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Increasing vapour pressure deficit is not necessarily atmospheric moisture loss: seasonal structure of change in Estonia, 1965–2024

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Research Article

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Abstract

Rising vapour pressure deficit (VPD) is often read as evidence of atmospheric drying, but under warming VPD increases even at constant relative humidity (RH). We asked when, within the growing season, atmospheric moisture has failed to keep pace with warming in Estonia, using daily data from 20 stations for April–September 1965–2024. As a scaling metric we used the ratio of the trends in actual and saturation vapour pressure (Δea/Δes), where 1 corresponds to constant RH, and we decomposed VPD trends into temperature and humidity components. VPD increased in April (0.17 hPa per decade), July, August and September. From July to September, actual vapour pressure increased at 70–80% of the rate of saturation vapour pressure, not significantly different from constant RH in July and August, so the VPD increase was mainly thermodynamic. In April, the scaling ratio was 0.38 (95% CI 0.13–0.73), RH declined by 0.93% per decade, and declining RH contributed as much to the VPD increase as warming. The April moisture lag was stronger at inland than at maritime stations (median ratio 0.28 vs 0.49). An earlier end of the snow season accounted for about one-fifth of the April RH trend. Results were robust to autocorrelation-corrected tests and to restricting the analysis to RH-homogeneous stations. An increase in VPD is therefore not necessarily a loss of atmospheric moisture: in Estonia, drying beyond the thermodynamic expectation is concentrated in early spring, a signal masked by seasonal means.

1. Introduction

Vapour pressure deficit (VPD), the difference between the saturation and actual vapour pressure of the air, controls the atmospheric demand for water. It regulates stomatal conductance, transpiration and photosynthesis and has become a central variable in assessments of climate impacts on vegetation and crops (Novick et al. 2016; Grossiord et al. 2020). Increasing VPD has been linked to reduced global vegetation growth since the late 1990s (Yuan et al. 2019), and tree-ring and observational reconstructions show that recent summer atmospheric drying in Europe is unprecedented in several centuries (Treydte et al. 2024; Nagavciuc et al. 2024).

An increase in VPD under warming is, however, partly expected on thermodynamic grounds. Saturation vapour pressure rises by about 6–7% per kelvin (Clausius–Clapeyron), so VPD increases even when relative humidity (RH) remains constant. An increase in VPD is therefore not necessarily a loss of atmospheric moisture. Whether the atmosphere is becoming drier in a physically more meaningful sense depends on whether actual vapour pressure keeps pace with saturation vapour pressure, that is, on the trend in RH. Over land, RH has decreased in many regions since the late 1990s (Willett et al. 2014; Vicente-Serrano et al. 2018). A widely discussed explanation is the land–ocean warming contrast: land warms faster than the ocean, which remains the main moisture source, so moisture supply to continental air does not keep pace with the increase in its saturation vapour pressure (Byrne and O'Gorman 2016, 2018). Land processes, particularly reduced evapotranspiration, modify this signal regionally (Vicente-Serrano et al. 2018). In northern Europe, warm-season RH changes are spatially heterogeneous, and parts of Scandinavia show increasing rather than decreasing RH (Vicente-Serrano et al. 2018).

Most analyses of VPD and RH trends use seasonal or annual means, gridded data or reanalyses. Less is known about how the balance between warming and moisture supply changes within the growing season, and whether the mechanisms differ between its parts. This is important in high-latitude regions, where the start of the growing season coincides with snowmelt, low sea-surface temperatures and leafless vegetation, all of which affect the surface moisture supply very differently from summer conditions. In Estonia, the end of the permanent snow cover has shifted earlier by 10–30 days since 1950 (Viru and Jaagus 2020) and snow cover duration has decreased by 3–4 days per decade (Jaagus et al. 2017).

Estonia is a suitable region to examine these questions. It lies on the boundary between maritime and continental climates, the Baltic Sea strongly modifies conditions in a narrow coastal zone, and a dense station network provides daily temperature and humidity observations since the 1960s. The contrast between coastal and inland stations allows the role of the sea as a moisture source to be assessed directly. The questions are, however, not specific to Estonia: many mid- and high-latitude regions combine a coast–inland gradient with seasonal snow cover, and the diagnostic used here can be applied wherever daily temperature and humidity records are available.

In this study, we analyse daily observations from 20 Estonian stations for the growing seasons of 1965–2024. We ask: (1) when during the growing season has VPD increased; (2) how much of the increase is due to warming at constant RH and how much to changes in RH; (3) does actual vapour pressure keep pace with saturation vapour pressure, and does this differ between maritime and inland stations; and (4) is the April humidity change related to the earlier end of the snow season? Seasonal aggregates (April–May, June–August, September) are used for summary statistics, but the analysis focuses on monthly and dekadal resolution, because the main signals are confined to individual months.

2. Data and methods

2.1 Station data

Daily observations of minimum, mean and maximum air temperature (Tmin, Tmean, Tmax), daily mean relative humidity (RH) and precipitation were obtained from the Estonian Environment Agency for 20 stations for 1965–2024 (Fig. 1, Table 1). The analysis covers the growing season from 1 April to 30 September, divided into 18 dekads (days 1–10, 11–20 and 21 to the end of each month). Stations were classified as maritime (n = 9), if located on the coast or on an island, or inland (n = 11). In Estonia this distinction is sharp, because the sea effect is concentrated in a narrow coastal zone. Daily RH for 21 June–31 August 2019, missing from the compiled dataset, was taken from the Environment Agency open-data service; where both sources overlapped, values agreed within 1 %. After this, 0.9 % of station-dekads lacked RH and 0.8 % lacked temperature.

Table 1. Stations used in the study. RH data: percentage of April–September days in 1965–2024 with valid daily mean RH (temperature completeness was ≥ 96.9 % at all stations). Snow end: mean day of year of the end of the snow season, with the number of years with snow data in parentheses (1965–

2024). April RH trend: Sen slope in % per decade; * $p < 0.05$, ** $p < 0.01$ (Mann–Kendall). Δea/Δes: ratio of the Sen slopes of April actual and saturation vapour pressure (1 = constant RH). Homogeneous: no relative inhomogeneity detected in April–May RH (Section 2.6).

Station	Lat (°N)	Lon (°E)	RH data (%)	Snow end (DOY)	April RH trend (% dec^{-1})	April Δea/Δes	Homo-geneous
Maritime stations (n = 9)							
Kihnu	58.10	23.97	99.8	93 (60)	−1.03**	0.49	yes
Kunda	59.52	26.54	99.9	100 (46)	−0.79*	0.44	yes
Lääne-Nigula	58.95	23.82	99.9	101 (60)	−1.42**	0.23	no
Pakri	59.39	24.04	99.8	100 (39)	−0.29	0.71	no
Ristna	58.92	22.07	98.8	95 (60)	−0.09	0.73	no
Sõrve	57.91	22.06	96.8	93 (57)	−0.85*	0.60	yes
Tallinn-Harku	59.40	24.60	99.9	99 (44)	−1.14*	0.36	yes
Vilsandi	58.38	21.81	97.1	89 (59)	−0.06	0.70	no
Virtsu	58.57	23.51	95.6	97 (57)	−1.21**	0.38	no
Inland stations (n = 11)							
Jõgeva	58.75	26.41	99.6	105 (60)	−1.00**	0.28	yes
Jõhvi	59.33	27.40	99.9	108 (60)	−0.92*	0.26	no
Kuusiku	58.97	24.73	97.6	106 (60)	−1.12**	0.30	yes
Narva	59.39	28.11	99.9	105 (47)	−0.72	0.38	no
Tartu-Tõravere	58.26	26.46	100.0	102 (59)	−1.41**	0.19	no
Tiirikoja	58.87	26.95	99.9	104 (60)	−1.16**	0.39	yes
Türi	58.81	25.41	99.7	104 (60)	−0.94*	0.33	yes
Valga	57.79	26.04	99.9	102 (60)	−1.51**	0.11	no
Viljandi	58.38	25.60	100.0	103 (60)	−1.11**	0.24	yes
Väike-Maarja	59.14	26.23	99.7	109 (60)	−1.15**	0.30	no
Võru	57.85	27.02	98.8	101 (59)	−1.32*	0.20	no

Means of the snow-season end are not directly comparable between stations with different numbers of years.

A station-dekad (or station-month) value was computed when at least 80 % of its days were available. National series were calculated as the mean of the 20 stations when at least 15 stations were available; this condition was met for all dekads.

Daily snow depth (06 UTC) for 1965–2024 was obtained for all 20 stations from the Estonian Environment Agency. Coverage in February–May was at least 90 % at 17 stations; Narva, Pakri (until 2003), Kunda (until 2013) and Tallinn-Harku (from 1980) have shorter or less complete records, and station-years with less than 90 % coverage were excluded. Where the record overlapped with the Environment Agency open-data download (1991–2024), the values were virtually identical (>99.9 % of days equal). For Jõgeva, the end date of the snow season for 1965–2019 was also available from the station's climatological yearbook compilation, together with the monthly number of days with minimum RH below 30 %.

2.2 Humidity variables

Saturation vapour pressure was calculated in kPa as the mean of es(Tmax) and es(Tmin), with es(T) = 0.6108 exp(17.27 T / (T + 237.3)) (Allen et al. 1998, eq. 11–12). Because only daily mean RH was available, actual vapour pressure was estimated as ea = RHmean/100 · (es(Tmax) + es(Tmin))/2 (Allen et al. 1998, eq. 19), and VPD = es − ea. This is the standard approximation when RHmax and RHmin are not available. It does not give the exact daily mean vapour pressure, because RH and temperature co-vary during the day, but the approximation is applied consistently over the whole period and therefore affects absolute values more than trends. VPD represents daily-mean rather than afternoon conditions. All vapour pressures are reported in hPa (1 kPa = 10 hPa).

2.3 Trend analysis

Trends in Tmean, es, ea, RH and VPD were estimated for each dekad, month and season (April–May, June–August, September) with the Sen slope (Sen 1968) and tested with the tie-corrected Mann–Kendall test (Mann 1945; Kendall 1975). Because serial correlation can inflate significance, results were checked with the Hamed–Rao modified test (Hamed and Rao 1998), with the variance correction applied only when it increased the variance of the test statistic, and with trend-free pre-whitening (Yue et al. 2002). For the 18 dekadal tests of each variable, the false discovery rate was controlled with the Benjamini–Hochberg procedure (Benjamini and Hochberg 1995). Trends are reported per decade.

2.4 Does moisture keep pace with warming?

If RH remains constant, ea increases in proportion to es. We therefore used the ratio of the Sen slopes of ea and es, Δea/Δes, as a scaling metric: a value of 1 indicates that atmospheric moisture keeps pace with warming (constant RH), and values below 1 indicate that moisture lags behind and RH declines. The ratio was calculated for each month, for all stations, for the RH-homogeneous subset (Section 2.6) and

for maritime and inland stations. 95 % confidence intervals were obtained from 2000 bootstrap resamples of years, recomputing both Sen slopes in each resample (pairs with identical resampled years were excluded from the slope calculation). Resampling individual years assumes weak serial dependence, which is supported by the small lag-1 autocorrelation of the detrended series ($|r1| \leq 0.36$).

2.5 Decomposition of VPD trends

Because $VPD = es(T)\cdot(1 - RH/100)$ depends non-linearly on temperature and RH, its trend cannot be split exactly into additive parts. We used an approximate decomposition with two counterfactual series. A temperature-only VPD was calculated with the observed Tmax and Tmin and RH fixed at its station-specific calendar-day climatology (1965–2024); its trend represents the change expected from warming at constant RH. A humidity-only VPD was calculated with the observed RH and Tmax and Tmin fixed at their calendar-day climatology; its trend represents the change due to RH alone. The difference between the observed trend and the sum of the two is reported as an interaction/residual term. Shares are given only as approximate proportions.

2.6 Homogeneity of RH

Spring (April–May) mean RH series were screened for inhomogeneities with the Pettitt test (Pettitt 1979) and the standard normal homogeneity test (SNHT; Alexandersson 1986). Both tests were applied to each station series (absolute test) and to a relative series, defined as the difference between the station and the mean of the other 19 stations. Climate variability and change that are common to the region largely cancel in the relative series, so a step change in it indicates a station-specific shift, such as a change of instrument, observation practice or surroundings, rather than a regional climate signal. The absolute tests were used only for description, because a break in an absolute series may reflect a real climatic shift. A station was flagged as inhomogeneous if its relative series showed a Pettitt break ($p < 0.05$) or an SNHT statistic above the 95 % critical value (8.1 for $n = 60$; Khaliq and Ouarda 2007); the size of the shift was estimated as the difference in mean relative RH after and before the break. Nine stations were not flagged; all main analyses were repeated with this subset. Because the reference series is itself an average of stations that may contain breaks, and because a change affecting the whole network simultaneously would not appear in relative series, these tests detect station-specific inhomogeneities only. Complete station metadata on changes of humidity instruments were not available, so detected breaks could not be attributed to specific changes.

2.7 Snow cover and April humidity

The end of the snow season was defined as the day after the last day in February–May with snow depth ≥ 1 cm. At Jõgeva, this definition agreed well with the yearbook dates for 1965–2019 ($r = 0.83$; mean difference −0.7 days). The relationship between April mean RH and the end of the snow season was estimated for 1965–2024 with a station fixed-effects regression, with standard errors clustered by year. Two control variables were included. A linear year term removes the common long-term trends of RH and snow, so that the snow coefficient is estimated from interannual covariation rather than from two

parallel trends. April mean temperature was included because warm Aprils both end the snow season earlier and lower RH; its inclusion tests whether snow is associated with RH beyond the effect of temperature. Because temperature also influences snow, the models were estimated with and without these controls and the snow coefficient is reported for all specifications. To assess how much of the April RH trend is statistically accounted for by the snow season, the year coefficient was compared between models with and without the end of the snow season. In addition, April days with and without snow cover were compared within classes of daily mean temperature.

All analyses were done in Python; code and derived data are available at https://doi.org/10.5281/zenodo.23222156.

2.8 AI-assisted code development

Claude (Anthropic) was used to assist with the development, debugging and review of the Python code for all analyses and figures, including data processing, trend tests, the bootstrap, the VPD decomposition, homogeneity tests and the snow-cover regression. The author specified the analyses, ran and checked all code, and verified the reported numbers against the analysis outputs.

3. Results

3.1 Seasonal structure of change

Air temperature increased in all months of the growing season, by 0.41 °C per decade in April, 0.37–0.45 °C per decade in July–September and less in May (0.26 °C) and June (0.20 °C, not significant) (Fig. 2). Saturation vapour pressure followed temperature. Actual vapour pressure increased significantly from June to September (0.22–0.37 hPa per decade), but in April it increased by only 0.11 hPa per decade, and in May the increase was not significant.

As a result, RH declined significantly only in April (−0.93 % per decade; $p = 0.010$), and in April–May as a whole (−0.81 % per decade; $p = 0.007$). Summer and September RH showed no significant change (June–August −0.07 % per decade, September −0.10 % per decade). At the dekadal scale, the RH decline was concentrated in the second dekad of April (−1.14 % per decade), although no single dekad remained significant after FDR correction.

VPD increased significantly in April (0.17 hPa per decade) and September (0.09 hPa per decade), and over the season as a whole (April–September, $p < 0.001$). The July and August increases were of similar magnitude to April (0.17 and 0.12 hPa per decade) but less significant ($p = 0.06$). June showed almost no change. At the dekadal scale, the significant increases in the first two dekads of April and the last two dekads of September remained significant after FDR correction and with both autocorrelation-robust tests, whereas mid-summer dekads did not.

3.2 Moisture lags behind warming in April

The scaling ratio Δea/Δes was lowest in April: 0.38 (95 % CI 0.13–0.73) (Fig. 3). Thus, in April atmospheric moisture increased by less than 40 % of the amount needed to keep RH constant. In May, the ratio was 0.51, but poorly constrained (CI −0.73 to 1.38). From July to September, the ratio was 0.70–0.79. Its confidence interval excluded 1 in September (0.51–0.98) but included 1 in July (0.48–1.05) and August (0.57–1.04), so summer moisture supply did not differ significantly from the constant-RH expectation. In June, the ratio was close to 1 (0.96) but undetermined, because both es and ea changed little. The pattern was the same for the nine RH-homogeneous stations (April 0.39, CI 0.13–0.68).

3.3 Thermodynamic and humidity contributions to VPD trends

In April, the temperature-only and humidity-only components contributed roughly equally to the VPD increase (0.07 and 0.08 hPa per decade of a total 0.17 hPa per decade; interaction 0.01) (Fig. 4). In July–September, the temperature-only component accounted for about 70–90 % of the trend and the humidity-only component for about 20–30 %. In June, the humidity-only component was negative and partly offset the temperature-only increase. The humidity-only series had a significant trend only in April ($p = 0.016$); the temperature-only series had significant trends in all months except June. The interaction term was small (≤ 0.02 hPa per decade) in all months.

3.4 Maritime and inland stations

The April moisture lag was stronger at inland stations (Fig. 5). The median April scaling ratio was 0.28 at inland stations and 0.49 at maritime stations (Mann–Whitney $p = 0.005$). The difference remained among RH-homogeneous stations (0.30 vs 0.47). April RH declined significantly at 10 of 11 inland stations (median −1.12 % per decade) and at 6 of 9 maritime stations (median −0.85 % per decade). The three stations without a significant April RH trend (Pakri, Ristna and Vilsandi) are exposed coastal or island sites, all of which were also flagged as inhomogeneous.

3.5 Snow cover and April humidity

Over 1965–2024, the end of the snow season advanced by 2.0 days per decade on average ($p = 0.008$), by 1.8 days per decade at inland stations ($p = 0.02$) and by 1.6 days per decade at maritime stations ($p = 0.05$); the snow season ended on average about one week later inland (day of year 104) than at the coast (day 96). Years with a later end of the snow season had a more humid April (Fig. 6a). Within stations, each day of later snow cover was associated with 0.09–0.10 % higher April RH, depending on whether temperature and the year term were included ($p = 0.001$–0.006). The relationship was strong at inland stations (0.15 % per day; $p < 0.001$) and absent at maritime stations (0.03 % per day; $p = 0.33$). On cold April days (daily mean ≤ 2 °C), RH was 5–7 percentage points higher with snow on the ground than on snow-free days at the same temperature; above 2 °C, the difference was small or absent (Fig. 6b).

Accounting for the end of the snow season reduced the estimated April RH trend in the station panel by about one-fifth, from −1.05 to −0.85 % per decade. Accounting for April temperature as well reduced it to −0.64 % per decade, so that interannual variations in snow and temperature together accounted for

about two-fifths of the trend. This suggests that declining snow cover contributes to, but does not dominate, the April humidity decline. At Jõgeva, the number of April days with minimum RH below 30 % increased by 0.8 days per decade ($p < 0.001$), indicating that the decline also affects afternoon humidity.

3.6 Homogeneity and robustness

Eleven of the 20 stations showed a significant break in the relative April–May RH series (station minus the mean of the other stations), with shifts of 1–3.5 percentage points; breaks at inland stations were mostly negative (drier) and at exposed coastal stations positive. Breaks in the station series (not relative) clustered in 1992–2001, which coincides with the warming step in the regional temperature record, and possibly also with changes of instruments or observation practice, which could not be verified without station metadata. All main results were reproduced with the nine unflagged stations: the April–May RH decline was −0.89 % per decade ($p = 0.002$), the April scaling ratio 0.39, and the VPD decomposition and seasonal pattern were unchanged (Table S1).

4. Discussion

4.1 An increase in VPD is not the same as a loss of moisture

The main result of this study is that the increase in VPD in Estonia has different meanings in different parts of the growing season. From July to September, actual vapour pressure increased at roughly three-quarters of the rate of saturation vapour pressure, a rate that in July and August did not differ significantly from constant RH; RH changed little and most of the VPD increase would have occurred even at constant RH. In these months, the higher VPD is mainly a thermodynamic consequence of warming, not evidence of a drier atmosphere in terms of moisture content, which in fact increased. April is different. Moisture supply increased by less than 40% of the amount required to maintain RH, RH declined by almost 1% per decade, and the decline in RH contributed about as much to the VPD increase as warming did. September also had a scaling ratio below 1, but the associated RH decline was small and not significant. April is therefore the month in which the atmosphere has most clearly become drier beyond what follows from warming alone.

Seasonal or growing-season averages hide this structure. Over April–September as a whole, VPD increased significantly and RH declined only weakly, which would suggest a uniform, temperature-driven change. The monthly analysis shows instead that the VPD increase from July to September is predominantly thermodynamic, whereas in April warming and declining RH contribute about equally.

4.2 Why April? The role of snow cover, the sea and vegetation

Three features of the Estonian spring can limit the moisture supply relative to warming. First, snow cover. Our day-level comparison shows that, at the same air temperature, cold April days with snow

cover have 5–7 percentage points higher RH than snow-free days. Physically plausible reasons are that snow keeps the surface near 0°C and limits sensible heating of the near-surface air, and that sublimation and melt may add moisture to it (Mott et al. 2018), although our analysis does not measure these fluxes directly. As the snow season ends earlier (Jaagus et al. 2017; Viru and Jaagus 2020; this study), more April days occur over bare, rapidly warming ground. Accounting for the end of the snow season reduced the estimated April RH trend by about one-fifth. This suggests that declining snow cover contributes to, but does not dominate, the April humidity decline. The snow effect was confined to inland stations, where the snow season is longer and ends later, which partly explains why the April humidity decline is stronger inland.

Second, the sea. In April, the Baltic Sea is still cold and is a weaker moisture source than in summer. Our data do not test the land–ocean warming contrast directly, but they show that the April moisture lag was much stronger at inland stations than at coastal and island stations, which receive air that has passed over the sea. This is consistent with the role of oceanic moisture supply in limiting continental RH decline (Byrne and O'Gorman 2016, 2018), and suggests that the proximity of the sea dampens the April humidity decline.

Third, vegetation. Before leaf-out, transpiration is small, and the land surface is a weak local moisture source. After leaf-out, evapotranspiration increases near-surface humidity and dampens the daytime temperature increase (Schwartz and Karl 1990; Fitzjarrald et al. 2001). Earlier warming in spring that is not matched by an equally early leaf-out would therefore increase VPD and lower RH in the period between snowmelt and green-up. The near-constant RH and weak VPD trend in June, when vegetation is fully developed and actual vapour pressure increased almost as fast as saturation vapour pressure, is consistent with this explanation. Testing it directly would require phenological observations matched to the station network; spring onset in Estonia has itself shifted earlier, and the size of the estimated shift depends on the reference period used (Saue 2026).

These mechanisms are not mutually exclusive. Together they suggest that the April moisture lag reflects a mismatch between the timing of warming and the timing of moisture sources that become fully effective only later in the season. Of these, only the snow-cover link was tested directly here.

4.3 Comparison with other studies

The predominance of the April signal agrees with the general tendency for land RH to decline where moisture supply from the ocean or from evapotranspiration is limited (Vicente-Serrano et al. 2018). The weak summer RH change in Estonia agrees with the small or positive warm-season RH trends found for Scandinavia (Vicente-Serrano et al. 2018) and with the weaker atmospheric drying in northern Europe compared with central and southern Europe (Treydte et al. 2024; Nagavciuc et al. 2024). Our results add that, in this region, VPD increases of similar size in April and in July–August have different compositions: in April, about half is due to declining RH, whereas in July–August most of it is thermodynamic.

4.4 Implications

The implications for vegetation and agriculture differ between seasons. In summer, the VPD increase is mainly thermodynamic and is accompanied by an increase in absolute humidity; its effect on crops is closely tied to warming itself. In April, the decline in RH occurs when soils are usually still moist after snowmelt and VPD is far below the levels that limit crop transpiration. The April change may therefore affect the drying of the soil surface, field operations and conditions for germination and emergence more than crop water stress. The increase in the number of April days with minimum RH below 30% at Jõgeva shows that the change also affects afternoon conditions, which are more relevant for plants than daily means. Assessing the agricultural consequences would require soil moisture and crop data, which were beyond the scope of this study. More generally, the results suggest that regions where spring warming coincides with snowmelt, a cold adjacent sea and leafless vegetation, such as other parts of the Baltic Sea and Fennoscandian region, may show a similar spring-specific moisture lag. Testing this with the scaling ratio requires only daily temperature and humidity observations, and seasonal or annual analyses are likely to miss it.

4.5 Limitations

The main limitation concerns the homogeneity of RH observations. Eleven of 20 stations showed relative inhomogeneities in April–May RH. The main results were unchanged when only the nine unflagged stations were used, but a network-wide change in instruments or observation practice would not be detected by relative tests. Breaks in the station series clustered in 1992–2001, which coincides with the regime shift in Estonian winter and spring climate around the late 1980s and 1990s (Jaagus et al. 2017). The temporal coincidence with a known climatic shift and the agreement between homogeneous and flagged stations support a climatic origin. In addition, a network-wide change of instruments would be expected to shift RH in all months, whereas the RH decline was confined to April and absent in summer. An instrumental contribution cannot be excluded without station metadata, but it is unlikely to explain the seasonal pattern. Second, daily mean RH does not represent afternoon conditions. Third, the snow analysis uses the end of the snow season only, not snow depth or the fraction of snow-covered area around the station. Finally, the attribution of the April humidity lag to the sea and vegetation is inferred from spatial and seasonal patterns, not tested directly.

5. Conclusions

1. An increase in VPD is not necessarily a loss of atmospheric moisture. In Estonia, VPD increased in April, July, August and September during 1965–2024, and changed little in May and June, but the composition of the increase differed between months.

2. From July to September, actual vapour pressure increased at roughly three-quarters of the rate of saturation vapour pressure, not significantly different from constant RH in July and August; the VPD increase was mainly a thermodynamic consequence of warming.

3. In April, moisture increased by less than 40 % of the amount needed to keep RH constant; RH declined by almost 1 % per decade, and the decline in RH contributed about as much to the VPD increase as

warming. April is the month in which the atmosphere has most clearly become drier beyond the effect of warming. The lag was stronger at inland than at maritime stations.

4. Accounting for the earlier end of the snow season reduced the estimated April RH trend by about one-fifth, mainly at inland stations; declining snow cover contributes to, but does not dominate, the April humidity decline. The remainder is consistent with a seasonal mismatch between rapid spring warming and moisture sources — the cold sea and leafless vegetation — that become effective only later in the season, although these were not tested directly.

5. Seasonal averages mask these differences. Assessments of atmospheric drying should separate the thermodynamic and humidity components and resolve their timing within the growing season.

Declarations

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The daily meteorological observations were obtained from the Estonian Environment Agency (Keskkonnaagentuur) and are available from the Agency; recent observations are also provided through its open-data service (https://www.ilmateenistus.ee). The analysis code, derived station and national series, and all results supporting the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.23222156.

Competing interests

The author declares no competing interests.

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no role in the design of the study; collection, analysis, or interpretation of data; or writing of the manuscript.

Author contributions

T.S.: Conceptualization, Methodology, Software, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the manuscript writing process

During the preparation of this work the author used Claude (Anthropic) to assist with drafting and revising the manuscript text and with the development of the analysis code described in Section 2.8. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

Supplementary information

Online Resource 1 (Table S1). Robustness of RH and VPD trends: monthly trends for all stations and RH-homogeneous stations, and dekadal trends, tested with the Mann–Kendall, Hamed–Rao and trend-free pre-whitening tests, with false discovery rate correction.

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Figures

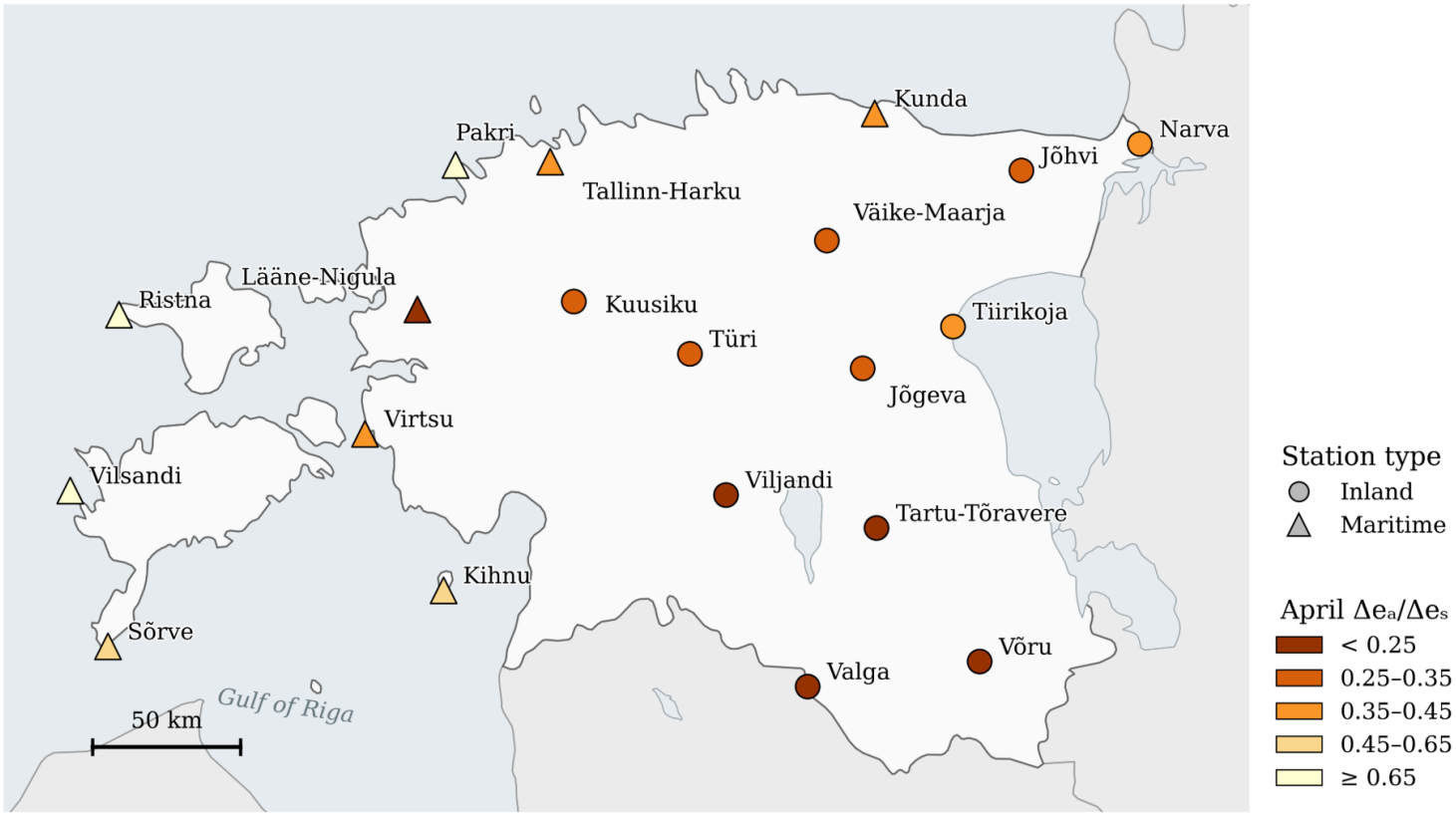


Figure 1

Location of the 20 meteorological stations. Triangles denote maritime (coastal and island) stations and circles inland stations; colour shows the April scaling ratio Δea/Δes (1965–2024) in five classes, where 1 corresponds to constant relative humidity and darker colours indicate a larger lag of atmospheric moisture behind warming.

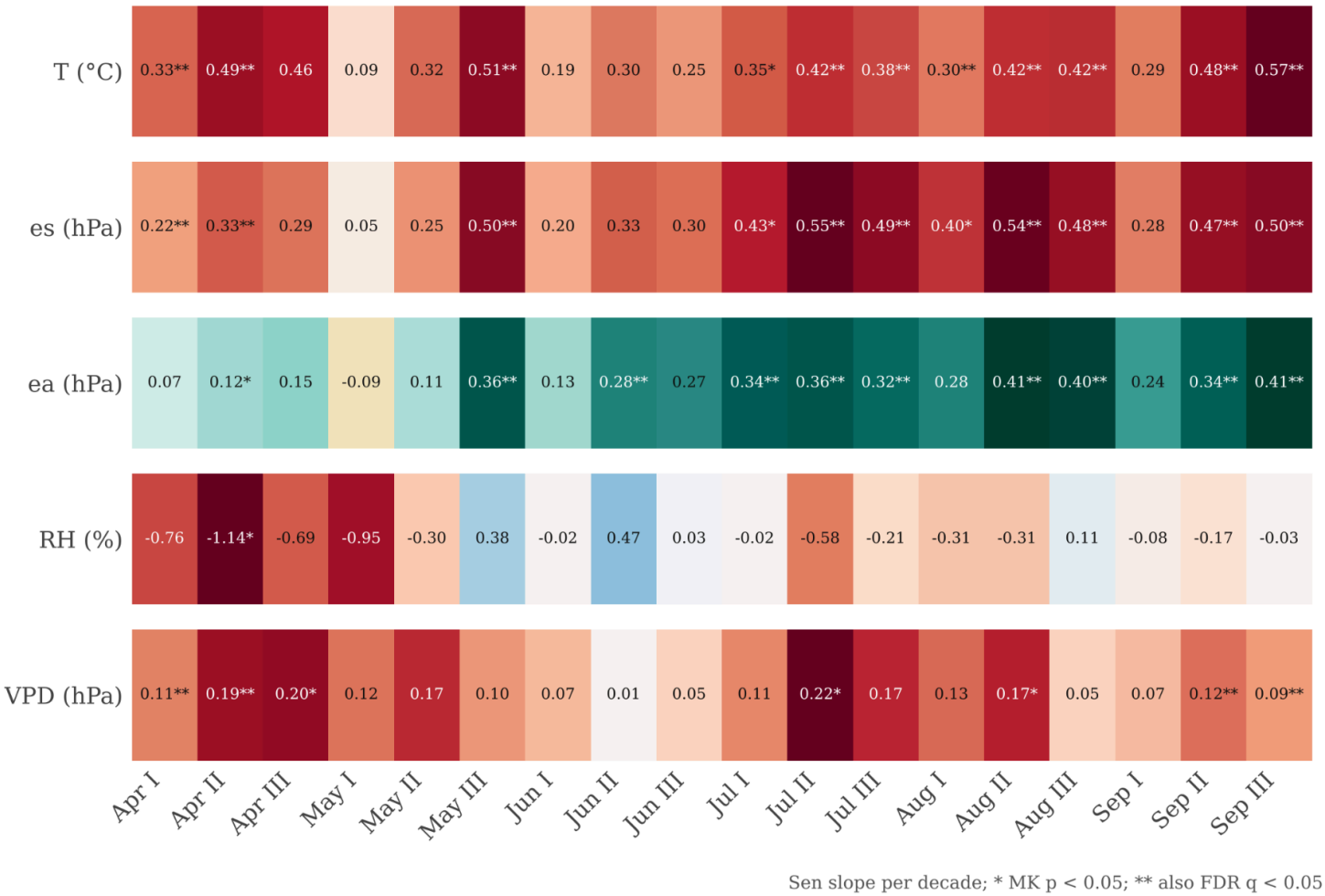


Figure 2

Trends in national mean air temperature (T), saturation vapour pressure (es), actual vapour pressure (ea), relative humidity (RH) and vapour pressure deficit (VPD) by dekad (I = days 1–10, II = 11–20, III = 21 to month end), April–September 1965–2024. Values are Sen slopes per decade. The colour scale is set separately for each variable; red shades indicate changes towards drier conditions (increasing T, es and VPD, decreasing RH), green shades increasing ea. *Mann–Kendall $p < 0.05$; also significant after Benjamini–Hochberg false discovery rate correction across the 18 dekads ($q < 0.05$)*

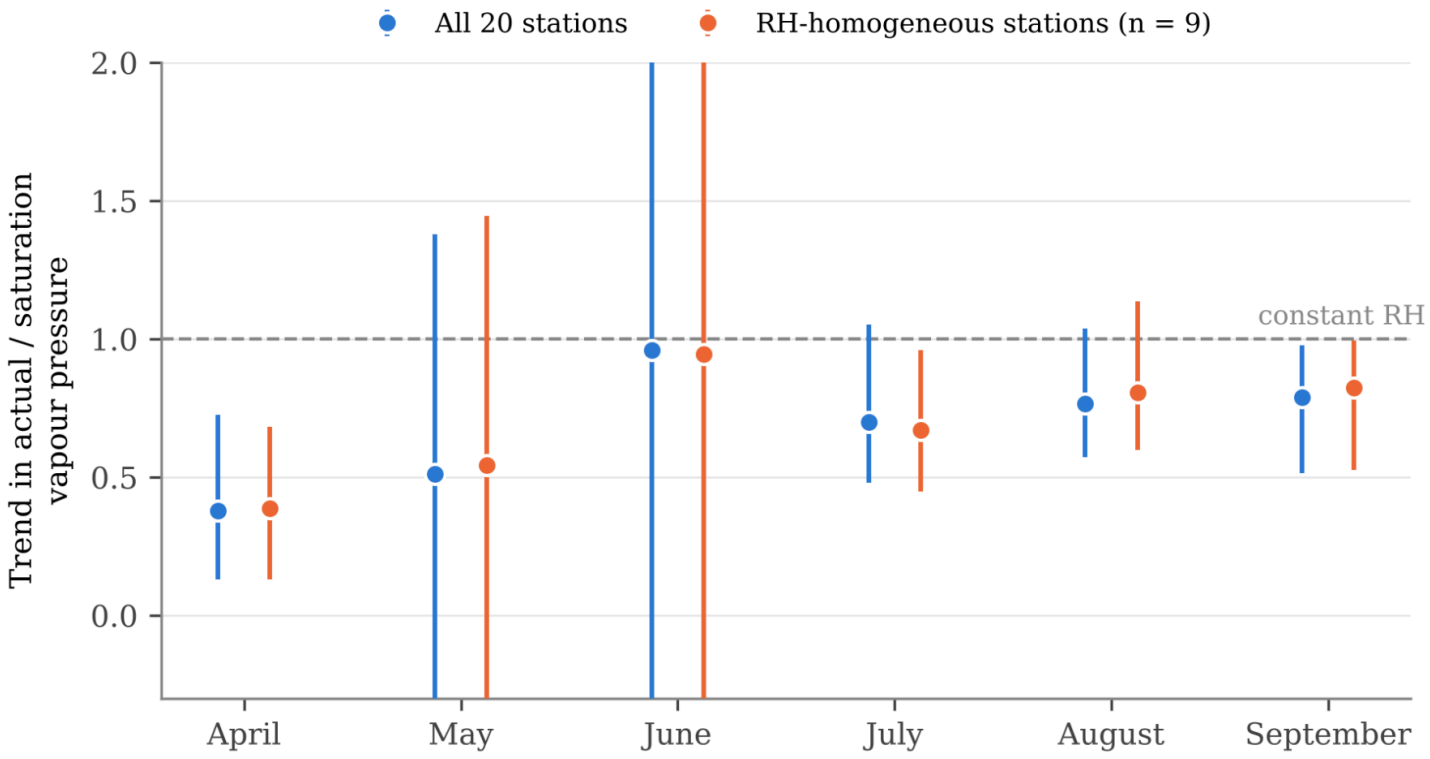


Figure 3

Monthly scaling ratio Δea/Δes, the ratio of the Sen slopes of actual and saturation vapour pressure, 1965–2024, for the national series from all 20 stations and from the nine RH-homogeneous stations. Vertical bars show 95 % confidence intervals from 2000 bootstrap resamples of years. The dashed line (ratio = 1) corresponds to constant relative humidity; values below 1 indicate that atmospheric moisture increased more slowly than saturation vapour pressure. Confidence intervals for May and June extend beyond the plotted range, because both es and ea trends were small in these months.

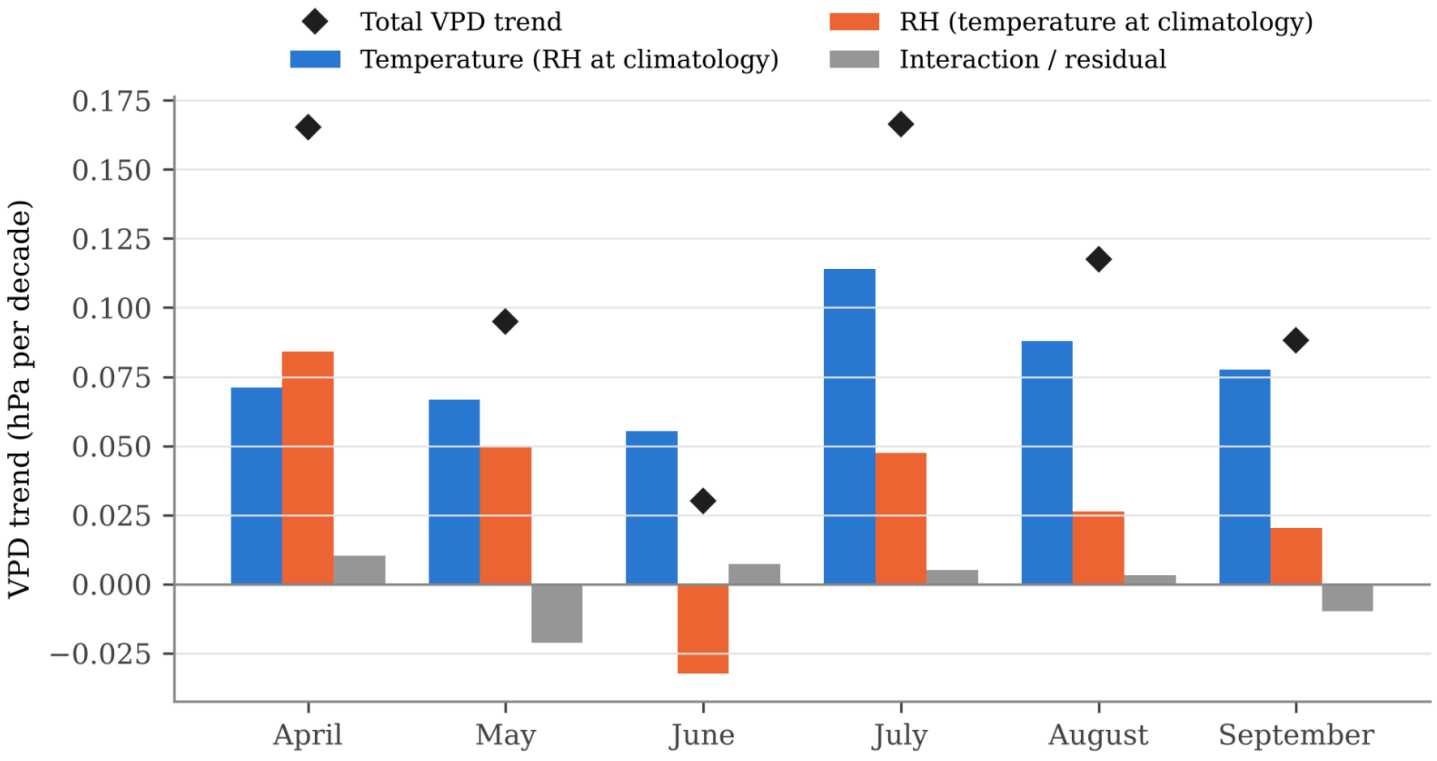


Figure 4

Decomposition of monthly VPD trends (hPa per decade), 1965–2024. Diamonds show the trend in observed VPD. Blue bars: temperature-only component (observed Tmax and Tmin, RH held at its station-specific calendar-day climatology); orange bars: humidity-only component (observed RH, temperature held at its climatology); grey bars: interaction (total minus the two components).

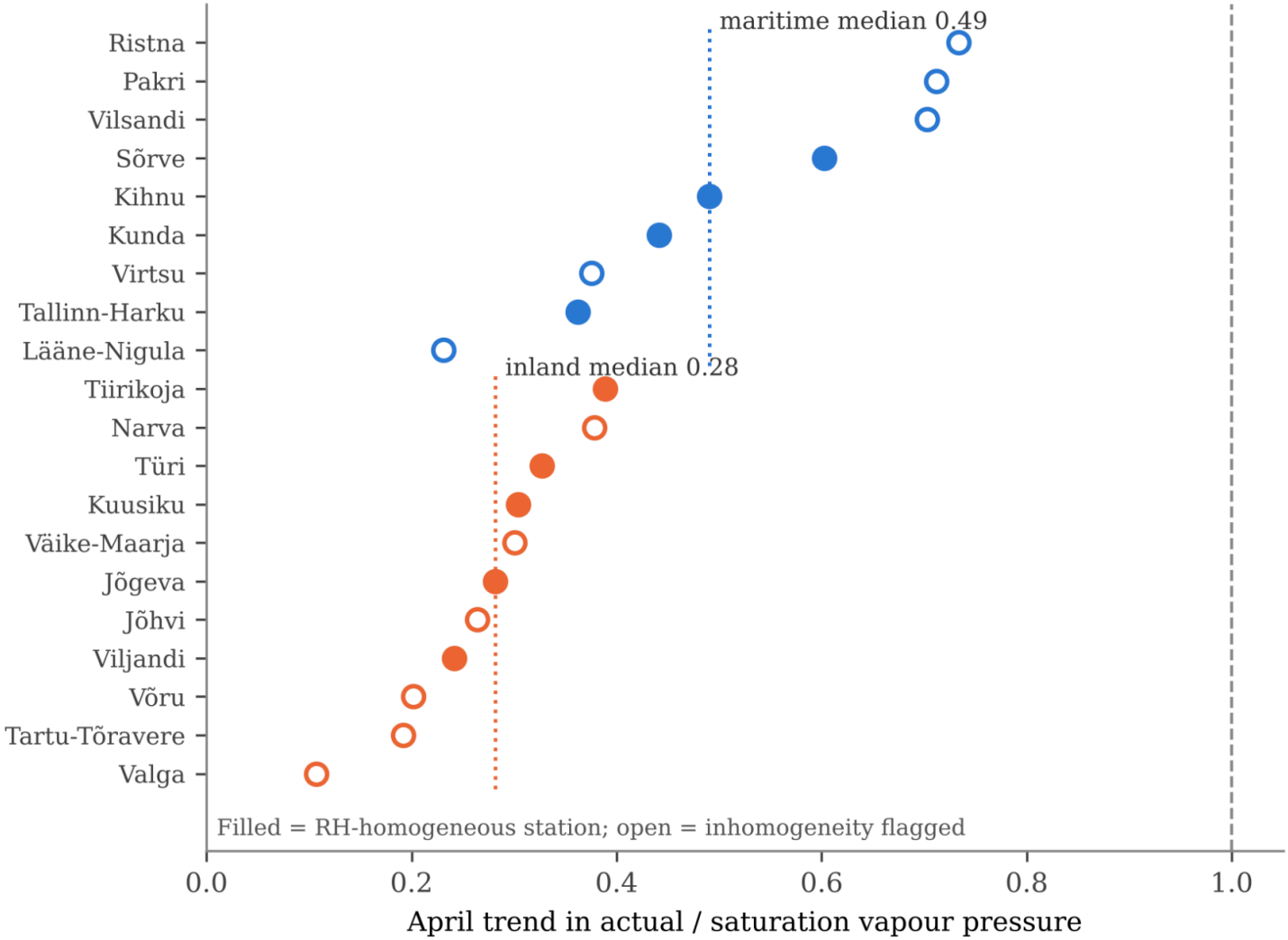


Figure 5

April scaling ratio Δea/Δes at individual stations, 1965–2024, for maritime (blue) and inland (orange) stations. Filled symbols denote RH-homogeneous stations and open symbols stations with a detected relative inhomogeneity in April–May RH. Dotted lines show the group medians; the dashed line (ratio = 1) corresponds to constant relative humidity.

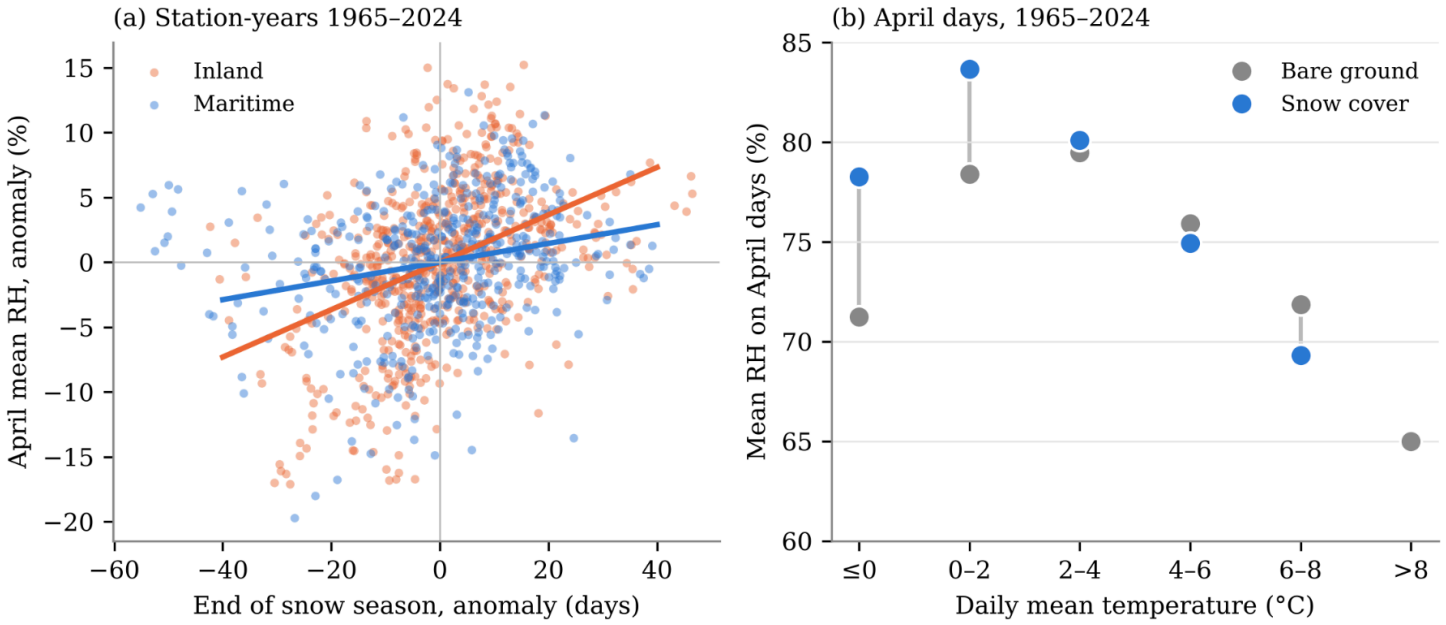


Figure 6

Snow cover and April relative humidity, 1965–2024. (a) Anomalies of April mean RH against anomalies of the end of the snow season (both relative to station means) for station-years at inland and maritime stations, with ordinary least-squares fits for each group. (b) Mean daily RH on April days with snow cover (snow depth ≥ 1 cm) and without snow cover, by class of daily mean temperature, pooled over all stations; vertical lines connect the two means within each class. Means for snow-covered days are shown only for classes with at least 30 such days.

Supplementary Files

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- VPDTableS1TAC.docx