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Paola Rodriguez Imazio

`pimazio@smn.gob.ar`

National Meteorological Service

Florencia Falkinhoff

Max Planck Institute for Dynamics and Self-Organization

Alejandro Godoy

National Meteorological Service

Florencia Zapata

Max Planck Institute for Dynamics and Self-Organization

Eugenia Garbarini

National Meteorological Service

Denise Auzmendis

National Meteorological Service

Ghloamhossein Bagheri

Max Planck Institute for Dynamics and Self-Organization

Eberhard Bodenschatz

Max Planck Institute for Dynamics and Self-Organization

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Multiscale structure and evolution of an intense atmospheric river connecting Patagonia and the Antarctic Peninsula

Paola Rodriguez Imazio^{1,2*}, Florencia Falkinhoff^{3†},
Alejandro Godoy^{1†}, Florencia Zapata^{3†}, Eugenia Garbarini¹,
Denise Auzmendis¹, Ghloamhossein Bagheri³,
Eberhard Bodenschatz^{3,4,5†}

¹SMN, Servicio Meteorológico Nacional, Dorrego 4019, CABA,
C1425EGA, Buenos Aires, Argentina.

²CONICET, Consejo Nacional de Investigaciones Científicas y
Técnicas, , CABA, C1425EGA, Buenos Aires, Argentina.

³Max Planck Institute for Dynamics and Self-Organization, Am
Faßberg 17, Göttingen, 37077, Lower Saxony, Germany.

⁴Institute for Dynamics and Complex Systems, Georg August University
of Göttingen, Friedrich-Hund-Platz 1, Göttingen, 37077, Germany.

⁵Laboratory of Atomic and Solid State Physics, Cornell University,
Clark Hall of Science, Ithaca, 14853, USA.

*Corresponding author(s). E-mail(s): pimazio@smn.gob.ar;

Contributing authors: florencia.falkinhoff@ds.mpg.de;

agodoy@smn.gob.ar; florencia.zapata@ds.mpg.de;

eberhard.bodenschatz@ds.mpg.de;

†These authors contributed equally to this work.

Abstract

We investigate an intense atmospheric river connecting southern Patagonia and the Antarctic Peninsula on 28–29 March 2026 using reanalysis, forecasts, high-cadence radiosondes, and two five-sonde grid deployments during the AR-LAMDA-S campaign. Enhanced integrated vapor transport occurred first at Ushuaia and approximately one day later at Base Marambio. At Ushuaia, the local moisture-transport proxy $Q = \mathbf{q}|\mathbf{V}|$ identified an elevated transport layer, mainly between 2 and 3 km MSL, that persisted for approximately 8–10 h. The

layer briefly weakened before intensifying and shifting upward, reaching 120–140 $\text{g kg}^{-1} \text{ m s}^{-1}$. The multisonde deployments revealed changes in its vertical extent, shear environment, and spatial variability. A downstream radiosonde at Marambio sampled another pronounced transport maximum near 2 km within an ice-supersaturated layer. These observations reveal substantial spatiotemporal reorganization within a coherent synoptic-scale moisture-transport corridor.

Keywords: Atmospheric River, Antarctic Peninsula, Moisture transport, Polar Meteorology

1 Introduction

Atmospheric rivers (ARs) act as efficient corridors of heat and moisture transport from lower latitudes toward Antarctica [1–3]. These narrow and elongated regions of enhanced water-vapor transport can substantially increase total-column moisture and play an important role in the Antarctic hydrological cycle and surface mass balance. Although enhanced snowfall remains one of their major present-day impacts, Antarctic ARs are also associated with extreme precipitation, changes in cloud and precipitation phase, surface melting, sea-ice disruption, and ice-shelf destabilization [2, 4–9]. The Antarctic Peninsula (AP) is particularly exposed to these intrusions, where ARs can contribute to intense warming, rainfall, widespread melting, and compound high-impact events [5, 8, 10–12].

Antarctic ARs are embedded within circulation patterns that connect synoptic and planetary scales. They commonly occur within amplified trough–ridge and surface low–high pressure configurations that promote strong poleward transport, and the most intense events can be associated with Rossby-wave activity extending from lower latitudes [2, 13]. Over the AP sector, anomalous cyclonic circulation over the Bellingshausen Sea and anticyclonic or blocking circulation near or east of the Drake Passage can favor northerly or northwesterly moisture transport toward the Peninsula [10, 12–14]. Recent work has also shown that large-scale circulation anomalies can simultaneously affect southern Patagonia and the AP, providing a dynamical connection between the two regions [15]. This places the southern South America–Drake Passage corridor in a key position for observing the upstream or gateway stage of ARs that subsequently affect the northern and western AP.

The large-scale identification of an AR, however, does not by itself determine its local atmospheric impact. In particular, stronger column-integrated moisture transport does not necessarily correspond to stronger precipitation. Recent studies show that the most precipitation-intensive Antarctic AR environments are distinguished more clearly by amplified synoptic-scale circulation and enhanced vertical motion than by larger local vertically integrated moisture anomalies [13]. In addition, AR geometry and orientation can evolve substantially during their life cycle. Other recent Antarctic studies have highlighted curved, zonal, meridional, and reversing moisture-transport pathways and have shown that directional or geometric constraints can obscure physically coherent AR structures [12, 16]. Over the AP, AR shape, direction, landfall

location, duration, and vertical profile can influence how the incoming flow interacts with the complex topography and thereby modulate its regional effects [12]. These findings emphasize that ARs should be considered not only in terms of integrated vapor transport (IVT), widely used to characterize ARs, but also as dynamically and geometrically structured transport systems.

An additional and comparatively poorly constrained dimension is their vertical structure. Column-integrated diagnostics such as IVT are well suited to identifying AR corridors and following their synoptic-scale evolution, but they do not identify where within the atmospheric column the transport is concentrated. Radiosonde observations have shown that Antarctic ARs can exhibit vertically displaced humidity maxima, low-level jets, humidity inversions, and enhanced moisture transport concentrated within particular tropospheric layers [7, 17]. More broadly, the three-dimensional structure and propagation of Antarctic ARs remain substantially less studied than their horizontal and column-integrated characteristics [17]. This observational limitation is especially important at high southern latitudes, where routine in situ measurements remain sparse over Antarctica and the surrounding Southern Ocean, and where additional radiosonde observations have been shown to improve atmospheric analyses and forecasts [18–20].

Existing studies therefore provide increasingly detailed descriptions of Antarctic AR climatology, synoptic dynamics, geometry, and vertical structure, but observations resolving how the local moisture-transport layer evolves on hourly time scales remain rare. Individual operational radiosondes provide detailed vertical profiles but only limited temporal sampling, while reanalyses and numerical models cannot directly resolve the small-scale variability encountered by multiple drifting in situ platforms. In particular, there is little direct observational information connecting a synoptically identified AR with both the temporal evolution and the spatial coherence of its local vertical moisture-transport structure as it passes through the southern Patagonia–Drake Passage gateway.

Here we examine the vertical and spatio-temporal structure of an intense atmospheric-river event that connected southern Patagonia, the Drake Passage, and the northern AP on 28–29 March 2026. The event was sampled in Ushuaia, Argentina, during the Antarctic Rivers and Lagrangian Atmospheric Multisonde Dispersion Analysis–South (AR-LAMDA-S) campaign. For this event, the observing strategy combined operational radiosondes, high-cadence lightweight-sonde profiles, and two simultaneous five-sonde grid deployments, complemented by reanalysis, satellite imagery, numerical forecasts, and an operational radiosonde observation at Base Marambio during the downstream stage of the event.

This combination allows us to examine three complementary aspects of the event: (i) the large-scale evolution of the AR from southern Patagonia toward the AP; (ii) the vertical and temporal evolution of the layer carrying the strongest local moisture transport over Ushuaia, together with its downstream vertical structure at Base Marambio; and (iii) the spatial coherence and kinematic structure of this layer as sampled by the multisonde deployments. In this way, the observations connect the synoptic-scale identification of the AR with vertically organized moisture transport sampled at successive stages of its passage through the southern Patagonia–Drake Passage gateway toward the northern AP.

The manuscript is organized as follows. Section 2 describes the observational dataset and sampling strategy, Section 3 presents the synoptic, surface, vertical, and multisonde results, Section 4 discusses their broader implications, and Section 5 details the calculation and processing methods used throughout the study.

2 In situ data

All measurements analyzed in this study were collected in the context of the Antarctic Rivers and Lagrangian Atmospheric Multisonde Dispersion Analysis–South (AR-LAMDA-S) campaign. The campaign was performed at the station VAG-Ushuaia, a World Meteorological Organization’s designated Global Atmosphere Watch site (GAW, WMO) located within the Ushuaia airport area, in Argentina. This location places the observing site in the gateway region between the Southern Ocean, southern South America, the Drake Passage, and the AP (Fig. 1a,b). The measurement strategy was designed to characterize both the local vertical and Lagrangian structure of moisture transport and the larger-scale thermodynamic and kinematic environment associated with the event.

The intensive observing period on 28 March 2026 included two types of radiosonde observations. The first type consisted of small lightweight sondes, the Windsonde S2H2 (SparvEmbedded) [21], referred to here as “Smarties”. These sondes have a mass of approximately 8.2 g and a length of 14.5 cm. They were released with small biodegradable 20 g weather balloons filled with 70 L of helium. Their low mass and small helium requirement make them suitable for short-range, high-cadence profiling. During the event, this configuration made it possible to perform hourly launches and two five-sonde grid deployments.

The second observing system consisted of operational Vaisälä RS41-SGP radiosondes. These radiosondes provide reference meteorological profiles through a deeper atmospheric column, reaching up to approximately 30 km. These sondes use approximately 3 m³ of helium per launch. The closely related Sparv Windsonde S1H2 has previously been intercompared with the Vaisala RS41-SGP under severe weather conditions, showing broadly comparable thermodynamic and wind measurements when sampling similar atmospheric volumes [21]. The S2H2 version used here differs primarily through an improvement in GNSS connectivity.

Figure 1 shows the observational setting of the campaign. Panel (a) shows the regional position of Ushuaia, southern Patagonia, the Drake Passage, and Base Marambio on the northern AP. Panel (b) shows the local setting of Ushuaia on Tierra del Fuego and the Beagle Channel, and panel (c) shows the detailed configuration of the Smartie launch sites, the VAG station, and the operational Ushuaia Aero station.

For the grid measurements, five Smarties were simultaneously launched from nearby locations around the Ushuaia observing site, with a mean separation between launch points of approximately 200 m. This sampling strategy provides a local launch-array view of the vertical structure of the event, complementing the hourly sequence of individual profiles and the deeper operational radiosonde soundings.

Because the VAG station is located within the Ushuaia airport area, the launch strategy was implemented under operational safety constraints. The observing plan

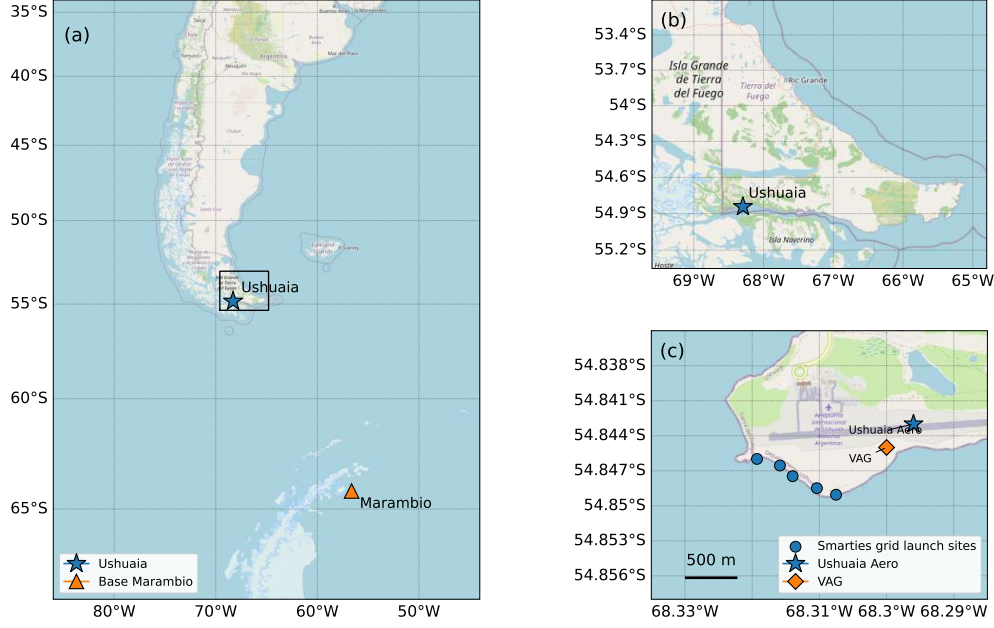


Fig. 1: Regional and local configuration of the AR-LAMDA-S observing sites in southern Patagonia and the Antarctic Peninsula. (a) Regional location of Ushuaia, southern Patagonia, the Drake Passage, and the northern AP. (b) and (c) Local configuration of the launch sites near the VAG station at Ushuaia airport and along the coast of the Beagle Channel. Markers indicate the Smarties launch positions used for the grid deployments and the operational radiosonde launch location. Background shading shows the local terrain and coastline from the base map.

consisted of approximately hourly launches of lightweight sondes and two grid deployments of five sondes each during the forecasted period of strongest AR influence. This strategy was successfully carried out, although individual launch times had to be coordinated with airport activity and were occasionally adjusted according to aircraft operations, surface wind direction, and the risk of balloon drift toward the runway. The resulting dataset therefore reflects the planned high-cadence and grid sampling strategy as implemented under real operational constraints. In the analysis, the actual launch positions and times are used for all profile, grid, and trajectory diagnostics.

In addition, surface meteorological observations from VAG-Ushuaia and Base Marambio observing sites are used to characterize the near-surface expression of the event at the upstream and downstream locations, respectively. The VAG-Ushuaia (which also includes Ushuaia aero) provides the surface temperature, relative humidity, wind speed, and precipitation records used here. Base Marambio provides the corresponding long-term operational surface record for the northern AP sector. These records are used both to describe the event evolution during 27–31 March 2026 and to compute the late-March historical reference ranges and percentiles.

Figure 2 shows the temporal distribution of the launches. The two shaded intervals indicate the grid deployments: Grid 1 at around 18:30 UTC, and Grid 2 at around 21:05 UTC. For the time–height analysis, each five-sonde grid is represented by its mean profile, while the individual grid members are retained for the grid-scale variability analysis. With this treatment, the intensive observing period provided representative vertical sampling approximately every hour, with a mean separation of about 63 min between launches. After removal of duplicated or incomplete Smarties profiles, the final representative sequence comprised 21 soundings, including 18 Smartie launches and three operational Väisälä radiosondes. The three operational Väisälä radiosondes were launched at approximately 15:02, 17:59, and 21:55 UTC. The intensive observing sequence, comprising 21 balloon launches including two five-sonde Smartie deployments, is detailed in Supplementary Table S1.

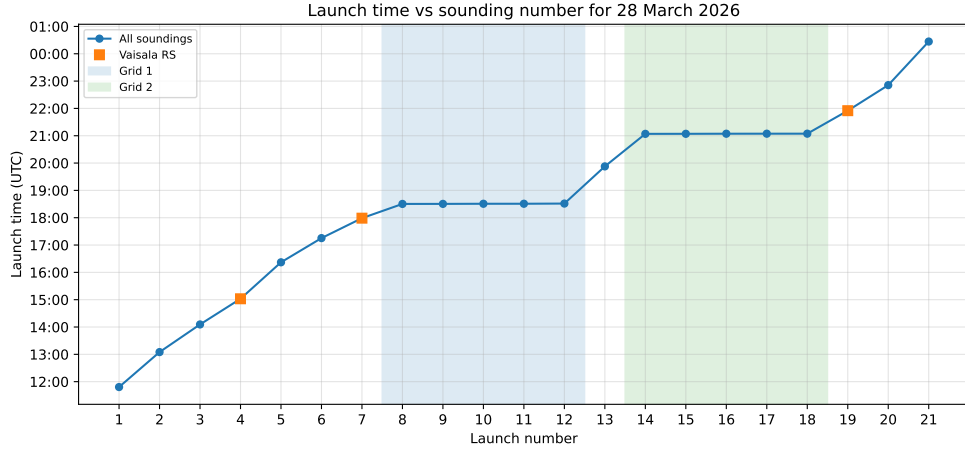


Fig. 2: Launch sequence during the 28 March 2026 intensive observing period at Ushuaia. Blue circles indicate the representative sounding sequence, including individual Smarties profiles, operational Väisälä radiosondes, and the grid-mean profiles used in the time–height analysis. Orange squares mark the operational Väisälä radiosonde launches. Shaded intervals indicate the two five-sonde Smarties grid deployments: Grid 1 around 18:30 UTC and Grid 2 around 21:05 UTC.

3 Results

The following sections analyze the event using complementary diagnostics of its large-scale, vertical, thermodynamic, and kinematic structure. Synoptic-scale moisture transport is characterized by IVT derived from ERA5 and the numerical forecasts [Eq. 1], together with observation-based IVT computed from the radiosonde profiles [Eq. 2]. The vertically resolved moisture-transport structure is examined using the local proxy $Q = q|\mathbf{V}|$ [Eq. 5], which is used to identify the altitude, intensity, and

spatio-temporal evolution of the strongest transport layer. Potential temperature θ , equivalent potential temperature θ_e , horizontal vector wind shear S [Eq. (7)], and relative humidity with respect to liquid water and ice [Eq. (11)] provide the thermodynamic and kinematic context of this layer. The calculation and processing procedures for all diagnostics are detailed in Section 5.

3.1 Synoptic/mesoscale context

Figure 3 shows the temporal evolution of integrated vapor transport (IVT) at VAG-Ushuaia and Base Marambio from 27 to 30 March 2026. At Ushuaia, WRF-SMN forecasts initialized at 00 UTC on 26, 27, and 28 March are compared with ERA5 and IVT estimates derived from operational Väisälä radiosondes and Smartie profiles. Of the 18 Smartie launches, 16 satisfied the vertical-coverage criterion described in Section 5: six were analyzed individually and ten formed the two five-sonde grid deployments. Complete and partial individual profiles are distinguished in the figure, while the grids are represented by their grid-mean IVT and within-grid variability. At Marambio, the corresponding comparison uses AMPS-WRF forecasts initialized at 00 UTC on 26, 27, and 28 March, ERA5, and the operational Väisälä radiosonde estimate.

At VAG-Ushuaia, ERA5 shows a progressive increase in IVT during 28 March, reaching a maximum of $508.7 \text{ kg m}^{-1} \text{ s}^{-1}$ at 21 UTC. AR conditions, defined by $\text{IVT} \geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$, persisted for 24 consecutive hours, from 03 UTC on 28 March to 02 UTC on 29 March, corresponding to an AR2 event according to Ralph et al. [22]. The three Väisälä estimates obtained on 28 March range from 362.9 to $387.2 \text{ kg m}^{-1} \text{ s}^{-1}$, while the complete individual Smartie estimates range from 327.7 to $404.2 \text{ kg m}^{-1} \text{ s}^{-1}$. The grid-mean IVT values for the two Smartie grids were 383.1 ± 32.5 and $383.1 \pm 23.1 \text{ kg m}^{-1} \text{ s}^{-1}$, respectively, close to the Väisälä estimates obtained at nearby times. Smartie sonde launched at 19:52 UTC (ID 16230, see Supplementary Table S1) produced a higher value of $434.2 \text{ kg m}^{-1} \text{ s}^{-1}$, but is classified as partial because of an internal gap in the profile. Taking these radiosonde-derived IVT estimates as an observational reference, ERA5 is broadly consistent with the in situ estimates, although its maximum later in the day is larger than the values sampled by the radiosondes.

The three WRF-SMN forecasts initialized at 00 UTC on 26, 27, and 28 March reproduce the overall increase and subsequent decrease in IVT, although the magnitude and timing of the maximum vary among initializations. The 26 and 28 March forecasts underestimate the ERA5 peak, whereas the 27 March initialization reaches a comparable intensity but anticipates the maximum by approximately 6 h. Nevertheless, all three forecasts identify 28 March as the main period of enhanced moisture transport over Ushuaia, coincident with the intensive sounding sequence.

At Base Marambio, the IVT increase occurs later, on 29 March. ERA5 reaches a maximum of $399.4 \text{ kg m}^{-1} \text{ s}^{-1}$, while polar AR conditions, defined by $\text{IVT} \geq 100 \text{ kg m}^{-1} \text{ s}^{-1}$, persist from 05 to 16 UTC. According to the polar extension of the AR scale proposed by Zhang et al. [23], the event is classified as AR P3. The three AMPS-WRF forecasts initialized at 00 UTC on 26, 27, and 28 March reproduce the

timing of the event but generally underestimate its maximum intensity. The operational radiosonde estimate lies close to the ERA5 peak, showing that the Marambio sounding sampled the downstream Antarctic stage of the event. Here, it should be noted that ERA5 assimilates operational RS launches from Base Marambio (routinely released at 12 UTC).

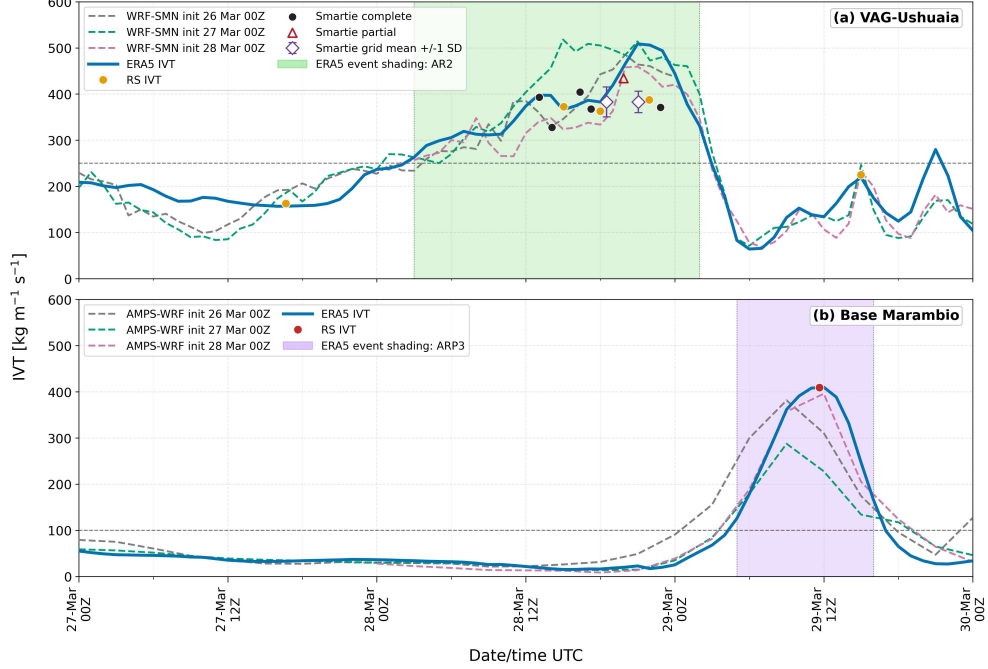


Fig. 3: Evolution of integrated vapor transport at Ushuaia and Base Marambio during 27–30 March 2026. Time series of integrated vapor transport (IVT) at (a) VAG-Ushuaia and (b) Base Marambio from 27 to 30 March 2026. Dashed lines show WRF-SMN forecasts at Ushuaia and AMPS-WRF forecasts at Marambio for initializations at 00 UTC on 26, 27, and 28 March, while thick blue lines show ERA5 IVT. Orange and red circles indicate IVT derived from Väisälä radiosondes at Ushuaia and Marambio, respectively. At Ushuaia, black circles denote complete Smartie profiles reaching 300 hPa, whereas the open red triangle denotes a partial profile. Purple diamonds show the grid-mean IVT for the two five-sonde grid deployments, with error bars indicating ± 1 standard deviation of the individual IVT magnitudes. For Ushuaia, AR classification follows the global IVT-based scale of Ralph et al. [22]; for Base Marambio, the Antarctic AR classification follows the polar-adapted scale of Zhang et al. [23].

Taken together, the two time series show a clear upstream-downstream phasing, with enhanced IVT occurring first at Ushuaia during the AR-LAMDA-S intensive observing period and approximately one day later at Base Marambio. The shaded

AR categories are used only as site-specific intensity references and should not be interpreted as a direct comparison between the two locations.

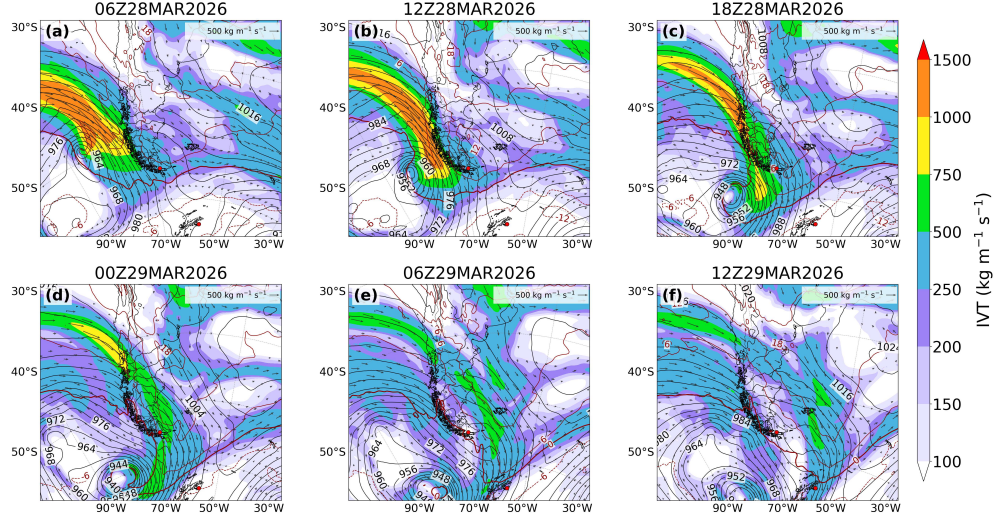


Fig. 4: Six-hourly ERA5 evolution of integrated vapor transport (IVT) during the 28–29 March 2026 atmospheric-river event. Shading shows IVT magnitude ($\text{kg m}^{-1} \text{s}^{-1}$), and black contours show mean sea-level pressure. Panels show (a) 06 UTC 28 March, (b) 12 UTC 28 March, (c) 18 UTC 28 March, (d) 00 UTC 29 March, (e) 06 UTC 29 March, and (f) 12 UTC 29 March. The sequence shows the development and poleward progression of a coherent moisture-transport corridor from the southeast Pacific across southern Patagonia and the Drake Passage toward the northern AP.

Figure 4 shows the six-hourly ERA5 evolution of integrated vapor transport (IVT) magnitude and direction, mean sea-level pressure, and 850-hPa temperature from 06 UTC on 28 March to 12 UTC on 29 March 2026 (Figs. 4a–f). At the beginning of the period (Fig. 4(a)), a corridor of enhanced IVT extended from the southeast Pacific toward Patagonia, with the largest values over the ocean west of the continent. Over the following 18 h (Figs. 4(a–d)), the cyclone west of Patagonia deepened and moved toward the Drake Passage sector. The moisture corridor was organized along its eastern flank, within a region of strong pressure gradient. The IVT vectors indicate initially southeastward transport, with an increasingly pronounced southward component near the southern tip of South America. Between 18 UTC on 28 March and 00 UTC on 29 March (Figs. 4(c,d)), the southern portion of the corridor became predominantly meridional, connecting southern Patagonia with Drake Passage. This orientation is consistent with one of the atmospheric river geometries identified over the AP, which can change during the evolution of an individual event [12].

The 850-hPa temperature field shows a poleward extension of relatively warm air along the cyclone’s eastern flank, alongside the moisture corridor, with colder air to the west (Figs. 4(b–f)). This configuration is consistent with warm advection and is

supported by the ERA5 850-hPa temperature, geopotential-height, and wind fields shown in Supplementary Fig. S1. At 500 hPa, the corresponding geopotential-height, temperature, wind, and relative-vorticity fields show a deep trough over the southeast Pacific, west of the moisture corridor (Supplementary Fig. S2). The AR evolution was therefore accompanied by a midtropospheric disturbance, with poleward moisture transport occurring ahead of the trough.

During 29 March (Figs. 4(d-f)), the southern portion of the corridor shifted eastward and extended toward the northern AP, reaching the Marambio sector as IVT decreased at Ushuaia. This evolution is consistent with the temporal sequence in Fig. 3, which shows enhanced IVT first at Ushuaia during the intensive observing period and a later maximum at Marambio. The synoptic evolution thus provides the context for interpreting the Ushuaia observations as sampling the upstream stage of the event before its arrival in the Antarctic sector, and for subsequently examining its expression in the vertical structure and surface conditions.

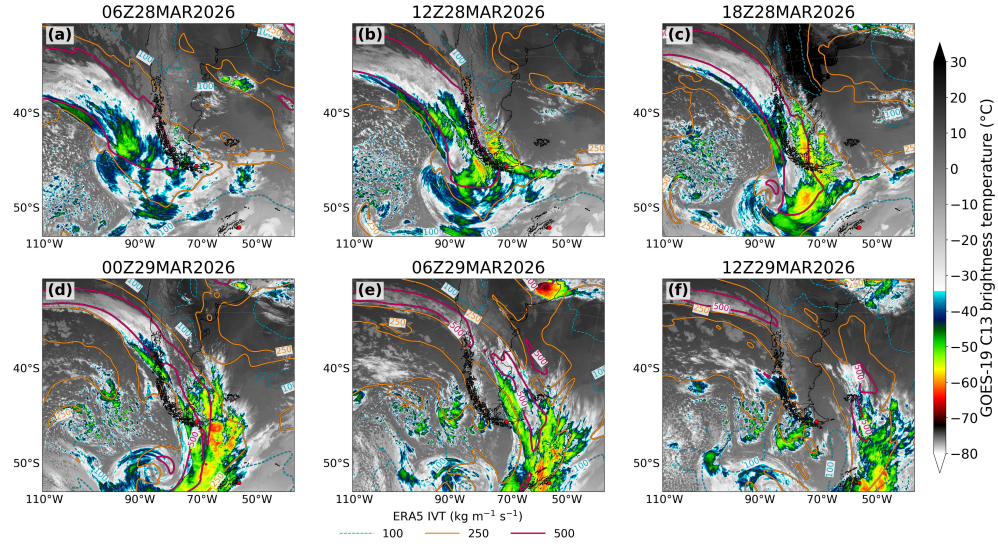


Fig. 5: Evolution of GOES-19 infrared brightness temperature and ERA5 integrated vapor transport during 28–29 March 2026. GOES-19 ABI Channel 13 infrared brightness temperature and ERA5 integrated vapor transport (IVT) during the 28–29 March 2026 atmospheric-river event. Shading shows Channel 13 brightness temperature, with lower values indicating colder cloud tops. Contours show ERA5 IVT at 100, 250, and 500 $\text{kg m}^{-1} \text{s}^{-1}$. Panels correspond to (a) 06 UTC, (b) 12 UTC, and (c) 18 UTC on 28 March, and (d) 00 UTC, (e) 06 UTC, and (f) 12 UTC on 29 March. Red markers indicate VAG-Ushuaia and Base Marambio.

Figure 5 shows GOES-19 ABI Channel 13 brightness temperature, overlaid with ERA5 IVT contours, from 06 UTC on 28 March to 12 UTC on 29 March 2026 at 6-h intervals. Channel 13 is an infrared window channel, so the brightness temperature

primarily represents cloud-top thermal structure, with lower values corresponding to colder cloud tops.

At 06 UTC on 28 March, the main cold-cloud band was located west and southwest of southern Patagonia, while enhanced IVT was still concentrated mainly over the southeast Pacific. By 12 UTC, the cloud band had extended eastward toward Tierra del Fuego and became increasingly aligned with the region of enhanced IVT and the cyclone over Patagonia. At 18 UTC, cold cloud tops covered much of southern Patagonia and the Ushuaia sector, while the strongest IVT corridor had acquired the pronounced meridional orientation seen in Fig. 4. During 29 March, the main cloud structures shifted progressively south and southeast across the Drake Passage, together with the downstream displacement of the enhanced-IVT corridor and the warm air mass over the Atlantic Ocean.

The rapid evolution of these deep cloud structures toward the AP shows good agreement with the large-scale progression inferred from ERA5 (Fig. 4). As will be shown later, surface precipitation observed at Ushuaia was modest despite the strong IVT registered during the intensive observing period. This highlights that enhanced moisture transport and extensive cloud cover did not translate directly into a strong local precipitation response.

3.2 Surface response at Ushuaia and Marambio

Figure 6 shows surface air temperature, relative humidity, wind speed, and daily accumulated precipitation at Ushuaia and Base Marambio during the 27–30 March period. At Ushuaia, near-surface temperature (see Fig. 6(a)) increased markedly during the targeted observing period, rising from pre-event values near 7–9 °C to values close to 15 °C during the radiosonde launch window. This warming placed the event above the historical late-March median and near, or above, the upper part of the historical 10th–90th percentile range. At Base Marambio, the temperature increase occurred later, during 29 March, with values rising toward the upper part of the local historical range (see Fig. 6(b)). This delayed warming follows the forecast IVT timing in Fig. 3.

The relative-humidity panels (Fig. 6 (c,d)) show different near-surface humidity behavior at the two stations. At Ushuaia, relative humidity decreases during the warmest part of the targeted observing period. The drop occurs while temperature and wind speed increase, indicating that the surface warming was not associated with near-surface saturation. At Marambio, relative humidity remains generally high during 29 March, with values mostly above 70–80%. The combination of warming, reduced relative humidity and enhanced winds in Ushuaia suggests that local dynamical effects, such as mixing or a downslope/Föhn-like influence, may have contributed to the event’s near-surface manifestation. While this is consistent with the known thermodynamic signature of Föhn conditions [24, 25], it is not possible to identify the mechanism from Fig. 6 alone.

Near-surface wind speed (Fig. 6(e,f)) also increased during the event, with different timing at the two stations. In Ushuaia, wind speed increased during the targeted observing period and showed short-lived peaks during and after the radiosonde launch window. In Marambio, the strongest wind response occurred later, on 29 March, close to the radiosonde launch time. This timing follows the upstream–downstream phasing

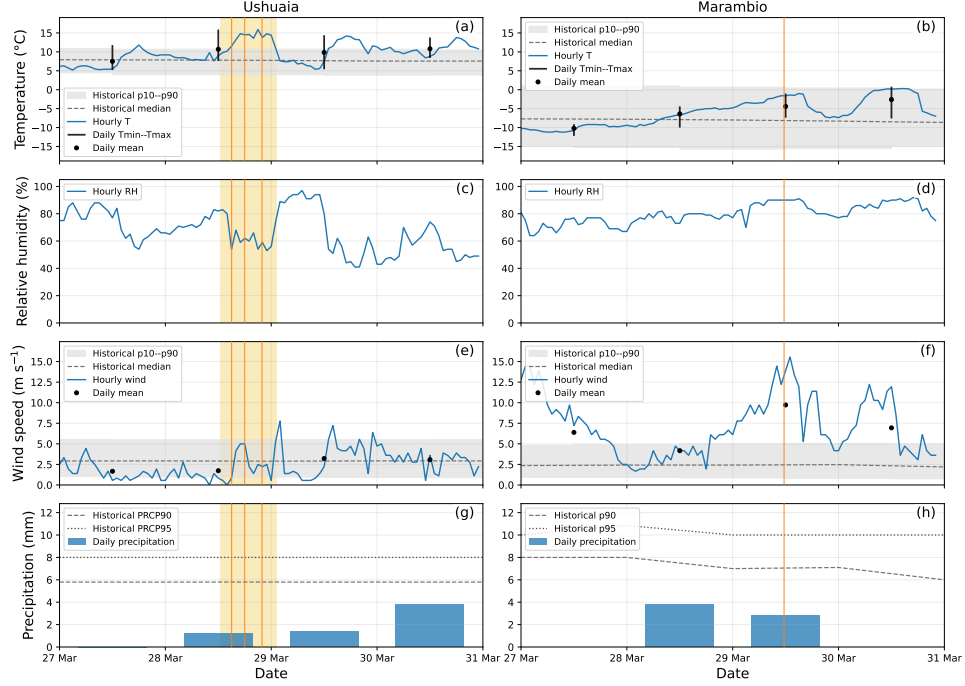


Fig. 6: Surface meteorological conditions at Ushuaia and Base Marambio during the atmospheric-river event. Hourly surface air temperature (a,b), relative humidity (c,d), wind speed (e,f) and daily accumulated precipitation (g,h) from 27 to 30 March 2026, for Ushuaia (left columns) and Base Marambio (right column). For temperature and wind speed, gray shading indicates the historical 10th–90th percentile range for late March, and dashed gray lines indicate the corresponding historical median. Amber shading in the Ushuaia panels marks the targeted observing period, and orange vertical lines mark the operational Väisälä radiosonde launches at Ushuaia and Marambio.

of the IVT forecasts, with enhanced near-surface winds first at Ushuaia and later over the northern AP sector. At Marambio, the daily mean wind speed on 29 March reached 35.0 m s^{-1} , exceeding the late-March 95th percentile of approximately 23.6 m s^{-1} computed from the 1993–2025 daily record for 25–31 March. Thus, the downstream surface response at Marambio was particularly pronounced in wind speed. Although the wind-speed increase cannot be attributed solely to the AR from Fig. 6 alone, enhanced low-level winds have been previously reported as a characteristic response associated with AR landfall over the Antarctic Peninsula (see, for instance [26, 27] and references therein).

Daily precipitation (Fig. 6(g,h)) remained modest at both sites, despite the concurrent warming, wind increase, and enhanced IVT. At Ushuaia, daily totals were 1.2, 1.4, and 3.8 mm on 28, 29, and 30 March, respectively. These values remained below the

late-March one-day PRCP90 and PRCP95 reference levels computed from the long-term Ushuaia Aero precipitation record for 25–31 March, which are approximately 5.8 and 8.0 mm, respectively. At Marambio, daily precipitation totals of 3.8 and 2.8 mm on 28 and 29 March were above the late-March median but remained below the corresponding 90th-percentile reference level computed from the long-term Base Marambio record. The precipitation response therefore did not mirror the stronger anomalies in wind speed and temperature.

In agreement with the satellite evolution, the modest precipitation at Ushuaia occurred despite strong moisture transport and substantial cloud development. As mentioned earlier, enhanced IVT nor extensive cloud cover alone was sufficient to produce a strong local precipitation response.

3.3 Observed vertical structure of moisture transport

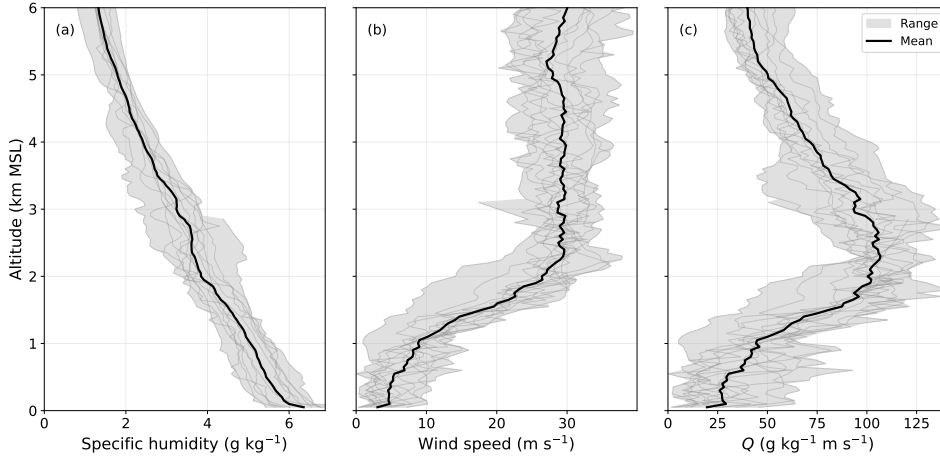


Fig. 7: Observed vertical structure of moisture and wind speed during the intensive observing period at Ushuaia. Vertical profiles of (a) specific humidity, (b) wind speed, and (c) the moisture-transport proxy Q [Eq. (5)]. Gray lines show the representative sounding profiles, including individual non-grid soundings and the mean profiles from the two five-sonde grid deployments. The shaded envelope indicates the profile-to-profile range, and the black line shows the mean profile.

Figure 7 shows the vertical profiles of specific humidity q , wind speed $|\mathbf{V}|$, and the local moisture-transport proxy Q (Eq. 5) during the intensive observing period in Ushuaia. Gray curves represent the individual non-grid soundings together with the mean profiles from the two five-sonde grid deployments, while the black curve and shaded envelope indicate the mean and the profile-to-profile range, respectively.

Specific humidity is largest within the lowest 1–2 km MSL and decreases rapidly with height, whereas wind speed increases above the lowest kilometre and remains large, reaching values of order 30 m s^{-1} , through a deeper layer. Consequently, the

mean Q profile reaches its maximum between approximately 2 and 3 km MSL, where the remaining moisture and strong winds overlap most effectively. The largest profile-to-profile variability in Q is also concentrated near this altitude, while above about 4 km MSL the decrease in moisture limits the transport despite persistent moderate to strong winds.

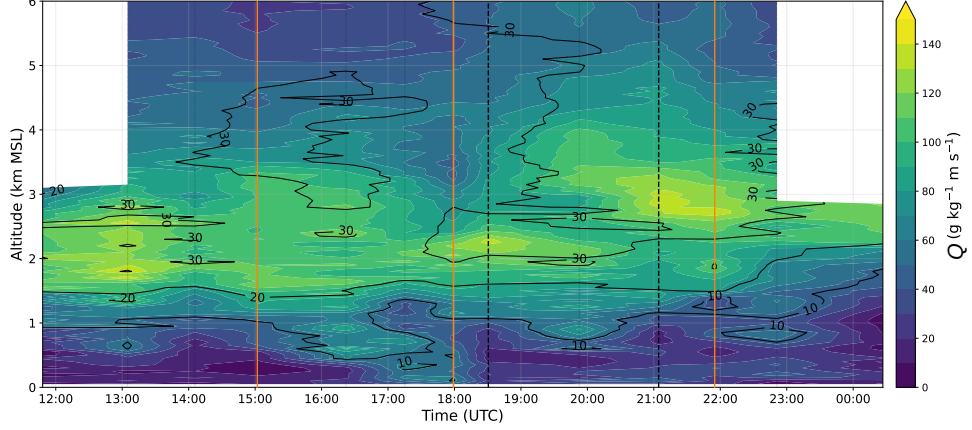


Fig. 8: Time–height evolution of the moisture-transport proxy over Ushuaia during the 28 March 2026 atmospheric-river event. Shading shows the local moisture-transport proxy Q . Black contours indicate wind speed at 10, 20, and 30 ms^{-1} . Vertical dotted lines mark individual Smarties profiles, solid orange lines mark Vaisälä radiosonde launches, and dashed lines mark the mean profiles from the two five-sonde grid deployments. The field is linearly interpolated between representative launch times for visualization only. White regions indicate missing sounding coverage rather than dry air. The largest Q values indicate the levels where moisture and strong winds overlap most strongly.

Figure 8 shows the time–height evolution of the local moisture-transport proxy Q from the representative launch sequence. The figure extends the profile-based result of Fig. 7 by showing that the lower- to mid-tropospheric transport layer persisted and evolved over several hours during 28 March. Enhanced values were already present by the first part of the sequence, with a well-defined layer between about 2 and 3 km MSL from approximately 14:00 to 17:30 UTC. Around 18:00 UTC, Q decreased locally within this layer, marking a short interruption or weakening in the sampled transport maximum. After about 19:00 UTC, enhanced Q reappeared and strengthened. The strongest part of the observed sequence occurred between approximately 20:00 and 22:00 UTC, when values reached about $120\text{--}140 \text{ g kg}^{-1} \text{ m s}^{-1}$ near 2.5–3.0 km MSL. During this later interval, the core of the strongest transport became more vertically concentrated near 2.5–3.0 km MSL, while enhanced Q also extended to higher levels than during the earlier phase. The evolution therefore involved not only

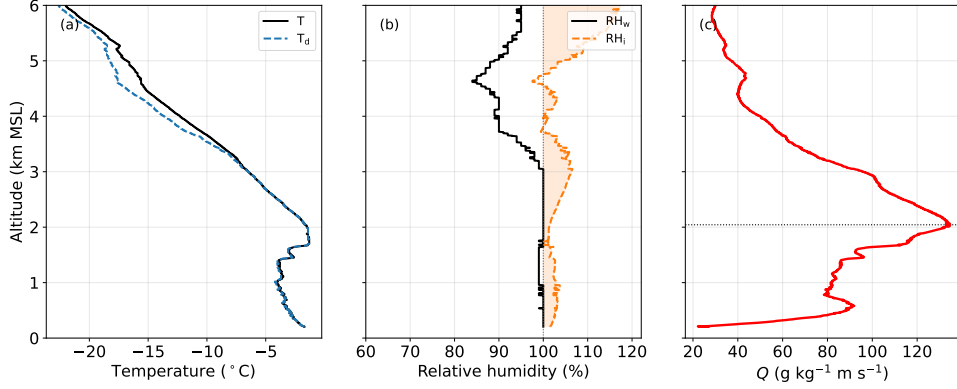


Fig. 9: Thermodynamic vertical structure observed by the operational radiosonde launched at Base Marambio on 29 March 2026, close to the downstream IVT maximum shown in Fig. 3. (a) Temperature T and dew-point temperature T_d . (b) Relative humidity with respect to liquid water, RH_w , and ice, RH_i ; the vertical dotted line marks 100% saturation and shading indicates levels supersaturated with respect to ice. (c) Local moisture-transport proxy Q . The sounding shows a deep subfreezing layer close to liquid-water saturation and supersaturated with respect to ice, coincident with a pronounced moisture-transport maximum near 2 km MSL.

an increase in magnitude and an upward displacement of the transport maximum, but also a reorganization of its vertical structure.

The large-scale evolution shown in Figs. 3 and 4 indicates that the enhanced moisture-transport corridor reached the northern AP approximately one day after its passage over Ushuaia. The operational radiosonde launched at Base Marambio on 29 March was obtained close to the local IVT maximum (Fig. 3), providing a complementary in situ snapshot of the downstream stage of the event. Figure 9 shows vertical profiles of the temperature T and dew-point temperature T_d , relative humidity with respect to liquid water, RH_w , and ice, RH_i [Eq. (11)], and the local moisture-transport proxy Q for the Marambio sounding. The lower troposphere was entirely below freezing, while T and T_d remained nearly coincident from the lowest observed levels to approximately 3 km MSL. This deep saturated layer is consistent with the downstream cloud field observed by GOES-19 during 29 March (Fig. 5). Over the same depth, RH_w remained essentially at liquid-water saturation, whereas RH_i exceeded 100%, indicating ice-supersaturated conditions throughout almost the entire sampled layer below 3 km. Within this saturated and ice-supersaturated layer, Q reached a maximum of approximately $134 \text{ g kg}^{-1} \text{ m s}^{-1}$ at 2.04 km MSL, showing that the strongest downstream vapor transport was concentrated within the same deep moist layer. This vertically concentrated transport within a deep saturated layer is consistent with the downstream expression of the AR identified from the large-scale IVT evolution. While a single sounding cannot resolve the temporal evolution of the AR over Marambio, it allows its vertical thermodynamic and moisture-transport structure to be examined at the time of strongest local IVT.

3.4 Grid deployments: trajectory sampling and launch-array variability

Figure 10 shows the individual vertical profiles of specific humidity, wind speed, local moisture-transport proxy Q , potential temperature θ , equivalent potential temperature θ_e , and horizontal vector wind shear S [Eq. (7)] for the two five-sonde grid deployments. Panels (e) and (j) also contain S computed from the closest operational radiosonde launches, denoted by bold orange curves. Grid 1 (shown in the upper panels) was launched around 18:30 UTC, shortly after the local weakening of Q and Grid 2 (shown in the lower panels) was launched around 21:05 UTC, during the later period of stronger and more elevated Q .

In Grid 1, the specific-humidity profiles are closely grouped below ~ 2 km MSL, whereas the largest profile-to-profile differences occur in wind speed near 2–2.5 km MSL. The corresponding Q profiles reach their largest values within the same layer, indicating that the observed variability in moisture transport was associated primarily with differences in the local wind field within an already moist lower troposphere. Grid 2 exhibits a different vertical organization: several sondes show enhanced specific humidity between approximately 2.5 and 3.2 km MSL, where strong winds produce a higher and vertically broader Q maximum.

The thermodynamic and shear profiles place these differences in a dynamical context. In Grid 1, enhanced shear is located close to the lower Q maximum, near 2–2.5 km MSL, while the θ and θ_e profiles remain relatively similar among the sondes. In Grid 2, the main Q layer is displaced upward and extends approximately from 2.5 to 4 km MSL within a thermodynamically coherent θ – θ_e structure, whereas the strongest shear occurs substantially lower, near 1–1.5 km MSL. The two deployments therefore resolve a change in the small-scale vertical organization of the AR-related flow: the earlier transport maximum was embedded close to a locally sheared layer, whereas the later maximum occupied a higher and deeper layer above the strongest shear. This evolution is consistent with the upward displacement and intensification seen in Fig. 8.

Figure 11 combines horizontal and vertical trajectory views of the two grid deployments. Panels (a),(b) show the horizontal paths of the drifting sondes, revealing the footprint sampled as the balloons were advected away from the launch array, while panels (c),(d) show the corresponding vertical evolution as altitude versus time since launch. In all panels, the trajectories are colored by the local moisture-transport proxy Q .

In both deployments, the sondes were rapidly advected away from the launch region and sampled elongated trajectories over the Beagle Channel. The displacement was directed mainly toward the south and southeast, consistent with the regional transport direction indicated by the IVT vectors in Fig. 4. The two deployments nevertheless sampled markedly different geometries. Horizontally, Grid 1 developed a much broader footprint as the sondes ascended, whereas Grid 2 remained comparatively compact. Vertically, the enhanced- Q layer shifted from approximately 1.8–3.0 km MSL in Grid 1 to 2.5–4.0 km MSL in Grid 2. The trajectory measurements therefore show that the change between the two deployments involved both the vertical position of the transport layer and the horizontal coherence of the sampled atmospheric volume.

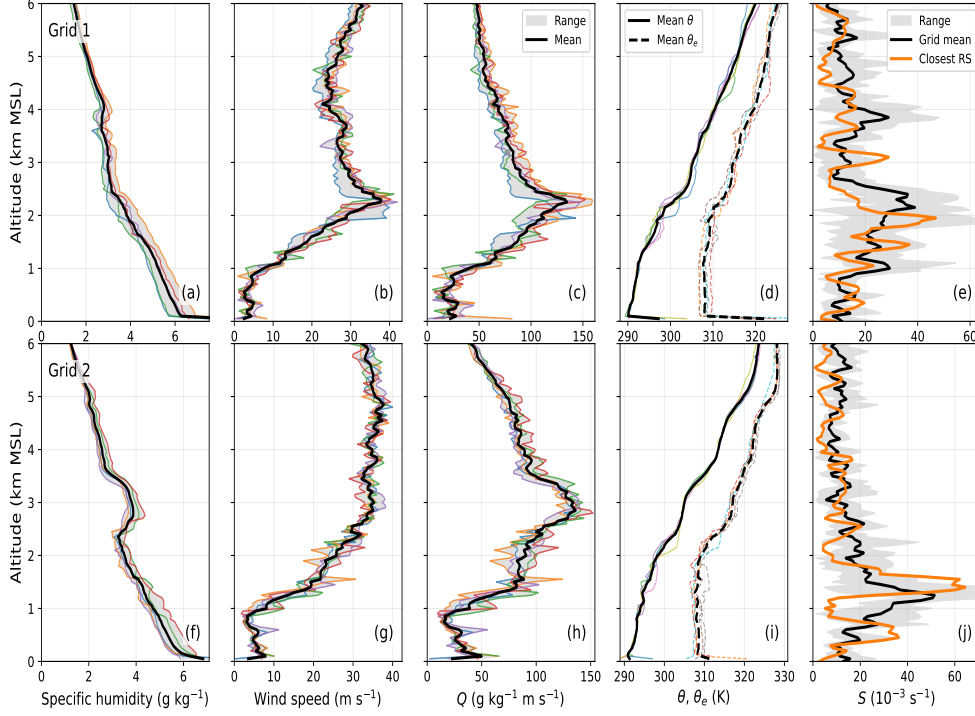


Fig. 10: Vertical thermodynamic and kinematic structure sampled by the two five-sonde deployments. Individual Smartie profiles from Grid 1, launched around 18:30 UTC, and Grid 2, launched around 21:05 UTC on 28 March 2026. Panels (a,f) show specific humidity, (b,g) wind speed, (c,h) the local moisture-transport proxy Q , and (d,i) potential temperature θ and equivalent potential temperature θ_e . Colored lines indicate individual sondes, and thick black lines indicate the grid-mean profiles. Grid 1 captures a lower Q maximum mainly associated with wind-speed variability near 2–2.5 km MSL, whereas Grid 2 captures a higher and deeper Q maximum associated with an elevated moist layer overlapping strong winds. Panels (e,j) show horizontal vector wind shear S [Eq. (7)], computed from wind speed and direction after vertical smoothing. Gray shading indicates the range among the five Smarties sondes, black lines indicate the grid-mean shear, and orange lines indicate the closest operational Vaisälä radiosonde profiles.

The apparent difference in trajectory spreading is quantified in Table 1 using the maximum pairwise horizontal sonde separation, $D_{\max}$ [Eq. (8)], at selected altitudes. In Grid 1, $D_{\max}$ increases rapidly with height, from 1.41 km at 1 km MSL to 15.47 km at 2 km MSL, reaching 33.14 km by 5 km MSL. In contrast, Grid 2 remains comparatively compact, with $D_{\max}$ between 4.12 and 6.75 km from 2 to 5 km MSL. This contrast in trajectory spreading between grids is consistent with the relative placement of shear and the moisture-transport layer in Fig. 10. In Grid 1, enhanced vector

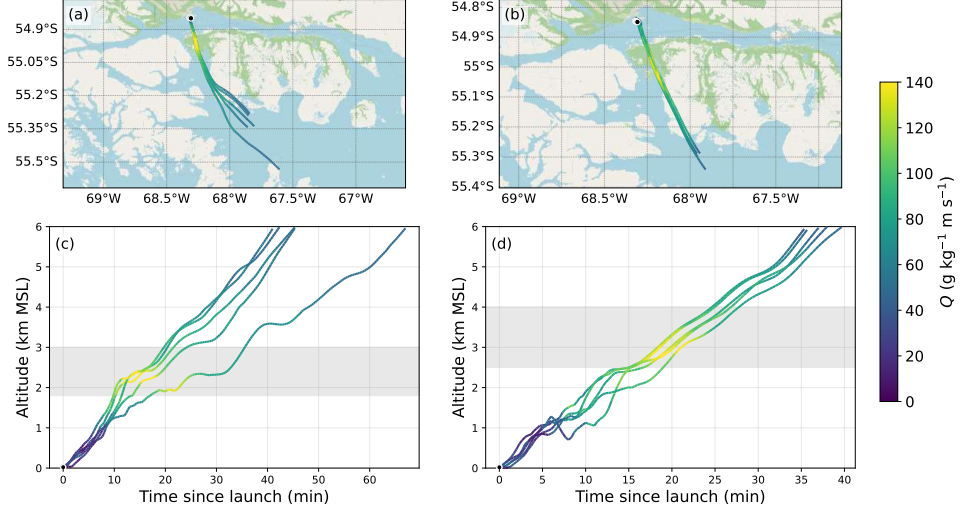


Fig. 11: Trajectory-based view of the two Smartie grid deployments during the 28 March 2026 atmospheric-river event. The upper panels show the horizontal trajectories of the individual sondes during (a) Grid 1 and (b) Grid 2, colored by the local moisture-transport proxy Q . The lower panels show the corresponding altitude–time evolution along each trajectory for (c) Grid 1 and (d) Grid 2. Gray shading indicates the altitude range of enhanced Q sampled by each grid: 1.8–3.0 km MSL for Grid 1 and 2.5–4.0 km MSL for Grid 2. The figure shows the drifting atmospheric volume sampled by the sondes during ascent, complementing the fixed launch-array view in Fig. 12.

shear is located near the lower Q maximum, around 2–2.5 km MSL, where the trajectories begin to fan out. In Grid 2, the strongest shear occurs below the main Q layer, while the enhanced moisture transport extends through a higher, thermodynamically coherent layer between approximately 2.5 and 4.0 km MSL. This vertical arrangement is consistent with the smaller pairwise separations observed in Grid 2. Thus, Grid 1 sampled the lower Q maximum across a broader drifting footprint, whereas Grid 2 sampled a higher and deeper Q layer within a more compact volume. The persistence of enhanced Q along several independent trajectories indicates that the maxima identified in the profiles and time–height section were coherent structures within the sampled AR-related flow, rather than isolated features from individual soundings.

Figure 12 examines the distribution of Q across the initial launch array of each grid at three fixed altitudes: 2.0, 2.5, and 3.0 km MSL. Unlike Fig. 7, which shows the vertical structure of each sonde, this diagnostic focuses on how the values sampled at the same height varied across the few-hundred-metre launch geometry. The values are plotted relative to the mean launch position of each grid and no horizontal interpolation is applied; the figure therefore represents launch-array variability rather than a reconstructed two-dimensional field.

Grid 1 shows its largest Q values at 2.0 and 2.5 km MSL, while values are generally weaker at 3.0 km MSL. This is consistent with the lower Q maximum seen in the

Table 1: Maximum pairwise horizontal separation among the five Smartie sondes during the two grid deployments. Values correspond to $D_{\max}$, computed at selected altitudes from the interpolated sonde positions.

Altitude (km MSL)	Grid 1 $D_{\max}$ (km)	Grid 2 $D_{\max}$ (km)
1.0	1.41	1.92
2.0	15.47	6.75
3.0	21.26	4.12
4.0	27.38	4.38
5.0	33.14	5.42

Grid 1 profiles, and indicates that the strongest part of the sampled transport layer was located below about 3 km MSL during this deployment. Differences among sondes are visible across the elongated launch array, showing that measurable variability existed even within the initial few-hundred-metre sampling geometry. Grid 2 shows a different vertical pattern. Q increases from 2.0 toward 3.0 km MSL, where several sondes record enhanced values across the launch array. This agrees with the elevated moist layer and higher Q maximum identified in the Grid 2 profiles. The launch-array view therefore reinforces the vertical shift between the two deployments: Grid 1 sampled stronger Q at lower levels, whereas Grid 2 sampled stronger Q at higher levels during the later stage of the event.

A complementary measure of launch-array variability is the relative spread $\Delta Q_{\%}$ [Eq. (10)], evaluated for Q at fixed altitude. For Grid 1, the relative spread remains between approximately 30% and 37% from 2.0 to 3.0 km MSL. For Grid 2, it decreases from 23% at 2.0 km to 8.8% at 2.5 km and 11% at 3.0 km MSL. This indicates that the later, elevated transport layer sampled by Grid 2 was more uniform in amplitude across the five launch positions.

4 Discussion and conclusions

This study examines a 28–29 March 2026 intense atmospheric-river event that connected southern Patagonia, the Drake Passage, and the northern AP using large-scale IVT fields, numerical forecasts, satellite observations, high-cadence radiosonde profiles, two five-sonde deployments at Ushuaia, and an operational radiosonde at Base Marambio. The observing strategy was specifically designed to resolve the vertical structure, horizontal variability, and temporal evolution of the AR at sub-synoptic scales, combining repeated vertical profiling with simultaneous multisonde sampling. The observations show that the coherent synoptic-scale AR contained a vertically organized transport layer whose altitude, intensity, depth, and spatial structure evolved substantially during its passage over southern Patagonia. The strongest local transport at Ushuaia was concentrated mainly near 2–3 km MSL and persisted for approximately 8–10 h, while a pronounced downstream Q maximum was sampled near 2 km MSL at Marambio approximately one day later.

At large scale, the event developed into a pronounced meridional moisture-transport corridor extending from southern Patagonia across the Drake Passage

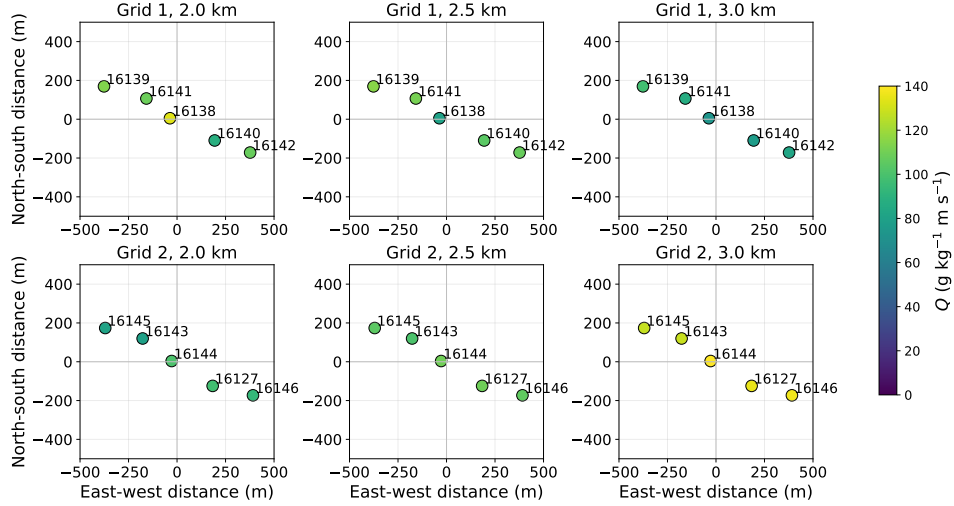


Fig. 12: Launch-site-indexed variability of the local moisture-transport proxy Q during the two Smartie grid deployments. The upper row shows Grid 1 and the lower row shows Grid 2. Columns show values sampled at 2.0, 2.5, and 3.0 km MSL. Each marker is plotted at the launch position of an individual Smartie sonde, expressed relative to the mean launch position of the corresponding grid, and is colored by the value of Q measured by that sonde when it reached the indicated altitude. Each Smartie is labeled by its corresponding ID number, specified in Supplementary Table S1.

toward the northern AP. Enhanced IVT occurred first at Ushuaia and later at Marambio, while GOES-19 Channel 13 imagery showed a rapidly evolving deep-cloud field broadly following this downstream progression. Despite the strong IVT and substantial cloud cover, precipitation remained modest at Ushuaia, where warming and enhanced winds were more pronounced. At Marambio, daily precipitation was also above the late-March median but remained below the 90th-percentile reference despite the strong wind response, high relative humidity, and pronounced downstream moisture-transport maximum. The surface response at both sites therefore illustrates that enhanced IVT and abundant atmospheric moisture do not translate directly into extreme local precipitation, consistent with recent work showing the importance of the accompanying dynamical forcing and ascent [13].

The high-cadence soundings show that the internal structure of the AR evolved considerably during this otherwise continuous large-scale event. At Ushuaia, the largest Q values occurred mainly between 2 and 3 km MSL, where enhanced moisture overlapped with strong lower- to mid-tropospheric winds. This layer persisted for approximately 8–10 h, briefly weakened, and later intensified and shifted upward. This observed vertical organization is consistent with previous Antarctic AR studies showing that moisture transport can be concentrated within distinct tropospheric layers and associated with strong low- to mid-level winds [7, 17]. The present observations extend this picture by resolving how such a transport layer evolves over hourly time

scales and across multiple simultaneously sampled trajectories. At Marambio, the operational radiosonde sampled another pronounced Q maximum near 2 km MSL close to the local IVT peak, embedded within a deep subfreezing layer near liquid-water saturation and supersaturated with respect to ice. These observations therefore connect the synoptic progression of the AR with vertically concentrated moisture transport sampled at successive upstream and downstream stages.

The two multisonde grid deployments further show that this evolution involved changes in both the kinematic environment and the spatial organization of the transport layer. Grid 1 sampled a lower transport maximum associated with stronger shear and larger trajectory spreading, whereas Grid 2 sampled a higher and deeper layer above the strongest shear and within a more compact sampling volume. The relative spread in Q across the launch array also decreased markedly in Grid 2, indicating that the later elevated layer was more uniform in amplitude across the sampled positions. The recurrence of enhanced Q along several independent trajectories supports the interpretation of these maxima as organized features of the AR-related flow rather than isolated sounding-scale structures.

Observations and analysis presented in this study reveal the AR as a dynamically organized transport system whose structure changed across a hierarchy of scales. At the synoptic scale, ERA5, forecasts and satellite imagery identify a coherent moisture-transport corridor progressing from southern Patagonia across the Drake Passage toward the Antarctic Peninsula. At the local scale, the high-cadence soundings show that the vertical transport maximum over Ushuaia evolved substantially over only a few hours, changing in altitude, intensity, and vertical organization while the large-scale AR remained continuously identifiable. At still finer scales, the multisonde deployments resolve simultaneous differences in shear, trajectory spreading, and within-layer variability, showing that the spatial coherence of the transport layer also evolved. The downstream Marambio observations then capture a vertically concentrated, saturated transport layer during the Antarctic stage of the event. Thus, a coherent column-integrated AR can conceal substantial internal reorganization from synoptic to local and multisonde scales. Resolving this hierarchy requires combining large-scale diagnostics with temporally dense and spatially distributed in situ observations, particularly in the southern Patagonia–Drake Passage–Antarctic Peninsula sector where direct atmospheric sampling remains sparse.

5 Methods

5.1 Large-scale data and IVT

The synoptic and mesoscale evolution of the event was characterized using WRF-SMN forecasts at Ushuaia, AMPS-WRF forecasts at Base Marambio, ERA5 reanalysis, and GOES-19 satellite imagery. WRF-SMN is the operational implementation of WRF-ARW v4.0 [28] used by the Argentine National Meteorological Service (SMN). It is run four times daily (00, 06, 12, and 18 UTC) at 4-km horizontal grid spacing and 45 vertical levels, with 72-h forecasts initialized from NCEP GFS analyses at 0.25° resolution [29, 30]. For this study, hourly profiles for the Ushuaia forecast point were obtained from the 0000 UTC runs initialized on 26, 27, and 28 March 2026.

At Base Marambio, forecasts were obtained from the Antarctic Mesoscale Prediction System (AMPS), a real-time numerical weather prediction system based on Polar WRF and developed primarily to support the U.S. Antarctic Program [31, 32]. Native NetCDF `wrfout` files from the two-way nested D02 domain were used for the same three 0000 UTC initializations. During the study period, D02 used WRF v4.3.3 with 8-km horizontal grid spacing, 60 vertical model levels, a model top at 10 hPa, and a forecast horizon of 120 h. The files were obtained from the AMPS WRF Outputs archive maintained by NSF NCAR [33].

ERA5 [34], at approximately 0.25° horizontal resolution and hourly frequency, provides a common reanalysis reference for both sites and was used to describe the regional evolution of the moisture-transport corridor. GOES-19 ABI Channel 13 ($10.3 \mu\text{m}$) infrared brightness-temperature imagery [35] was used to characterize the evolution of the cloud field during the event.

The principal large-scale diagnostic was vertically integrated water-vapor transport (IVT). For ERA5, WRF-SMN, and AMPS-WRF, IVT magnitude was computed from the eastward and northward vertically integrated water-vapor flux components as

$$\text{IVT} = [(\text{ivt}_u)^2 + (\text{ivt}_v)^2]^{1/2}. \quad (1)$$

ERA5 IVT was also used to characterize the synoptic evolution and to classify the event at each site. At Ushuaia, AR intensity follows the global IVT-based scale of Ralph et al. [22], whereas at Base Marambio the polar AR scale of Zhang et al. [23] is used. These classifications are employed only as site-specific intensity references and are not directly compared between the two locations.

Observation-based IVT was computed from the radiosonde profiles as

$$\text{IVT}_{\text{RS}} = \frac{1}{g} \left[\left(\int_{p_t}^{p_s} qu \, dp \right)^2 + \left(\int_{p_t}^{p_s} qv \, dp \right)^2 \right]^{1/2}, \quad (2)$$

where q is specific humidity, u and v are the zonal and meridional wind components, p_s is the surface pressure, and $p_t = 300$ hPa is the upper integration bound. The integration was limited to the surface–300-hPa layer following the radiosonde-based Antarctic AR analysis of Gorodetskaya et al. [7]. This layer contains most of the tropospheric water vapor and horizontal moisture transport relevant to the event, while excluding the very dry upper troposphere and lower stratosphere.

Smartie profiles were considered complete for the IVT calculation when valid thermodynamic and wind observations provided sufficient coverage from near the surface to 300 hPa without internal pressure gaps affecting the integration. For the comparison shown in Fig. 3, profiles that did not satisfy this criterion but reached at least 500 hPa were retained as partial, whereas shallower profiles were excluded.

Single Smartie launches were treated individually, while the five profiles in each grid were integrated from near the surface to a common upper-pressure bound set by the shallowest profile. This common upper bound was 324.7 hPa for Grid 1 and 300 hPa for Grid 2. For each sonde j , the zonal and meridional IVT components, denoted by $\text{IVT}_{u,j}$ and $\text{IVT}_{v,j}$, respectively, were obtained from the corresponding pressure integrals in Eq. (2) over this common vertical range. The representative grid IVT was then calculated as

$$\begin{aligned}\overline{\text{IVT}}_{u,\text{grid}} &= \frac{1}{N} \sum_{j=1}^N \text{IVT}_{u,j}, & \overline{\text{IVT}}_{v,\text{grid}} &= \frac{1}{N} \sum_{j=1}^N \text{IVT}_{v,j}, \\ \text{IVT}_{\text{grid}} &= \left[\left(\overline{\text{IVT}}_{u,\text{grid}} \right)^2 + \left(\overline{\text{IVT}}_{v,\text{grid}} \right)^2 \right]^{1/2}.\end{aligned}\tag{3}$$

Here, N is the number of sondes in each grid ($N = 5$). Therefore, the representative grid IVT shown in Fig. 3 corresponds to the magnitude of the vector mean of the five individual IVT vectors. Accordingly, Grid 1 represents a partial IVT estimate, whereas Grid 2 represents a complete surface-to-300-hPa estimate. Within-grid spread was represented by ± 1 sample standard deviation of the five individual IVT magnitudes calculated over the same vertical range.

5.2 Surface observations and climatological references

Surface observations from VAG–Ushuaia, Ushuaia Aero, and Base Marambio were obtained from operational records maintained by the Argentine National Meteorological Service (SMN). Hourly surface air temperature, relative humidity, and wind speed were used to characterize the event evolution at Ushuaia and Marambio, together with daily accumulated precipitation. Daily mean, minimum, and maximum temperatures and daily mean wind speed were additionally derived or read from the corresponding station records for comparison with the historical reference distributions.

Historical reference distributions for temperature and wind speed were constructed for each event date using observations within a ± 3 -day calendar window from all available years prior to 2026. The calculation was restricted to March, and only valid observations were included. At Ushuaia, these reference distributions were derived from the 1990–2025 hourly record, from which daily mean temperature and wind speed were calculated. At Base Marambio, the corresponding reference distributions were derived from the daily station record for 1986–2025. Historical conditions are summarized by the median and the 10th–90th percentile range.

Precipitation was treated separately because of differences in the available historical products. At Ushuaia Aero, the event-period daily precipitation totals were compared with historical one-day PRCP90 and PRCP95 extreme-event thresholds. These thresholds were obtained from the SMN historical extreme-precipitation records by selecting one-day events beginning between 25 and 31 March. The resulting late-March reference values are approximately 5.8 and 8.0 mm for PRCP90 and PRCP95, respectively. At Base Marambio, daily precipitation percentiles were calculated from the available historical daily record using the same ± 3 -day calendar-window approach as for temperature and wind. Valid late-March precipitation observations span 1993–2025, with gaps in individual years.

5.3 Representative profiles and local moisture transport

All sounding profiles were first interpolated onto a common vertical grid from the surface to 6 km MSL, with vertical spacing $\Delta z = 50$ m. For a generic observed variable

X , the interpolated profile for sounding i is denoted by

$$X_i(z_k),$$

where z_k is the common height grid. No vertical extrapolation was applied: levels below the lowest valid observation or above the highest valid observation of each profile were retained as missing values.

For each of the two five-sonde grid deployments, a representative grid-mean profile was calculated at every vertical level as

$$\bar{X}_{\text{grid}}(z_k) = \frac{1}{N_k} \sum_{j=1}^{N_k} X_j(z_k), \quad (4)$$

where N_k is the number of sondes with valid data at height z_k . The grid-mean profile was assigned to the mean launch time of the corresponding deployment. The grid-mean profile was assigned to the mean launch time of the corresponding deployment. Individual grid members were retained for the spatial and trajectory-based analyses.

The local moisture-transport proxy was calculated at each height as

$$Q_i(z_k) = q_i(z_k) |\mathbf{V}_i(z_k)|, \quad (5)$$

where q_i is specific humidity and $|\mathbf{V}_i|$ is horizontal wind speed. In the figures, q is expressed in g kg^{-1} , giving Q units of $\text{g kg}^{-1} \text{ m s}^{-1}$. Here, Q is used to identify the altitude and temporal evolution of enhanced local moisture transport.

For the vertical-profile summary, $q_i(z_k)$, $|\mathbf{V}_i(z_k)|$, and $Q_i(z_k)$ were evaluated for each representative profile in the launch sequence. This set includes the individual non-grid soundings and the two grid-mean profiles defined by Eq. (4). At each height, the mean and full profile-to-profile range were calculated across this representative set. The range therefore describes variability across the intensive observing period rather than simultaneous spatial variability alone.

5.4 Time–height evolution

The time–height sections were constructed from the whole launch sequence, consisting of the individual non-grid soundings and the two grid-mean profiles. At each height level, values between consecutive representative launch times t_i and t_{i+1} were linearly interpolated in time for visualization:

$$X(z_k, t) = X_i(z_k) + \frac{t - t_i}{t_{i+1} - t_i} [X_{i+1}(z_k) - X_i(z_k)], \quad t_i \leq t \leq t_{i+1}. \quad (6)$$

Interpolation was performed only when valid values were available from both surrounding profiles at the corresponding height. No extrapolation in time or height was applied. White or missing regions in the time–height sections therefore indicate lack of sounding coverage rather than zero humidity or weak transport. The interpolated fields are used only to visualize the evolution between discrete sounding times; quantitative profile values are taken from the individual observations.

5.5 Grid thermodynamic and kinematic diagnostics

The individual profiles from each five-sonde deployment were used to examine the thermodynamic and kinematic structure sampled simultaneously by the grids. In addition to q , $|\mathbf{V}|$, and Q , potential temperature θ and equivalent potential temperature θ_e were used to characterize the stratification and moist thermodynamic structure of the sampled layers.

Horizontal vector wind shear was computed from the vertical gradients of the zonal and meridional wind components as

$$S(z) = \left[\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right]^{1/2}. \quad (7)$$

Before differentiation, the wind-component profiles were smoothed using a five-level centered running mean, corresponding to approximately 250 m, in order to reduce small-scale noise before differentiation. The same procedure was applied to the individual Smartie profiles and to the closest operational Vaisälä radiosonde used for comparison.

5.6 Trajectory separation and launch-array variability

The GPS records from the individual Smarties were used to characterize the horizontal displacement and spreading of the five-sonde deployments during ascent. For comparisons at fixed altitude, latitude and longitude from each trajectory were linearly interpolated to the selected height levels. No trajectory position was extrapolated beyond the altitude range sampled by a sonde.

For each grid and altitude z^* , the horizontal separation between every pair of sondes was calculated from their interpolated positions. The maximum pairwise horizontal separation,

$$D_{\max}(z^*) = \max_{j < k} D_{jk}(z^*), \quad (8)$$

was used as a compact measure of the horizontal spreading of the five-sonde ensemble, where D_{jk} is the horizontal distance between sondes j and k at the same altitude. $D_{\max}$ was evaluated at the selected levels reported in Table 1.

A complementary launch-array diagnostic was used to quantify differences in Q across the initial five-sonde sampling geometry. For each sonde, the first valid GPS position in the flight-history file was taken as the launch position. Launch coordinates were expressed as local Cartesian distances (x, y) relative to the mean launch position of each grid, with x positive eastward and y positive northward. Because the launch arrays extended only a few hundred metres, longitude and latitude were converted to local distances using a small-domain approximation.

At each selected altitude z^* , Q was obtained by vertically interpolating the individual profile defined by Eq. (5) to the target height:

$$Q_j(z^*) = q_j(z^*) |\mathbf{V}_j(z^*)|. \quad (9)$$

No horizontal interpolation was applied between launch sites. The resulting diagnostic therefore represents variability among the five sampled profiles indexed by their launch positions, rather than a reconstructed two-dimensional atmospheric field.

Launch positions, rather than the subsequent balloon positions at the selected altitudes, were used to define this horizontal sampling geometry. This preserves the intended configuration of the launch array and keeps this diagnostic distinct from the trajectory analysis, for which the actual drifting balloon positions were used.

The amplitude variability in Q across each launch array was quantified by the relative spread

$$\Delta Q_{\%}(z^*) = 100 \frac{Q_{\max}(z^*) - Q_{\min}(z^*)}{\overline{Q}(z^*)}, \quad (10)$$

where $Q_{\max}$, $Q_{\min}$, and $\overline{Q}$ are, respectively, the maximum, minimum, and mean Q among the five sondes at the same altitude. This metric was used to compare the within-grid amplitude variability of the two deployments.

5.7 Humidity reference for the Marambio sounding

The Base Marambio radiosonde sampled subfreezing conditions from the surface through the lower troposphere. Because standard radiosonde relative humidity is reported with respect to liquid water, the profile was also expressed with respect to ice for $T < 0^\circ\text{C}$. Saturation vapor pressure over ice, $e_i(T)$, was calculated following Murphy and Koop [36], while saturation vapor pressure over liquid water, $e_w(T)$, was obtained from the Goff–Gratch formulation [37]. Relative humidity with respect to ice was then computed as

$$\text{RH}_i = \text{RH}_w \left(\frac{e_w(T)}{e_i(T)} \right), \quad (11)$$

where T is expressed in Kelvin. This conversion was used to distinguish saturation with respect to liquid water from supersaturation with respect to ice in the Marambio profile shown in Fig. 9. The treatment is consistent with previous radiosonde studies in cold environments, where humidity measurements require particular care at subfreezing temperatures [38].

Supplementary information

Table S1: Summary of individual balloon launches during the 28 March 2026 atmospheric-river case in Ushuaia. Smartie launch times were estimated from the corresponding raw flight-history files when available; operational Vaisälä radiosonde times are taken from the SMN file names. Grid labels identify the two five-sonde Smartie deployments.

Launch	Date	Time (UTC)	Sonde type	System	Sonde ID / grid
1	2026-03-28	11:48	Smartie	MPI	11866
2	2026-03-28	13:04	Smartie	MPI	16188
3	2026-03-28	14:05	Smartie	MPI	16189
4	2026-03-28	15:02	Väisälä RS	SMN	—
5	2026-03-28	16:22	Smartie	MPI	16163
6	2026-03-28	17:15	Smartie	MPI	16116
7	2026-03-28	17:59	Väisälä RS	SMN	—
8	2026-03-28	18:30	Smartie	MPI	16138 / Grid 1
9	2026-03-28	18:30	Smartie	MPI	16141 / Grid 1
10	2026-03-28	18:30	Smartie	MPI	16139 / Grid 1
11	2026-03-28	18:30	Smartie	MPI	16140 / Grid 1
12	2026-03-28	18:31	Smartie	MPI	16142 / Grid 1
13	2026-03-28	19:52	Smartie	MPI	16230
14	2026-03-28	21:04	Smartie	MPI	16144 / Grid 2
15	2026-03-28	21:04	Smartie	MPI	16127 / Grid 2
16	2026-03-28	21:04	Smartie	MPI	16143 / Grid 2
17	2026-03-28	21:04	Smartie	MPI	16145 / Grid 2
18	2026-03-28	21:04	Smartie	MPI	16146 / Grid 2
19	2026-03-28	21:55	Väisälä RS	SMN	—
20	2026-03-28	22:51	Smartie	MPI	16224
21	2026-03-29	00:26	Smartie	MPI	16225

ERA5: 850-hPa temperature, geopotential height and wind

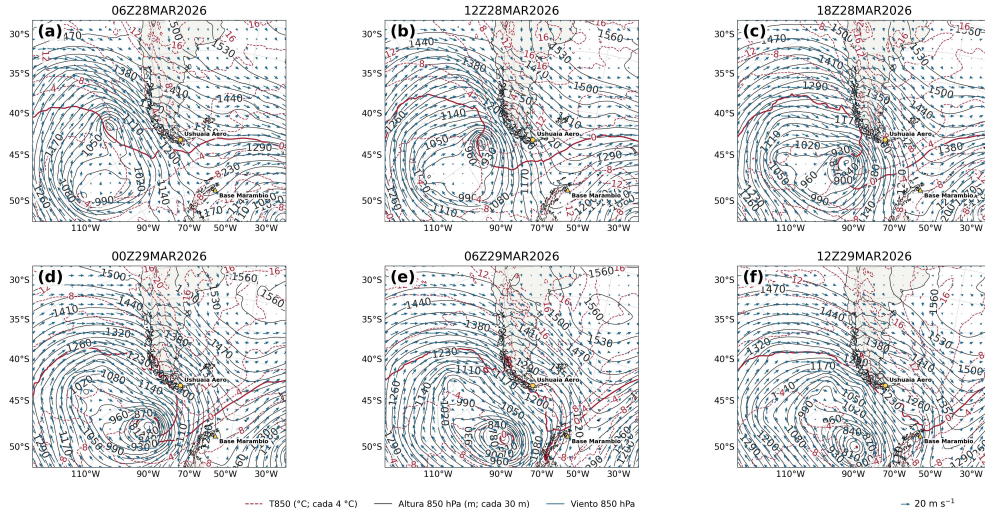


Fig. S1: ERA5 evolution of 850-hPa temperature, geopotential height, and horizontal wind from 06 UTC on 28 March to 12 UTC on 29 March 2026.

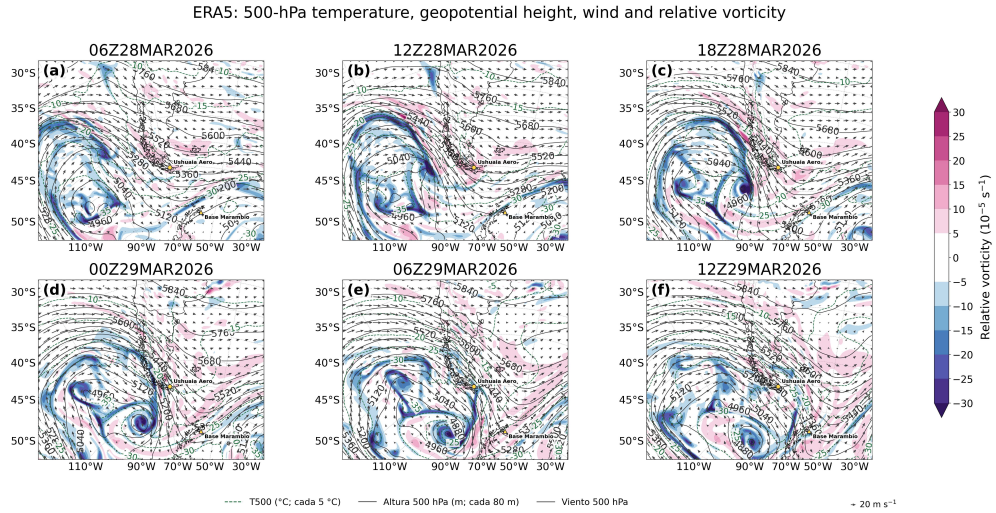


Fig. S2: ERA5 evolution of 500-hPa temperature, geopotential height, horizontal wind, and relative vorticity from 06 UTC on 28 March to 12 UTC on 29 March 2026.

Declarations

The authors declare no competing interests.

Data availability

ERA5 data are available from the ECMWF Copernicus Climate Change Service (C3S) at <https://cds.climate.copernicus.eu>. The complete set of data files used in this study is freely available through Zenodo Rodriguez Imazio et al. [39].

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References

- [1] Gorodetskaya, I.V., Tsukernik, M., Claes, K., Ralph, M.F., Neff, W.D., Van Lipzig, N.P.: The role of atmospheric rivers in anomalous snow accumulation in east antarctica. *Geophysical Research Letters* **41**(17), 6199–6206 (2014)
- [2] Wille, J.D., Favier, V., Gorodetskaya, I.V., Agosta, C., Baiman, R., Barrett, J.E., Barthelemy, L., Boza, B., Bozkurt, D., Casado, M., Chyhareva, A., Clem, K.R.,

- Codron, F., Datta, R.T., Francis, D., Hoffman, A.O., Kolbe, M., Krakovska, S., Linscott, G., MacLennan, M.L., Mattingly, K.S., Mu, Y., Pohl, B., Leroy-Dos Santos, C., Shields, C.A., Toker, E., Winters, A.C., Yin, Z., Zou, X., Zhang, C., Zhang, Z.: Atmospheric rivers in antarctica. *Nature Reviews Earth & Environment* **6**, 178–192 (2025) <https://doi.org/10.1038/s43017-024-00638-7>
- [3] MacLennan, M.L., Winters, A.C., Shields, C.A., Thaker, R., Barthelemy, L., Codron, F., Wille, J.D.: Rising atmospheric moisture escalates the future impact of atmospheric rivers in the antarctic climate system. *Communications Earth & Environment* **6**(1), 369 (2025)
- [4] Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.-K., Rogelj, J., et al.: Climate change 2021: the physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change; technical summary (2021)
- [5] Wille, J.D., Favier, V., Dufour, A., Gorodetskaya, I.V., Turner, J., Agosta, C., Codron, F.: West antarctic surface melt triggered by atmospheric rivers. *Nature Geoscience* **12**(11), 911–916 (2019)
- [6] Turner, J., Marshall, G.J., Clem, K., Colwell, S., Phillips, T., Lu, H.: Antarctic temperature variability and change from station data. *International Journal of Climatology* **40**(6), 2986–3007 (2020)
- [7] Gorodetskaya, I.V., Silva, T., Schmithüsen, H., Hirasawa, N.: Atmospheric river signatures in radiosonde profiles and reanalyses at the dronning maud land coast, east antarctica. *Advances in Atmospheric Sciences* **37**(5), 455–476 (2020)
- [8] Wille, J.D., Favier, V., Jourdain, N.C., Kittel, C., Turton, J.V., Agosta, C., Gorodetskaya, I.V., Picard, G., Codron, F., Leroy-Dos Santos, C., *et al.*: Intense atmospheric rivers can weaken ice shelf stability at the antarctic peninsula. *Communications Earth & Environment* **3**(1), 90 (2022) <https://doi.org/10.1038/s43247-022-00422-9>
- [9] Barthélemy, L., Codron, F., Wille, J., Favier, V., Clem, K.R.: Future atmospheric rivers in antarctica: Characteristics and impacts with the ipsi model. *Journal of Geophysical Research: Atmospheres* **131**(1), 2025–043398 (2026) <https://doi.org/10.1029/2025JD043398> <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2025JD043398>. e2025JD043398 2025JD043398
- [10] Gorodetskaya, I.V., Durán-Alarcón, C., González-Herrero, S., Clem, K.R., Zou, X., Rowe, P., Rodriguez Imazio, P., Campos, D., Leroy-Dos Santos, C., Dutrievoz, N., *et al.*: Record-high antarctic peninsula temperatures and surface melt in february 2022: a compound event with an intense atmospheric river. *npj climate and atmospheric science* **6**(1), 202 (2023)

- [11] Bozkurt, D., Carrasco, J.F., Cordero, R.R., Fernandoy, F., Gómez-Contreras, A., Carrillo, B., Guan, B.: Atmospheric river brings warmth and rainfall to the northern antarctic peninsula during the mid-austral winter of 2023. *Geophysical Research Letters* **51**(13), 2024–108391 (2024)
- [12] Zou, X., Rowe, P.M., Gorodetskaya, I.V., Orr, A., Bromwich, D.H., Lubin, D., Lazzara, M.A., Zhang, Z., Kawzenuk, B., Wille, J.D., Cordeira, J.M., Hansen, N., Li, J., Gan, P., Ralph, F.M.: Föhn-induced melting over larsen c modulated by atmospheric river shape, direction and landfall location. *Nature Communications* (2026) <https://doi.org/10.1038/s41467-026-71359-2>
- [13] Baiman, R., Winters, A.C., Pohl, B., Favier, V., Wille, J.D., Clem, K.R.: Synoptic and planetary-scale dynamics modulate antarctic atmospheric river precipitation intensity. *Communications Earth & Environment* **5**, 127 (2024) <https://doi.org/10.1038/s43247-024-01307-9>
- [14] Bozkurt, D., Rondanelli, R., Marín, J.C., Garreaud, R.: Foehn event triggered by an atmospheric river underlies record-setting temperature along continental antarctica. *Journal of Geophysical Research: Atmospheres* **123**(8), 3871–3892 (2018)
- [15] Torres, C., Bozkurt, D., Favier, V., Buffet, V., Bravo, C., Fettweis, X., Dethinne, T., Rabatel, A., Viale, M., Park, S.-J., Arigony-Neto, J.: Compound intense warming and precipitation events in the patagonian icefields and the antarctic peninsula ice sheet – part 1: Event frequency, atmospheric circulation and impacts on glacier surface. *EGUsphere* (2026) <https://doi.org/10.5194/egusphere-2026-3508> . Preprint
- [16] Buffet, V., Favier, V., Pohl, B., Wille, J.D.: Curved atmospheric rivers and their moisture remnants: a new detection tool for antarctica. *Weather and Climate Dynamics* **7**, 1189–1210 (2026) <https://doi.org/10.5194/wcd-7-1189-2026>
- [17] Kolbe, M., Bintanja, R., Linden, E.C., Cordero, R.R.: Vertical structure and surface impact of atmospheric rivers reaching antarctic sea ice and land. *Atmospheric Research* **315**, 107841 (2025) <https://doi.org/10.1016/j.atmosres.2024.107841>
- [18] Bromwich, D.H., Werner, K., Casati, B., Powers, J.G., Gorodetskaya, I.V., Massonnet, F., Vitale, V., Heinrich, V.J., Liggett, D., Arndt, S., *et al.*: The year of polar prediction in the southern hemisphere (yopp-sh). *Bulletin of the American Meteorological Society* **101**(10), 1653–1676 (2020)
- [19] Sato, K., Inoue, J., Alexander, S.P., McFarquhar, G., Yamazaki, A.: Improved reanalysis and prediction of atmospheric fields over the southern ocean using campaign-based radiosonde observations. *Geophysical Research Letters* **45**(20), 11–406 (2018)
- [20] Choi, Y., Kim, S.-J., Bromwich, D.H., Powers, J.G., Kwon, H., Park, S.-J.: Effects

- of assimilation of yopp-sh additional radiosonde observations on analyses and forecasts over antarctica in austral summer. *Quarterly Journal of the Royal Meteorological Society* **149**(756), 2719–2741 (2023) <https://doi.org/10.1002/qj.4528> <https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.4528>
- [21] Diedrichsen, M.R., Coniglio, M.C., Waugh, S.: An intercomparison of the sparv windsond s1h2 and vaisala rs41-sgp in severe weather environments. *Journal of Atmospheric and Oceanic Technology* **42**, 1601–1615 (2025) <https://doi.org/10.1175/JTECH-D-25-0006.1>
 - [22] Ralph, F.M., Rutz, J.J., Cordeira, J.M., Dettinger, M., Anderson, M., Reynolds, D., Schick, L.J., Smallcomb, C.: A scale to characterize the strength and impacts of atmospheric rivers. *Bulletin of the American Meteorological Society* **100**(2), 269–289 (2019) <https://doi.org/10.1175/BAMS-D-18-0023.1>
 - [23] Zhang, Z., Ralph, F.M., Zou, X., Kawzenuk, B., Zheng, M., Gorodetskaya, I.V., Rowe, P.M., Bromwich, D.H.: Extending the center for western weather and water extremes (cw3e) atmospheric river scale to the polar regions. *The Cryosphere* **18**(11), 5239–5258 (2024)
 - [24] Garreaud, R., Lopez, P., Minvielle, M., Rojas, M.: Large-scale control on the patagonian climate. *Journal of Climate* **26**(1), 215–230 (2013) <https://doi.org/10.1175/JCLI-D-12-00001.1>
 - [25] Viale, M., Valenzuela, R., Garreaud, R.D., Ralph, F.M.: Impacts of atmospheric rivers on precipitation in southern south america. *Journal of Hydrometeorology* **19**(10), 1671–1687 (2018) <https://doi.org/10.1175/JHM-D-18-0006.1>
 - [26] Orr, A., Marshall, G.J., Hunt, J.C.R., Sommeria, J., Wang, C.-G., Lipzig, N.P.M., Cresswell, D., King, J.C.: Characteristics of summer airflow over the antarctic peninsula in response to recent strengthening of westerly circumpolar winds. *Journal of the Atmospheric Sciences* **65**(4), 1396–1413 (2008) <https://doi.org/10.1175/2007JAS2498.1>
 - [27] Orr, A., Kirchgaessner, A., King, J., Phillips, T., Gilbert, E., Elvidge, A., Weeks, M., Gadian, A., Kuipers Munneke, P., Broeke, M., Webster, S., McGrath, D.: Comparison of kilometre and sub-kilometre scale simulations of a foehn wind event over the larsen c ice shelf, antarctic peninsula using the met office unified model (metum). *Quarterly Journal of the Royal Meteorological Society* **147**(739), 3472–3492 (2021) <https://doi.org/10.1002/qj.4138> <https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.4138>
 - [28] Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Liu, Z., Berner, J., Wang, W., Powers, J.G., Duda, M.G., Barker, D.M., Huang, X.Y.: A description of the advanced research WRF model version 4. National Center for Atmospheric Research: Boulder, CO, USA 145 (2019)

- [29] García Skabar, Y., Matsudo, C., Sacco, M., Ruiz, J.J., Righetti, S.: Implementación modelo de pronóstico numérico WRF. Nota Técnica SMN 2018-45. (2018)
- [30] Dillon, M.E., Matsudo, C., García Skabar, Y., Sacco, M.: Implementación del sistema de pronóstico numérico en el HPC: Configuración de los pronósticos determinísticos. Nota Técnica SMN 2020-78 (2020)
- [31] Hines, K.M., Bromwich, D.H.: Development and testing of polar weather research and forecasting (WRF) model. part i: Greenland ice sheet meteorology. *Monthly Weather Review* **136**(6), 1971–1989 (2008) <https://doi.org/10.1175/2007MWR2112.1>
- [32] Powers, J.G., Manning, K.W., Bromwich, D.H., Cassano, J.J., Cayette, A.M.: A decade of antarctic science support through amps. *Bulletin of the American Meteorological Society* **93**, 1699–1712 (2012) <https://doi.org/10.1175/BAMS-D-11-00186.1>
- [33] Manning, K.W., Powers, J.G.: Antarctic Mesoscale Prediction System (AMPS) WRF Outputs. NSF National Center for Atmospheric Research. Accessed 22 September 2026 (2025). <https://gdex.ucar.edu/datasets/d473003/>
- [34] Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.-N.: The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* **146**(730), 1999–2049 (2020) <https://doi.org/10.1002/qj.3803> <https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.3803>
- [35] Schmit, T.J., Griffith, P., Gunshor, M.M., Daniels, J.M., Goodman, S.J., Lebar, W.J.: A Closer Look at the ABI on the GOES-R Series. *Bulletin of the American Meteorological Society* **98**(4), 681–698 (2017) <https://doi.org/10.1175/BAMS-D-15-00230.1>
- [36] Murphy, D.M., Koop, T.: Review of the vapour pressures of ice and supercooled water for atmospheric applications. *Quarterly Journal of the Royal Meteorological Society* **131**(608), 1539–1565 (2005) <https://doi.org/10.1256/qj.04.94>
- [37] Goff, J.A.: Saturation pressure of water on the new kelvin temperature scale. *Transactions of the American Society of Heating and Ventilating Engineers* **63**, 347–354 (1957)

- [38] Jensen, M.P., Holdridge, D.J., Survo, P., Lehtinen, R., Baxter, S., Toto, T., Johnson, K.L.: Comparison of vaisala radiosondes rs41 and rs92 at the arm southern great plains site. *Atmospheric Measurement Techniques* **9**(7), 3115–3129 (2016)
- [39] Rodriguez Imazio, P., Falkinhoff, F., Godoy, A., Zapata, F., Garbarini, E., Auzmendia, D., Bagheri, G., Bodenschatz, E.: Dataset for Multiscale Structure and Evolution of an Intense Atmospheric River from Southern Patagonia Toward the Antarctic Peninsula. <https://doi.org/10.5281/zenodo.23063603>