Investigation of Mesosphere and Lower Thermosphere Dynamics over Central and Northern Peru Using SIMOnE Systems

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(Manuscript received 24 February 2023, in final form 4 November 2023, accepted 9 November 2023)

ABSTRACT: One year of Spread spectrum Interferometric Multistatic meteor radar Observing Network (SIMOnE) measurements are analyzed and compared for the first time between two low-latitude locations in Peru: Jicamarca (12°S, 77°W) and Piura (5°S, 80°W). Investigation of the mean horizontal winds and tides reveals that mesosphere and lower thermosphere (MLT) planetary-scale dynamics are similar between these two locations, although differences can be seen in some tidal components, e.g., the diurnal tide. On the other hand, 28-day median values of the momentum fluxes obtained with 4-h, 4-km time–altitude bins indicate that the mesoscale dynamics differ significantly between Jicamarca and Piura, places separated by approximately 850 km. From the middle of July until October 2021, a strong acceleration of the background zonal wind by westward-propagating gravity waves (GWs) is observed above ~90 km at both locations, although with larger amplitudes over Jicamarca. From the middle of January until April 2022, a second strong acceleration of the background zonal wind, again by westward-propagating GWs, is observed, but this time with larger amplitudes over Piura. The latter is further supported by the dominance of negative vertical gradients of the zonal momentum flux above 89 km of altitude. Thus, these results observationally confirm the previous studies based on general circulation model simulations indicating that the directions of the zonal GW drag and the zonal background wind coincide in the low-latitude MLT. The weak correlations between the horizontal wind gradients over Jicamarca and Piura reinforce the fact that the mesoscale dynamics are different at these two locations.

KEYWORDS: Gravity waves; Mesoscale processes; Radars/Radar observations

1. Introduction

Gravity waves (GWs) are ubiquitous in the terrestrial atmosphere. They are mainly generated in the troposphere and lower stratosphere by, e.g., deep convection, orographic wind flow, and dynamical instabilities (e.g., Fritts 1984; Sato et al. 2009). This variety of sources results in a wide spectrum of waves, covering periods from a few minutes to many hours, and scales of tens of meters to several hundred kilometers. Depending on the conditions of the background atmosphere, GWs can propagate deeply into the upper parts of the atmosphere and reach the thermosphere–ionosphere region (e.g., Vadas et al. 2014; Yi˘gıt et al. 2021). In the upper mesosphere and lower thermosphere (MLT), GWs typically deposit most of their energy and momentum (e.g., Yi˘gıt and Medvedev 2015). By doing so, they not only influence the local dynamics, but also drive global processes such as the summer-to-winter-pole residual circulation (Garcia and Boville 1994; Smith 2012). GWs can also alter the behavior of tides (e.g., Achatz et al. 2008; Yi˘gıt and Medvedev 2017), which are planetary-scale waves generated primarily by solar radiation absorption, latent heat release, and gravitational forces (e.g., Forbes 1984; Hagan and Forbes 2002).

The current knowledge of wave dynamics in the MLT is limited by the scarcity of observations at horizontal scales less than ~400 km and the inability of general circulation models to resolve these subgrid scales (e.g., Ern et al. 2004; Morgenstern et al. 2010). To increase the amount of available observations at those scales, some existent meteor radars have been upgraded to multistatic capabilities, while new ones have been recently installed in different parts of the world, for example, South America (e.g., Poblet et al. 2023). On the other hand, to account for the missing effects of subgrid-scale gravity waves, model developers implement first principle GW parameterization schemes (e.g., Yi˘gıt et al. 2008; Neale et al. 2013). However, while these schemes are continuously developed, they still have limitations to realistically represent the influence of subgrid-scale waves, owing to the complexity of GW processes (e.g., Yi˘gıt and Medvedev 2016). Consequently, a good synergy between better distributed observations at horizontal scales of a few hundred kilometers, i.e., mesoscales, and state-of-the-art GW parameterizations is key to further the understanding of MLT dynamics and their impact on other atmospheric regions.

Internal wave activity in the low-latitude MLT has been found to have a considerable degree of influence in the equatorial ionosphere weather. At planetary scales, e.g., nonmigrating diurnal tides have been shown to modulate changes in the F-region electron density around the magnetic equator (Immel et al. 2006). At mesoscales, it has recently been revealed that GWs can induce irregularities in the E-region plasma (Hysell et al. 2017). Studies like these have helped to shed light on the role of the low-latitude MLT in the equatorial...
vertical coupling, and more importantly, demonstrate the need to routinely study it using ground-based observations. Recently, the Leibniz Institute of Atmospheric Physics (IAP) installed two multistatic specular meteor radars (SMRs) in Peru; one around the magnetic equator (Jicamarca) and a second one close to the geographic equator (Piura). These instruments can help, among others, to bridge the gap between equatorial MLT radar-based wind measurements and thermospheric winds estimated from satellite observations (Hysell et al. 2022).

Gravity waves influence middle and upper atmosphere dynamics by depositing the momentum they carry from the sources that generated them. Hence, information on the momentum fluxes becomes crucial to understand the role that GWs play at MLT altitudes (e.g., Alexander et al. 2018). On the one hand, the momentum flux estimates provide information about the population of GWs, i.e., about the average amplitude, periods, and scales of the waves that carry that momentum. On the other hand, the vertical gradient of the momentum flux indicates momentum deposition, and thus provides a direct measure of the effects of GWs on the background flow (e.g., Fritts et al. 2021; Ern et al. 2021). Provided good meteor detection statistics and relatively long integration intervals (Kudeki and Franke 1998), these two estimates, i.e., the momentum flux and its vertical gradient, can be exploited using SMR measurements.

In this work, one year of data from the above-mentioned multistatic SMRs are used to investigate mesoscale GW effects in the low-latitude MLT. The rest of this paper is structured as follows. The next section presents a description of the instruments and the estimation procedures used to extract information on the MLT dynamics over Peru. The main findings are presented in section 3 and discussed in section 4. Finally, section 5 is used to delineate the main conclusions of this work.

2. Materials and methods

Specular meteor radars have been proven reliable tools to investigate planetary-scale dynamics in the MLT (e.g., Holdsworth et al. 2004; Hoffmann et al. 2007; Iimura et al. 2011; Babu et al. 2012; Conte et al. 2019). This type of radars measure the Doppler shift of specular meteor trail echoes due to the drift with the neutral wind. The measured Doppler shifts are used in combination with the positions of the meteor detections to estimate hourly wind vectors every 2–3 km, for altitudes between ~80 and 100 km (e.g., Hocking et al. 2001). The estimated wind vectors are in essence mean values of the dynamics that develop in horizontal scales the size of the observed area or larger ($\lambda_{ij} \approx 400 \text{ km}$). These dynamics are usually interpreted as the superposition of a mean background wind and different period waves that propagated from other regions of the atmosphere (e.g., the troposphere and stratosphere) or were generated in situ. A variety of techniques can be implemented to extract information on these waves; for example, least squares fitting (e.g., Hoffmann et al. 2010). The latter approach has been selected for this study, and it consists in solving the following equation independently for the zonal ($u$) and meridional ($v$) components of the wind,

$$\begin{align*}
(u, v) = (U_0, V_0) + \sum_{i=1}^{N} (A_u \cdot A_v) \cos \left( \frac{2\pi \left[ t - (\phi_u, \phi_v) \right]}{T_i} \right).
\end{align*}$$

Here, $U_0$ and $V_0$ are the mean zonal and meridional winds; $A_u$ ($A_v$) and $\phi_u$ ($\phi_v$) are the amplitude and phase, respectively, of the zonal (meridional) component of the wave with period $T_i$; $t$ is the universal time (UT) in hours; and $N$ is the total amount of waves under consideration. In this work, $N = 5$, and $T_1 = 48 \text{ h}$, $T_2 = 24 \text{ h}$, $T_3 = 12 \text{ h}$, $T_4 = 8 \text{ h}$, and $T_5 = 12.4 \text{ h}$, for the quasi-2-day wave, the solar diurnal, semi-diurnal and terdiurnal tides, and the quasi-lunar semi-diurnal tide, respectively. The cosine of a sum was used to linearize Eq. (1), which was then solved in time-altitude running bins of 21 days and 2 km, shifted by 1 day and 1 km, respectively.

SMRs have also been used to study MLT dynamics at horizontal scales of a few hundred kilometers. This can be done by, for example, exploring the mean vertical fluxes of horizontal momenta, $\rho(u'w')$ and $\rho(v'w')$ (e.g., Liu et al. 2013; Moss et al. 2016). However, momentum flux estimations from SMR measurements have to be treated carefully. This is because $\rho(u'w')$ and $\rho(v'w')$ are adversely affected by the (unresolved) geophysical variability of the atmosphere and by some caveats of the SMR observation geometry (e.g., Charuvil Asokan et al. 2022). Nonetheless, Kudeki and Franke (1998) and Conte et al. (2021) showed that the adverse effect of the unresolved atmospheric variability is significantly reduced when $\rho(u'w')$ and $\rho(v'w')$ are averaged over intervals of 25 days or more (at MLT altitudes). Besides, increasing the amount of meteor detections and enriching the viewing-angle diversity of the observation volume can help to reduce the overestimation in $\rho(u'w')$ and $\rho(v'w')$ due to the correlated errors (e.g., Vierinen et al. 2019; Spargo et al. 2019). These improvements in the meteor detection statistics can be accomplished by implementing multistatic SMR configurations, such as SIMOnE (Vierinen et al. 2019).

SIMOnE stands for Spread spectrum Interferometric Multistatic meteor radar Observing Network, and refers to the first realization of a multistatic specular meteor radar network with coded continuous-wave technology (Chau et al. 2019). SIMOnE systems have been developed by the IAP (Germany), in collaboration with MIT Haystack (United States) and the Arctic University of Norway. In this work, we have employed data from the SIMOnE systems installed in Peru, around Jicamarca (11.9°S, 76.8°W) and Piura (5.5°S, 80.4°W). A detailed description of the implementation of these systems can be found in Chau et al. (2021).

The momentum flux estimates used in this study were obtained after solving the equation (Hocking 2005)

$$\rho = \left( \frac{1}{2} \left( \lambda \mathbf{f} - \hat{\lambda} \right) \right)^2.$$  

In this expression, $\mathbf{k} = (k_x, k_y, k_z)$ is the Bragg wave vector (scattered minus incident wave vectors) in the meteor-centered east–north–up coordinate system, $\mathbf{f}$ is the measured Doppler shift for each meteor detection, and $\mathbf{u'} = (u', v', w')$ represents the perturbed wind vector, which is unknown. Since the equation is squared, there are six quantities to determine: $u'^2$, $v'^2$, $w'^2$, $u'v'$, $u'w'$, and $v'w'$. The mean Doppler shift $\hat{\mathbf{f}}$ is calculated as $\hat{\mathbf{f}} = \mathbf{u} \cdot \mathbf{k}/(2\pi)$, where $\mathbf{u} = (u_n, v_n)$ is the mean wind vector obtained after previously solving $\mathbf{u} \cdot \mathbf{k} = 2\pi f$. Both the latter and Eq. (2), were solved in time–altitude running bins of 4 h, 4 km, shifted by 30 min and 1 km, respectively. To reduce the impact of the errors in the determination of the meteor positions, only
those meteor detections with zenith angles smaller than 60° were taken into account. Finally, to obtain the estimates of the momentum flux, $u'w'$ and $v'w'$ were multiplied by air density values obtained from the U.S. Standard Atmosphere 1976.

As shown in previous studies, measurements from multistatic SMRs like SIMONe can also be used to estimate the horizontal wind gradients (e.g., Chau et al. 2017). Wind gradients are influenced by planetary-scale waves such as tides, but they can also be helpful to extract information on the mesoscale dynamics (e.g., Charuvil Asokan et al. 2022). The horizontal wind gradients used in this study were obtained after solving $u \cdot k = 2\pi f$, again in time–altitude bins of 4 h, 4 km, but in this case with

$$u = \begin{pmatrix} u_0 + u_z \Delta x + u_y \Delta y + u_z \Delta z \\ v_0 + v_x \Delta x + v_y \Delta y + v_z \Delta z \\ w_0 \end{pmatrix}.$$  

(3)

The subscripts $x$, $y$, and $z$ indicate the derivatives with respect to the east–west, north–south, and up–down directions, respectively. The displacements $\Delta x$, $\Delta y$, and $\Delta z$ are calculated considering the World Geodetic System 1984, i.e., taking into consideration an ellipsoidal geometry in the Earth-centered, Earth-fixed coordinate system (see appendix in Stober et al. 2018). As in the case of the momentum fluxes, only the meteor detections with zenith angles smaller than 60° were used.

All the results presented hereafter fall within the period 15 July 2021–15 July 2022. This is because the installation of SIMONe Piura was finalized during the first weeks of July 2021, and because the main purpose of this work is to compare the MLT dynamics over Jicamarca and Piura during the same period.

3. Results

a. Planetary-scale dynamics

Figures 1 and 2 present results on the horizontal mean winds and planetary-scale waves obtained after solving Eq. (1). Figure 1 shows the case for the zonal direction and Fig. 2 for the meridional one. In both figures, the results for Jicamarca and Piura are shown in the left and right columns, respectively. The mean winds are depicted in the first row, while the second, third and fourth rows are reserved for the corresponding amplitudes of the quasi-2-day wave (Q2DW), the solar diurnal (DT) and solar semidiurnal (SDT) tides, in that order. The fifth row shows the mean winds calculated using the 3-hourly assimilated meteorological fields (V5.12.4) from Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), at the grid points closest to the actual coordinates of the transmitting sites of SIMONe Jicamarca and SIMONe Piura. Although the solar terdiurnal and quasi-lunar semidiurnal tides were taken into account when solving Eq. (1), they both show very small amplitudes and hence are not considered further in this work.

Inspection of Fig. 1 reveals that the mean zonal wind and the zonal component of the quasi-2-day wave and the solar tides are very similar between Jicamarca and Piura. At both locations, from late autumn until the end of the Southern Hemisphere’s winter, $U_0$ is predominantly eastward directed below ~93 km and westward above. The spring and fall transitions are dominated by westward zonal winds at all observed altitudes, in accordance with model simulations (Yiğit and Medvedev 2017; Pedatella et al. 2021). Some alternation between eastward and westward is noticeable in $U_0$ at the two locations during late spring and the summer. Over Jicamarca and Piura, the zonal component of the quasi-2-day wave (Q2DW) is very weak.
during almost the entire year analyzed in this work. Only over Jicamarca, between the end of December 2021 and middle of January 2022, Q2DW$_U$ enhances enough to reach amplitudes on the order of 20–30 m s$^{-1}$. Similarly, the zonal component of the semidiurnal solar tide does not exhibit significant amplitudes, except between October 2021 and January 2022 above ~90 km, when amplitudes on the order of 25–35 m s$^{-1}$ can be appreciated over Jicamarca and Piura.

A quick look at Fig. 2 shows that the mean meridional winds and planetary-scale wave components also present similar values between Jicamarca and Piura. However, Q2DW$_V$ and SDT$_V$ exhibit considerably larger amplitudes than their zonal counterparts. Similar to what is observed at middle latitudes in the Southern Hemisphere (Kumar et al. 2018; Conte et al. 2021), the Q2DW$_V$ presents clear amplitude enhancements of 50 m s$^{-1}$ or more during the summer. The strongest one develops around January 2022 and extends over the entire observed altitude range. Although with weaker amplitudes, Q2DW$_V$ is also active during the winter, particularly over Piura. Concerning the 12-h period tide, SDT$_V$ shows a nearly symmetric behavior with respect to the beginning of the year 2022 and extends over the entire observed altitude range. Although with weaker amplitudes, Q2DW$_V$ is also active during the winter, particularly over Piura. Concerning the 12-h period tide, SDT$_V$ shows a nearly symmetric behavior with respect to the beginning of the year 2022 and extends over the entire observed altitude range. Although with weaker amplitudes, Q2DW$_V$ is also active during the winter, particularly over Piura.

Over both locations, the diurnal tide is highly active during most parts of the year. Furthermore, it is clearly the dominant wave, which in turn is expected given that Jicamarca and Piura are located at low latitudes. Over Piura, the amplitudes of DT$_U$ and DT$_V$ compare differently depending on the time of the year and the altitude. At Jicamarca, on the other hand, the meridional component of DT presents amplitudes that are about 40% larger than those of its zonal counterpart. Moreover, below ~86 km of altitude, these amplitude differences are even more pronounced, reaching values of up to 75%. Both DT$_U$ and DT$_V$ reach their maximum amplitudes around the September equinox and exhibit the weakest amplitude values during the summer, in accordance with previous studies (Hays et al. 1994; Davis et al. 2013). However, the second maximum of DT, usually expected around the March equinox, develops a couple of months later over Piura. The larger diurnal amplitudes observed over Jicamarca may be in part related to a higher contribution from nonmigrating tidal components (e.g., Wu et al. 2008). However, assessing the influence of nonmigrating tides is out of the scope of the present study, since observations made at different longitudinal sectors are needed for that purpose (e.g., He et al. 2018).

The mean zonal ($U_M$) and meridional ($V_M$) winds calculated using MERRA-2 data are presented only to provide a general view of the mean background conditions in the stratosphere and lower mesosphere over Jicamarca and Piura. Overall, $U_M$ behaves similarly at the two locations, while $V_M$ exhibits some differences in magnitude and variability.

### b. Mesoscale dynamics

The main findings on the momentum fluxes are shown in Fig. 3 for the zonal component and in Fig. 4 for the meridional one. In both figures, the left and right columns show the results at Jicamarca and Piura, respectively. The top panels are used to present the 28-day running-median values of the 4-h, 4-km estimates of the third ($u^'w^'$) and sixth ($u^'w^'$) components of the stress tensor. The 28-day running-median values of 4-h, 4-km mean zonal ($u_0$) and meridional ($v_0$) winds are shown in the middle panels. And the bottom panels are used to present 28-day running-median values of the zonal ($\rho u^'w^'$) and meridional ($\rho v^'w^'$) momentum fluxes. The length of the running window was selected to be equal to 28 days to be consistent with our previous works (Conte et al. 2021, 2022). Besides, computing mean values resulted in the appearance of some smoothing artifacts, particularly in the

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**Fig. 2.** As in Fig. 1, but for the meridional component. Notice the different color scale for MERRA-2 mean meridional winds ($V_M$).
case of $\langle u'w' \rangle$ and $\langle v'w' \rangle$. For this reason, median values were calculated instead.

A first look at Fig. 3 reveals that the only significant difference between $\langle u'w' \rangle$ and $\rho\langle u'w' \rangle$ lies in their amplitudes. Both estimates have the same direction and present identical variability in space and time. The same is observed in the case of the meridional component (Fig. 4). For this reason, hereinafter $\langle u'w' \rangle$ and $\rho\langle u'w' \rangle$ ($\langle v'w' \rangle$ and $\rho\langle v'w' \rangle$) will be indistinctly referred to as zonal (meridional) momentum flux.

The momentum fluxes presented in this study are driven by waves with horizontal scales the size of the observation area or smaller (i.e., mesoscales). This is so because the influence of waves with scales larger than the observation volume is removed when the so-called mean Doppler shift ($\hat{f}$) is subtracted from the measured Doppler shifts [see Eq. (2)]. Note that $\hat{f}$ is calculated using the estimated mean winds ($u$), which are representative of the dynamics that develop in horizontal scales larger than the observation area ($\lambda_H \gtrapprox 400$ km). It is also worth mentioning that, since the momentum fluxes here analyzed are 28-day values, it is reasonable to expect that they are mostly dominated by upward-propagating GWs. In other words, it is assumed that the contribution of downward-

![Fig. 3](image1.png)

**Fig. 3.** (top to bottom) 28-day values of the third component of the stress tensor ($\langle u'w' \rangle$), the mean zonal wind ($u_0$), and the vertical zonal momentum flux ($\rho\langle u'w' \rangle$), respectively, at (left) Jicamarca and (right) Piura. Data gaps are shown in black. The x-axis and y-axis minor ticks appear every 6 days and 1 km, respectively.

![Fig. 4](image2.png)

**Fig. 4.** (top to bottom) 28-day values of the sixth component of the stress tensor ($\langle u'w' \rangle$), the mean meridional wind ($v_0$), and the vertical meridional momentum flux ($\rho\langle v'w' \rangle$), respectively, at (left) Jicamarca and (right) Piura. Data gaps are shown in black. The x-axis and y-axis minor ticks appear every 6 days and 1 km, respectively.
propagating GWs is negligible when averaged over an interval of 28 days. For this reason, positive (negative) values of $\rho'(u'v')$ are associated with eastward (westward) zonal momentum, and positive (negative) values of $\rho'(u'u')$ with northward (southward) momentum.

From Fig. 3, it can be seen that the zonal momentum flux observed above ~89 km of altitude behaves similarly at Jicamarca and Piura. At those altitudes, $\rho'(u'v')$ is mainly westward directed. On the other hand, below ~90 km clear differences can be identified between the two locations. At Jicamarca, $\rho'(u'v')$ alternates between positive and negative values on several occasions, while at Piura, $\rho'(u'v')$ is dominated by positive (or eastward) values during most of the time investigated in this work. At the altitudes where $\rho'(u'w')$ is dominated by westward-directed values, both locations exhibit strong accelerations of the mean zonal wind. The first acceleration of $u_0$ takes place between the middle of July and middle of October 2021. It exhibits larger amplitudes over Jicamarca. The second acceleration of the mean zonal winds occurs around the middle of January 2022 and extends until April of that same year, with larger amplitudes over Piura. Notice that the two reported accelerations of the mean zonal wind take place when the latter is westward directed. During the periods dominated by eastward zonal winds, the majority of the GWs driving the observed $\rho'(u'w')$ propagate against the background wind at both locations.

The differences between Jicamarca and Piura are even more pronounced in the case of the meridional momentum flux ($\rho'(u'v')$). Over Jicamarca, $\rho'(u'v')$ is mostly positive, i.e., northward directed before the middle of November 2021 and after April 2022 (see Fig. 4). These positive values are seen at most parts of the altitude range here analyzed (80–98 km). Between December 2021 and March 2022, $\rho'(u'v')$ is mainly southward directed. In the case of Piura, a clear reversal in the direction of $\rho'(u'v')$ is observed between 88 and 93 km of altitude, with southward $\rho'(u'v')$ below and northward $\rho'(u'v')$ above, varying considerably in amplitude. This reversal (i.e., the negative–positive pattern) is observed during the entire period of time explored in this work.

In Fig. 5, a comparison between the horizontal wind gradients over Jicamarca and Piura is shown for April–July 2022. The estimates of the horizontal wind gradients, particularly of the gradients in the zonal and meridional directions ($u_x$, $v_x$, and $u_y$, $v_y$, respectively), strongly depend on the spatial distribution of the meteor detections. Besides, $u_x$, $v_x$, $u_y$, and $v_y$ have amplitudes on the order of 0.2–0.6 m s$^{-1}$ km$^{-1}$, while the vertical gradients can easily exceed amplitudes of 20 m s$^{-1}$ km$^{-1}$ (e.g., Chau et al. 2021; Conte et al. 2021). Thus, relatively bad meteor-detection statistics usually result in estimates of $u_x$, $v_x$, $u_y$, and $v_y$ with values that are smaller than the corresponding statistical uncertainties. For this reason, the horizontal wind gradients are investigated here only during April–July 2022, a period with good meteor detection statistics at both locations. The left and middle columns show daily averages of the 4-h, 4-km horizontal wind horizontal gradients over Jicamarca and Piura, respectively: from top to bottom, $u_x$, $v_x$, $u_y$, and $v_y$ (units: m s$^{-1}$ km$^{-1}$). The column on the right is reserved to present the 2D histograms of each wind gradient at 95 km of altitude. The corresponding correlation coefficient is indicated in red. The histograms and the correlation coefficients were determined using the 4-h, 4-km estimates (and not the daily values).
the mean provides a practical picture of GW processes and interactions with wave by the background atmosphere. The linear theory predicts equal the background wind, whereby the wave vertical direction as the background wind. According to the linear theory, GWs are propagating in the same direction. Moreover, note that the periods of strong zonal wind acceleration by westward-propagating GWs approximately coincide with periods characterized by a highly active diurnal tide (see Figs. 1 and 3). Conversely, it could also be that these westward-propagating GWs are enhancing the amplitude of the diurnal tide, as it has been previously shown by, for example, Watanabe and Miyahara (2009) and Yiğit and Medvedev (2017). In fact, Yiğit and Medvedev (2017) performed simulations with the Coupled Middle Atmosphere Thermosphere 2 general circulation model, implementing a nonlinear whole atmosphere GW parameterization scheme with a GW anisotropy mechanism, and found that the directions of the zonal GW drag and zonal background wind coincide in the low-latitude MLT. The anisotropy mechanism assumes that the GWs with horizontal phase velocities (both positive and negative) are directed along the vector of the local mean wind at the source level (Yiğit et al. 2008). This approach showed that modeled tidal amplitudes are improved with respect to observations (Yiğit and Medvedev 2017). Thus, nonlinear feedback and GW–tidal interactions, among others, may result in momentum fluxes and background winds having the same direction. Moreover, note that the periods of strong zonal wind acceleration by westward-propagating GWs approximately coincide with periods characterized by a highly active diurnal tide (see Figs. 1 and 3). Conversely, it could also be that these westward-propagating GWs are enhancing the amplitude of the diurnal tide, as it has been previously shown by, for example, Watanabe and Miyahara (2009) and Yiğit and Medvedev (2017). In fact, Yiğit and Medvedev (2017) performed simulations with the Coupled Middle Atmosphere Thermosphere 2 general circulation model, implementing a nonlinear whole atmosphere GW parameterization scheme with a GW anisotropy mechanism, and found that the directions of the zonal GW drag and zonal background wind coincide in the low-latitude MLT. The anisotropy mechanism assumes that the GWs with horizontal phase velocities (both positive and negative) are directed along the vector of the local mean wind at the source level (Yiğit et al. 2008). This approach showed that modeled tidal amplitudes are improved with respect to observations (Yiğit and Medvedev 2017). Thus, nonlinear feedback and GW–tidal interactions, among others, may result in momentum fluxes and background winds having the same direction. Moreover, note that the periods of strong zonal wind acceleration by westward-propagating GWs approximately coincide with periods characterized by a highly active diurnal tide (see Figs. 1 and 3). Conversely, it could also be that these westward-propagating GWs are enhancing the amplitude of the diurnal tide, as it has been previously shown by, for example, Watanabe and Miyahara (2009) and Yiğit and Medvedev (2017).

4. Discussion

When inspected in combination with the mean zonal wind \( u_0 \), the large negative values observed in \( \rho'(u'w') \) above \( \sim 89 \text{ km} \) of altitude are perhaps the most salient feature of Fig. 3. This is because at those altitudes, \( u_0 \) is also directed toward the west, which then means that the GWs are propagating in the same direction as the background wind. According to the linear theory, GWs are filtered out when their horizontal phase speeds equal the background wind, whereby the wave vertical wavelength approaches zero, resulting in the absorption of the wave by the background atmosphere. The linear theory provides a practical picture of GW processes and interactions with the mean flow; however, nonlinear processes are ubiquitous in the MLT region (e.g., Liu et al. 2008; Yiğit and Medvedev 2015). In fact, Yiğit and Medvedev (2017) performed simulations with the Coupled Middle Atmosphere Thermosphere 2 general circulation model, implementing a nonlinear whole atmosphere GW parameterization scheme with a GW anisotropy mechanism, and found that the directions of the zonal GW drag and zonal background wind coincide in the low-latitude MLT. The anisotropy mechanism assumes that the GWs with horizontal phase velocities (both positive and negative) are directed along the vector of the local mean wind at the source level (Yiğit et al. 2008). This approach showed that modeled tidal amplitudes are improved with respect to observations (Yiğit and Medvedev 2017). Thus, nonlinear feedback and GW–tidal interactions, among others, may result in momentum fluxes and background winds having the same direction. Moreover, note that the periods of strong zonal wind acceleration by westward-propagating GWs approximately coincide with periods characterized by a highly active diurnal tide (see Figs. 1 and 3). Conversely, it could also be that these westward-propagating GWs are enhancing the amplitude of the diurnal tide, as it has been previously shown by, for example, Watanabe and Miyahara (2009) and Yiğit and Medvedev (2017).

To confirm that mesoscale GWs are depositing westward zonal momentum and thus accelerating the mean zonal wind, estimates of the vertical gradient of \( \rho'(u'w') \) divided by the air density \( \rho^{-1} \partial \rho'(u'w')/\partial z \) are presented in Fig. 6. The 28-day running-median values of this estimate are shown in the first row, for Jicamarca on the left, and Piura on the right. The second row is used to present the corresponding 28-day running-median values of this estimate are shown in Fig. 6. The 28-day running-median values of this estimate are shown in the first row, for Jicamarca on the left, and Piura on the right. The second row is used to present the corresponding 28-day running-median values of the mean zonal wind. Note that the strong westward values observed in \( \rho'(u'w') \) and \( u_0 \) above \( \sim 89 \text{ km} \) approximately coincide with relatively large negative values of \( \rho^{-1} \partial \rho'(u'w')/\partial z \), at both Jicamarca and Piura. This negative gradient indicates that the zonal momentum flux is becoming more negative as the altitude increases or, in other words, that westward-propagating GWs (because \( \rho'(u'w') \) is negative) are depositing momentum into the mean zonal wind, causing an acceleration of the latter toward the west.
Alternatively, the GW forcing, i.e., \( a_{gw} = -p^{-1}a(\rho(u'w'))/a_z \), is then positive at these altitudes, which indicates an acceleration of the background zonal wind due to the dissipation of gravity waves.

The negative values of \( p^{-1}a(\rho(u'w'))/a_z \) weaken a few kilometers higher up, and eventually become positive above \(-95 \text{ km}\) (see Fig. 6). This suggests that by the time they reach these altitudes, the westward-propagating GWs have exhausted most of their energy, and hence eastward-propagating GWs start to play a more relevant role. At this point, the reader should have in mind that a westward momentum flux, for example, does not mean that there are no eastward-propagating GWs. It rather means that, on average, the westward-propagating GWs dominate over those propagating to the east.

Model simulations accounting for wave–wave interactions and employing anisotropic GW sources in which the waves propagate in the direction of the background wind have considerably improved the representation of the middle atmosphere seasonal cycle (Medvedev et al. 1998). Global-scale modeling later revealed new insights in the direct propagation of GWs into the thermosphere (from the tropopause up to altitudes of \(-250 \text{ km}\)), showing that anisotropic wave propagation can allow GWs to survive their isotropic critical level filtering (Yiğit et al. 2009). In Fig. 1, \( U_M \) is entirely westward directed below \(-5 \text{ km}\) of altitude. It is therefore likely that anisotropic GWs generated in the troposphere have favorable upward-propagation conditions to reach higher altitudes with appreciable amplitudes and eventually deposit their energy and momentum via nonlinear diffusive damping at the altitudes where our SIMONE systems observe a strong wind acceleration of the mean zonal wind. Another possibility is that these westward-propagating GWs are generated in the lower stratosphere. In the study by Lane and Sharman (2006), GWs generated by deep convection were shown to break due to above-cloud wind shear. The breaking eventually produces new waves that have smaller horizontal scales than the primary waves. This breaking and generation of new waves might be happening around 25 km of altitude, where the direction of \( U_M \) abruptly changes from eastward to westward (see Fig. 1).

Secondary GWs have been shown to also play a role in the dynamics of the MLT (e.g., Liu et al. 2019). These waves can be generated by linear and nonlinear processes. Linear secondary GWs are characterized by horizontal scales of 1000 km or more (Vadas et al. 2018), and hence cannot be present in the momentum fluxes analyzed in this work. As it was mentioned in the previous section, the procedure implemented to estimate \( (u'w') \) and \( (w'w') \) removes most waves with horizontal scales larger than \(-400 \text{ km}\). On the other hand, secondary GWs triggered by nonlinear processes have horizontal scales on the order of a few hundred kilometers or less (Chun and Kim 2008; Heale et al. 2020). Therefore, it is possible that they are present in the momentum fluxes here discussed. For example, sudden changes in the sign of \( \rho(u'w') \) as the altitude increases indicate wind shear, which can result in the generation of nonlinear secondary GWs (e.g., Lane and Sharman 2006).

Concerning the meridional component, strong positive values of \( \rho(v'w') \) are observed over Jicamarca at approximately the same periods and altitudes characterized by large amplitudes of the DT\(_V\) tide. The case is different over Piura (see Fig. 4). From Figs. 1 and 2, it can be seen that while the mean background conditions in the zonal component are approximately the same at both locations, some clear differences can be noticed in the meridional direction. These can be of help to understand the markedly distinct behavior of \( \rho(v'w') \) at Piura, since different mean background conditions translate into different filtering and dissipative effects for the GWs propagating over the two locations. On the other hand, there are periods when the mean background conditions are also similar in the meridional component, which indicates that the corresponding differences in \( \rho(v'w') \) are the result of different GW sources at Jicamarca and Piura. GWs generated by deep convection are abundant at low latitudes (e.g., Jewtoukoff et al. 2013; Walterscheid and Christensen 2016), although waves generated by the orography cannot be discarded given the proximity of the Andes mountain range.

Statistical analyses of the total momentum flux (TMF) can be useful to determine if large-amplitude GWs (e.g., mountain waves; Fritts et al. 2021, and references therein) are the main drivers of the observed momentum fluxes. The logarithmic distributions of the total momentum flux during the winter are very similar between Jicamarca and Piura. This can be seen in the top panels of Fig. 7, which also shows the distributions for the summertime in the bottom panels. The left and right columns present the case for Jicamarca and Piura, respectively. The TMF was calculated as \( \sqrt{\left(\rho(u'w')\right)^2 + \left(\rho(v'w')\right)^2} \), using the 4-h, 4-km estimates averaged between 88 and 92 km of altitude, where the uncertainties in the momentum flux estimates are minimal. The lognormal function that best fits the data is shown in red. Notice that during the summer, the tail of the lognormal function is wider over Piura. This indicates a more intermittent behavior of GWs at that location, since the further a distribution is from a Gaussian shape, the higher the intermittency is (e.g., Pouquet 2018; Ern et al. 2021). The 95th quantile and the percentage of TMF associated with values larger than this quantile are indicated in the legend box of each plot. The percentages were calculated following Hertzog et al. [2012, see Eq. (2) in that work], and they indicate that the strongest 5% of GWs contribute to the total flux in similar amounts at both locations: 18%–19% and 20%–23% for winter and summer seasons, respectively. Such relatively small percentages indicate that the momentum fluxes here analyzed are driven by medium- to small-amplitude gravity waves.

A final comment is reserved for the horizontal wind gradients. The variability observed in these estimates results from the influence of both planetary-scale and mesoscale waves. However, most of the effects due to planetary waves and tides is contained in the mean winds, \( u_0 \) and \( v_0 \), and the vertical gradients, \( u_x \) and \( v_y \) (e.g., see Fig. 4 in Conte et al. 2021). Furthermore, the weak correlations obtained for \( u_x, u_y, v_x, \) and \( v_y \), confirm the dominant role that mesoscale GWs play in shaping the mean structure and variability of the low-latitude MLT winds. If tidal waves were driving the variability observed in the horizontal wind gradients, the correlations would be much stronger, given that the tides behave similarly over Jicamarca and Piura. Nevertheless, it is possible that the slightly stronger correlations obtained for \( u_x \) and \( v_y \) are in part due to tidal influence, particularly the
diurnal tide (notice in Figs. 1 and 2 that during May–July 2022, above ~93 km of altitude, DT$_U$ and DT$_V$ exhibit similar amplitudes and less variability at both locations).

5. Summary and conclusions

Multistatic specular meteor radar observations made with SIMONE Jicamarca and SIMONE Piura have been used to investigate mesosphere and lower-thermosphere dynamics over central and northern Peru. Estimates of the mean horizontal winds, the quasi-2-day wave and the solar tides were calculated in order to analyze dynamics at planetary scales. Both the mean zonal and meridional winds exhibit similar variability in time and altitude over Jicamarca and Piura. The same is observed in the case of the Q2DW and the semidiurnal solar tide. Only the diurnal solar tide presents clear differences in its amplitude, particularly in the case of the meridional component. The latter is found to be considerably larger over Jicamarca, which may be related to a greater contribution from nonmigrating tidal components and enhanced gravity wave activity.

Concerning mesoscales, the small correlations between the horizontal wind gradients over Jicamarca and Piura indicate that the variability over periods of a few months is weakly influenced by tides and, therefore, must be driven by internal gravity waves. Besides, the analysis of 28-day median values of the zonal momentum flux reveals a strong acceleration of the mean zonal wind by westward-propagating gravity waves. This is observed at both locations above ~89 km of altitude, but with larger amplitudes over Jicamarca during winter and spring, and over Piura during the summer. The latter is demonstrated by results on the vertical gradient of the zonal momentum flux divided by the density, \( \rho^{-1} \delta (\rho (u'w')) / \delta z \). at approximately the same time and altitudes where these wind accelerations have been reported, \( \rho^{-1} \delta (\rho (u'w')) / \delta z \) exhibits relatively large negative values. This indicates the deposition of zonal momentum that accelerates the zonal background flow toward the west. Hence, these results serve as observational confirmation of previous studies based on general circulation model simulations indicating that the directions of the zonal GW drag and zonal background wind coincide in the low-latitude MLT.

Logarithmic distributions of the total momentum flux indicate that the contribution from large-amplitude gravity waves to the total flux is similar between Jicamarca and Piura. During winter, the strongest 5% of gravity waves contribute with 18% of the total flux at Jicamarca and 19% at Piura. During the summer, these contributions respectively increase to 20% and 23%. Considering that mesoscale dynamics have been found to differ between Jicamarca and Piura, these nearly identical percentages suggest that middle- to small-amplitude waves drive the dynamics at horizontal scales of a few hundred kilometers over central and northern Peru.

Acknowledgments. This work was partially funded by the Bundesministerium für Bildung und Forschung via project WASCLIM-IAP part of the ROMIC-II program. The authors thank Karim Kuyeng and the staff at the Radio Observatory of Jicamarca and the Estación Científica of University of Piura.
for their support and help in maintaining SIMONe Jicamarca and SIMONe Piura systems. The authors thank the reviewers for their helpful comments.

Data availability statement. The SIMONe data products used to prepare the figures of this paper are available in HDF5 format at https://doi.org/10.22000/938. The MERRA-2 data used in Figs. 1 and 2 are available from the Goddard Earth Sciences Data and Information Services Center (GES DISC) at https://doi.org/10.5067/QBZ0MC944HW0. Details on the U.S. Standard Atmosphere 1976 can be found at https://www.ngdc.noaa.gov/stp/space-weather/online-publications/miscellaneous/us-standard-atmosphere-1976/.

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