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RESEARCH ARTICLE

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Unravelling the transport of moisture into the Saharan Air Layer using passive tracers and isotopes

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Abstract

The subtropical free troposphere plays a critical role in the radiative balance of the Earth. However, the complex interactions controlling moisture in this sensitive region and, in particular, the relative importance of long-range transport compared to lower-tropospheric mixing, remain unclear. This study uses the regional COSMO model equipped with stable water isotopes and passive water tracers to quantify the contributions of different evaporative sources to the moisture and its stable isotope signals in the eastern subtropical North Atlantic free troposphere. In summer, this region is characterized by two alternating large-scale circulation regimes: (i) dry, isotopically depleted air from the upper-level extratropics, and (ii) humid, enriched air advected from Northern Africa within the Saharan Air Layer (SAL) consisting of a mixture of moisture of diverse origin (tropical and extratropical North Atlantic, Africa, Europe, the Mediterranean). This diversity of moisture sources in regime (ii) arises from the convergent inflow at low levels of air from different neighbouring regions into the Saharan heat low (SHL), where it is mixed and injected by convective plumes into the large-scale flow aloft, and thereafter expelled to the North Atlantic within the SAL. Remarkably, this regime is associated with a large contribution of moisture that evaporated from the North Atlantic, which makes a detour through the SHL and eventually reaches the 850–550 hPa layer above the Canaries. Moisture transport from Europe via the SHL to the same layer leads to the strongest enrichment in heavy isotopes (δ^2H correlates most strongly with this tracer). The vertical profiles over the North Atlantic show increased humidity and δ^2H and reduced static stability in the 850–550 hPa layer, and smaller cloud fraction in the boundary layer in regime (ii) compared to regime (i), highlighting the key role of moisture transport through the SHL in modulating the radiative balance in this region.

KEYWORDS
atmospheric humidity, moisture sources, moisture transport, Saharan Air Layer, stable water isotopes, turbulent mixing

1 | INTRODUCTION

The free-tropospheric humidity and low-level cloud cover over the subtropical oceans fundamentally affect the global radiative balance via the greenhouse effect (Held & Soden, 2000; Schmidt et al., 2010) and through their influence on albedo (Bony & Dufresne, 2005; Stephens, 2005). However, the relative contributions of long-range moisture transport compared to lower-tropospheric turbulent and convective mixing for moistening the free troposphere are not well known and difficult to estimate. The representation and coupling of these processes in model simulations critically influences climate projections (Bony et al., 2015; Sherwood et al., 2014; Stevens & Bony, 2013).

Mixing processes are hard to assess from model outputs and observations. The stable isotopic composition of water vapour is sensitive to mixing and can thus provide important observation-based information about this process, complementary to conventional diagnostics (e.g., Dahinden et al., 2021; Galewsky, 2018; González et al., 2016; Lacour et al., 2017; Noone et al., 2011). Isotopes are natural tracers of moist processes in the atmosphere and can be observed in the free troposphere either in situ with aircraft observations (Dyroff et al., 2015; Sodemann et al., 2017) or by remote sensing (Schneider et al., 2016).

Several studies have demonstrated the usefulness of water vapour isotopes to study moisture variability in the subtropical North Atlantic free troposphere (Dahinden et al., 2021; González et al., 2016; Lacour et al., 2017; Schneider et al., 2016). Using trajectory diagnostics, these studies have found that transport of air from the Saharan heat low (SHL) plays a key role for the moisture budget in this region. In summer, mainly dry convective mixing of low-level moisture advected into the SHL and transported at higher levels out to the North Atlantic acts to moisten the dry subtropical free troposphere. This moisture transport pathway is characterized by a distinct water vapour isotopic signature. However, these studies suffer from a common drawback, which is the limited ability of the adopted trajectory approaches to explicitly diagnose mixing processes. Since the spatiotemporal resolution of the wind fields used to calculate the trajectories is beyond the scales of convective and turbulent mixing, these processes can be only indirectly identified from the evolution of specific humidity along the trajectories. Furthermore, the shares of individual moisture sources blended in the SHL and advected within the so-called Saharan Air Layer (SAL) to the North Atlantic have not been quantified so far.

Eulerian moisture tagging models can provide information about the atmospheric moisture transport from a detailed process-based perspective, since they represent all relevant processes of the hydrological cycle as represented in a numerical model, including convective and turbulent mixing (e.g., Winschall et al., 2014). Despite this advantage, such models have not yet been applied to quantify the importance of convective mixing in the SHL for the free-tropospheric humidity over the subtropical North Atlantic.

In this paper, we investigate the key role of convective mixing in the SHL for free-tropospheric moisture in a region frequently affected by the SAL in summer, that is, at 600 hPa over the Canary Islands region (CAN; 16.2° W, 27.5° N). To this end, we use high-resolution simulations with the regional weather and climate prediction model COSMO$_{\text{isotag}}$ that has been equipped with stable water isotopes (Pfahl et al., 2012) and passive water vapour tracers (Winschall et al., 2014). The moisture tagging approach enables quantifying the relative contributions of moisture originating from pre-specified source regions to the moisture above CAN. Furthermore, the combination of the Eulerian tagging with a Lagrangian moisture source diagnostic provides insight into where turbulent and convective mixing occurs along the long-range transport route of atmospheric moisture. More specifically, this study aims to (1) quantify the role of mixing processes in the SHL and the contributions from different source regions to the moisture in the SAL, (2) investigate how this moisture source distribution relates to variations in the isotopic composition of water vapour above CAN, and (3) analyse the impact of transport from the SHL on the vertical structure of moisture, stability and low-level clouds above CAN.

2 | DATA AND METHODS

2.1 | Eulerian methods: COSMO$_{\text{isotag}}$

Three 4-month COSMO$_{\text{isotag}}$ simulations for June to September 2016–2018 are conducted in this study. The 4-month period, June to September, was chosen based on the 40-year monthly climatology of transport regimes affecting the Canary Islands from Dahinden et al. (2021). This study showed that the SAL above CAN occurs most frequently in July to August (50% occurrence frequency) with a rapid increase of the frequency from June (13%) to July and decay in September and October. Technical information about the isotope implementation can be found in the Supporting Information S1 and in Pfahl et al. (2012), about the tagging approach in Winschall et al. (2014), and about the isotag fusion in Dahinden (2022). The simulations are run with a horizontal grid spacing of 0.1° (corresponding to approximately 12 km on a rotated stereographic grid), 60 hybrid levels in the vertical and with fully explicit convection. Previous studies have shown that precipitation patterns over West Africa are better simulated with explicit convection even with relatively coarse grid spacing (Berthou et al., 2019; de Vries et al., 2022; Marsham et al., 2013; Pante & Knippertz, 2019). Details of the model setup are given in Supporting Information S1 and in Dahinden (2022). In short, ECHAM5-wiso (Werner et al., 2011) provides initial and boundary conditions, and horizontal winds above 850 hPa are spectrally nudged towards ECHAM5-wiso, which itself is nudged to reanalysis data. Thereby the simulations are kept as close as possible to the real meteorology.

The model domain includes all relevant source regions of moisture for the SHL by covering large parts of the North Atlantic and tropical Atlantic, West Africa, the Mediterranean, as well as southern and western Europe, as shown in Figure 1, which also introduces the labels used to specify the tracers. Four passive water vapour tracers are used to tag moisture from evaporative source regions within the model domain, four tracers tag incoming moisture from the lateral boundaries, and the ninth tracer tags water vapour contained in the inner domain at the beginning of the simulation. Throughout all simulations, differences between the sum of the nine tagged water species and the total water are on average less than 1% of the total vapour in the lower and middle troposphere, which is acceptable for the requirements of this study. Larger deviations occur in the upper troposphere, but they do not affect the results in this study. A detailed discussion of mass conservation in the $COSMO_{isotag}$ simulations is provided in appendix A of Dahinden (2022).

2.2 | Lagrangian moisture source diagnostic

Seven-day backward trajectories are calculated with the Lagrangian analysis tool LAGRANTO (Sprenger & Wernli, 2015; Wernli & Davies, 1997) based on three-dimensional hourly $COSMO_{isotag}$ wind fields. The trajectories are started every 3 h in July to September 2018 at 600 hPa in a region that is frequently affected by the SAL, south of the Canary Islands (CAN; 16.2° W, 27.5° N; Figure 1) as well as from the eight neighbouring grid points displaced by 0.1°. Moisture uptakes along these trajectories are quantified with the moisture source diagnostic of Sodemann et al. (2008) in a slightly modified version for identifying the sources of water vapour instead of precipitation (Pfahl & Wernli, 2008). This method, which is complementary to the Eulerian tagging approach, considers the water budget of water vapour in

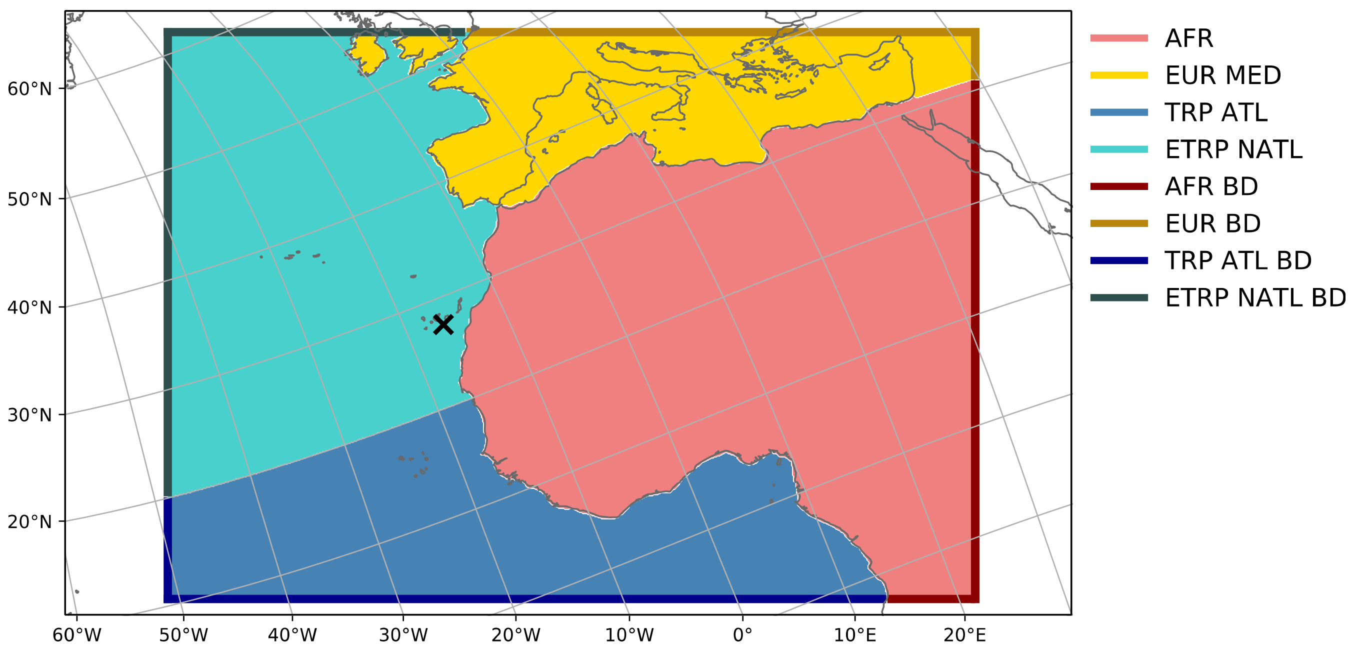

FIGURE 1 Model domain and tracer initialization setup for the 3 $COSMO_{isotag}$ simulations. Land or sea areas from which tagged water evaporates (by slab initialization) are shown by coral (Africa; AFR tracer), yellow (Europe and Mediterranean; EUR MED), blue (tropical Atlantic; TRP ATL) and turquoise (extratropical North Atlantic; ETRP NATL) shadings. Atmospheric sections that are initialized with tagged water (by box initialization) are shown in dark red (African boundary; AFR BD), dark yellow (European boundary; EUR BD), dark blue (tropical Atlantic boundary; TRP ATL BD) and dark green (extratropical North Atlantic boundary; ETRP NATL BD). The moisture that is initially present in the model domain is separately tagged (INIT MOIST, not shown here). The black cross indicates the Canary Islands region (CAN).

an air parcel. An increase in specific humidity is regarded as an uptake of moisture by the air parcel, a decrease as a loss of moisture (i.e., precipitation). Only uptakes larger than 0.05 g kg^{-1} per hour are considered here to avoid the influence of numerical noise (a sensitivity study without threshold is shown in the Supporting Information Figure S2). Each uptake is weighted according to its contribution to the final humidity of the air parcel. If precipitation occurs along the trajectory, the weight of all previous uptakes is reduced proportionally. This method has been widely used for the identification of moisture sources for precipitation and for the interpretation of stable water isotope signals in vapour and precipitation (e.g., Aemisegger et al., 2021; Pfahl & Wernli, 2008). In this study, we use this diagnostic to quantify uptakes of specific water vapour tracers from the $COSMO_{isotag}$ simulations along backward trajectories, which represent the moistening of the Lagrangian air parcels through turbulent mixing with humidity from the pre-specified sources (see again Dahinden, 2022, for more details).

3 | RESULTS

3.1 | Origin of free-tropospheric moisture and associated isotope signals in the CAN

The sources of moisture in the subtropical mid-troposphere at 600 hPa above CAN (Figure 2b) reveal two alternating regimes, which correspond to well-known regional circulation patterns in summer (Dahinden et al., 2021; Lacour et al., 2017). Regime (i) with an occurrence frequency of 54% in the three summers 2016–2018 is associated with moisture transport from the western and north-western model domain boundaries (referred to as the NA regime: fraction of q_v from tracer ETRP NATL BD > 90%). In contrast, regime (ii) with an occurrence frequency of 37% is characterized by a mixture of moisture from different source regions (referred to as the MIX regime: total fraction of q_v from tracers AFR, EUR MED, ETRP NATL and TRP ATL > 40%). These contrasts in atmospheric water vapour transport are related to substantial temporal variability in the stable water isotope signal with variations up to 240‰ (Figure 2a). Low δ^2H values (< −200‰) mainly occur in the NA regime and high δ^2H values (> −200‰) in the MIX regime. Short-term isotopic variations also appear within the regimes, but they are clearly smaller than the average differences between the regimes. The δ^2H variations within the MIX regime are mainly linked to changes in the relative contribution of different moisture sources to q_v. Some of the strongly depleted values of δ^2H can be explained by a higher fraction of q_v from boundary tracers, in particular from ETRP NATL BD, and a lower fraction from evaporative surface source regions (e.g., on 31 August 2018). Particularly enriched δ^2H values appear to be often associated with a high relative share of moisture evaporated over the Mediterranean and Europe (EUR MED; e.g., on 4 September 2018).

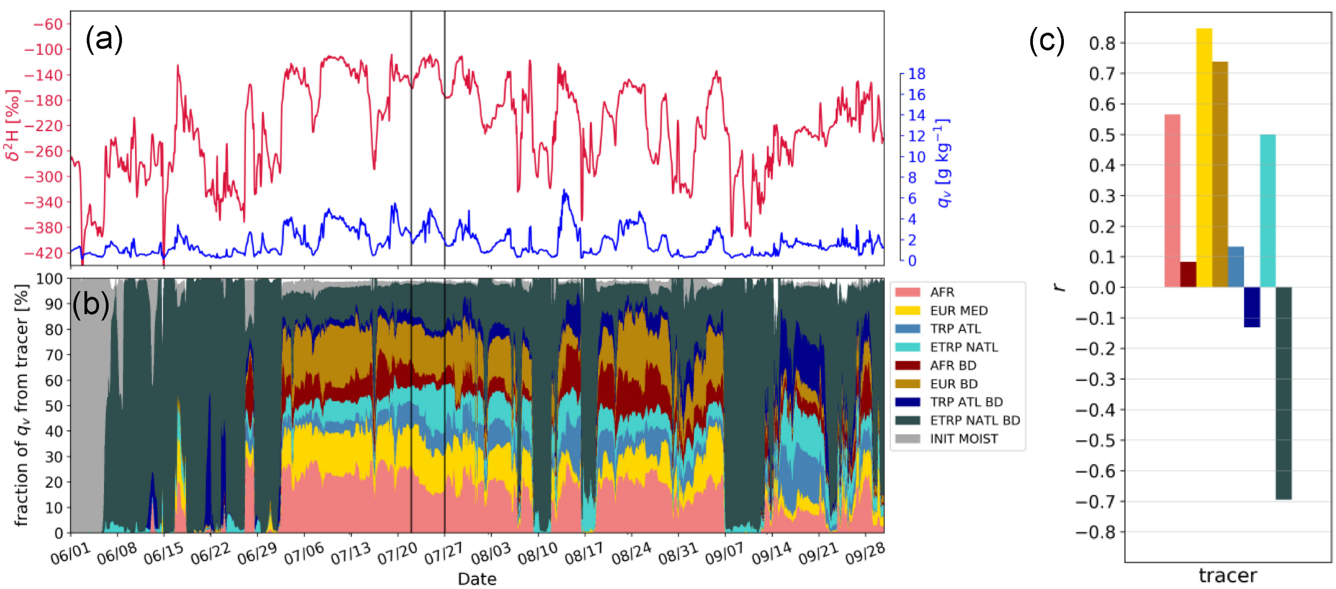

FIGURE 2 Time series of (a) δ^2H and q_v, and of (b) fraction of q_v from tracers at 600 hPa above CAN from June to September 2018, averaged over 3 × 3 grid points centred at CAN. Black vertical lines depict the selected time period investigated in more detail in this paper. The year 2018 is representative for the 3 years considered in this study. (c) Correlation of δ^2H with fraction of q_v from tracers at 600 hPa above CAN in July to August 2016–2018.

The impact of the two contrasting circulation regimes on the isotopic composition above CAN is reflected in the correlations of δ^2H with the fraction of q_v from passive tracers (Figure 2c). We find a high negative correlation of δ^2H with the ETRP NATL BD tracer fraction (Pearson correlation $r \sim -0.7$), indicating that low δ^2H signals are associated with high fractions of moisture originating from the upper-level extratropical North Atlantic. This is consistent with previous studies that associated depleted conditions above CAN with large-scale subsidence from the extratropics (Dahinden et al., 2021; González et al., 2016; Lacour et al., 2017; Schneider et al., 2016). High δ^2H signals, by contrast, are linked to high fractions of moisture originating from surface evaporation within the model domain and in particular, from the EUR MED tracer region ($r > 0.8$). Accordingly, water vapour evaporated over the Mediterranean and Europe plays a key role in isotopically enriching the mid troposphere above CAN. Since humid, enriched conditions over CAN are known to be associated with transport from the SHL region (e.g., Dahinden et al., 2021; Lacour et al., 2017), we can hypothesize that these surface tracers have been advected at low levels into the SHL, convectively lifted to the middle troposphere, and thereafter expelled within the SAL over the North Atlantic. This hypothesis will be addressed in the next section with the help of trajectories. Correlations of q_v with the different tracer fractions show similar tendencies as for δ^2H (Supporting Information Figure S3), but the magnitudes of the correlation coefficients are lower, indicating that δ^2H is more closely related to the moisture source contributions than q_v.

Given that the water vapour evaporated over the Mediterranean and Europe is very important for isotopically enriching the mid troposphere above CAN, we extend the correlation analysis of δ^2H with the relative contribution of the EUR MED tracer to the entire model

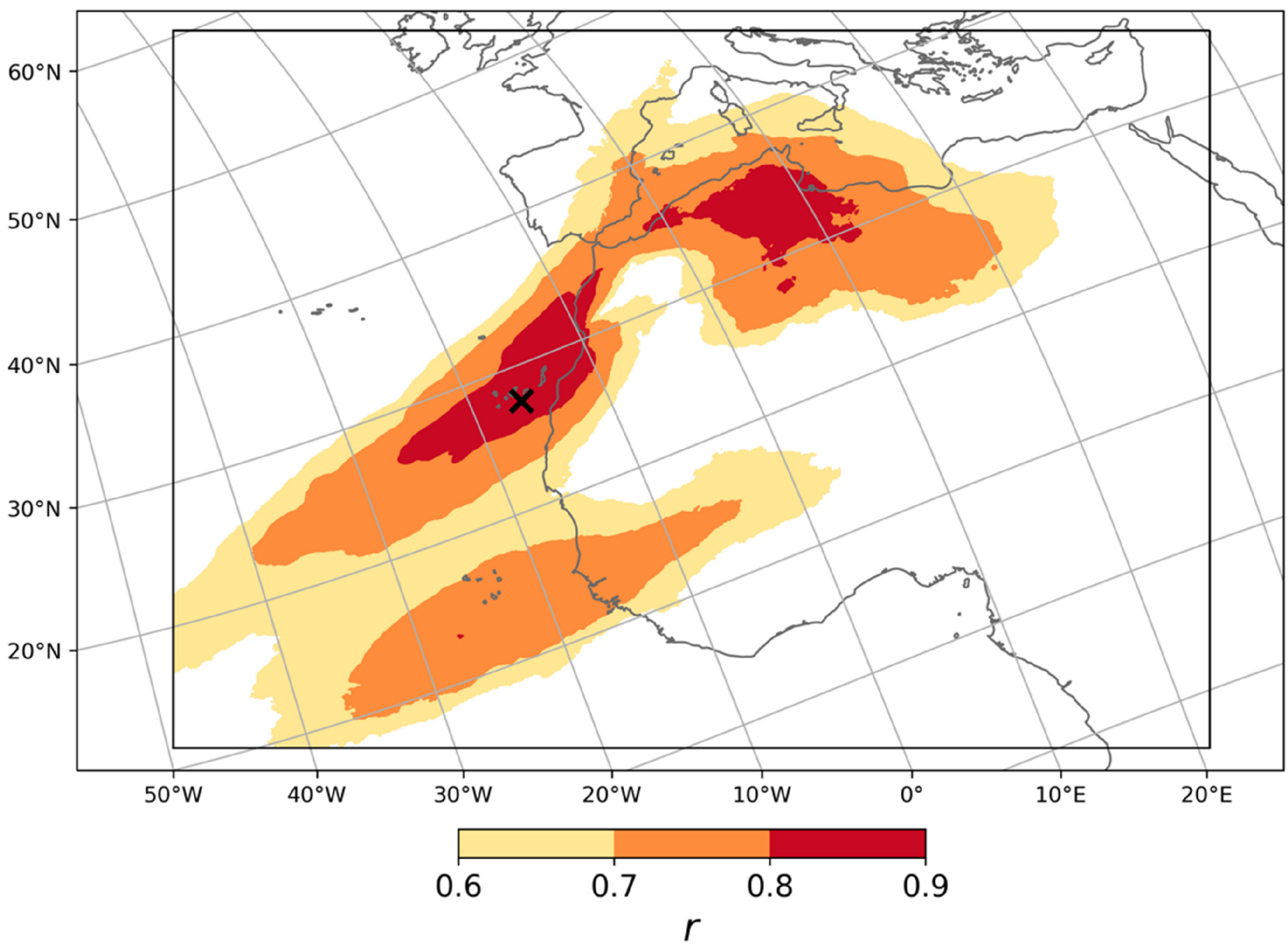

FIGURE 3 Pearson correlation coefficient r of δ^2H with the fraction of q_v from the EUR MED tracer at 600 hPa (both quantities taken at the same local grid point) as simulated by $COSMO_{isotag}$ for July to August 2016–2018. The black rectangle indicates the model domain and the black cross CAN.

domain. This allows us to identify the spatial extent of the region, in which this source region plays a key role for understanding variations in δ^2H. Figure 3 reveals that evaporation over the Mediterranean and Europe is an important source of enriched moisture for large parts of the mid troposphere over the subtropical and tropical North Atlantic. The remarkably high positive correlations between δ^2H and the EUR MED fraction of q_v results from either (i) an anomalously high δ^2H at the EUR MED sites of evaporation or (ii) a low probability of cloud and precipitation formation along the EUR MED tracer transport pathways to the respective locations.

3.2 | The importance of the SHL for moistening the free troposphere over the subtropical North Atlantic

To investigate the pathway of different tracers in the MIX regime, the Eulerian moisture source analysis is complemented with Lagrangian backward trajectories. An exemplary set of trajectories for the period 22–26 July 2018 demonstrates that the humid high-δ^2H air composed of moisture from mixed source regions is associated with transport from North Africa (Figure 4). Dry air subsides from the extratropics to the SHL region where it experiences moistening (Figure 4a) and a considerable

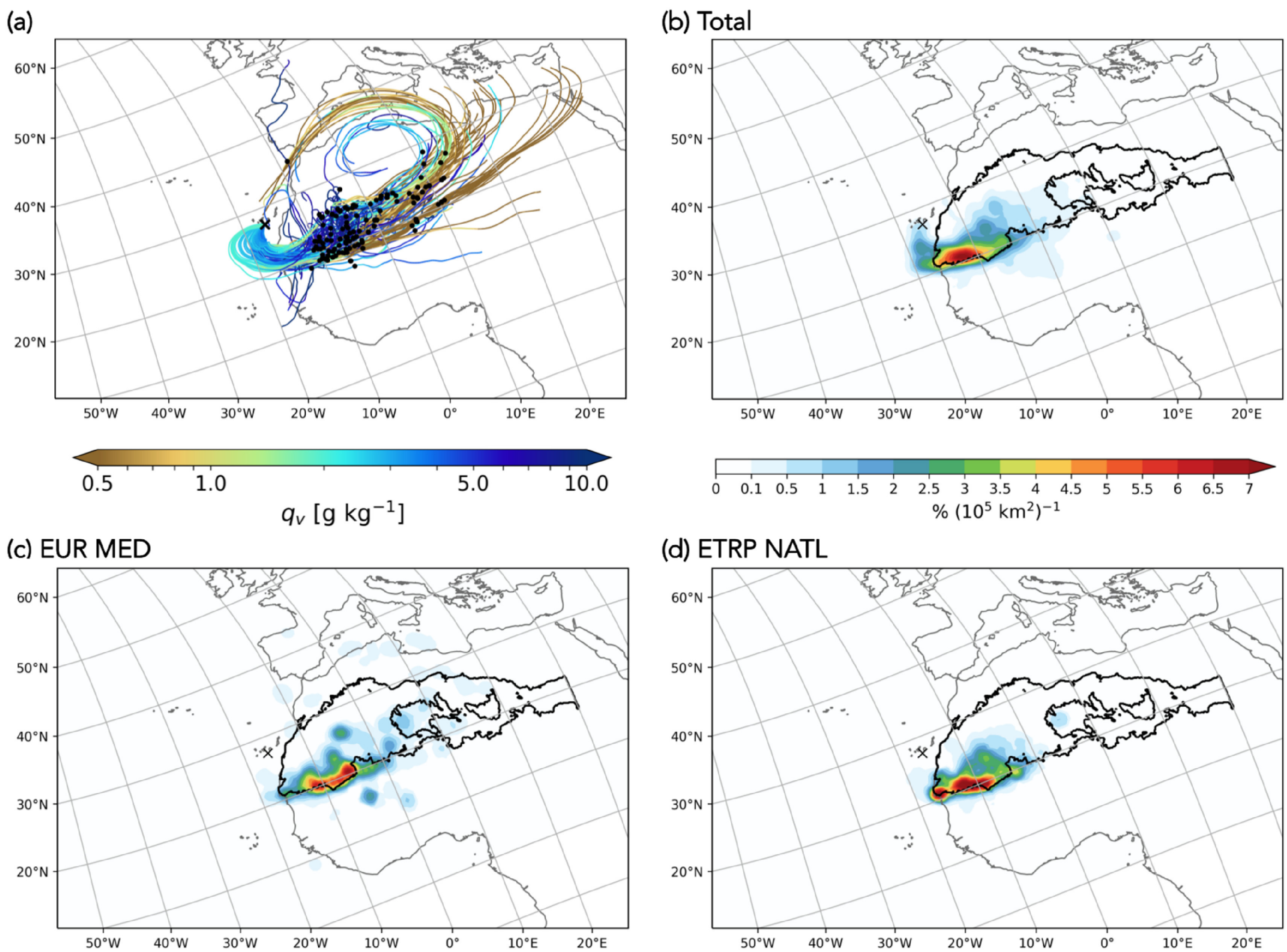

FIGURE 4 (a) $\text{COSMO}_{\text{isotag}}$ 7-day backward trajectories started every 3 h at 600 hPa from 3 × 3 grid points centred at CAN in the period of 22–26 July 2018. The trajectories are coloured according to q_v. The black cross depicts the starting positions above CAN and the black dots the trajectory positions 4 days backward in time. Due to readability, only every third trajectory is shown. (b–d) Uptakes of moisture along backward trajectories from CAN at 600 hPa, referring to (b) total specific humidity (c) Europe and Mediterranean tracer (EUR MED) and (d) the extratropical North Atlantic ETRP NATL, in the respective time period. The relative contribution of uptakes per 10^5 km^2 to the final tagged humidity of the respective tracer at 600 hPa above CAN is shown in colours. The black contour indicates the region in which the non-stationary SHL is located during the considered time period. The SHL location from the $\text{COSMO}_{\text{isotag}}$ simulation output is identified according to the method described in Dahinden et al. (2021) but with a higher percentile (89.5) due to the lager model domain.

enrichment in heavy isotopes (not shown, see Dahinden et al., 2021 for details), due to convective mixing with humid, high-δ^2H air that has been advected at low levels into the SHL. However, this sub-grid-scale mixing cannot be directly inferred from the trajectories and they do not reveal the origin of the low-level moisture that is mixed into the large-scale flow. Here, these limitations are overcome by adopting the Eulerian and Lagrangian perspectives jointly. We can assess the effects of sub-grid-scale convective mixing by comparing the uptake locations of the total humidity (Figure 4b) with those of the tagged humidity of each tracer (Figure 4c,d, Supporting Information Figure S1).

The Lagrangian–Eulerian moisture source analysis reveals that the moisture is mostly taken up in the region of the SHL (Figure 4b). Specifically, there is a maximum of moisture uptakes at the southern boundary of the SHL, where convergence of the moist south-westerly monsoon flow and the dry north-easterly Harmattan winds along the so-called intertropical discontinuity leads to strong convective instability triggering the upward transport of low-level moisture. Since the uptake patterns of all surface tracers peak in the same region (Figure 4c,d, Supporting Information Figure S1), these hotspots of moisture uptakes can be interpreted as dry convective plumes that coherently inject low-level moisture from different source regions into the large-scale flow aloft, thereby producing the characteristic mix of tracers in the SAL. Vertical moisture transport within the SHL, as discussed in this case study, is likely to play a crucial role for the generally large contributions of moisture uptake over Africa to the free-tropospheric humidity above CAN in July and August (see fig. 5.21 in Dahinden, 2022).

3.3 | Impact of contrasting circulation regimes on vertical structure above the CAN

The two contrasting regimes exhibit different characteristics in terms of humidity, isotopic composition, origin of moisture, static stability and cloud fraction in the entire vertical profile above CAN as summarized in Figure 5 for June to September in the years 2016–2018. The isotope profiles of the two regimes are similar in the lower troposphere (> 850 hPa) but differ strongly in the middle and upper troposphere (Figure 5b). While δ^2H continuously decreases with increasing height in the NA regime, it remains almost constant in the middle troposphere in the MIX regime (mean $\delta^2\text{H} \sim -150$‰ between 850 and 550 hPa). This homogeneous, enriched isotope layer is associated with high specific humidity (Figure 5a), relative humidity (not shown), reduced stability within the lower part of the SAL layer (900–550 hPa, Figure 5c) and is vertically isolated from its environment through two layers of enhanced stability at its lower (950–900 hPa) and upper boundary (550–350 hPa). The high humidity and its interaction with radiation, the limited cloud formation and muted vertical mixing are the necessary ingredients that allow for long-range coherent transport of the SAL layer across the North Atlantic (including its dust loading, see Gutleben et al., 2019).

Not surprisingly, the decomposition of the mid-tropospheric water budget of the MIX regime shows important contributions from all tagged surface and boundary tracers (Figure 5e,f). The NA regime, by contrast, is clearly dominated by the tracer ETRP NATL BD in the middle and upper troposphere with a maximum percentage around 600 hPa. The fact that the MIX regime is associated with larger contributions of extratropical North Atlantic moisture evaporated within the domain (ETRP NATL) than the NA regimes highlights the importance of the detour of this tracer through the SHL for being mixed upward into the free troposphere and transported back to the North Atlantic. The higher mid-tropospheric specific humidity (Figure 5a) and cloud fraction (Figure 5d) in the MIX regime compared to the NA regime suggest a strong radiative impact of moisture transported in the SAL (e.g., Barreto et al., 2022; Gutleben et al., 2020).

In the lower troposphere (>850 hPa), the tracers ETRP NATL and ETRP NATL BD prevail in both regimes, implying that local evaporation and moisture advection from the north-western model boundary are the main moisture sources. The fraction of lower-tropospheric q_v from the ETRP NATL tracer is somewhat larger for the NA regime than for the MIX regime (Figure 5e), which points to a stronger impact of vertical mixing up to about 825 hPa under NA conditions. In addition, the temperature inversion is located at a slightly higher altitude (950 hPa) and is somewhat weaker compared to the MIX regime (975 hPa; Figure 5c), resulting in a deeper boundary layer that is more frequently covered by low-level clouds (Figure 5d). In addition, the remarkable differences in the relative importance of the tagging tracers between the lower and middle troposphere as well as the temperature inversion at the boundary layer top indicate that the low- and mid-tropospheric water budgets are only weakly coupled through local vertical exchange (e.g., Galewsky et al., 2022) and largely controlled by different circulation regimes.

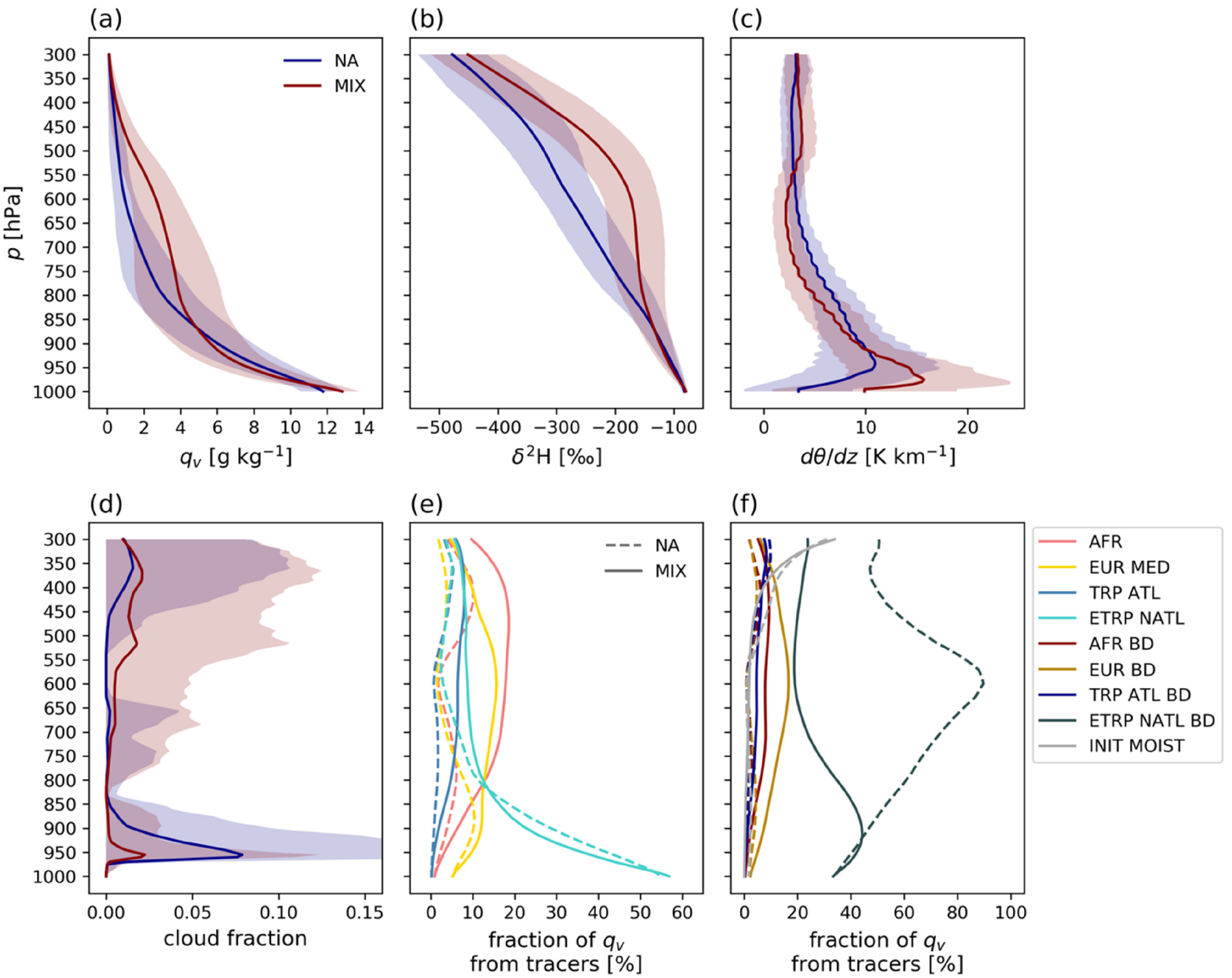

FIGURE 5 Vertical profiles of (a) q_v, (b) δD, (c) the vertical derivative of potential temperature, (d) cloud fraction and (e,f) relative contributions of tagged water to the total moisture in the Canary Islands region (black cross in Figure 1) in June to September 2016–2018 for the two contrasting mid-tropospheric moisture circulation regimes identified at 600 hPa. Blue lines and shadings represent the mean and standard deviation of the NA regime, red lines and shadings of the MIX regime. Dashed and solid lines in (e,f) depict the mean tracer fraction in the NA and MIX regime.

4 | DISCUSSION AND CONCLUSIONS

A combination of Eulerian tagging simulations with a Lagrangian moisture source diagnostic was used to infer novel aspects of the atmospheric water cycle in the subtropical eastern North Atlantic in summer. Their combination allowed quantifying the relative contributions of different water vapour tracers to the model's prognostic humidity and assess the actual uptake location of the tagged moisture by the large-scale flow.

The main caveats of this study are associated with uncertainties in the representation of convection in COSMO$_{isotag}$ and with slight inaccuracies in the mass conservation of the tagging implementation discussed in appendix A of Dahinden (2022). Regarding the representation of convective mixing in COSMO$_{isotag}$, there is evidence that the findings presented in this paper are overall reliable. First, Grams et al. (2010) showed in a comprehensive model inter-comparison study with airborne measurements that COSMO, run with a horizontal grid spacing of 7 km and parameterized convection, captures the thermodynamic structure and depth of the Saharan boundary layer accurately. Since model biases in the representation of the SHL have been primarily attributed to issues with convective parameterizations (e.g., Garcia-Carreras et al., 2013; Marsham et al., 2011), we expect that our COSMO$_{isotag}$ simulations with explicit convection represent the SHL dynamics well. Second, the good agreement between the modelled and observed q_v

and δ^2H values in the middle troposphere above CAN in July to August 2013 presented in Dahinden et al. (2021), who used $COSMO_{iso}$ simulations with a similar setup, points to a realistic representation of the SHL dynamics in $COSMO_{isotag}$.

The correlation of the simulated δ^2H over CAN with contributions of different tracers indicates that the two large-scale circulation regimes (MIX and NA) and the associated variations in moisture sources imprint on the water isotope signal. In particular, the highest correlation is obtained with the EUR MED tracer, as the concentration of this tracer does not only reflect the switch between the large-scale regimes but is also important for the comparatively small isotope variations within the SAL regime.

The humid, isotopically enriched SAL above CAN was further shown to exhibit different characteristics in terms of vertical profiles of humidity, origin of moisture, isotopic composition, static stability and low-level cloud fraction compared to the contrasting NA regime of dry, depleted air from the upper-level extratropical North Atlantic boundary. The fact that SAL events are associated with larger contributions of extratropical North Atlantic moisture evaporated within the domain than the NA regime underscored the importance of the detour of this tracer through the SHL for being mixed upward into the free troposphere and transported again over the North Atlantic. This unexpected pathway of the North Atlantic moisture into the SAL was identified explicitly through our combined Lagrangian–Eulerian analysis highlighting coherent uptakes of the SHL mixture of tracers within convective plumes in the SHL region. Furthermore, the higher specific humidity and cloud fraction in the middle troposphere as well as the lower occurrence of shallow clouds in the boundary layer under SAL conditions imply a strong impact of moisture transport in the SAL on the radiative budget (see Barreto et al., 2022; Gutleben et al., 2020). These results emphasize the importance of a precise understanding and numerical modelling of the SHL dynamics and the vertical structure of the SAL for reliable climate projections.

AUTHOR CONTRIBUTIONS

Fabienne Dahinden: Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing – original draft. **Franziska Aemisegger:** Conceptualization; investigation; methodology; software; supervision; visualization; writing – review and editing. **Heini Wernli:** Conceptualization; funding acquisition; methodology; supervision; writing – review and editing. **Stephan Pfahl:** Conceptualization; funding acquisition; methodology; software; supervision; writing – review and editing.

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DATA AVAILABILITY STATEMENT

The output of the simulations is available from the authors upon reasonable request. The particular version of the COSMO model used in this study is based on the official version 4.18 with additionally implemented stable water isotope physics and is available under licence (see http://www.cosmo-model.org/content/consortium/licencing.htm for more information; COSMO, 2021). The Fortran code for the trajectory calculations is available under http://iacweb.ethz.ch/staff/sprenger/lagranto/download.html.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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