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# Direct comparison between a non orographic gravity wave drag scheme and constant level balloons

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## Key Points:

- A non-orographic parameterization tuned to produce a realistic tropical quasi-biennial oscillation is used to predict in-situ observations
- Parameterized gravity waves needed in large-scale models have realistic amplitudes in the tropical lower stratosphere
- Day-to-day variations of the estimated gravity wave momentum fluxes correlate well with observations

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**Abstract**

17 The parameterization scheme that represents gravity waves due to convection in LMDz-  
18 6A, the atmospheric components of the IPSL coupled climate model (IPSLCM6), is di-  
19 rectly compared to Strateole-2 balloon observations made in the lower tropical strato-  
20 sphere from November 2019 to February 2020. The input meteorological fields necessary  
21 to run the parameterization offline are extracted from the ERA5 reanalysis and corre-  
22 spond to the instantaneous meteorological conditions found underneath the balloons. In  
23 general, we find a fair agreement between measurements of the momentum fluxes due  
24 to waves with periods less than 1 hr and the parameterization. The correlation of the  
25 daily values between the observations and the results of the parameterization is around  
26 0.4, which is statistically elevated considering that we consider around 600 days of data  
27 and surprisingly good considering that the parameterization has not been tuned: the scheme  
28 is just the standard one that helps producing a Quasi-Biennial Oscillation in the IPSLCM6  
29 model. Online simulations also show that the measured values of the momentum fluxes  
30 are also well representative of the zonally and averaged values of momentum fluxes needed  
31 in LMDz-6A to simulate a QBO. The observations also tell that longer waves with pe-  
32 riods smaller than a day roughly carry about twice as much fluxes as waves with peri-  
33 ods smaller than an hour, which is a potential problems since low period waves that make  
34 the difference are potentially in the “grey zone” of most climate models.  
35

**Plain Language Summary**

36  
37 In most large-scale atmospheric models, gravity wave parameterizations are based  
38 on well understood but simplified theories which parameters are keyed to reduce system-  
39 atic errors on the planetary scale winds. In the equatorial regions, the most challeng-  
40 ing error concern the quasi biennial oscillation. Although it has never been verified di-  
41 rectly, it is expected that the parameterizations tuned this way should transport a re-  
42 alistic amount of momentum flux in both the eastward and westward directions and when  
43 compared to direct observations. Here we show that it is the case, to a certain extent,  
44 using constant-level balloon observations at 20 km altitude. The method consists in com-  
45 paring directly, each day and at the location of the balloon the measured momentum fluxes  
46 and the estimation of a gravity wave parameterization using observed values of the large-  
47 scale meteorological conditions of wind, Temperature and precipitation.

## 48 1 Introduction

49 It is well known that precipitations force gravity waves (GWs) that propagate in  
 50 the stratosphere (Fovell et al., 1992; Alexander et al., 2000; Lane & Moncrieff, 2008). These  
 51 waves carry horizontal momentum vertically and interact with the large scale flow when  
 52 they break. The horizontal scale of these waves can be quite short, much shorter than  
 53 the horizontal scale of General Circulation Models (GCMs) so they need to be param-  
 54 eterized (Alexander & Dunkerton, 1999). Although there are other sources of gravity waves  
 55 that need to be parameterized, like mountain waves (Palmer et al., 1986; Lott, 1999) and  
 56 frontal waves (Charron & Manzini, 2002; Richter et al., 2010; de la Cámara & Lott, 2015),  
 57 the convective GWs are believed to dominate largely in the tropics. In these regions, they  
 58 contribute significantly to the forcing of the Quasi-Biennial Oscillation (QBO), a near  
 59 28-month oscillation of the zonal mean zonal winds that occurs in the lower part of the  
 60 equatorial stratosphere (Baldwin et al., 2001). For these reasons, the parameterization  
 61 of convective GWs is necessary for most GCMs to explicitly realize the QBO.

62 Although convective gravity wave parameterization are now used in many mod-  
 63 els with success (Beres et al., 2005; Song & Chun, 2005; Lott & Guez, 2013; Bushell et  
 64 al., 2015), their validation using direct in situ observations remains a challenge. There  
 65 exists observations of GWs using global satellite observations (Geller et al., 2013) but  
 66 the GWs identified this way still have quite large horizontal scales, and some important  
 67 quantities like the Momentum Fluxes (MFs) are often deduced indirectly, for instance  
 68 from temperature measurements using polarization relations (Alexander et al., 2010; Ern  
 69 et al., 2014). For these two reasons, in situ observations are essential, and may be the  
 70 most precise ones are those provided by constant-level long-duration balloons, like those  
 71 made in the Antarctic region during Strateole-Vorcore (Hertzog, 2007) and Concordiasi  
 72 (Rabier et al., 2010), or in the deep tropics during PreConcordiasi (Jewtoukoff et al., 2013),  
 73 and more recently during Strateole 2 (Haase et al., 2018). Among many important re-  
 74 sults, these balloon observations have shown that the momentum flux entering in the strato-  
 75 sphere is extremely intermittent (Hertzog et al., 2012). This intermittency implies that  
 76 the mean momentum flux is mostly transported by few large-amplitude waves that po-  
 77 tentially break at lower altitudes than if the GW field were more regular. This property,  
 78 when reproduced by a parameterization (de la Cámara et al., 2014; Kang et al., 2017;  
 79 Alexander et al., 2021), can help reducing systematic errors in the midlatitudes, for in-  
 80 stance on the timing of the final warming in the Southern Hemisphere polar stratosphere  
 81 (de la Cámara et al., 2016), or on the QBO (Lott et al., 2012). Balloon observations have  
 82 also been used to characterize the dynamical filtering by the large scale winds (Plougonven  
 83 et al., 2017), and to validate the average statistical properties of the GW momentum flux  
 84 predicted offline using reanalysis data (Kang et al., 2017; Alexander et al., 2021).

85 However, to the best of our knowledge, the evaluations of parameterizations using  
 86 balloon observations have remained quite indirect so far, with the common belief that  
 87 the best a parameterization can do is to reproduce the right statistical behaviour (Jewtoukoff  
 88 et al., 2015; Kang et al., 2017; Alexander et al., 2021). The fact that a parameterization  
 89 could be used to simulate the observed momentum flux at a given time and place has  
 90 never been tried, even though offline calculations of GW drag have been carried out suc-  
 91 cessfully in the past (Jewtoukoff et al., 2015; Kang et al., 2017; Alexander et al., 2021).  
 92 There are many reason for that, one is that parameterization are often based on simpli-  
 93 fied quasi-linear wave theory, assume spectral distributions that are loosely constrained,  
 94 and ignore lateral propagation almost entirely (some attempt to include it can be found  
 95 in Amemiya and Sato (2016)). Nevertheless, if in most parameterizations the theory is  
 96 indeed linear, the wave amplitude is systematically limited by a breaking criteria that  
 97 encapsulates nonlinear effects. Furthermore, many parameterizations explicitly relate  
 98 launched waves to sources, and there is constant effort to improve the realism of the con-  
 99 vective ones (Liu et al., 2022). Also, observations systematically suggest that dynam-  
 100 ical filtering by the large scale wind is extremely strong for upward propagating GWs

101 (Plougonven et al., 2017), and this central property is represented in most GWs param-  
 102 eterizations. For all these reasons, it may well be that a GW parameterization keyed to  
 103 the large scale conditions found at a given place and time gives MFs that can be directly  
 104 compared to the MFs measured by a balloon at the same place.

105 Based on the relative success of the offline calculations done in the past using re-  
 106 analysis data (Jewtoukoff et al., 2015; Kang et al., 2017; Alexander et al., 2021), the pur-  
 107 pose of this paper is to attempt such a direct comparison using the most recent obser-  
 108 vations. We will use for that the balloons of the first Strateole 2 campaign that flew in  
 109 the lower tropical stratosphere between November 2019 and February 2020 (Corcos et  
 110 al., 2021). For each of these flights and each time, we will identify the grid point in the  
 111 ERA5 reanalysis (Hersbach et al., 2020) that is the nearest and used the vertical pro-  
 112 files of wind and Temperature as well as the surface value of precipitation to emulate the  
 113 Lott and Guez (2013)’s (LG13) parameterization of convective GWs. The plan of the  
 114 paper is as follows. Section 2 describes the methodology used, section 3 analyzes in-depth  
 115 the statistics and compare with online simulations. Some perspectives and the conclu-  
 116 sions are provided in Section 4.

## 117 2 Data and method

### 118 2.1 Parameterization of convective gravity waves

119 We take the LG13 parameterization of non-orographic gravity waves forced by con-  
 120 vection that is operational in LMDz6-A (Hourdin et al., 2020) the atmospheric compo-  
 121 nent of the IPSL Earth System model used to complete the CMIP6 experiments (IPSLCM6,  
 122 Boucher et al. (2020)). This version of the parameterization is also used for the LMDz  
 123 experiments carried out in the frame of the QBO intercomparison project (QBOi) (Bushell  
 124 et al., 2022; Holt et al., 2022). Among the salient aspect of the scheme, one is that it is  
 125 multiwave and stochastic, the subgrid scale GWs field (e.g., vertical wind disturbance  
 126  $w'$ ) being represented by stochastic Fourier series of monochromatic waves,

$$w'(x, y, t, z) = \sum_{n=1}^{\infty} C_n \hat{w}_n(z) e^{i(\mathbf{k}_n \cdot \mathbf{x} - \omega_n t)}, \quad (1)$$

127 where the intermittency parameters satisfy  $\sum_{n=1}^{\infty} C_n^2 = 1$ , and where  $\mathbf{k}_n$  and  $\omega_n$  are  
 128 the horizontal wave vector and frequency respectively. To determine the wave amplitude  
 129 the variance of the subgrid scale precipitation field,  $P'$ , is assumed to compare in am-  
 130 plitude with the gridscale averaged precipitation  $P$  by writing

$$P' = \sum_{n=1}^{\infty} C_n P e^{i(\mathbf{k}_n \cdot \mathbf{x} - \omega_n t)}. \quad (2)$$

131 We then translate precipitation into diabatic heating which we distribute vertically over  
 132 a fixed depth  $\Delta z$  in the troposphere. For each harmonics the heating produces a GW  
 133 whose MF varies with the square of the precipitation  $P^2$  times a tuning parameter  $G_{uw0}$   
 134 (see Eq. 9, in LG13) and which is imposed at a fixed launching altitude  $z_l$ . Three fac-  
 135 tors then limit vertical propagation, (i) the presence of critical levels, (ii) a dissipative  
 136 term controlled by a kinematic viscosity  $\nu$ , and (iii) a criteria for saturation controlled  
 137 by a saturation parameter  $S_c$ . All these effects are summarized in Eq. 12 of LG13, but  
 138 to illustrate how the background flow controls the outcome of the scheme, we recall the  
 139 third criterion that saturation limits the amplitude of the Momentum Flux MF trans-  
 140 ported by each harmonics to values below

$$|\rho \hat{\mathbf{u}}_n \hat{w}_n^*| \leq \rho_r S_c^2 \frac{|\mathbf{k}_n \cdot (\mathbf{c}_n - \mathbf{U}(z))|^3}{N(z)} \frac{k_m}{|\mathbf{k}_n|^4}, \quad (3)$$

141 where the star stands for the complex conjugate,  $\hat{\mathbf{u}}_n$  being the harmonic of the horizon-  
 142 tal wind vector disturbance, and  $\mathbf{U}(z)$ ,  $N(z)$  being the vertical profiles of horizontal wind,

143 buoyancy frequency, and density respectively. Still in (3) the reference density  $\rho_r = 1\text{kgm}^{-3}$ ,  
 144 and  $k_m$  corresponds the minimal horizontal wavelength that needs to be parameterized,  
 145 and whose inverse scales with the gridcell horizontal size. Compared to LG13, we have  
 146 slightly reformulated the saturation criteria to make explicit that the saturated MF has  
 147 small amplitude when the intrinsic phase speed  $\mathbf{c}_n - U(z)$  is small, the absolute hori-  
 148 zontal phase speed being  $\mathbf{c}_n = \mathbf{k}_n\omega_n/|\mathbf{k}_n|^2$ . This mechanism is referred to has dynam-  
 149 ical filtering in the following and is probably central in explaining the good correlations  
 150 we describe next between the observed and parameterized MFs.

151 In practice, we make a distinction between the time scale of the life cycle of the waves  
 152  $\Delta t$  which we consider to be shorter than one day and the physical time step that separ-  
 153 ates two calls of the parameterization, and which is around  $\delta t = 10\text{mn}$  online. This  
 154 distinction permits to launch few waves each time-step, typically  $J = 8$ , and to accu-  
 155 mulate their effect over the day via an AR-1 process with decorrelation time of one day.  
 156 On average and each day, the GWs field is then made of  $J\frac{\Delta t}{\delta t} \approx 1000$ , a number of har-  
 157 monics we judge sufficient to represent a realistic gravity waves field. In the offline com-  
 158 parison we will not use such a large number of waves, essentially because it makes lit-  
 159 tle sense to interpolate ERA5 along 10mn intervals, but we will still launch 8 waves per  
 160 hours, to left the scheme unchanged, and average over the day. To test if the reduction  
 161 in terms of number of harmonics involved harmonics is significant, we have rather made  
 162 statistics averaging the parameterization results over 9 adjacent gridpoints, in this case  
 163 the number of harmonics involved become comparable to that used online, and did not  
 164 found large qualitative differences. For completeness, we recall here the operational val-  
 165 ues of the different tuning parameters of the scheme used for CMIP6,

$$z_l = 5\text{km}, \Delta z = 1\text{km}, G_{uw0} = 0.23, S_c = 0.6, \rho_r = 1\text{kg/m}^3, k_m = 0.02\text{km}^{-1}. \quad (4)$$

166 The scheme selects randomly the horizontal wave number between  $k_s < k < k_m$  us-  
 167 ing uniform distribution and select the intrinsic phase speed at the launch level  $z_s$  ac-  
 168 cording to a Gaussian distribution with standard deviation  $C_M$ . The operational val-  
 169 ues for these parameters are,

$$k_s = 1\text{km}^{-1}, C_M = 30\text{m/s}, z_s = 5\text{km}. \quad (5)$$

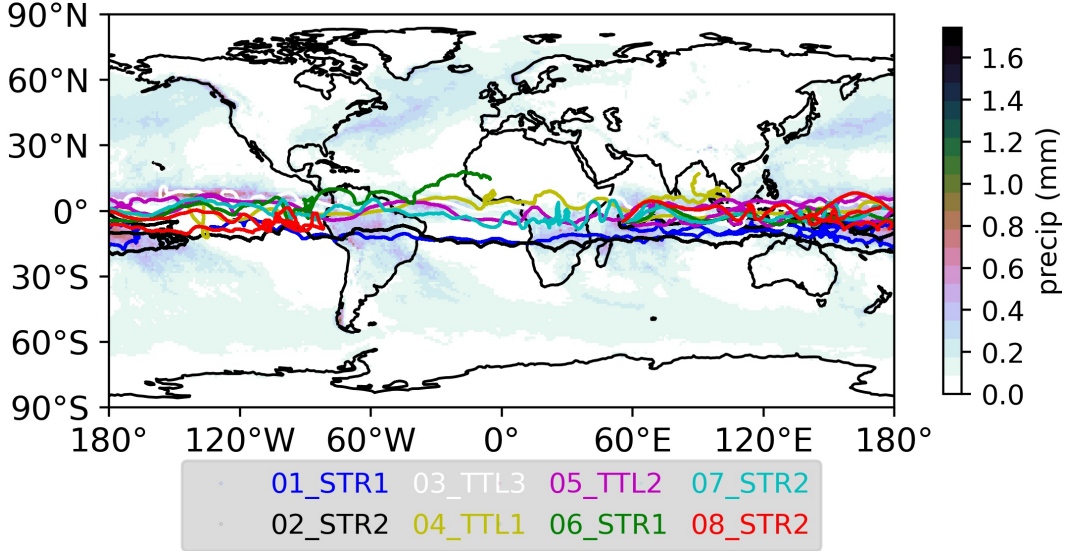
170 It is important to emphasize that the scheme select phase speeds rather than frequency,  
 171 whereas the balloon data measure MFs as a function of intrinsic frequency. We there-  
 172 fore analysed the characteristic distribution of the intrinsic frequency of the parameter-  
 173 ized waves that enter in the stratosphere and verified that more than 75% of the param-  
 174 eterized momentum fluxes are carried by harmonics with intrinsic period around and be-  
 175 low 1hr (not shown). Note also that in its operational version, and to limit computational  
 176 costs, only waves with horizontal wavenumber in the zonal direction are launched.

## 177 2.2 Offline parameterization runs

178 To activate the scheme in offline mode we will use ERA-5 3-hourly datas of winds,  
 179 surface pressure and temperature at  $1^\circ \times 1^\circ$  horizontal grid to mimic a large scale cli-  
 180 mate model resolution. In the vertical we use data at 67 model levels, taking one every  
 181 two ERA5 levels, to fasten calculations but also to mimic the vertical resolution we have  
 182 in the LMDz-6A GCM and which is slightly below 1km (in ERA5 and around 20km the  
 183 vertical resolution is around 500m when all the 137 levels are considered). All these data  
 184 are then linearly interpolated on 1hr time step, which is the minimum time step at which  
 185 ERA5 precipitations are available.

## 186 2.3 Strateole 2 balloon observations

187 The in situ observations we use are from the 8 constant level balloon flights which  
 188 flew between 18.5 and 20km altitude for about 2-3 months during the Nov. 2019-February



**Figure 1.** Strateole 2 balloon trajectories taking place between November 2019 and February 2020. Shading presents the precipitation field from ERA5 averaged over the period.

189 2020 periods of Strateole-2 (Corcos et al., 2021). Their trajectories are shown in Fig. 1,  
 190 superimposed to the averaged precipitation. In the MFs calculated from observations,  
 191 and that we referred to as observed MFs in the following, (Corcos et al., 2021) distin-  
 192 guish the waves with short periods (1hr-15mn) from waves with period up to one day  
 193 (1d-15mn), they also distinguish the eastward waves giving positive MF in the zonal di-  
 194 rection from the westward waves giving negative MF, and the MF amplitudes includ-  
 195 ing all the directions of propagation. It is coincidental that the flights took place dur-  
 196 ing the 2nd documented QBO disruption (Anstey et al., 2021), but the fact that the mea-  
 197 surements are below the altitude at which the disruption manifests strongly make us be-  
 198 lieve that our comparison between gravity waves MFs over the period is not much af-  
 199 fected by the disruption (beyond the fact that the disruption potentially affect the large  
 200 scale winds, which is something that translate well in the parameterization).

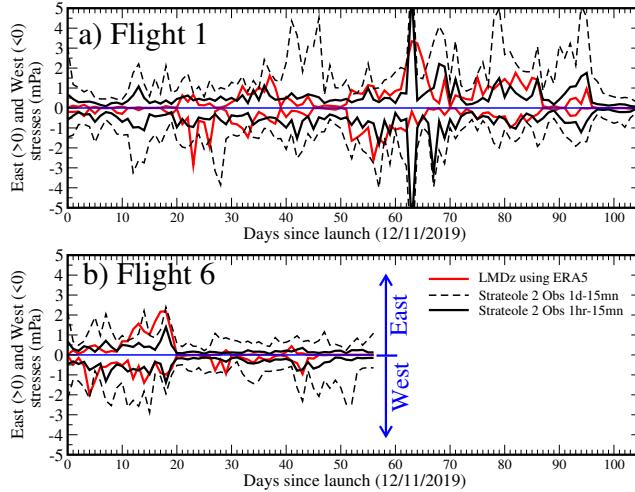
201 In the following we will compare the momentum fluxes derived from the balloon  
 202 data, emphasize the intrinsic frequencies that the scheme represents (the intrinsic pe-  
 203 riods below 1hr) and considering the ERA5 data at the points that is the nearest from  
 204 the balloon. The prediction is then made every hour, and averaged over the day, again  
 205 because this is the time scale needed for our scheme to sample realistically a multiwave  
 206 GWs field, but also because it takes around a day for a balloon flight to cover about a  
 207 model gridscale. We will discuss sensitivities to these choices in the discussion section.

## 208 2.4 Online simulations

209 An important aspect of our work is that it uses an operational scheme without prior  
 210 tuning, and that we compare the scheme in offline mode. We will therefore test if the  
 211 passage from offline to online impacts the amplitude of the momentum fluxes by mak-  
 212 ing comparison between offline and online calculations over around 3 QBO cycles (8 years).  
 213 For this purpose we will make global estimations with the GW scheme using 8 year of  
 214 ERA5 6hourly data (2013-2020) and repeat the experiment with the LMDz-6A atmo-  
 215 spheric model at its medium horizontal resolution (144x143 regular longitude-latitude  
 216 grid) and 80 vertical levels, the model top being at 1Pa. The simulations are forced with  
 217 the observed seasonal cycle of sea surface temperatures and sea-ice from the CMIP database

218 for the period, and the ozone climatology is built from the ACC/SPARC ozone database.  
 219 All runs have the same settings of the parameterization of the orographic GWs (Lott,  
 220 1999), convective GWs, and of the GWs due to fronts and jet imbalances (de la Cámara  
 221 & Lott, 2015) as referred in (Hourdin et al., 2020). To make a smooth transition from  
 222 the offline estimations with ERA5 to the free run done with LMDz-6A, we will also present  
 223 LMDz-6A simulation where the field of horizontal winds and temperature are nudged  
 224 toward ERA5 every 6hr with a relaxation constant of  $1\text{hr}^{-1}$ .

225 **3 Results**

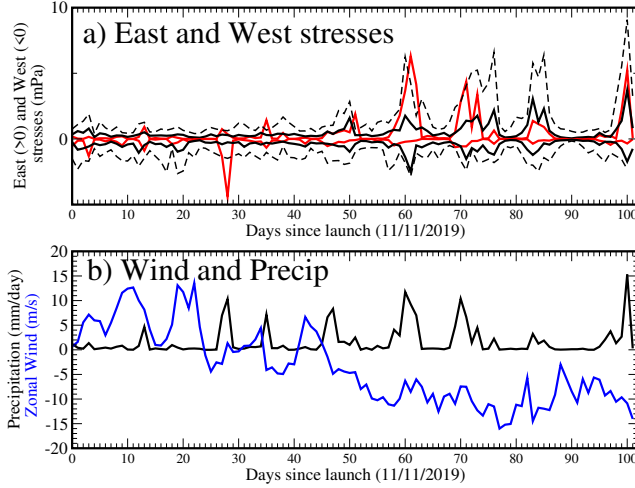


**Figure 2.** Comparison between daily averaged values of the eastward and westward stresses measured by balloons and estimated by the GWs scheme at the balloon location and altitude. Red curves are for the GWs prediction using ERA5, black are for the observed MF due to the 15mn-1hr GWs, the thin dashed are for the 15mn-1day GWs.

226 **3.1 Offline estimate of the observed values**

227 Figure 2 shows time series of momentum fluxes measured during two balloon flights  
 228 and the corresponding offline estimates. For figure clarity we present results for the East-  
 229 ward and westward MF only, we will return more briefly to the cumulated MF and to  
 230 the MF amplitude later. Note nevertheless that for the parameterization at least these  
 231 last to MFs resume to the eastward and westward MFs, the cumulated MF being their  
 232 sum the MF amplitude being their difference. Overall one sees in the top panels that the  
 233 amplitudes of the momentum flux corresponding to the 1hr-15mn periods in the mea-  
 234 surements compare well to the parameterised amplitudes in both the eastward and west-  
 235 ward directions, the eastward and westward fluxes being of comparable amplitude but  
 236 of opposite sign, as expected. For both, the observed momentum fluxes related to the  
 237 15mn-1day waves are substantially larger. In general and for flight 1 in Fig. 2a, one sees  
 238 that the parameterized fluxes are sometime small in amplitudes and in both directions  
 239 (between days 10 and 20), something that rarely happens in the observations. One also  
 240 see a tendency for the observed and estimated values to become larger jointly, like for  
 241 instance the Eastward fluxes between days 60 and 95, before becoming small jointly  
 242 afterward. This contrast between periods with larger and smaller MFs are even more pro-  
 243 nounced in the flight 6, shown in Fig. 2b. In it, one sees that the MF are large in both  
 244 directions before day 20, and becomes afterward. If we look at the trajectory on Fig. 1



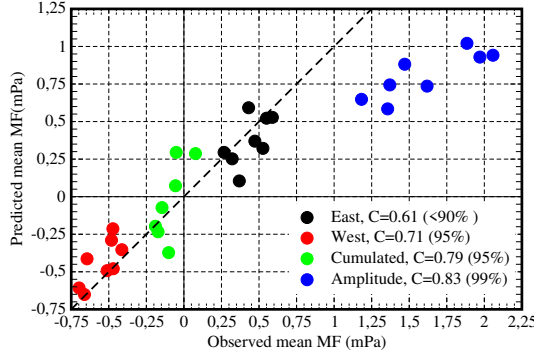


**Figure 3.** a) Same as Fig. 2 but for Strateole Flight 2. b) ERA5 precipitations and zonal wind at the flight altitude.

245 one sees that at its end, Flight 6 moves from the equatorial regions toward the subtrop-  
 246 ics, end up over Sahel, i.e. regions where precipitations are quite small. To give a bet-  
 247 ter sense of what can cause the resemblances and differences between the observed MFs  
 248 and their estimation, we plot in Fig. 3a the eastward and westward MFs for flight 2, and  
 249 in Fig. 3b the precipitation and the (ERA5) zonal wind at the flight altitude. This is an  
 250 interesting period since the zonal wind during this flight changes direction. Without a  
 251 surprise, one sees in Fig. 3a that the estimated flux peaks when the precipitation is large  
 252 (Fig. 3b), the MFs peak are more pronounced in the direction opposed to the zonal wind  
 253 consistent with the fact that waves with large amplitude intrinsic phase speed can carry  
 254 more momentum than waves with small intrinsic phase speed (by dynamical filtering,  
 255 see the first numerator in Eq. 3). To a certain extent, the relation with intense precipi-  
 256 tation can be seen in the observations, mainly in the eastward direction after day 40.  
 257 Dynamical filtering is also active for the measured fluxes, the observed westward fluxes  
 258 being small compared to the eastward flux when the zonal wind becomes positive (e.g.  
 259 after day 50). Again, when the precipitation are small the simulated MFs are often very  
 260 small, whereas the observed ones always have non-zero backgrounds.

261 The fact that the parameterization estimates fluxes of about the right amplitude  
 262 is summarized in Fig. 4, where the average of the fluxes over the 8 entire flights are shown.  
 263 It confirms systematically that the offline estimations are quite good on average and in  
 264 the zonal direction, for the eastward and westward components again, but also on the cu-  
 265 mulated flux (i.e the sum of the two and where the contributions from eastward and west-  
 266 ward propagating GWs largely oppose each other). In terms of stress amplitude one sees  
 267 that the observations give larger value on average, but this is due to the fact that in (Corcos  
 268 et al., 2021) the amplitude include the meridional component of the stress which is not  
 269 included in the parameterization tested here. In the panel are also shown the correla-  
 270 tions between the balloon averaged values of the stresses, they are often quite significant,  
 271 despite the fact that only 8 flights are used.

272 The curves in Figs. 2-3 also suggest that observations and offline estimations evolve  
 273 quite jointly day after day, both measured and parameterized MFs being sensitive to pre-  
 274 cipitation and dynamical filtering. To test more systematically this relationship, we next  
 275 calculate the correlations between measured and estimated MFs and for each flight (Ta-  
 276 ble 3.1). To test the significance, we measure the number of Degree of Freedom (DoF)

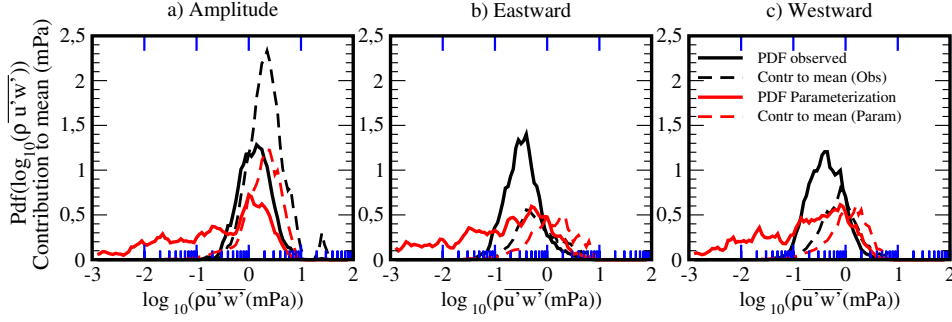


**Figure 4.** Scatter plot of the momentum fluxes measured by the balloon versus parametrized. Eight values are averages for the eight balloon flights. Significant test are for the correlation between the values, significance is estimated via a Pearson test with 6 degrees of freedom.

277 presents in each dataset, and calculate for that the decorrelation time scale, which we  
 278 take as the lag in day beyond which the lag-autocorrelation of the series falls below 0.2.  
 279 As this time-lag varies from one series to the other, we give explicitly in column 5, the  
 280 number of DoF, which is the duration of the flight divided by the decorrelation time scale.  
 281 Note that for their decorrelation time, we consider for simplicity that evaluated with daily  
 282 averaged observations, but found that it is not much different from that evaluated with  
 283 the offline estimates (not shown). In each case, we find positive correlations, they are  
 284 often significant in the Eastward direction direction and for the amplitude, the estimated  
 285 westward fluxes presenting more errors. Even weaker correlations occur for the accumu-  
 286 lated stress, which most certainly reflects that in the accumulated stresses, large quan-  
 287 tities of opposite sign balance on another, the resulting balance being more difficult to  
 288 predict.

**Table 1.** Correlation coefficient (24 hours averaged) between Strateole -2 Balloon flight (1hour15 min waves) and offline estimation (Notations for Significance Level: 99% : bold black with underline; 95%: bold black; 90% : solid; below 90%: solid italic). The significance are attributed following a Pearson test with degrees of freedom measured as the number of day divide by the decorrelation time of the series.

Flight	Altitude	Launch	End	Duration DOF	Cumu- lated	Ampli- tude	East	West
01_STR1	20.7	12/11/2019	28/02/2020	107/53	0.23	<b>0.28</b>	<b>0.46</b>	<i>0.07</i>
02_STR2	20.2	11/11/2019	23/02/2020	103/51	<i>0.21</i>	<b>0.62</b>	<b>0.62</b>	<i>0.05</i>
03_TTL3	19.0	18/11/2019	28/02/2020	101/33	<b>0.49</b>	<b>0.42</b>	<b>0.49</b>	<b>0.43</b>
04_TTL1	18.8	27/11/2019	02/02/2020	67/22	<b>0.41</b>	<b>0.55</b>	<b>0.55</b>	<b>0.53</b>
05_TTL2	18.9	05/12/2019	23/02/2020	79/19	0.36	<i>0.29</i>	0.36	<i>0.24</i>
06_STR1	20.5	06/12/2019	01/02/2020	57/10	<i>0.39</i>	<b>0.67</b>	<b>0.71</b>	<b>0.59</b>
07_STR2	20.2	06/12/2019	28/02/2020	83/16	<i>0.01</i>	<i>0.09</i>	<i>0.08</i>	<i>0.06</i>
08_STR2	20.2	07/12/2019	22/02/2020	77/12	<i>0.18</i>	<b>0.7</b>	<b>0.66</b>	<i>0.37</i>
ALL	x	x	x	670/170	<b>0.30</b>	<b>0.41</b>	<b>0.51</b>	<b>0.29</b>

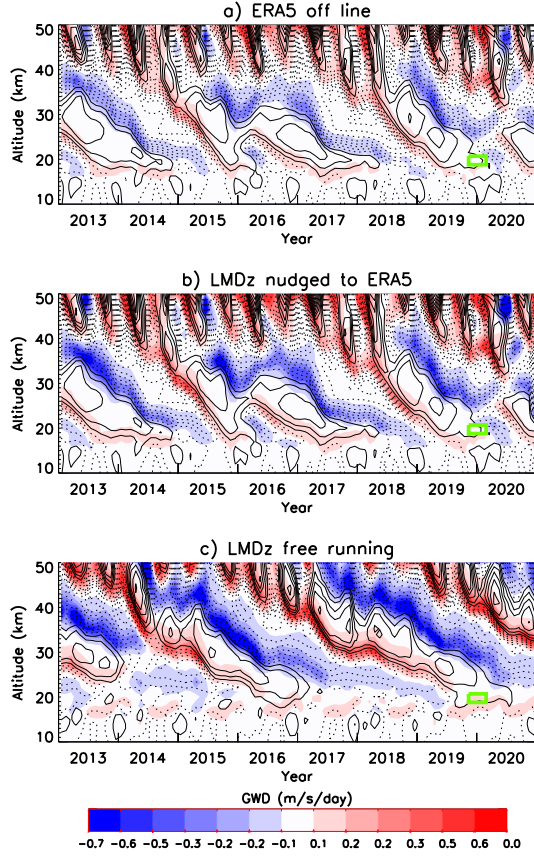


**Figure 5.** PDFs of daily values of momentum flux distribution (solid lines). The PDFs are calculated from histograms of 670 MF daily values within intervals of  $\Delta(\log_{10}(\overline{\rho u'w'}) \text{ (mPa)}) = 0.05$ , thereafter smoothed by a 5 point non-recursive filter with weight (0.1, 0.2, 0.4, 0.2, 0.1). For the contribution of the waves to the MF (dashed lines), the PDF values are multiplied by the MF values  $\overline{\rho u'w'}$  (in mPa). Measured values are in black, estimations using ERA5 data and the LG13 GWs parameterization are in red.

289 As already noticed a defect of the scheme is it lacks of background wave activity  
 290 in the absence of precipitation. This means that momentum fluxes are underestimated  
 291 in many circumstances, despite the fact that the amplitudes are realistic when consid-  
 292 ering long term averages. To analyse better this difference and its potential consequences,  
 293 the Fig. 5 presents PDFs of the distributions of the momentum fluxes considering all the  
 294 daily data. For the PDFs (solid line), one sees that the balloons almost systematically  
 295 measure fluxes with amplitude between 0.1mPa and 10mPa (see Fig. 5a), whereas in the  
 296 parameterization there are much more contributions from the smaller amplitude momen-  
 297 tum fluxes (solid red), not mentioning that the zero values are excluded from the curves,  
 298 the PDF being for the logarithm of MF amplitudes. To test if this difference in MF am-  
 299 plitude distribution has consequences, the dashed lines represent the contribution of a  
 300 given MF value to the mean stress (which is just the PDF multiply by the MF value it-  
 301 self). For the amplitudes, the values which actually contribute lie between 0.1mPa and  
 302 10mPa in both the observations and the offline estimations. The fact that the small am-  
 303 plitude waves are more frequent in the estimations is also true for the westward and east-  
 304 ward components of the stress (Figs. 5b and 5c respectively). For both, nevertheless, the  
 305 contribution to the average stress is due to larger amplitude waves in the estimations than  
 306 in the observations, as indicated by the shifts towards larger values of the MFs between  
 307 the black dotted curve and the red dotted curve in Figs. 5b and 5c.

### 308 3.2 Global prediction and comparison with GCMs results

309 To appreciate whether the offline GW drag estimations using ERA5 are represen-  
 310 tative of the GWs MF a GCM requires to simulate a QBO, Fig. 6a) presents time-altitude  
 311 sections of the equatorial zonal winds and GWD predicted by the scheme globally and  
 312 in offline mode between 2013-2020. In it we see that the gravity wave drag is negative  
 313 (positive) where the zonal mean zonal wind vertical shear is negative (positive) consis-  
 314 tent with the fact that it contributes to the descent of the QBO. We also note that the  
 315 amplitudes vary between  $\pm 0.5\text{m/s/day}$ , a range characteristic of the parameterized GW  
 316 tendency used in GCMs that produce a quasi-biennial oscillation (Butchart et al., 2018).  
 317 The figure also indicates with a green rectangle the region and period during which the  
 318 balloons operated.

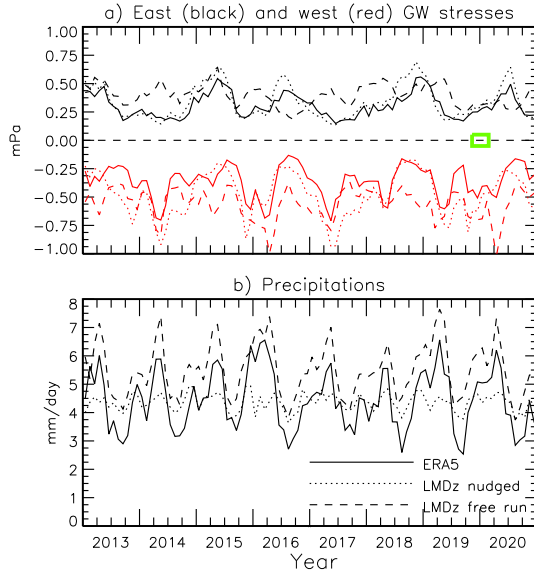


**Figure 6.** Time vertical sections of the zonal mean zonal wind ( $CI=10m/s$ , negative values dashed) and non orographic gravity wave drag zonal tendency (color) averaged over the equatorial band ( $5^{\circ}S-5^{\circ}S$ ). Input data and GWD tendency are from a) ERA5 reanalysis and offline GWD scheme; b) LMDz-6A nudged to ERA5 and online GWD scheme; c) LMDz-6A free run and online GWD scheme. The green box indicates schematically the altitude and time ranges of the Strateole-2 flights considered in this study.

319 To check that the comparable relations between GW drag and zonal wind shear  
 320 occur in the model we first make a test where the wind and temperature fields in LMDz-  
 321 6A are relaxed towards ERA5. The results are shown in Fig. 6b), and there is a strong  
 322 resemblance in the GW drag, the amplitudes being nevertheless substantially larger (around  
 323 25%) in LMDz-6A. If we then look at the free run in Fig. 6c) one sees again quite re-  
 324 alistic relations between wind shears and drag, the GW drag is again substantially larger  
 325 than that predicted using ERA5, despite the fact that the QBO period in LMDz-6A shown  
 326 here is quite long (about 3 years here, LMDz-6A being a GCM with a long QBO (Bushell  
 327 et al., 2022)). Note that this longer period could be reduced by enhancing the GW am-  
 328 plitude via for instance the tuning parameter  $G_{uw0}$  in Eq. 4 (see a systematic discussion  
 329 in Garfinkel et al. (2022)).

330 To address the differences in amplitude more quantitatively, the Fig. 7 shows the  
 331 zonal mean of GW stresses averaged over the equatorial band at 20km (i.e. about the  
 332 balloon flights altitude) in the three runs, and the corresponding averaged precipitations  
 333 (Fig. 7c). In it we see that the amplitude of the GW stress in Fig. 7a) is about 25% and  
 334 systematically larger in the free run (long dash) than in the offline test (solid), the nudge  
 335 simulation being in between (dotted). Also interesting, the average of the stress ampli-

336 tude in the offline calculations is near 0.75mPa, which is quite close from the average value  
 337 of the amplitude of the stress estimated locally and measured during the balloon flights  
 338 (see  $y$  values of the blue dots in Fig. 4). The same remarks hold for the eastward and  
 339 westward stresses in Fig. 7b).



**Figure 7.** Time series of the  $z = 20\text{km}$  zonal mean zonal non-orographic GW stresses and of the zonal mean precipitation averaged over the equatorial band ( $5^{\circ}\text{S}$ - $5^{\circ}\text{S}$ ). Same input datas as in Fig. 6.

340 As said in the introduction, the version of the parameterization used is operational  
 341 in the atmospheric component of the IPSLCM6 model, and we have tried to change it  
 342 as little as possible, which forces us to make choices. One is that we only call the param-  
 343 eterization every hour in offline mode, using interpolated data from ERA5, rather than  
 344 every 10mn in the model. Another is that LMDz-6A has a different grid yielding inter-  
 345 polation errors that could make the behaviour of the parameterization very different be-  
 346 tween ERA5 and LMDz-6A. Despite these differences it is remarkable that the errors are  
 347 not outrageous, they also have a cause that is quite identifiable. In Fig. 7c one sees that  
 348 in the free run, LMDz-6A overestimates by about 15% precipitation compared to ERA5,  
 349 as in the scheme the source use square precipitation (see Eq. 9 in LG13), a 25% differ-  
 350 ence in the MFS is therefore not a surprise. The MFs in the nudged runs (dotted line)  
 351 follows more the offline predictions using ERA5, but in them, the precipitation seems  
 352 to fail in representing an annual cycle suggesting a mismatch between the nudged fields  
 353 of temperature and winds and the model representation of diabatic processes.

#### 354 4 Conclusion

355 The main result of this paper is that a state of the art parameterization of GWs  
 356 due to convection reproduces reasonably well the momentum flux due to the high-frequency  
 357 waves (periods between 15mn and 1hr) deduced from in situ measurements done onboard  
 358 constant-level balloons. The parameterization represents well the eastward and westward  
 359 values of the stress and its variations from day to day. We have made sensitivity test to  
 360 the procedure, considering averages over 3hrs or 6hrs instead of a day, averaged over nei-  
 361 ghbouring points to increase the number of harmonics in the offline predictions and found  
 362 little qualitative differences. For instance, averaging balloon data and predictions over

363 shorter period, say 3hrs, result in much more noisy and decorrelated series, the corre-  
 364 lation between observations and measurements is lower but the DoF increase so the level  
 365 of significance stay about the same as when using daily data as in Table 3.1. We have  
 366 the impression that the best relations between observations and predictions are always  
 367 for periods around a day and above. Note that this does not contradict our understand-  
 368 ing of what a parameterization should do or a single balloon flight sample. In fact, a pa-  
 369 rameterization like LG13 needs successive iterations to evaluate the large number of har-  
 370 monics needed to represent realistically a GWs field. Quite similarly, a balloon that pro-  
 371 gresses at a speed around 10m/s takes about 3 hours to travel through a  $1^\circ$  long model  
 372 gridcell, and this is just one transect. An ergodicity argument could be used to justify  
 373 that averaging over a few 3-hours transects to cover a gridcell is equivalent to averag-  
 374 ing the balloon data over 1day. This being said, we cannot exclude that better could be  
 375 done with an other parameterization and over shorter time scale, but it has to be kept  
 376 in mind that the signals we handle are quite noisy, these average we do, on top of mak-  
 377 ing some sense in the GW context help to increase the signal/noise ratio.

378 Another important aspect of our work is that these results demonstrate that the  
 379 GWs parameterization used in a large scale model to simulate a QBO parameterize MFs  
 380 directly comparable with in situ observations. Although the measurements are extremely  
 381 local, we verify that the average value they give is representative of the global values needed  
 382 by a large-scale models to produce a QBOs. This is an important result in our opinion  
 383 and for three reasons.

384 The first is that according to a common believe, there are discrepancies of a fac-  
 385 tor larger than 2 between the MFs parameterized in models and the global observations  
 386 (Geller et al., 2013), at least in the mid-latitudes. In the equatorial regions, and using  
 387 the same data as as here, (Corcos et al., 2021) gave bulk arguments to justify that the  
 388 MF carried by the 15mn-1day waves is about what a model requires to generate a QBO.  
 389 The change in region and the higher resolution of the observations could explain that  
 390 the observations now give larger but more realistic MFs, but we refine the results here  
 391 and suggest that the contributions from the 15mn-1hr is sufficient. Of course this result  
 392 should be refined, it may well be that LMDz-6A needs larger GW drag to decrease its  
 393 QBO period or increase its intensity at lower altitudes. This is ongoing work, with a pri-  
 394 ority to include a background of GWs in LG13, and to optimize the scheme parameters  
 395 using the available data. To be more complete quantitatively in terms of MFs, it is no-  
 396 ticeable that we have not checked the contribution of the waves with period slower than  
 397 1day that should be explicitly resolved in the model, but we suspect it is quite small sim-  
 398 ply because the LMDz-6A spatial resolution is quite coarse (for an evaluation of the large  
 399 scale waves in LMDZ-6A see (Maury & Lott, 2014; Holt et al., 2022)).

400 The second is that balloon measurements are extremely rare. Showing that they  
 401 are representative of what occurs over much longer periods and over many different places  
 402 tell that they could be used, in conjunction with other products to provide much larger  
 403 datasets where GWs momentum fluxes and large scale conditions are combined. Among  
 404 the datasets to consider, and on top of the satellite data (Ern et al., 2014; Alexander et  
 405 al., 2021), the global convection permitting models look promising (Stephan et al., 2019)  
 406 and since we know that high resolution models represent increasingly better gravity waves  
 407 (Sato et al., 1999; Shibuya & Sato, 2019). . Such large dataset will become mandatory  
 408 if the tuning of GWs parameterization necessitate data assimilation techniques (Tandeo  
 409 et al., 2015) and even more with the more recent development of machine learning based  
 410 parameterizations of GWs (Matsuoka et al., 2020; Chantry et al., 2021; Espinosa et al.,  
 411 2022). For these, it seems crucial that physically based techniques can be validated against  
 412 in situ data before shifting to machine learning techniques using synthetic data. We there-  
 413 fore plan to extent the analysis to the Loon LLC superpressure balloon data (Lindgren  
 414 et al., 2020) which covers extratropical regions as wall as tropical. It will permit to test,

415 and may be calibrate better, the orographic and frontal GWs parameterizations used in  
 416 LMDz-6A (Lott, 1999; de la Cámara & Lott, 2015).

## 417 5 Open Research

418 Balloon data can be extracted from the STRATEOLE 2 dedicated web site: //web-  
 419 str2.ipsl.polytechnique.fr

420 ERA5 reanalysis data can be extracted from the COPERNICUS access hub: <https://scihub.copernicus.eu/>

421 The LMDz GCM can be directly installed from the dedicated webpage (in french):  
 422 <https://lmdz.lmd.jussieu.fr/utilisateurs/installation-lmdz>

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