Research Article

Vertical Structure of Moisture Content over Europe

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The vertical structure of water vapor content in the atmosphere strongly affects the amount of solar radiation reaching the Earth's surface and processes associated with the formation of clouds and atmospheric precipitation. The purpose of this study was to assess the vertical differentiation of water vapor over Europe on a seasonal basis and also to evaluate the role of atmospheric circulation in changes therein. Daily values of specific humidity (SHUM) for the time period 1981–2015 were obtained from pressure levels available from ECMWF Era-Interim reanalysis data and used in the study. Eight grid points were analyzed in detail. Each point is representative of a region with different moisture conditions. SHUM profiles were then used to identify cases of moisture inversion. Horizontal flux of specific humidity (SHUMF) was analyzed for principal pressure levels that occur in both inversion-type and inversion-free situations. In addition, SHUM and SHUMF anomalies were identified for advection directions. The research results showed the existence of differences in the vertical structure of water vapor content in the troposphere over Europe, and the Northeastern Atlantic and the presence of moisture inversions not only in areas north of 60°N but also in temperate and subtropical zones. Inversions can occur in two different forms—surface-based and elevated. The occurrence of inversions varies with the seasons. The role of atmospheric circulation is observable in the winter and triggers both surpluses and shortages of moisture via the effect of specific pressure system types (significant role of seasonal pressure high) and via advection directions. In addition, there exists a clear difference between the structure of moisture in the atmospheric boundary layer and in the free atmosphere.

1. Introduction

The vertical structure of water vapor content in the Earth's atmosphere strongly impacts the amount of solar radiation reaching the surface of the planet and the process of formation of clouds and atmospheric precipitation. In light of this, water vapor is thought to be the most important trace gas in the atmosphere, and mutual feedbacks triggered by water vapor affect climate change the most by increasing its sensitivity. The total water vapor feedback factor is estimated to equal 0.47 [1, 2], although water vapor in the free atmosphere is believed to play a much more important role than that in the planet's boundary layers [2]. Increases in the quantity of water vapor increase the amount of longwave radiation trapped near the surface of the Earth and at the

same time lead to an increase in air temperature and exacerbated warming. Given that it is air temperature that determines the pressure of saturated water vapor, the spatial distribution of water vapor and its vertical structure closely depend on temperature changes, which further implies an increased intensity of atmospheric processes.

The complexity of relationships between air temperature and water vapor content affects the radiation balance and water circulation patterns. For these very reasons, studies on the vertical structure of water vapor in the atmosphere, its variability over time, and differentiation across geographic space play a key role in the analysis of climate change including parametrization of climate models and weather forecasting [3, 4]. Studies are conducted first and foremost in areas where water vapor is especially vital due to its complex

linkages with local conditions that also affect weather processes on a global scale in subtropical areas and polar areas. Many studies on the vertical structure of water vapor content focus on the key relevance of moisture inversions and their impact on selected processes related to water circulation and energy exchange. Kloesel and Albrecht [5] note the substantial role of the Earth's boundary layer in the regulation of water vapor transfers into the free atmosphere in the tropics, especially via convection, which is driven by low moisture inversions. The importance of studies in tropical areas is observable in the work of Holloway and Neelin [6] in the content of entrainment in convective boundary layers. In addition, Peters and Neelin [7] investigated factors that determine the formation of atmospheric precipitation. Finally, Wagner et al. [8] examined differences in the vertical structure of water vapor over the Atlantic Ocean. A large influx of solar energy along with strong air temperature inversions, cloud cover that is sensitive to multiple factors, and mesoscale circulation determining moisture transport through meridional inflows cause large differences in water vapor content across geographic space and in the vertical profile in polar areas. This subject is examined in multiple studies that emphasize the importance of the vertical structure of water vapor content in energy balances [9, 10]. Increases in the amount of water vapor present with altitude (moisture inversion) imply an increased share of the downward component of longwave radiation in the radiation balance, as shown by Devasthale et al. [11] for the winter season when water vapor from a moisture inversion constitutes more than 50% of the total column water vapor. This yields a significant effect on cloud cover [12]. The frequent occurrence of inversions in the Arctic and Antarctic was confirmed by Tomasi et al. [13], Vihma et al. [14], and Nygård et al. [15, 16] who showed their link with temperature inversions and the occurrence of low clouds.

Most research studies on this subject were conducted based on either regular weather balloon measurements or occasional field measurements. However, they also note the point nature of these measurements and the lack of opportunity to make measurements over areas of sea. One potential way to solve this problem is the use of reanalysis data, as noted by Serreze et al. [17] and Nygård et al. [15, 16]. Brunke et al. [18] compared data from five reanalysis attempts and were able to show that moisture inversions can also occur outside Arctic and Antarctic areas, although much less frequently and with less intensity. This is especially true in stratus regions and temperate regions—mostly in the cooler months of the year. On the contrary, frequencies exceed 80% in the winter, but only 10% in the summer, near the Arctic and Antarctic circles. The former are associated with lower (near the ground) temperature inversions over land areas and often are accompanied by the occurrence of fog [18, 19, 20]. These studies show that given the significance of water vapor content in key atmospheric processes, detailed analysis of the vertical structure of water vapor content in Arctic and Antarctic areas may provide additional information on factors modifying changes in moisture content in the atmosphere. At the same time, it

FIGURE 1: Study area with selected grid point locations representing different humidity regions in Europe (polygons); slanted lines are used to denote areas situated above the average 950 hPa level.

may help in the parametrization of regional climate models (RCMs) and mesometeorological forecasting models.

The purpose of this study was to evaluate the vertical differentiation of water vapor content in the atmosphere over Europe from a seasonal perspective and to examine the role of atmospheric circulation and its impact thereupon. Moisture content was identified at pressure levels up to 300 hPa with a special focus on cases of moisture inversion. Circulation patterns were described via advection directions for air masses including eastward intensity along with the northward moisture flux.

2. Data and Methods

Three spatial domains were examined: (1) the study area, (2) distinguished moisture regions, and (3) selected grid points. The study area consisted of Europe and the Northeastern Atlantic between 27°W and 45°E as well as 33°N and 73.5°N, with the exception of Greenland (Figure 1). Moisture regions (Figure 1; polygons) were identified by Wypych et al. [21] via the use of three variables describing moisture content, that is, total column water vapor of the entire atmosphere, specific humidity, and relative humidity at selected pressure levels (950 hPa, 850 hPa, 700 hPa, and 500 hPa). Cluster analysis helped identify six regions with different moisture conditions: Northern-Atlantic, Northern-Continental, Mid-Atlantic, Mid-Continental, Subtropical-Atlantic, and Mediterranean. Although the distinction was based on the grouping of the *k*-means method via largest possible differences and largest similarities within each type, internal cohesion tests for the identified moisture regions have shown them to be quite different. In addition, the studied moisture regions differ in the surface area (Figure 1). Hence, detailed analyses were carried out at key grid points (Figure 1). This included an analysis of the vertical structure of moisture conditions and the intensity of moisture flux. Moisture conditions at the studied grid points were similar to areal averages for the studied regions. At the same time, they also are representative of latitudinal (50.25°N) and longitudinal (15.75°W, 20.25°E) cross sections of the study area manifesting the effect of geographic

TABLE 1: Location of selected grid points.

Point ID	Latitude (°N)	Longitude (°)
NW	63.75	15.75 W
WW	50.25	15.75 W
SW	36.75	15.75 W
W	50.25	2.25 E
N	63.75	20.25 E
KRK	50.25	20.25 E
E	50.25	38.25 E
S	36.75	20.25 E

location on moisture conditions. Table 1 shows the location of all the grid points used in the study.

The study uses data from the period 1981–2015 obtained from ECMWF reanalysis data sets (ERA-Interim) at a base horizontal resolution of 0.75° [22]. Daily specific humidity values (q or SHUM) served as the basis for the study and were obtained for 18 pressure levels ranging from 950 hPa to 300 hPa.

The 1,000 and 975 hPa levels were not examined, as the average height of their location over the surface may be questionable with respect to their use in the analysis of large parts of the study area. In addition, the mean daily height of isobaric surfaces was checked in order to exclude cases where they were located underground at selected grid points.

The data were 6-hour averages. The use of daily data led to the omission of cases characterized as extremes. This is not an accidental omission, and it did make it possible to realize the principal goal of the study: the climatologic analysis of the vertical differentiation of water vapor content. The use of a 35-year-long daily data series (1981–2015) provides a sample large enough to produce a detailed climatologic analysis focused on extreme conditions. Wypych [23] was able to show differentiation in vertical profiles of specific humidity over Europe on both spatial and seasonal bases. Despite the smoothing of moisture fields in the course of reanalysis, this differentiation shows that moisture variables may be used to perform climatologic analyses while maintaining vital characteristics of mesoscale processes. Although climatologic reanalysis remains a somewhat questionable method due to its lack of full agreement with measured data, it represents a way to study moisture variables in the face of a lack of homogeneous data series. In addition, reanalysis remains insensitive to spatial changes and instrumental changes in the observation network. Numerous comparative studies [4, 17, 18] have shown the usefulness of reanalysis in the study of moisture fields.

The first step in the research study consisted of the preparation of a SHUM profile and the identification of cases of moisture inversion. The depth and strength of moisture inversions were determined using a formula provided by Brunke et al. [18] based on Vihma et al. [14] (1):

$$QIS = \frac{q(p_{\min}) - q(p_{\max})}{|p_{\min} - p_{\max}|}, \quad (1)$$

where QIS is the inversion strength ($\text{g}\cdot\text{kg}^{-1}\cdot(50\text{ hPa})^{-1}$), q is the specific humidity ($\text{g}\cdot\text{kg}^{-1}$), $p_{\min}$ is the height of the inversion top (hPa), and $p_{\max}$ is the height of the inversion base (hPa).

The denominator of (1) describes the depth of an inversion layer. The strength of the inversion is calculated based on a layer with a depth of 50 hPa. Additionally, an analysis of inversion intensity based on normalized values was performed because of the general exponential decrease in humidity with height resulting in a decrease in inversion strength. Given the methods utilized in this study, only inversions of a certain intensity and those lasting over longer periods of time were examined (the positive gradient q present in averaged daily data). SHUM gradient (Δq) is calculated between consecutive 50 hPa layers. Inversion layers separated by a negative SHUM gradient were treated as separate moisture inversions. The study only considers cases where $\Delta q > 0.009\text{ g}\cdot\text{kg}^{-1}$ (10% positive lapse rate). Cases of inversion were classified as surface-based cases (inversion base ≥ 900 hPa) and elevated cases (inversion base < 900 hPa). The same method was used to identify inversions of the air temperature, although cases where $\Delta t < 0.6\text{ K}$ were ignored (10% positive lapse rate). Cases where moisture inversions and temperature inversions occur simultaneously were also noted by calculating the frequency of occurrence and the coefficient of correlation for Δq and Δt . Water vapor transport was characterized via the specific humidity flux index (SHUMF, $\text{g}\cdot\text{kg}^{-1}\cdot\text{m}\cdot\text{s}^{-1}$) calculated using (2), specific humidity q , and zonal (u) and meridional (v) wind component values for every available vertical level up to 300 hPa:

$$\text{SHUMF} = \sqrt{(q \cdot u)^2 + (q \cdot v)^2}. \quad (2)$$

The advective flux of specific humidity ($\text{g}\cdot\text{kg}^{-1}\cdot\text{m}\cdot\text{s}^{-1}$) was calculated for the zonal direction ($u \cdot \Delta q|_x$) and for the meridional direction ($v \cdot \Delta q|_y$), where u and v are the horizontal wind speeds in the respective directions and $\Delta q|_x$ and $\Delta q|_y$ are the horizontal humidity gradients in the respective directions.

The effect of atmospheric circulation on the vertical structure of water vapor content in the air was determined based on SHUM and SHUMF anomalies in advection directions. The study uses a simple division based on advection directions obtained directly from geostrophic wind directions. In addition, advection-free situations were identified with a wind speed not in excess of the 5th percentile, identified separately for each studied pressure level. Thresholds for the studied pressure levels were as follows: $2.0\text{ m}\cdot\text{s}^{-1}$ for 950 hPa, $2.2\text{ m}\cdot\text{s}^{-1}$ for 850 hPa, $2.7\text{ m}\cdot\text{s}^{-1}$ for 700 hPa, $3.7\text{ m}\cdot\text{s}^{-1}$ for 500 hPa, and $5.5\text{ m}\cdot\text{s}^{-1}$ for the 300 hPa level. SHUM and SHUMF anomalies were calculated relative to mean monthly values and then standardized.

The use of climatologic reanalysis data in the study assures homogeneous spatial information for the study area in the context of water vapor data in the atmosphere. Multiple comparative studies [4, 17, 18] confirm the usefulness of reanalysis data in the examination of water vapor fields. A positive error was detected in temperature analysis results for the near-surface layer, which undoubtedly impacts moisture content values, and this is significant in cases of SHUM inversion occurrence [17, 24, 25]. In addition, research has shown a lack of adequate representativeness in moisture convection in research models [6]. However, despite a lack of agreement with respect to the occurrence of

FIGURE 2: Monthly mean specific humidity at selected pressure levels (1981–2015); slanted lines are used to denote areas situated above the average of selected pressure levels.

SHUM inversions in reanalysis data and aerologic surveys, Brunke et al. [18] were able to show the usefulness of reanalysis data in climatologic studies or studies with a lower time resolution (daily or monthly averages), representing a larger geographic area. New knowledge on the moisture variable in newer reanalysis data including ERA-Interim has led to much improved parametrization of water circulation patterns. In turn, this results in a reduction in the size of errors in humidity-sensitive variables [4, 17, 18, 26].

3. Results and Discussion

3.1. Vertical Structure Climatology. Water vapor content in the air varies over time and across geographic space, which is closely linked with changes in temperature conditions. The relationship between air temperature and water vapor

pressure (saturated) is described by the Clausius–Clapeyron equation. It assumes a decline of about 7% in water vapor content in the atmosphere due to a 1 K decrease in air temperature. This tendency, best observed over ocean areas, may be affected over land areas by rapid moisture transport, various processes affecting the near-surface zone of the air layer driven by local conditions, and convection.

The stated relationships indicate that the largest amount of water vapor in Europe is found in the area over the Atlantic Ocean at subtropical latitudes and in the south of the continent. Both areas are regions with the smallest fluctuations in water vapor content with high air temperatures throughout the year. The smallest amount of water vapor is detected in the atmosphere in the northern part of the study area, especially over the ocean, an area characterized by small fluctuations in air temperature on an annual

FIGURE 3: Monthly mean specific humidity (SHUM) vertical profiles at selected grid points (for details, see Figure 1 and Table 1); whiskers show the range defined by minimum and maximum SHUM values in a moisture region represented by the given grid point: (a) January; (b) July (1981–2015).

basis. In temperate zones, especially across continental Europe, annual fluctuations in water vapor content in the air are the highest in the study area due to the increasingly continental climate of the interior of Europe. In the winter, water vapor content over land areas corresponds to that detected at polar latitudes, while in the summer, it is greater than that determined for subtropical regions [21]. Given that the presence of water vapor in the Earth's atmosphere is substantial up to an altitude of about 2 km, determined by a negative temperature gradient, the greatest differentiation in the vertical profile is noted up to the 700 hPa level (Figure 2).

Changes in the atmospheric boundary layer yield 950 hPa and 850 hPa levels characterized by the occurrence of significant differences in SHUM values. This applies to differentiation in the vertical profile and also in the spatial sense, as expressed by an areal standard deviation (σ) calculated using all the domain grid points (Figures 2 and 3). In July, its values for mentioned pressure levels were as follows: $\sigma_{\text{areal}} = 1.6 \text{ g}\cdot\text{kg}^{-1}$ and $\sigma_{\text{areal}} = 1.2 \text{ g}\cdot\text{kg}^{-1}$, and in January, its values were $\sigma_{\text{areal}} = 1.4 \text{ g}\cdot\text{kg}^{-1}$ and $\sigma_{\text{areal}} = 0.75 \text{ g}\cdot\text{kg}^{-1}$. In January, the effect of warm North Atlantic and Norwegian currents may be observed along the western and northwestern coasts of the continent up to the 850 hPa level along with related increases in moisture levels across Western Europe (Figure 2). On the contrary, the interior of the European continent is affected by a seasonal high and characterized by much lower SHUM values. In July, the high SHUM content is readily observable in the troposphere over land areas, higher than that over the ocean at all three studied levels (Figure 2).

The stated characteristics of water vapor content are provided in detail in the vertical SHUM profiles produced for selected grid points in Figure 3.

From a climatologic perspective, the decline in the mean monthly water vapor content in the Earth's atmosphere,

based on the Clausius–Clapeyron equation, is exponential in nature. This type of pattern, however, is representative mainly of points located across ocean areas. The vertical SHUM profile is quite similar for January (Figure 3(a)) and July (Figure 3(b)) and shifted in July in the direction of higher values. The Mediterranean Sea is partly affected by the surrounding land masses. The point located on the Mediterranean Sea (S) in July features a higher than oceanic moisture content at levels between 950 and 650 hPa (Figure 3(b)) and follows a similar pattern in January (Figure 3(a)). Northern areas (NW) have low air and water temperatures and are characterized by the smallest differences in SHUM in July. In January, on the contrary, northern areas have a higher water temperature than land temperature and experience evaporation off the ocean's surface, resulting in a moisture supply leading to a vertical SHUM gradient that is larger than that over continental areas (grids N and E). As stated previously, land areas are characterized by the largest differences in water vapor content. The SHUM gradient in layers from 950 hPa to 800 hPa at sites located deep inland equals about $2 \text{ g}\cdot\text{kg}^{-1}\cdot(150 \text{ hPa})^{-1}$, while its value in the troposphere over the ocean (grid SW) is about $6 \text{ g}\cdot\text{kg}^{-1}\cdot(150 \text{ hPa})^{-1}$ (Figure 3(b)).

There exist special cases in the troposphere characterized by increasing water vapor content in line with increasing altitude. Moisture inversions may assume variable depths and degrees of strength in relation to location and season of the year. In some cases, several inversion layers may be observed within one vertical SHUM profile [11, 15–18].

Given the procedural assumptions made in this study, only inversions lasting longer periods of time are considered (positive SHUM gradient in daily averages) as well as those of appropriate strength (Section 2). The frequency of inversions in the troposphere over Europe varies substantially

FIGURE 4: Frequency (%) of humidity inversion occurrence (1981–2015); slanted lines are used to denote areas situated above the average 950 hPa level.

FIGURE 5: Frequency (%) of humidity inversion occurrence: (1) surface-based and (2) elevated at selected grid points (for details, see Figure 1 and Table 1) (1981–2015).

FIGURE 6: Mean height (hPa) of humidity inversion base (1981–2015); slanted lines are used to denote areas situated above the average 950 hPa level.

according to season and across geographic space. Inversions occur much more frequently in the winter (January) over land areas—sometimes in excess of 80% of days in the Scandinavian Peninsula and roughly 50% of days in Eastern and Southeastern Europe (Figures 4 and 5; KRK and E). In addition, inversions occur on 30% to 40% of days across the subtropical areas of the Atlantic (Figure 5; SW). However, in the summer, inversions are almost entirely limited to the subtropical zone across the Atlantic Ocean (40% to 50%) and the Mediterranean Sea (30% to 40%) (Figures 4 and 5; SW and S).

The temporal differentiation and spatial differentiation of the level of inversion occurrence are readily observable (Figure 6). In January, the mean base of the inversion layer over most land areas does not exceed 850 hPa, while in Western Europe, Southwestern Europe, and western coastal areas, it is 700 hPa. On the contrary, most inversions occurring over ocean areas are characterized by a lower level above 700 hPa (Figure 6). The mean base of the inversion layer in July in Eastern Europe and the Iberian Peninsula exceeds 700 hPa, while over the Caucasus, it is above 550 hPa (Figure 6). A large number of winter inversions take the form of surface-based inversions occurring over continental areas (Figure 5; W, N, KRK, and E). On the contrary, elevated-type inversions are the predominant type over sea and ocean areas regardless of season, while the few surface-based inversions that are detected may be designated marginal in significance (Figure 5; NW, SW, and S).

The current study has confirmed and expanded on the study by Brunke et al. [18], who used data from 5 different sets of reanalysis data and compared them with weather balloon surveys in order to show the occurrence of inversions in polar areas, mostly in the winter season, and the low base of these inversions. Nygård et al. [15, 16] and Vihma et al. [14] found statistically significant relationships between the occurrence of moisture inversions in relation to temperature inversions in near-polar areas in the northern and southern hemispheres. The similar conditions present in the winter in the atmospheric boundary layer over land areas (i.e., European interior areas) including negligible cloud

cover, strong cooling of surfaces, and the associated water vapor condensation all suggest the simultaneous occurrence of moisture and temperature inversions also in polar regions.

Research has shown that surface-based SHUM inversions are accompanied by temperature inversions 70% of the time, which then increase to 90% in the direction of the continent's interior (grid E), while in Western Europe, they do not exceed 60%. This dependency declines to an average of 50% in the layer between 900 and 800 hPa. The correlation coefficient for the moisture gradient and air temperature on days with inversions reaches a statistically significant ($\alpha = 0.05$) average value of 0.5. For July, the absence of any type of relationship between the occurrence of moisture and temperature inversions confirms the dynamic origin of this particular linkage resulting from the advection of moisture or convection.

Although SHUM inversions occur more frequently in the winter, their depth is small, especially in privileged areas, and they range from <70 hPa in the Scandinavian Peninsula to about 80 hPa over other land areas (Figure 7). The deepest layer wherein water vapor content grows with altitude is most often detected over the North Atlantic (~100 hPa). Summer inversions are shallow and do not exceed 80 hPa over water and about 60 hPa over land (Figure 7). The strength of inversions varies negligibly over the study area. Somewhat higher values may be detected in July at an average of $0.2 \text{ g} \cdot \text{kg}^{-1} \cdot (50 \text{ hPa})^{-1}$: from more than $0.3 \text{ g} \cdot \text{kg}^{-1} \cdot (50 \text{ hPa})^{-1}$ over subtropical ocean areas to $0.1 \text{ g} \cdot \text{kg}^{-1} \cdot (50 \text{ hPa})^{-1}$ over land. The strength of winter inversions is greatest over the Scandinavian Peninsula ($>0.3 \text{ g} \cdot \text{kg}^{-1} \cdot (50 \text{ hPa})^{-1}$) and over parts of continental Europe ($0.2\text{--}0.3 \text{ g} \cdot \text{kg}^{-1} \cdot (50 \text{ hPa})^{-1}$). Other parts of the study area do not exceed $0.15 \text{ g} \cdot \text{kg}^{-1} \cdot (50 \text{ hPa})^{-1}$.

In order to reduce bias originating due to the exponential decrease in the amount of water vapor in the atmosphere, the analysis was repeated using standardized values. The procedure confirmed the most intensive inversions occurring in January in the northern (Scandinavian Peninsula) and northeastern parts of Europe (Northern Continental moisture region) but highlighted also the strength of

FIGURE 7: Mean humidity inversion depth (hPa) and intensity ($\text{g} \cdot \text{kg}^{-1} \cdot (50 \text{ hPa})^{-1}$) (1981–2015); slanted lines are used to denote areas situated above the average 950 hPa level.

FIGURE 8: Mean standardized humidity inversion intensity ($\text{g} \cdot \text{kg}^{-1} \cdot (50 \text{ hPa})^{-1}$) (1981–2015); slanted lines are used to denote areas situated above the average 950 hPa level.

inversions over the Subtropical Atlantic region (Figure 8), which are mostly elevated, with the base between the levels of 700 and 550 hPa (Figure 6). The strength of summer inversions over the Subtropical Atlantic region was noted but was also determined over the continent where it was smoothed over by the moisture decrease bias (Figure 8).

3.2. Atmospheric Circulation Impact. Water vapor transport is one of the most important processes determining differences in its distribution across Europe. Existing research strongly suggests that atmospheric circulation, especially the

North Atlantic Oscillation (NAO), shapes moisture content in the air in the winter [27–29]. Air saturated with water vapor is transported from over ocean areas in the direction of land, thanks to zonal circulation, and in the northerly direction, also known as meridional flux. Significantly weaker dependencies were noted in the warm half of the year when differences in water vapor content originate in convection, while horizontal moisture flux plays a secondary role.

In the present study, the analysis of water vapor transport concerns the advection of air masses or horizontal moisture flux at principal pressure levels: 950 hPa, 850 hPa, 700 hPa, and 500 hPa. Moisture transport is strongly aided

FIGURE 9: Monthly mean specific humidity flux and wind direction (arrows) at selected pressure levels (1981–2015); slanted lines are used to denote areas situated above the average of selected pressure levels.

by advection at the 850 hPa level. The limited impact of the atmospheric boundary layer enables the flux of air masses in the direction of the continent, and this includes not only Western Europe, as in the case of altitudes closer to the surface of the Earth (Figure 9), but also Central Europe.

Moisture transport strongly varies by season due to the amount of water vapor available per given air temperature and due to circulation in each given season. The substantial role of seasonal pressure highs is observable in January, in particular at the 950 hPa level, limiting the horizontal

FIGURE 10: Climatologic mean profiles of specific humidity advective flux: eastward (u) and northward (v) during inversion (solid curve) and noninversion (dashed curve) events (detailed description in the text) at selected grid points (for details, see Figure 1 and Table 1).

motion of air masses (advection-free in many cases) and substantially affecting temperature conditions. The role of orographic barriers is also quite significant. Despite a high SHUM in July, SHUM transport is limited. In the south of Europe, this is associated with a shift in the intertropical convergence zone in the northerly direction and a predominance of longitudinal flux with a northerly component in the Mediterranean region. The influx of moisture becomes observable only in the free atmosphere (Figure 9).

Figure 10 uses dashed curves to show the significance of zonal and meridional transport of the moisture content in the air. Vertical profiles of specific humidity advective flux show a virtual lack of advection in January in continental Europe (grids W, N, KRK, and E). Small amounts of SHUM are carried by meridional flux along with relatively small differences in moisture transport over the ocean in the

temperate and near-polar zones (grids WW and NW, resp.). On the contrary, large differences do occur in the subtropical zone, in particular over the Mediterranean Sea (grid S). Meridional flux assumes significant negative deviations, while zonal flux assumes equally large positive deviations (Figure 10). July vertical profiles show significant variability in specific humidity advective flux in continental Europe, especially in cases of days with SHUM inversions (solid lines).

Figure 11 shows in detail the role of selected advection directions in moisture transport based on selected grid points. Negative SHUM anomalies in January occur with advection from the north and east at all pressure levels, although in the interior of the continent (grids KRK and E), the deviations are largely closer to the surface of the Earth (levels 950 hPa and 850 hPa).

FIGURE 11: Specific humidity anomalies ($\text{g}\cdot\text{kg}^{-1}$) in advection directions (with respect to monthly mean, standardized) at selected pressure levels (1981–2015) and selected grid points (for details, see Figure 1 and Table 1), based on Wypych [23].

FIGURE 12: Specific humidity flux anomalies ($\text{g}\cdot\text{kg}^{-1}\cdot\text{m}\cdot\text{s}^{-1}$) in advection directions (with respect to monthly mean, standardized) at selected pressure levels (1981–2015) and selected grid points (for details, see Figure 1 and Table 1), based on Wypych [23].

The same holds true for water vapor transport (Figure 12), which indicates a significant role of the atmospheric boundary layer and mesoscale processes such as a seasonal high. Effects deemed continental may be observed in moisture transport

also over the ocean (see grid point WW), although changes in the air mass associated with an increasing distance from a land mass yield a situation where moisture influx from the east produces a small positive anomaly (Figure 12).

Positive moisture anomalies and moisture transport in the winter are associated with advection from the west—or in the case of points located farthest to the east—and also from the south.

The insignificance of air circulation in the summer is confirmed by almost nonexistent SHUM and SHUMF anomalies in July at selected grid points (Figures 11 and 12).

One special case of the role of moisture advection is the occurrence of SHUM inversions (Figure 12). The significance of moisture inversions in the formation of total column water vapor (TCWV) has often been noted in the context of near-polar regions [14–16]. Given generally low water vapor content in the air, an inversion column may recharge TCWV up to 40%, whereas given a larger water vapor content, the effect of inversion on the TCWV value declines to about 15%. Therefore, the occurrence of inversions and share in the radiation balance are most substantial in the winter and spring. As noted previously, most cool season moisture inversions are associated with the occurrence of temperature inversions, often accompanying high pressure systems. The lowering of air temperature near the surface of the ground leads to the condensation of water vapor present in the air or the drying of the air mass resulting in an inversion of air moisture levels. Another factor that favors the occurrence of an inversion is the advection of moist air at higher levels or dry air near the surface of the Earth. Figure 10 shows mean profiles of specific humidity advective flux and mean inversion levels: top of surface-based inversions (solid lines) and bottom and top of elevated inversions (dashed lines). It may be readily observed that, in the case of surface-based inversions in January, the moisture flux effect is not significant. There is no meaningful difference between days with an inversion (solid curve) and days without an inversion (dashed curve). The grid point *E* is an exception where moisture advection is noted at the top of the surface-based inversion. On the contrary, in July, a month characterized by far fewer moisture inversions and especially by elevated inversions over regions of land, the significant role of meridional moisture flux may be observed on the top of surface-based inversions at points located in the northern part of the study area (grids NW and N) along with the advection of dry air (regardless of moisture flux direction) at the bottom of elevated inversions at the point KKK. Dependencies determined at selected grid points are consistent with results produced by studies in near-polar areas [14–16], as well as on the macroscale [21], which underscore the significance of meridional moisture flux and the convergence and convection of water vapor in the summer season.

4. Conclusions

Studies on the vertical structure of SHUM yield better parametrization of both climate models and mesometeorological models. Water vapor condensation in the atmospheric boundary layer is determined first and foremost by its vertical flux, as it is the structure of moisture both in the atmospheric boundary layer and in the free atmosphere that determines the strength and direction of water vapor transport [30]. For

example, the presence of moisture inversions plays a decisive role in shifts in convection at subtropical latitudes [5] and also helps support the cloud layer by making evaporation off its upper part impossible [11] and assists in fog formation [12].

The present study constitutes a climatologic analysis based on averaged daily data and shows the existence of differences in the vertical structure of water vapor content in the troposphere over Europe and the North Atlantic, including the presence of moisture inversions beyond 60°N and at temperate and subtropical latitudes. Inversions may be surface-based or elevated, and their occurrence follows a seasonal pattern. Land areas are characterized by the presence of surface-based inversions in the winter and elevated inversions in the summer, while ocean areas are characterized by lower inversions in the summer versus winter, although these are not true surface-based inversions, which tend to occur sporadically over the ocean.

Atmospheric circulation plays an important role in changes in water vapor content, especially in the winter season, and determines both surpluses and shortages of moisture through effects generated by different pressure system types (especially important is the seasonal high) and advection directions. Anomalies in the atmospheric boundary layer occur primarily over land areas. Vertical profiles of water vapor content are characterized by large standard deviations due to the large variety of physical characteristics of incoming air masses. Over ocean areas, the vertical structure of moisture is quite stable at lower levels, with some deviations related to advection direction; however, at higher pressure levels, it becomes differentiated. In summer months, the vertical structure of moisture remains largely unaffected by changes in circulation conditions, which given a variable SHUM content at subsequent pressure levels indicating the significance of processes occurring in the atmospheric boundary layer in the shaping of moisture content in the troposphere.

The results of the present study suggest a need for further research on the subject of variances in the vertical structure of water vapor content over Europe, with a special focus on subdaily data that would make it possible to examine differences in water vapor content in a dynamic sense. The use of reanalysis data bears the burden of near-surface biases that also do impact the structure of moisture; nevertheless, given a large array of variables available, it allows for a comprehensive analysis of processes determining moisture levels and an evaluation of their role in relation to ongoing weather changes.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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