SST variability in
45 climate studies.

46 We have verified that removing the EESC preprocessing does not materially
47 affect the results:

48 a. The revised EOF2 spatial pattern (the MIOD mode) has a pattern correlation
49 of 0.8 with the original version.

50 b. The identified MIOD event years differ by only one year on each side.

51 c. The composite atmospheric circulation and temperature responses remain
52 nearly unchanged.



53

54 **Figure R1.** SST patterns of (a) EOF1 and (b) EOF2, and principal component time series of (c)
55 EOF1 and (d) EOF2, derived from Indian Ocean SST anomalies during austral winter (JJA) for
56 1980–2020 over the domain 60°S–5°N, 40°E–145°E.

57 The updated EOF patterns and PCs are shown in Figure 1 of the revised
58 manuscript. In the updated analysis, EOF1 and EOF2 explain 21.3% and 13.4% of the
59 total variance, respectively. These tests demonstrate that the MIOD pattern and its
60 associated atmospheric impacts are robust to the choice of SST preprocessing.
61 Notably, removing the EESC step has only a minor effect on the identification of
62 MIOD years—the revised positive-event list differs by only one year from the original
63 selection. The details of this comparison are provided in our response to Comment 2.

64 **Corresponding Revisions in the manuscript:**

- 65 • The previous description of detrending and EESC regression (former Eq. 9
66 and related text in Section 2.1) has been removed.
- 67 • The Methods section now states that the EOF analysis is applied directly to
68 **JJA SST anomalies without detrending or EESC adjustment.**
- 69 • The figure caption of Fig. 1 has been updated to reflect the revised
70 preprocessing.
- 71 • EESC is now discussed only in the context of long-term changes in the
72 atmospheric circulation and temperature fields, and is no longer used in the
73 SST processing or in the definition of the MIOD index.

74

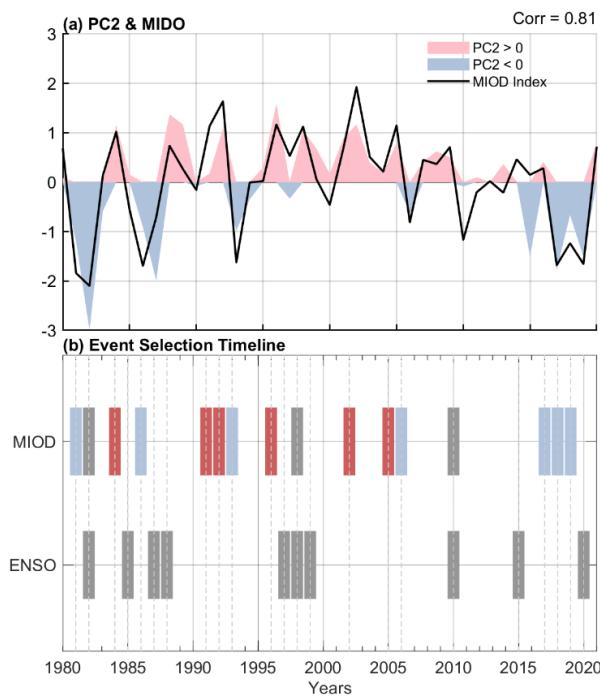
75 **2) Event selection and ENSO aliasing**

76 *The paper aims to separate MIOD impacts from ENSO, but the threshold-based
77 exclusion (JJA Niño-3.4 $\pm 1\sigma$) is a blunt tool. A case in point is 2016: the trailing
78 influence of the 2015–16 El Niño plausibly persists into mid-2016, yet 2016 enters the
79 “positive MIOD” set. Given the small sample, one influential year can strongly color
80 the composites in Fig. 3. Threshold exclusion is weaker than regression-based
81 control. The latter is standard and makes better use of the record. At a minimum the
82 reader needs to see a 2016-excluded positive composite and a regression-controlled
83 view to judge robustness.*

84 **Response:** Thanks for this helpful comment. You noted that excluding ENSO years
85 solely by applying a JJA Niño-3.4 $\pm 1\sigma$ threshold may not fully separate MIOD from
86 ENSO influences, especially for 2016, which may still carry residual effects from the
87 strong 2015-2016 El Niño.

88 After revising our SST preprocessing to use JJA SST anomalies directly (see
 89 Response to Comment 1), the temporal evolution of the MIOD index also changed
 90 slightly. As a result, **2016 is no longer selected as a positive MIOD year**, even under
 91 the original $\pm 1\sigma$ threshold method. The revised MIOD event lists differ from the
 92 original submission by only one event on each side.

93 To further assess robustness, we followed the reviewer's suggestion and
 94 performed an additional test by **removing the linear influence of ENSO from the**
 95 **MIOD index**. Specifically, we regressed the MIOD index onto the JJA Niño-3.4
 96 index and repeated the event identification using the ENSO-removed residual. This
 97 regression-based selection yields a set of MIOD years that is nearly identical to the
 98 threshold-based set, again differing by only one event (**Figure 2R**).



99
 100 **Figure R2:** (a) Austral winter (JJA) MIOD index with the linear Niño-3.4 contribution removed
 101 (black) and the corresponding PC2 time series, with positive (negative) PC2 values shaded in red
 102 (blue). (b) Two-line timeline summarizing MIOD event selection. Gray bars mark ENSO years.
 103 Red and blue bars represent positive and negative MIOD anomalies, respectively, while gray bars
 104 in the MIOD row indicate years in which MIOD events overlap with ENSO and are thus excluded
 105 from the independent MIOD composites.

106 Importantly, the composite atmospheric circulation and temperature responses
107 remain essentially unchanged across all sensitivity tests of the revised threshold-based
108 selection and the regression-controlled MIOD index.

109 These results indicate that the MIOD-related atmospheric signals are not
110 sensitive to whether 2016-or any ENSO-influenced year-is included, and that MIOD
111 and ENSO impacts are effectively separated for the purposes of this study.

112 We have updated Figure 2 (event selection) and the related text in the manuscript
113 to reflect the revised MIOD years as “As a robustness check, we also removed the linear
114 influence of ENSO by regressing the MIOD index onto the JJA Niño-3.4 index before
115 identifying events. The resulting MIOD years were nearly identical to those obtained
116 using the threshold-based approach, differing by only one positive event”.

117 The MIOD years used in the final analysis are:

118 **Positive MIOD:** 1984, 1992, 1996, 2002, 2005

119 **Negative MIOD:** 1981, 1986, 1993, 2006, 2017, 2018, 2019

120 It is true that both the positive and negative MIOD are modest in number, which
121 limits statistical power. Nevertheless, all reasonable perturbations to events selection
122 (leave-one-out removal, Niño-3.4 regression control, and threshold perturbations)
123 converge on the same qualitative asymmetry, indicating that no single year is
124 disproportionately influencing the results.

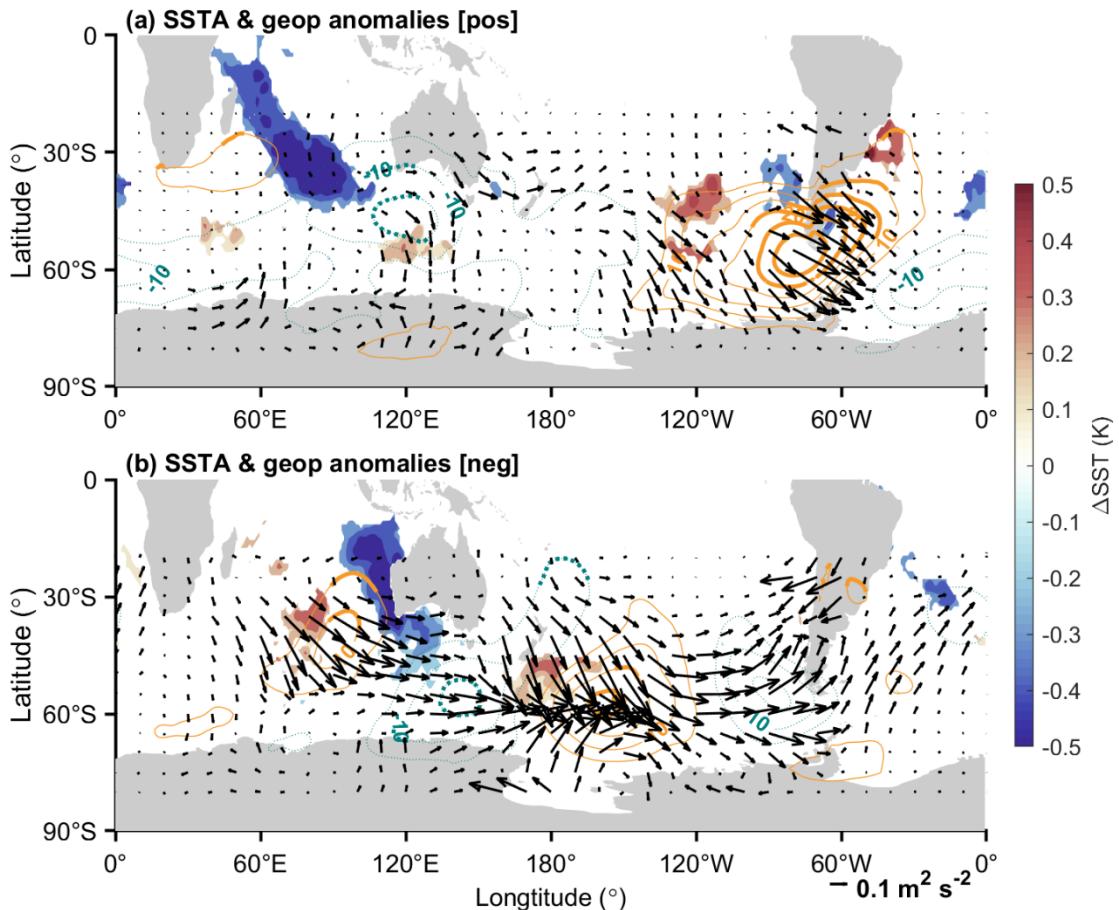
125 **3) Positive-negative asymmetry: mechanism and power**

126 *The descriptive evidence for asymmetry is good (Fig. 5), but the paper stops short of
127 explaining why the SST patterns in Fig. 4 project so differently onto the large-scale
128 wave field. There is room, and need, for a more mechanistic line: stationary-wave
129 sources/diabatic heating anomalies, Charney–Drazin refractive index/waveguide
130 diagnostics, or MIOD→WN-1 amplitude regressions would move the argument
131 beyond “constructive vs destructive interference”. The negative-event null should
132 also be tempered by an explicit acknowledgement of limited power (7 cases) and
133 supported by leave-one-out and threshold-sensitivity checks. A brief discussion of
134 MIOD’s relationship to the SAM would give useful context for vertical propagation
135 and annular-mode fingerprints.*

136 **Response:** We appreciate your suggestion to further substantiate the mechanism
137 underlying the positive-negative asymmetry. To determine whether the planetary-

138 wave anomalies in the composites originate from the Indian Ocean SST forcing, we
139 include the Takaya–Nakamura (TN) wave-activity flux to diagnose the stationary-
140 wave response and its source region.

141



142

143 **Figure R3 (Figure 4 in the revised manuscript):** Composite anomalies for positive MIOD
144 events during June–August (JJA). (a) Sea surface temperature (SST) anomalies (shading), with
145 only regions passing the 90% Monte Carlo confidence test shown. Overlaid contours indicate
146 zonal anomalous geopotential height at 850 hPa, with orange (blue) lines representing positive
147 (negative) anomalies. Contours are bolded where the anomalies are statistically significant at the
148 90% confidence level. Black arrows show the Takaya-Nakamura wave activity flux (TN flux) at
149 850 hPa, illustrating the horizontal propagation of anomalous planetary wave activity. (b) is the
150 same as (a) but for composite of negative events.

151 As shown in Figure 3R (Fig. 4 in the revised manuscript), the MIOD SST dipole
152 modifies lower-tropospheric thermal contrast and diabatic heating, providing a
153 planetary wave source over the midlatitude Indian Ocean. Consistent with this
154 forcing, both positive and negative MIOD events generate clear TN-flux anomalies at

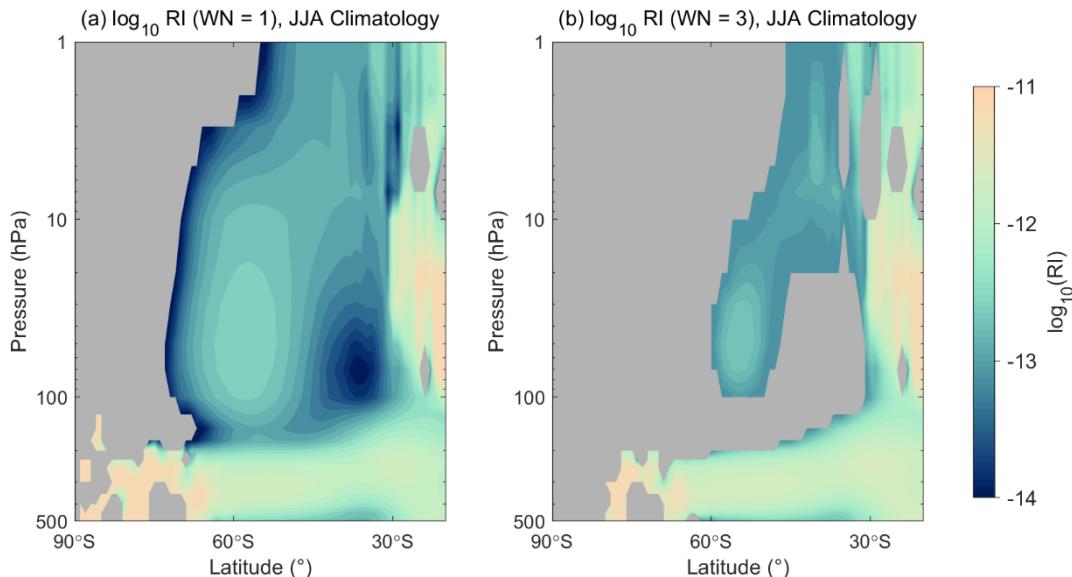
155 850 hPa (**Figure 3R**), indicating that the SST pattern projects onto the large-scale
156 wave field in both phases. However, the associated geopotential height anomalies
157 reveal a fundamental structural difference: positive MIOD events are dominated by a
158 zonal wavenumber-1 pattern, whereas negative MIOD events project mainly onto
159 wavenumber-3.

160 This distinction is crucial for vertical propagation. As shown by the Charney–
161 Drazin refractive index diagnostics (**Figure 4R**), the JJA waveguide from the upper
162 troposphere to the lower stratosphere favors the propagation of WN-1, while WN-3 is
163 strongly refracted or trapped below the tropopause. Thus, the null result for negative
164 events should not be interpreted as an absence of wave forcing, but rather as
165 ineffective vertical transmission due to the unfavorable WN-3 structure.

166 The related description and discussion are added in lines 438-448 of the revised
167 manuscript as “*To access whether the Indian SST anomalies and the global
168 geopotential anomalies are associated, we further examined the TN wave-activity flux
169 at 850 hPa (as indicated by the vector in Fig. 4). For either positive or negative
170 MIOD cases, TN-flux perturbations extend from the midlatitude eastward to the south
171 Pacific, indicating that SST anomalies in either events can modulate the large-scale
172 wave field. The similarity of the TN-flux patterns between positive and negative
173 MIOD events indicates that both phases are capable of exciting planetary-wave
174 activity over the midlatitude Indian Ocean. Thus, the contrasting atmospheric
175 responses between the two phases are unlikely to arise from differences in the strength
176 or spatial extent of the planetary -wave forcing itself. Instead, this result suggests that
177 the differences in the structure and phase of the associated geopotential height
178 anomalies may motivates a more targeted diagnosis of the planetary-wave
179 characteristics.”*”

180 Finally, as suggested by the reviewer, we added a brief discussion in the revised
181 manuscript noting that the enhanced upward propagation of WN-1 during positive
182 MIOD events weakens the stratospheric polar vortex and therefore projects onto the
183 negative phase of the Southern Annular Mode (SAM) as “*The zonal wind and*

184 temperature anomalies (weakened midlatitude westerlies, strengthened high-latitude
 185 westerlies, and polar-cap warming) closely resemble the canonical negative phase of
 186 the Southern Annular Mode (SAM)” in lines 379-381 of the revised manuscript. This
 187 SAM-like pattern is included in the revised manuscript as a familiar dynamic
 188 fingerprint of the diagnosed stratospheric circulation anomalies.



189

190 **Figure R4 (also as Figure 6 in revised manuscript):** June–July–August (JJA) climatological
 191 refractive index (RI) for (a) zonal wavenumber-1 (WN-1) and (b) zonal wavenumber-3 (WN-3),
 192 averaged over 1979–2020. Negative RI values are masked and shown in gray. The pressure axis is
 193 plotted on a logarithmic scale.

194

195 **4) SD-WACCM6 framing**

196 *The SD configuration is nudged to reanalysis: it provides diagnostic consistency (e.g.,
 197 gravity-wave drag, MLT structure) rather than an independent forced response. The
 198 manuscript sometimes reads as if the model “confirms” the mechanism. It would be
 199 more accurate to present SD-WACCM6 as a way to diagnose fields not available in
 200 reanalysis, with language calibrated accordingly. If any free-running sensitivities or
 201 prior literature exist that align with the sign/structure of the MLT anomalies, pointing
 202 to them would help.*

203 **Response:** Thank you for this important clarification. We fully agree that, because the
 204 SD-WACCM6 configuration is nudged toward reanalysis in the troposphere and
 205 stratosphere, it should not be interpreted as an independent simulation of an MIOD-

206 forced response. We have revised the section 4 in the manuscript accordingly to avoid
207 any language suggesting model “confirmation” of the mechanism.

208 To clarify, nudging in SD-WACCM6 is confined to the lower and middle
209 atmosphere (approximately below 50–60 km), and the mesosphere–lower
210 thermosphere (MLT) remains free-running. The mesosphere response discussed in the
211 manuscript (e.g., gravity-wave drag, residual circulation, and thermal anomalies)
212 therefore represent internally generated variability that is dynamically conditioned by-
213 but not prescribed by-the imposed stratospheric anomalies associated with the MIOD.

214 In light of this, SD-WACCM6 is now presented solely as a diagnostic tool that
215 provides access to dynamical quantities and vertical structures not available from
216 reanalysis (such as gravity-wave drag or mesospheric zonal wind). The revised
217 manuscript calibrates the language to emphasize this diagnostic role and remove any
218 implication of causal validation.

219 We also note in the Discussion that the simulated mesospheric response shows
220 structural consistency with HALOE-SABER observations, which supports the
221 plausibility of the proposed upward-coupling mechanism without treating SD-
222 WACCM6 as an independent forcing experiment.

223

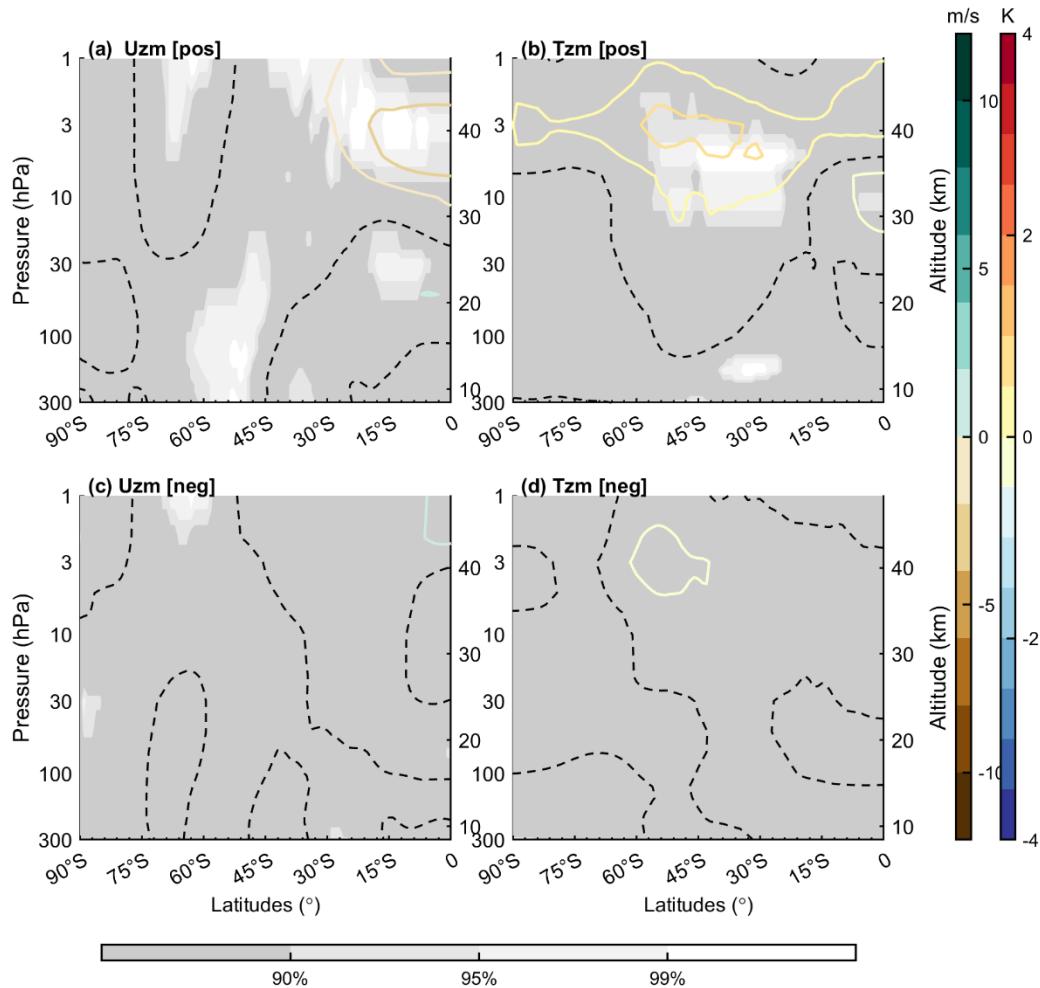
224 **5) Temporal evolution and breadth of robustness**

225 *The proposed pathway invites questions about onset/persistence and seasonality.*
226 *Lead–lag views (MAM→JJA→SON) would clarify timing and any spring imprint,*
227 *and a second reanalysis (JRA-55, MERRA-2) for key figures would demonstrate that*
228 *results are not a one-dataset artifact. Claims about vortex “morphology” would*
229 *benefit from simple, objective metrics (PV or geopotential on an isentrope; centroid,*
230 *ellipticity, equivalent area).*

231 **Response:** We appreciate the reviewer’s suggestion to examine the temporal
232 evolution and robustness of the diagnosed MIOD influence. To address this, we
233 performed additional lead-lag composite analyses and reanalysis cross-validation.

234 **(1) Lead–lag seasonal evolution (MAM → JJA → SON).**

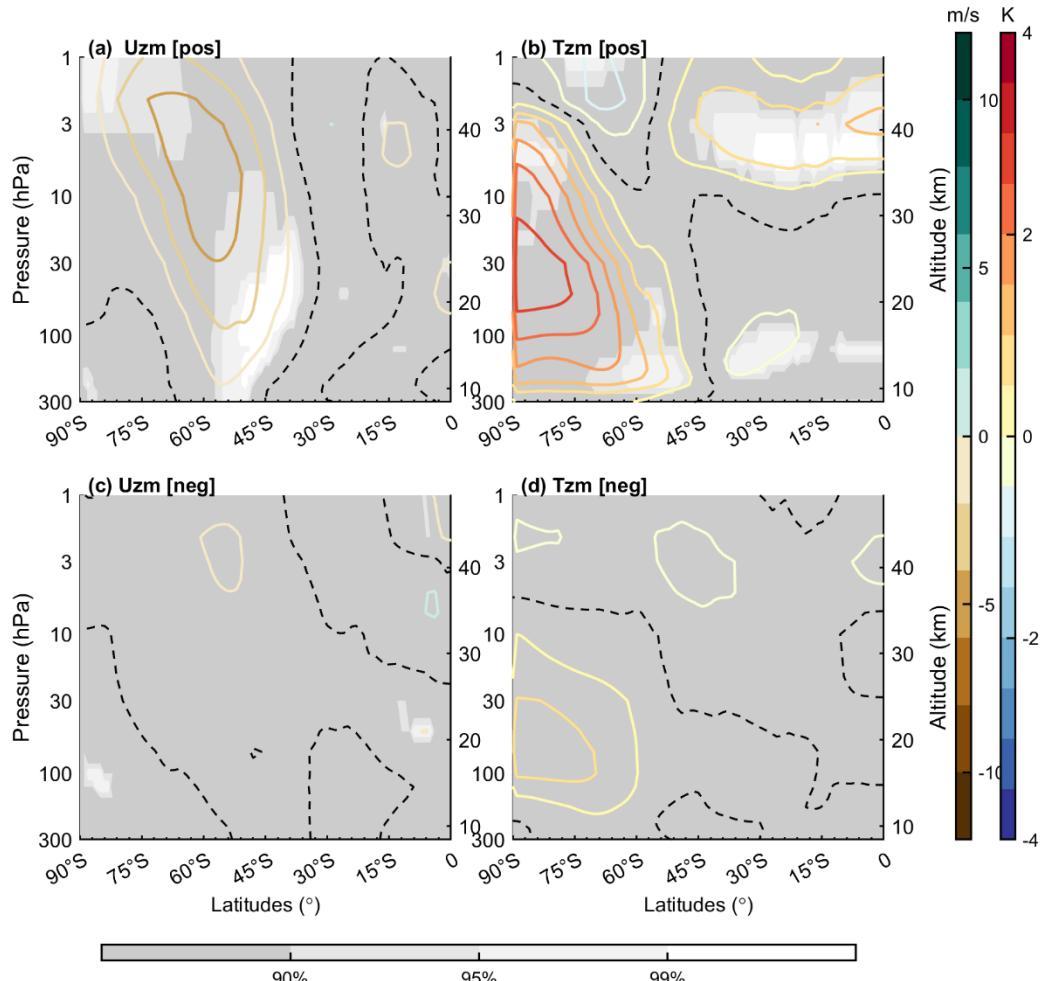
235 We conducted composite analyses for MAM and SON using the same MIOD
 236 event years. In MAM, only very weak midlatitude stratospheric temperature and zonal
 237 wind anomalies were detected (<1 K and <3 m/s), most of which are not significant
 238 (**Figure R5**). In SON, a vortex-weakening pattern (high-latitude warming and
 239 decreased zonal winds near 60° S) was apparent, but generally lacked statistical
 240 significance (**Figure R6**).



241
 242 **Figure R5:** (a) Composite zonal-mean zonal wind anomalies for positive MIOD events during
 243 MAM. Contours represent wind anomalies, with the dashed contour denoting the zero line.
 244 Shading indicates statistically significant regions based on a Monte Carlo test. (b) Same as (a), but
 245 for the zonal mean temperature anomalies. (c) and (d), similar to (a) and (b) but for negative
 246 MIOD events.

247 These results indicate that the MIOD influence is most dynamically organized
 248 during JJA, consistent with the seasonality of the SH wintertime waveguide and
 249 planetary-wave transmission. For this reason, and to maintain a clear scientific

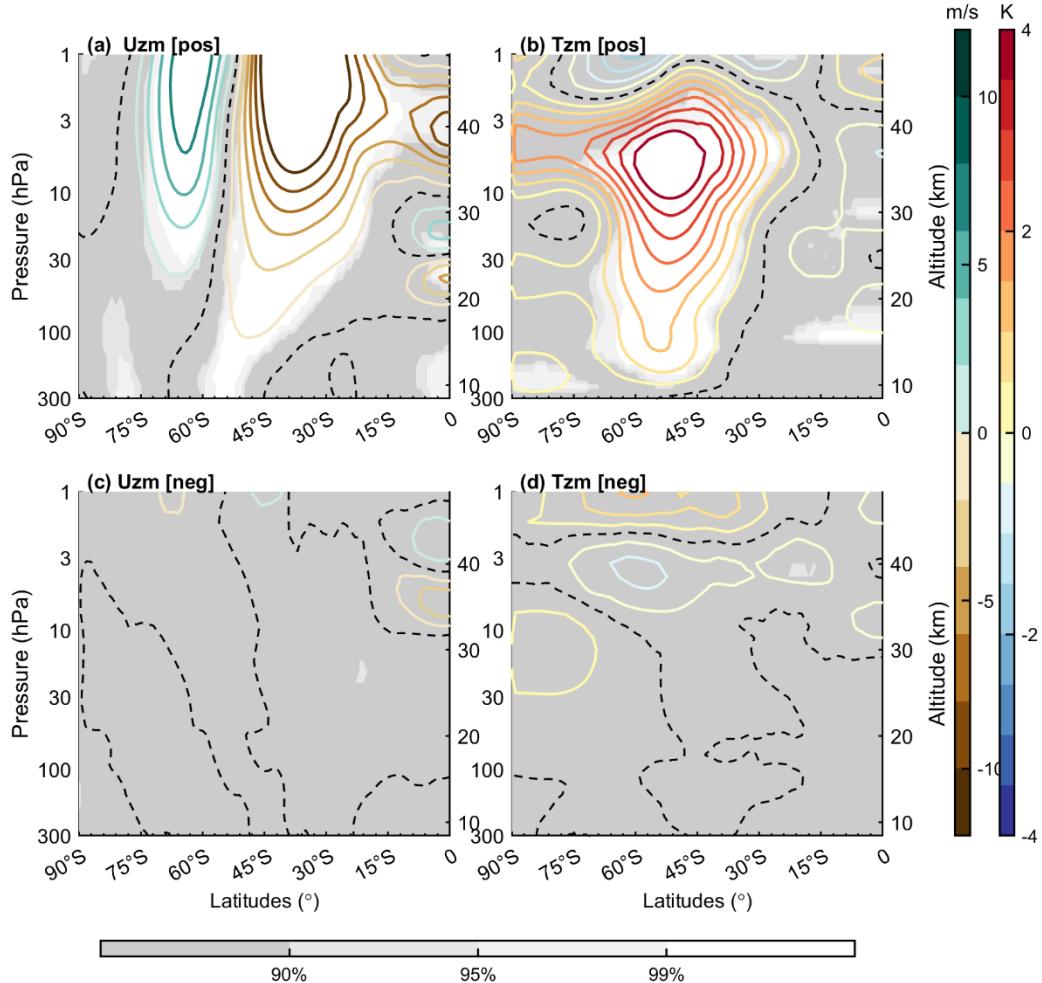
250 narrative, we do not include them in the revised manuscript, but summarize them here
 251 as here as part of the robustness assessment here.



252
 253 **Figure R6:** Same as Figure R5, but for composite of SON.
 254

255 **(2) Cross-reanalysis robustness (ERA5 vs. MERRA-2).**

256 To assess dataset sensitivity, we repeated the key JJA composites using
 257 MERRA-2. The spatial structure and amplitude of the temperature, zonal-wind, and
 258 planetary-wave anomalies closely resemble those in ERA5 (Fig. R7), indicating that
 259 the main results are not dependent on a single reanalysis product.
 260



261

262 **Figure R7:** (a) Composite zonal-mean zonal wind anomalies for positive MIOD events based on
 263 MERRA2 datasets. Contours represent wind anomalies, with the dashed contour denoting the zero
 264 line. Shading indicates statistically significant regions based on a Monte Carlo test. (b) Same as
 265 (a), but for the zonal mean temperature anomalies. (c) and (d), similar to (a) and (b) but for
 266 negative MIOD events.

267

268 **(3) Objective vortex morphology diagnostics**

269 As you suggested, we evaluated PV composites on the 850-K isentropic surface.
 270 Positive MIOD events display a clear zonally asymmetric PV anomaly and a
 271 westward displacement of the vortex boundary (as shown in Fig. 9 of the revised
 272 manuscript), consistent with the stationary WN-1 response diagnosed from the
 273 geopotential height and wave-activity fields. The related discussion is added in lines
 274 573-584 of the revised manuscript as “*Fig. 9 provides an objective view of how*

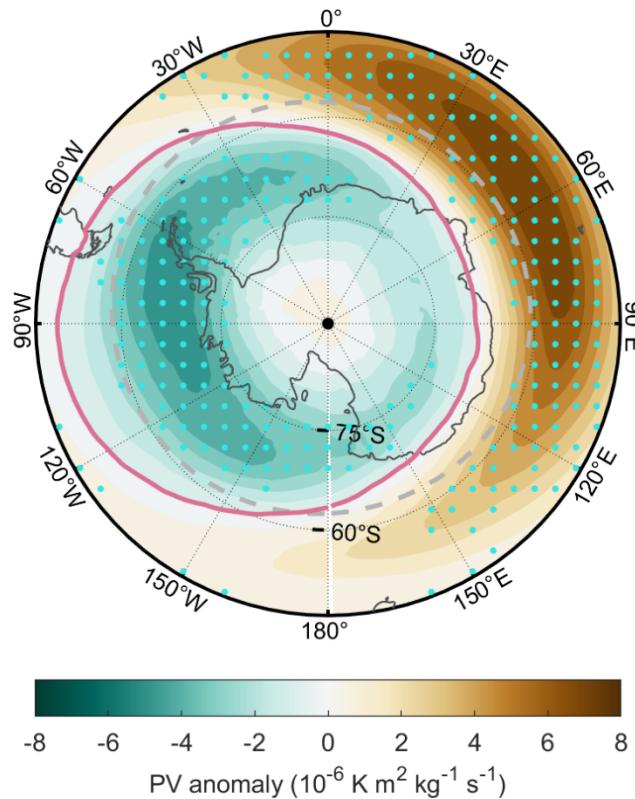
275 *positive MIOD events modify the Southern Hemisphere polar vortex by examining*
276 *potential vorticity (PV) anomalies on the 850-K isentropic surface. During positive*
277 *MIOD events, a zonally asymmetric PV anomaly pattern appears, with reduced PV*
278 *over the high-latitude western sector, while enhanced PV appears between 30°–60°S*
279 *in the eastern sector. This anomaly distribution is associated with a westward*
280 *displacement of the composite vortex boundary (pink solid contour) relative to its*
281 *climatological position (dashed gray circle). Such a deformation of the vortex edge*
282 *represents a geometric manifestation of a stationary zonal wavenumber-1 (WN-1)*
283 *perturbation, consistent with the WN-1 geopotential height anomalies identified in*
284 *Figs. 4–5 and the associated refractive-index conditions that favor vertical*
285 *propagation. The PV-based metric therefore provides a structural complement to the*
286 *earlier diagnostics, illustrating how the MIOD-related wave perturbations project*
287 *onto the vortex geometry.”*

288 In contrast, negative-event PV anomalies are weak, spatially incoherent, and
289 generally not statistically significant, and the inferred vortex boundary shows no
290 meaningful displacement relative to the climatology. Because this does not constitute
291 a dynamically interpretable signal, we chose to present only the positive-event PV
292 composite in the main text.

293 We think these additional analyses address the reviewer’s robustness concerns by
294 demonstrating the seasonal dependence of the MIOD influence, reproducibility across
295 reanalysis products, and objective vortex-shape diagnostics that corroborate the
296 structure of the JJA response.

297

(a) MIOD Positive Composite (JJA)



298

299 **Figure R8 (Figure 9 in the revised manuscript):** Composite anomalies of the potential vorticity
300 (PV) field for positive MIOD events at the 850 K isentropic level during June–August (JJA).
301 Shading indicates the PV anomalies (units: $10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$), with stippling showing regions
302 exceeding the 95% Monte Carlo significance level. The dashed gray contour marks the
303 climatological polar vortex boundary derived from the JJA-mean PV field. The solid pink contour
304 shows the composite vortex boundary.

305

306 6) Ozone transport vs chemistry and gravity-wave filtering evidence

307 *The TCO/ozone anomalies are interpreted primarily as transport. Where available in
308 SD-WACCM6-SD, an ozone tendency decomposition (transport vs chemistry) or at
309 least correlations with residual vertical velocity would strengthen that interpretation.
310 For the MLT, the gravity-wave filtering story is plausible. If SABER gravity-wave
311 potential energy proxies or related diagnostics can be composited, they would provide
312 a welcome observational cross-check.*

313 **Response:** Thank you for the helpful suggestions to further substantiate the

314 interpretation of MIOD-related ozone anomalies as being primarily transport driven.

315 (1) Stratospheric ozone: strengthening the dynamical transport interpretation

316 All stratospheric ozone diagnostics in the manuscript are based solely on
 317 reanalysis ozone and winds rather than SD-WACCM6 output. Building on the
 318 reviewer's suggestion, we now include an observationally constrained TEM-style
 319 transport proxy computed from anomalous residual circulation multiplied by the
 320 climatology ozone gradients:

$$321 \quad T_{dyn} = -v^{*'} \frac{\partial [O3]}{\partial y} - \Delta w^{*'} \frac{\partial [O3]}{\partial z}$$

322 where $v^{*'}$ and $w^{*'}$ denote the anomalies of the TEM meridional and vertical
 323 residual velocities relative to their climatological means, and $\frac{\partial [O3]}{\partial y}$ and $\frac{\partial [O3]}{\partial z}$ are
 324 taken from the climatological zonal-mean ozone field. **This diagnostic therefore**
 325 **quantifies the anomalous dynamical transport associated with circulation**
 326 **anomalies, without relying on any model-derived tendency terms.**

327 MIOD-related transport anomalies are then obtained by compositing T_{dyn} over
 328 positive MIOD years, and these composites closely resemble the corresponding TCO
 329 and lower-stratospheric ozone anomalies (new Fig. 10), reinforcing the interpretation
 330 that the observed ozone responses arise predominantly from anomalous dynamical
 331 transport rather than chemistry. Because the reanalysis does not provide full ozone
 332 tendency partitions, this TEM-based diagnostic serves as a practical and robust
 333 observational constraint. The related discussion is added in the revised manuscript as
 334 “*The diagnostic transport terms further substantiate that these ozone anomalies arise*
 335 *primarily from dynamical redistribution rather than in situ chemistry. To quantify the*
 336 *contribution of large-scale dynamic transport to the ozone response, we diagnose an*
 337 *anomaly-based TEM transport proxy defined as:*

$$338 \quad T_{dyn} = -v^{*'} \frac{\partial [O3]}{\partial y} - \Delta w^{*'} \frac{\partial [O3]}{\partial z} \quad (13)$$

339 where $v^{*'}$ and $w^{*'}$ are anomalies of the meridional and vertical residual velocities
 340 relative to their climatological means, and the ozone gradients are computed from the
 341 climatological zonal-mean ozone field. This diagnostic represents the anomalous
 342 dynamical transport associated with circulation anomalies and is used to construct the
 343 horizontal and vertical transport components. Fig. 10c and 10d show the composite

344 anomalies of these meridional and vertical transport terms during positive MIOD
345 events.

346 The meridional transport component (Fig. 10c) exhibits a dipole-like anomaly
347 pattern, with negative values near the subtropical stratopause ($\sim 30^\circ$ S, ~ 3 hPa) and
348 positive values over the midlatitudes around $\sim 60^\circ$ S and ~ 10 hPa. This dipole
349 structure indicates a strengthened poleward transport branch between these regions:
350 the negative anomalies near 30° S, 3 hPa are consistent with tendencies that remove
351 ozone from the subtropical stratopause, whereas the positive anomalies near 60° S,
352 10 hPa reflect tendencies that add ozone into the midlatitude stratosphere, in line with
353 the corresponding ozone anomalies. The vertical transport term (Fig. 10d) exhibits
354 anomalies that are consistent with the MIOD-related residual circulation. Negative
355 anomalies near $\sim 50^\circ$ S and ~ 3 hPa are consistent with an enhanced downward
356 branch of the anomalous residual circulation (Fig. 10a), which tends to export of
357 ozone-rich air from the stratopause region. At higher latitudes, the positive anomalies
358 between $\sim 70^\circ$ S and 10-20 hPa likely reflect the corresponding downward transport
359 of ozone into lower levels. The combined behavior of the meridional and vertical
360 transport terms closely matches the spatial pattern of ozone tendencies, indicating an
361 MIOD-related redistribution of ozone from the subtropical upper stratosphere toward
362 the midlatitude lower-middle stratosphere. This dynamical interpretation accounts
363 for the dominant features of the ozone response, although contributions from
364 chemical processes or other factors cannot be ruled out" in lines 647-664

365 To avoid confusion regarding the role of SD-WACCM6, we emphasize that the
366 model is used only to examine the possible upward influence of MIOD-induced
367 stratospheric dynamical perturbations on the mesosphere–lower thermosphere (e.g.,
368 gravity-wave filtering and mesospheric thermal responses). Because SD-WACCM6 is
369 nudged to reanalysis winds and temperatures in the stratosphere, its stratospheric
370 circulation is not freely evolving. A model-based ozone tendency decomposition
371 (transport vs. chemistry) would therefore not constitute an independent diagnosis of
372 ozone variability and would be difficult to interpret physically. For this reason, all

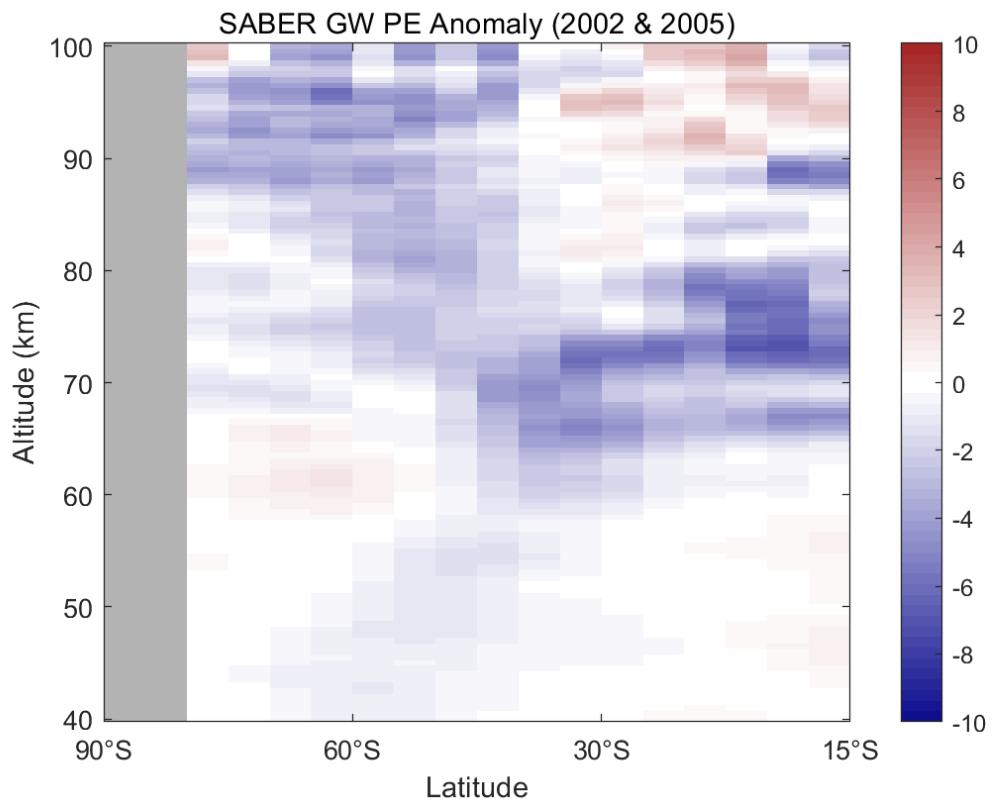
373 stratospheric ozone diagnostics and interpretations rely exclusively on reanalysis data,
374 while SD-WACCM6 is used only for quantities that are not available from reanalysis
375 and for exploring the upward dynamical coupling into the mesosphere.

376 (2) Mesosphere–lower thermosphere: observational support for gravity-wave filtering

377 While we agree that such diagnostics would be valuable, SABER’s observational
378 constraints limit the feasibility of constructing statistically meaningful MIOD
379 composites. In particular, SABER’s Southern Hemisphere sampling window begins
380 only in mid-July each year, and the SABER data record overlaps with only two robust
381 MIOD positive/negative event pairs (2002 and 2005). This small sample size prevents
382 reliable isolation of MIOD-related signals from other sources of interannual
383 variability such as ENSO, QBO, or volcanic influences. Furthermore, GWPE provides
384 information on wave amplitude but not propagation direction, and thus cannot
385 independently diagnose gravity-wave drag.

386 Nevertheless, we analyzed detrended SABER GWPE anomalies for the available
387 years as qualitative case studies. Both 2002 and 2005 exhibit reduced GWPE above
388 ~60 km in the winter midlatitudes during mid-July to late August, consistent with
389 stronger filtering by enhanced stratospheric westerlies during positive MIOD
390 conditions. Although these examples do not allow statistical attribution, they provide
391 observationally grounded, non-conclusive support for the plausibility of the proposed
392 filtering mechanism. The corresponding GWPE plots are included in the Supplement
393 for completeness and transparency, and the manuscript refers to them only as
394 qualitative evidence.

395 A detailed clarification of the diagnostic role of SD-WACCM6 in the MLT is
396 provided in our response to Comment 4, and the revised manuscript has been
397 calibrated accordingly.



398

399 **Figure R9.** Mean detrended anomalies of SABER-derived gravity wave potential energy (PE) for
 400 2002 and 2005. Anomalies are computed relative to the 2002–2022 climatology and after
 401 removing the linear trend. Gray shading indicates missing data.

402

403 **Minor comments**

404 *The caption (Line 502) identifies the plot as showing TCO for negative MIOD events,
 405 but the pattern shown is a direct and obvious consequence of the circulation changes
 406 described for positive events in Figure 8a. The caption and text must be reconciled
 407 with the figure's content.*

408 **Response:** Thank you. The caption was mislabeled and has been corrected.

409

410 *The x-axis of Figure 6 (both panels) is incorrectly labeled "Longitude (°)." As this is a
 411 zonal-mean plot, the axis must be corrected to "Latitude (°)."*

412 **Response:** Thank you. The axis label has been corrected to “Latitude (°)” in the revised
 413 figure.

414 *The numbering is incorrect and inconsistent in Section 2.2. There are two equations*
415 *labeled (4), a jump from (5) to (9), and an unnumbered thermal wind equation. Please*
416 *correct all numbering to be sequential.*

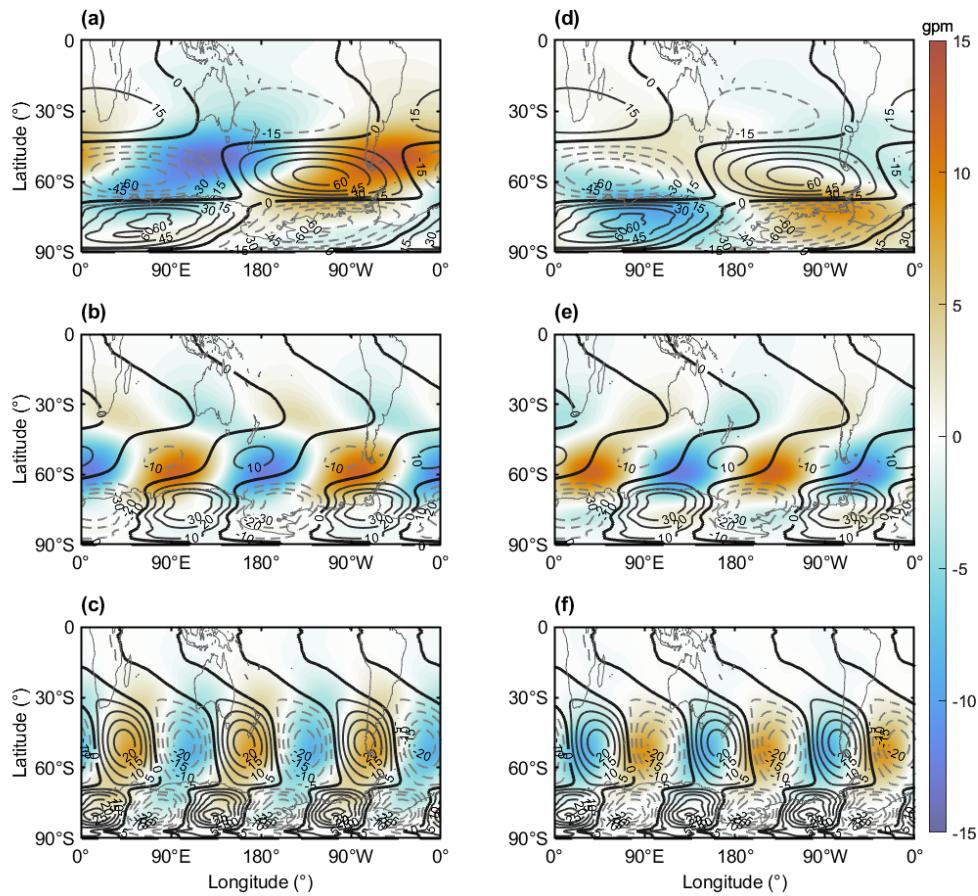
417 **Response:** We thank the reviewer for pointing this out. The equation numbering in
418 Section 2.2 has been corrected to be fully sequential. The duplicated label (4) has
419 been removed, the jump from (5) to (9) has been fixed, and the thermal wind equation
420 is now properly numbered as Eq. (10).

421 *Figure 2b Visualization: The overlapping symbols are confusing and inefficient for*
422 *conveying the event selection process. This figure should be replaced with a clearer*
423 *visualization, such as a timeline or a table.*

424 **Response:** Figure 2b has been completely redesigned. The previous overlapping
425 symbols have been removed and replaced with a two-line timeline visualization that
426 clearly distinguishes ENSO years from positive and negative MIOD anomaly years.
427 The revised timeline avoids symbol overlap, improves readability, and more
428 effectively conveys the event-selection procedure.

429 *Figure 5 Clarity: The climatology contours are difficult to distinguish from the zero*
430 *contour of the anomaly shading. Please use a different color or line style to improve*
431 *readability.*

432 **Response:** Thank you for noting this clarity issue. In the revised manuscript, we have
433 adjusted the color and line weight of the climatology contours to clearly distinguish
434 them from the zero-anomaly shading. The updated figure (revised Fig. 5) now
435 provides much improved visual separation and readability.



436

437 **Figure 5:** Composite anomalies of 850 hPa geopotential height for different zonal wavenumber
 438 planetary wave components during Southern Hemisphere winter (June–August, JJA), overlaid
 439 with the long-term climatological mean. (a–c) Composite results for positive MIOD events for
 440 zonal wavenumbers 1, 2, and 3, respectively; (d–f) same as (a–c), but for negative MIOD events.
 441 Shading indicates geopotential height anomalies, and contours represent the climatological mean.

442 ***Text-Figure Mismatch (Line 347): The text refers to Figure 4b as showing "positive-***
 443 ***phase MIOD events," but the figure shows the composite for negative events. Please***
 444 ***correct this.***

445 **Response:** Thank you for noting this oversight. The text has been corrected so that
 446 the description of Figure 4b now matches the negative-phase MIOD composite shown
 447 in the figure.

448 ***Typographical Errors:***

- 449 • ***Line 446: The latitude range "50°S-7°S" appears to be a typo and should***
 450 ***likely be "50°S-70°S."***
- 451 • ***Line 555: The sentence beginning "The spatial phase of this cold band..." is***
 452 ***redundant and should be revised or removed.***

453 **Response:** The latitude range has been corrected from “50°S–7°S” to “50°S–70°S,”
454 and the redundant sentence beginning with “The spatial phase of this cold band...”
455 has been removed in the revised manuscript.

456 *Methodological Justification:*

457 • *E-P Flux Normalization (Figure 6): The non-standard "two-layer*
458 *normalization approach" requires justification. Explain why this was*
459 *chosen over standard methods.*

460 **Response:** Thank you for the comment. A brief clarification has been added to the
461 manuscript: “For clarity, the tropospheric (900-300 hPa) and stratospheric (300-1 hPa)
462 E-P fluxes are plotted using separate normalization factors to improve the clarity of
463 the plotted vectors since the value in the tropospheric and stratospheric differ
464 substantially in magnitude.” in lines **521-523**. This clarification is now included in the
465 text accompanying Figure 7.

466 • *MIOD Index vs. PC2: Briefly elaborate on why a physically-based box*
467 *definition is preferable to the mathematically derived PC time series.*

468 **Response:** Thank you for the comment. The manuscript has been revised to briefly
469 clarify why a physically based SST box index is used instead of the EOF-derived PC2.
470 The box index provides a more intuitive and stable measure of MIOD variability **and**
471 **avoids the sensitivity of EOF-based PCs to the choice of analysis period and**
472 **preprocessing.** In addition, the box index is easier to compute and is directly
473 comparable across datasets and studies, similar to commonly used ENSO indices. This
474 makes it more suitable for identifying individual positive and negative MIOD events
475 and for constructing composites. The revised text now includes this explanation in the
476 section describing the construction of the MIOD index.

477 It has been explained as “*Using this physically based index rather than PC2 provides a*
478 *simpler and more intuitive metric for subsequent analyses and avoids the sensitivity of*
479 *EOF-derived PCs to choices of analysis period and preprocessing*” in lines 324-326 of
480 the revised manuscript.

481

482 **Comments on “Impact of the Indian Ocean Sea Surface Temperature on the**
483 **Southern Hemisphere Middle Atmosphere” by Yang et al.**

484 *This study investigates the impacts of the midlatitude Indian Ocean sea surface*
485 *temperatures (SSTs) on the Southern Hemisphere middle and upper atmosphere*
486 *based on the proposed midlatitude Indian Ocean Dipole (MIOD) index. The*
487 *authors show that positive MIOD events enhance planetary-wave propagation from*
488 *the Indian Ocean sector, leading to variations in temperature, zonal winds, as well*
489 *as a strengthening of the residual meridional circulation, while negative MIOD*
490 *events have relatively weak impacts on the Southern Hemisphere middle and upper*
491 *atmosphere. The issues tackled in this study are worthwhile and well within the*
492 *scope of this journal. However, some conclusions are lack of sound verification. It*
493 *needs major revisions before it is accepted for publication. The following are some*
494 *specific comments and suggestions:*

495
496 1. *Line 38-39: The stratospheric thermal radiation only can not insert*
497 *significant influences on both tropical and extratropical circulation, it is radiative-*
498 *chemical-dynamic coupling that is important.*

499 **Response:** Thank you for the comment. We agree that stratospheric impacts on
500 circulation arise from the combined effects of radiative, chemical, and dynamical
501 processes rather than thermal radiation alone. Accordingly, we have revised the
502 sentence in lines 37–41 to read:

503 “*Stratospheric processes—including thermal radiation and radiative-chemical—*
504 *dynamical coupling—have been shown to influence both tropical and extratropical*
505 *circulation, with further effects on surface temperature (Joshi et al., 2006; Maycock*
506 *et al., 2013; Shindell, 2001; Solomon et al., 2010; Tandon et al., 2011).*”

507 This revision clarifies that it is the coupled radiative–chemical–dynamical
508 processes that underpin the stratosphere’s influence on the climate system.

509
510 2. *Line 104-105: The statement “Yet the atmospheric background conditions*
511 *during austral winter are more favorable for planetary wave propagation into the*
512 *stratosphere” needs reference support.*

513 **Response:** Thank you for the comment. We have added a citation to **Charney and**
514 **Drazin (1961)**, which demonstrated that planetary waves can propagate vertically
515 only under westerly background flow, thereby providing the theoretical basis for why
516 austral winter conditions favor upward planetary-wave propagation.

518 3. *Line 164-166: what is the top level of MERRA-2 reanalysis? The WACCM6-*
519 *SD run at the model top near 140 km. On which model level does the nudging begin to*
520 *perform?*

521 **Response:** Thank you for the comment. We have added a clarification in lines 164–
522 170 of the revised manuscript as “*In the SD configuration, meteorological fields are*
523 *nudged toward MERRA-2 reanalysis every six hours to reduce internal variability*
524 *and model bias. WACCM6 is nudged toward MERRA-2 below approximately 0.1 hPa*
525 *(~50–60 km), with a smooth tapering of the relaxation coefficient near the upper*
526 *boundary of the nudged region. Above this altitude, including the mesosphere and*
527 *lower thermosphere, the model evolves freely. This setup allows the stratospheric*
528 *variability to follow the reanalysis while retaining internally generated dynamics in*
529 *the mesospheric region*”.

530

531 4. *Line 180: “between 40 and 80 kilometers” >>> “between 40 and 80 km”*

532 **Response:** Revised.

533 5. *Line 346: “positive-phase MIOD events” >>> “negative -phase MIOD events”*

534 **Response:** Revised.

535 6. *Line 362: what is hgt?*

536 7. *Line 368: HGT>>hgt*

537 **Response:** Thank you for the comment. We have clarified in the revised manuscript
538 that *hgt* denotes geopotential height, as introduced in the Data section. In addition, the
539 inconsistent appearance of the uppercase form *HGT* has been corrected, and the
540 notation has been standardized to *hgt* throughout the manuscript to ensure clarity and
541 consistency.

542 8. *Line 440: Figure 6: Longitude>>Latitude*

543 **Response:** Revised

544 9. *Line 510: “ozone deletion” >> “ozone decrease”. The depletion generally means*
545 *destroyed rather the transported.*

546 **Response:** Thank you for pointing this out. We agree that “ozone depletion” may
547 imply chemical destruction rather than transport-related decreases. We have revised
548 the wording in the manuscript and now use “ozone decrease” to accurately describe
549 the transport-driven changes.

550 *10. My major concern is related to Section 4. This section presents the results in the
551 mesosphere. It looks strange to put those results in Discussion Section. Are those
552 results are preliminary?*

553 **Response:** Thank you for raising this important point. Section 4 is not intended to
554 introduce preliminary or additional observational results. Instead, its purpose is to
555 extend the analysis vertically into the mesosphere and to provide a dynamical
556 interpretation of how the MIOD-related stratospheric perturbations documented in
557 Section 3 may project upward. Because gravity-wave processes and MLT variability
558 cannot be directly observed, we combine merged HALOE–SABER temperature data
559 with the free-running mesosphere of SD-WACCM6 to evaluate whether the observed
560 mesospheric patterns are dynamically consistent with those generated internally by the
561 model. To clarify this intent and avoid the impression that Section 4 presents a separate
562 set of results, we have revised the opening paragraph as “*The stratospheric responses
563 described above suggest that MIOD-related perturbations may extend upward into the
564 mesosphere, raising the question of how far the influence of MIOD projects vertically.
565 To investigate the full vertical structure of the atmospheric response, we complement
566 the stratospheric analysis with merged HALOE–SABER temperature observations
567 spanning 10–100 km and SD-WACCM6 simulations. Because the free-running nature
568 of SD-WACCM6 above ~50–60 km allows the mesosphere–lower thermosphere (MLT)
569 variability to evolve independently of the imposed stratospheric state, the comparison
570 between observations and model output provides a basis for examining whether the
571 mesospheric anomalies inferred from observations are dynamically consistent with
572 those that arise internally in the model. This framework enables us to assess potential
573 pathways through which MIOD-related stratospheric perturbations may influence the
574 mesosphere, without presupposing the underlying dynamical mechanism*” in lines 666–
575 677 of the revised manuscript to provide a smoother transition from the stratospheric

576 analysis and updated the title of Section 4 to better reflect its interpretative nature.

577

578 **11. Line 540: Figure 9: above 80 km, there is no consistency between the satellite**
579 **observations and model results. Is it due to nudging approach?**

580 **Response:** Thank you for the comment. The lack of consistency above \sim 80 km arises
581 from several factors. First, SD-WACCM6 is nudged toward reanalysis only below
582 approximately 0.1 hPa (\sim 50–60 km), and the mesosphere–lower thermosphere above
583 this level is fully free-running. As a result, the model does not reproduce event-
584 specific variability in the upper mesosphere that is not directly controlled by the
585 imposed lower-atmospheric state. Second, the observational composite (HALOE–
586 SABER, 1991–2022) and the model composite cover different sampling periods,
587 which may further contribute to differences at altitudes where internally generated
588 variability dominates. We have added a clarification in the revised text as “*However,*
589 *the midlatitude warming in mesosphere/lower thermosphere region seen in*
590 *observations is largely absent in the model, and the tropical anomaly remains below 1*
591 *K and is not statistically significant. This discrepancy between the observations and*
592 *SD-WACCM6 may indicate that the processes giving rise to the upper-mesospheric*
593 *and lower-thermospheric response are not fully captured, as SD-WACCM6 is not*
594 *constrained in the mesosphere. An additional contributing factor may be the non-*
595 *overlapping portions of the observational record (1991–2022) and the model*
596 *simulation period used here.*” (Lines 700-706) to make these points explicit.

597 **12. Line 590-594: The authors stated that “Discrepancies between thermal wind**
598 **estimates and reanalysis winds are largely attributable to planetary wave**
599 **breaking”. This is not true! various processes may have contributions to those**
600 **discrepancies.**

601 **Response:** Thank you for pointing this out. We agree that our original formulation
602 was overly assertive and did not adequately reflect the range of processes that can
603 lead to discrepancies between thermal-wind estimates and reanalysis winds. Our EP-
604 flux and planetary-wave diagnostics suggest that wave forcing is a plausible
605 contributor, but other processes not explicitly analyzed here (e.g., diabatic heating and

606 radiative–chemical tendencies) may also play a role. We have therefore revised the
607 sentence as “*Deviations between thermal-wind estimates and reanalysis winds further*
608 *point to a dynamical contribution from planetary-wave forcing, although diabatic,*
609 *radiative, and chemical processes may also play a role*” in lines 748-750 of the
610 revised manuscript to state that planetary-wave forcing likely contributes to the
611 discrepancies, while acknowledging that additional processes may also be important.

612 *13. Line 597-598: The authors stated that “The influence of the MIOD extends into*
613 *the mesosphere and lower thermosphere (MLT) through gravity-wave filtering*
614 *modulated by stratospheric wind perturbations”. This statement has no support.*

615 **Response:** Thank you for the comment. We agree that the original statement
616 overstated the vertical extent and certainty of the mechanism. We have revised the
617 wording to reflect only the supported mesospheric response and to frame the gravity-
618 wave contribution more cautiously. The revised sentence now reads: “*In the*
619 *mesosphere, SD-WACCM6 produces a response that is structurally similar to satellite*
620 *observations. Within the model, MIOD-related stratospheric wind anomalies*
621 *modulate gravity-wave filtering and wave-mean flow interactions, leading to coherent*
622 *mesospheric drag and circulation anomalies. While discrepancies persist, particularly*
623 *at higher altitudes, these results indicate that gravity-wave filtering provides a*
624 *physically plausible pathway linking MIOD-related stratospheric disturbances to the*
625 *mesospheric response*” in lines 751-756 of the revised manuscript.

626
627 *14. Line 625-627: “The findings are consistently supported by satellite observations*
628 *and WACCM6 simulations, lending robustness to the identified SST atmosphere*
629 *coupling”. However, there are no any comparisons between the model results and*
630 *satellite observations in the stratosphere.*

631 *15. Line 628-629: “with the Southern Hemisphere atmosphere being more sensitive*
632 *due to its unique background circulation during winter”. There are no any*
633 *discussions on this statement.*

634 **Response:** Thank you for these helpful comments. We agree that the original wording
635 overstated both the degree of observational–model consistency and the interpretation
636 of hemispheric sensitivity. We have revised the conclusion to make clear that the
637 consistency between satellite observations and SD-WACCM6 refers specifically to

638 the mesospheric response. We have also removed the statement that the Southern
639 Hemisphere atmosphere is “more sensitive due to its unique background circulation
640 during winter” and now frame the role of MIOD more generally as a potential
641 additional driver of large-scale atmospheric variability alongside established
642 influences such as ENSO and the QBO. This part has been revised as “*Satellite*
643 *observations and SD-WACCM6 simulations further indicate that MIOD-related*
644 *anomalies extend into the Southern Hemisphere mesosphere, with the model*
645 *suggesting a role for gravity-wave drag modulation in linking stratospheric wind*
646 *anomalies to the mesospheric response. The MIOD-related atmospheric signal*
647 *identified here indicates that Indian Ocean SST variability acts as an additional*
648 *source of large-scale dynamical variability in the Southern Hemisphere,*
649 *complementing established influences such as ENSO and the QBO, and highlighting a*
650 *previously underappreciated pathway through which tropical ocean variability affects*
651 *the middle and upper atmosphere on interannual timescale.*” In lines 773-780 of the
652 revised manuscript.

653

654 16. Line 632-633: “*The analysis further suggests that long-term trends in Indian*
655 *Ocean SST may have contributed to the observed variability in Antarctic ozone*
656 *depletion and recovery*”. *There are no any discussions on the long term trends of*
657 *variables. How can you draw this conclusion?*

658 **Response:** Thank you for pointing this out. We agree that the original sentence
659 introduced an implication regarding long-term SST trends and ozone variability that
660 was not directly analyzed in this study. Since our focus is on the interannual response
661 of the middle and upper atmosphere to MIOD variability, we have removed this
662 statement from the conclusion to avoid overinterpretation.