Response to comments by Reviewer #1

Thank you very much for your valuable comments and suggestions. Please see below for our answers to yours.

General comment:

This study examines 30-year climatology of the major variables and terms of the transformed Eulerian-mean (TEM) momentum and thermodynamic equations by using four global reanalyses data including MERRA-2, JRA-55, ERA-Interim, and CFSR for boreal winter (December–February, DJF) and summer (June–August, JJA). By calculating the reanalysis ensemble mean (REM) of the individual terms in the TEM equations, the authors illustrate the climatological properties and relative importance of the terms. Through this analysis, a significant magnitude of the residual is identified in both the momentum and thermodynamic energy equations and their potential sources are also discussed. Differences in each of the four reanalysis datasets compared to the REM exhibit distinct features, indicating inconsistency among the reanalysis data in representing the dynamical structures of the troposphere and the stratosphere.

Thank you very much for your very nice summary of our results.

While the authors make the best effort to calculate and visualize the various terms in TEM equations with caution, 1) the sequence of analysis in this paper makes it challenging to connect specific results with their respective causes. In this regard, the differences among each reanalysis data are just listed without a comprehensive summary. 2) Insufficient elucidation regarding the causes of the differences also calls for additional clarification. Moreover, 3) despite the division of analysis into DJF and JJA, the discussion on seasonal variations appears insufficient, giving the impression that the aspects observed in winter are likewise depicted in summer. Therefore, I hope that the authors will refine the manuscript taking into account the suggested revisions, making it novel enough for publication in ACP. The specific comments are as follows.

Regarding 1), we will follow your practical suggestions which are written below.

Regarding 2), we thank the reviewer for the suggestions of additional discussion which are written below. They are very helpful.

Regarding 3), three reviewers have provided us with different suggestions on the choice of season(s).

Reviewer #1 suggested that it may be sufficient to show either DJF or JJA only in the main text and move the other to the Supplement. Reviewer #2 suggested to add annual means and/or some additional months. Reviewer #3 suggested to show either MAM or SON.

We would like to keep the current choice, i.e. showing both DJF and JJA with MAM and SON being shown in the Supplement. This is because DJF and JJA are the two contrasting seasons often discussed in tandem in the literature. Our analysis shows that the characteristics of the differences are qualitatively similar (with quantitative differences) in the winter/summer hemisphere for DJF and JJA. Therefore, if we show only the results for e.g. DJF in the main text, we expect that readers would wonder about the other season, JJA, or vice versa, whereas leaving results for the equinox seasons MAM and SON in the supplement saves space while still making these seasons available for examination.

Major comments

1. As the analysis alternates between the momentum and the thermodynamic equation, there appears to be a deficiency in establishing a seamless connection between the results and their underlying causes. Hence, it is recommended to commence the analysis with the momentum equation and subsequently address the thermodynamic energy equation, accompanied by a rearrangement of the figures accordingly.

Thank you for your suggestion. We will follow your advice and switch Figures 2 and 3, Figures 6-7 and 8-9, etc. in the revised manuscript.

2. A matter related to Major Comment 1 is observed concerning the discussion of differences among reanalysis datasets. The content addressing these distinctions appears detached and comes much later without a link, making it challenging to summarize the causes and outcomes of these differences. Examples are as follows:

A. Differences in the meridional circulation: Regarding a stronger (weaker) residual-mean meridional circulation represented by JRA-55 (MERRA-2) compared to REM (Figure 5, L356–357), the authors attribute stronger (weaker) $\bar{v}^*$ described in Supplementary Folder 3 as a responsible cause. Since $\bar{v}^*$ is associated with the resolved wave forcing (Eq. 1), I expect the analysis of EPFD following this finding. However, the discussion about EPFD takes place in L412–418 with Figure 9 after the discussion on radiative heating. Accordingly, the fact that JRA-55 (MERRA-2) has negative (positive) EPFD differences in the dominant negative EPFD regions, which indicates that the overestimation (underestimation) of negative EPFD in comparison to REM, is not perceived to be connected to the stronger (weaker) meridional circulation in JRA-55 (MERRA-2). As Figure 8 describes the Coriolis forcing $f\bar{v}^*$, rearranging the order to present Figures 5 followed by Figure 8 and 9 could enable the authors to maintain the same explanation, while providing a comprehensive summary for the distinct meridional circulations between JRA-55 and MERRA-2.

Thank you very much for pointing these characteristics out. In the revised manuscript, we will change the order of figures and paragraphs in the Differences section as you suggested to improve the flow of the manuscript.

B. Differences in the total radiative heating in Figure 11: According to Figure 2, 6, and 7, it is identified that ERA-Interim and CFSR tend to overestimate the longwave (LW) cooling as well as shortwave (SH) warming, although the responsible cause are different. Conversely, MERRA-2 and JRA-55 tend to underestimate them. However, in Figure 11, MERRA-2 and ERA-Interim (JRA-55 and CFSR) exhibit positive (negative) deviation of the total heating from REM. Based on the findings in Figure 6 and 7, the differences in total heating shown in Figure 11 could be connected to the aforementioned tendencies with respect to LW and SW. In the case of CFSR (ERA-Interim), the overestimation of LW cooling is greater (less) than that of SW warming, contributing to the negative (positive) total heating difference. In contrast, for JRA-55 (MERRA-2), underestimation of LW cooling is less (greater) than that of SW warming, leading to negative (positive) total heating difference.

Thank you very much for describing all these characteristics, which will be included in the revised manuscript.

3. The authors conduct the same analyses during both winter and summer, presenting the same figures for both seasons. However, if seasonal variations do not significantly impact the results, it might be more concise and appropriate to show only the key differences in the main results and move the remaining details to the supplementary material, emphasizing the essential findings.

As explained above, we prefer to keep both DJF and JJA in the main text. In the Abstract and in Section 4 (Summary), we think that your point is clear.

Minor comments

1. L90: The sentence is not well organized. Below sentence is one of the recommendations.
We first present the findings for the reanalysis ensemble mean (REM), followed by an analysis of the

discrepancies of each reanalysis from the REM during DJF and JJA.

Will be considered in the revised manuscript.

2. L212–213: I think there is no need to separate the temperature description by altitude since the Northern Hemisphere stratosphere is consistently colder than the Southern Hemisphere stratosphere across all altitudes.

Will be considered in the revised manuscript.

3. L215: Please specify the altitude of two maxima of the upwelling in the tropics

The two small local maxima in w_res (Figure 1e) are located around 50-70 hPa (both at 50 hPa and at 70 hPa, two maxima are found at 15S and at 12.5N). The point is that the equatorial 50-70 hPa has a minimum, not a maximum.

4. L244: reanalyses.The > reanalyses. The

A space will be added.

5. L244: Remove the closing parenthesis at the end of this sentence.

Will be removed.

6. L312: Podglajen et al., 2020 > Podglajen et al. (2020)

Will be corrected.

7. L351–353: Please consider adding a brief mention or acknowledgment of the observed temperature differences in the reanalyses, as the temperature plays a significant role in the radiative heating.

Will be added.
DJF: In the upper stratosphere, JRA-55 is colder and CFSR is warmer with MERRA-2 and ERA-Interim being in the middle. (For longwave heating, JRA-55 shows positive anomalies, and CFSR shows negative anomalies; in other words, CFSR has stronger cooling, consistent with the cooling to

space theory, i.e. the Newtonian cooling approximation.)
JJA: The tendencies are the same as those in DJF.

8. L310–315, L515–519: CFSR and MERRA-2 reanalysis data provide the parameterized orographic gravity wave drag (GWD) and the sum of orographic and non-orographic GWD, respectively. JRA-55 also offer the parameterized GWD, while the Rayleigh damping effect is also included. Therefore, it would be beneficial to analyze the contribution of these GWD to the residual as a means of validating the authors speculation.

The residual here means those components that are not resolved on the common grids of the zonal mean data set, and is not directly (at least not "directly") related to e.g. the particular gravity wave parameterization used in each reanalysis system. Observational data assimilation is also a key component of the reanalysis system and governs the quality of the final reanalysis products at leading order. The GWD parameterization (please see S-RIP Final Report Chapter 2 (SPARC, 2022), Table 2.7 for the gravity wave drag parameterization used in the forecast model of each reanalysis) provides drag to the system within the forecast model part, but observational data assimilation probably still exerts the largest influence on the final data products.

Nevertheless, the reviewer is correct that all four reanalyses provide zonal acceleration (zonal wind tendencies) due to gravity wave drag parameterization and other parameterizations (please see the final 3 pages of this letter for detailed information on which data are available from each reanalysis), and looking at these data does provide some insight. Figures R1 to R4 show zonal wind tendencies due to parameterizations from the four reanalyses. These figures confirm our original speculation that, in the stratosphere, GWD plays a major role in this residual. Note that different reanalyses apply different schemes for the parameterizations (see Chapter 2 of SPARC, 2022), resulting in different distributions for e.g. GWD among different reanalyses. In particular, JRA-55 applies a Rayleigh dampling at pressures less than 50 hPa that mimics drag due to non-orographic GWD (Section 3.1of Sato and Hirano, 2019; private communication with Yayoi Harada and Chiaki Kobayashi of JMA, 2024) whose data have been added to the provided parameterized GWD data, which is, most probably, the cause of the signals in the upper stratosphere. We will add this discussion to the revised manuscript (the main text) and the figures for all four seasons in the Supplement.

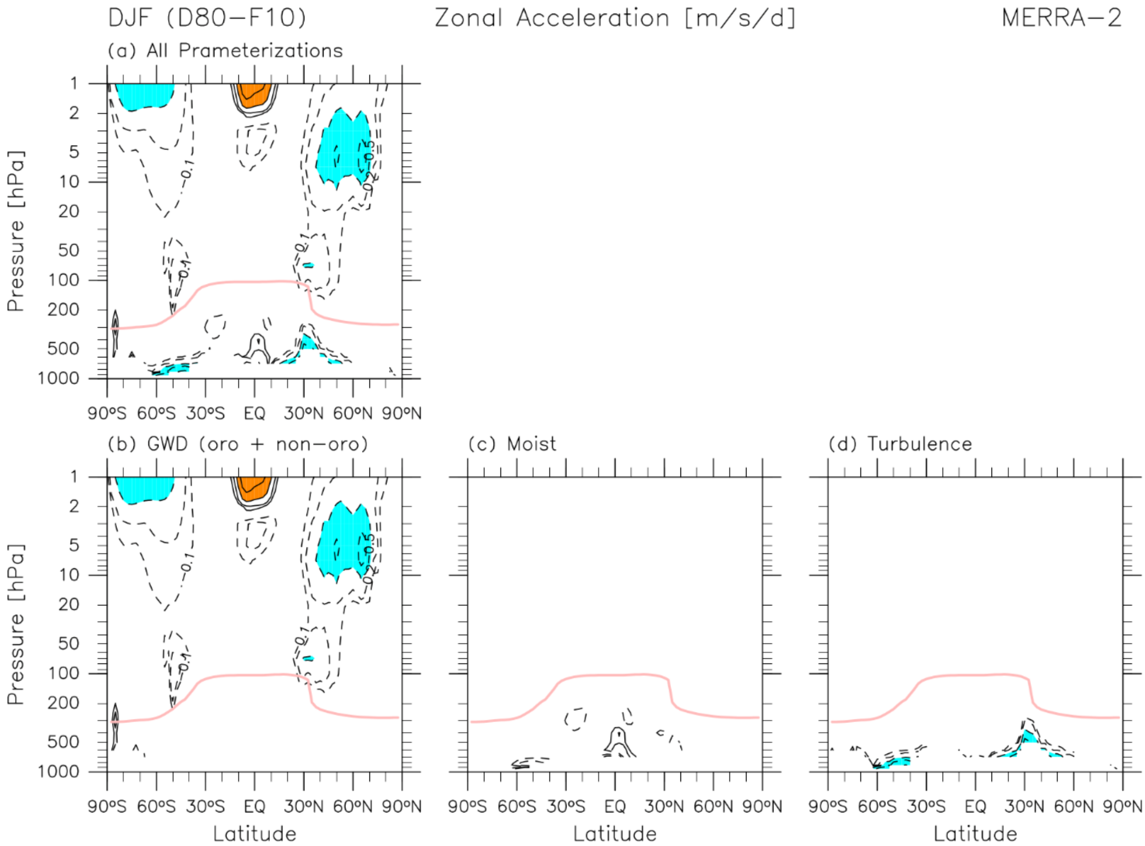

Figure R1. Zonal acceleration due to (a) all parameterizations, (b) parameterized gravity wave drag (including both orographic and non-orographic gravity waves), (c) moist processes, and (d) turbulence for MERRA-2 based on 30-year DJF means (1980-2010). The contours and colour shading are the same as for Figure 3.

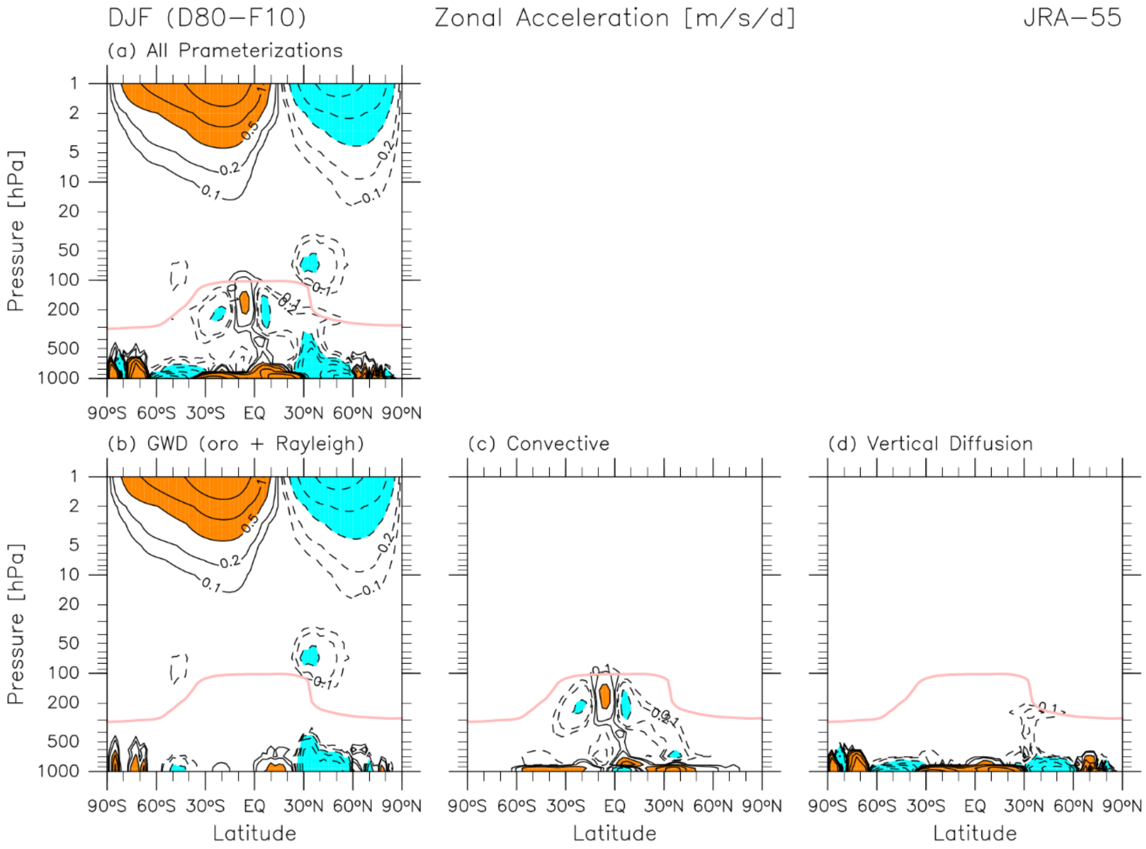

Figure R2. Zonal acceleration due to (a) all parameterizations, (b) parameterized gravity wave drag (orographic gravity wave drag only, plus a Rayleigh damping applied at pressures less than 50 hPa that mimics drag due to non-orographic gravity waves; see Sato and Hirano (2019)), (c) convective processes, and (d) vertical diffusion for JRA-55 based on 30-year DJF means (1980-2010). The contours and colour shading are the same as for Figure 3.

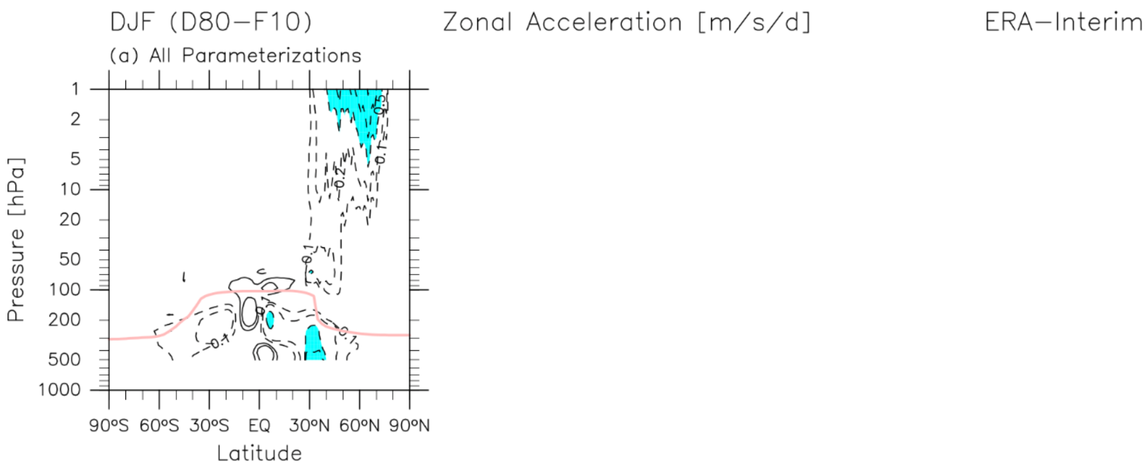

Figure R3. Zonal acceleration due to all parameterizations for ERA-Interim based on 30-year DJF means (1980-

2010). The contours and colour shading are the same as for Figure 3.

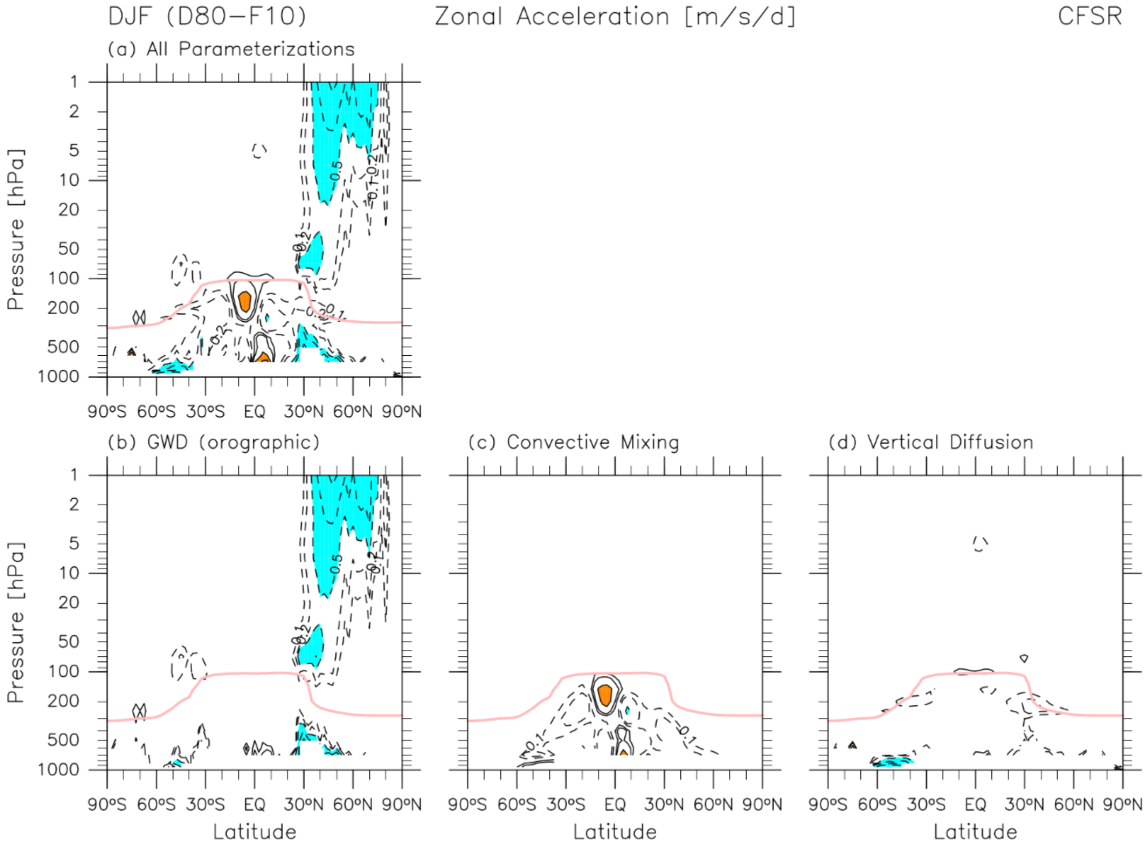

Figure R4. Zonal acceleration due to (a) all parameterizations, (b) parameterized gravity wave drag (orographic only), (c) convective mixing, and (d) vertical diffusion for CFSR based on 30-year DJF means (1980-2010). The contours and colour shading are the same as for Figure 3.

Reference:

Sato, K. and Hirano, S.: The climatology of the Brewer–Dobson circulation and the contribution of gravity waves, Atmos. Chem. Phys., 19, 4517–4539, https://doi.org/10.5194/acp-19-4517-2019, 2019.

SPARC: SPARC Reanalysis Intercomparison Project (S-RIP) Final Report, edited by Fujiwara, M., Manney, G. L., Gray, L. J., and Wright, J. S., SPARC Report No. 10, WCRP-6/2021, 612 pp., https://doi.org/10.17874/800dee57d13, available also at https://www.sparc-climate.org/sparc-report-no-10/ (last access: 16 February 2023), 2022.

See also the next 3 pages for the detailed information on the zonal acceleration tendencies provided by each reanalysis.

Information on zonal acceleration (zonal wind tendency) data provided by each reanalysis:

[1] MERRA-2

Documentation:

https://gmao.gsfc.nasa.gov/pubs/docs/Bosilovich785.pdf

tavg3_3d_udt_Np (M2T3NPUDT): Wind Tendencies

Data files:

https://doi.org/10.5067/YSR6IA5057XX

MERRA-2 tavgM_3d_udt_Np: 3d,Monthly mean,Time-Averaged,Pressure-Level,Assimilation,Wind Tendencies V5.12.4 (M2TMNPUDT)

Relevant variables:

DUDTANA:long_name = "total_eastward_wind_analysis_tendency" ; (Not shown in the figures)

DUDTDYN:long_name = "tendency_of_eastward_wind_due_to_dynamics" ; (Not shown in the figures)

DUDTGWD:long_name = "tendency_of_eastward_wind_due_to_GWD" ;

DUDTMST:long_name = "zonal_wind_tendency_due_to_moist" ;

DUDTTRB:long_name = "tendency_of_eastward_wind_due_to_turbulence" ;

[2] JRA-55:

Documentation:

https://jra.kishou.go.jp/JRA-55/document/JRA-55_handbook_LL125_en.pdf

4.1.12. Isobaric average diagnostic fields (fcst_phy3m125)

Data files:

https://data.diasjp.net/dl/storages/filelist/dataset:204

--> Hist, Monthly, fcst_phy3m125

--> gwdua.

Relevant files/variables:

fcst_phy3m125_gwdua : Gravity wave zonal acceleration (*)

fcst_phy3m125_adua : Adiabatic zonal acceleration (Not shown in the figures)

fcst_phy3m125_cnvua : Convective zonal acceleration fcst_phy3m125_vdfua : Vertical diffusion zonal acceleration

(*) Note that fcst_phy3m125_gwdua includes zonal acceleration due to both orographic GWD and Rayleigh damping. The latter is applied at all pressures less than 50 hPa and mimics non-orographic GWD. The references on this are Sato and Hirano (2019, Section 3.1) and private communication with Yayoi Harada and Chiaki Kobayashi of JMA (2024).

Reference:

Sato, K. and Hirano, S.: The climatology of the Brewer–Dobson circulation and the contribution of gravity waves, Atmos. Chem. Phys., 19, 4517–4539, https://doi.org/10.5194/acp-19-4517-2019, 2019.

[3] ERA-Interim:

Documentation:

https://confluence.ecmwf.int/display/CKB/ERA-Interim%3A+documentation

Table 10. Accumulated model full levels net tendencies

Relevant variables:

"u tendency" (parameter ID: 112; the original units: m s-1 (for 6-hour accumulation))

Monthly mean zonal mean data were created by Marta Abalos for the paper by Abalos et al. (JGR, 2015) based on 6-hourly model-level data above ~500 hPa.

Reference:

Abalos, M., Legras, B., Ploeger, F., and Randel, W. J.: Evaluating the advective Brewer-Dobson circulation in three reanalyses for the period 1979–2012, J. Geophys. Res., 120, 7534–7554, https://doi.org/10.1002/2015JD023182, 2015.

[4] CFSR:

Data files:

https://rda.ucar.edu/datasets/ds093.2/dataaccess/

Relevant variables:

Convective gravity wave drag zonal acceleration (Not shown; it was found that this variable is filled with zero or fill/missing value)

Convective zonal momentum mixing acceleration

Gravity wave drag zonal acceleration

Vertical diffusion zonal acceleration

Other settings when downloading:

Monthly Mean (4 per day) of 6-hour Average (initial+0 to initial+6)

GRID: 2.5deg. x 2.5 deg.

(Thus, the file names are diabl06.gdas.YYYYMM.grb2, where YYYYMM is e.g. 201001)