Comparison between non orographic gravity wave drag parameterizations used in QBOi models and Strateole 2 constant level balloons

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Key Points:

- The non-orographic parameterization tuned to produce a realistic tropical quasi-biennial oscillation in global climate models are 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 in some cases with observations, except when launching level are near the tropopause.
- The probability density distribution of the parameterized momentum fluxes are better reproduced when the schemes are not related to their convective sources and/or when the launching level is in the lower and middle troposphere.

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Abstract

Gravity Waves (GWs) parameterizations from 14 General Circulation Models (GCMs) participating to the Quasi-Biennial Oscillation initiative (QBOi) are directly compared to Strateole-2 balloon observations made in the lower tropical stratosphere from November 2019 to February 2020 (phase 1) and from October 2021 and January 2022 (phase 2). The parameterizations used span the 3 state of the arts techniques used in GCMs to represent subgrid scale non-orographic GWs, the two globally spectral techniques developed by Hines (1997) and Warner and McIntyre (1999) respectively and the "multiwaves" approaches following Lindzen (1981). The input meteorological fields necessary to run the parameterizations offline are extracted from the ERA5 reanalysis and correspond to the instantaneous meteorological conditions found underneath the balloons. In general, the amplitudes are in fair agreement between measurements of the momentum fluxes due to waves with periods less than 1 hr and the parameterizations. The correlation of the daily values between the observations and the results of the parameterization can be around 0.4, which is statistically elevated considering that we analyse around 1200 days of data and sometime good considering that the parameterizations have not been tuned: the schemes used are just the standard ones that help producing a Quasi-Biennial Oscillation (QBO) in the corresponding model. These correlations nevertheless vary considerably between schemes and depend little on their formulation (globally spectral versus multiwaves for instance). We therefore attribute it to dynamical filtering all schemes taking good care of it, whereas only few relate the gravity waves to their sources. Except for one parameterization, significant correlations are mostly found for eastward propagating waves, which may be due to the fact that during both Strateole 2 phases the QBO phase is easterly at the altitude of the balloon flights. On the other hand, statistical properties, like pdf of momentum fluxes seem better represented in spectral schemes with constant sources than in schemes ("spectral" or "multiwaves") that relate GWs to their convective sources.

Plain Language Summary

In most large-scale atmospheric models, gravity wave parameterizations are based on well understood but simplified theories and parameters which are keyed to reduce systematic errors on the planetary scale winds. In the equatorial regions, the most challenging errors concern the Quasi Biennial Oscillation. Although it has never been verified directly, it is expected that the parameterizations tuned this way should transport a realistic amount of momentum flux in both the eastward and westward directions when compared to direct observations. Here we show that it is the case, to a certain extent, using constant-level balloon observations at 20 km altitude. The method consists in comparing directly, each day and at the location of the balloon the measured momentum fluxes and the estimations from the gravity wave parameterizations used in the global models that participate to the Quasi-Biennal Oscillation intiative and when using observed values of the large-scale meteorological conditions of wind, temperature, precipitation, and diabatic heating.

1 Introduction

It is well known that the large scale circulation in the middle atmosphere is in good part driven by gravity waves (GWs) that propagate in the stratosphere (Andrews et al., 1987). These waves carry horizontal momentum vertically and interact with the large scale flow when they break. The horizontal scale of these waves can be quite short, much shorter than the horizontal scale of General Circulation Models (GCMs) so they need to be parameterized (Alexander & Dunkerton, 1999). In the tropics, the convective GWs are believed to dominate largely (Fovell et al., 1992; Alexander et al., 2000; Lane & Moncrieff, 2008), they contribute significantly to the forcing of the Quasi-Biennial Oscillation (QBO), a near 28-month oscillation of the zonal mean zonal winds that occurs in the lower part of the equatorial stratosphere (Baldwin et al., 2001). For these reasons, the parameterization of convective GWs is necessary for most GCMs to explicitly realize the QBO.

Although gravity wave parameterizations are now used in many models with success including in the tropics (Scinocca, 2003; Song & Chun, 2005; Beres et al., 2005; Orr et al., 2010; Lott & Guez, 2013; Bushell et al., 2015; Anstey et al., 2016; Christiansen et al., 2016; Serva et al., 2018), their validation using direct in situ observations remains a challenge. There exist observations of GWs using global satellite observations (Geller et al., 2013) but the GWs identified this way still have quite large horizontal scales, and some important quantities like the Momentum Fluxes (MFs) are often deduced indirectly, for instance from temperature measurements using polarization relations (Alexander et al., 2010; Ern et al., 2014). For these two reasons, in situ observations are essential, and the most precise ones are provided by constant-level long-duration balloons, like those made in the Antarctic region during Strateole-Vorcore (Hertzog, 2007) and Concordiasi (Rabier et al., 2010), or in the deep tropics during PreConcordiasi (Jewtoukoff et al., 2013) and Strateole 2 (Haase et al., 2018). Among many important results, these balloon observations have shown that the momentum flux entering in the stratosphere is extremely intermittent (Hertzog et al., 2012). This intermittency implies that the mean momentum flux is mostly transported by few large-amplitude waves that potentially break at lower altitudes than when the GW field is more uniform. This property, when reproduced by a parameterization (de la Cámara et al., 2014; Kang et al., 2017; Alexander et al., 2021), can help reduce systematic errors in the midlatitudes, for instance on the timing of the final warming in the Southern Hemisphere polar stratosphere (de la Cámara et al., 2016), or on the QBO (Lott et al., 2012). Balloon observations have also been used to characterize the dynamical filtering by the large scale winds (Plougonven et al., 2017), and to validate the average statistical properties of the GW momentum flux predicted offline using reanalysis data (Kang et al., 2017; Alexander et al., 2021).

However, the evaluation of parameterizations using balloon observations often done in the past were often quite indirect , and concern more their statistical behaviours (Jewtoukoff et al., 2015; Kang et al., 2017; Alexander et al., 2021) then there capacity to to directly predict instantaneous values of momentum fluxes. Maybe a good reason to believe so is that parameterizations are based on simplified quasi-linear wave theory, they assume spectral distributions that are loosely constrained, and they ignore lateral propagation almost entirely (some attempt to include it can be found in Amemiya and Sato (2016)). Nevertheless, some factors could mitigate these weaknesses. One is that in most parameterizations the wave amplitude is systematically limited by a breaking criterion that encapsulates nonlinear effects. An other is that some parameterizations explicitly relate launched waves to sources, and there is constant effort to improve the realism of the convective ones (Liu et al., 2022). Also, observations systematically suggest that dynamical filtering by the large scale wind is extremely strong for upward propagating GWs (Plougonven et al., 2017), and this central property is represented in most GW parameterizations. For all these reasons, it may well be that GW parameterizations keyed to the large scale conditions found at a given place and time gives MFs that can be directly compared to the MFs measured by a balloon at the same place.

Based on the relative success of the offline calculations done in the past using reanalysis data (Jewtoukoff et al., 2015; Kang et al., 2017; Alexander et al., 2021), Lott et al. (2023) have shown that such a direct comparison gives result of interest. The first is that a state of the art convective gravity wave drag scheme, predicts momentum fluxes in the low equatorial stratosphere which amplitude can be directly compared with those measured during phase 1 of the Strateole-2 balloon campaign. It gives a direct in-situ observational confirmation that the theories and modelling of the QBOs developed over the last 50 years were in good part correct about the significance of the GWs to the QBO forcing. Also interesting, the comparison showed a good level of correlation between the day to day variability in momentum fluxes between measured and observed fluxes, a correlation that is much better for waves carrying momentum fluxes in the eastward direction than in the westward direction. It was suggested that such a good ccorrelation was due to the fact that the Lott and Guez (2013)'s scheme analysed relate the gravity waves to their convective sources (not all schemes do) and that the GWs experience significant dynamical filtering in the middle troposphere and lower stratosphere. Lott et al. (2023) nevertheless revealed that a scheme that relates gravity waves to convection exclusively somehow failed in predicting the right statistical behaviour of the momentum fluxes, the probability density function of the momentum fluxes amplitude showing long tails for low values of the MFs, suggesting missing processes like lateral propagation or the presence of a background of waves which origin remains a challenge to predict.

The purpose of this paper is to continue such a direct comparison including more recent Strateole 2 observations and near all the gravity wave parameterization schemes used by the modelling groups participating to the Quasi-Biennial Oscillation initiative (QBOi, Butchart et al., 2018). We will follow for that Lott et al. (2023) and use the 8 balloons of the first phase of the Strateole 2 campaign that flew in the lower tropical stratosphere between November 2019 and February 2020 and extent it to the 15 balloons that flew more than one day during the second phase of the Strateole 2 campaign, between October 2021 and January 2022. For each of the flights and each time, we have identified the grid point in the ERA5 reanalysis (Hersbach et al., 2020) that is the nearest and used the vertical profiles of wind and temperature as well as the surface value of precipitation to emulate the parameterization of GWs used in the global models that participated to the Quasi-Biennial Oscillation initiative (QBOi). We also extract from the analysis and short range forecast, diabatic heatings and the cloud base and top altitudes needed in some schemes to predict gravity waves.

2 Data and method

2.1 Parameterizations of non orographic gravity wave schemes

The parameterizations schemes used to predict orographic gravity waves belongs to two well separated families, dating back from the 1980's when it becomes evident that a good simulation of the middle atmosphere by global atmospheric models could not be done without taking into account non-orographic gravity waves. The first family roots in the formulation by Lindzen (1981), where the gravity wave field is represented by gravity waves that are monochromatic in the horizontal space and time. It was extended to treat a large ensemble of waves by Alexander and Dunkerton (1999) making the assumption that the breaking of each waves could be made independent from the others. An advantage of such schemes is that it roots in linear theories where sources like convection and/or fronts can be introduced using closed form theories (Beres et al., 2005; Song & Chun, 2005; Richter et al., 2010; Lott & Guez, 2013; de la Cámara & Lott, 2015). In the following we will refer to such schemes as "multiwave", they are expensive because they request a large amount of waves to represent well a realistic wave field, but this limit

	p_l	F_{LT}	$2\pi/m_*$	$C_{\min}$
CMAM	100hPa	1.3mPa	1km	0.25 m/s
IFS	450hPa	5mPa	3km	0.5 m/s
ECEarth	450hPa	3.75mPa	2km	0.25 m/s
UKMO	1000hPa	Precip	4.3km	?

Table 1. WMI Parameters changing between CMAM, IFS, ECEarth, and UKMO. UKMO is shown distinctly because it is based on (Warner & McIntyre, 1999) simplified version of WMI rather than on (Scinocca, 2003)'s and realte launched MF to precipitations.

can easily be circumvented by using stochastic approaches (Eckermann, 2011; Lott et al., 2012). As an alternative, but also to better represent breaking, many centers developed globally spectral schemes. These schemes uses the observational fact that in observations the vertical shape of the spectra have a quite universal character. In the early 1990's Hines (1991) developed a theory where GW breaking is represented by imposing an upper limit to the range of vertical wavenumber, the limit being calculated according to the large scale wind and including a Doppler spreading by the other gravity waves (see also Hines, 1997). The scheme has been implemented with success in various GCMs (see for instance Manzini, McFarlane, & McLandress, 1997), and will be referred to as "HDS" in the following. As an alternative, the theory in Warner and McIntyre (1996) imposes gravity wave saturation according to an empirical spectra but treat vertical changes in the spectra following GWs propagation invariant character. The theory has been simplified and/or optimized to permit implementation, for instance in the UKMO model (Warner & McIntyre, 1999; Scaife et al., 2002) and in the CMAM model (Scinocca, 2003) respectively, and will be refered to has "WMI" in the following. To a certain extent, the spectral schemes can also take into account the relation with sources, for instance the HDS scheme has been related to fronts in (Charron & Manzini, 2002), and the UKMO version of the WMI scheme to precipitations in (Bushell et al., 2015).

In the present paper, we are going to compare the GWs schemes used in 14 of the models that participate to QBOi, all belonging to one of the three type of schemes described above (WMI, HDS, and Multiwave). As all the multiwave schemes used relate GWs to their convective sources and as only one of the spectral scheme is doing so, the UKMOgws WMI scheme in (Bushell et al., 2015), the former will be discussed with the source-related multiwave schemes.

Among the 14 models, three use the (Scinocca, 2003)'s version of the WMI: CMAM, IFS and ECEarth. Their version for QBOi and further detailed in (Anstey et al., 2016; Orr et al., 2010; Davini et al., 2017), they essentially differ by four parameters, the launch level pressure p_l, the launched momentum flux F_{LT}, the characteristic vertical wavenumber m_* and a minimum intrinsic phase speed in the launched spectra, the values of each being given here in Table 2.1. Note that for EC-Earth the exact value of the parameters in Table 2.1 are from J. Garcia Serrano (private communication).

Still among the 14 models, 5 uses the (Hines, 1997)'s parameterization schemes presented in (Manzini et al., 1997). Between the five models, and in the Hines scheme, only changes between models the launching level p_l, the root mean square of the horizontal wind variability due to GWs at launch level σ, as well as an effective horizontal wavenumber K^*. There are also more numerical parameters that eventually changes, a minimum value for the the cutoff vertical wavenumber $m_{\min}$, and two parameters that control smoothing in the vertical of the GWs root mean square variance and cut-off vertical wavenum-

	p_l	σ_s	$2\pi/K^*$	m_{min}	C_{smo}	N_{smo}
ECham5	450hPa	1.	125km	0	2	5
MIROC	650hPa	0.95	250km	6.5 10^{-5}	2	2
MPIM	650hPa	1.2	125km	0	2	2
MRI-ESM	700hPa	1.9	1250km	3.3 10^{-4}	4	2
EMAC	650hPa	1.	125km	0	2	2

Table 2. HDS Parameters changing between ECHam5, MIROC, MPIM, MRI-ESM, and EMAC.

	p_l	Phase Speed	Δz	Source
LMDz	500hPa	-30m/s<Intrinsic<30m/s	1km	Precip
Yonsei	900hPa-100hPa	-100m/s<Absolute<100m/s	100m-15km	Heating rate
WACCM	?			Heating rate

Table 3. Some parameters changing between LMDz, YONSEI and WACCM, for information only the schemes being extremely distinct

ber, the coefficient C_{smo} and the number of time the smoothing is applied N_{smo} (see Table 2.1).

Finally the last 4 schemes we consider all links GWs to sources (convection or precipitation), 3 are multiwaves and have been developed independently one from the others, LMDz, YONSEI, and WACCM and 1 uses the ultra simple version of the WMI schemes presented in (Warner & McIntyre, 1999; Bushell et al., 2015) rather than the (Scinocca, 2003)'s version. The differences between the 3 multiwave schemes are numerous it is impossible to details them, the reader is referred to the corresponding papers. The most salient differences are in the source term, the launching levels and the intrinsic phase speed of the launched waves. In LMDz is made the choice to relate the launched MF to square precipitation P_r^2 consistent with linear theory before breaking (Lott & Guez, 2013) whereas in (Bushell et al., 2015) it is related to $\sqrt{P_r}$ (see Table 2.1). Still in LMDz, the waves are launched from the mid troposphere, whereas they are launched from the surface inthe UKMOgws model. In the Yonsei's and WACCM scheme (Song & Chun, 2005; Choi & Chun, 2011), the launched momentum flux is directly related to convective heating distributed in the vertical between the cloud bottom and cloud top, the launch altitude being at the cloud top. In this case the launching level can vary between $2km$ and 15km typically and the depth of the heating between 100m and $15km$. Also, the absolute phase speed cover the ranges 100m/s $< C_{abs} <$ 100m/s.

2.2 Offline parameterization runs

To activate the schemes in offline mode we will use ERA-5 hourly data of precipitation and 3-hourly data of winds, surface pressure, temperature, cloud liquid and ice water content at $1^o \times 1^o$ horizontal grid to mimic a large scale climate model resolution. Winds, surface pressure, temperature, and water contents are then linearly interpolated on 1hr time step to be synchronised with precipitation. In the vertical we use data at 67 model levels, taking one every two ERA5 levels again to mimic large scale models vertical resolution but also to speed up calculations. To estimate convective heating rates vertical profiles, we follow (Fueglistaler et al., 2009) and evaluate diabatic heating using ERA5 hourly data from short range forecast and as a residual between the parameterized temperature tendency and the radiative heatings (longwave plus shortwave). When needed, we also evaluate the cloud bottom height and top height using the cloud water content (liquid+ice) from ERA5 reanalysis.

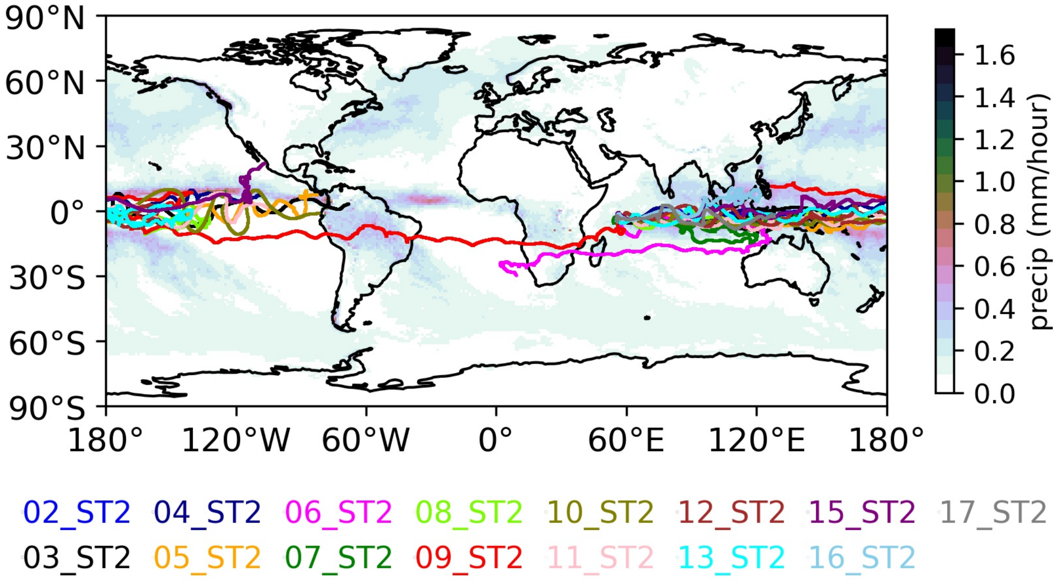

Figure 1. Strateole 2, Phase 2 balloon trajectories taking place between October 2021 and January 2022. Shading presents the precipitation field from ERA5 averaged over the period.

2.3 Strateole 2 balloon observations

The in situ observations we use are from the 8 balloons of the first phase of the Strateole 2 campaign that flew in the lower tropical stratosphere between November 2019 and February 2020 and from the 15 balloons that flew more than one day during the second phase of the Strateole 2 campaign, between October 2021 and January 2022. The trajectories during phase 2 are shown in Figure 1, superimposed upon the averaged precipitation (the same Figure but for phase 1 is in Lott et al. (2023)). In the MFs calculated from observations Corcos et al. (2021) distinguish the waves with short periods (1hr-15mn) from the waves with period up to one day (1d-15mn). They also distinguish the eastward waves giving positive MF in the zonal direction from the westward waves giving negative MF. It is important to notice that during phase 2, the large scale winds conditions in the lower stratosphere are almost as during phase one at balloons altitudes (end of eastward QBO phase).

In the following we will compare the momentum fluxes derived from the balloon data, emphasize the intrinsic frequencies that the scheme represents (the intrinsic periods below $1hr$) and consider the ERA5 data at the points that are the nearest from the balloon. The prediction is then made every hour and averaged over the day, partly because it is the time scale needed for the some schemes to sample realistically a GW field, and also because it takes around a day for a balloon flight to cover a model gridscale. Note that some of the sensitivities to these choices are discussed in the Lott et al. (2023)'s conclusion.

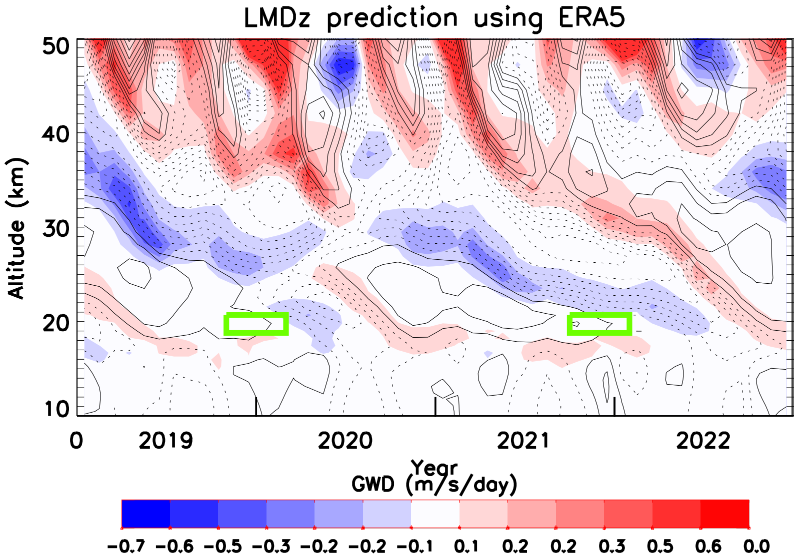

Figure 2. Time vertical sections of the zonal mean zonal wind (CI=10m/s, negative values are dashed and non-orographic gravity wave tendency averaged over the Equatorial band ($-6^oS \quad - \quad +6^oN$). Input data are from ERA5 reanalysis and GWs prediction from the LMDz scheme. The 2 green boxes indicate schematically the altitude and time ranges of the Strateole 2 phase 1 and 2 flights considered in this study.

3 Results

Figure 3 shows time series of daily values of momentum fluxes predicted by the parameterizations and measured during balloon flights 2 from strateole 2 phase 1. This is also the flight shown in Fig. 3 in Lott et al. (2023), and where was also shown the time series of daily precipitation and zonal wind at flight altitude. The top panel is for the WMI based schemes, the middle panel for the HDS schemes and the bottom panels for the schemes relating the GWs fluxes to their sources. In all panels the black curves are for the daily observations. For clarity we present results for the Eastward and westward MFs only. Overall ones sees that the schemes predict momentum flux values that somehow compare with the observed one, at least in term of amplitude. There are nevertheless significant differences in behaviour. For instance, the IFS's schemes present substantial peaks in eastward flux during the second half of the flight, which is a period during which the zonal wind at flight altitude becomes westward (see Figure 3b in Lott et al. (2023)), potentially favoring eastward waves, a process we refer to as dynamical filtering in (Lott et al., 2023) (see Eq. 3 there and the following discussion). Note that in this paper, we showed that the 3 peaks in measured fluxes around days 60, 75, and 83 also correspond to dates when there are precipitations near the balloon location. These correspondences made us believe that the relation with convective sources is essential, we see here that dynamical filtering alone may well be the main cause. Although having smaller amplitudes, the Figure show that in EC-Earth, the momentum fluxes behave almost as in IFS. The results from CMAM are quite different nevertheless. In this model it was chosen to place the launching altitude near the tropopause the daily series present much less fluctuations and long lasting "plateaus", clearly in this model, the distance between the launching level (100hPa see Table 2.1) and the balloon altitude is too small for dynamical filtering to be efficient. The second panel for the HDS schemes is not fundamentally different from what was discussed above. The amplitude and fluctuations are comparable to observed, some schemes predicting values which look either larger or smaller

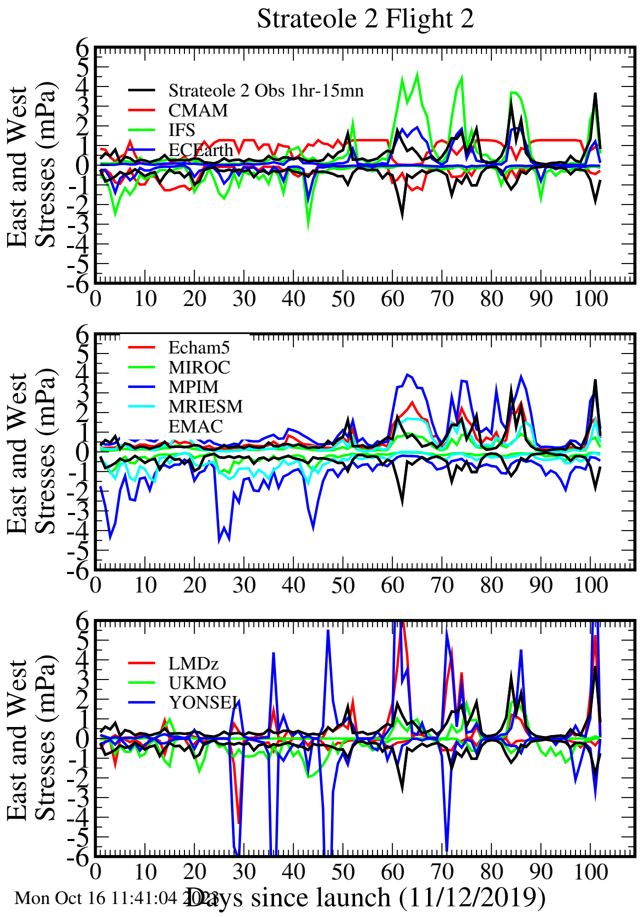

Figure 3. Comparison between daily averaged values of the eastward and westward MFs measured by the balloons during Strateole 2 phase 1 Flight 2 and estimated by the GW schemes at the balloon location and altitude. Colored curves are for the GW schemes predictions using ERA5 and from different models, black curves are for the observed MFs due to the 15mn-1hr GWs. a) WMI schemes; b) HDS Schemes; c) Multiwaves schemes relating launched MFs with convective sources or precipitations.

but staying within the range of observations. The behaviour of the source related schemes in the last panel is more contrasted. As expected, there are long periods during which the schemes predicted small and null momentum fluxes fluxes, interrupted by short lasting peaks with values easily going beyond ±5mPa, values that were never reached by any of other schemes during this flight. In contrast with LMDz and YONSEI, the UKMO scheme present smaller amplitude and broader peaks, we attribute this to that it relates the launched flux to $\sqrt{P_r}$ rather than P_r^2 in LMDz, or the square of heating in YONSEI's.

An other example of timeseries is provided in Fig. 4, which corresponds to a flight during the second phase of strateole 2. Beyond the fact that the flight is shorter than in Fig. 3, a difference in duration that characterize most of the flights during phase 2,the overall behaviours stay about the same, with the spectral schemes presenting fluctuations with broader peaks, except maybe CMAM, again because the launching altitude is quite high and dynamical filtering not yet efficient at balloon flight altitude. The last panel also shows that UKMO present long periods with almost no fluxes, in it, the fact

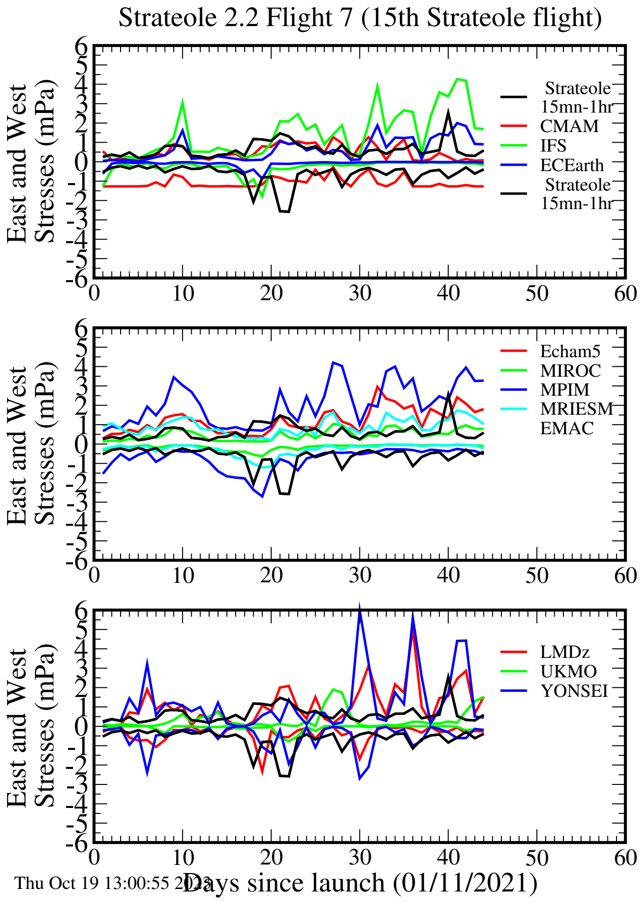

Figure 4. a) Same as Fig 2 but for Strateole 2 Phase 2 Flight 7.

that the launching height is near the surface produces much more critical level situations during the propagation through the tropopause.

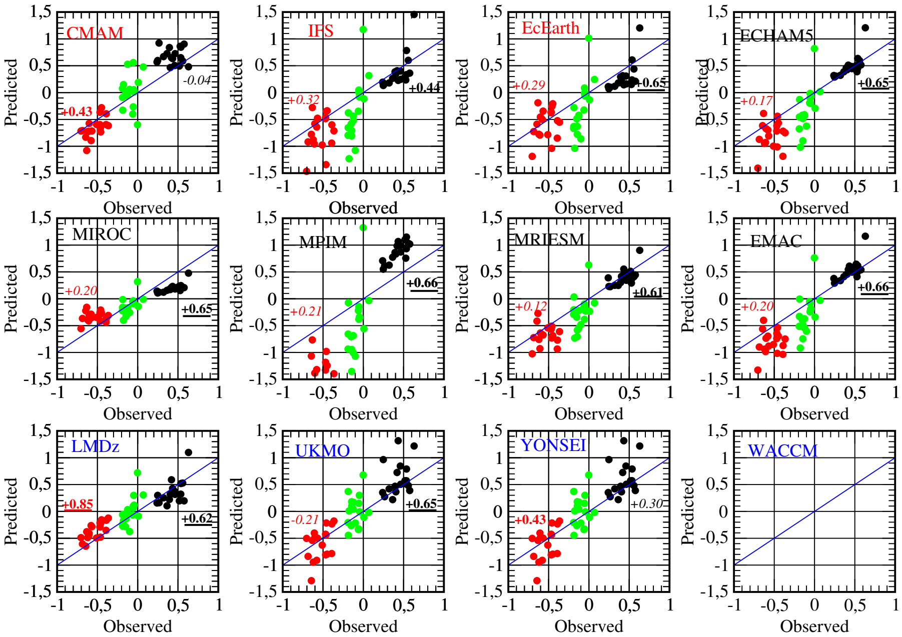

Figure 5. Scatter plot of the momentum fluxes measured by the balloon versus parameterized using different models. Only considered here the 18 balloon flights that last more than a month (East: black; West: red; Cumulated: green). Also shown are the correlations between observations and predictions, 99% significant levels are bold underlined, 95% are bold. Non significant values are shown in italic for information. The number of DoF for Pearson test is 18, about the number of balloon flights that last more than a month.

The fact that the different schemes estimate momentum fluxes of about the right amplitude is summarized in Fig. 5 where the average of the fluxes over the 18 flights that last more than a month (8 during phase 1, 10 during phase 2) are shown. In it we see that the predicted values align quite well with the observed one, some schemes having tendency to slightly underestimate the fluxes (MIROC, LMDz), other to overestimate them (CMAM, YONSEI), with the tendency to overestimate being in general more pronounced for the westward fluxes. The numbers in each panels also show the correlation between the 18 values averaged over each flights, showing that the correlations become strong in many models, at least in the eastward direction. Interestingly some models also have significant medium to high correlations in the westward direction (CMAM, LMDz, YONSEI).

The Figure 6 group the models averaging the eastward and westward fluxes over all the balloon flights, confirming again that the parameterizations used fall around the observed values. There is variabilities between the models, but there is no systematic tendency among the modellers to overstate or understate the MFs flux amplitude. This is summarized by the green curve which represents the average over models and over balloon flights. The average amplitude of the eastward flux is very near that observed (a 10% overestimation between 0.45mPa in parameterizations against 0.40mPa observed), whereas the westward flux are overestimated by the models by less than 20% (-0.65mPa parameterized against -0.55mPa observed). This 10%-20% errors explain the quite large

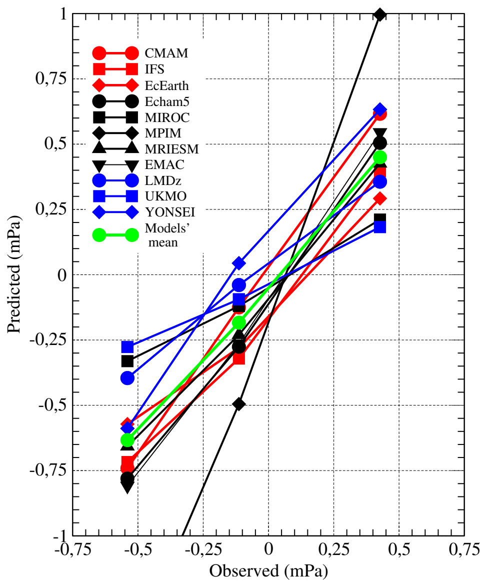

Figure 6. East, West and cumulated zonal momentum fluxes averaged over the Strateole 2 phase 1 and 2 period and according to participating models.

relative error (50%) in the cumulated flux but for it the large relative error is in good due to the fact that large positive and negative fluxes opposed each other.

The daily series in Figs 3 and 4 also suggest that observations and offline estimations sometimes evolve similarly day after day, a reason could be that both measured and parameterized MFs are sensitive to dynamical filtering, some schemes also taking into account sources. In the two examples given here, it is quite apparent in the first (Figure 3) and for instance for the peaks in the eastward direction as already discussed. Correspondences are less obvious to visualize in the second case (Figure 4) where the evolution of the measured MFs present less variations than the predicted MFs. In (Lott et al., 2023) we analysed these daily variabilities flights by flights and indeed found that is some flights the series correlate well whereas in others they do not. The contrast between flights made that in the end the correlations where significant but "medium" in the eastward direction $C \approx 0.5$ and "low" in the westward direction $C \approx 0.3$. Here and the following, we referred to "medium" positive correlations with $0.3 < C < 0.5$ and small correlations when $0.1 < C < 0.3$. As such a result was obtain from the LMDz parameterization during Strateole 2 phase 1 the coefficients are given again in the 9th column of Table 4. In it are also given the same coefficients but for Phase 2, confirming with an independent datasets the results in Lott et al. (2023). Consistent with Lott et al. (2023) but evaluating correlations over phases 1 and 2, we indeed found medium correlation in the Eastward phase ($C = 0.4$) and small in the westward phase ($C = 0.34$). Here and for completeness, note that as in (Lott et al., 2023), and to test the significance, we measure the number of Degrees of Freedom (DoF) present in each dataset, and calculate for that the decorrelation time scale, which we take as the lag in day beyond which the lag-autocorrelation of the series falls below 0.2. As this time-lag varies from one series to the other, we give explicitly in column 5, the number of DoF, which is the duration of the flight divided by the decorrelation time scale. Note that for their decorrelation time, we consider for simplicity that evaluated with daily averaged observations, but found that it is not much different from that evaluated with the offline estimates (not shown).

East	Day Dof	CM AM	IFS	ECE ARTH	Ech am5	MI ROC	MPI M	MRI ESM	EM AC	LMD z	UK MO	YON SEI
Phase 1	670-216	-0.07	0.53	0.52	0.52	0.48	0.49	0.44	0.48	0.51	0.34	0.32
Phase 2	621-322	-0.19	0.41	0.38	0.38	0.33	0.34	0.30	0.33	0.40	0.34	0.20
Phase 1+2	1291-538	-0.11	0.49	0.47	0.45	0.41	0.41	0.36	0.40	0.46	0.34	0.27
West	Day Dof	CM AM	IFS	ECE ARTH	Ech am5	MI ROC	MPI M	MRI ESM	EM AC	LMD z	UK MO	YON SEI
Phase 1	670-216	0.14	-0.07	-0.07	-0.13	-0.03	-0.04	-0.04	-0.04	0.29	-0.03	0.10
Phase 2	621-322	0.21	0.18	0.16	0.03	0.00	0.01	0.05	-0.01	0.40	0.04	0.13
Phase 1+2	1291-538	0.17	0.05	0.04	-0.05	-0.02	-0.02	0.01	-0.02	0.34	0.00	0.11

Table 4. Correlation between observed and measured fluxes, strateole phases 1 and 2.

If we now look at the schemes used in the other models, the result are contrasted but quite in agreement. A lot a variations between flights (not shown) the overall behaviour being well summarized in the global correlation coefficients shown in Table 4. First, and as for LMDz, the correlations evaluated using Phase 2 data stay robust when compared to correlations evaluated using phase 1, and whatever is the level of correlation (”medium”, ”low”, or ”non significant”). Second, is that many schemes managed to have ”medium” correlations ($0.3 < C < 0.5$) in the eastward direction, except the CMAM scheme. We attribute this to the fact that in this model the launching level is near the tropopause which strongly mitigates dynamical filtering. Also interesting, the YONSEI scheme is the one is the lowest correlation after CMAM, in case of deep convections it also launch waves from quite high levels in the troposphere suggesting that in it as well and for some waves with strong eastward flux, dynamical filtering did not have time to differentiate the waves between the launching level and the balloon level. The results in the westward direction are more intriguing, the correlations are always small except for 1 scheme (LMDz) and some but ”low” correlations are found for the two schemes that launch waves quite near the tropopause. We have difficulties in interpreting this last result, it may be tells that the approaches where some waves are launched from near the tropopause should not be disregarded, and that launching from a fixed altitude well in the tropospheres fails in some cases. But if this is the case, the performance of LMDz are somehow in contradiction, in it the launching level is in the mid troposphere, as many other schemes according to tables 2.1-2.1-2.1, maybe its skill come from the fact that LMDz explicitely launch waves according to their intrinsic frequency at launch level a property that is maybe more indirect in the spectral schemes.

Controversy here? Are we right when writting the above two lines? They are quite vague and can be deleted.

Whatever is the explanation, it is maybe more interesting to notice that there is room to improve GWs parameterizations to obtain better fits between predicted and measured fluxes in both directions of propagation.

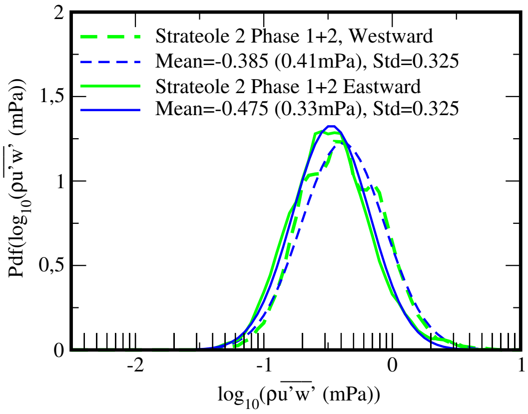

Figure 7. PDFs of daily values of Momentum flux distribution evaluated from Strateole Phases 1 and 2. The PDFs are calculated from histograms of 1291 MFs daily value within intervals of $\Delta\left(\log_{10}\rho\overline{u'w'}(\text{mPa})\right) = 0.05$, thereafter smoothed by a 5 point non-recursive filter with weight $(0.1, 0.2, 0.4, 0.2, 0.1)$. Measured values are in green, log normal fits are in blue. Solid lines are for Eastward, dashed lines are for Westward. Here the log normal probability density function is defined as $P(X) = \frac{1}{\sqrt{2\pi\sigma}}e^{-(X-M)^2/(2S^2)}$, where $X = \log_{10}\rho|\overline{u'w'}|$, and M and S the mean and standard deviations given in caption.

As said in the introduction, more than predicting the right fluxes at the right time, it is often believed that parameterizations should better be validated against their global statistical behaviour. A reason is that observed gravity waves show a strong level of intermittency such an intermittency impacting the the effect of the waves on the large scale flow and climate in the middle atmosphere. In a recent Paper, Green et al. (2023) showed that this behaviour is well captured when the GWs MFs have pdfs following a log-normal distribution. These authors even concluded that in all directions of propagation, momentum fluxes characteristics could be summarized in terms terms of the mean and variance of log normal distributions. As shown before in (Lott et al., 2023) such lognormal distributions describe well the Strateole-2 data, a behaviour illustrated further well when evaluating the pdfs over phase 1 and 2 (see Fig. 7. One also sees that the balloons almost systematically measure fluxes with amplitude between 0.1mPa and 10mPa, the pdf of the westward fluxes being shifted toward higher values compared to that for eastward flues the shapes being little changed.

To analyse our schemes in this framework the Figure 8 presents PDFs of the distributions of the momentum fluxes considering all the daily data. For the observed PDFs (green solid for eastward fluxes, green dashed for westward fluxes), When one consider the parameterizations schemes, one notice that the pdf are often much broader than the observed pdfs with the WMI schemes than whereas the HDS schemes seem more realistic in this respect. The HDS schemes are also those for which the shift of the westward pdf toward higher values is the more realistically reproduced. Finally, the schemes that relate GWs to convection systematically have much broader pdfs, they all present a tail toward small values of the MFs, suggesting that in them miss a background of wave activity existing even in the absence of convection nearby.

We also notice that the in all models, the pdf of the westward fluxes are shifted to higher values compared to the pdfs of the eastward fluxes, and this is consistent with the fact that in an easterly phase, waves in the westward direction can reach larger amplitudes than the waves in the eastward direction (dynamical filtering again and always consistent with observations). To a large extent, and for most of the spectral scheme this

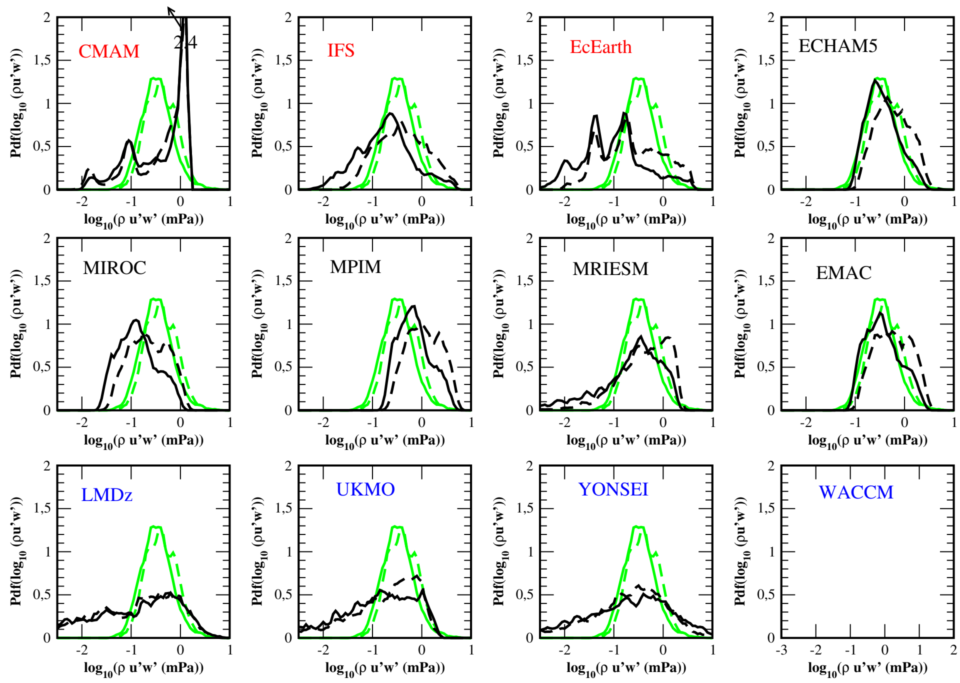

Figure 8. PDFs of daily values of Momentum flux distribution, same method as in Fig. 7. Measure values are in green, estimations using ERA5 data and the parameterizations are in black. Solid lines are for Eastward, dashed lines are for Westward.

supports the results in Green et al. (2023) where the difference in GW momentum fluxes between direction of propagations could essentially be summarized by log-normal pdfs shifted by differences in mean values.

4 Conclusion

The main result of this paper is that state of the art parameterizations of GWs reproduce reasonably well the momentum flux due to the high-frequency waves (periods between 15mn and 1hr) deduced from in situ measurements made onboard constant-level balloons. The parameterizations represent well the eastward and westward values of the stress and in some cases their variations from day to day. Although the various schemes performed differently regarding the day to day correlations, our results show that improvement can be done in this regard. Some scheme for instance present "medium" correlations in the eastward direction, telling that such correlation levels can be reached. In the westward direction, the day to day correlations are "low", to the best and in 1 model, we can only say that such a level can also be reached in the tropical regions.

Due to the low to medium level of correlations we found, we could ask ourselves if it is mandatory to improve GW schemes according to such a criteria. After all, when the momentum fluxes are averaged over periods near a month (here we rather consider averages over balloon flights), the correlations become "medium" to "strong" in the eastward direction (see 5) and frequently medium in the westward direction, which is probably enough in the context of the QBO forcing, the QBO evolving over time scales much larger than a month.

An other substantial difference concerns the pdfs of the parameterized momentum fluxes against those of the measured fluxes. Many spectral schemes have log-normal pdfs consistent with observations, providing that the launch level is not to close from the balloon location, whereas the schemes that relate the GWs to their convective sources all present tails toward small values which seem unrealistic. As intermittency is a key factor controlling the altitude at which GWs break, a factor that can have climatic impacts ((de la Cámara et al., 2016)), this should be considered seriously, at least by introducing a background in wave launching amplitude in the schemes that only consider convective sources. This issue may well also be partly sorted out by introducing lateral propagation (Amemiya & Sato, 2016), a process that is important in the balloon observations used here (Corcos et al., 2021), but this will not be sufficient over quite large and dry regions.

We did not try to fit the parameters of the schemes we use in order to improve daily correlations or pdfs or both, but we plan to do it in the near future. We have not much data though, but could use the Loon data post-processed in a comparable way as Strateole 2 by (Green et al., 2023), which would permit to cover much wider regions. We should also test if improving the schemes parameters to improve the fit with observations improve or do not degrade the models climate. It well may be that parameterizations compensate for potentially resolved equatorial waves for instance, the latter showing a lot of variability between the QBOi models (Holt et al., 2022). Also, we could also hope that a better fit with observed values would help reduced persistent systematic errors in the QBO simulations, one of them being that models underestimate the QBO amplitude in the low stratosphere. Unfortunatly, our results so far are not much positive: a common beleive is that such an error could well be reduced by launching waves from near the tropopause, the only model which do so here is not much realistic when it comes to predict MFs variabilities.

5 Open Research

Balloon data presented in Haase et al. (2018) can be extracted from the STRATEOLE 2 dedicated web site: https://webstr2.ipsl.polytechnique.fr

ERA5 reanalysis data are described in Hersbach et al. (2020) and can be extracted from the COPERNICUS access hub: https://scihub.copernicus.eu/

The LMDz-6A GCM used for CMIP6 project is described in Hourdin et al. (2020), it can be directly installed from the dedicated webpage: https://lmdz.lmd.jussieu.fr/utilisateurs/installation-lmdz

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Appendix: Running the offline code

To run the models parameterizations in offline mode and compare with daily values of momentum fluxes measured during strateole 2, download the file offline_v9_Strateole_QBOi_Open.tar, on the web page:

wget `https://web.lmd.jussieu.fr/~flott/DATA/offline_v9_Strateole_QBOi_Open.tar.gz`

Then gunzip and do tar -xvf offline_v9_Strateole_QBOi_Open.tar

In the directory, offline_v9_Strateole_QBOi_Open:

Run directory It basically contains a script that compile the programs, link to the input dataset and produce various outputs. The Makefile certainly needs to be adapted to the computer.
To launch predictions for Strateole-2 phase 1, launch: ./laun_ph1ball_gwd_era5.sh
For phase 2, ph1→ph2.

Fortran Codes: all the fortran routines are located in prog.
laun_gwd_era5.f90: Main program loading input data in netcdf format and calculating drag and momentum fluxes at the balloon place.
preci_gwd_LMDz_QBOi.f90: LMDz Multiwaves routines predicting gwdrag from precipitation
gwsat_Modnam.f90: the globally spectral scheme using the Warner and McIntyre (1996)'s scheme version by J. Scinocca.
hinesgw6g_plus_subs.f HDS scheme
gw_ussp_core.f90: The WMI scheme with amplitude keyed to precipitation used in some UKMO runs.
cgwcalc.f90: Multiwave scheme developped at Yonsei's university

Input Data: All the input data are located in the directories hourly_ph1 and hourly_ph2 for phase 1 and 2 respectively. For instance, 1hr average of the strateole2 momentum fluxes are in
ALL_STRATEOLE2_Balloon_ph1_1day15min.nc
and
All_STRATEOLE2_Balloon_ph1_1hrs15min.nc
for the waves with periods between 1day and 15mn and between 1Hr and 15 mn respectively.
Still in this directory, the ERA5 reanalysis products, which include winds temperature, cloud liquid water, and surface log pressure, over a 5°x5° domain centered at the balloons drifting locations are in Input_ERA5_data_all_variables_balloons_ph1.nc.
Precipitation every hours are also included. The diabatic heatings are from fore-

cast. All datas that are only provided every 3hr are linearly interpolated in time to give hourly values.

Output data (Part 1)
: All the ouputs are in the output_ph1 and output_ph2 directories:

Netcdf: contains the output of the schemes in netcdf format on the vertical column and over the 5°x5° domain over which the ER5 data are provided. There is one netcdf dataset by balloons flight each contains output from all the schemes.

Balloon_alt After post processing by the python scripts launch_script_obs.py, are extracted the MFs at balloon flight altitude.

Python Scripts
: A serie of Python scripts, located into python_script are proposed to compare the outputs of the scheme to the balloon data.

launch_script_obs.py: Reads the balloon flight data of MFs and averaged over 1day and writte them in text format (ending with '.dat') and stored in **output/Balloon_alt/obs_output**

launch_prediction_eachB_ysei.py: extract from the prediction the values of the MFs at the balloons place and altitude. Results stored in text format (".dat" in **Balloon_alt/Pred_output_Balloon_altitude/**.

The next python scripts are cosmetic in the sense that they use the above two datasets to make plots of timeseries balloon averaged values, evaluate correlations, and histograms.

timeseries_obs_pred_plot_all.py Produces a lot of time series for each model and flights.

Output data (Part2) As a result, you can visualize timeseries of each flight here:
: **output_*ph*1/Balloon_alt/figure_timeseries**

Histograms here: **output_ph1/histo**

Scatter plots and correlations here **output_ph1/correlation**

For phase 2, change ph1 in ph2.

xmgrace Alternative to calculate these diagnostics using fortran programs and xmgrace, the programs permit to combine statistics over the 2 phases of Strateole2.

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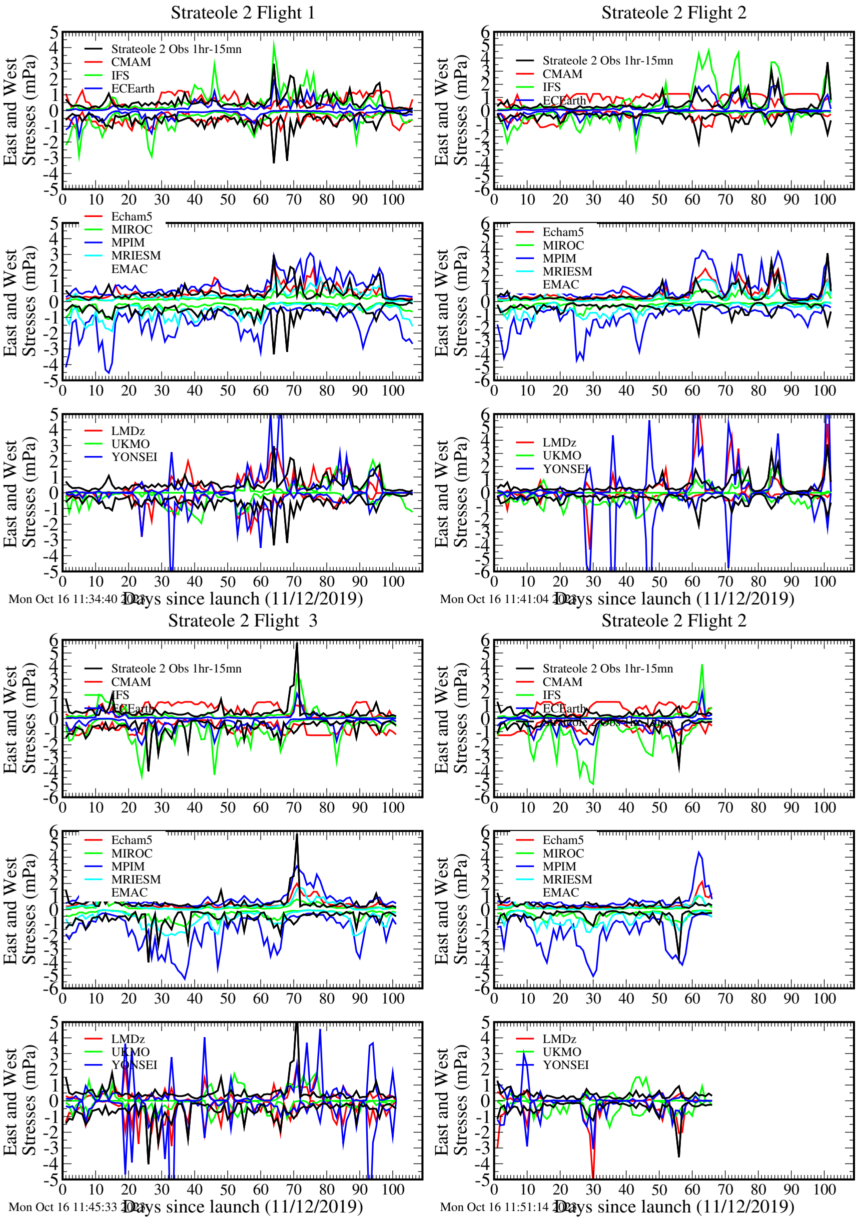
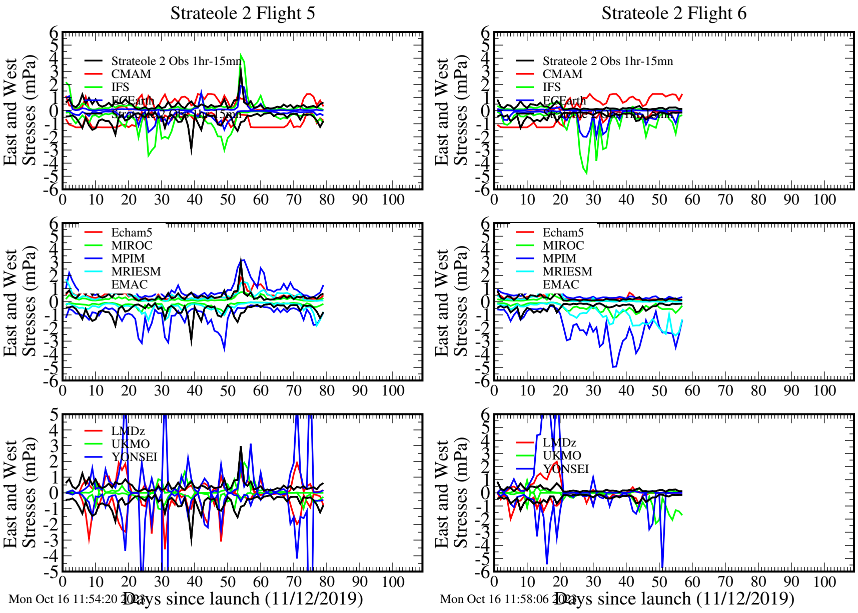
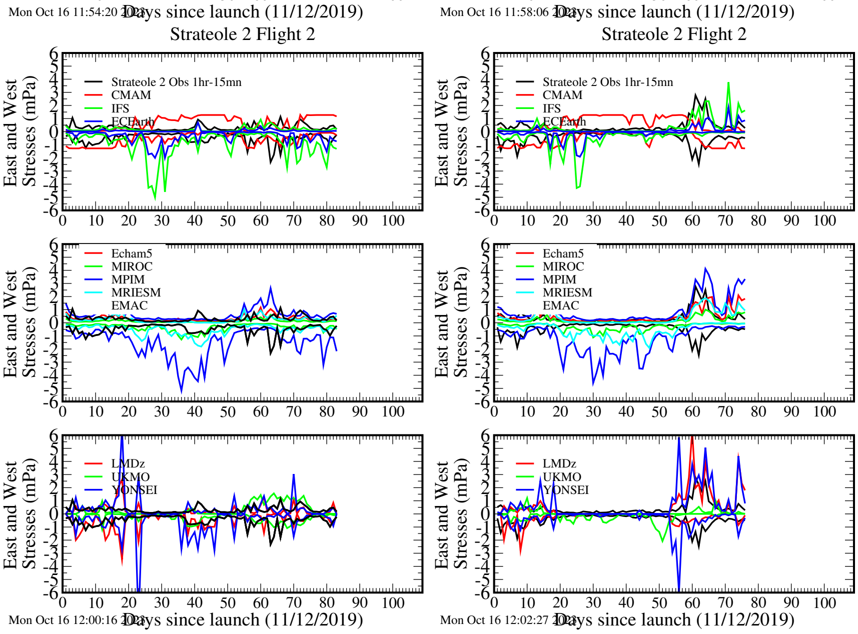
Supplementary: Phase 1 flights and models

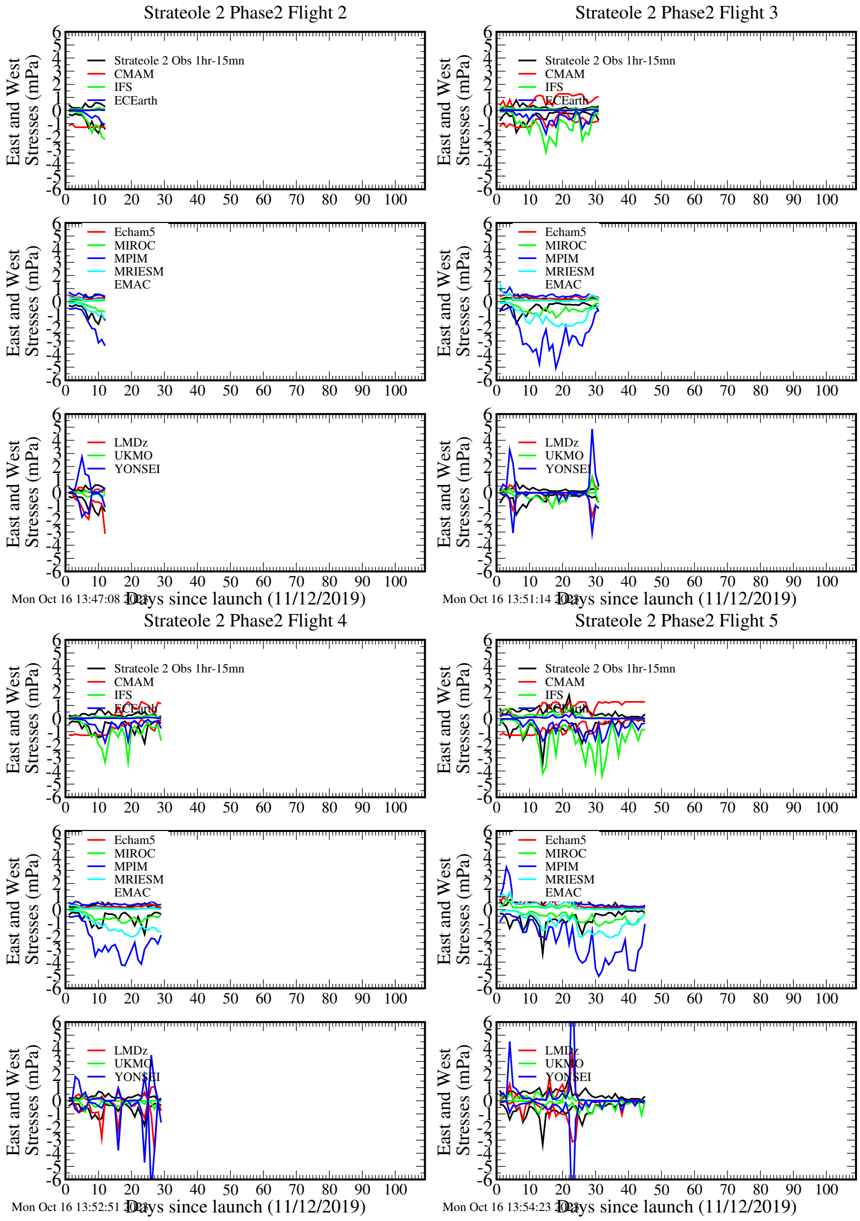


Supplementary: Phase 1 flights and models (continued)





Supplementary: Phase 2 flights and models



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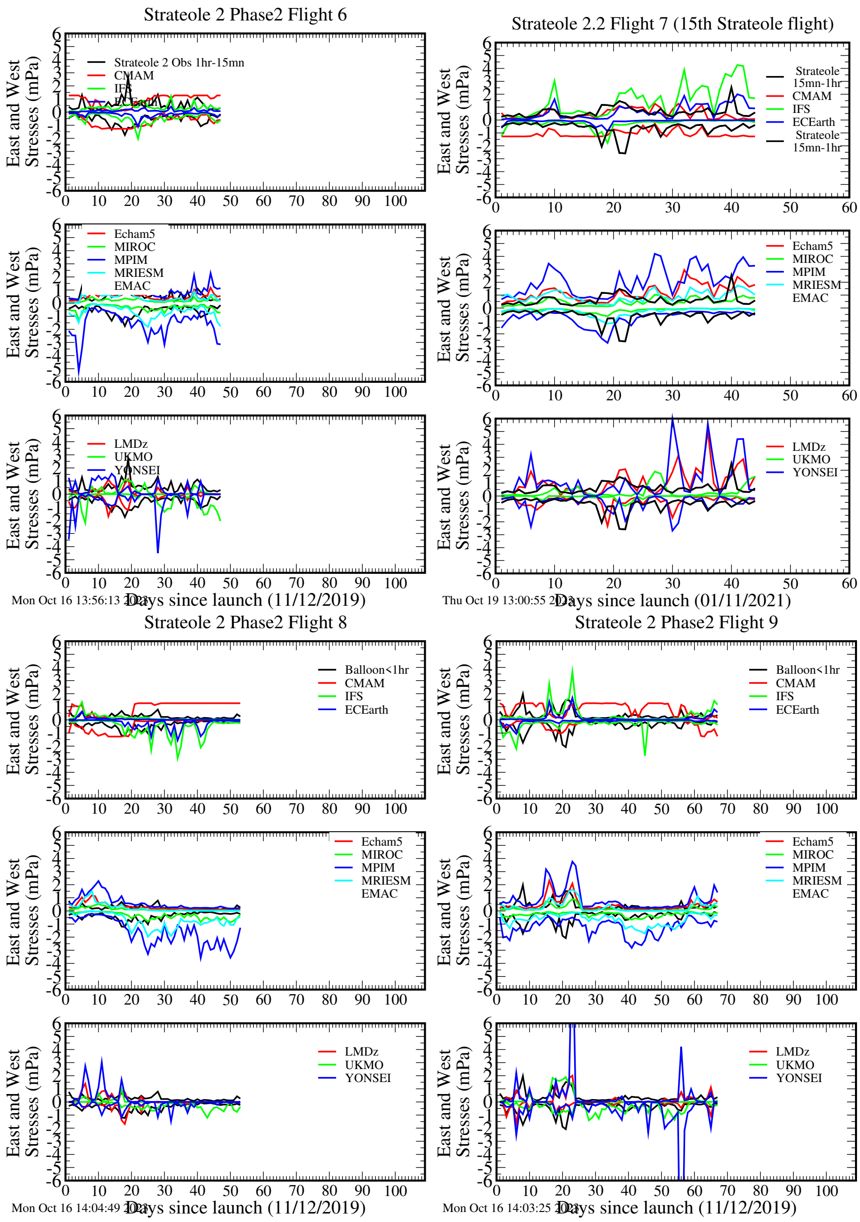

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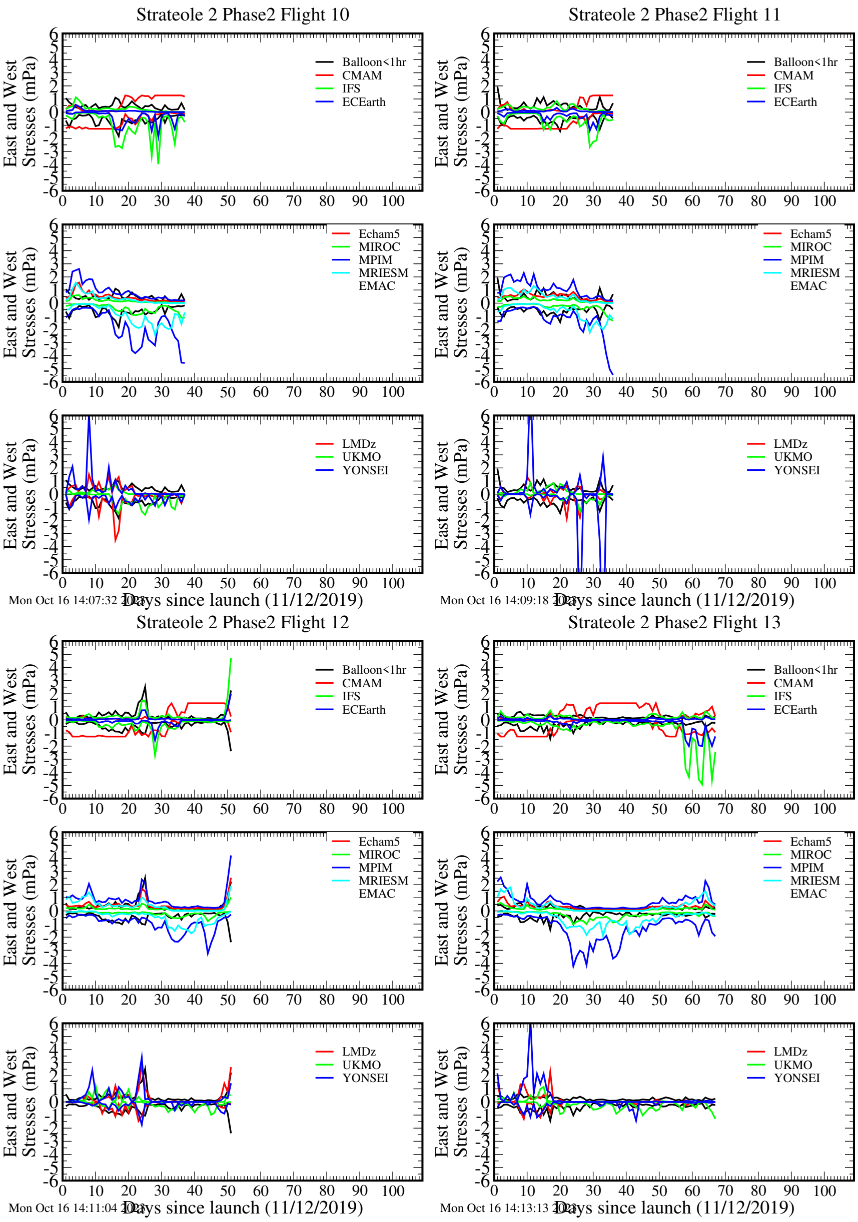
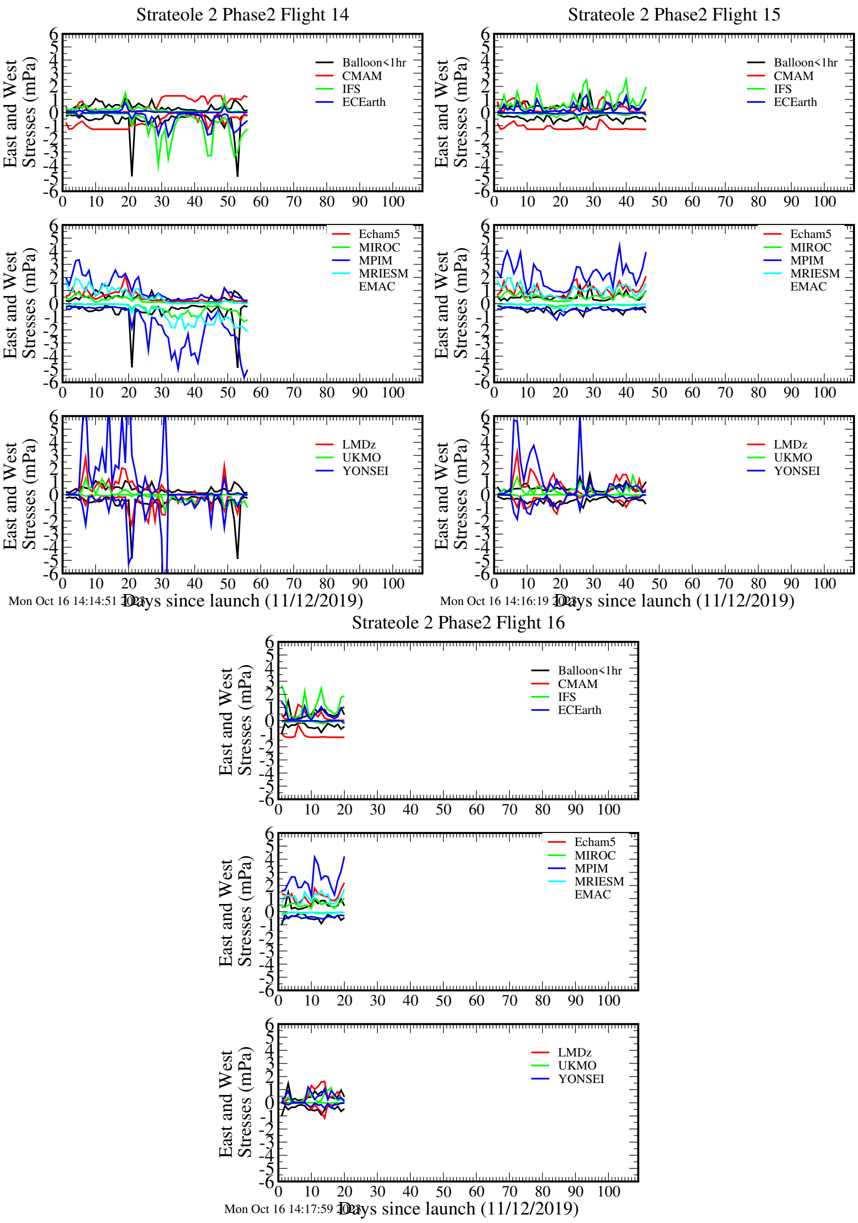


Supplementary: Phase 2 flights and models (continued)


Strateole 2 Phase2 Flight 14
Strateole 2 Phase2 Flight 15
Strateole 2 Phase2 Flight 16
East and West Stresses (mPa)
Balloon<1hr
CMAM
IFS
ECEarth
Echam5
MIROC
MPIM
MRIESM
EMAC
LMDz
UKMO
YONSEI
Days since launch (11/12/2019)
Mon Oct 16 14:14:51 2023
Mon Oct 16 14:16:19 2023
Mon Oct 16 14:17:59 2023