First studies of mesosphere and lower thermosphere dynamics using a multistatic specular meteor radar network over southern Patagonia

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November 30, 2022

Abstract

This paper presents for the first time results on winds, tides, gradients of horizontal winds, and momentum fluxes at mesosphere and lower thermosphere (MLT) altitudes over southern Patagonia, one of the most dynamically active regions in the world. For this purpose, measurements provided by SIMONe Argentina are investigated. SIMONe Argentina is a novel multistatic specular meteor radar system that implements a SIMONe (Spread Spectrum Interferometric Multistatic meteor radar Observing Network) approach, and that has been operating since the end of September 2019. Average counts of more than 30000 meteor detections per day result in tidal estimates with statistical uncertainties of less than 1 m/s. Thanks to the multistatic configuration, horizontal and vertical gradients of the horizontal winds are obtained, as well as vertical winds free from horizontal divergence contamination. The vertical gradients of both zonal and meridional winds exhibit strong tidal signatures. Mean momentum fluxes are estimated after removing the effects of mean winds using a four-hour, eight-kilometer window in time and altitude, respectively. Reasonable statistical uncertainties of the momentum fluxes are obtained after applying a 28-day averaging. Therefore, the momentum flux estimates presented in this paper represent monthly mean values of waves with periods of four hours or less, vertical wavelengths shorter than eight kilometers, and horizontal scales less than 400 km.

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Key Points:

- First observations of MLT dynamics over one of the most dynamically active regions in the world
- Estimates of mean horizontal winds and their gradients are possible, thanks to the multistatic configuration.
- Mean momentum fluxes are estimated with vertical velocity estimates free of horizontal divergence contamination.

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Abstract

This paper presents for the first time results on winds, tides, gradients of horizontal winds, and momentum fluxes at mesosphere and lower thermosphere (MLT) altitudes over southern Patagonia, one of the most dynamically active regions in the world. For this purpose, measurements provided by SIMONe Argentina are investigated. SIMONe Argentina is a novel multistatic specular meteor radar system that implements a SIMONe (Spread Spectrum Interferometric Multistatic meteor radar Observing Network) approach, and that has been operating since the end of September 2019. Average counts of more than 30000 meteor detections per day result in tidal estimates with statistical uncertainties of less than 1 m/s. Thanks to the multistatic configuration, horizontal and vertical gradients of the horizontal winds are obtained, as well as vertical winds free from horizontal divergence contamination. The vertical gradients of both zonal and meridional winds exhibit strong tidal signatures. Mean momentum fluxes are estimated after removing the effects of mean winds using a four-hour, eight-kilometer window in time and altitude, respectively. Reasonable statistical uncertainties of the momentum fluxes are obtained after applying a 28-day averaging. Therefore, the momentum flux estimates presented in this paper represent monthly mean values of waves with periods of four hours or less, vertical wavelengths shorter than eight kilometers, and horizontal scales less than 400 km.

1 Introduction

The mesosphere and lower thermosphere (MLT) is the atmospheric region that couples the lower and upper parts of the terrestrial atmosphere. For this reason, knowledge of its dynamics is of great importance in order to understand the behavior of the atmosphere as a whole. The coupling is accomplished mainly via propagation of three dominant types of waves: planetary waves (PWs), tides, and gravity waves (GWs). PWs are waves with scales of thousands of kilometers and periods of up to ~ 30 days. They are mainly generated in the troposphere by land-sea discontinuities, or triggered in-situ by, e.g., baroclinic instabilities and filtered gravity waves (e.g., Rossby, 1939; McCormack et al., 2014; H.-L. Liu & Roble, 2002). Tides are also waves with horizontal scales of thousands of kilometers, but periods that are sub-harmonics of the solar and lunar days. Thermal tides are mainly a consequence of solar radiation absorption by water vapour in the troposphere and ozone in the stratosphere, while the lunar tide results from the gravitational pull of the Moon (e.g., Lindzen & Chapman, 1969; Forbes, 1984). GWs are small to medium scale waves with periods ranging from about 5 minutes to many hours. They can be triggered by a myriad of different sources, e.g., the orography, thunderstorms, shear instabilities, convection, etc. (e.g., Hines, 1988; Piani et al., 2000; Fritts & Alexander, 2003).

During the last decades, specular meteor radars (SMRs) have been extensively used to study winds and atmospheric waves in the MLT (e.g., Hocking, 2005; Clemesha et al., 2009; Hoffmann et al., 2010; A. Z. Liu et al., 2013; Laskar et al., 2016; Jia et al., 2018, and references therein). They have also been used to study GWs, which are known to play an important role in determining the wind and thermal structure of the MLT (e.g., Fritts, 1984). Particularly, some studies have focused on extracting information about GW-driven momentum fluxes from SMR measurements (e.g., Fritts et al., 2010; Placke et al., 2011a; Andrioli et al., 2015). However, understanding the results on momentum flux estimates based on SMR winds is not trivial, mainly because of the uncertainties associated with the estimation procedure (e.g., Fritts et al., 2012b). In fact, Vincent et al. (2010) showed that the accuracy in the momentum flux estimation is highly dependent on the number of meteor detections. Consequently, the usage of multistatic meteor radar systems represents one way to reduce the uncertainties of the momentum flux estimates (e.g., Spargo et al., 2019). Furthermore, by detecting more meteors and being able to observe them from different viewing points, multistatic SMR systems also allow for more reliable estimations of horizontal wind gradients.

The MLT over the southern part of Argentina and Chile is considered to be one of the most dynamically active regions in the globe. Satellite-based studies have revealed that GW-driven momentum fluxes increase considerably at both stratosphere and MLT altitudes over Patagonia (e.g., Trinh et al., 2018; Vadas et al., 2019a). Numerical model simulations have reported generation of secondary GWs with horizontal scales of up to 2000 km at mesospheric altitudes over the southern Andes (Vadas & Becker, 2019). Nevertheless, wave coupling processes in the MLT region over the Patagonian sector are still not well understood, partly because the installation of ground-based instruments has not been possible, either due to logistics challenges or instrument requirements. In this work, we present preliminary results of a multistatic SMR network that allows, for the first time, measurements of MLT dynamics in the Patagonian region. Besides the local support, our success has been possible thanks to a novel approach that we call SIMONe (Spread Spectrum Interferometric Multistatic meteor radar Observing Network) (Chau et al., 2019). SIMONe makes use of modern radar practices like spread-spectrum, MIMO (Multiple-Input, Multiple-Ouput), and compressed sensing applied to atmospheric radars (Vierinen et al., 2016; Urco et al., 2018, 2019). This allows for much easier installation, operation and expansion of the network than previous equivalent systems.

The paper is organized as follows. Section 2 introduces the SIMONe Argentina system. Section 3 provides a detailed description of the different analyses performed to the data. The main results and findings are presented and discussed in Section 4. Finally, the concluding remarks are provided in section 5.

2 SIMONe Argentina

SIMONe Argentina is a state-of-the-art network of multistatic specular meteor radars that was installed in September of 2019 in the southern province of Santa Cruz, Argentina. It is comprised of one single transmitting site with five linearly polarized Yagi antennas in a pentagon configuration, and five receiving sites with one dual-polarization Yagi antenna each. The receivers are placed between 30 and 270 km of distance from the transmitting site, which is located at 49.6° S, 71.4° W (see Figure 1 for details on the geographical distribution of the sites). This type of network configuration is known as MISO (Multiple-Input, Single-Output), since only one antenna is used on reception (e.g., Chau et al., 2019).

SIMONe Argentina is the result of an effort led by the Leibniz Institute of Atmospheric Physics (Germany) in collaboration with the Universidad Nacional de la Patagonia Austral (Argentina), and the Arctic University of Norway. A similar system has been installed in Peru (SIMONe Peru). SIMONe systems use coded spread spectrum on transmission (Vierinen et al., 2016). A phase coded signal based on pseudo-random sequences is generated and transmitted on each antenna independently. Transmission is done at a frequency of 32.55 MHz and with an average power of 400 W per antenna. All five transmitted codes are simultaneously decoded at each receiving site by means of compressed sensing (e.g., Urco et al., 2019). Hardware and software details of both systems, i.e., SIMONe Peru and SIMONe Argentina, can be found in Chau et al. (2020).

SIMONe Argentina started operations by the end of September 2019 and has been running since then with almost no interruptions. Figure 2 shows a summary of the detection statistics for the first seven months of operations. The upper panel indicates the normalized percentage of meteor counts for each individual link. The bottom panel is used to present the average daily total counts for each month. Problems with the local power supply at the transmitting site resulted in fewer meteor detections during April of 2020. Besides, the receiving site at Gobernador Gregores was out of operation dur-

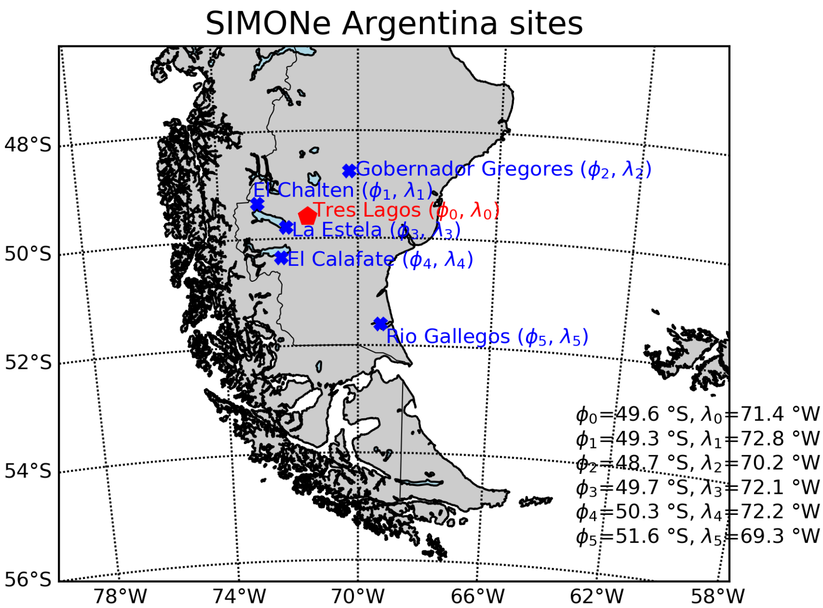

Figure 1. Map of SIMONe Argentina. The transmitter is indicated with a filled red pentagon, and the receivers are indicated with blue crosses.

ing December of 2019 due to damage in the antenna cables. Nevertheless, for most of the time, the number of counts was much higher than in standard specular meteor radars. The links concentrating most of the meteor detections are Tres Lagos-El Calafate and Tres Lagos-La Estela. Starting in March 2020, the link Tres Lagos-Rio Gallegos exhibits a considerable increase in the counts, as a result of having rotated the transmitting antennas by 90 degrees. By month, January presents the largest counts, with an average of more than 50000 meteor detections per day.

3 Data analysis

Specular meteor radars (SMRs) are used to measure the Doppler shift of meteor trails due to their drifting with the mesospheric neutral winds (e.g., Jones et al., 1998). In order to extract the wind information from the measurements, one may implement an all-sky fit of the Doppler velocities measured during a certain period of time and within a given altitude interval (e.g., Hocking et al., 2001; Holdsworth et al., 2004). In other words, one must solve the following equation:

$$\mathbf{u} \cdot \mathbf{k} = 2\pi f + \zeta, \tag{1}$$

where $\mathbf{u} = (u, v, w)$ is the neutral wind vector, with u, v and w being its zonal (east-west), meridional (north-south) and vertical (up-down) components, respectively. $\mathbf{k} = (k_u, k_v, k_w)$ is the Bragg wave vector (scattered minus incident) in the meteor-centered east-north-up coordinate system (perpendicular to the meteor trail); f is the Doppler shift; and ζ is the Doppler shift uncertainty. For this equation to be valid, one must make the assumption that the winds at each given height interval are uniform during the selected period of time (homogeneous method). The results using the homogeneous method have been obtained assuming $w = 0$.

Monostatic SMRs commonly allow for hourly horizontal wind estimations every 2-3 km in altitude (e.g., Jacobi et al., 1999; Hoffmann et al., 2010). The wind estimates are representative of mean values over an area of $\sim$ 200 km in radius. These horizon-

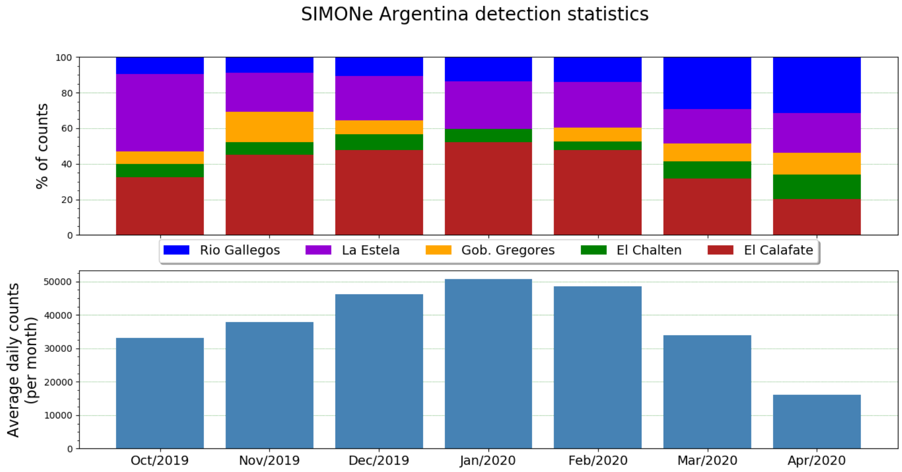

Figure 2. Upper panel: normalized percentage of meteor counts, color coded for each individual link. Bottom panel: monthly daily mean counts for all the links combined (see text for details).

tal winds can be further processed in order to obtain information about large scale waves such as planetary waves and tides (e.g., Murphy et al., 2006; Chau et al., 2015; Conte et al., 2018).

One of the advantages of using multistatic SMR networks is that the amount of meteor detections is significantly increased (e.g., Stober & Chau, 2015). During most of the time since it started operations, SIMONe Argentina has been capable of detecting more than 30000 meteors per day (see Figure 2). With such amounts of meteor detections, one can not only reliably estimate horizontal winds with higher time and vertical resolutions ($\sim$ 15 min and 1 km, respectively), but also investigate second order parameters such as the squares of the perturbation components of the radial velocities, i.e., the momentum flux components (e.g., Spargo et al., 2019). Another advantage multistatic SMR networks present is that they are capable of sampling the observed volume from different viewing angles. In this scenario, the increased number of meteor detections can be further exploited in order to estimate first-order derivatives of the horizontal winds, and in this way include in the estimation a mean vertical wind free of horizontal divergence contamination (e.g., Chau et al., 2017).

Below, we describe the main procedures used in this work, i.e., tidal estimation, wind estimation using a gradient method, and mean momentum flux estimation. For each of the three procedures, a first wind estimation is carried out in order to remove outliers. That is, Equation 1 is solved in bins of the same size as that used later on in each given procedure (e.g., 4 hour, 4 km in the gradient method); and then the radial velocities the values of which have a corresponding residual of more than 3 standard deviations are removed. This first wind estimation is carried out only in those bins containing a minimum of 10 meteor detections.

3.1 Tidal estimation

Horizontal winds obtained from meteor radar measurements have been used for several decades to investigate tides and planetary waves in the MLT (e.g., Hocking & Thayaparan, 1997; Fritts et al., 2012a). Different mathematical techniques such as least squares or wavelet analysis can be applied to the wind data in order to extract the tidal information (e.g., Stening et al., 1997; Sandford et al., 2006; He et al., 2017). To avoid zero-padding or interpolating when encountering data gaps, a least squares approach was selected for this study.

After removing the outliers, Equation 1 was again fitted to the Doppler shift measurements. For this purpose, a weighted least squares (WLS) technique was implemented using bins of 1 hour and 2 km (in altitude), shifted by half an hour and 1 km, respectively. The inverse of the squared Doppler shift uncertainties (ζ in Eq. 1) were used as weights. The WLS was carried out only in those bins containing a minimum of 10 meteor detections. Then, under the assumption that the obtained hourly horizontal winds are the result of the superposition of a mean wind and different period oscillations, the following equation was fitted to the zonal (u) and meridional (v) wind components

$$[u + \psi_u, v + \psi_v] = [U_0, V_0] + \sum_{i=1}^{4} [A_u, A_v]_i \cos\left(2\pi \frac{(t - [\phi_u, \phi_v]_i)}{T_i}\right). \tag{2}$$

Here, ψ_u and ψ_v are the Doppler shift uncertainties (error) propagated into the estimated winds; U_0 and V_0 are the mean zonal and meridional winds; A_{u_i} (A_{v_i}) and ϕ_{u_i} (ϕ_{v_i}) are the amplitude and phase, respectively, of the zonal (meridional) component of each considered wave; $T_1 = 2$ day; T_i for $i > 1$ is the period of each considered tide ($T_2 = 24$ h, $T_3 = 12$ h and $T_4 = 8$ h, for the diurnal, semidiurnal and terdiurnal solar tides, respectively); and t is the Universal Time (UT) in hours. The cosine of a sum was used to linearize Equation 2, which then was solved by applying the WLS method using a running window of 4 days shifted by 1 day.

3.2 Wind field gradient method

If one relaxes the assumption of homogeneity, the wind field inside the observed area may be estimated using the gradient method. This method consists in approximating the horizontal winds with their first-order Taylor expansion terms (e.g., Burnside et al., 1981; Browning & Wexler, 1968; Chau et al., 2017). This means introducing the following expression into Equation 1

$$\mathbf{u}(x, y, z, t) = \mathbf{u}_0(z, t) + \mathbf{u}_x(z, t)(x - x_0) + \mathbf{u}_y(z, t)(y - y_0) + \mathbf{u}_z(z, t)(z - z_0), \tag{3}$$

where $\mathbf{u}_0 = (u_0, v_0, w_0)$ represents the mean wind; $\mathbf{x}_0 = (x_0, y_0, z_0)$ is a reference point; and

$$\begin{aligned}
\mathbf{u}_x &= \left(\frac{du}{dx}, \frac{dv}{dx}, \frac{dw}{dx}\right) \\
\mathbf{u}_y &= \left(\frac{du}{dy}, \frac{dv}{dy}, \frac{dw}{dy}\right) \\
\mathbf{u}_z &= \left(\frac{du}{dz}, \frac{dv}{dz}, \frac{dw}{dz}\right).
\end{aligned}$$

The mean wind and the first order derivatives depend only on time and height. The coordinates (x, y, z) are in km, and calculated taking into consideration the latitude, longitude and altitude of each meteor detection and the radius of the Earth at the reference point. $\mathbf{x}_0$ is determined using the latitude and longitude of the transmitting site, and the altitude of each height level considered in the WLS fit. The latter was implemented using bins of 4 hour and 4 km (in altitude), shifted by 15 minutes and 1 km, respectively. For this study, we have assumed that $(dw/dx,\ dw/dy,\ dw/dz) = \mathbf{0}$, which means solving for nine unknowns. In this method, a condition of having a minimum of forty meteor detections per bin was selected.

Mathematically speaking, the zero order approximation ($\mathbf{u}_0$) as well as the first order derivatives ($\mathbf{u}_x$, $\mathbf{u}_y$ and $\mathbf{u}_z$) are defined at the reference point, $\mathbf{x}_0$. However, the dependence of our nine estimates on this reference point is not explicitly written in Equation 3 for the following reason. The mean winds and the gradients are obtained after fitting measurements made at points randomly distributed within an area of roughly ~ 200

km of radius around $\mathbf{x}_0$. Thus, it is assumed that they represent a "mean" zero order approximation, and "mean" first order derivatives, not only at the reference point, but over the whole area aforementioned.

3.3 Momentum flux estimates

The procedure followed in this study to estimate the GW momentum flux is based on the works by Thorsen et al. (1997) and Hocking (2005). It consists in applying a least square method to solve the following equation

$$(\mathbf{u}' \cdot \mathbf{k})^2 = (2\pi(f - \hat{f}))^2. \tag{4}$$

In this expression, $\mathbf{k}$ and f are, respectively, the same Bragg wave vector and same Doppler shift as in Equation 1, but $\mathbf{u}'$ represents the perturbed wind vector instead. $\hat{f}$ is a so-called mean Doppler shift,

$$\hat{f} = \mathbf{u} \cdot \mathbf{k}/2\pi, \tag{5}$$

where $\mathbf{u}$ is the mean wind that results from solving Equation 1 or 3. To guarantee more reliable values of the six unknowns (<u'u'>, <v'v'>, <u'w'>, <v'w'>, <u'v'> and <w'w'>), the fit was performed only in those bins containing forty meteor detections or more.

From Equations 4 and 5, it follows that different momentum flux estimates may be obtained depending on the mean wind that is used to determine $\hat{f}$. In this study, the wind estimates that result from applying the gradient method were used to calculate $\hat{f}$ (see previous section). That is, Equation 3 (with $dw/dx = dw/dy = dw/dz = 0$) was introduced into Equation 1, and the latter then solved using bins of 4 hour and 8 km, shifted by 15 min in time and 1 km in altitude. Finally, Equation 4 was solved in bins of 4 hour and 4 km (in altitude), shifted by 30 min and 1 km, respectively.

4 Results and discussion

One of the main goals of this work is to provide, for the first time, information on the MLT dynamics over southern Patagonia obtained using SIMONe Argentina. For this reason, our results are discussed as they are presented.

4.1 Mean winds and tides

In Figure 3, we present the mean zonal (U_0) and meridional (V_0) winds, and the total amplitudes of the quasi two-day planetary wave (Q2DW) and the diurnal (D1), semidiurnal (S2) and terdiurnal (T3) solar tides. The vertical black dashed line indicates January 1st 2020. The term *total amplitude* refers to the magnitude of the vector sum of the corresponding zonal and meridional components of each fitted wave. The statistical uncertainties of the estimated parameters are shown in the right column panels. All quantities were obtained after applying the procedure detailed in Section 3.1. Data gaps are shown in white.

From inspection of Figure 3, two features stand out: the S2 tide is the dominant wave, with amplitudes in the order of 40-65 m/s, and the Q2DW exhibits strong enhancements after 4 January 2020. It is well known that the semidiurnal solar tide at middle latitudes dominates over all other tidal components (e.g., Andrews et al., 1987; Pancheva & Mukhtarov, 2011). Furthermore, many studies of tides in the northern hemisphere have reported that S2 decreases significantly around the onset of a sudden stratospheric warming (SSW) event, to later on recover and reach even larger amplitudes than those exhibited prior to the SSW (e.g., Chau et al., 2015; Siddiqui et al., 2018; Conte et al., 2019). In September of 2019, approximately 12 days before the 27th (first day of available data from SIMONe Argentina), a SSW event was registered in the southern hemisphere (e.g., Yamazaki et al., 2020). Interestingly enough, the largest amplitudes of S2 are seen between 27 September and 12 October, which may be an indicative of the recovery phase of S2 after the weakening associated with a SSW event. On the other hand, it is also possible that the reported enhancement of S2 is simply the result of changes in the propagation conditions of this tidal component. For example, the S2 amplitudes may change due to different responses of the symmetric and antisymmetric Hough modes to the weaker and more hemispherically symmetric mean zonal wind typical of the equinox times. Previous studies of the S2 tide at middle latitudes of the southern hemisphere have shown a decrease of S2 in the beginning of September, and a later recovery by the beginning of October (e.g., Conte et al., 2017). However, this decrease/increase behavior of S2 during the September-October months is not obvious every year. Lastly, note that for the entire dataset analyzed in this study, S2 presents significant intraseasonal variability, which becomes evident in the many, although weaker, enhancements observed after $\sim$ 31 October.

The Q2DW at middle latitudes has been reported to reach maximum amplitudes during the summer (e.g., Kumar et al., 2018). In our results, the Q2DW is active mostly in summer, in agreement with previous studies. Even more, it becomes the dominant wave by the end of January 2020, with amplitudes larger than those corresponding to S2. Offermann et al. (2011) showed that the Q2DW exhibits a triple peak structure in the NH during summer. Although it may not be obvious at first, after a more through inspection of Figure 3, it can be noticed that the largest amplitudes of the Q2DW are distributed in three subsequent enhancements, around 7, 13 and 19 January. A fourth enhancement can be seen around 9 February, but the latter is significantly weaker than the previous three.

Both the diurnal and terdiurnal solar tides exhibit considerable intraseasonal variability. In the case of D1, its activity becomes more evident mostly below $\sim$ 90 km and during summer. Above $\sim$ 92 km, and mainly during equinox times, T3 becomes more noticeable, with amplitudes similar to those corresponding to D1.

Compared to five-year average values at 54° S presented by Conte et al. (2017), the summer reversal of the mean zonal wind shown in Figure 3 is observed at altitudes approximately two km lower. This is consistent with previous studies reporting a decrease with latitude of the height of the zonal wind summer reversal (e.g., Hoffmann et al., 2010; Wilhelm et al., 2019). Besides, it might seem that U_0 starts the transition into summer conditions relatively early, around 3 October. However, above $\sim$ 92 km, U_0 experiences a late reversal to westward conditions around 24 October, to finally go into summer conditions (i.e., eastward above the mesopause) about five days later. V_0 blows mainly towards the equator, and only after 10 March poleward values start to dominate.

The statistical uncertainties of all the fitted parameters presented in Figure 3 are very small. Only above 103 km and below 77 km, values of $\sim$ 2-3 m/s are obtained (not shown). The low statistical uncertainties are a consequence of the large amount of meteor detections provided by SIMONe Argentina. By solving Equation 1 in bins of one hour and two km, one guarantees wind estimates with very low uncertainties. The latter, combined with the fact the WLS method used to solve Equation 2 is applied to a very well conditioned matrix, results in small statistical uncertainties.

4.2 Gradients and vertical wind

In Figure 4, we present one week of 4-hour, 4-km mean winds and gradients obtained after applying the procedure described in Section 3.2. The first row shows, from left to right, the mean zonal (u_0), meridional (v_0) and vertical (w_0) winds. The panels in the middle row are used to show the zonal eastward, northward and upward (first order) derivatives, i.e., u_x, u_y and u_z, respectively. The bottom row shows the same as the middle one, but for the meridional component, i.e., v_x, v_y and v_z. The mean winds are given in m/s, and the gradients in m/s/km. The mean vertical wind and the gradients

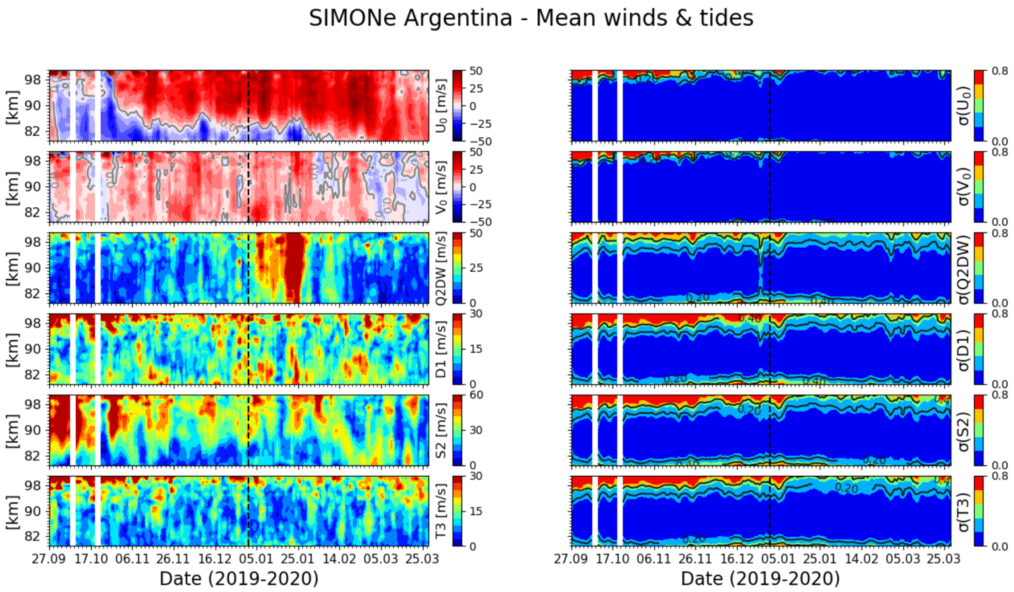

Figure 3. Mean zonal (U_0) and meridional (V_0) winds, the quasi two-day planetary wave (Q2DW), and the diurnal (D1), semidiurnal (S2) and terdiurnal (T3) solar tides during September 2019 - April 2020 over SIMONe Argentina. The corresponding statistical uncertainties (in m/s) are shown in the right column. All parameters were estimated using a four-day running window shifted by one day. The vertical black dashed line indicates January 1st 2020.

are shown only between 80 and 97 km of altitude, where the data coverage is good enough to estimate them more reliably.

Before starting the description of the main features observed in Figure 4, it is important to stress here that the variability seen in the mean winds is representative of large scale structures, with periods greater than four hours and vertical wavelengths larger than four km. Both u_0 and v_0 exhibit a clear diurnal and semidiurnal periodicity, the latter being more evident, something expected given the latitude of SIMONe Argentina. The semidiurnal periodicity is also very clear in the vertical gradients, u_z and v_z, which indicates a strong influence of the S2 tide in the vertical changes of the horizontal winds. Although they may not be evident in Figure 4, other periodicities are present in the vertical gradients. For example, GW effects can be noticed below 90 km. At these altitudes, u_z is mainly positive (with mean values in the order of 20 m/s/km). In fact, during most of the summertime, below $\sim$ 90 km of altitude, and when averaged over longer periods of time, e.g., 1 day, u_z is strongly dominated by positive amplitudes (not shown here). During the summer, westward zonal winds are dominant in the stratosphere and mesosphere. This condition allows eastward propagating GWs to easily reach mesospheric altitudes, where they break and deposit momentum and energy. This deposition of momentum creates an eastward drag that decelerates the zonal (westward) wind. Due to the Coriolis effect, the deceleration of the zonal wind introduces an equatorward meridional wind component, which in turn leads to an upward motion and a subsequent (adiabatic) cooling of the mesopause region (e.g., Smith, 2012). Finally, due to the thermal wind equation, $u_z \approx -\alpha(\phi)\partial T/\partial y$ (where y is positive towards north, T is the temperature, and α is a factor that depends on the sine of the latitude, ϕ), the adiabatic cooling results in the positive values of u_z. In the case of v_z, the amplitudes are in the order of 3-5 m/s/km weaker than those of u_z, but the semidiurnal periodicity is seen at all altitudes. No evident pattern or structure in time can be noticed when v_z is averaged over longer periods of time.

In the case of u_x and v_x, amplitude values are in the order of 0.1-0.3 m/s/km. The larger amplitudes of u_y (compared to u_x) may be an indicative of zonal wind latitudinal changes related to the Antarctic polar vortex, part of which usually locates below the region seen by SIMONe Argentina (e.g., Figure 8 in Orte et al. (2019)). The upward component of the relative vorticity can be coarsely approximated by $v_x - u_y$ (for a precise calculation, one needs to include the latitude information; see Equation A16 in Chau et al. (2017)). Below $\sim$ 84 km, $v_x - u_y$ values are mainly positive, which suggests counterclockwise vortical effects. Besides, differences between the amplitudes of u_y, v_x and u_x, v_y, suggest that changes in the horizontal gradients due to GWs depend on the propagation direction of the these waves.

The errors in both the horizontal and vertical gradients are in the order of 5-10 %. For example, for the week of data shown in Figure 4, the root mean square errors of u_x, u_y, u_z, v_x, v_y, and v_z are 0.011, 0.023, 1.1, 0.022, 0.013, and 0.99 m/s/km, respectively.

Previous observational studies have investigated the horizontal gradients in the zonal and meridional winds (e.g., Conde & Smith, 1998; Meriwether et al., 2008; Chau et al., 2017). However, the present study is the first one to show results on both the horizontal and vertical gradients of MLT horizontal winds over southern Patagonia. Chau et al. (2017) showed that horizontal divergence values of $\sim$ 0.1 m/s/km are large enough to introduce a mean apparent vertical wind of 1-2 m/s. After calculating $u_x + v_y$, one obtains values in the order of 0.4-0.5 m/s/km. Consequently, one can now understand the importance of estimating the vertical wind together with the gradients. By doing so, one eliminates the effects of biases introduced in w_0 by the mean horizontal variability of u and v. However, the horizontal variability within scales smaller than the observed volume is not removed, and will affect the vertical wind estimates.

The four-hour mean vertical winds (w_0) exhibit large amplitudes and considerable variability both in time and height. The errors in these estimates are in the order of 1-2 m/s. After computing daily averages, vertical wind amplitudes are reduced to a few m/s, which are still considerably large values. Previous studies have investigated MLT mean vertical winds using specular meteor radars. For example, Babu et al. (2012) and Egito et al. (2016) reported that the vertical winds at low latitudes may reach magnitudes of 6-10 m/s. Using VHF radar measurements, Fritts et al. (1990) observed that at summer mesopause altitudes vertical velocities may reach values of up to 10 m/s, but within time scales of 5-30 minutes. That is, vertical winds should exhibit values in the order of a few to tens cm/s when averaged over periods of 1 day or more (e.g., Lu et al., 2017).

There are several factors that adversely affect our vertical wind estimates. (1) The daily variability in the meteor counts (meteor detections maximize early in the morning and minimize in the evening) can result in irregular time sampling at altitudes where the detections are lower, i.e., above 97 km and below 80 km, in the case of SIMONe Argentina. For this reason, we have limited our analysis of w_0 to altitudes between 80 and 97 km. (2) Despite the multistatic configuration, sometimes the meteor detections are not well distributed among all five links. This affects in a similar way every altitude observed by SIMONe Argentina. (3) Small-scale horizontal variability is not removed after applying the gradient method. Hence, horizontal changes of the zonal and meridional winds occurring within the observed volume can easily leak into the vertical winds, and thus result in the large w_0 values presented in Figure 4. To better understand and quantify the adverse impact of points (2) and (3), we are currently working in applying the gradient method to forward modelled data using different geometric configurations. This will shed light on the reliability of the vertical winds presented in this study as well as other studies using multistatic SMR configurations.

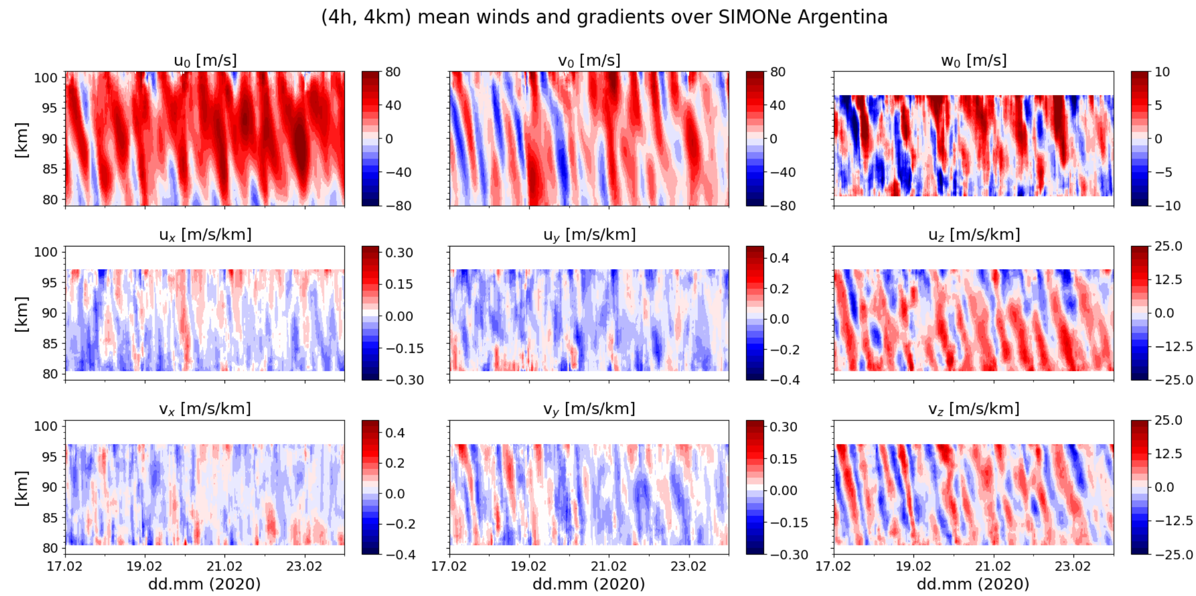

Figure 4. SIMONe Argentina estimates of: (first row) mean zonal (u_0), meridional (v_0) and vertical (w_0) winds; (second row) zonal eastward (u_x), meridional (u_y) and upward (u_z) derivatives; (third row) meridional eastward (v_x), northward (v_y) and upward (v_z) derivatives. All parameters were estimated using a 4 hour, 4 km (in vertical) bin, shifted by 15 min and 1 km, respectively.

Despite the large amplitudes, coherent phase structures can be seen in w_0. For example, around 17 February one can observe a clear diurnal periodicity. Diurnal wave signatures in w_0 have been found throughout the entire SIMONe Argentina dataset (not shown). Moreover, similar features have been observed in the mean vertical winds over Peru and northern Germany (Chau et al., 2020; Charuvil Asokan et al., 2020). Hence, it is possible that our results on w_0 are also revealing real geophysical features, e.g., diurnal tidal effects. This will be carefully investigated in future studies.

4.3 Gravity-wave-driven momentum flux

We now present and discuss the momentum flux estimates obtained after subtracting the mean winds calculated following the gradient method, i.e., the u_0, v_0 and w_0 that were estimated together with the gradients. In Figure 4, it can be seen that the horizontal wind gradients and the vertical mean wind exhibit considerable variability, both in time and altitude. Part of this variability is leaked into the mean horizontal winds when one solves Equation 1 without including the gradients and w_0 in the wind vector $\mathbf{u}$. This implies that the u_0 and v_0 obtained using the gradient method constitute a better representation of the real mean wind, provided that enough meteors are detected in order to accomplish a robust wind estimation. Besides, it is important to have in mind that the subtracted winds were estimated in bins of 4 hour and 8 km (in altitude). This means that the corresponding momentum flux estimates are representative mostly of waves with temporal and vertical scales of less than 4 hour and 8 km, respectively.

In Figure 5, we present 28-day averages of the momentum flux estimates that result from subtracting the $\hat{f}$ that was calculated using the u_0, v_0, w_0 mentioned in the previous paragraph (see Equation 4). The averages were calculated over 28 days in order to obtain estimates that are statistically more significant. The upper panels present U and V, which correspond to the 28-day averages of the mean zonal and meridional winds, respectively. The middle panels are used to show the 28-day mean horizontal momentum vertical fluxes, <u’w’>, <v’w’>. The statistical uncertainties of <u’w’> and <v’w’>, i.e., σ(u’w’) and σ(v’w’), respectively, are shown in the bottom panels.

Momentum flux estimations based on SMR observations were first presented by Hocking (2005). Since then, several studies have investigated momentum fluxes using meteor radar winds (e.g., Fritts et al., 2010; Placke et al., 2011b; Fritts et al., 2012b; Andrioli et al., 2013; Placke et al., 2015, and references therein). More recently, de Wit et al. (2016) observed a modulation by the quasi-biennial oscillation (QBO) of the momentum fluxes over Tierra del Fuego, an island south of Santa Cruz province. Typical amplitudes of <u’w’> and <v’w’> reported in these previous studies rarely reach values larger than 60-70 m^2/s^2. Using a multistatic meteor radar network over southern Australia, Spargo et al. (2019) observed values for <u’w’> and <v’w’> in the order of 40-60 m^2/s^2, which are larger than momentum flux absolute values obtained from satellite measurements (e.g., Ern et al., 2011; Trinh et al., 2018). The latter is most likely due to observational filtering inherent to satellites.

From Figure 5, it can be seen that our momentum flux estimates have amplitudes in the order of 25-45 m^2/s^2. Some large amplitudes of about 90 m^2/s^2 can be observed above 96 km of altitude, where the corresponding statistical uncertainties are in the order of 10 % or more (see bottom panels). Both momentum flux estimates exhibit variability in time and height, although it is more evident in the case of <u’w’>. Notice that despite the 28-day averaging, the magnitudes of <u’w’> and <v’w’> are considerable throughout the entire period of time analyzed in this study. Momentum flux estimates averaged over 20 days presented by Placke et al. (2015) exhibit maximum amplitudes of 6-8 m^2/s^2 during the summer of the northern hemisphere. The largest amplitudes of ten-day momentum flux estimates shown by Spargo et al. (2019) reach values of 30-40 m^2/s^2 in the beginning of the spring of the southern hemisphere. On the other hand, de Wit et al. (2017) observed monthly mean momentum fluxes over Tierra del Fuego with amplitudes larger than 70 m^2/s^2 during the summer. These amplitude values are in the same order as those obtained in our study. Hence, it is clear that the wave activity in the MLT region over the Patagonian sector is very strong. This is also consistent with previous studies based on satellite measurements (e.g., Ern et al., 2011), and numerical simulations (e.g., Lund et al., 2020).

As GWs propagate upwards, they transfer momentum and energy into the mean flow. Consequently, a decrease in the vertical flux of zonal momentum should correspond with an increase in the zonal wind speed (e.g., Fan et al., 1991). In other words, a decrease of the momentum flux indicates that a wave drag has been introduced into the mean flow, thus triggering an acceleration of the zonal wind. Our results are consistent with this reasoning, since for altitudes below 90-92 km, <u’w’> amplitudes, which are mostly positive, exhibit a clear vertical gradient: as the altitude increases, they progressively decrease from values of around 70-75 m^2/s^2 below 82 km, to values of $\sim$ 10 m^2/s^2 above 90 km. The latter is also consistent with the results on u_z presented in the previous section. Besides, note that after 22 February, negative values of <u’w’> start to develop below 90-91 km. At that time of the year, U has become eastward at all altitudes observed by SIMONe, a condition that allows westward propagating GWs to reach higher altitudes and, most likely, induce the aforementioned <u’w’> negative values.

In the case of <v’w’>, an upward movement of southward momentum dominates mostly below $\sim$ 91 km, from the beginning of October until the end of March. During the last week of December 2019, positive values of <v’w’> start to dominate above 92-94 km, an altitude range that had been dominated by negative values of <v’w’> since the beginning of November 2019. During the latter, and approximately above 96 km of altitude, an upward movement of eastward momentum can be noticed again. These positive values of <u’w’> develop very abruptly around 26 November, and remain dominant above 96 km for more than 25 days. We wonder if this might be an indicative of eastward momentum deposition by GWs that were in-situ generated at altitudes above 90 km.

Momentum flux estimates obtained after subtracting the mean winds determined with the homogeneous method were also analyzed (not shown). In this case, only the 4-hour, 8-km mean horizontal winds are used to determine $\hat{f}$ (see Equation 5). These momentum flux estimates have similar amplitudes to those presented in Figure 5. However, they exhibit some differences in their variability in time and altitude, and their statistical uncertainties are larger than those shown in Figure 5. It is for the latter and for consistency reasons, that the present study has been focused on analyzing the momentum fluxes that result from subtracting the mean horizontal and vertical winds obtained after applying the gradient method.

To finalize, we discuss the procedure followed to estimate σ(u’w’) and σ(v’w’), and the reason for calculating 28-day averages. Unless one knows with some degree of certainty that a given wave event has occurred, the effects of GWs should be treated as stochastic processes. In other words, the mean momentum flux estimates are highly dependent on the effects of geophysical variability. Kudeki and Franke (1998) showed that in order to obtain statistically significant momentum flux estimates at mesospheric heights, one must consider averaging intervals of more than 25 days. Specifically, they found that the statistical uncertainty of <u’w’> can be approximated with:

$$\sigma(u'w') = \sqrt{\frac{(< u'u' >)(< w'w' >)}{T/\tau}}, \tag{6}$$

where, <u’u’> and <w’w’> are averaged over the interval of time T; and τ is equal to half of the mesosphere Brunt-Väisälä period ($\sim$ 7 min). σ(v’w’) is obtained using same Equation 6, but replacing <u’u’> by <v’v’>. Selection of an averaging window T = 28 days resulted in the values presented in Figure 5. In this way, the <u’w’> and <v’w’> obtained from our study must be understood as representatives of a monthly mean momentum flux due to waves with periods of 4 h or less, and horizontal scales less than 400 km. Besides, for those estimates corresponding to altitudes lower than $\sim$ 98 km, statistical uncertainties between 2 and 15-16 m^2/s^2 should be taken into consideration.

The momentum flux estimates are also affected by the correlated Doppler shift errors. In other words, because the Doppler shift uncertainties are squared when introduced into Equation 4, the resulting momentum flux estimates are in fact an overestimation of the real <u’w’> and <v’w’> (Vierinen et al., 2019). However, given that the error propagated Doppler shift uncertainties we obtained are small ($\sim$ one order of magnitude smaller than the statistical uncertainties) and that the amplitudes of <u’w’> and <v’w’> are large, the effects of the correlated errors were neglected in this study. We plan to further investigate this issue by extending our analysis to include non-zero lag second-order statistics of the wind velocities.

5 Concluding remarks

The first multistatic meteor radar based studies of mean winds, tides, gradients and momentum flux over the southern part of Patagonia have been presented in this paper. By doing this, we have demonstrated the ability of SIMONe Argentina to obtain not only information on typical MLT parameters such as mean winds and tides, but also to successfully estimate previously little investigated parameters, such as horizontal and vertical gradients of the horizontal winds. Using the latter, one can estimate, e.g., the horizontal divergence and the relative vorticity, parameters from which global circulation models can benefit and in this way help to further the understanding of MLT dynamics.

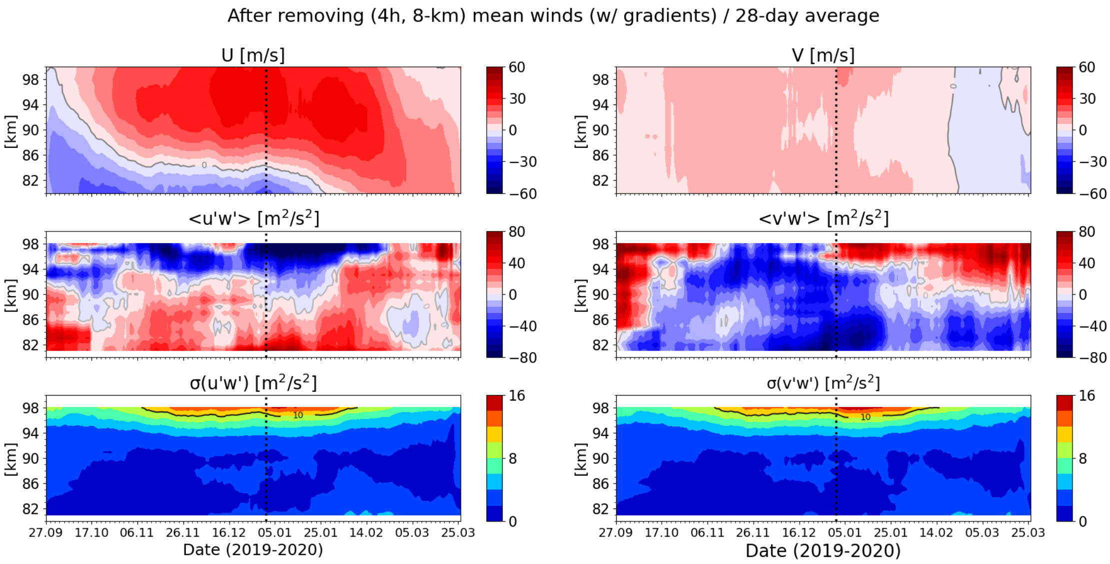

Figure 5. 28-day averages of 4-h, 8-km mean zonal and meridional winds (U and V, respectively), horizontal momentum vertical fluxes (<u'w'>, <v'w'>) and their corresponding statistical uncertainties (σ(u'w'), σ(v'w')). 4 hour, 8 km (in altitude) mean horizontal and vertical winds estimated in combination with the gradients (i.e., the u_0, v_0, w_0 described in Section 3.2) were subtracted before estimating the momentum flux. The vertical black dashed line indicates 1 January 2020.

Our results show a strong positive vertical gradient in the zonal wind during the summer, in agreement with the residual mean meridional circulation. Besides, the northward zonal gradient (u_y) is stronger than the eastward zonal gradient (u_x), which indicates latitudinal changes of the zonal wind most likely due to the influence of the southern hemisphere polar vortex. Mean vertical winds (w_0) have also been estimated, but only when the horizontal and vertical gradients were taken into account.

Momentum fluxes, <u'w'> and <v'w'>, have been estimated after removal of horizontal and vertical mean winds that were fitted together with the horizontal wind gradients. Compared to some previous studies, our momentum flux estimates exhibit larger amplitudes, which indicates that the GW activity in the MLT over southern Patagonia is very strong. The statistical uncertainties of <u'w'> and <v'w'> were also included in the analysis. The latter revealed that in order to have statistically significant momentum flux estimates, one should consider averages of at least 28 days. In this way, our results must be considered as representative of monthly mean momentum fluxes, driven by waves with periods shorter than 4 hours, vertical wavelengths shorter than 8 km, and horizontal scales less than 400 km.

We are confident that SIMONe Argentina has also the potential to investigate nonzero lag second-order statistics of MLT wind velocities, e.g., by using correlation function techniques such as those presented in Vierinen et al. (2019). This will be explored in future studies. Besides, we also plan to investigate momentum flux estimates without averaging over long periods of time, provided there is evidence of specific (deterministic) wave events occurring in the troposphere/stratosphere.

Acknowledgments

We deeply thank Nico Pfeffer, Matthias Clahsen, Jens Wedrich and Thomas Barth (at IAP) for their invaluable help and expertise during the installation of SIMONe Argentina; and Jonathan Quiroga and Nahuel Díaz (CONICET) for helping with the logistics prior to the installation. We would also like to thank Darío Godoy and Facundo Olivares (at Tres Lagos); Pablo Quiroz (at La Estela); Martín "el griego" Palopoli and National Parks staff (at El Chaltén); the Consejo Agrario de la Provincia de Santa Cruz (at Gob. Gregores and El Calafate); and the BAM-GAL (Argentina Air Force) for their support and help in maintaining the sites.

We thank Dr. Xinzhao Chu for her useful and constructive comments, which have helped us to improve our work.

This work was partially supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under SPP 1788 (DynamicEarth) CH 1482/2 (DYNAMITE2), and by the Bundesministerium für Bildung und Forschung via project WASCLIM-IAP part of the ROMIC-II program.

The data used to produce the figures is available in HDF5 format at DOI: 10.22000/342.

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