



Effects of lateral wave propagation on the intermittency of nonorographic gravity waves

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Abstract. The statistical distribution and intermittency of gravity-wave (GW) amplitudes are shaped by wave evolution during propagation as well as by source variability. While propagation effects have been studied mostly within a 1-dimensional framework, the role of lateral propagation remains poorly understood. Here, we investigate this role by comparing global model experiments using 3-dimensional (3D) and 1-dimensional (1D) variants of a transient GW parameterization. The statistical distributions of momentum flux in the 3D experiment are generally narrower than those in the 1D experiment, indicating lower GW intermittency. They also tend toward lognormal distributions for both convectively generated GWs and waves from a steady background source, suggesting that lateral propagation and the associated spatial redistribution of wave activity contribute to the approximately lognormal distributions widely found in observations. Lateral propagation also substantially modifies the spatiotemporal structure of GW intermittency: the excessive vertical increase in intermittency found in the extratropics in the 1D experiment largely disappears, while intermittency instead tends to vary with mean-wind magnitude. Similar latitude–season structures of intermittency and their association with the mean wind are found in HIRDLS and SABER observations. These results highlight lateral propagation as a fundamental dynamical process shaping GW amplitude distributions and intermittency and provide a basis for considering its effects in GW parameterizations.

1 Introduction

Internal gravity waves (GWs) play a pivotal role in large-scale circulation and its variability in the middle atmosphere (Fritts and Alexander, 2003; Kim et al., 2003; Achatz et al., 2024). Once generated in the lower atmosphere, GWs transport momentum through wave propagation and deposit it into the flow at higher altitudes, especially where they dissipate. In the GW–mean-flow interaction, the wave amplitude is an important characteristic that determines the location and extent of wave dissipation and momentum deposition (e.g., de la Cámara et al., 2016). For example, waves with large amplitudes can break



20 and deposit momentum at relatively low altitudes compared to small-amplitude waves. Therefore, the statistical distribution of GW amplitudes provides key information for quantitatively describing the middle-atmosphere circulation.

Recent observational studies have suggested that the distribution of GW momentum-flux magnitudes is approximately log-normal, exhibiting a long tail (Hertzog et al., 2012; Ern et al., 2022; Lott et al., 2023; Green et al., 2024). In particular, skewness of the distribution has been extensively investigated, as it reflects the intermittent occurrence of large-amplitude waves that can contribute substantially to the momentum-flux budget. Super-pressure balloon (SPB) observations in the lower stratosphere indicated that about 35% (10%) of the momentum-flux budget was accounted for by intermittent, high-amplitude waves above the 90th (99th) percentile over oceanic regions, and such an intermittent nature of GWs was even more pronounced over mountainous regions (Hertzog et al., 2012; Green et al., 2024). Similar intermittent features of GWs were also found in other measurements, such as satellite and radar observations (e.g., Wright et al., 2013; Minamihara et al., 2020; Ern et al., 2022), although details in the statistical distributions of momentum fluxes varied among the measurements, due to differences in observational filters and wave retrieval methods.

Understanding the physical processes that control the observed statistical distribution of GW amplitudes and their intermittency is crucial for diagnosing and improving GW parameterization and its impact on the middle-atmosphere circulation. Variability in wave-source processes (e.g., in convective activity or flows over topography), as well as wave dissipation, contributes substantially to the formation of amplitude distributions and intermittency (Alexander et al., 2010; Hertzog et al., 2012; Wright et al., 2013; Kim et al., 2021). The amplitude distribution is also affected by transient evolutions of GWs during propagation. From general circulation model (GCM) experiments using a transient parameterization of vertically propagating GWs, Bölöni et al. (2021) and Kim et al. (2021) showed that even GWs from a constant background source (i.e., with no source variability) exhibited substantial variability in amplitude in the middle atmosphere due to transient interactions of waves with temporally varying mean flow. They further showed that, for broad-spectrum GWs such as convectively generated waves, vertical and temporal spreading of different wave components through dispersive propagation could significantly increase the frequency of GW occurrence at a given location, thereby lowering their intermittency.

While the above processes have been studied mostly in the 1-dimensional (vertical-column) framework, lateral wave propagation is also considered an important process affecting the observed statistical distribution of GW amplitudes (Plougonven et al., 2017). In particular, it has been demonstrated that GWs considered to be horizontally distributed in the lower atmosphere propagate obliquely at different zenith angles depending on the mean-flow structure along their paths, resulting in the focusing of the waves toward the strong jet region at higher altitudes (Dunkerton, 1984; Sato et al., 2012). From SPB observations, operational analysis, and wave-resolving simulations, Plougonven et al. (2017) consistently found a positive correlation between GW momentum-flux magnitudes and ambient wind magnitudes (a finding subsequently supported by Minamihara et al. (2020) and Green et al. (2024)), and suggested that lateral propagation and associated focusing into strong-wind regions likely contribute to this relationship. In addition, lateral propagation should also lead to 3-dimensional



wave dispersion, which may potentially lower GW intermittency through a mechanism analogous to that described above for vertical dispersion (Kim et al., 2021).

In this study, we use a 3-dimensional transient GW parameterization, the Multi-Scale Gravity Wave Model (MS-GWaM; see Sect. 2.1), to investigate the effects of lateral wave propagation on the statistical distribution of GW amplitudes and their intermittency. This study extends the work of Kim et al. (2021), in which the 1-dimensional transient parameterization was employed to investigate the effects of wave transience. Section 2 describes the model experiments and analysis methods. Section 3 presents the effects of lateral wave propagation on the statistical distributions and intermittency of GW momentum fluxes, including their seasonal variations and dependence on the wind. The main findings are summarized and discussed in Sect. 4.

2 Methods

2.1 Model and experiments

To model the 3-dimensional GW dynamics, MS-GWaM is employed as a parameterization in the ICOSahedral Non-hydrostatic model (ICON) (Zängl et al., 2015). Using a Lagrangian approach, it solves the evolution of GW action density $\mathcal{N}(\mathbf{k}, \mathbf{x}, t)$ in the six-dimensional phase space $(\mathbf{k}, \mathbf{x})$

$$\frac{D\mathcal{N}}{Dt} = \left(\frac{\partial}{\partial t} + \dot{\mathbf{x}} \cdot \nabla_{\mathbf{x}} + \dot{\mathbf{k}} \cdot \nabla_{\mathbf{k}} \right) \mathcal{N} = \mathcal{S} \quad (1)$$

along with the changes in wavenumber $\mathbf{k}$ and position $\mathbf{x}$, which follow the ray equations for nonhydrostatic GWs in 3-dimensionally varying mean flow. $\mathcal{S}$ is the nonconservative source/sink term due to wave generation and dissipation as well as wave–wave interaction, although the latter is currently not taken into account. The numerical methods and ICON implementation of MS-GWaM are described in Bölöni et al. (2021), Kim et al. (2021), and Voelker et al. (2024) (for the detailed theoretical basis, refer to Achatz et al., 2023). We also use the 1-dimensional variant of MS-GWaM for comparison, which solves the same equations except that the changes in the horizontal components of $\mathbf{k}$ and $\mathbf{x}$ are neglected.

As a nonorographic GW source, MS-GWaM employs the convective source formulated by Song and Chun (2005), which depends on the properties of parameterized cumulus convection and the ambient flow. In the extratropics, an additional source is employed to account for other nonorographic sources such as jets and fronts. This, referred to as the background source, is prescribed to be steady with an isotropic spectrum at the launch level of 300 hPa (Bölöni et al., 2021). The orographic source scheme of Chew et al. (2024) has recently been implemented in MS-GWaM but still requires rigorous tuning, and is therefore not used in this study. Instead, a separate orographic parameterization (Lott and Miller, 1997) is active in the ICON simulations.



80 We use experiments conducted in Kim et al. (2024), which were designed to simulate the quasi-biennial oscillation (QBO) with the 3-dimensional GW dynamics. In particular, two experiments that respectively employed the 3-dimensional and 1-dimensional variants of MS-GWaM, referred to as the 3d-TR and 1d-TR experiments in that paper, are used here (hereafter, 3D and 1D experiments, for brevity). The model top of the experiments is at 120 km with a sponge layer from 85 km. In these experiments, the background source is prescribed poleward of 25° with seasonally varying absolute pseudomomentum flux. 85 The flux is maximum (minimum) at the winter (summer) solstice with a value of 10 mPa (6 mPa) poleward of 55° , with a smooth transition to zero in $25\text{--}55^\circ$. The convective-source implementation is described in Kim et al. (2021) and Kim et al. (2024). The experiments are performed with climatological annual-cycle forcing, and each experiment is run for 20 years after a spin-up period of ~ 2 years. The full 20-year period is used for the analysis.

2.2 Analysis

90 Previous studies of GW intermittency have used various indices along with the probability density function (PDF) of GW momentum fluxes (Hertzog et al., 2008, 2012; Plougonven et al., 2013, 2017). Commonly used indices include the ratio between the median and a high-percentile momentum flux (Hertzog et al., 2008), the contribution of high-percentile fluxes to the total flux budget (Hertzog et al., 2012), and the Gini index (Gini, 1912, 1914) for momentum fluxes (Plougonven et al., 2013). In this study, we present the PDF and Gini index results, as in Kim et al. (2021). For a lognormal distribution, all those indices can 95 be expressed solely in terms of the geometric standard deviation (GSD; $\exp\{\sigma[\ln F]\} \geq 1$, where $\sigma[\cdot]$ is the standard deviation and F denotes the momentum flux). For reference, the relation between the GSD and the Gini index as well as the other indices mentioned above is shown in Fig. A1. Note that a wider PDF on a logarithmic axis corresponds to a larger GSD and thus a larger Gini index, indicating higher intermittency.

All the PDF and intermittency analyses conducted in this study use the absolute pseudomomentum flux of GWs, following 100 Kim et al. (2021) and many observational studies that relied on GW polarization relations for the flux retrieval. The absolute flux is integrated over the parameterized nonorographic (convective and background) GW spectrum in each model-grid cell at each 3-hourly output time. Throughout the paper, the absolute pseudomomentum flux is referred to simply as momentum flux. The Gini index is calculated for each month using the 3-hourly momentum-flux samples and averaged over years for each calendar month. The analyses in this study are generally based on the locally calculated Gini index (unless otherwise stated), 105 including its global distributions and zonally averaged structures.

2.3 Satellite observations

For comparison with the parameterized GWs, we use Gini indices derived from measurements by the limb-sounding satellite instruments High Resolution Dynamics Limb Sounder (HIRDLS; Gille et al., 2008) and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER; Mlynczak, 1997; Remsberg et al., 2008). For each instrument, temperature



110 fluctuations due to GWs are derived by removing the large-scale temperature background determined from a comprehensive spectral analysis of global-scale waves (for details, see Ern et al., 2018; Mathew et al., 2026). Momentum fluxes are calculated from these temperature fluctuations using GW polarization relations and retrieved wavenumbers (Ern et al., 2004). Finally, the global distributions of the Gini index for the momentum fluxes are calculated as described in Ern et al. (2022). The HIRDLS and SABER data used here cover 2005–2008 and 2010–2015, respectively.

115 3 Results

3.1 Statistical distributions in boreal winter

In the tropics, GW momentum flux fields are dominated by convectively generated waves. Figure 1(a, b) shows the PDFs of convective GW momentum fluxes in the tropics, constructed on a logarithmic axis, at 20, 40, 60, and 80 km altitudes in December in the 3D and 1D experiments. At each altitude, the mean value is indicated by the vertical tick at the top axis. The PDFs show distinct distributions between the two experiments even in the lower stratosphere (red curves) although the mean values are comparable. The flux distributions in the 3D experiment are approximately lognormal, consistent with observations of tropical GWs (e.g., Green et al., 2024), whereas those in the 1D experiment are left-skewed on the logarithmic axis, showing more frequent occurrence of small fluxes compared to the 3D experiment. The left-skewed distributions in the 1D experiment (Fig. 1b) are consistent with Kim et al. (2021, Fig. 5a). Qualitatively similar left-skewed distributions have also been obtained from multiple conventional (steady-state, 1D) parameterizations of convective GWs (Lott et al., 2024).

Although the difference between the two experiments first becomes noticeable in the smallest-flux range, we focus on fluxes with substantial magnitudes since the impact of very small fluxes on the atmosphere may be limited. Specifically, fluxes above the threshold that collectively account for 99% of the total flux budget are considered, with the threshold indicated by the filled circle in Fig. 1(a, b). When the smallest-flux range that contributes to only 1% of the flux budget (to the left of the filled circle) is ignored, the shapes of the PDFs in the two experiments seem to be qualitatively similar. However, the occurrence frequency of substantially large fluxes ($\gtrsim 10$ mPa) tends to be higher in the 1D experiment at 20–60 km (also see Fig. 1c, where the 20 km PDFs are presented with a linear axis to better illustrate the difference in that flux range). Taken together, these results indicate that, on the logarithmic scale, the PDFs in the 3D experiment are narrower than those in the 1D experiment, with less spread toward both low and high fluxes. This narrower distribution implies lower intermittency of tropical GWs in the 3D experiment, as explained in Sect. 2.2.

The narrower distributions of momentum flux in the 3D experiment than in the 1D experiment at both low and high magnitudes can be explained by spatial smoothing of fluxes associated with lateral wave propagation. When a convection event occurs in the real atmosphere, GWs spanning a broad spectrum are generated and disperse both horizontally and vertically according to their respective group velocities. This process is represented in the 3D parameterization. By contrast, the 1D

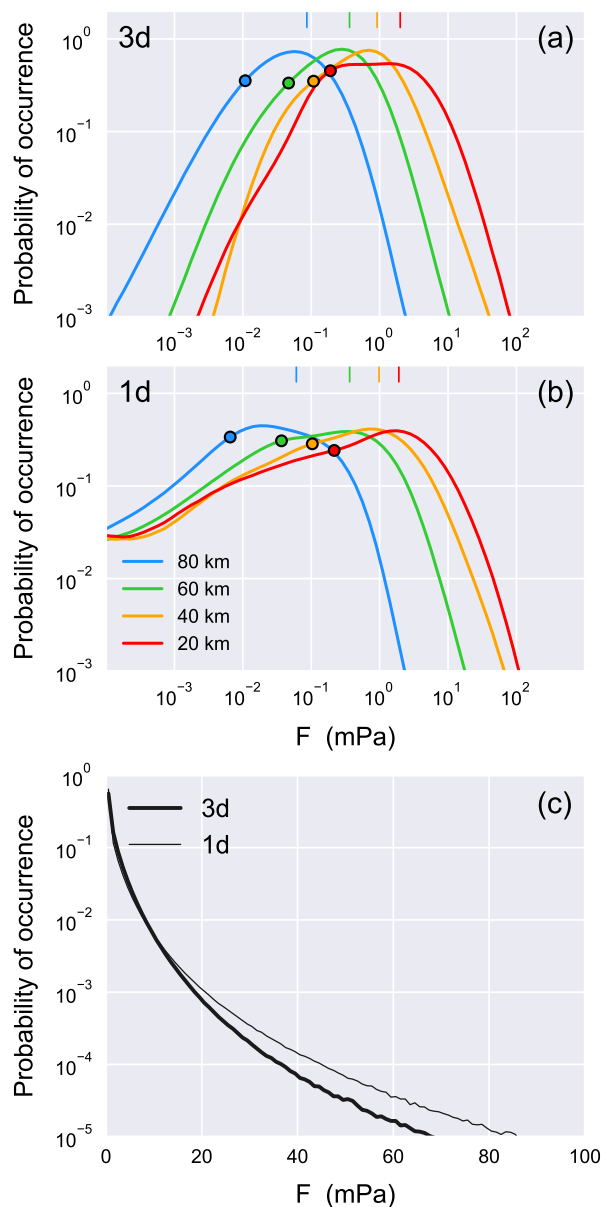


Figure 1. PDFs (solid curves) of absolute pseudomomentum flux for convective GWs in 15°N – 15°S at 20, 40, 60, and 80 km in December in the (a) 3D and (b) 1D experiments with a logarithmic axis for the flux. For each PDF in (a) and (b), the lower threshold for the fluxes that collectively contribute to 99% of the total flux budget is indicated by a filled circle, and the mean flux is indicated by a vertical tick at the top of the plot. Also shown are (c) the PDFs at 20 km in the 3D and 1D experiments (thick and thin curves, respectively) plotted with a linear axis for the flux.



140 parameterization neglects horizontal dispersion and therefore overestimates the local momentum flux directly above the convective source. This explains why substantially large fluxes ($\gtrsim 10$ mPa) occur more frequently in the 1D experiment than in the 3D experiment.

On the other hand, after the convection ceases, the local momentum flux gradually diminishes and eventually becomes extremely small, which accounts for the smallest-flux range of the PDFs in Fig. 1a and b. Such extremely small fluxes may occur less frequently in the 3D experiment than in the 1D experiment because the local flux can be augmented by waves propagating laterally from other convective regions. This mechanism is consistent with observations of non-negligible GW momentum fluxes distant from active convection in the tropics (e.g., Corcos et al., 2021). The augmentation effect suggests that the difference in the smallest-flux range between the 3D and 1D experiments should be large where convective sources are spatially ubiquitous, as in the tropics.

150 The two effects of lateral wave propagation on momentum flux fields, i.e., horizontal dispersion and augmentation, can also explain PDFs in the extratropics. Figure 2 shows the PDFs in the southern midlatitudes (25° – 65° S) in December for both convective and background GW momentum fluxes as well as the fluxes from total nonorographic GWs. For convective GWs, the occurrence of large fluxes is less frequent in the 3D experiment than in the 1D experiment at 20–60 km (left panels in Fig. 2a–c), as in the tropics, due to the horizontal dispersion. In the smallest-flux range, however, the PDF at 20 km (red curve) appears to be left-skewed in the 3D experiment, contrary to the lognormal PDF in the tropics (cf. Fig. 1a). This may reflect spatially more sporadic convection in the extratropics. With sporadic convective sources, augmentation of momentum fluxes by waves from distant sources is weaker, thereby allowing the local flux to continue to diminish after convection ceases. Nonetheless, above 20 km, continued wave propagation under strong mean flow leads to further horizontal transport and augmentation of small fluxes, eventually shaping the lognormal PDF (Fig. 2a, yellow and green curves).

160 PDFs of momentum fluxes from the background source are approximately lognormal in the 3D experiment and left-skewed in the 1D experiment (center panels in Fig. 2a and b), qualitatively similar to those from the convective source in the tropics (Fig. 1a and b). King et al. (2026) also found that momentum-flux distributions produced by a conventional 1D parameterization employing a steady source remained left-skewed over a range of parameter settings. The approximately lognormal distribution in our 3D experiment therefore suggests that lateral wave propagation may be an important process in shaping such a distribution. A notable difference from the convective GW distributions is observed at 20 km: large fluxes occur more frequently in the 3D experiment than in the 1D experiment (see Fig. 2c, center panel). Unlike the convective source, the background source is activated everywhere in the extratropics and at all times; thus, wherever waves converge due to spatiotemporal variations of mean flow, momentum fluxes are enhanced regardless of their magnitudes. Furthermore, because this source prescribes a nearly constant momentum flux of $\mathcal{O}(10$ mPa) (Sect. 2.1), the smallest fluxes typically arise from severely dissipated waves (e.g., near the critical level). In the 3D parameterization, the local flux can be augmented even above a critical level by waves propagating laterally from other regions. This augmentation may reduce the occurrence frequency of the smallest fluxes relative to the 1D experiment, driving the PDF toward a lognormal shape rather than a left-skewed distribution.

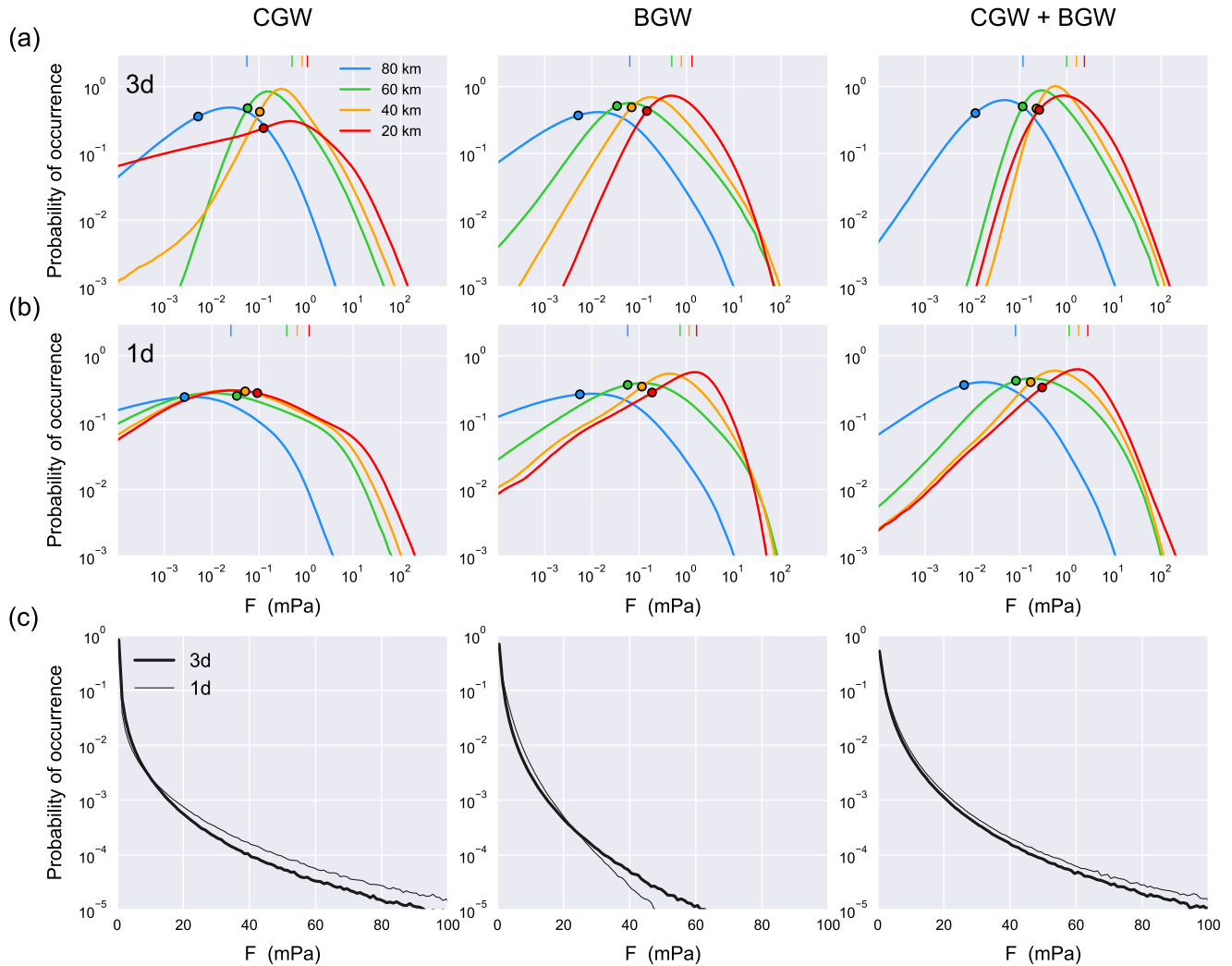


Figure 2. As in Fig. 1, but for (left) convective, (center) background, and (right) total nonorographic GWs in 25°–65° S.

PDFs of total GW momentum fluxes (right panels in Fig. 2) qualitatively resemble those of the background GW momentum fluxes in both experiments because this source is dominant over the sporadic convection in the extratropics, while the overall distributions are shifted toward larger magnitudes and narrowed. Nonetheless, the occurrence of very large fluxes (~ 100 mPa) at 20 km is due to convective GWs (Fig. 2c). The vertical evolution of the PDFs in the extratropics is discussed in more detail below.

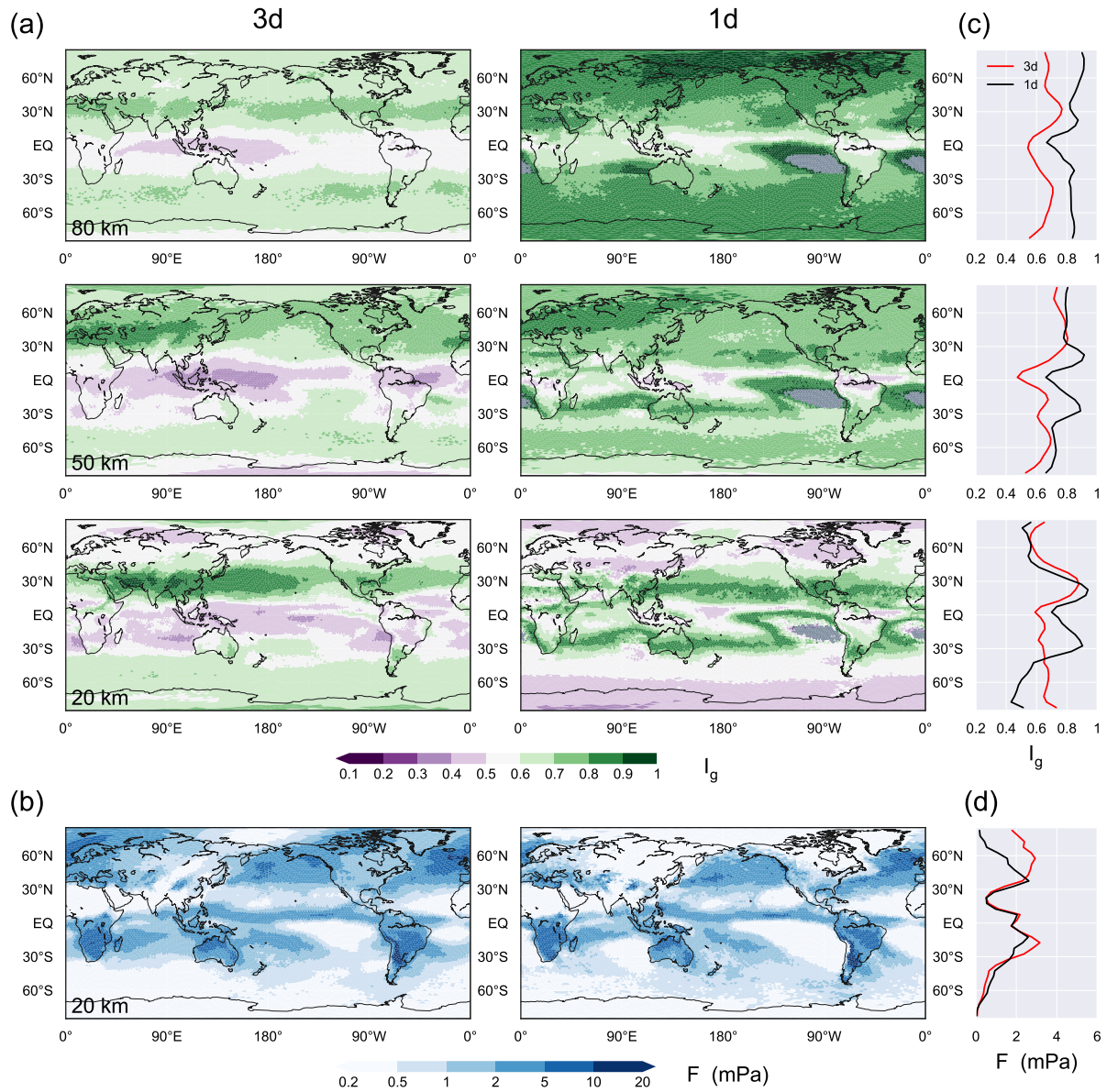


Figure 3. (a) Global maps of monthly Gini index for total nonorographic GW pseudomomentum fluxes at 20, 50, and 80 km (from bottom to top) and (b) monthly-mean convective GW pseudomomentum flux at 20 km in December in the (left) 3D and (right) 1D experiments. Also shown are the (c) monthly Gini index calculated from flux samples pooled over all longitudes and (d) zonal-mean convective GW pseudomomentum flux in the 3D and 1D experiments (red and black lines, respectively).



3.2 Gini index in boreal winter

The Gini index for the total nonorographic GW momentum fluxes (I_g) during December is calculated locally at each model-
 180 grid cell, and its global maps at 20, 50, and 80 km are presented in Fig. 3a. In addition, the monthly-mean convective GW
 momentum fluxes at 20 km are illustrated in Fig. 3b to identify their spatial distribution. The I_g distribution in the 1D exper-
 iment (right panels in Fig. 3a) is broadly consistent with that shown in Kim et al. (2021, Fig. 9, left panels), exhibiting the
 following features: (i) in the tropics, I_g is close to 0.5 over convectively active regions (e.g., southern Africa, South America,
 and near-equatorial oceans, which are characterized by large mean momentum fluxes in Fig. 3b); (ii) elsewhere in the tropics,
 185 I_g increases rapidly with decreasing mean momentum flux, because less frequent convection increases GW intermittency (I_g)
 while reducing the mean flux; (iii) in the extratropics, I_g is relatively low at 20 km but increases markedly with height. The
 vertical increase in I_g in the extratropics was attributed to the transience effect associated with temporal variations of mean
 flow, as well as to the filtering effect by vertical variations of the flow (Böhlöni et al., 2021; Kim et al., 2021). Changes in the
 mean flow cause GWs to converge or diverge in the vertical direction and time, leading to a broadening of statistical distribu-
 190 tions of momentum fluxes as waves propagate vertically. This effect was large for GWs from the background source, as this
 source initially yields very narrow flux distributions near the source level owing to the constant source flux.

Compared to the 1D experiment, I_g in the 3D experiment exhibits a smoother horizontal distribution in the tropics, with
 overall smaller magnitudes at all altitudes (left panels in Fig. 3a). The rapid increase in I_g away from the convectively active
 regions, shown in the 1D experiment, is less evident here. The overall smaller I_g is expected from the narrower PDFs of
 195 momentum fluxes shown in Fig. 1(a, b), which can be attributed to horizontal dispersion and augmentation of fluxes due to
 lateral wave propagation, as discussed in the previous section. The smoother distribution of I_g and its weaker relationship with
 the monthly-mean flux in the 3D experiment may imply that local PDFs tend toward lognormal distributions of similar widths
 (i.e., similar GSDs; refer to Fig. A1 for the relationship between the GSD and the Gini index) while their mean values vary
 spatially. In the extratropics, I_g does not exhibit the pronounced vertical increase found in the 1D experiment or large horizontal
 200 variations. The maximum of I_g in the 3D experiment is found in the northern subtropics (around 30°N) at 20 km: I_g reaches
 ~ 0.8 , as wintertime convection is quite intermittent at these latitudes owing to suppressed convective activity in the descending
 branch of the Hadley circulation. However, this peak gradually decreases with altitude, leading to a flattened I_g distribution at
 higher altitudes (Fig. 3a). For a more quantitative comparison between the two experiments, Fig. 3c presents latitudinal profiles
 of I_g , which are obtained by sampling fluxes over all longitudes following Kim et al. (2021, Fig. 9c).

205 Figure 4 shows latitude–height cross sections of zonal-mean I_g and zonal winds in the two experiments. The vertical evo-
 lutions of I_g exhibit distinct behaviors between the two experiments. In the 1D experiment, I_g continuously increases with
 altitude in the extratropics, as also seen in Fig. 3(a, c). In contrast, in the 3D experiment, I_g does not show a monotonic in-
 crease but, above ~ 30 km, tends to vary with altitude following vertical changes in the magnitude of the mean wind, for both
 westerlies and easterlies. Accordingly, its local maxima appear at 50–60 km in the northern hemisphere and around 70 km
 210 in the southern hemisphere, associated with the strong westerly and easterly jets, respectively. The dependence of I_g on the

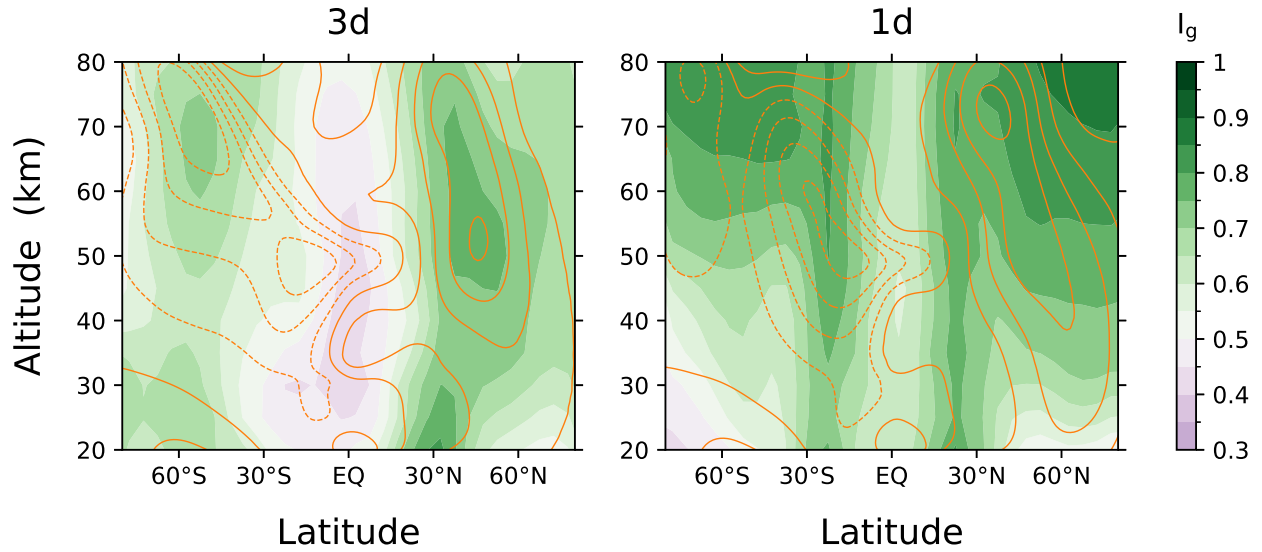


Figure 4. Zonal-mean Gini index for total nonorographic GWs (shading) and zonal wind (contours with dashed lines for easterly winds and solid lines for zero and westerly winds, at intervals of 15 m s^{-1}) as a function of latitude and height in December in the 3D and 1D experiments (left and right, respectively).

mean-wind magnitude is shown more clearly in the next section. I_g in the tropics does not change vertically as much as that in the extratropics in both experiments, while its magnitude is overall smaller in the 3D experiment than in the 1D experiment. It is noteworthy that the overall latitude–height structure of I_g in the 3D experiment is qualitatively similar to that obtained from SABER observations in Ern et al. (2022, Fig. 16l), even though the considered wavelength range may be different between
 215 the observed GWs and the parameterized waves (for the observational filter of SABER, see Ern et al., 2018). Taken together, these results imply that lateral wave propagation plays a key role in forming the observed statistical distribution of momentum fluxes.

3.3 Seasonal variations

The annual cycle of zonal-mean I_g is shown as a function of latitude at 20, 50, and 80 km in Fig. 5. In the 3D experiment,
 220 peaks of I_g tend to appear where the mean wind is strong regardless of its direction: e.g., at 50 km altitude, at the northern hemisphere midlatitudes in boreal winter and summer and at the southern hemisphere mid-to-high latitudes in austral winter (with an exceptional peak without a strong wind at 20 km at $\sim 30^\circ\text{N}$ in boreal winter, due to the intermittent convective source associated with the descending branch of the Hadley circulation, as mentioned earlier in Fig. 3a). Figure 5a also reveals that I_g tends to change vertically in response to the changes in mean-wind magnitude, as most clearly seen in the vertical evolutions
 225 of the austral winter polar jet and I_g between the three altitudes. The relationship between I_g and mean wind is weaker in the

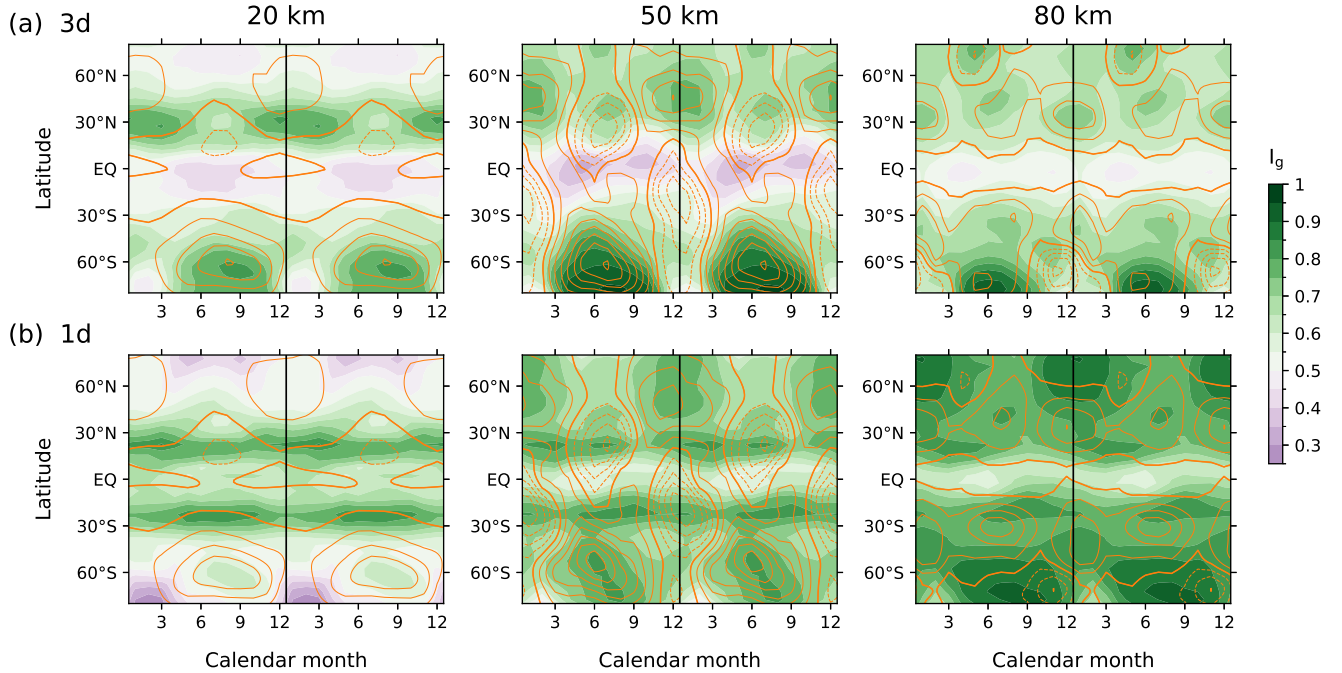


Figure 5. Annual cycles of zonal-mean Gini index for total nonorographic GWs (shading) and zonal winds (contours with dashed lines for easterly winds and solid lines for zero and westerly winds, at intervals of 15 m s^{-1}) at 20, 50, and 80 km (left to right) in the (a) 3D and (b) 1D experiments.

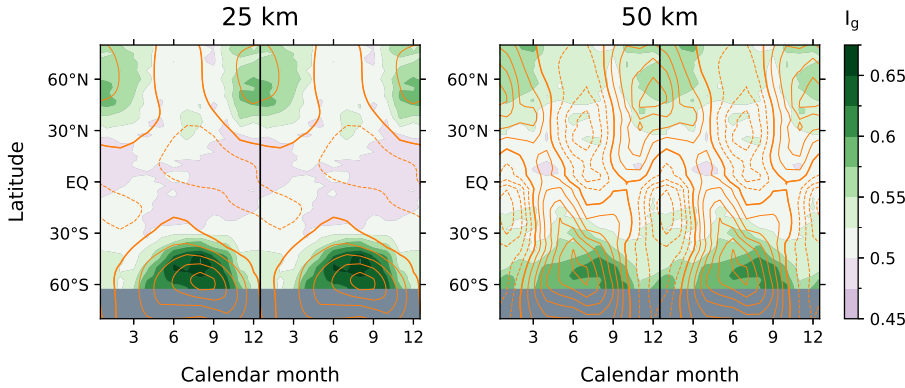
1D experiment, indicating an important role of lateral wave propagation in this relationship as well as in the seasonal variation of GW intermittency.

A similar relationship is found in the observations from HIRDLS and SABER. Figure 6 presents the annual cycle of I_g obtained from HIRDLS at 25 and 50 km and from SABER at 30, 50, and 80 km, with the levels selected within their available
 230 ranges (25–50 km for HIRDLS and 30–90 km for SABER). Also shown is the annual cycle of zonal winds from the European
 Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA5; Hersbach et al., 2020) below 50 km and
 from the Upper Atmosphere Research Satellite (UARS) Reference Atmosphere Project (URAP; Swinbank and Ortland, 2003)
 at 50 and 80 km. Both HIRDLS and SABER exhibit the northern hemisphere midlatitude peaks in boreal winter and summer
 at 25–30 km and 50 km altitudes (with the summer peak being clearer in SABER than in HIRDLS) as well as the southern
 235 hemisphere mid-to-high latitude peak in austral winter at the same altitudes, although the annual cycles at high latitudes in
 SABER may be affected by seasonally varying sampling coverage (see grey shading in Fig. 6b).

Overall, the spatiotemporal variations in I_g are weaker in both observations than in the 3D experiment, especially at higher altitudes. For example, at 80 km altitude, SABER exhibits a rather flattened distribution of I_g in both latitude and time. That is, while lateral GW propagation leads to a dependence of wave intermittency on the mean-wind magnitude, the intermittency (or



(a) HIRDLS



(b) SABER

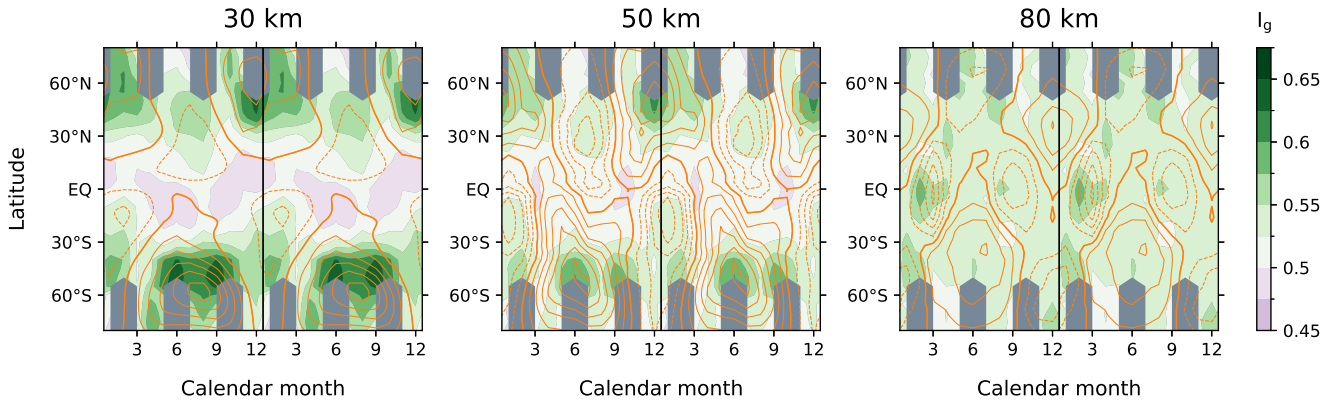


Figure 6. As in Fig. 5 but for the Gini index for GWs observed by (a) HIRDLS at 25 and 50 km and (b) SABER at 30, 50, and 80 km (left to right), with zonal winds from ERA5 below 50 km and URAP at 50 and 80 km. The HIRDLS and SABER results are obtained over the periods of 2005–2008 and 2010–2015, respectively. The grey shading indicates unavailable latitude ranges in each dataset. The color scale is different from Fig. 5, with higher contrasts for a narrower range of values.

the width of the statistical distribution) tends to be homogenized as waves propagate to higher altitudes. The reason why the homogenization effect is larger in these observations than in the model experiment is unclear, but may partly be attributable to the observational filters of HIRDLS and SABER, which suppress GWs with relatively small horizontal wavelengths (Ern et al., 2018), GW processes currently not represented in MS-GWaM, such as wave–wave interaction and secondary-wave generation, and biases in simulated circulations in the upper mesosphere close to the sponge layer (compare the wind contours at 80 km in Figs. 5a and 6b).

Although both the 3D experiment and HIRDLS/SABER observations suggest a relationship between GW intermittency and the monthly-mean wind, further evidence from independent datasets would be valuable. Its underlying mechanism, however,



remains unclear. In addition to the seasonal variations explored in this section, the dependence of GW intermittency on the QBO phase is also examined in Appendix B and found to be relatively weak.

250 3.4 Local-wind dependence

Observational studies have found that GW momentum-flux magnitudes increase with local instantaneous wind speed (Plougonven et al., 2017; Minamihara et al., 2020; Green et al., 2024). In particular, for nonorographic GWs over the Southern Ocean, Plougonven et al. (2017) showed that their momentum fluxes have a larger median value when sampled at larger local-wind magnitudes, while the GSD is invariant with wind magnitude (note that this dependence on the instantaneous
255 wind should be distinguished from that on the monthly mean wind discussed in the previous sections). Both features were consistently found in SPB observations, operational analysis, and numerical model data. Furthermore, they suggested that this wind dependence is likely attributable to lateral wave propagation, since other possibilities, such as source variability and purely vertical propagation, could not fully explain it in their analysis.

The local-wind dependence of momentum-flux statistics is investigated in our model experiments. Figures 7 and 8 show the
260 medians and GSDs, respectively, of momentum fluxes sampled with respect to local instantaneous wind speed (U) in $50\text{--}65^\circ\text{S}$ during September–December, at four altitudes from 20 to 80 km in the two experiments. The months and latitudes are chosen following Plougonven et al. (2017), and the statistics are obtained for GWs from the two nonorographic sources separately as well as from both combined. The medians are normalized at each altitude by those for $U = 20\text{--}30\text{ m s}^{-1}$. At 20 km, the total nonorographic GW momentum fluxes in the 3D experiment have medians decreasing with increasing U (red curve in Fig. 7a,
265 left panel), opposite to the results in the observational studies mentioned above. Given that the medians almost do not change with U in the 1D experiment (Fig. 7b), the decreasing trend of medians at 20 km with respect to U in the 3D experiment results from lateral wave propagation. On the other hand, the GSDs at 20 km increase with U (Fig. 8a, left panel) rather than being invariant as in Plougonven et al. (2017) and Green et al. (2024). Both the median and GSD values at this altitude for total nonorographic GWs are very close to those for the background GWs (center panels in Figs. 7a and 8a).

270 The discrepancies between the observations and the model experiment may arise from the simplified background-source specification in the parameterization. A mechanism for the increasing trend of observed momentum fluxes with respect to U suggested in those previous studies was the tendency toward focusing of GW rays into a region of larger U , when GWs are considered to have phase speeds lower than the mean-flow speed (i.e., intrinsic phase velocities, $\hat{c}$, are in the opposite direction to the flow) (for the details, see Dunkerton, 1984; Sato et al., 2012). This consideration is reasonable based on observations
275 and high-resolution model simulations where GWs predominantly appear to have such intrinsic phase velocities in the extratropical upper troposphere and stratosphere, as indicated by the signs of zonal momentum fluxes opposite to mean winds (e.g., Hertzog et al., 2008; Sato et al., 2009; Kim et al., 2016). However, in the current parameterization, the prescribed background source is simplified to have an isotropic $\hat{c}$ spectrum at the launch level in the upper troposphere (300 hPa). The fraction of the spectrum with $\hat{c}$ in the same direction as the flow is therefore excessive compared with that in the real atmosphere. Those

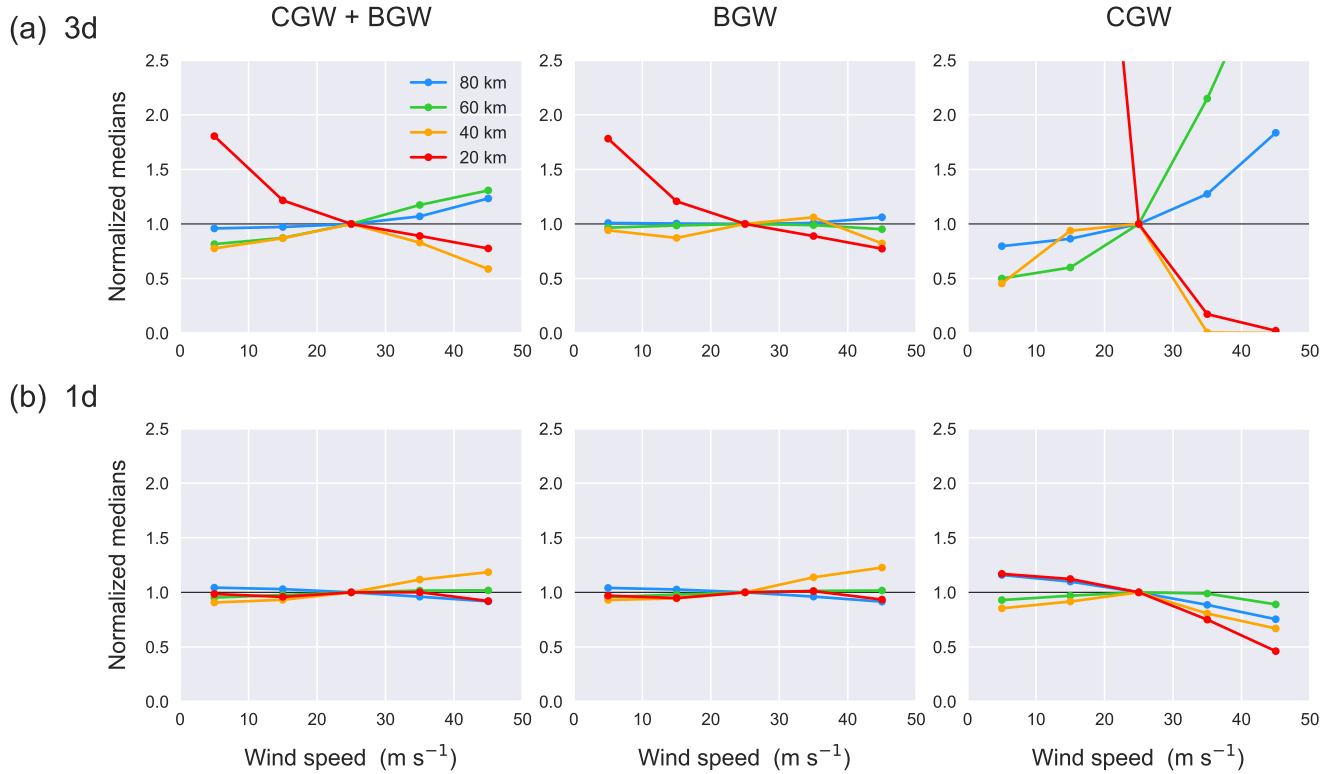


Figure 7. Medians of pseudomomentum fluxes for (left) total nonorographic GWs, (center) background GWs, and (right) convective GWs, sampled for local instantaneous wind speeds binned with 10 m s^{-1} widths from 0 to 50 m s^{-1} , at 20, 40, 60, and 80 km altitudes (red, yellow, green, and blue lines, respectively) in $50\text{--}65^\circ\text{S}$ during September–December in the (a) 3D and (b) 1D experiments. The medians are normalized at each altitude by the values for $20\text{--}30 \text{ m s}^{-1}$ wind speeds.

280 wave components tend to diverge away from the region of large U , in a similar manner to the aforementioned wave-focusing mechanism but in the reverse direction due to the opposite $\hat{c}$. That is, waves in the region of stronger U have relatively smaller intrinsic frequencies and thus tend to horizontally propagate away while those in the region of weaker U have larger intrinsic frequencies and propagate more vertically, which together result in the decreasing trend of momentum-flux magnitude with respect to U as found in the 3D experiment at 20 km.

285 The wave components with $\hat{c}$ in the same direction as the mean flow are gradually filtered out during their propagation through the stratosphere, causing the GW spectrum to become more anisotropic with increasing altitude. Therefore, the decreasing trend of background GW momentum flux with respect to U , shown at 20 km in the 3D experiment, should be weakened and eventually disappear, as found at 40 km and higher altitudes (Fig. 7a, center panel). In the mesosphere (green and blue curves), the medians of total nonorographic GW momentum fluxes begin to deviate from those of background GW momentum
 290 fluxes, showing an increasing trend with U . This implies that the contribution of convective GWs to this statistic increases in

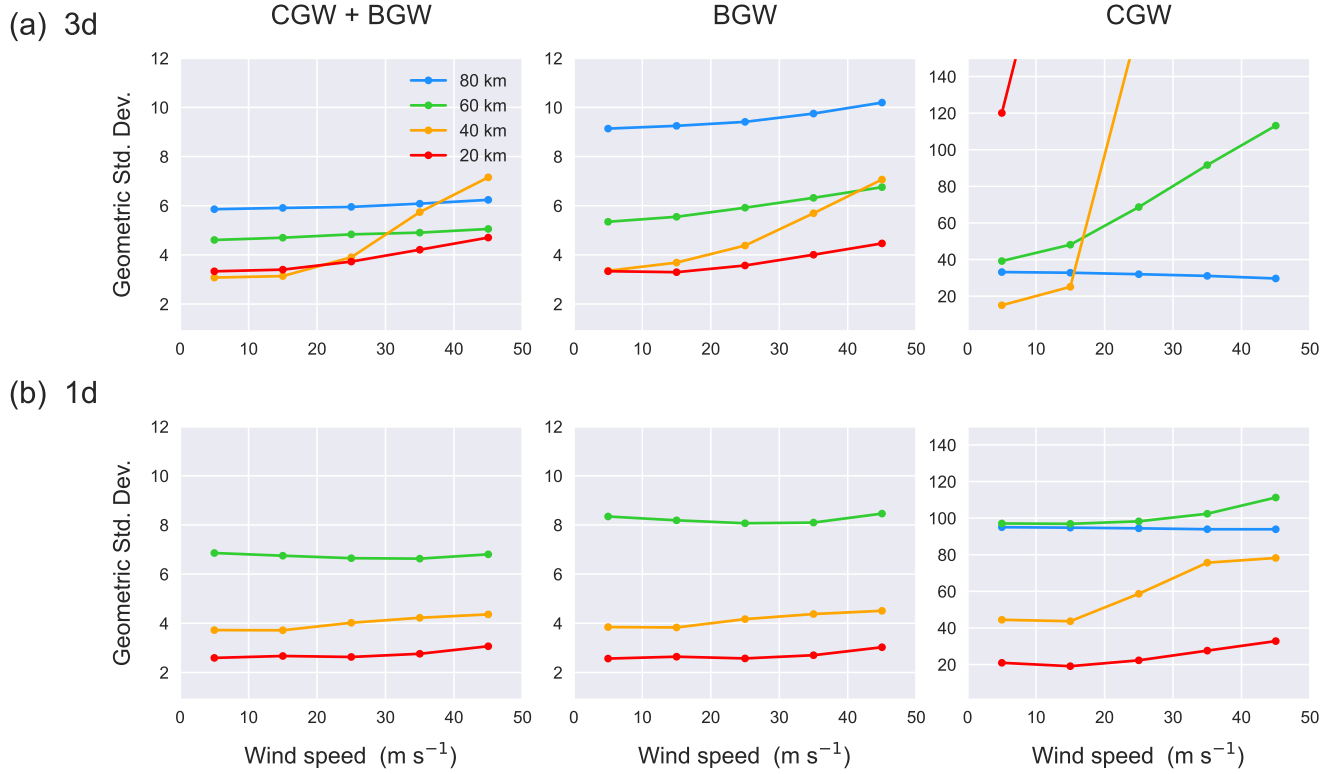


Figure 8. As in Fig. 7 but for the geometric standard deviations.

the mesosphere. Similarly, the GSDs for total GWs also begin to deviate from those for background GWs in the mesosphere (Fig. 8a). While the background GW momentum fluxes have quite large GSDs (~ 10 at 80 km), the contribution of convective GWs to the total fluxes yields a reduction in GSDs (~ 6 at 80 km) as well as weaker variations with U . The reduction in GSDs, i.e., the narrowing of statistical distributions, is explained primarily by a shift of the low-flux tail toward larger magnitudes due to the convective GW contribution, as seen in Fig. 2a (green and blue curves) despite different latitude bands and months. Overall, the local-wind dependences of the median and GSD in the mesosphere in the 3D experiment are qualitatively similar to those in the observations in the stratosphere (Plougonven et al., 2017; Minamihara et al., 2020; Green et al., 2024).

4 Conclusions

In this study, we investigated the effects of lateral wave propagation on the statistical distribution and intermittency of nonorographic GW momentum fluxes using the 3-dimensional transient GW parameterization MS-GWaM. By comparing experiments using the 3-dimensional and 1-dimensional variants of MS-GWaM, we isolated the effects of lateral propagation from those of



transient vertical propagation considered in previous work (Kim et al., 2021). The results demonstrate that lateral propagation substantially modifies not only the magnitude of GW intermittency but also its spatial and temporal structures.

The momentum-flux PDFs in the 3D experiment are generally narrower than those in the 1D experiment, with reduced occurrence of both very small and substantially large fluxes. This behavior is consistent with spatial redistribution of wave activity through lateral propagation, including horizontal dispersion and augmentation of local fluxes by waves propagating from other regions. Consequently, GW intermittency is overall lower in the 3D experiment. Furthermore, the PDFs tend toward lognormal distributions not only for convectively generated GWs but also for waves from the steady background source, for which the prescribed source flux has little intrinsic variability. In contrast, the corresponding PDFs in the 1D experiment remain left-skewed on a logarithmic scale. In particular, the approximately lognormal distribution of background GW momentum fluxes in the 3D experiment is noteworthy given the difficulty of obtaining such a distribution by tuning steady-source parameters within a conventional 1D framework (King et al., 2026). These results suggest that 3-dimensional wave propagation can contribute to the formation of the approximately lognormal momentum-flux distributions widely found in observations.

Lateral propagation also substantially alters the spatiotemporal structure of GW intermittency. In the 1D experiment, the Gini index generally increases with altitude in the extratropics, reflecting the effects of transient vertical propagation and wave filtering. This monotonic increase largely disappears in the 3D experiment, where the horizontal and vertical variations of the Gini index are smoother and its overall magnitude is smaller. Instead, the intermittency tends to vary with the magnitude of the monthly-mean wind, with relatively large values associated with strong westerly and easterly jets. Similar latitude–season structures are found in HIRDLS and SABER observations, although the observed intermittency becomes more homogeneous at higher altitudes than in the model. The mechanism underlying the relationship between the mean wind and GW intermittency, however, remains to be clarified.

The dependence of momentum-flux statistics on local instantaneous wind further highlights the interaction between lateral propagation and the wave spectrum. In the lower stratosphere, the 3D experiment does not reproduce the observed increase in median momentum flux with local wind magnitude. This is likely attributable to the simplified isotropic spectrum prescribed for the background source. As the GW spectrum evolves with altitude through wave filtering, however, the local-wind dependence of nonorographic GWs in the mesosphere becomes qualitatively similar to that observed in the stratosphere. These results indicate that the effects of lateral propagation on GW amplitude statistics depend on the characteristics of the wave spectrum on which the propagation acts.

Overall, our results identify lateral propagation as a fundamental dynamical process shaping the statistical distribution and intermittency of GWs, complementing the previously recognized roles of source variability, transient vertical propagation, and wave dissipation. It can redistribute wave activity spatiotemporally, promote lognormal-like momentum-flux distributions, and modify the dependence of intermittency on the background circulation. These effects cannot be represented explicitly in conventional 1-dimensional GW parameterizations. The present results therefore provide a dynamical basis for considering



335 how the effects of lateral propagation on GW amplitude statistics and intermittency might ultimately be accounted for, either effectively within 1-dimensional frameworks or explicitly in 3-dimensional ones.

Data availability. The full model output is archived at DKRZ and is available from the corresponding author upon request. The satellite data used here are open-access: SABER data are available from GATS Inc. at https://saber.gats-inc.com/browse_data.php, and HIRDLS Level-2 data are available via the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) at [https://search.earthdata.nasa.gov/search/granules?p=C1251101072-GES_DISC&pg\[0\]\[v\]=f&pg\[0\]\[gsk\]=-start_date&q=HIRDLS](https://search.earthdata.nasa.gov/search/granules?p=C1251101072-GES_DISC&pg[0][v]=f&pg[0][gsk]=-start_date&q=HIRDLS). The
340 ERA5 reanalysis data are publicly available at <https://doi.org/10.24381/cds.bd0915c6>. The URAP zonal-wind data were obtained previously from the SPARC Data Centre (https://data.ceda.ac.uk/sparc/ref_clim/urap/wind/). A current public access point for these data could not be identified at the time of submission.

Appendix A: Relations between indices

Assuming the lognormal distribution, the relation between the GSD and the Gini index as well as the other indices mentioned
345 in Sect. 2.2 is shown in Fig. A1. For example, a Gini index of 0.5 ($GSD \sim 2.6$) implies that the ratio of the median to the 90th-percentile flux is ~ 0.3 , and the fluxes above the 90th percentile contribute to the total flux budget by $\sim 37\%$.

Appendix B: QBO dependence

In the 3D experiment, the QBO is simulated with a constant period of 2 years (Kim et al., 2024). Therefore, the QBO dependence of the GW intermittency is investigated using a 24-month cycle of I_g , constructed by averaging ten QBO cycles
350 over the 20-year simulation period. Figure B1 shows the 24-month cycles of zonal-mean I_g and zonal winds in the tropical stratosphere in this experiment. The first and second 12-month segments each reflect seasonal variations of I_g and zonal winds, while their difference represents the response of I_g to opposite QBO phases. Overall, the QBO-related variation in I_g is rather weak (less than 0.05), compared to the seasonal variations (~ 0.1) at 20–30 km altitudes. At 40 km altitude, it is even weaker, probably because I_g is further controlled by the semiannual oscillation (see the wind contours for this oscillation). In the real
355 atmosphere, investigation of the QBO impact on the wave intermittency requires a much larger sample size to fully isolate the QBO signal from the seasonal variations, since the QBO is not synchronized to an exact 2-year cycle, unlike in this experiment. Observational datasets of GW intermittency with sufficient duration for such an analysis may not currently be available.

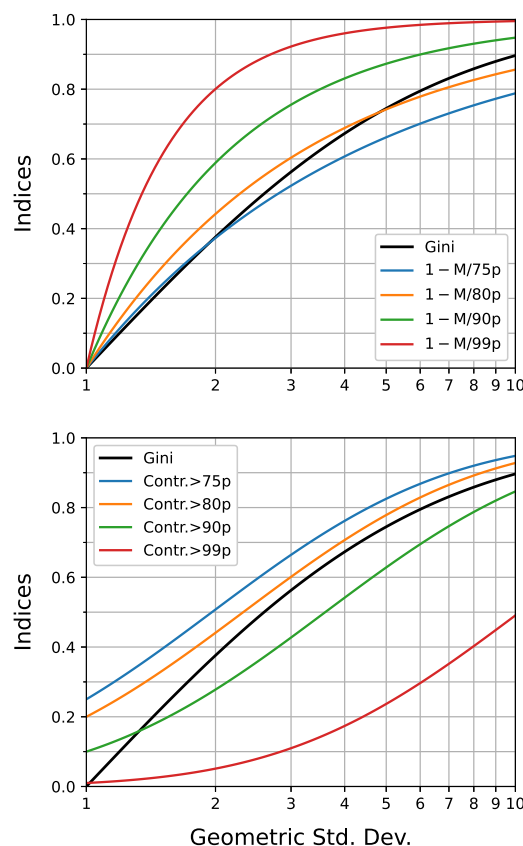


Figure A1. Relationships between the geometric standard deviation and intermittency indices for lognormally distributed quantities: (upper) one minus the ratio of the median to a given high percentile and (lower) relative contribution of values above a given high percentile to the mean, along with the Gini index (black curve) in both panels. The high percentiles shown are the 75th, 80th, 90th, and 99th (blue, orange, green, and red curves, respectively).

Author contributions. YHK, GSV, GB, and UA contributed to the development of the MS-GWaM parameterization used in this study. ME and PP produced the HIRDLS and SABER results presented in this study. YHK designed and carried out the analyses and prepared the initial manuscript draft. All authors contributed to the interpretation and discussion of the results and to revising the manuscript.

Competing interests. The authors declare no competing interests.

Acknowledgements. YHK was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (RS-2023-00244727). SWS was funded by the Korea Meteorological Administration Research and

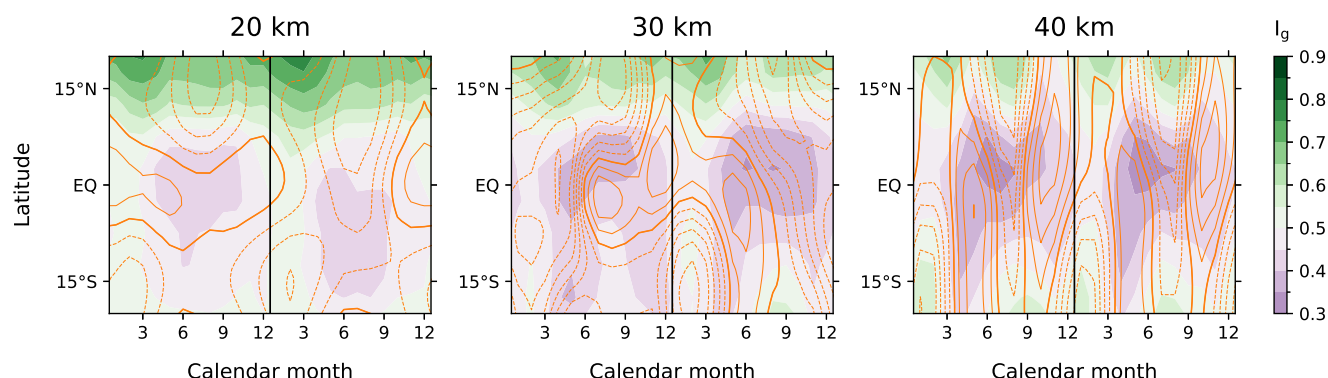


Figure B1. 24-month cycles of zonal-mean Gini index for total nonorographic GWs (shading) and zonal winds (contours with dashed lines for easterly winds and solid lines for zero and westerly winds) in the tropics at 20, 30, and 40 km (left to right) in the 3D experiment, averaged for each calendar month at 2-year intervals. The contour intervals for the winds are 5 m s^{-1} at 20 and 30 km and 10 m s^{-1} at 40 km.

Development Program (RS-2025-02313090). UA thanks the German Research Foundation (DFG) for partial support through CRC 301
 365 “TPChange” (Project No. 428312742 and Projects B06 “Impact of small-scale dynamics on UTLS transport and mixing”, B07 “Impact
 of cirrus clouds on tropopause structure”, and Z03 “Joint model development and modeling synthesis”), and UA and GSV thank DFG
 for support through the CRC 181 “Energy transfers in Atmosphere and Ocean” (Project No. 274762653 and Projects W01 “Gravity-wave
 parameterization for the atmosphere” and S02 “Improved Parameterizations and Numerics in Climate Models”). This work used resources of
 the Deutsches Klimarechenzentrum (DKRZ) granted by its Scientific Steering Committee (WLA) under project 1097 Multiscale Dynamics
 370 of Atmospheric Gravity Waves. UA acknowledges support for this work through Schmidt Sciences (“DataWave” project).



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