

Ice Supersaturation and Enhanced Overturning during Antarctic Moisture Intrusions: Observations from the T-SCAN Campaign

PAOLA CAROLINA RODRIGUEZ IMAZIO

PIMAZIO@SMN.GOB.AR

Consejo Nacional de Investigaciones Científicas y Técnicas

PABLO DANIEL MININNI

Universidad de Buenos Aires

ALEJANDRO ANIBAL GODOY

National Meteorological Service

YANINA GARCIA SKABAR

National Meteorological Service

EUGENIA MARIA GARBARINI

National Meteorological Service

FERNANDO NOLLAS

National Meteorological Service

ADRIANA MARIA GULISANO

Argentine Antarctic Institute

VITO VITALE

National Research Council

Article

Keywords: Moisture intrusions, Antarctic Peninsula, overturning, ice supersaturation

Posted Date: October 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11129737/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Ice Supersaturation and Enhanced Overturning during Antarctic Moisture Intrusions: Observations from the T-SCAN Campaign

Paola Rodriguez Imazio^{1,2*†}, Pablo Daniel Mininni^{3,4†},
Alejandro Godoy^{1†}, Yanina García Skabar¹,
Eugenia María Garbarini¹, Fernando Nollas¹,
Adriana María Gulisano^{3,5,6}, Vito Vitale⁷

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

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

³Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales,
Departamento de Física, Intendente Güiraldes 2160, CABA, C1428EGA,
Argentina.

⁴CONICET - Universidad de Buenos Aires, Instituto de Física
Interdisciplinaria y Aplicada, (INFINA), Intendente Güiraldes 2160,
CABA, C1428EGA, Argentina.

⁵CONICET - Universidad de Buenos Aires, Instituto de de Astronomía y
Física del Espacio, (IAFE), Intendente Güiraldes 2160, CABA,
C1428EGA, Argentina.

⁶IAA, Instituto Antártico Argentino, Dirección Nacional del Antártico,
25 de mayo 1143, San Martín, B1650, Buenos Aires, Argentina.

⁷CNR, Consiglio Nazionale delle Ricerche, Istituto di Scienze Polari
(ISP), Via Gobetti 101, Bologna, 40129, Italy.

*Corresponding author(s). E-mail(s): pimazio@smn.gob.ar;
Contributing authors: mininni@df.uba.ar; agodoy@smn.gob.ar;

[†]These authors contributed equally to this work.

Abstract

Moisture intrusions, including Antarctic atmospheric rivers (AARs) and cyclonically driven transport, are major drivers of cloud-layer development and thermodynamic variability over the Antarctic Peninsula, yet their influence on stability, overturning, and vertical mixing remains poorly constrained. Here we analyze 32 high-resolution radiosonde soundings collected during the Turbulence and Supercooled Clouds in Antarctica (T-SCAN) campaign at Marambio Base during the 2025 austral summer, complemented by a limited set of in situ supercooled liquid water measurements from selected flights. Enhanced moisture conditions are associated with deep saturated and ice-supersaturated layers extending up to 6–8 km. Supersaturation with respect to ice accounts for $\approx 60\%$ of saturated-layer depth on average and up to $\approx 90\%$ in individual cases, while supercooled liquid water appears only intermittently in shallow layers. When phase-dependent moist thermodynamics is included in the stability diagnosis, Thorpe-derived overturning becomes more vertically extensive: moist overturning fractions exceed dry estimates in 31 of the 32 soundings, reach $\approx 60\text{--}70\%$ in the strongest cases, and exceed 40% in 72% of the profiles. Our results identify phase-dependent stability as a missing link between large-scale Antarctic moisture transport and small-scale overturning structure. They further show that dry-stability diagnostics can systematically underestimate the vertical extent of resolved overturning in ice-supersaturated polar air masses.

Keywords: Moisture intrusions, Antarctic Peninsula, overturning, ice supersaturation

1 Introduction

The Antarctic atmosphere plays a critical role in the global climate system, influencing large-scale circulation, radiation balance, and cryospheric processes [1–4]. Despite its generally cold and dry conditions, the Antarctic troposphere exhibits complex thermodynamic and dynamical structures, particularly in coastal regions where interactions between synoptic-scale systems and local processes lead to strong variability in cloud properties and vertical transport [5]. Clouds in polar regions are known to exert a strong influence on the surface energy balance and climate feedbacks, yet their microphysical structure and phase composition remain challenging to represent accurately in models [5, 6].

In recent years, atmospheric rivers (ARs) have been identified as a key mechanism for transporting moisture from lower latitudes into Antarctica [7]. These narrow, filamentary structures can dramatically increase the total column water vapor and are frequently associated with extreme precipitation events, surface melting, and changes in cloud phase [8–14]. Observational and modeling studies have shown that ARs play a disproportionate role in Antarctic hydrology and energy balance, particularly over the Antarctic Peninsula, where they can drive extreme warming events and widespread surface melt [13]. In this study, AARs are treated as one subset of polar moisture-intrusion regimes, distinguished by coherent and elongated corridors of enhanced vertically integrated water-vapor transport, whereas cyclonically driven

moisture transport refers more broadly to moisture enhancements associated with nearby low-pressure systems or regional circulation anomalies that do not necessarily satisfy the spatial coherence or persistence criteria of an AAR.

Observations from the Arctic have shown that mixed-phase clouds frequently exhibit a layered structure, with supercooled liquid water often residing near cloud top and ice particles extending below [6]. Field campaigns such as the Mixed-Phase Arctic Cloud Experiment (M-PACE) have documented persistent liquid layers at temperatures as low as -30°C , even in otherwise ice-dominated clouds [15]. These liquid-topped mixed-phase clouds play a central role in Arctic radiation and turbulence, and can persist in both stable and weakly overturning environments [16]. In contrast, Antarctic cloud systems have historically been less well observed, although recent coordinated efforts such as the Year of Polar Prediction–Southern Hemisphere (YOPP-SH) have significantly improved the availability of observations in this region. Existing studies indicate that Antarctic clouds are generally more ice-dominated, particularly at higher altitudes, with mixed-phase conditions largely confined to the lower troposphere [5, 17]. However, the extent to which liquid-topped structures comparable to those observed in the Arctic occur in the Antarctic troposphere, particularly under strongly ice-supersaturated conditions, remains less clear.

In the upper troposphere, ice-supersaturated regions (ISSRs) are frequently observed and can persist over large spatial scales, providing a reservoir of water vapor for cirrus formation [18]. In such environments, radiative cooling at the top of supersaturated layers can reduce static stability and amplify small-scale perturbations, leading to cloud formation through the interaction of large-scale and mesoscale processes [18]. Furthermore, cirrus clouds are often far from thermodynamic equilibrium, with persistent ice supersaturation maintained by vertical motions, mixing, and shallow convective processes [19]. In the Antarctic, cloud systems are predominantly ice-phase at higher altitudes and remain strongly controlled by large-scale dynamics and moisture variability, although their vertical structure and phase composition are still not fully understood [5]. These findings highlight the inherently dynamical nature of ice clouds and the importance of multiscale processes in their evolution.

While the thermodynamic impacts of ARs are increasingly well documented (see, for instance [20]), their influence on turbulence, vertical mixing and radiosonde-diagnosed overturning remains less understood. Recent direct observations from the GODSILA campaign at Syowa Station have nevertheless documented vertically localized turbulent layers and their dynamical sources in the Antarctic atmosphere [21]. In polar environments, where temperatures are often well below freezing, phase changes of water, especially deposition onto ice crystals, can significantly modify static stability through latent heat release [5]. Previous studies have shown that accounting for moist thermodynamics substantially modifies overturning detection and turbulence diagnostics in saturated atmospheric layers, leading to larger overturning scales relative to dry stability estimates [22]. However, the role of these moist processes in AARs and polar moisture-intrusion regimes remains poorly constrained.

In this study, we use observations from the Turbulence and Supercooled Clouds in Antarctica (T-SCAN) field campaign to investigate how Antarctic moisture intrusions, including ARs and broader cyclonically driven moisture transport, modify the

vertical thermodynamic structure of the northern Antarctic Peninsula troposphere. The novelty of the analysis lies in examining moist Thorpe diagnostics in a cold, predominantly ice-supersaturated environment, where ice-phase thermodynamics is expected to play an important role. By combining high-resolution radiosonde observations, phase-dependent stability diagnostics, ERA5 synoptic context, and limited in situ SLWC measurements, we examine how large-scale moisture transport is expressed locally through saturation, ice supersaturation, changes in effective static stability, and radiosonde-diagnosed overturning.

Saturated and ice-supersaturated layers are identified from radiosonde RH profiles using phase-dependent saturation criteria adapted from Zhang et al. [23] and Wilson et al. [22], with height-dependent thresholds used to reduce sensitivity to known radiosonde humidity uncertainties [24]. These diagnosed layers are used to construct a composite potential temperature that accounts for dry and moist stability, from which Thorpe sorting is applied to identify resolved overturning structures and their characteristic vertical scales [25]. Comparison with the corresponding dry calculation isolates the influence of moist and ice-phase thermodynamics on the diagnosed overturning. Throughout the manuscript, these quantities are interpreted as radiosonde-based Thorpe-scale overturning diagnostics relevant to turbulence, rather than as direct measurements of the full turbulent velocity field.

2 Data: the T-SCAN campaign

2.1 In situ data

This study uses data acquired during the Turbulence and Supercooled Clouds in Antarctica (T-SCAN) field campaign, conducted at the Marambio Argentinian station, located on Seymour Island, north of the Antarctic Peninsula (64.23°S–56.63°W), between 12 January and 18 February 2025. The campaign was conducted during the austral summer, when the probability of sampling liquid-containing or mixed-phase cloud layers is greater than during the colder Antarctic season.

During T-SCAN, a total of 32 balloon-borne measurements were performed on a near-daily basis. The observations consist of vertical profiles of temperature (T), relative humidity (RH), pressure (P), wind speed (w_s), wind direction (w_d), and geopotential height (z) obtained from Vaisälä RS41-SGE radiosondes (RS), together with vertical profiles of supercooled liquid water content (SLWC) obtained using Anasphere SLWC probes. Due to unsuitable weather conditions, the SLWC sensors could be launched on only 19 of the 32 flights (see below). The availability and screening of SLWC-probe measurements are summarized in Table 1.

Because radiosonde data from Marambio are assimilated by several operational numerical prediction systems, the nominal launch time was set to 12 UTC. In addition to these nominal launches, the observing strategy included additional launches when forecasts indicated conditions favorable for supercooled liquid water. This targeted strategy was particularly important because direct in situ detection of SLWC in the Antarctic atmosphere is challenging: liquid-containing layers can be shallow and intermittent, while severe surface weather frequently limits balloon operations. Conversely, severe weather occasionally restricted field operations. Strong or gusty winds, which

can exceed 40-50 kt during Antarctic summer in the AP, as well as graupel, rain, or heavy snowfall sometimes prevented radiosonde or cloud sensor deployments. As an operational safety rule, no radiosonde launches were attempted when sustained winds exceeded 23 kt, while the more restrictive wind limit for launching the Anasphere SLWC probes was 17 kt. Radiosonde-only launches were conducted under clear sky or when precipitation (rain, graupel, or snowfall) precluded launching the additional SLWC instrumentation.

Table 1 Summary of RS launching and SLWC probe availability and screening during the T-SCAN campaign. As a reference, note that three ranked AAR events took place during the campaign.

Category	Number of soundings
Total radiosonde soundings	32
Soundings with SLWC probe attached	19
Soundings with potentially usable SLWC signal	5
Soundings with plausible SLWC signatures shown in Fig. 9	3
Plausible SLWC cases shown: flights 1, 5, and 6	
Launch times: 12 Jan 2025 17:23 UTC; 15 Jan 2025 12:00 UTC; 16 Jan 2025 12:00 UTC	

2.2 Numerical data: ERA5

The synoptic and moisture-transport environment during T-SCAN was characterized using the ERA5 reanalysis, which provides hourly atmospheric fields on a regular latitude-longitude grid, with a horizontal resolution of approximately 0.25° [26]. In this study, ERA5 was used to analyze the large-scale circulation affecting Marambio and the northern Antarctic Peninsula during the campaign period.

The main variable used for the identification of Antarctic atmospheric river (AAR) periods was the vertically integrated water vapor transport (IVT). ERA5 provides the vertically integrated eastward and northward water-vapor flux components, from which the IVT magnitude was computed as

$$\text{IVT} = \left[(\text{ivt}_u)^2 + (\text{ivt}_v)^2 \right]^{1/2},$$

where ivt_u and ivt_v are the eastward and northward components of the vertically integrated water-vapor flux, respectively. The ERA5 IVT time series at the grid point nearest to Marambio was used to identify moisture-transport episodes during the campaign and to classify AAR periods following the polar AR scale of Zhang et al. [27].

In addition to the IVT time series, ERA5 fields of IVT magnitude, IVT vectors, mean sea-level pressure, and 2-m temperature were used to examine the spatial structure of the main moisture-transport episodes. These fields were inspected to distinguish direct AAR landfall from moisture enhancements associated with nearby cyclones, troughs, or mesoscale low-pressure systems. This distinction is important because high IVT values at Marambio do not necessarily imply direct landfall of

a coherent AAR corridor; local cyclonic circulation can also recirculate or redirect moisture toward the Antarctic Peninsula.

For comparison with the reanalysis, IVT was also estimated independently from the radiosonde profiles by vertically integrating the horizontal water-vapor flux through the troposphere, as:

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

where q is the specific humidity, u and v are the horizontal wind components, p_s is surface pressure, and $p_t = 300 \text{ hPa}$ is the upper integration limit. This upper limit was chosen following the radiosonde-based Antarctic AR analysis of Gorodetskaya et al. [12], who examined moisture transport profiles from the surface to 300 hPa at Antarctic coastal stations. Because water-vapor mixing ratios and moisture transport are concentrated mainly in the lower and middle troposphere during Antarctic AR events, this limit captures the relevant tropospheric moisture transport while avoiding sensitivity to dry upper-tropospheric and lower-stratospheric layers.

3 Results

The results presented below are derived from the radiosonde, SLWC-probe, and ERA5 datasets described above, using the processing and diagnostic procedures detailed in Section 6 (and Section 2.2 for IVT calculations). Saturated layers are identified from the radiosonde RH profiles using phase-dependent humidity criteria, including correction of RH with respect to ice at subfreezing temperatures. These layers are then used to construct the composite potential temperature θ^* , which accounts for dry and moist stability regimes and is used, together with dry potential temperature θ , in the Thorpe-sorting analysis.

We first establish the synoptic and mesoscale context of the campaign, and then examine the vertical thermodynamic structure, phase-dependent saturation, Thorpe-scale overturning diagnostics, and SLWC observations. The analysis proceeds from representative profiles to campaign-wide statistics in order to connect large-scale moisture transport with the local vertical structure sampled during T-SCAN.

3.1 Synoptic and mesoscale conditions

The synoptic environment over the northern Antarctic Peninsula during the T-SCAN campaign was characterized by alternating periods of AAR-related moisture transport, extra-tropical cyclone activity, mesoscale polar low-pressure systems, and stable blocking patterns. This classification is relevant because previous Antarctic Peninsula studies have shown that ARs can produce strong anomalies in moisture, temperature, precipitation, cloudiness, and near-surface energy fluxes, and can interact with local dynamical processes such as Foehn winds and turbulence [13]. The objective here, however, is not to provide an AAR climatology, but to establish the synoptic context needed to interpret radiosonde, SLWC, cloud-phase, and overturning measurements collected during T-SCAN.

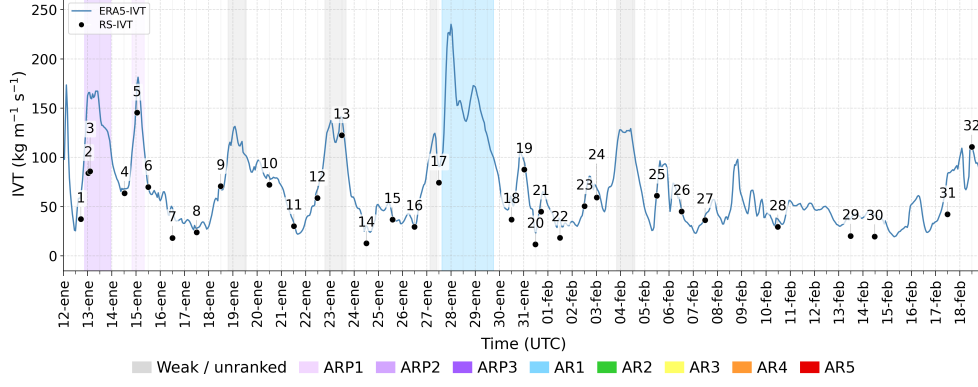


Fig. 1 Temporal evolution of ERA5 IVT at Marambio during the T-SCAN campaign, with detected AAR periods classified following the polar AR scale in [27]. Shading indicates the corresponding event category. Points denote IVT obtained from RS data and computed according to Eq. (1).

Figure 1 shows the ERA5 IVT time series at Marambio, together with the detected AAR periods and their corresponding AR categories according to [27]. IVT computed from RS data following Eq. (1) are also shown. Two main AAR-related periods were identified during the campaign, together with one weaker secondary moisture pulse. The first AAR-related period occurred between 12 January 2025 at 21 UTC and 13 January 2025 at 23 UTC, lasting 27 h and reaching a maximum IVT of $167.3 \text{ kg m}^{-1} \text{ s}^{-1}$, corresponding to ARP2 category. A secondary moisture enhancement occurred between 14 January 2025 at 20 UTC and 15 January 2025 at 08 UTC. Although this event reached a maximum IVT of $181.4 \text{ kg m}^{-1} \text{ s}^{-1}$ and formally satisfied ARP1 criteria from the Eulerian IVT time series, its spatial organization differed substantially from the main AAR episodes. The clearest and most persistent AAR event occurred between 27 January 2025 at 15 UTC and 29 January 2025 at 18 UTC, lasting 52 h and reaching a maximum IVT of $235.2 \text{ kg m}^{-1} \text{ s}^{-1}$. This event corresponds to AR1 category, and represents the most coherent AAR structure observed during the campaign.

Radiosonde-derived IVT values computed following Eq. (1) are shown as discrete points in Fig. 1 to provide an in situ reference for the ERA5 time series. Although the temporal variability is generally consistent between both datasets, ERA5 tends to overestimate the radiosonde-derived IVT at Marambio, particularly during periods of enhanced moisture transport. This difference is expected given the point-like nature of the radiosonde estimate, the horizontal displacement of the balloon during ascent, and the grid-box representation of moisture and wind fields in ERA5.

Figure 2 shows panels with ERA5 IVT magnitude, mean sea-level pressure, and 850 hPa temperature for the main January moisture-transport episodes identified in Fig. 1 (i.e., 13, 15 and 28 of January 2025, from left to right, respectively). On 13 January (Fig. 2a), enhanced meridional moisture transport extended from mid-latitudes toward the northern Antarctic Peninsula within the warm conveyor-belt sector of an

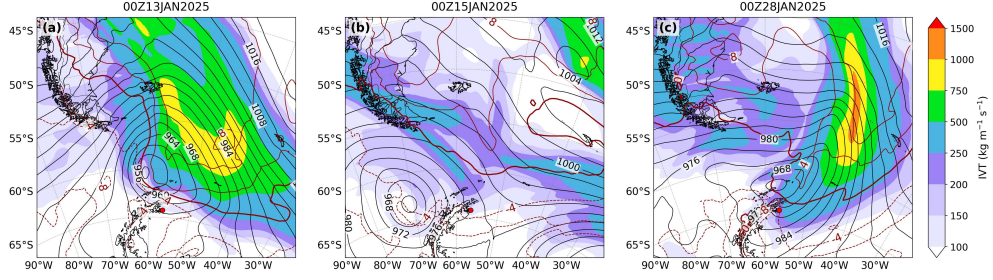


Fig. 2 ERA5 synoptic conditions during the main January moisture-transport episodes affecting Marambio. Shading indicates IVT magnitude, black contours denote mean sea-level pressure, and red contours show 850 hPa temperature. Zero degrees isotherm is highlighted in bold red. Panels correspond to (a) 00 UTC 13 January 2025, associated with enhanced moisture transport east of Marambio; (b) 00 UTC 15 January 2025, showing a secondary cyclonically driven moisture enhancement; and (c) 00 UTC 28 January 2025, corresponding to the most coherent AAR structure during the campaign. The red dot indicates the Marambio Base.

extratropical cyclone. However, the main IVT axis remained displaced east of Marambio, indicating that the moisture increase observed at the station was likely favored by the surrounding cyclonic circulation rather than by direct landfall of the strongest AAR core.

The secondary IVT enhancement on 15 January (Fig. 2b) exhibited a different spatial organization. Rather than forming a coherent and elongated AR corridor, the moisture transport was embedded within a cyclonic circulation over the Bellingshausen Sea–Antarctic Peninsula sector. This pattern suggests that part of the moisture associated with the earlier AAR was subsequently recirculated and redirected to the Peninsula by evolving low-pressure systems. Therefore, this episode is interpreted as a cyclonically driven moisture enhancement rather than as an independent major AAR landfall. The evolution of this secondary moisture enhancement is illustrated in Supplementary Animation S1. The animation also provides context for the transition from direct AAR influence to cyclonically driven moisture transport during the campaign.

In contrast, the late-January event showed a substantially more coherent and elongated IVT corridor directly oriented toward the Antarctic Peninsula and Marambio (Fig. 2c). This event was associated with a deep extratropical cyclone, which improved meridional moisture transport and produced strong winds over the northern Antarctic Peninsula. Unlike the earlier episodes, the IVT structure exhibited the narrow, persistent geometry characteristic of direct Antarctic atmospheric river landfall. At the surface, this event coincided with significant snowfall and a marked temperature decrease at Marambio.

Outside the main AAR events, the synoptic environment over the Antarctic Peninsula was dominated by frequent passages of synoptic-scale extratropical cyclones and mesoscale low-pressure systems embedded within the circumpolar flow. These systems favored cloudy conditions, snowfall, drizzle, intermittent lower-tropospheric moisture enhancements, and periods of strong winds, particularly through moisture advection from the Weddell and Bellingshausen Sea sectors. Nevertheless, most of these

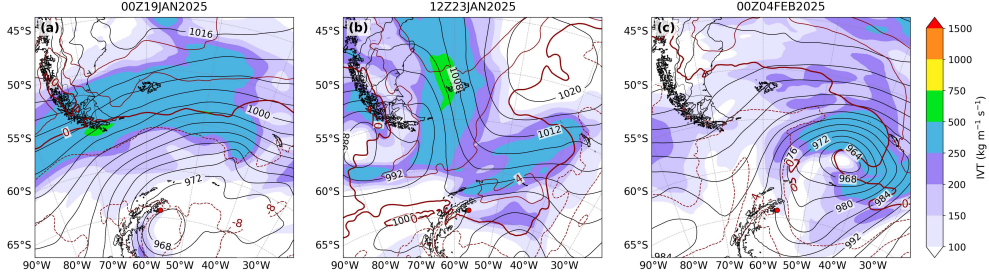


Fig. 3 Representative non-AAR synoptic regimes during the T-SCAN campaign. Shading indicates IVT magnitude, black contours denote mean sea-level pressure, and red contours show 850 hPa temperature. Zero degrees isotherm is highlighted in bold red. Panels correspond to (a) 00 UTC 19 January 2025; (b) 12 UTC 23 January 2025; and (c) 00 UTC 04 February 2025. The red dot denotes the Marambio Base.

episodes lacked the duration, spatial coherence, and elongated IVT geometry characteristic of direct AAR landfall. After the first moist period (i.e., from 12 to 15 of January), several cyclonic systems affected the region during mid-January. Moisture transport during these episodes, characterized by moderate peaks of IVT values between $\sim 100\text{--}135 \text{ kg m}^{-1} \text{ s}^{-1}$ (see gray shaded events in Fig. 1), was mainly associated with local cyclonic circulation rather than with organized and persistent atmospheric river structures.

Figure 3 shows panels with ERA5 IVT magnitude, mean sea-level pressure, and 850 hPa temperature for the three representative non-AAR synoptic configurations during the T-SCAN campaign. On 19 January (Fig. 3a) the IVT field shows moderate values east of the Antarctic Peninsula, while the main moisture-transport axis remains displaced from Marambio. Mean sea-level pressure contours indicate broad anticyclonic or weak-gradient conditions over the Bellingshausen Sea–Antarctic Peninsula sector, with no narrow IVT corridor directed toward the station. On 23 January (Fig. 3b), IVT values near Marambio remain weak to moderate, and the pressure field again lacks a deep cyclone or elongated moisture plume intersecting the northern Antarctic Peninsula. A clear warm anomaly is also evident in the 850 hPa temperature field, where the 0°C isotherm shows a pronounced southward excursion toward the Antarctic Peninsula. These two cases correspond to the relatively stable and warm period identified during 19–25 January, when clearer conditions and unusually warm surface temperatures were observed at Marambio.

On 4 February (Fig. 3c), the pressure field shows a cyclonic system affecting the Drake Passage–Weddell Sea sector. In this case, localized IVT enhancements occur around the Antarctic Peninsula, but the moisture transport is organized around the cyclonic circulation rather than as a persistent, elongated AAR corridor. This pattern is consistent with the strong winds and localized moisture enhancements observed during the fourth week of measurements. During the final part of the campaign, from 9 to 18 February (fifth and sixth weeks), fewer measurements were possible due to prolonged strong winds and more stable synoptic conditions. This period was dominated by persistent southerly flow and the advection of polar air masses, which limited

the transport of moisture from lower latitudes toward Marambio. Consequently, no relevant AAR event was identified during this final stage of the campaign.

Overall, the synoptic analysis demonstrates that not all moisture enhancements observed at Marambio corresponded to direct Antarctic atmospheric river landfall. Enhanced saturation, ice supersaturation, cloud-layer development, and overturning occurred both during direct AAR influence and during cyclonically driven moisture advection associated with extratropical cyclones and mesoscale low-pressure systems. Therefore, this synoptic classification provides a physical framework for distinguishing radiosonde observations collected under direct AAR conditions from those associated with weaker cyclonic moisture transport or non-AAR polar regimes.

3.2 Vertical profiles and thermal structure

The radiosonde observations presented in this section reflect the variety of synoptic environments identified during the T-SCAN campaign, including direct AAR influence, cyclonically driven moisture transport, and more stable polar regimes. Several profiles associated with enhanced moisture and saturation conditions occurred during periods dominated by extratropical cyclones and mesoscale low-pressure systems rather than during direct AAR landfall. This distinction is important because similar thermodynamic signatures were observed under both coherent AAR conditions and localized cyclonic moisture advection.

Figure 4 shows the weekly temperature profiles during the campaign, compared against an above sea level (ASL) climatology computed from the 1987-2024 period. Colored lines represent individual profiles for each week, the dashed black line denotes the ASL climatological mean, and the shaded gray area indicates the 10%–90% climatological percentiles. The different number of profiles in each panel reflects the launch opportunities described in Section 2, with weeks 1 (from 12 to 18 January) and 3 (from 26 January to 1 February) containing the largest number of soundings.

The profiles show substantial variability in the lower and middle troposphere, consistent with the sequence of synoptic regimes described in Sec. 3.1. During the first week, when the campaign sampled the initial AAR-related moisture intrusion and the subsequent cyclonically driven moisture enhancement, the profiles exhibit marked thermal variability through much of the troposphere. This variability provides the thermal background against which the humidity, saturation, and stability structure are examined in the following sections. During the second week, profiles are comparatively warmer in the lower troposphere, consistent with the more stable and warm conditions associated with weak-gradient or blocking-like circulation over the Bellingshausen Sea sector, also in agreement with the southward displacement of the 0°C isotherm in the non-AAR synoptic examples shown in Fig. 3a, 3b. In contrast, the late-January and early-February profiles show stronger vertical variability, reflecting the transition toward the most coherent AAR event and subsequent cyclonic disturbances.

Figure 4 also shows that subfreezing conditions extend through much of the troposphere during the campaign, with temperatures generally remaining above the homogeneous-freezing threshold (-38°C , see Section 6). The depth and altitude of this layer vary between weeks, reflecting the changing thermal structure associated

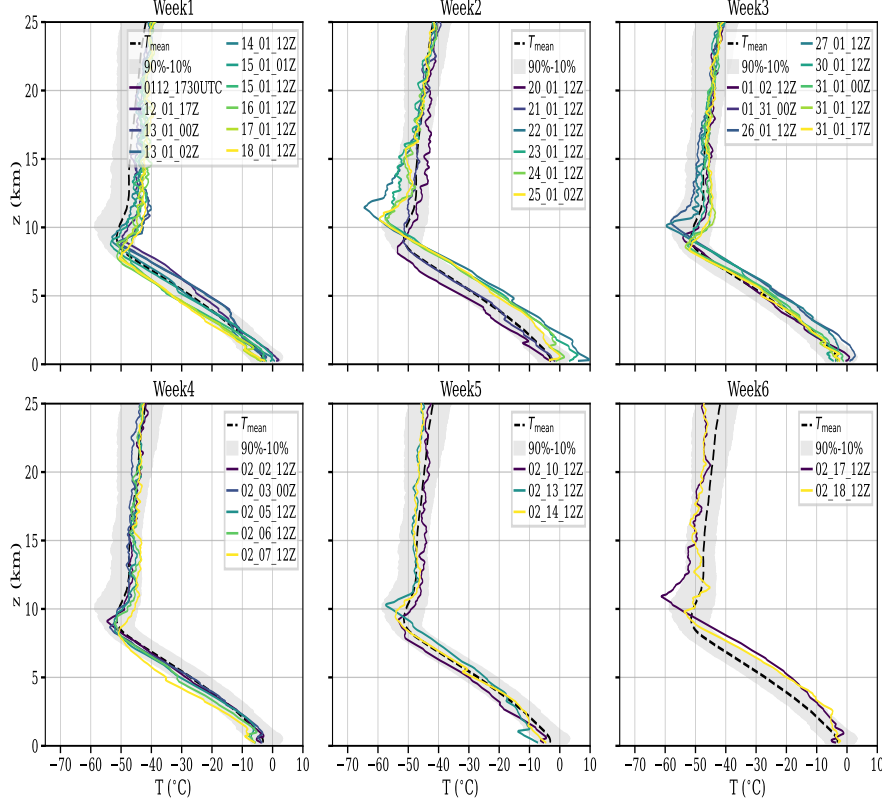


Fig. 4 Vertical profiles of the temperature obtained from RS launching during the T-SCAN campaign, ordered by week. Color lines represent individual profiles for each week, the dashed black line denotes the above sea level (ASL) climatological mean (1987–2024), and the shaded gray area indicates the 10%–90% climatological percentiles

with the different synoptic regimes. This provides the temperature context for the humidity, cloud-phase, and stability diagnostics examined below.

A recurrent tropopause-level inversion is also evident in most profiles, generally between 8 to 12 km. This feature indicates substantial UTLS variability during the campaign and may reflect frequent upper-level dynamical disturbances affecting the northern Antarctic Peninsula. However, the analysis below focuses primarily on the tropospheric cloud-bearing layers, where saturation, ice supersaturation, and phase-dependent stability corrections are most relevant.

The following section examines representative case studies of the campaign, combining temperature, dew-point temperature, RH, RH_{ice}, and dry and moist stability diagnostics to show how the thermal background in Fig. 4 can be used to study cloud-layer structure and overturning.

3.3 Representative profiles and Thorpe-scale diagnostics

Figure 5 shows the vertical profiles of the temperature (dry-bulb, T , and dew point T_d , left panels), relative humidity over liquid and ice (RH and RH_{ice} , middle panels), and dry and moist potential temperatures θ and θ^* (right panels). Ice and moist corrections (i.e., RH_{ice} and θ^*) were computed following the methods described in Sections 6.2 and 6.3, respectively. From top to bottom, the profiles in Fig. 5 correspond to flights 2, 14 and 19 (launched on 13 Jan 2025 00:00 UTC, 24 Jan 2025 12:00 UTC, and 31 Jan 2025 00:00 UTC). These selected profiles represent contrasting synoptic environments, including direct Antarctic atmospheric river influence and cyclonically driven moisture transport, mediated by comparatively stable conditions. Flights close to the dates of atmospheric-rivers (AR) crossing the north of the AP show the deepest cloud layers (notably flights 2 and 19). As we shall see later, these conditions of enhanced saturation and moisture prevail over the rest of the flights made during the campaign.

As mentioned in Sec. 3.2, temperature profiles exhibit sharp inversions with tropopause heights of 8.8, 10.7 and 8.64 km for flights 2, 14 and 19, respectively, which are mirrored by sharp drops in RH above those levels. Cloud layers (where $T \approx T_d$) occupy much of the troposphere in flights 2 and 19, whereas flight 14 contains thinner cloud layers that are less obvious from inspecting T vs. T_d alone. The RH and RH_{ice} profiles make the cloud base and top, as well as the magnitude of ice supersaturation, explicit. The height-dependent RH_{min} and RH_{max} thresholds used to identify saturated layers are also shown in the middle panels, following the criteria described in Sec. 6.2; cyan shading denotes the resulting diagnosed saturated regions. In all three cases the supersaturated layers agree well with regions where T and T_d are nearly equal.

Above ≈ 2 – 3 km the profiles indicate ice-dominated conditions ($RH_{ice} > 100\%$), while below the boundary layer mixed phase conditions (coexisting liquid and ice) are likely to occur, as expected from coastal Antarctic observations (see, for instance, e.g., Bromwich et al. [5], Listowski et al. [17]). In the right panels of Fig. 5 it can be seen how incorporating supersaturation with respect to ice in the RH profiles steepens the gradient of the potential temperature θ^* relative to dry θ , particularly where thick saturated/supersaturated layers are present (flights 2 and 19). This is an indicator that phase changes and ice supersaturation substantially modify vertical stability. It is important to note that, above the tropopause, where dry atmospheric conditions prevail, both dry and moist potential temperature have similar gradients.

Figure 6 presents the vertical distribution of the Thorpe length (L_T , see equation (12) of Section 6.4) obtained from dry (θ) and moist (θ^*) potential temperature profiles of the three selected flights. The lower panels show the corresponding squared vertical wind-shear magnitude, $S^2 = (\partial u / \partial z)^2 + (\partial v / \partial z)^2$, computed from smoothed radiosonde wind profiles. In all cases, (L_T) values derived from θ^* (white bars) are systematically larger and more vertically extensive than those based on θ (gray bars), particularly within the cloud-bearing and supersaturated layers identified for each flight (see cyan regions in the mid panels of Fig. 5). This reflects the enhanced instability produced when latent heat release from ice-phase processes is included in the buoyancy correction. The strongest differences appear between 2 km and 8 km,

coinciding with regions of mixed-phase or ice-supersaturated conditions, whereas in the dry upper troposphere the two estimates converge. Several enhanced L_T^* layers occur close to localized maxima in S^2 , particularly in flights 2 and 19. Although the radiosondes do not provide direct velocity-based verification of turbulence, the selected profiles show layers where moist static stability is strongly reduced, resolved Thorpe displacements are present, and vertical wind shear is locally enhanced. This combination indicates overturning in a dynamically favorable environment for turbulence generation or maintenance, rather than a purely thermodynamic diagnosis of potential instability. In these profiles it can be directly seen that neglecting moist effects can lead to a substantial underestimation of overturning depth within cloudy layers. The enhancement of L_T under moist conditions is therefore consistent with a weakening of static stability and an increased susceptibility to overturning driven by phase changes of water. Because ice-saturated conditions prevail in these profiles, deposition-related latent heating is likely to contribute more strongly than liquid-water condensation to the moist stability correction. As will be shown in Sec. 3.4, these conditions are observed in all the profiles obtained throughout the campaign.

Finally, since L_T represents the vertical displacement required for an air parcel to recover static stability, it can also provide an estimate of the size of resolved overturning structures. Under the assumption of local isotropy, L_T is commonly related to the Ozmidov scale L_O (the scale at which overturning motions become comparable to buoyancy-dominated motions) through $L_T = KL_O$, with $L_O = (\varepsilon/N^3)^{1/2}$. This relation allows an indirect, order-of-magnitude estimate of the turbulence kinetic energy dissipation rate ε from the observed overturning scale, provided that the assumptions linking L_T and L_O are applicable.

Taking typical values for the dimensionless constant K (0.8–1, see, for instance, [28, 29]), the typical overturning scales obtained in this study ($L_T \approx 50$ –200 m), together with a representative weakly stratified value $N \approx 5 \times 10^{-3} \text{ s}^{-1}$, yield dissipation rates in the range $\varepsilon \approx 2 \times 10^{-4}$ – $8 \times 10^{-3} \text{ m}^2 \text{ s}^{-3}$. The corresponding eddy dissipation rate (EDR), defined as $\text{EDR} = \varepsilon^{1/3}$ and commonly used as a flag parameter to describe the severity of turbulence in aviation (see, for instance, [30–33]), is approximately 0.06–0.20 $\text{m}^{2/3} \text{ s}^{-1}$, suggesting dynamically significant overturning scales where the assumptions relating L_T to L_O are applicable, particularly within moist and supersaturated layers.

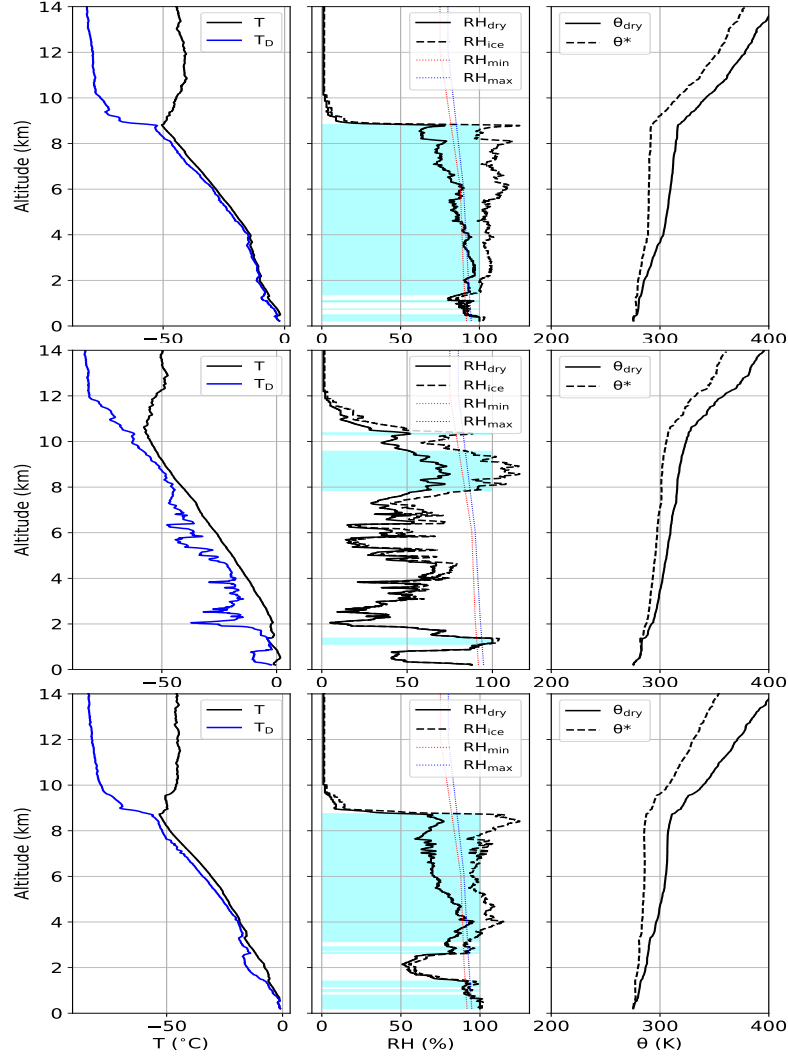


Fig. 5 Vertical profiles of temperature (T), dew-point temperature (T_d), relative humidity with respect to liquid water (RH), relative humidity with respect to ice (RH_{ice}), dry potential temperature (θ), and moist potential temperature (θ^*) for flights 2, 14, and 19 (13 January 2025 00:00 UTC, 24 January 2025 12:00 UTC, and 31 January 2025 00:00 UTC, respectively) during the T-SCAN campaign. In the RH panels, the dotted and dashed reference curves indicate the height-dependent RH_{min} and RH_{max} thresholds used to diagnose saturated layers, and cyan shading denotes the identified saturated regions (see Sec. 6.2).

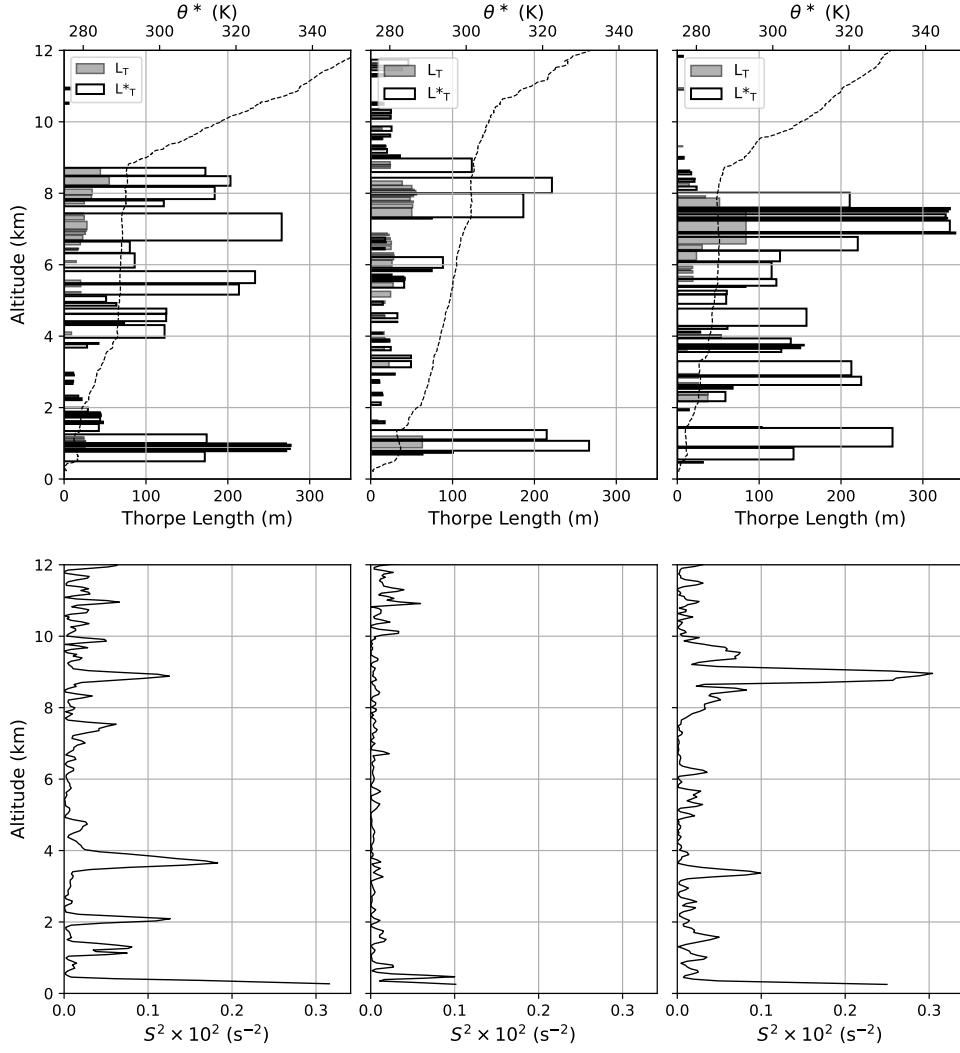


Fig. 6 Vertical distribution of the Thorpe length (L_T) estimated from dry (θ ; gray bars) and moist (θ^* ; white bars) potential temperature profiles for the same flights of Fig. 5 (2, 14, and 19, from left to right). The corresponding moist potential temperature profiles are displayed as a reference on each panel (dotted lines). The lower panels show the squared vertical wind-shear magnitude, S^2 , computed from smoothed radiosonde wind profiles. Enhanced overturning depths derived from θ^* occur primarily within cloud-bearing and ice-supersaturated layers (see Fig. 5), indicating that moist processes substantially increase the diagnosed overturning depth relative to dry stability estimates.

3.4 Campaign-wide saturation and overturning statistics

Figure 7 shows the fractions of saturated and supersaturated layers for the 32 radiosonde soundings, computed both over the full tropospheric column and below 3 km. This figure provides a statistical view of the cloud-phase environment sampled during T-SCAN. Saturation with respect to ice dominates the full tropospheric column, whereas saturation with respect to liquid water is mostly confined to the lowest levels. Below 3 km, liquid-water saturation becomes more frequent but remains vertically limited, with the largest fractions corresponding to shallow portions of the lower troposphere (≈ 1 km). This indicates that mixed-phase or liquid-containing conditions were mostly shallow and boundary-layer-confined.

In contrast, supersaturation is overwhelmingly associated with RH_{ice} , both in the full column and below 3 km. This result indicates that the moist layers sampled during the campaign were not simply near-saturated with respect to liquid water, but frequently ice-supersaturated. On average, approximately 60% of saturated layers were supersaturated with respect to ice, reaching up to $\approx 90\%$ in individual soundings (e.g., flights 2, 3, 5, and 24). This vertical phase structure is important because it implies that the moist correction to static stability is primarily controlled by ice-phase processes, especially deposition-related latent heating, rather than by condensation alone. The saturated-layer statistics provide the thermodynamic basis for interpreting the subsequent overturning analysis.

Figure 8 shows the total Thorpe-diagnosed overturning fraction estimated from the dry and moist stability criteria (labeled as L_T and L_T^* , respectively) for the 32 soundings. These fractions were computed as the total depth of the identified overturns (such as those shown in Fig. 6) normalized by the tropopause height for each flight. This quantity represents the fraction of the tropospheric column occupied by resolved and accepted overturning structures, rather than a direct measurement of the overturning fraction at all scales. The overturning fraction is underestimated by the dry diagnostic in 31 of the 32 flights (97%), and in 3% of the cases this underestimation exceeds 50%. While the dry fraction generally remains below 40% of the tropospheric depth, reaching a maximum of $\approx 41\%$, the moist fraction reaches values of $\approx 60\text{--}70\%$ in extreme cases, and exceeds 40% in 72% of the soundings. This systematic increase reflects the sensitivity of Thorpe-diagnosed overturning to the treatment of moist stability, particularly within cloud-bearing and supersaturated layers. The phase structure quantified in Fig. 7 indicates that many of these layers were supersaturated with respect to ice; therefore, the larger overturning fractions obtained from L_T^* are mainly associated with the reduction of effective static stability by ice-phase thermodynamics, rather than with liquid-water condensation alone.

Although several of the largest moist overturning fractions occur during or near moisture-enhanced periods, the relationship with IVT is not monotonic. For example, flight 32 occurred under relatively elevated IVT but shows only a modest moist correction, indicating that the impact of moist thermodynamics depends not only on the column-integrated moisture transport but also on the vertical distribution of saturation, cloud phase, and static stability. Thus, IVT provides useful synoptic context for moisture availability, but the diagnosed overturning enhancement is controlled by the local thermodynamic structure sampled by each radiosonde.

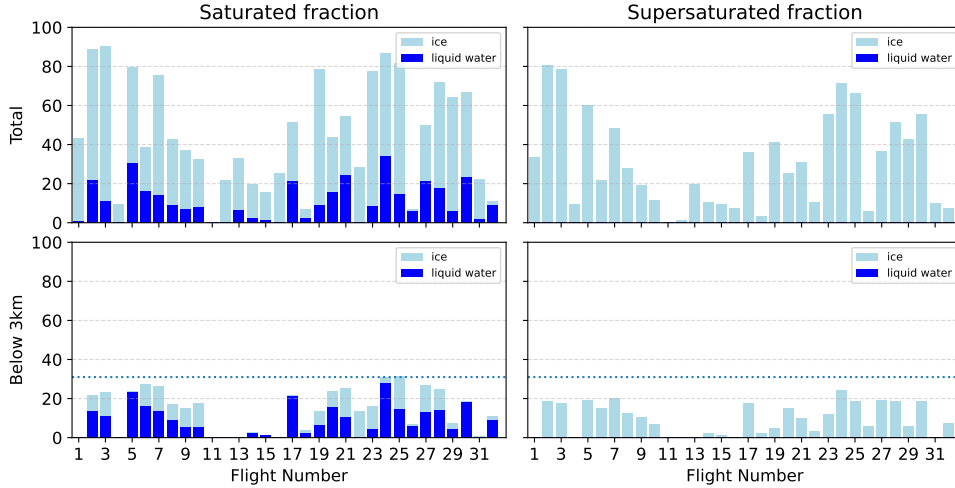


Fig. 7 Fraction of saturated (left panels) and supersaturated (right panels) layers for the 32 radiosonde flights during the T-SCAN campaign. Top panels show the fractions computed over the full tropospheric column, while bottom panels show only the portion below 3 km altitude. Saturation and supersaturation with respect to ice (cyan) and liquid water (blue) were derived from RH_{ice} and RH , respectively.

3.5 Supercooled liquid water signatures

The occurrence of supercooled liquid water was assessed using the Anasphere vibrating-wire probes, which were launched in 19 of the 32 radiosonde soundings. Of the 19 soundings with SLWC probes, only 5 showed potentially usable signals, and 3 exhibited plausible SLWC signatures, as summarized in Table 1. The SLWC observations are therefore used here as qualitative evidence of localized liquid-containing layers rather than as a campaign-wide statistical characterization. One example of a usable SLWC-probe profile without a plausible non-zero SLWC signature is shown in Supplementary Figure S2. This profile illustrates the screening distinction between technically usable vibrating-wire data and thermodynamically consistent SLWC detections.

Figure 9 shows the vibration frequency of the wire as a function of altitude for the plausible SLWC signature cases (namely flights 1, 5, and 6). The shaded areas represent the permitted SLWC zone, defined by favorable thermodynamic conditions for the persistence of supercooled liquid droplets (relative humidity greater than 80% and temperatures warmer than -39°C). Within this region, variations in the vibrating-wire frequency are consistent with intermittent liquid-water accretion.

For the three flights, observed wire frequencies fluctuate around the natural frequency of ≈ 22 Hz, with values typically ranging between approximately 15 and 25 Hz. Localized deviations of several Hz from this baseline occur within relatively narrow vertical intervals, exceeding the typical background variations reported in previous studies for mid-latitudes (on the order of 2–4 Hz, see, for instance [34]). These enhanced fluctuations suggest intermittent but detectable liquid water accretion onto

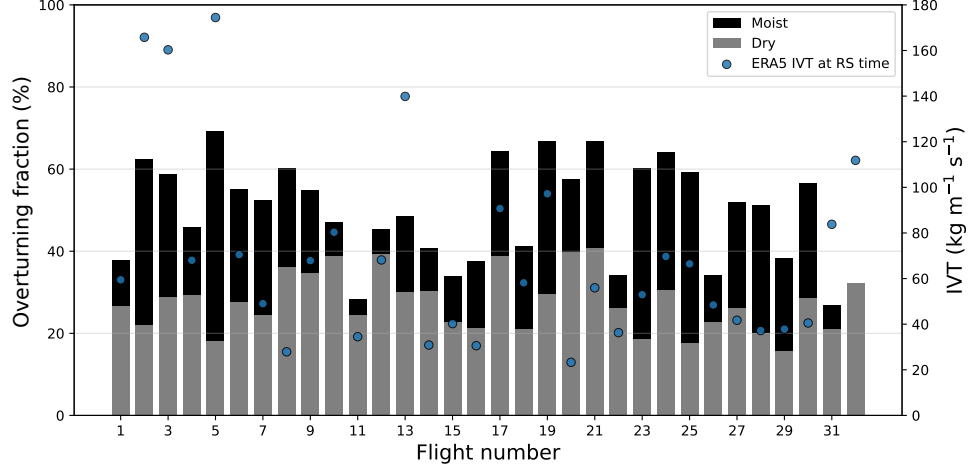


Fig. 8 Total overturning fraction estimated from dry and moist instability diagnostics for the 32 radiosonde soundings. Fractions were computed as the total depth of identified overturning regions normalized by the tropopause height for each flight. Gray bars represent overturning fractions estimated using the dry potential temperature (resulting in L_T), while white bars use the moist potential temperature (or L_T^*). ERA5 IVT is sampled at the radiosonde launch times, and shown to indicate the moisture-transport environment associated with each sounding. The full ERA5 IVT evolution, including periods without radiosonde launches, was shown in Fig. 1.

the probe. Notably, such frequency perturbations are confined to shallow layers, often less than a few hundred meters thick, embedded within broader cloud structures. In several portions of the profiles, enhanced frequencies occur within the permitted thermodynamic region, consistent with the presence of supercooled liquid droplets embedded within predominantly ice-phase cloud layers. However, below approximately 2 km, the presence of droplets cannot be interpreted unambiguously as in-situ SLWC formation, since small droplets may originate from drizzle or sedimentation from higher cloud layers.

In flight 1 (left panel of Fig. 9), the largest wire-frequency perturbation occurs near ≈ 6 km, within the thermodynamically permitted SLWC zone, while smaller oscillations are also present at lower levels. In flight 5 (mid panel of Fig. 9), the wire frequency exhibits several sharp excursions between approximately 6 and 8 km, together with weaker fluctuations in the lower troposphere. In flight 6 (right panel of Fig. 9), the strongest perturbations are concentrated mostly below ≈ 4 km, with additional narrow excursions near 6–7 km. In all three cases, the frequency perturbations are vertically localized rather than distributed continuously throughout the permitted SLWC zones.

The timing of the plausible SLWC signatures also shows that the connection between large-scale moisture transport and liquid-water occurrence is not direct. Flight 1 was launched during the initial AAR-related moisture period, and flight 5 occurred during the subsequent secondary moisture enhancement. In contrast, flight 6 is not related with any clear AAR maximum in the time series of IVT (see Fig. 1,

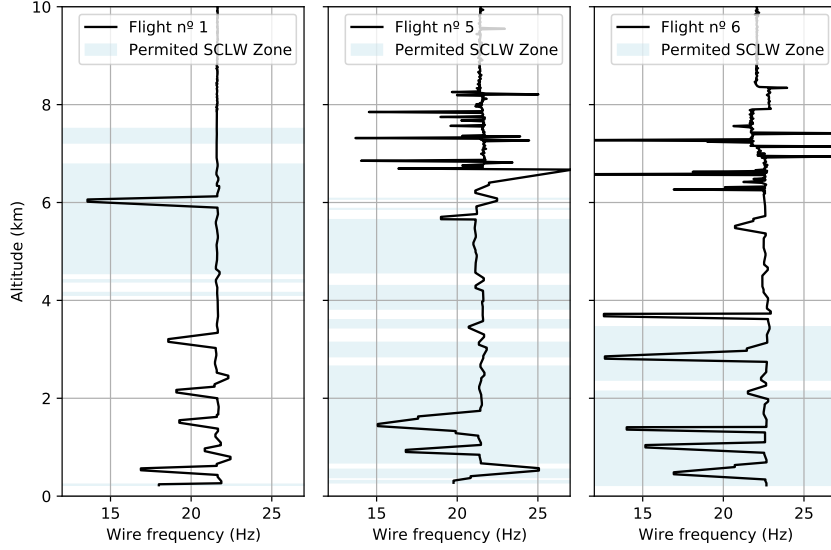


Fig. 9 Vertical profiles of vibrating-wire frequency for flights 1, 5, and 6. Shaded regions indicate the thermodynamically permitted supercooled liquid water cloud (SLWC) zone, defined by temperatures warmer than -39°C and relative humidity greater than 80%. The selected flights correspond to the clearest plausible SLWC signatures among the usable SLWC-probe launches.

on January 16). This indicates that AARs and cyclonically driven moisture intrusions provide favorable large-scale moisture conditions, but the presence of plausible SLWC signatures depends on the local vertical thermodynamic structure, cloud phase, and cloud microphysical evolution sampled by each radiosonde. Therefore, the SLWC observations are interpreted as localized evidence of liquid-containing layers within the broader moisture-intrusion environment, rather than a direct indication of AAR signatures.

The interpretation of these perturbations depends on their thermodynamic context. For flight 1, the upper-level perturbation occurs in a layer where the saturation analysis indicates ice-dominated conditions, making an extended liquid-water layer unlikely but allowing the possibility of a thin and intermittent SLWC pocket embedded within an ice-phase cloud. In contrast, the lower-level oscillations in this flight occur outside layers identified as saturated in Fig. 7; they are therefore not interpreted as local SLWC detections, except possibly as signatures of droplets sedimenting from liquid-containing layers aloft. For flights 5 and 6, the strongest perturbations occur within or near altitude ranges where liquid-water saturation is more thermodynamically plausible (see right panels of Fig. 7), particularly in the lower troposphere, and can be therefore interpreted as the clearest qualitative evidence of shallow liquid-containing layers during the campaign.

To estimate the potential magnitude of the liquid water content, the vibrating-wire response was interpreted using the droplet collection efficiency shown in Fig. 10, which depends on the assumed droplet diameter. The selected droplet size range is representative of supercooled liquid droplets typically observed in polar and stratiform

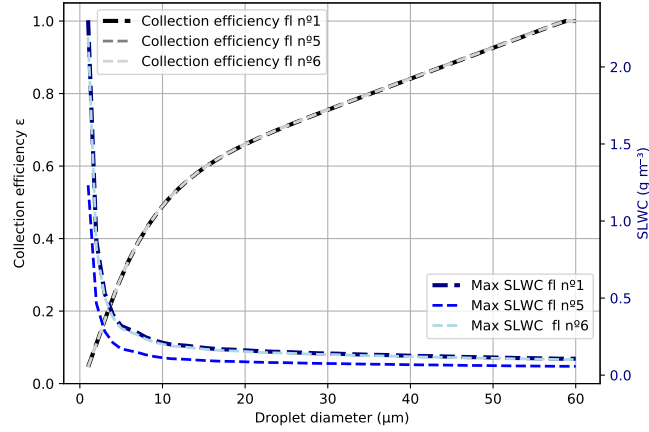


Fig. 10 On the left axis, the droplet collection efficiency of the vibrating-wire probe is shown as a function of the droplet diameter, which is used to estimate the response of the instrument to supercooled liquid droplets. On the right axis, the maximum estimated supercooled liquid water content (SLWC) is shown, as derived for selected flights using the measured vibrating-wire response and the corresponding collection efficiencies.

cloud environments, where droplet diameters are generally on the order of a few to several tens of micrometers (see, for instance [5]). In the present case, the relatively low liquid water content, the shallow vertical extent of the detected layers, and the absence of strong convective signatures suggest that droplet growth is limited, favoring small to intermediate droplet sizes rather than large precipitation-sized particles.

Overall, SLWC signatures are shallow, intermittent, and locally collocated with saturated layers and enhanced moist overturning. Although these observations do not establish a causal relationship, they are consistent with the presence of localized liquid-containing layers embedded within otherwise ice-dominated cloud environments. Because no independent collocated cloud-water instrument was available during T-SCAN, these SLWC estimates are interpreted qualitatively rather than as definitive quantitative retrievals.

4 Discussion

During the T-SCAN campaign (12 January-18 February 2025), the radiosonde soundings captured moisture-intrusion regimes with different degrees of synoptic organization, including direct AAR influence and cyclonically driven moisture advection. This distinction is important because the strongest moisture transport, as measured by IVT, did not map uniquely onto the largest moist overturning corrections. Instead, IVT provided the large-scale context for moisture availability, while the response of the Thorpe-scale overturning diagnostics depended on the vertical thermodynamic structure sampled by each radiosonde.

The representative case studies and campaign-wide statistics (Sec. 3.3 and Sect. 3.4, respectively) show that moisture-enhanced periods were characterized by deep layers where temperature and dew-point temperature nearly coincided, indicating widespread saturation. In many of these layers, particularly above $\approx 2\text{--}3\text{ km}$, saturation occurred with respect to ice rather than liquid water. Thus, the relevant thermodynamic environment was not simply a moist troposphere, but a cold, cloud-bearing column in which ice supersaturation occupied a substantial fraction of the saturated layer depth. This vertical phase structure explains why the relationship between IVT magnitude and overturning fraction is not monotonic: bulk moisture transport is necessary to provide moisture, but the moist correction becomes important only where that moisture is vertically organized into saturated or ice-supersaturated layers with reduced effective stability. The radiosonde-derived shear profiles shown for the representative cases further indicate that several enhanced moist overturning layers occur in dynamically active parts of the wind profile.

The three plausible SLWC signatures likewise do not map uniquely onto the strongest IVT periods, reinforcing the interpretation that large-scale moisture transport provides the environmental context, whereas the occurrence of liquid-containing layers depends on the local vertical distribution of temperature, humidity, saturation phase, and cloud microphysical conditions. Their occasional coincidence with saturated layers and enhanced moist overturning is consistent with localized liquid-containing pockets embedded within an otherwise ice-dominated environment. Turbulent mixing may contribute to their persistence by redistributing heat and water vapor across sharp vertical gradients, although the limited number of robust SLWC cases prevents a quantitative assessment of this pathway. Overall, the moist overturning correction is controlled primarily by the local distribution of saturation, cloud phase, and static stability, with IVT acting as synoptic context rather than as a direct predictor.

The reported Thorpe-scale statistics are therefore interpreted as radiosonde-diagnosed overturning structures relevant to turbulence, rather than as direct measurements of the full turbulent velocity field.

This phase structure also distinguishes the Antarctic Peninsula environment sampled here from liquid-topped mixed-phase cloud structures commonly reported in the Arctic. Arctic mixed-phase clouds often contain persistent supercooled liquid layers near cloud top [6, 15, 35]. In contrast, the T-SCAN profiles show a transition toward ice-dominated conditions with altitude, while liquid-water saturation and plausible SLWC signatures remain shallow, intermittent, and largely confined to localized layers. The SLWC observations therefore provide secondary, qualitative support for the presence of liquid-containing pockets, but they do not indicate vertically extensive liquid-water cloud layers. This behavior is also consistent with Antarctic cloud-phase studies showing that supercooled-liquid and mixed-phase conditions occur in Antarctica but are often shallower and less vertically extensive than in the Arctic [5, 17].

5 Conclusions

This study used 32 high-resolution radiosonde soundings collected during the T-SCAN campaign at Marambio Base during the 2025 austral summer to examine how moisture intrusions, including AAR conditions, modify tropospheric stability and radiosonde-diagnosed overturning over the northern Antarctic Peninsula. By applying Thorpe sorting to both dry potential temperature (θ) and a phase-dependent composite potential temperature (θ^*), we quantified the influence of moist thermodynamics on resolved overturning structures. The moist diagnostic produced more vertically extensive overturning than the dry diagnostic in 31 of the 32 soundings, with the largest overturning fractions reaching approximately 60–70%.

A central result is that these moisture-enhanced periods were characterized by a predominantly ice-supersaturated thermodynamic structure. Supersaturation with respect to ice accounted for approximately 60% of saturated-layer depth on average and up to $\approx 90\%$ in individual cases, whereas liquid-water saturation was largely confined to the lowest ≈ 1 km. The moist correction therefore acted primarily within cold, ice-supersaturated layers, showing that the phase-dependent structure of the Antarctic troposphere is important for radiosonde-based overturning diagnostics and that dry stability estimates systematically underestimate the vertical extent of resolved overturning in these conditions.

These effects can be diagnosed using standard high-resolution radiosonde observations, providing an observationally accessible framework for assessing moist stability and overturning in data-sparse polar environments and for evaluating their representation in numerical weather prediction and climate models. The limited SLWC measurements provide qualitative support for shallow, localized liquid-containing layers embedded within an otherwise predominantly ice-supersaturated environment, but they are not used as the basis for the campaign-wide overturning statistics.

6 Methods

6.1 Radiosonde data and preprocessing

Raw data were processed at 1 Hz to preserve the maximum vertical resolution (≈ 3 – 5 m), following the procedures described by Wilson et al. [28]. Temperature noise levels are typically $\approx 3 \times 10^{-2}$ K. Geopotential altitude was derived from pressure, and thermodynamic variables were recomputed from the raw measurements. Because Antarctic profiles frequently remain below 0°C , we expect predominantly ice-phase clouds and possible supersaturation with respect to ice. In this context, an accurate interpretation of humidity is essential, and therefore raw RH profiles were corrected following the method described below.

As mentioned earlier, data were obtained nearly on a daily basis between 12 January and 18 February 2025. Vertical profiles obtained during this period (32 in total) are grouped in weeks for more clarity, and described in Section 3.2.

6.2 Identification of saturated layers

In standard radiosondes, relative humidity (RH) is reported with respect to liquid water. For temperatures $T < 0^\circ\text{C}$, RH was converted to an ice reference, considering the saturation vapor pressure over ice, $e_i(T)$, computed following Murphy and Koop [36] as,

$$e_i(T) = \exp\left(28.9074 - \frac{6143.7}{T}\right), \quad (2)$$

where T is in Kelvin and e_i is in Pascals. Saturation over liquid water, $e_w(T)$, was obtained using the Goff–Gratch formulation [37]. Then, RH was corrected as:

$$\text{RH}_{\text{ice}} = \text{RH}_{\text{liq}} \left(\frac{e_w(T)}{e_i(T)} \right). \quad (3)$$

To identify cloud layers, we applied the empirical method of [23]. A layer was classified as saturated when

$$\min(\text{RH}) \geq \text{RH}_{\min}(z), \quad (4)$$

$$\max(\text{RH}) \geq \text{RH}_{\max}(z), \quad (5)$$

where the thresholds decrease with altitude (approximately from 95%→80% for $\text{RH}_{\min}$ and 92%→75% for $\text{RH}_{\max}$). For $T < 0^\circ\text{C}$, RH was evaluated with respect to ice also considering the above thresholds, in both cases intended to reduce the impact of cold-environment humidity biases reported in radiosonde sensors [24]. As a result, subsaturation, saturation and supersaturation with respect to liquid water (from RH profiles) or ice (with respect to RH_{ice}) can be studied separately, and will be also applied to the stability criteria.

6.3 Dry and moist stability

Since the formulation of atmospheric stability depends on the thermodynamic regime, dry (subsaturated) and moist (saturated) conditions need to be identified before applying the Thorpe method. In the atmosphere, the dry potential temperature θ is commonly used to describe stability under subsaturated conditions, obtained as:

$$\theta = T \left(\frac{P_0}{P} \right)^{R/c_{pd}}. \quad (6)$$

From this, the associated dry Brunt-Väisälä frequency is

$$N_d^2 = \frac{g}{\theta} \frac{\partial \theta}{\partial z}. \quad (7)$$

To account for latent-heat release in saturated regions, we computed the moist Brunt-Väisälä frequency N_m^2 following Lalas and Einaudi [38]:

$$N_m^2 \approx \frac{g}{T} \left[\left(\frac{\partial T}{\partial z} \right) + \Gamma_m \right] \left(1 + \frac{L_v q_s}{RT} \right) - \frac{g}{1 + q_w} \frac{\partial q_w}{\partial z}, \quad (8)$$

where q_s is the saturation mixing ratio, $q_w \approx q_s$ in clouds, and Γ_m is the moist adiabatic lapse rate. Following Durran and Klemp [39], $\partial q_w / \partial z$ was replaced by $\partial q_s / \partial z$ due to unavailable condensate profiles. For layers identified as saturated with respect to ice, q_s and the latent-heat term in Eq. (8) were evaluated using the ice saturation vapor pressure and the latent heat of deposition, respectively. Liquid-water saturation and the latent heat of vaporization were retained only where the RH-based criteria indicated liquid-saturated conditions. Because no independent vertical profile of condensate mass was available, condensate loading was not included as an observed term in the stability calculation. The resulting moist correction is therefore interpreted as a phase-dependent thermodynamic stability correction based on diagnosed saturation, rather than as a full microphysical representation of cloud condensate.

From all this, we constructed a composite potential temperature θ^* by integrating

$$\theta^*(z + \Delta z) = \theta^*(z) \left(1 + \frac{N^2(z) \Delta z}{g} \right), \quad (9)$$

using N_d^2 in subsaturated layers and N_m^2 in saturated layers. This provides a continuous variable suitable for Thorpe sorting in Antarctic conditions, where deep ice saturated layers are common. From here, modifications to stability given by the extra release of latent heat in moist dynamics will be accounted by θ^* , where dry dynamics is also included by default.

6.4 Thorpe sorting and overturning diagnostics

Once dry and moist conditions were established, the Thorpe method [25] was applied to both θ and θ^* . The moist Thorpe analysis follows the framework proposed by Wilson et al. [22], in which moist-conservative thermodynamic variables are used to better identify overturning structures within saturated atmospheric layers. This method diagnoses overturning by comparing an observed vertical profile of a quasi-conservative variable with a statically stable reference profile obtained through vertical reordering. The resulting vertical displacements quantify overturning structures associated with overturning mixing. In this study, the quasi-conservative variable is the composite potential temperature θ^* , which accounts for both dry and moist stability regimes depending on the presence of saturation.

Let $\theta^*(z_i)$ denote the measured composite potential temperature at level z_i . A reordered profile θ_{sorted}^* is constructed by sorting θ^* into a monotonic increasing sequence such that

$$\theta_{\text{sorted}}^*(z_i^{\text{sorted}}) \leq \theta_{\text{sorted}}^*(z_{i+1}^{\text{sorted}}), \quad (10)$$

ensuring static stability throughout the column.

The Thorpe displacement at each level is then defined as

$$d_i = z_i - z_i^{\text{sorted}}, \quad (11)$$

i.e., the vertical distance an air parcel must be displaced to recover static stability. Positive and negative displacements correspond to air elements that, respectively, lie above or below their displaced positions in the sorted profile. A contiguous sequence of non-zero displacements with alternating signs indicates an overturning region. Since noise can produce spurious small-scale reversals, candidate overturns were classified as valid only when their vertical extent exceeded 30 m and their Thorpe displacement signal exceeded the noise-based selection threshold, following Wilson et al. [28]. This procedure rejects small inversions that cannot be distinguished from instrumental-noise-induced reversals. This is essential in polar conditions, where weak but real overturns may coexist with low signal-to-noise ratios.

For each detected overturn, the Thorpe scale L_T is defined as the root-mean-square (RMS) of the displacements on overturns:

$$L_T = \sqrt{\frac{1}{N} \sum_{i=1}^N d_i^2}, \quad (12)$$

where N is the number of samples within the overturning patch. The overturning fraction for a radiosonde was then computed from the summed vertical extent of accepted overturns located below the independently diagnosed tropopause, and normalized by the tropopause height of each sounding. Given the 3–5 m vertical sampling of the RS41 profiles and the minimum overturn-selection threshold used here, the effective lower detection limit is approximately 30–50 m. Smaller overturns may be missed or rejected as indistinguishable from noise-induced inversions. Therefore, the overturning fractions reported below represent the fraction of the tropospheric column occupied by resolved and accepted overturning structures, not the total overturning fraction at all scales. In Antarctic soundings, this fraction is particularly sensitive to the treatment of saturated layers, where the use of θ^* (rather than dry θ alone) can reveal overturns that would otherwise remain undetected due to the reduction of static stability by latent heat release.

6.5 Detection of supercooled liquid water

Supercooled liquid water content (SLWC) can be obtained by means of Anasphere probes [34], which were directly attached to the Väisälä RS system, intended to rise at the same velocities (3–5 m/s). As mentioned previously, only 19 of the 32 flights included Anasphere probes, because their deployment was restricted to suitable conditions, including surface winds below 17 kt and the absence of precipitation likely to compromise the instrument.

Of the 19 SLWC-probe launches, five were retained as potentially usable after visual and instrumental screening of the vibrating-wire signal. The remaining profiles were discarded because the signal was either incomplete, strongly affected by instrumental artifacts, or did not show a stable baseline suitable for interpretation. Among the five retained profiles, only three flights (1, 5, and 6) showed localized frequency

perturbations occurring within, or close to, thermodynamically permitted SLWC layers. These three cases are therefore treated as plausible SLWC detections, whereas the SLWC dataset as a whole is used only qualitatively.

Anasphere probes operate by measuring the buildup of ice on a thin vibrating wire, and recording the frequency of the wire as the sensor ascends. This vibrating wire technology has been used in aircraft and balloon borne measurements for in situ detection of supercooled water droplets in the atmosphere [34, 40]. Since the mass of the ice changes the vibration frequency of the wire, the rate of change of vibration frequency can be used to quantitatively determine the supercooled liquid water content of the cloud, via the following expression

$$\text{SLWC} = -\frac{2b_0f_0^2}{\epsilon DVf_s} \frac{\partial f}{\partial t}, \quad (13)$$

where b_0 is the steel wire weight per unit length, f_0 is the base “un-iced” wire frequency, D is the wire diameter, V is the air velocity relative to the wire, f is the wire frequency at a given time during flight, $\partial f/\partial t$ is the time rate of change in frequency, and ϵ is the drop collection efficiency. Corresponding values of the parameters for the Anasphere probe used here are $f_0 = 22$ Hz, $D = 0.75$ mm and $b_0 = 0.0224$ g cm⁻¹. The drop collection efficiency was computed for a mean air ascent speed of 5 m s⁻¹ following the approach in [41], for a range of relevant water droplet diameters (between 5 and 60 μ m). More details on the calibration and setup can be found in [34].

Data availability. ERA5 data are available via ECMWF Copernicus Climate Change Service (C3S, <https://cds.climate.copernicus.eu>). Radiosonde and SLWC probe data collected during the T-SCAN campaign are provided by the Group of Atmospheric Turbulence of the National Weather Service (GTA-SMN), and are available at <https://doi.org/10.5281/zenodo.21263411>

7 Supplementary information

Supplementary Animation S1. ERA5 evolution of moisture-intrusion dynamics during the T-SCAN campaign. Shading shows IVT magnitude, vectors indicate horizontal IVT direction, black contours show mean sea-level pressure, and the red marker indicates Marambio Base. The animation illustrates the transition between direct AAR influence, secondary cyclonically driven moisture enhancement, and non-AAR moisture transport affecting the northern Antarctic Peninsula. Supplementary Figure S2. Example of a usable SLWC-probe profile without a plausible non-zero SLWC detection. The figure shows the vibrating-wire frequency as a function of altitude together with the thermodynamically permitted SLWC zone, illustrating the distinction between technically usable SLWC data and profiles retained as plausible localized SLWC signatures.

Acknowledgements. PRI and PDM acknowledge support from the project REMATE of Redes Federales de Alto Impacto, Argentina. The T-SCAN campaign was endorsed by the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO), and the authors acknowledge WWRP-WMO

for its support of international polar prediction research activities. Researchers from SMN would like to thank COCOANTAR for logistical support and Gonzalo Gambarte, Denise Auzmendi, and Noemi Troche for their outstanding technical support and forecasts during the T-SCAN campaign.

Declarations

The authors declare no competing interests.

A Sensitivity to saturation-threshold selection

Because the moist stability correction depends on the identification of saturated and ice-supersaturated layers, we tested the sensitivity of the main statistics to the RH thresholds used in the cloud-layer detection algorithm. For this, two alternative configurations were tested against the reference thresholds described in Section 6: a relaxed case, in which both $\text{RH}_{\min}$ and $\text{RH}_{\max}$ were reduced by 5 percentage points, and a strict case, in which both thresholds were increased by 5 percentage points. Thus, the three configurations were: relaxed $\text{RH}_{\min} - 5\%$, $\text{RH}_{\max} - 5\%$, base $\text{RH}_{\min}$, $\text{RH}_{\max}$, and strict $\text{RH}_{\min} + 5\%$, $\text{RH}_{\max} + 5\%$. Note that the base configuration is the one explained in Section 6 and used for the analysis shown in Section 3.

The resulting sensitivity ranges are shown in Fig. 11, and the corresponding summary statistics are reported in Table 2. Panel (a) shows the fraction of saturated-layer depth that is supersaturated with respect to ice. Panel (b) shows the moist overturning fraction obtained from the L_T^* diagnostic, and panel (c) shows the difference between the moist and dry overturning fractions. In all panels, the shaded envelope indicates the range spanned by the relaxed, base, and strict RH-threshold configurations, while the black markers show the base-threshold results.

The largest threshold sensitivity occurs in the saturation statistic shown in Fig. 11(a). The strict configuration generally produces higher values of the supersaturated fraction within saturated layers, whereas the relaxed configuration gives lower values for several flights. This behavior reflects the definition of the plotted quantity: the numerator is the ice-supersaturated depth, while the denominator is the total saturated-layer depth. Cases in which no saturated layer was identified under a given threshold configuration are undefined for this metric and are therefore not plotted.

In contrast, the overturning diagnostics are much less sensitive to the threshold choice. The moist overturning fraction in Fig. 11(b) remains close across the three configurations for most flights, and the moist–dry difference in Fig. 11(c) preserves the same overall structure. Consistently, Table 2 shows that the moist diagnostic yields larger overturning fractions than the dry diagnostic in 31 of the 32 soundings for all three threshold configurations. Thus, while the diagnosed ice-supersaturated fraction depends on the saturation criteria, the systematic enhancement of overturning fraction by the moist diagnostic is not an artifact of a single RH-threshold choice.

The moist overturning fraction changes only weakly among the relaxed, base, and strict configurations, with mean values of 50.58%, 49.45%, and 48.53%, respectively. In all three configurations, the moist diagnostic yields larger overturning than the

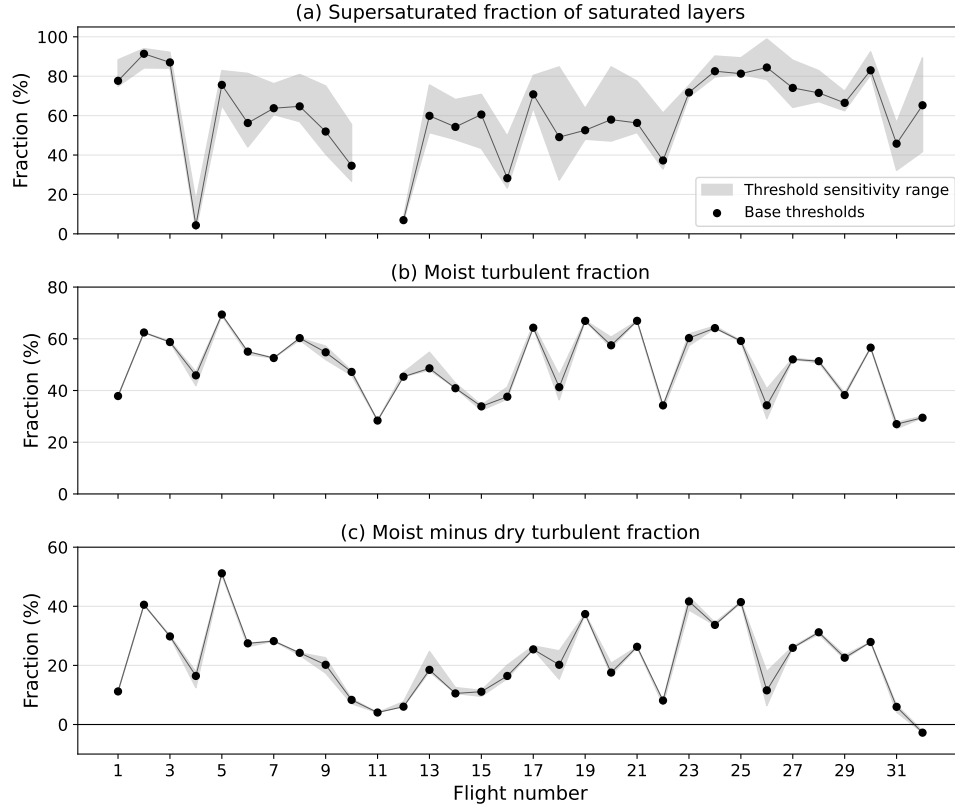


Fig. 11 Sensitivity of the main humidity and overturning diagnostics to the RH thresholds used for saturated-layer detection. The shaded envelope indicates the range obtained from the relaxed, base, and strict configurations, corresponding to offsets of -5 , 0 , and $+5$ percentage points applied to both $\text{RH}_{\min}$ and $\text{RH}_{\max}$. Black markers indicate the base-threshold result. Panels show (a) the fraction of saturated-layer depth that is supersaturated with respect to ice, (b) the moist overturning fraction, and (c) the difference between moist and dry overturning fractions. Cases with no detected saturated layer under a given threshold configuration are undefined in panel (a) and are therefore not plotted. Although the diagnosed supersaturated fraction varies with threshold choice, the moist overturning fraction and the moist-dry correction remain robust across the three configurations.

dry diagnostic in 31 of the 32 soundings, and only one sounding shows a moist-dry difference exceeding 50 percentage points. Thus, although the absolute amount of diagnosed ice supersaturation depends on the saturation criteria, the systematic enhancement of overturning fraction by the moist diagnostic is not an artifact of a single RH-threshold choice.

Table 2 Sensitivity of saturation and overturning statistics to RH threshold choice.

Metric	Relaxed	Base	Strict
Mean ice-supersaturated fraction (%)	52.86	60.23	74.31
Max ice-supersaturated fraction (%)	84.20	91.39	98.91
Flights where moist fraction > dry fraction	31/32	31/32	31/32
Flights with moist-dry difference > 50 percentage points	1/32	1/32	1/32
Mean moist overturning fraction (%)	50.58	49.45	48.53

References

- [1] Hanna, E.: The role of antarctic sea ice in global climate change. *Progress in physical geography* **20**(4), 371–401 (1996)
- [2] Turner, J., Bindshadler, R., Convey, P., Di Prisco, G., Fahrbach, E., Gutt, J., Hodgson, D., Mayewski, P., Summerhayes, C.: *Antarctic Climate Change and the Environment*, (2009)
- [3] Singh, H.K., Bitz, C.M., Frierson, D.M.: The global climate response to lowering surface orography of antarctica and the importance of atmosphere–ocean coupling. *Journal of Climate* **29**(11), 4137–4153 (2016)
- [4] Liu, S., Wu, T., Wang, X., Wu, X., Yao, X., Liu, Q., Zhang, Y., Wei, J., Zhu, X.: Changes in the global cryosphere and their impacts: A review and new perspective. *Sciences in Cold and Arid Regions* **12**(6), 343–354 (2021)
- [5] Bromwich, D.H., Nicolas, J.P., Hines, K.M., Kay, J.E., Key, E.L., Lazara, M.A., Lubin, D., McFarquhar, G.M., Gorodetskaya, I.V., Grosvenor, D.P., Lachlan-Cope, T., Lipzig, N.P.M.: Tropospheric clouds in antarctica. *Reviews of Geophysics* **50**(1) (2012) <https://doi.org/10.1029/2011RG000363> <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2011RG000363>
- [6] Shupe, M.D., Walden, V.P., Eloranta, E., Uttal, T., Campbell, J.R., Starkweather, S.M., Shiobara, M.: Clouds at arctic atmospheric observatories. part i: Occurrence and macrophysical properties. *Journal of Applied Meteorology and Climatology* **50**(3), 626–644 (2011)
- [7] 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)
- [8] Jones, M.E., Bromwich, D.H., Nicolas, J.P., Carrasco, J., Plavcová, E., Zou, X., Wang, S.-H.: Sixty years of widespread warming in the southern middle and high latitudes (1957–2016). *Journal of Climate* **32**(20), 6875–6898 (2019)
- [9] 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)
- [10] 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)
- [11] 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)
- [12] 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)
- [13] 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)
- [14] Barthélemy, L., Codron, F., Wille, J., Favier, V., Clem, K.R.: Future atmospheric rivers in antarctica: Characteristics and impacts with the ipsl 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
- [15] Verlinde, J., Harrington, J.Y., McFarquhar, G., Yannuzzi, V., Avramov, A., Greenberg, S., Johnson, N., Zhang, G., Poellot, M., Mather, J.H., *et al.*: The mixed-phase arctic cloud experiment. *Bulletin of the American Meteorological Society* **88**(2), 205–222 (2007)
- [16] Morrison, H., De Boer, G., Feingold, G., Harrington, J., Shupe, M.D., Sulia, K.: Resilience of persistent arctic mixed-phase clouds. *Nature Geoscience* **5**(1), 11–17 (2012)
- [17] Listowski, C., Delanoë, J., Kirchgaessner, A., Lachlan-Cope, T., King, J.: Antarctic clouds, supercooled liquid water and mixed phase, investigated with dar-dar: geographical and seasonal variations. *Atmospheric Chemistry and Physics* **19**(10), 6771–6808 (2019)
- [18] Fusina, F., Spichtinger, P.: Cirrus clouds triggered by radiation, a multiscale phenomenon. *Atmospheric Chemistry and Physics* **10**(11), 5179–5190 (2010)
- [19] Spichtinger, P.: Shallow cirrus convection—a source for ice supersaturation. *Tellus A: Dynamic Meteorology and Oceanography* **66**(1), 19937 (2014)
- [20] Payne, A.E., Demory, M.-E., Leung, L.R., Ramos, A.M., Shields, C.A., Rutz, J.J., Siler, N., Villarini, G., Hall, A., Ralph, F.M.: Responses and impacts of atmospheric rivers to climate change. *Nature Reviews Earth & Environment* **1**(3), 143–157 (2020)

- [21] Doddi, A., Luce, H., Lawrence, D., Mixa, T., Tomikawa, Y.: Guided observations of dynamic shear instability layers over antarctica (godsila) field campaign. *Journal of Geophysical Research: Atmospheres* **131**, 2025–045830 (2026) <https://doi.org/10.1029/2025JD045830>
- [22] Wilson, R., Luce, H., Hashiguchi, H., Shiotani, M., Dalaudier, F.: On the effect of moisture on the detection of tropospheric turbulence from in situ measurements. *Atmospheric Measurement Techniques* **6**(3), 697–702 (2013)
- [23] Zhang, J., Chen, H., Li, Z., Fan, X., Peng, L., Yu, Y., Cribb, M.: Analysis of cloud layer structure in shouxian, china, using rs92 radiosonde aided by 95 ghz cloud radar. *Journal of Geophysical Research* **115**, 00–30 (2010) <https://doi.org/10.1029/2010JD014030>
- [24] 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)
- [25] Thorpe, S.: A method of producing a shear flow in a stratified fluid. *Journal of Fluid Mechanics* **32**(4), 693–704 (1968)
- [26] Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., et al.: The era5 global reanalysis, quarterly journal of the royal meteorological society (2020)
- [27] 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)
- [28] Wilson, R., Dalaudier, F., Luce, H.: Can one detect small-scale turbulence from standard meteorological radiosondes? *Atmospheric Measurement Techniques* **4**, 795–804 (2011) <https://doi.org/10.5194/amt-4-795-2011>
- [29] Gavrilov, N.M.: Estimates of turbulent diffusivities and energy dissipation rates from satellite measurements of spectra of stratospheric refractivity perturbations. *Atmospheric Chemistry and Physics* **13**(23), 12107–12116 (2013)
- [30] Sharman, R.D., Cornman, L.B., Meymaris, G., Pearson, J., Farrar, T.: Description and Derived Climatologies of Automated In Situ Eddy-Dissipation-Rate Reports of Atmospheric Turbulence. *Journal of Applied Meteorology and Climatology* **53**(6), 1416–1432 (2014) <https://doi.org/10.1175/jamc-d-13-0329.1>
- [31] Strauss, L., Serafin, S., Haimov, S., Grubišić, V.: Turbulence in breaking mountain waves and atmospheric rotors estimated from airborne in situ and Doppler radar measurements. *Quarterly Journal of the Royal Meteorological Society* **141**(693), 3207–3225 (2015) <https://doi.org/10.1002/qj.2604>

- [32] Bramberger, M., Dörnbrack, A., Wilms, H., Ewald, F., Sharman, R.: Mountain-Wave Turbulence Encounter of the Research Aircraft HALO above Iceland. *Journal of Applied Meteorology and Climatology* **59**(3), 567–588 (2020) <https://doi.org/10.1175/JAMC-D-19-0079.1>
- [33] Rodriguez Imazio, P., Mininni, P.D., Godoy, A., Rivaben, N., Dörnbrack, A.: Not All Clear Air Turbulence Is Kolmogorov—The Fine-Scale Nature of Atmospheric Turbulence. *Journal of Geophysical Research: Atmospheres* **128**(2), 2022–037491 (2023) <https://doi.org/10.1029/2022JD037491> <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2022JD037491>. e2022JD037491 2022JD037491
- [34] Serke, D., Hall, E., Bogner, J., Jordan, A., Abdo, S., Baker, K., Seitel, T., Nelson, M., Ware, R., McDonough, F., Politovich, M.: Supercooled liquid water content profiling case studies with a new vibrating wire sonde compared to a ground-based microwave radiometer. *Atmospheric Research* **149**, 77–87 (2014) <https://doi.org/10.1016/j.atmosres.2014.05.026>
- [35] Achtert, P., O’Connor, E.J., Brooks, I.M., Sotiropoulou, G., Shupe, M.D., Pospichal, B., Brooks, B.J., Tjernström, M.: Properties of arctic liquid and mixed-phase clouds from shipborne cloudnet observations during acse 2014. *Atmospheric Chemistry and Physics* **20**(23), 14983–15002 (2020) <https://doi.org/10.5194/acp-20-14983-2020>
- [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*, 347–354 (1957)
- [38] Lalas, D.P., Einaudi, F.: On the correct use of the wet adiabatic lapse rate in stability criteria of a saturated atmosphere. *Journal of Applied Meteorology* **13**, 318–324 (1974)
- [39] Durran, D.R., Klemp, J.B.: On the effects of moisture on the brunt–väsälä frequency. *Journal of the Atmospheric Sciences* **39**(10), 2152–2158 (1982) [https://doi.org/10.1175/1520-0469\(1982\)039\(2152:OTEOMO\)2.0.CO;2](https://doi.org/10.1175/1520-0469(1982)039(2152:OTEOMO)2.0.CO;2)
- [40] Hill, G.E., Woffinden, D.S.: A balloonborne instrument for the measurement of vertical profiles of supercooled liquid water concentration. *Journal of Applied Meteorology and Climatology* **19**(11), 1285–1292 (1980)
- [41] Lozowski, E.P., Stallabrass, J., Hearty, P.: The icing of an unheated, nonrotating cylinder. part i: A simulation model. *Journal of applied meteorology and climatology* **22**(12), 2053–2062 (1983)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [S2.pdf](#)
- [JAN2025SLPIVT.gif](#)
- [FEB2025SLPIVT.gif](#)